Microbes on Mars can't get to Earth “faster and better protected in a meteorite” - if Mars has native microbes, some may be like the invasive diatom "Dydimo" in New Zealand, and can't get here at all

Author: Robert Walker (contact email [robert@robertinventor.com](mailto:robert@robertinventor.com))

Preprint DOI [10.31219/osf.io/rk2gd](https://osf.io/rk2gd) (previous DOI: [10.31219/osf.io/s8gcn](https://osf.io/s8gcn) for earliest versions)

**For latest version of this preprint** please visit: (url <https://osf.io/rk2gd>)

(This version 24th December, 2022)

[MID EDIT TO TAKE ACCOUNT OF THE CHANGE IN THE EIS APPROVAL PROCESS WHICH CAN NOW BE COMPLETED IN LESS THAN A YEAR - SOME SECTIONS STILL REFER TO THE OLDER 6-7 YEARS PROCESS]

For NASA’s draft EIS see my preprint: [Such serious flaws in NASA's Environmental Impact Statement for a Mars Sample Return - omits major impacts – uses old science later overturned – statements cited to sources that say the opposite – no response to significant public concerns - and haven’t done the update for size limits recommended by the ESF in 2012 after they reduced it from 0.2 to 0.05 microns in just 3 years](https://osf.io/2jfnv)

For higher resolution graphics download original [Word document](http://robertinventor.com/booklets/NASA_expected_sterilize_Mars_samples_before_2039.docx) or [high resolution pdf](http://robertinventor.com/booklets/NASA_expected_sterilize_Mars_samples_before_2039.pdf). [Some figures omitted - need permission]

Please note this preprint is not yet peer reviewed and is currently in the process of development with frequent updates.

Section titles are written like mini-abstracts. For a fast overview, read the headings, and drill down into sections of interest for more details

Table of Contents

# **Could Martian life have got to Earth on meteorites? Our Martian meteorites come from at least 3 m below the surface in high altitude regions of Mars**

If Earth frequently encounters Martian life, then we have no need to protect Earth with special precautions, by Greenberg’s “Natural Contamination Standard” [(Greenberg et al, 2001)](#kix.r2syrcl7s0ll).

However, our Martian meteorites all come from at least 3 meters below the surface [(Head et al, 2002:1355)](#4ut9kfm5zz3j), and left Mars over a period spanning 20 million years. They were probably thrown up into space after glancing collisions into the Elysium or Tharsis regions, high altitude southern uplands [(Tornabene et al, 2006)](#kix.a4ip5t4d8249). The atmosphere for these high altitude regions on Mars is thin, making ejection to Earth easier. The subsurface below about 12 cms has a uniform temperature of around 200°K or -73°C ([Möhlmann, 2005:figure 2](#b_Möhlmann_2005)). With such a thin atmosphere, present day life at those altitudes is unlikely (except perhaps for deep subsurface geothermal hot spots).

So it seems unlikely that any life has got to Earth in the last few million years. The Martian meteorites we have are from one of the least likely to be habitable regions on Mars, the sub-surface of the high altitude Martian uplands.

It is not totally impossible life could get into the Martian meteorites, but would require a high measure of luck. Some Martian volcanoes have been active in the geologically recent past, as recent as 2 million years ago. Olympus Mons also shows signs of glacial activity as recent as four million years ago which suggests it likely has ice protected beneath the dust on its slopes. . [(Neukam et al., 2004)](#b_Neukum_2004)

A lucky asteroid impact on Mars could throw up material from a subsurface cave, or a geothermal hot spot, or fumarole. But such events would surely be rare.

So, it’s possible that some exceptionally hardy life has got here, even in geologically recent times. Perhaps life from geothermal vents after a lucky strike of a meteorite into a geologically active geothermal system on the flanks of Olympus Mons.

It’s not impossible that a lucky asteroid impact could send back life from Mars from a cave or a geothermal vent just below the surface, but most wouldn’t send any life this way.

Just as there are many species on Earth that could never get to Mars on a meteorite, if Mars has a diversity of microbial species, there are likely to be many species on Mars that could never get to Earth that way.

## [Larger impacts could send material to Earth - but unlikely to transfer fragile surface dirt, ice and salts](#h_larger_impacts)

Larger impacts in the recent geological past could send material to Earth from other potentially more habitable parts of Mars. However:

* **Many proposed habitats are in surface layers of dirt, ice and salts**. These would likely never get into space
* **Other proposed habitats are millimeters below the surface of rocks**. These layers would ablate away during entry into the Earth's atmosphere
* **Life on Mars could be extremely localized to only a few square kilometers over the entire planet,** for instance, only to the RSL's, or only above geological hot spots, making it less likely that the habitats are hit by an asteroid able to send material all the way to Earth in the large chunks needed for protection from cosmic radiation during the transfer.   
  .

It was easier for Mars to exchange life with Earth in the early solar system. However even the ejecta from an impact into a Martian ocean need not necessarily transmit life to Earth.

The first challenge is the shock of ejection. Microbes are suddenly accelerated from rest to escape velocity in a fraction of a second. The microbes can be destroyed by cell rupture or by DNA damage. All cells of Chroococcidiopsis are killed at 10 GPa [(Nicholson, 2009)](#b_Nicolson_2009)

ALH84001 experienced a shock of ejection of ∼35 − 40 GPa. The Nahkalites were least shocked at 15 to 25 GPa. This is still too much for Chroococcidiopsis ([Nyquist, 2001](#b_Nyquist_2001))

Some deep subsurface layers are sent to orbit with much less shock especially for the larger impacts. These low levels of shock arises from interaction between the shock wave moving away from the forming crater and a reflected shock wave moving backwards. The shock moving back is 180 degrees out of phase so the two shock waves cancel, creating a lightly shocked "spall" zone where the two interact. The spall zone depth is proportional to the radius of the impactor, so a large impactor would have a thicker spall zone. Some of the ejecta would survive shock of less than 1 GPa [(Mileikowsky, 2000: 393)](#8hxwmd2aon4m)

For the Mars meteorites, from modelling, about 2% of the ejecta is lightly shocked in this way. ([Nyquist, 2001](#b_Nyquist_2001):147).

More shock resistant microbes can survive better. Of the order of 1 in 10,000 of microbes of b. subtilis and the photobiont and microbiont partners in the lichen X Elegans could survive 40 to 50 GPa [(Nicholson, 2009)](#b_Nicolson_2009). In one paper, samples of a marine photosynthetic algae nannochloropsis oculata frozen in ice were able to survive 6.93 km / sec impacts into water with approximate shock pressure of 40 GPa [(Pasini, 2014)](#b_Pasini).

The Martian life then has to survive the fireball of exit from the Martian atmosphere. The lower gravity reduces the Martian escape velocity from 11.19 to 5.03 km / sec [(NASA, n.d.mfs)](#3i92khuqkils), but the Martian atmosphere has to have nearly three times the mass of the Earth’s atmosphere for the same surface pressure, and the Martian atmosphere was likely several bars for early Mars [(Mileikowsky et al, 2000: 423)](#8hxwmd2aon4m).

It then has to survive the cold and vacuum conditions of space and cosmic radiation. Cosmic radiation sterilizes the surface of a meteorite to a depth of 2 cm within 100,000 years by breaking up the nucleic acids . That's below the maximum depth you'd expect to find photosynthetic life in normal circumstances, even in fine cracks.

It is theoretically possible for some rocks to get to Earth as soon as ten years after ejection from Mars. But most take between a hundred thousand and ten million years to get there. Assuming a maximum ejection velocity of 6 km / sec, in a simulation with 2100 particles, incorporating the gravitational effects of all the planets from Venus through to Neptune, most took over 100,000 years in transit. The fastest transfer in the simulation was 16,000 years [(Gladman et al, 1996)](#b_Gladman_2005).

It also has to survive the fireball of re-entry to Earth, Cockell inculcated an artificial gneiss rock with Chrooccoccidiopsis at a depth where it occurs naturally, and affixed it to the re-entry shield of a Soyuz rocket. None survived re-entry, nor did any organics. He concluded that it might not be impossible for photosynthetic life to get to Earth from Mars, but it would need an extraordinary combination of events [(Cockell, 2008)](#kix.jztdleevmtmy)

Some terrestrial extremophiles might survive these processes but the fireball of re-entry would sterilize most of them.

The interior of a rock can be better protected. The interior of ALH84001 never got hotter than 40°C during entry into our atmosphere [(Weiss et al, 2000)](https://docs.google.com/document/d/1QJgApnOW88OXgjuC7ktzaYiiE7UQHay2ihBWC9TARKw/edit#bookmark=kix.43dyislwi4gd). But how does the photosynthetic life get deep into a Martian rock? It can flourish in cracks, if light filters in through them - but that also would give cracks that channel hot gases into the interior of the rock during re-entry. Cracks like that would also be places where the rocks are quite likely to break apart during ejection from Mars or re-entry to Earth.

Charles Cockell's concludes that it might not be impossible for photosynthetic life to get to Earth from Mars, but it would need a rather extraordinary combination of events [(Cockell, 2008)](https://docs.google.com/document/d/1QJgApnOW88OXgjuC7ktzaYiiE7UQHay2ihBWC9TARKw/edit#bookmark=id.sj1jq9bxdb1a):

"Thus, the planetary exchange of photosynthesis might not be impossible, but quite specific physical situations and/or evolutionary innovations are required to create conditions where a photosynthetic organism happens to be buried deep within a rock during ejection to survive atmospheric transit."

His final conclusion is that photosynthetic life has the potential to make dramatic changes to a planet, but that this transfer of photosynthetic life is less likely than for heterotrophs (which use organic carbon) or chemotrophs (which use chemical reactions as a source of energy and synthesize all their organics from carbon dioxide, living in places such as hydrothermal vents).

In addition, panspermia experiments are based on capabilities of terrestrial life. Capabilities of any native Martian life are unknown. Many Earth microbes could not survive this journey.

It’s not impossible that Martian life made the transition. However, even if there has been some transfer of llife from Mars to Earth, there are likely to be many species of Martian life that don’t have the capability to get to Earth in this way, as for their Earth counterparts, either because they live in fragile habitats like dust and salts that can’t be transferred via meteorites, or because they don’t have the extremophile adaptations needed to be able to survive the transfer.

So we can’t apply the Greenberg “Natural Contamination Standard” [(Greenberg et. al, 2001)](#kix.r2syrcl7s0ll) for microbial life from Mars. It’s possible that a sample return could return microbes that wouldn’t be able to get to Earth on meteorite impacts.

# **[Could life get transferred from Earth to Mars? With Earth’s high gravity and thick atmosphere the challenges are far greater but may be more possible in the early solar system with impacts large enough to blow out part of Earth’s atmosphere](#h_could_life_get_transferred)**

In the opposite direction from Earth to Mars, the challenges are far greater. When meteorites hit Earth, the deceleration during reentry slows down the initial impact velocity of kilometers per second to meters per second. In the opposite direction, an ejected rock has to be travelling fast enough to pass through the atmosphere fast enough to leave it at 11.2 km / second, the escape velocity of Earth. This means it has to leave Earth’s surface at far higher than 11.2 km / second. Although ejection at that speed is possible, and the Chicxulub impact sent meteorite fragments as far as Mars, the shock of ejection and the fireball of exit from Earth’s atmosphere would have likely sterilized any life on the meteorites before they left Earth’s atmosphere.

The best opportunity for transfer from Earth to Mars is after very large impact events, large enough to blow out at least part of Earth’s atmosphere, so leaving a low pressure region for the ejection fragments to exit through [*(*Stöffler et al, 2007)](#b_Stoffler_2007)..

*“'Lithopanspermia' also includes a potential transfer of microorganisms in the opposite direction, i.e., from Earth to Mars. A direct transfer scenario is severely limited because very high ejection velocities in the solid state are required to escape the Earth's gravity field and to pass its dense atmosphere. Favorable transfer conditions may be only achieved by very large impact events, which blow out at least part of the atmosphere. Such impact events happened frequently during the 'early heavy bombardment phase',”*

So it is possible that terrestrial and martian life is related through transfer from Earth to Mars, especially if early life had the capabilities to survive transfer from impacts large enough to blow out part of Earth’s atmosphere, but if so the two biospheres have likely evolved separately for billions of years.

There could also be unfamiliar life on Mars that evolved there independently co-existing with life that was transferred from Earth to Mars.

## [Report by the National Research Council couldn’t discount the possibility of past mass extinctions caused by Martian life - could the Great Oxygenation Event be an example?](#h_report_extinctions_GOE)

If it turns out that some terrestrial microbes did originate on Mars and transferred from Mars to Earth in the past, this does not mean it is safe to return material from Mars today. Martian life might have already harmed Earth’s biosphere in the past. We wouldn’t know.

The National Research Council looked into this question in their "Assessment of Planetary Protection Requirements for a Mars Sample Return". They were unable to rule out the possibility that life from Mars could have caused past mass extinctions on Earth [(Board et al, 2009: 48).](#kix.xed3c1hm3p4k)

They gave no examples, but the Great Oxygenation Event could be relevant. Chroococcidiopsis may be partially responsible for the oxygenation of our atmosphere. One minority view explains the unusual ionizing radiation resistance of Chroococcidiopsis as a natural adaptation of Martian organisms [(Pavlov et al, 2006)](#kix.6kz2ugfajs01).

This is weak evidence since the ionizing radiation resistance of chroococcidiopsis could be a byproduct of the repair mechanisms that chroococcidiopsis uses for UV resistance and desiccation resistance. Cyanobacteria originated in the Precambrian era. It could have developed these mechanisms back then, when, with no oxygen in the atmosphere, there was no ozone layer to shield out UV radiation [(Casero et al, 2020)](#kix.5e3cnw9bwsp9) [(Rahman et al, 2014)](#b_Rahman_2014)

However, the early Martian atmosphere was rich in oxygen [(Lanza et al, 2016)](#kix.hxbmnc1rd0et) before Earth and though much of that may well be due to ionizing radiation from solar storms splitting the water it’s not impossible that it had photosynthetic life.as well.

Some astrobiologists have hypothesized that terrestrial life originated on Mars as we saw in

* [Discovery of a familiar microbe like chroococcidiopsis does not prove all life in the sample is familiar – if terrestrial life originated on Mars, it could have extra domains of life that never got to Earth](#h_discovery_chroococcidiopsis_Mars)

## Whether or not chroococcidiopsis caused the Great Oxygenation Event – it gives a practical example of a way life from another Mars-like planet could in principle cause large scale changes to an Earth-like planet

If something like chroococcidiopsis evolved on Mars, it is not impossible it got to Earth via meteorites - though as we saw in the last section, ejection from Mars would be a major challenge [(Cockell, 2008)](#kix.jztdleevmtmy).

Whether this happened for Mars and Earth, it does give a practical example of a way that life from another planet such as Mars could in principle cause large scale changes to an Earth-like planet.

So was this an extinction event? The Great Oxygenation Event might have forced rapid evolution rather than extinction. Early anaerobes may have retreated to anaerobic habitats as obligate anaerobes, which we still have today [(Lane, 2015)](#kix.1v0mroc400lk).

However, there is some evidence suggesting extinctions. There is evidence of exceptionally large sulfur reducing bacteria from this time, 20 to 265 µm in size, which also occasionally occur in short chains of cells. This may be part of a diverse ecosystem that predated the GOE [(Czaja et al, 2016)](#kix.fwlywarqzqts). If such an ecosystem existed, most traces of it are gone now. However it seems not impossible that the GOE had major impacts on a prior diverse ecosystem.

There are many other confirmed mass extinctions in the fossil record. In many cases the cause is not fully known or debated leaving it at least hypothetically possible that microbial transfer from Mars could be part of the explanation.

Whether or not this ever happened in the past, this worked example of the Great Oxygenation Event shows how in the worst case scenario, independently evolved life from another planet could lead to large scale transformations of the chemistry of Earth’s atmosphere or oceans, climate and ecosystems. Humans with modern technology would surely survive a gradual transformation of our atmosphere and oceans but it could make the planet significantly less habitable in the short term for humans and other species.

# [**Scenario: evolution on Mars evolves faster than on Earth because of an oxygen rich atmosphere and frequent freeze / thaws of oceans, leading to life of the same genomic complexity as Earth or even greater, and with multicellularity evolving early**](#h_scenario_evolution_faster)

We saw that there is a strong case for life on Mars to be at an early stage, see

* [Possibility of early discovery of extraterrestrial microbes of no risk to Earth such as pre-Darwinian life as suggested by Weiss – if microbial challenge experiments show they are quickly destroyed by pervasive terrestrial microbes](#h_poss_early_discovery) (above)

However we can also argue a strong case in the opposite direction too. in this scenario it goes in the other direction, as advanced as Earth life, perhaps even more complex, with more evolved genomes than for Earth life.

Perhaps rapid evolution would be favoured by the many changes in habitability of early Mars or by the high levels of oxygen in early Mars. For the changes in habitability see:

* [Evidence that habitability of Mars frequently changes in brief episodes of warmer conditions](#h_Evidence_habitability) (above)

If this is true, it is not impossible Mars developed its first multicellular life billions of years before Earth did.

Genetic complexity needn’t mean intelligent life. This could mean microbial life, sponges, lichens, molds and so forth with genes more complex than any equivalent Earth life has yet developed. E.g. the Martian chroococcidiopsis might have had the equivalent of another several billion years of terrestrial evolution and have a wider variety of capabilities than any of the terrestrial strains. Or perhaps multicellular life evolved on Mars many times, and has been able to explore types of multicellular life novel to us and not classifiable as multicellular algae, fungi, animals or plants.

The frequent freezings of the Martian oceans in early Mars, possibly every Martian year when its eccentricity is high, and the ionizing radiation, might have led to populations repeatedly reduced to a fraction of the previous numbers, then rapidly growing again. Boyle et al argued a similar process led to the development of multicellular life on Earth during its “snowball Earth” glaciations ([Boyle et al, 2007](#b_Boyle_2007)).

Their suggestion is that during snowball Earth phases, colonies would often be founded by a single cell from the previous generation, the founder effect, leading to habitats colonized by large numbers of almost identical cells. These cells would be confined to small habitats, and so encounter each other more often, increasing the benefits of mutual altruism. The rate of reproduction would also be slow, reducing the benefit to “cheats” that do not contribute to the benefit of the colony as a whole.

In this scenario, they suggest, there would be more importance in mutually beneficial modification of a microhabitat through production of chemicals that are costly for individual cells to produce. They suggest that differentiation of cells, the first steps towards multicellularity, would be especially useful in harsh conditions.

Although they do not apply their theory to Mars, these are conditions that applied to early Mars frequently.

This process would still continue today, with the frequent short term changes in habitability of Mars. See:

* [Evidence that habitability of Mars frequently changes in brief episodes of warmer conditions](#h_Evidence_habitability) (above)

Another possibility is that oxygen triggered the explosion of multicellular life. The last common ancestor of the eukaryotes may have lived between 1.855 and 1.677 billion years ago. That's at a time when the oceans were only moderately oxygenated. Most of the varieties (clades) of eukaryotes diverged before 1 billion years ago, probably before 1.2 billion years ago. But the huge diversity we have today within those clades only started 800 million years ago when the oceans started to change to their modern chemical [(Parfrey et al, 2011)](#kix.2194ds7axidc). Curiosity’s Chemcam instrument found manganese oxides which suggest that at the time of Gale crater lake, three billion years ago [(NASA, 2017)](#kix.tjzxrp4w3koy). the water was oxygen rich [(Lanza et al, 2014)](#kix.7pu0hbvl21ep).

So, perhaps the case can be argued both ways, that the harsh conditions could have slowed down evolution, or that the ionizing radiation and the frequent “snowball Mars” phases, combined with the oxygen rich early atmosphere and frequent localized temporary habitats and the oxygen rich brines of present day Mars, could have triggered a more rapid evolution on Mars, and possibly even complex multicellular life billions of years before it became common on Earth.

If Mars had multicellular life early on, perhaps that multicellular life is still there, as a relic biosphere. Stamenković et al, 2018 research suggests the possibility of enough oxygen for simple animal life such as sponges exploiting the oxygen in extremely cold oxygenated salty brines when the axial tilt of Mars is less than 45 degrees.

As we saw, present day Mars may also have conditions for oxygen rich brines anywhere on the surface, by taking up oxygen from the atmosphere, a process that happens most easily in cold conditions. Extremely cold brines in polar regions could reach oxygen saturation levels similar to those needed for primitive sponges [(Stamenković et al, 2018)](#kix.b5k93sevqv0j) [(Walker, 2019)](#Walker2019). The south pole subglacial lake ([Orosei et al, 2018](#b_Orosei_2018)), ([Witze 2018](#b_Witze_2018)), if they exist, may provide habitats for multicellular life. These habitats may also be oxygen rich, through radiolysis of the ice, favouring animal life [(Walker, 2019:](#Walker2019) [section on subglacial lakes](https://encyclopediaofastrobiology.org/wiki/Sponges_on_Mars%3F_We_ask_Stamenkovi%C4%87_about_their_oxygen-rich_briny_seeps_model)), [(Stamenković et al, 2018)](#kix.b5k93sevqv0j). See:

* [Some Martian brines could be oxygen rich permitting aerobes or even primitive sponges or other forms of multicellularity - Stamenković‘s oxygen-rich briny seeps model](#h_some_brines_could)

(above)

Mars also has times of volcanic activity leading to hydrothermal systems where ice meets with lava. These lead to lakes that last for thousands of years, as happened 210 million years ago on one of the flanks of Arsia Mons, two lakes with around 40 cubic kilometers of water each, and a third one of 20 cubic kilometers of water, liquid for hundreds, or even thousands of years [(Scanlon et al, 2014)](#kix.vafoe4n0yj70). Our infrared mappers can only directly measure the top few millimeters of the surface, and there could be present day hydrothermal systems at depths of up to tens or hundreds of meters below the surface, where biological activity may still survive ([Nisbet et al, 2007](#b_Nisbet_2007), page 108ff).

If it is true that the rapid changes in habitability and or the oxygen speed up evolution of multicellular life, this could also lead to a scenario of frequent extinction and then renewed evolution of multicellularity.

This is similar to Cockell’s suggestion  [(Cockell, 2014)](#kix.1w5s0x4py5zu):

*There are other trajectories of greater complexity that can be envisaged. Examples include an inhabited Mars on which life becomes extinct and then reoriginates (or is transferred from Earth) at some later time.*

The step from unicellular to multicellular life could be something that happens on Mars frequently as it fluctuates in habitability. Primitive multicellular creatures such as sponges and lichens might evolve anew during the longer periods of habitability and then go extinct again over and over in Martian history.

One possibility is life on Mars and Earth has a common origin, seeded from each other. Both could also be seeded from other stars in the birth nebula of our solar system which could exchange life readily when the stars were closer together ([Valtonen et al, 2008](#b_Valtonen_2008)) ([Belbruno et al, 2012](#b_belbruno_2012)). Life in our sun’s birth cluster could also originate in a star older than our sun, spread from cluster to cluster by life bearing stars ([Adams et al, 2005](#b_Adams_2005))

Sharov et al. graphed genetic complexity of non redundant nucleotides against the time of origin of an organism, and found that the complexity of the most complex organism increased at almost the same uniform rate of exponential increase of a 7.8 fold increase in complexity every billion years (log of complexity increased by 0.89 every billion years) ([Sharov, 2006](#b_Sharov_2006)).

To get this graph, Sharov et al. first had to deal with the issue of “junk DNA” as it is popularly called, DNA that doesn’t encode for proteins. For the prokaryotes, cells without a nucleus including the archaea and bacteria, there is a single genetic sequence in a closed loop and nearly all is functional. However for eukaryotes, cells with a separate nucleus enclosed in a membrane inside the cell, often most of the DNA is non coding, doesn’t make proteins.   
  
Some eukaryote microbes have more DNA than a human being - much of that consisting of Transposable Elements (TEs) which sequences that are either copied to RNA and pasted back into the DNA (retrotransposons) or cut and pasted directly from one part to another of the DNA (transposable DNA) ([Pray, 2008](#b_Pray_2008)) ([Elliot et al., 2015](#b_Elliott_2015)). They can sometimes take some of the gene sequence along with them when they jump ([Pray, 2008](#b_Pray_2008)). Some of these eventually get incorporated into genes that code for proteins([Elliot et al., 2015](#b_Elliott_2015)), for instance, 2% of the genes encoding proteins in rice are chimeric proteins that have TEs as part of the gene sequence ([Sakai et al., 2007](#b_Sakai_2007)).

However, a lot of the gene sequences in eukaryotes seem to serve no function – if they were removed the organism would likely behave much the same way, except that they can slow down replication as there is more gene sequence to copy each time a cell replicates, and they are useful for future evolution of chimeric protiens. This is the so called C Value Enigma ([Nicolau et al., 2021](#b_Nicolau_2021)). Measuring the DNA by functional non redundant nucleotides deals with that issue.

Projecting back, if evolution of genetic complexity continued at the same rate since the origins of life, Sharov finds that Earth life originated around ten billion years ago. If so, life on Earth could be billions of years older than our solar system ([Sharov, 2006](#b_Sharov_2006)).

Chart

Description automatically generated

This diagram shows an estimate for the complexity of each type of organism when it first appears in the record. It uses the complexity of the DNA as measured using the number of functional non redundant nucleotides ([Sharov, 2013](#b_Sharov_2013)). This is a better measure of the genetic complexity than the total length of its DNA.

The graph is from ([Sharov, 2013](#b_Sharov_2013):Figure 1) with the section from the origins of Earth onwards also in ([Sharov, 2006](#b_Sharov_2006)), which also explains in detail how it was derived.

Notice that the prokaryotes; the simplest primitive cell structures we know; are well over half way in complexity between the potential earliest forms of life and ourselves.

Mammals have around 3.2 billion base pairs or 3.2× 109, but only 5% is conserved between species. Sharov et al. add another 10% as their estimate for other regions that are likely functional but vary between species for a total of 480 million base pairs in ([Sharov, 2006](#b_Sharov_2006)).   
  
The found that the smallest prokaryote base pair has 500,000 base pairs (for Nanoarchaeum equitans and Mycoplasma genitalium) or 5 × 105. These microbes are host dependent and don’t make all their proteins, but they used them as an estimate for the size for the first most primitive prokaryotes in ([Sharov, 2006](#b_Sharov_2006)),.

Sharov et al. found that plants gain in complexity more slowly than mammals. The first flowering plants had a third of the genetic complexity of mammals yet appear in the record at around the same time. The most complex archaea increased only 1.9 fold every billion years and the most complex Eubacteria increased only 2.5 fold every billion years ([Sharov, 2006](#b_Sharov_2006)).

However, if the constant is planet dependent, Martian life could exist at a different stage of complexity. Perhaps abundance of life leads to faster evolution of non redundant genomes. If so Earth might have faster exponential growth in complexity than Mars. Or perhaps the frequent alterations between more and less habitable and disconnected habitats where life can evolve separately could lead to more diversity and faster genomic evolution, then Mars could have faster exponential growth in complexity than Earth.

Martian life could be at a less advanced level or a more advanced level than terrestrial life, with genome sequences either less or more complex than we have on Earth at present. Indeed, it would be a significant coincidence if the genomic complexity of present day independently evolved life on Mars is identical to the genetic complexity of terrestrial life.

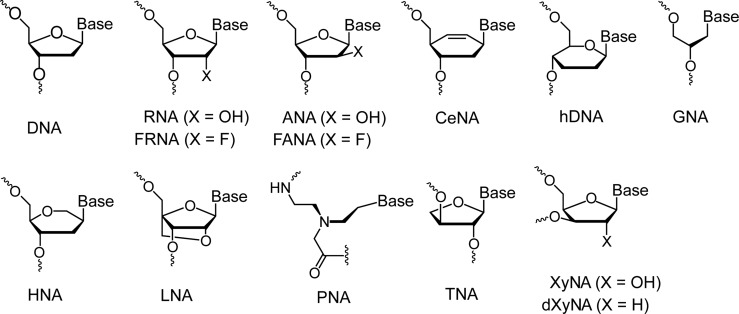
For instance, if Mars has chroococcidiopsis with a common ancestor with Earth, is it possible that it could have greater genomic complexity than any of its terrestrial strains?

Also though Mars couldn’t have evolved mammals, could it have evolved other forms of life at a similar level of genomic complexity, Or would the maximum complexity be similar to the fastest evolving terrestrial microbes or plants, or be much less than either of those?

# **[Potential diversity of extraterrestrial life based on alternatives to DNA such as RNA, PNA, TNA, additional bases and an additional or different set of amino acids](#h_potential_diversity_et_life)**

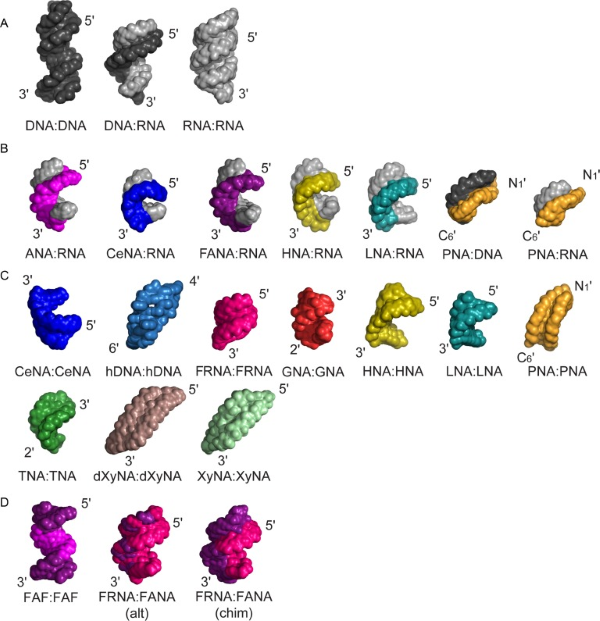
Martian biochemistry may not resemble Earth life. The simplest form of transformation is mirror life, and we use this as the main example because it is universally recognized as a possibility. Another possibility is RNA world life which doesn’t have DNA. Other possibilities include PNA or TNA which have a different backbone from DNA or RNA [(NASA, 2001)](#m4e9tott2ztz),

However there are many ways now known to construct the backbone of an informational biopolymer. Some of these might also potentially be available to extraterrestrial life.



[Figure 58](#figur_DNA_alternatives): some of the proposed “backbones” for alternatives to DNA for a bioinformational polymer [Figure 2 of [(Anosova et al, 2015)](#kix.e14ki8zas6p8)]

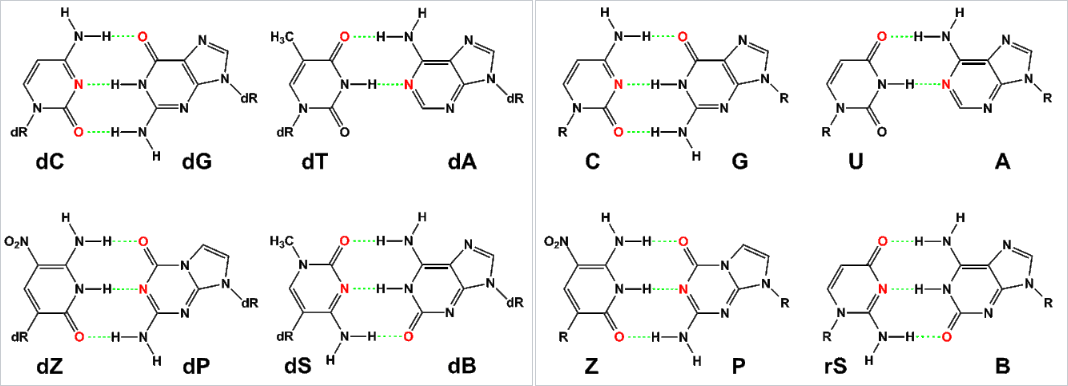
These can then be combined with each other in a couple of dozen different paring systems.



[Figure 59](#figur_base_pairing_systems): Some of the base pairing systems that could be used for synthetic biopolymers and may be available for extraterrestrial life.  
  
[Figure 3 of [(Anosova et al, 2015)](#kix.e14ki8zas6p8)]

Then as well as a diversity of backbones, Martian life that uses the same two biopolymers as terrestrial life might use additional bases. Two extra bases “X” and “Y” have been added to DNA, and the resulting microbe could make a fluorescent green protein that included unnatural amino acids [(Zhang et al, 2017)](#kix.lv7664c0kd60).

This was later expanded to an eight base system called Hachimoji



[Figure 60](#figur_Hachimoji): The eight base Hachimoji system which extends the four bases of conventional DNA and RNA.  
  
[Figure 1 of [(Hoshika et al, 2019)](#kix.7yh9gckbgm8u) as redrawn by [(WolfmanSF, 2019)]](#ilkuu861mni)

Then life with the same backbone and the same bases can still have differences in the proteins. Proteins are built from amino acids, and of the 20 amino acids (or 22 including the two non standard amino acids) coded for by RNA, several have changed assignment, which shows that the language is flexible. The ones in blue in this diagram have had changes of assignment in some organisms.

[Figure needs permission, redraw or new source]

[Figure 61](#figur_codons_reassignment): Codons shown in red have changed reassignment. The two amino acids coloured in red in the outer circle are non standard amino acids (selenocysteine and pyrrolysine). The black squares denote stop codons

[Figure 1 of [(Ambrogelly et al., 2007)](#kix.9ywn5yi42yte) ]

An extraterrestrial biology could use many more amino acids than the 20 encoded. There are 140 that occur naturally in terrestrial biology, but not in proteins [(Ambrogelly et al., 2007)](#kix.9ywn5yi42yte). 52 amino acids have been identified in the Murchison meteorite [(Cronin, 1983)](#kix.l8slghbnpbwa). A computer search turned up nearly 4,000 biologically reasonable amino acids [(Meringer, 2013)](#kix.qubfew9c9gv) [(Doyle, 2014)](#kix.19tf8efo9qks).

Many of those won’t occur in nature, but terrestrial biology also includes non natural amino acids. Meanwhile also many of the natural amino acids don’t occur in terrestrial biology and might potentially be used in extraterrestrial biology.

# **[Many ways present day Martian life could harm terrestrial organisms](#h_present_day_life_harm_terrestrial)**

First, Martian life could survive on Earth. Oxygen in Earth’s atmosphere is not likely to inhibit Martian life given that the Mars surface has highly oxidising peroxides, and hydrogen peroxide. The Martian atmosphere also has 0.13 - 0.19% oxygen [(Trainer et al)](#kix.6c37lp2f20m) in the atmosphere and oxygen is also possibly present at higher concentrations in the cold brines [(Stamenković et al, 2018)](#kix.b5k93sevqv0j). See

* [Some Martian brines could be oxygen rich permitting aerobes or even primitive sponges or other forms of multicellularity - Stamenković‘s oxygen-rich briny seeps model](#h_some_brines_could)

(below)

Martian life is likely to have antioxidants similar to the terrestrial antioxidant enzymes such as superoxide dismutase to convert superoxide radicals into hydrogen peroxide, and catalase to convert hydrogen peroxide into water and oxygen gas [(Goodsel, 2004)](#kix.8f68puawb3z7).

Martian life doesn’t need to be adapted to terrestrial biology to harm terrestrial organisms. One example here, micro-algae produce secondary metabolites including accidental liver toxins. These often damage the livers of cattle and dogs that eat the algal mats that often form in the Great Lakes [(Hoff et al, 2007)](#kix.plnxi9y5lg0). Algae also produce accidental neurotoxins and dermatoxin. These secondary metabolites may be used by the microbes to deter microbial competition [(Leflaive et al, 2007)](#kix.mgckrmsl03ix).

We do have invasive microbial species such as invasive diatoms in New Zealand lakes such as Didymosphenia geminata, probably brought there from the northern hemisphere damp sports equipment, and many invasive diatoms in the Great lakes including Stephanodiscus binderanus which clogs water treatment systems and creates foul tastes and odours in the water [(Spaulding et al, 2010)](#b_Spaulding_2010).

Microbes also produce accidental toxins that harm humans. Warmflash gives examples such as Tetanus, Botulism and Ergot disease all of which are caused by microbes that infect us, or that we ingest, that produce accidental toxins.[(Warmflash, 2007)](#inpazll45dhz). As these examples show, there is no need for Martian life to be adapted to us for it to produce coincidentally toxic substances like this.

Martian microbes could cause infectious diseases too. We mentioned legionnaires’ disease as an infection of biofilms that can also infect human lungs [(Warmflash, 2007)](#inpazll45dhz). Let’s try to fill this out in a bit more detail.

The adaptations that legionella pneumonia have are specific to terrestrial protists (single cell eukaryotes, with nucleus and organelles, but not part of a fungus, animal or plant). L. pneumonia is able to enter the white blood cells, the phagocytes that normally would eliminate pathogens. It can survive in vacuoles that don’t fuse with the lysosomes that would normally destroy the pathogen. It’s able to inhibit that fusion [(Todar, 2006)](#kix.o4bpf3ak9mib).

Martian life could be closely related to terrestrial life through panspermia, transferred to Earth on meteorites in the early solar system, or perhaps in the other direction from Earth to Mars. If so,the Martian biosphere could include protists, or closely related organisms. Most protists are aerobes, but there are terrestrial anaerobic protists and even a small animal, loricifera that never uses oxygen at any stage of its life-cycle [(Fang, 2010)](#kix.dz6zg0s4li6d). Also if there are indeed significant amounts of oxygen in the Martian brines [(Stamenković et al, 2018)](#kix.b5k93sevqv0j), this would expand the possibilities for Martian protists.

## Mars could have opportunistic fungi – these kill 1.5 million people on Earth every year

We mentioned earlier in this article that the endolithic yeast Exophiala jeanselmei can survive simulated Martian conditions, without any source of water except atmospheric humidity [(Zakharova et al, 2014)](#kix.ojnjic4hyuz0). See [Experiments with black yeasts, fungi and lichens in Mars simulation conditions suggest life could use the night time humidity directly without liquid water](#h_experiments_black_yeasts) (above)

Exophiala jeanselmei is closely related to opportunistic human pathogens. It can be an opportunistic human pathogen itself, causing superficial and localized infections in humans, in skin, nails, cornea and superficial wounds and is occasionally serious for immunocompromised individuals and is naturally resistant to most antifungals on the market [(Urbaniakt al, 2019).](#kix.54k04aufndc2)

Most healthy people have fungi in their sinuses, but these are harmless to them. Sometimes in patients with normal immune systems, these may form “fungal balls” that occupy the empty spaces in our sinuses.

When the immune system is not functioning properly, fungi can penetrate mucosal barriers and the epithelial layer and invade the host tissues and when this happens the results can be serious [(Soler et al, 2012)](#kix.eqq6az9yn29f). A diverse range of fungal species can cause a lethal infection in immunocompromised hosts and these are often resistant to antibiotics [(Pfaller et al, 2004)](#kix.1pvds0p8j3zi).

Opportunistic fungi kill an estimated 1.5 million people worldwide every year [(Brown et al, 2012)](#kix.jjb1r3cr4sax)

## Martian life could be a pathogen of Martian biofilms sufficiently closely adapted to infect protists on Earth – or it might be ignored by the white blood cell phagocytes and live in intercellular spaces of our lungs

So the first possibility is a pathogen of Martian biofilms sufficiently closely related to terrestrial life that it is already adapted to infect protists and the white blood cells. It would use the same mechanisms that let it avoid digestion by protist analogues on Mars to infect similar cells on Earth. Some protists are anaerobic ([Hirakata et al, 2020](#b_hirakata_et_al_2020)) and Mars also may have reasonably oxygen rich brines.

Legionella doesn’t form spores, and surely couldn’t survive on Mars and wouldn’t be in the sample return. However, a Martian analogue would be likely to evolve spores or some other way to survive dust storms and spread to a new habitat. Such a capability would be highly favoured in the Martian environment. Using the same methods it could then survive the journey back to Earth in the sample container.

On the other hand, if Martian life is widely separated from terrestrial life, evolutionarily, with an independent origin or it split off before most of the capabilities of modern life evolved, there is a possibility that the Martian pathogen would not be recognized as life by terrestrial biology and terrestrial life wouldn't mount an immune response [*(Lederberg, 1999b)*](#kix.ar87fg72xwf2). In this case the pathogen might be ignored by the white blood cell phagocytes, and it might live in the intercellular spaces in our lungs.

One of the microbes best able to grow in Mars simulation conditions of low atmospheric pressure, CO₂ atmosphere and low temperature is Serratia liquefaciens [(Schuerger et al, 2013)](#kix.2km0kycvbamd) [(Fajardo-Cavazos et al., 2018)](#kix.b3x1xiuwzasl).

S. liquefaciens is a widespread bacteria in the environment, found in soil, water, and also associated with plants and animals [(Grimont et al, 1978)](#kix.f4tiu63behj4). It is also motile, capable of swimming, biofilm formation and also synchronized biofilm swarming at a rate of up to 1 cm per hour [(Eberl et al, 1999)](#kix.qda60h7uq91s).

S. liquefaciens is an opportunistic human pathogen [(Fajardo-Cavazos et al., 2018)](#kix.b3x1xiuwzasl). It can also colonize the human respiratory tract, and urinary tract. S. Liquefaciens is a frequent cause of nosocomial outbreaks (outbreaks in hospitals) usually due to lapses in hygiene and is sometimes fatal [(Mahlen, 2011)](#kix.3dwzf7cy8y0m) with examples of deaths of children in Ghana [(Ikumapayi et al, 2016)](#kix.y1mpx9e7mbrp) and US recipients of blood contaminated by it [(Roth et al, 2000)](#kix.aihmzsq4v256). It has also caused eye infections, urinary tract infections, bloodstream infections, abscesses, septic arthritis, and fatal meningoencephalitis [(Mahlen, 2011:769)](#kix.3dwzf7cy8y0m).

Martian microbes could also infect directly as biofilms. Over 80 percent of human microbial infections are associated with invasive biofilms, and moreover, many of these biofilms are particularly antibiotic resistant [(NIH, n.d.)](#kix.sjgbeec6t92w) [(Lebeaux et al, 2013)](#kix.1fcmba2ay1zp).

## Our antibiotics target specific enzymes and processes so might not work with unrelated martian life – meanwhile related life might have naturally evolved accidental antibiotics like the Shewnella algae which seems to be the origin of the gene that confers resistance to quinolones – a new non naturally occurring synthetic antibiotic

Our antibiotics might not work with Martian life. They target specific enzymes and processes within living cells based on Earth's biochemistry [(Kapoor et al, 2017)](#kix.2ogp9gt6me7s). Let’s take penicillin as an example. It targets transpeptidase which is essential for cross linking in the final stage of cell wall synthesis to make rigid cell walls [(Yocum et al, 1980)](#kix.ti4bmjqvlzh2). It does that by forming a highly stable penicilloyl-enzyme intermediate. One way that microbes develop resistance to this antibiotic is by using different enzymes that perform the same function in the cell [(Gordon et al, 2000).](#iq3r0gk2jymx)

For related life, a gene that modifies those processes can give a microbe antibiotic resistance even if it isn't actually originally evolved to develop resistance, indeed, even if it never encountered the antibiotic.

When human pathogens develop antibiotic resistance, this often comes from other microbes by horizontal gene transfer, as they arise too quickly for the microbes to evolve it themselves. These resistance genes are found for every type of antimicrobial ([Martínez, 2012](#b_Martinez_2012)).

Many of the naturally occurring antibiotic resistance genes probably originate in microbes that make those antibiotics themselves and need the resistance gene to protect themselves from their own antibiotics. But the gene that gives antibiotic resistance to quinolones, a new non naturally occurring synthetic antibiotic, seems to have originated in a Shewanella algae which doesn't produce antibiotics itself. So it seems likely to have a different role in it ([Martínez, 2012](#b_Martinez_2012)).

In the same way, even related Martian microbes could have antibiotic resistance through genes evolved for other purposes on Mars that lead to their internal processes changing in ways that make the antibiotics no longer effective

.

## Ways that our immune system may not notice an alien biochemistry without the natural antimicrobials or immune responses for alien opportunistic pathogens and other diseases

We saw that natural and synthetic antibiotics target specific enzymes. An alien biochemistry might have different enzymes already, through independent evolution so may be naturally resistant to all our antibiotics.

Our immune system probably stops many fungal infections by recognizing particular patterns, the pathogen-associated molecular patterns (PAMPs). It likely does this using pattern recognition receptors (PRRs) which then trigger the immune response. These are targeted to the molecular patterns from the most common fungi that attack humans, species from three genera: Candida, Aspergillus, and Cryptococcus with different molecular patterns specific to each genera [(Kumar et al, 2018)](#b_Kumar_et_al_2018).

Our immune system wouldn’t have these pattern reception receptors for a martian fungus with an alien biochemistry. It may not have them even for related martian fungal species in a different genera from any terrestrial biology.

We have only a few effective antifungal medicines, making antifungal resistant microbes a problem [(Cowen et al, 2015)](#kix.zg2yugivuqil). Alien life might be naturally antifungal resistant, if they don’t have the biochemistry targeted by antifungal medicines.

It may be a similar situation for immune systems. An alien microbe, perhaps a disease of biofilms invading our lungs might not be recognized as a threat by our bodies.

This is how John Rummel put it in the foreword to “When Biospheres Collide”:

*"Likewise, we don't know what would happen if alien organisms were introduced into Earth's biosphere. Would a close relationship (and a benign one) be obvious to all, or will Martian life be so alien as to be unnoticed by both Earth organisms and human defenses? We really have no data to address these questions, and considerate scientists fear conducting these experiments without proper safeguards. After all, this is the only biosphere we currently know - and we do love it!"*

Joshua Lederberg, who got his Nobel prize for his work on microbial genetics was a key figure in the early work on planetary protection [(Scharf, 2016)](#kix.t6u255axqlml). He first began to give it his attention in 1957 [(Lederberg, 1959)](#kix.sewr7np8b4ap). He put it like this:

*“Whether a microorganism from Mars exists and could attack us is more conjectural. If so, it might be a zoonosis to beat all others. On the one hand, how could microbes from Mars be pathogenic for hosts on Earth when so many subtle adaptations are needed for any new organisms to come into a host and cause disease? On the other hand, microorganisms make little besides proteins and carbohydrates, and the human or other mammalian immune systems typically respond to peptides or carbohydrates produced by invading pathogens. Thus, although the hypothetical parasite from Mars is not adapted to live in a host from Earth, our immune systems are not equipped to cope with totally alien parasites: a conceptual impasse."* [*(Lederberg, 1999b)*](#kix.ar87fg72xwf2)

Our immune system and defenses are keyed to various chemicals produced by Earth life. such as peptides and carbohydrates. Mars life might use different chemicals. In the best case (for us), the Martian microbes are unable to make anything of terrestrial biochemistry and give up. However, in the worst case, it’s the other way around. This time, it’s our defense systems that are mystified. The microbes don’t resemble Earth life and so our defenses don’t recognize the attackers as life or attempt to do anything about them.

Carl Sagan put it like this [(Sagan, 1973:162)](#kix.urfjjsuep509):

*"Precisely because Mars is an environment of great potential biological interest, it is possible that on Mars there are pathogens, organisms which, if transported to the terrestrial environment, might do enormous biological damage - a Martian plague, the twist in the plot of H. G. Wells' War of the Worlds, but in reverse. This is an extremely grave point. On the one hand, we can argue that Martian organisms cannot cause any serious problems to terrestrial organisms, because there has been no biological contact for 4.5 billion years between Martian and terrestrial organisms. On the other hand, we can argue equally well that terrestrial organisms have evolved no defenses against potential Martian pathogens, precisely because there has been no such contact for 4.5 billion years. The chance of such an infection may be very small, but the hazards, if it occurs, are certainly very high.*

By way of example, it is possible that the skin gives little protection against Martian microbes. Its first line of defence consists of sixteen broad spectrum antimicrobial peptides and the second line of defence consists of T cell responses with inflammatory cascades in the subepithelial tissue [(Abdo et al, 2020)](#kix.52ycowr634ru).

The antimicrobials might have no effect on an alien biochemistry, and the immune response might not be triggered by it. If this were to happen, Martian life might penetrate these barriers without being noticed by our skin’s defences and enter the underlying flesh and bloodstream.

Immunocompromised people are especially at risk from opportunistic pathogens such as fungi, S. Liequefaciens, etc. However for alien life we may all be effectively immunocompromised if the broad spectrum antibiotics in our skin and epithelium have no effect on the alien life, and our innate or adaptive immune systems don’t recognize it as pathogenic.

## [Could a Martian originated pathogen be airborne or otherwise spread human to human?](#h_airborne_martian_pathogen)

There are various ways that a Martian originated pathogen could spread from human to human, for instance it could form a skin infection similar to fungal infections, and spread via contact.

In this section we will mainly look at respiratory diseases, using Legionnaires’ disease as an example, to explore potential capabilities of a Martian Legionnaires’ disease analogue. It might be adapted to protists similar to the terrestrial disease, or it might be a totally alien form of life that evolves on Earth to take advantage of phagocytosis to replicate. See

* [Example of technician in quarantine with acute respiratory distress and symptoms similar to Legionnaires’ disease – a disease of biofilms and amoebae that adventitiously infects humans – and sometimes mentioned in planetary protection discussions](#h_technician_legionnaires)

There are many airborne microbial infections, spread to other humans through the finer droplets of the breath. These include whooping cough, meningitis, tuberculosis and pneumonia [(Deacon, 2016)](#kix.y6i5w5tmzmr2).

So could a Martian respiratory disease be airborne? Legionnaires’ disease may not seem a good example here. Although it is spread in droplets small enough to breathe in, these don’t normally originate in the human breath. Legionnaires’ disease is usually spread from droplets in sources such as shower heads or fountains fed by water from a contaminated tank.

However there are rare cases with good empirical evidence of person to person spread of Legionnaires disease. One case is of a mother who got it from her son after eight hours of close-up care when he was coughing [(Correia et al, 2016)](#kix.enu9ccovisjq). So, it is possible for a Legionnaires’ disease analogue to be airborne.

Legionnaires’ disease is symptomless in many individuals, or at least, subclinical [(Boshuizen et al, 2001)](#kix.ay7zlk3sga3p).

By analogy with Legionnaires’ disease, an airborne respiratory disease from Mars with symptomless spreaders [(Boshuizen et al, 2001)](#kix.ay7zlk3sga3p) seems not impossible.

An airborne disease with symptomless spreaders would be especially hard to control using quarantine as there would be no indication that the technician is infected. Also, for an unknown pathogen, there would be no way to decide how long a quarantine period should be.

A novel unknown pathogen could be highly infectious. You would not be able to tell how infectious a novel pathogen is, for as long as the technician remains isolated from anyone else

Flu may be a suitable model for a worst case here. Flu is hard to control because much of the transmission is through asymptomatic spreaders [(Hayward et al, 2014)](#kix.t5ph1het1ago) [(Leung et al, 2015)](#kix.oeaemullqwsa). Also, flu is airborne [(Yan et al, 2018)](#kix.37lsk2kn5x5f) and vaccines are of limited effectiveness.

For a worst case Martian analogue, Hib is a microbial disease that especially affects children under age 5 and is airborne like flu. Many of those who get it are symptomless but it can cause severe pneumonia, and other issues, such as meningitis and death. It is controlled through childhood vaccination [(WHO, 2014)](#kix.vgg0myhws7jo) [(CDC, n.d.)](#kix.9ibavainnoib)

A Martian originated microbial airborne respiratory disease resistant to antibiotics could be as hard to control as Hib or flu once it leaves quarantine. Indeed, it could be harder since we would have no vaccines initially, and no previous experience of such a disease.

This does not need to be a probable scenario. It is enough if it is a credible worst case scenario for a Martian respiratory pathogen. If so, this would need to be considered in legal discussions of worst case situations for quarantine procedures.

There are many other possibilities for human to human transfer, for instance, one possibility is that Martian fungi could contribute to the opportunistic fungal infections that kill over 1.5 million people a year [(Brown et al, 2012)](#kix.jjb1r3cr4sax). They often invade the sinuses and in immunocompromised people can also cross barriers and infect tissues [(Soler et al, 2012)](#kix.eqq6az9yn29f). For a martian fungus with an unfamiliar biochemistry we may all resemble immunocompromised people.

A fungus could be transferred human to human for instance via contact or through surfaces, or from humans to the environment and then back to humans.

## [Microplastics and nanoplastics as an analogue for cells of alien life entering our bodies unrecognized by the immune system](#h_microplastics_analogue)

Our immune system could be as mystified by alien life as it is by microplastics and nanoplastics. Microplastics are of course not alive and not adapted to terrestrial life or trying to evade the immune systems in any way. Nor are they able to take advantage of the biochemistry of our bodies. This may be a good analogy for the situation where both forms of life are mystified by each other as described by Rummel, Lederberg and Sagan [*(Lederberg, 1999b)*](#kix.ar87fg72xwf2) [(Sagan, 1973:162)](#kix.urfjjsuep509) [(Meltzer, 2012)](#kix.cewdeelxmotf). For instance even if some Martian analogue of the fungus Exophiala jeanselmei [(Zakharova et al, 2014)](#kix.ojnjic4hyuz0) can invade our sinuses, if the biochemistry is sufficiently different, perhaps it is so mystified by our biochemistry that it can’t grow there? We can’t know this in advance but it is a possibility.

If an alien biology has similar capabilities to terrestrial biology, and neither form of biology has a significant advantage over the other, it can spread through the terrestrial environment. After a period of time to adapt to terrestrial conditions, evolve, and diversify, the equilibrium state might well have roughly equal numbers of cells of the alien biology in the soil, water, atmosphere and our environment generally.

Even if there were orders of magnitude fewer of the alien cells than terrestrial cells, they would still vastly outnumber nanoplastics. Initially of course there would be more of the terrestrial microbes in every microbiome, but there seems no particular reason why the end state would have more of terrestrial life, indeed there are possible scenarios where the alien biology has capabilities terrestrial life doesn’t have, such as

* more efficient photosynthesis
* not requiring some of the limiting elements that terrestrial life requires, such as being able to use phosphorus in the absence of sulfur [(Davies et al, 2009)](#kix.yborthmzo25j),
* a biology that can adapt to a wider range of temperature conditions and grow faster in cold conditions,
* if the alien biology has smaller cells on average with a more efficient, simpler biology, the alien cells might be more numerous than terrestrial cells.

We go into this in more detail in the section [Martian microbes better adapted to terrestrial conditions than terrestrial life, example of more efficient photosynthesis](#h_Martian_microbes_better_adapted) (below)

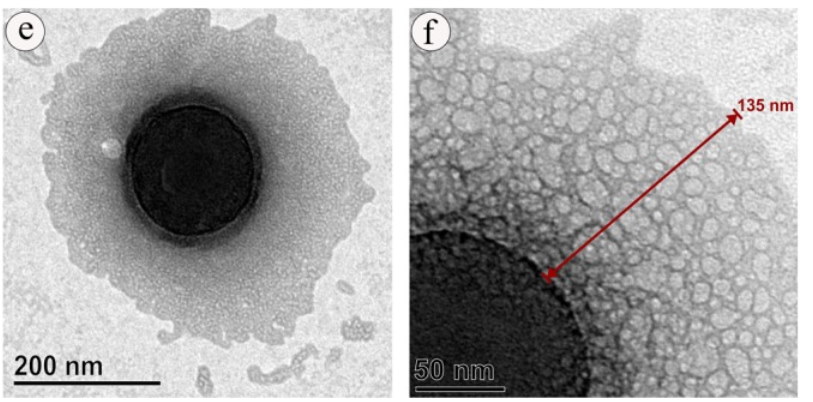
So we need to consider a situation where alien cells are more pervasive in the environment than the microplastics and nanoplastics. Microplastics of 10 µm (10,000 nm) or less can enter the skin and cross the linings of the lungs and should be able to

*"access all organs, cross cell membranes, cross the blood–brain barrier, and enter the placenta, assuming that a distribution of particles in secondary tissues, such as the liver, muscles, and the brain is possible."* [*(Campanale et al, 2020)*](#kix.k9ynqems2czp)*.*

This could also happen for any extraterrestrial microbes that are ignored by the immune system. They would enter our bodies just because of their minute size, since the body is not impervious to nanoscale or microscale particles.

Though microplastics and the smaller nanoplastics are not hugely harmful to humans, they can damage our cells. Small polystyrene nanoparticles were able to stop cells from replicating, and lower cell viability [(Campanale et al, 2020)](#kix.k9ynqems2czp) Polystyrene nanoplastics can also form Polystyrene-protein coronas enclosing them, through interaction with blood. This gives them a new biological entity that hides them from the immune system and lets them translocate to all organs. [(Gopinath et al, 2019)](#kix.khjumyezxuzy)

These encapsulated nanoplastics can then enter into cells through processes such as phagocytosis where a white blood cell engulfs them to try to destroy them, unsuccessfully. They can also enter by macropinocytosis, where they are mistaken for desirable materials such as fat droplets in the blood, and they can also enter via clathrin coated vesicles, [(Gopinath et al, 2019)](#kix.khjumyezxuzy).



[Figure 62](#figur_coronated_polystyrene): Coronated polystyrene nanoplastics. An alien biology ignored by the immune system might perhaps interact with the blood plasma in the same way on entering the blood and form alien chemicals / protein coronas that would hide it from the immune system and make it more likely for our cells to ingest them through phagocytosis or macro pinocytosis or clathrin coated vesicles.

[Detail from figure 2 of [(Gopinath et al, 2019)](#kix.khjumyezxuzy)]

So to summarize what we have so far, if we assume the alien life is mutually mystified and can't make anything of terrestrial life, then first, like microplastics and nanoplastics it would penetrate the epithelium from the skin, sinuses, stomach etc.

Assuming the targeted antibiotics in the epithelium have no effect, alien life would circulate in the body and blood like nanoplastics and microplastics. However, the numbers would be far higher, potentially billions of them entering the body a day, once they reach the point where they are widespread in the terrestrial environment.

This wouldn't happen immediately of course, it would likely take decades to perhaps centuries to build up to these levels, especially if only a few species were introduced to Earth, and the importation of life was stopped immediately, no more sample returns and the life already introduced had to evolve and adapt with new capabilities before it could spread to most ecosystems.

However, this process couldn't be stopped and reversed once started. Also, if a microbe was able to replicate in a terrestrial environment right away, it might overwhelm it quickly. Sagan once calculated that a terrestrial microbe with a generation time of two months could, in the absence of other ecological limitations reproduce to the point where there is as much of it on Mars as in all the terrestrial soils, within a decade [(Sagan et al, 1968)](#kix.fpa6qyxsabjo).

The same could happen on Earth. If a Martian microbe, perhaps one that can be spread in dust storms on Mars, was adapted to terrestrial soils already, a polyextremophile aerobe, as is not impossible, and if it is easily spread in the wind (perhaps because of adaptations to the UV on Mars), then it could be pervasive in all the soils on Earth within its habitat niche well within a decade.

So then- if this microbe is mutually ignored by terrestrial life, we might have exposure to billions of them a day as soon as a decade after the sample return breach in the worst case. It might take decades or centuries if significant adaptation is needed first or it spreads more slowly.

The worst case is that Martian microbes, as they evolve and adapt to terrestrial conditions, eventually pervade all terrestrial ecosystems and also permeate all macroscopic life which are essentially porous to them. This may take years or decades but it is a possible end state.

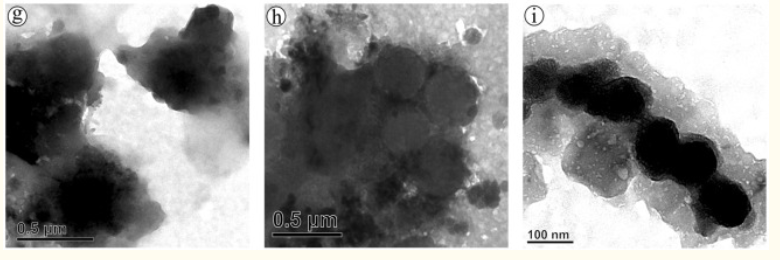
Given that the body, and all our organs, are likely permeable to such microbes, what happens next?

First, if the alien life can do nothing with terrestrial organics, then it might just circulate harmlessly in our blood and be present harmlessly in our organs. If it doesn’t form coronas either then it might have minimal impact.

However, microplastics also give examples of side effects from chemicals released from the microplastics. Although these are for the most part minor in humans, these may be analogues to the chemicals that alien life might release for signaling, protection etc mentioned in the previous section which could potentially be more hazardous. For instance BPA, found in some plastics, is an endocrine disruptor, interfering with the systems that produce hormones. It has a relatively simple structure. (CH₃)₂C(C₆H₄OH)₂ [(PubChem, n.d.)](#kix.a8o0vs2sqvs) Amongst other things, it increases the risk of heart attacks in women to levels similar to men [(Bruno et al, 2019)](#kix.z7uo439bx39e).

We cover examples like this for potential alien life in the section [Exotoxins, protoxins, allergens and opportunistic infection](#h_Exotoxins)

Then the martian microbes could form a corona around each cell, either naturally, or adapt to do this, by producing chemicals that interact with blood plasma and basically make it sticky as for nanoplastics. These could merge to make larger accumulations of cells since they would stick to each other, again like nanoplastics, and this could cause blockages in the circulation of the blood, similarly to plaque formation in the bloodstream.



[Figure 63](#figur_coalescing_coronated_polystyrene): Coalescence of protein coronas of nanoplastics and microplastics in human blood plasma. The levels of nanoplastics in our bodies are low enough for this to not be a serious issue. However if coronated alien cells do this then it could lead to circulation issues and heart attacks.

[Detail from figure 2 of [(Gopinath et al, 2019)](#kix.khjumyezxuzy)]

At present coronated micro and nanoplastics are few in number, and don't seem to cause us noticeable problems. However when the environment is filled with trillions of alien cells, with our body essentially permeable to them, if these cells then form similar coronas in our blood stream they may be more of an issue. If those coronas stick together then conglomerates of coronated alien cells in our arteries may well cause problems such as heart attacks.

Nanomaterial exposure can also cause sterile inflammation [(Leso et al, 2018)](#kix.3fq4dmdeq8wc) as a result of the secretion of alarmins similarly to asbestosis. Nanomaterials can also cause gout, when monosodium urate crystals trigger responses from the innate immune system in response to damage [(Busso et al, 2010)](#kix.tq9qmzqusp6t).

Non pathogenic alien cells circulating in our bodies and reaching to every organ could perhaps cause minor damage leading to similar responses to gout. Yong et al describe a possible process here for nanoplastics which perhaps is also a possibility for alien life that passes into our permeable bodies:

*However, the components of the innate immune system, such as the Toll-like receptors (TLRs), could also respond to a set of endogenous or secreted molecules collectively known as alarmins, or damage-associated molecular patterns (DAMP), and the outcome is what is termed sterile-inflammation, i.e. inflammatory responses without pathogenic infection. In the body, pro-inflammatory cytokines released from such localized inflammations would attract circulating immune cells, and this could worsen the local inflammation, and cause cell and tissue death.*

[(Yong et al, 2020)](#kix.zgvqx8ni9ruh)

Then the next risk is that the coronated alien microbes could be taken up by cells of the body by macropineosis, or by the white blood cells.

The clathrate coated vesicles surrounding nanoplastics form as a result of accidental triggering of receptor mediated endocytosis by the nanoplastic in carboxyl-functionalized polystyrene [(Jiang et al, 2011)](#kix.qdem60mrqgal).

[Figure needs permission, or new source]

[Figure 64](#figur_polystyrene): Upper figure shows macropinocytosis of 100 nm polystyrene particles, and lower figure shows receptor mediated endocytosis by carboxyl-functionalized polystyrene, in clathrate covered vesicles. The endocytosis is faster. Both types of particle are coated in anionic detergent for stabilization.

[ Figure from abstract of  [(Jiang et al, 2011)](#kix.qdem60mrqgal).]

The phagocytosis is not unlike the way that Legionnaires disease uses phagocytosis mentioned before [*(Alberts et al 2002)*](#kix.dceso8baikzv), but the corona enveloped microplastics are not adapted to avoid destruction by protists. Instead, microplastics are hydrophobic and in this way resist breakdown by the enzymes that catalyse hydrolysis in the acid conditions of the lysosomes. Once inside cells, they can rupture blood cells (Hemolysis), kill cells (cytotoxicity), and damage genes (genotoxicity) [(Gopinath et al, 2019)](#kix.khjumyezxuzy). To resist digestion in this way Martian life would need to form hydrophobic cell walls.

Microbes that evade phagocytosis actively resist digestion. The microbe Legionella pneumonia, the causative agent for Legionnaires disease, survives inside the macrophage because it remains in vacuoles and disables fusion with lysosomes, the vesicles containing the digestive enzymes of the cell, Other microbes use other methods to bypass these defences [(Todar, 2006)](#kix.o4bpf3ak9mib).

The enzymes inside the lysosomes can break up proteins, nucleic acids, carbohydrates and lipids. Perhaps the alien life cell wall might not be made of any of these and can resist the enzymes, but it seems likely it would be destroyed. This would be true for all the processes described, the lysosomes that destroy the vesicles that form during macropinocytosis and endocytosis as well as phagocytosis.

These would most likely be digested by the enzymes inside lysosomes unless they accidentally triggered some chemical effect that inhibited fusion.

The lysosomes would be able to digest DNA, RNA, proteins, and lipids in alien life. However, if the cell wall of the alien life is made of something that the terrestrial enzymes can't digest, like the hydrophobic nanoplastics, then it would resist this. This perhaps is not impossible but seems unlikely.

So then the next risk is that the chemicals that are the byproduct of this microbial digestion harm the cells, damage the DNA or change cell processes. Martian life might for instance have perchlorates and hydroxides inside in addition to the chlorides of terrestrial microbes or it might have unfamiliar or mirrored amino acids that could be misincorporated in terrestrial biology.

If this happens it could lead to the cell dying or the immune system recognizing that it has been damaged and attacking it. At this point then it's a question of what happens to the macrophages after they digest the alien biochemistry. Perhaps they also are damaged and if so this could lead to wider issues.

If any of this happens, with billions of alien cells entering the body, there could be an inflammatory response and possibly autoimmune disease responses similar to those for AIDS.

However, this is not the end of the story. If mutually mystified at first, later the alien life, unlike microplastics, can evolve to attack terrestrial hosts and other microbes. Meanwhile the hosts are not likely to develop new capabilities for their immune systems fast enough to stop an alien pathogen.

So - even if initially terrestrial and martian life forms are mutually mystified, the microbial martian life has an advantage over multicellular animals and plants because of its faster evolution rate. It may at any time, perhaps through multiple evolutionary steps, develop the ability to metabolize terrestrial life, and use its biochemicals, and perhaps even hijack cell processes such as phagocytosis or macro pinocytosis in various ways to grow and to replicate.

Meanwhile, once there is enough of the Martian life in the environment to provide selection pressure, terrestrial microbes would surely evolve in turn to metabolize the Martian life too, and use it, or develop symbiosis with it, or defend against it in various ways.

Even with beneficial symbiosis with alien life, the resulting microbiomes would be different in microbial composition and may function differently from the ones we have now, Neabwguke macroscopic life might find it harder to adapt to the novel situation with their slower replication rate. Macroscopic life might also be attacked directly by the extraterrestrial microbes as just described, or it might trigger autoimmune responses and other problems.

It is also possible that the alien life is already pre-adapted to be able to use the unfamiliar biochemistry of terrestrial life, as with the example of mirror life that has already evolved isomerases in order to digest organics from meteorite infall.

It does remain possible that alien life is completely harmless to terrestrial life, that it spreads through our bodies but does nothing, and is just like inert matter, like water, not even having as much effect as the nanoplastics.

Alien life could also be beneficial to us. The archaea provide an example of an entire realm of terrestrial biology that is not known to cause disease in either humans or any animals or plants, not even as opportunistic pathogens [(Kumondorova et al, 2019)](#kix.b1n6ejnld573) [(Chong, 2017)](#kix.bptd3sxzi2pa). Extraterrestrial life might perhaps be similar.

However the reasoning given here suggests that the situation where the two forms of biology are mutually mystified and essentially ignore each other has more potential issues than one might at first think.These need careful consideration in discussions of worst case outcomes of the unintended release of an alien biology into the terrestrial environment.

## [Exotoxins, protoxins, allergens and opportunistic infection](#h_Exotoxins)

Other issues may arise from secondary metabolites, for instance, *Wallemia, an* airborne extremophile fungus, is found in food, especially highly salted or sweetened food such as salted fish, jams and cake. It is adapted to low water activity, and produces the secondary toxic metabolites wallimidione, walleminol and walleminon. W. sebi is a common cause for spoiled food through its production of secondary metabolites. The most toxic of these is wallimidione [(Desroches et al, 2014)](#kix.tmpytrnezh8h). Mars conditions are likely to favour life adapted to low water activity levels, and so, as for w. sebi, could be a nuisance particularly for highly salted or sugary foods, where they also might produce secondary metabolites.

Martian life could cause allergic reactions. W. sebi has been found to cause allergic sensitization [(Desroches et al, 2014)](#kix.tmpytrnezh8h). Another example is the fungus Aspergillus which can trigger asthma, and as an opportunistic infection can also cause the more serious illness of aspergillosis, and death [(Latgé, 1999)](#kix.3d2lyr3d5jgk).

The common allergic reaction to poison ivy is due to Urushiol, a Catichol C6H4(OH)2 with one or more alkyl chains substituted in the 3 position. It forms antigens by binding to surface proteins of the dermis or epidermis so forming an antigen, which leads to an allergic response on the second exposure [(Bryson, 1996, page 680)](#kix.tbvygys1bbvy). This again is a simple enough chemical so that it may occur in an alien biology, or something else similar.

For another example, sesquiterpines is a toxic signaling chemical (semiochemical) produced by potatoes under stress [(Matthews et al, 2006)](#kix.ut0rxgneat1c). Could semiochemicals produced by an alien biochemistry be accidentally toxic to Earth life.

Alien biochemistries could also produce, or contain protoxins, which when metabolized break down into toxic products. For instance hypoglycin A, which is not itself toxic, is broken down into the highly toxic MCPA-CoA on digestion and can lead to the fatal Jamaican vomiting sickness after eating the unripe fruit of the Ackee tree, a national foodstuff in Jamaica [(Holson, 2015)](#kix.p0vd92lldznn). A more commonplace example is methanol which is converted into toxins when digested [(Mégarbane, 2005)](#kix.3nr9zvc2r282).

Again, toxicity may be more common if the secondary metabolites or protoxins are based on a different biochemistry.

The chemistry of alien cells may itself be toxic to Earth life. One suggestion is that Martian life might use hydrogen peroxide and perchlorates in its intracellular fluids in place of the chlorides used by Earth life, similarly to the composition of the brines it inhabits [(Schulze-Makuch et al, 2010a)](#kix.pi3n4jm5lyn5). This could adversely affect Earth microbes that interact with Martian cells or scavenge dead Martian life.

Waste products and metabolic intermediaries could also be accidentally toxic or allergenic.

As before all, if humans are unaffected, these effects could still harm other creatures in Earth’s biosphere, and harm us indirectly, if other creatures we depend on are affected.

## [Accidental similarity of amino acids forming neurotoxins such as BMAA](#h_accidentall) which resembles L-serine – a putative cause for the motor neurone disease LouGherig’s disease or ALS

Certain algae blooms, including Chroococcidiopsis produce β-N-methylamino-L-alanine or BMAA (table 2 of [Cox et al, 2005](#kix.w0m67ck803lr)) which is a neurotoxin which can contaminate drinking water and in worst cases cause death [(Cox et al, 2005)](#kix.w0m67ck803lr).

In laboratory experiments BMAA can get misincorporated into proteins in human cells, and is a putative cause for the motor neurone disease ALS, or Lou Gherig’s disease [(Dunlop et al, 2013)](#6m28kcei5wu). This time BMAA is not produced as an exotoxin. The poisoning is accidental, it gets misincorporated because of its accidental partial resemblance to l-serine.

There are thousands of potential amino acids an alien biology might use. See:

* [Potential diversity of extraterrestrial life based on alternatives to DNA such as RNA, PNA, TNA, additional bases and an additional or different set of amino acids](#h_potential_diversity_et_life) (above)

If two biospheres collide that are based on a different vocabulary of amino acids, there may be many such accidental similarities. In the case of BMAA, it’s been suggested that proteobacteria in our gut provide some protection by removing it [(Baugh et al, 2017)](#kix.i91b5ab1axfq). However there might be no helpful microbes to protect us by removing similarly close analogs of our amino acids from an alien biochemistry.

## Martian microbes better adapted to terrestrial conditions than terrestrial life, example of more efficient photosynthesis

Alien life doesn’t have to invade our bodies, or even create accidental toxins to harm us. It can also harm by competition with our microbes. To take an example, photosynthetic life on Earth operates at well below its theoretical peak efficiency for photosynthesis. Martian photosynthesis could be more efficient than terrestrial photosynthesis.

Martian life would then be like an invasive weed. If the result isn’t a “drop in replacement” for the photosynthetic life already in our ecosystems this might change how the ecosystem functions, which could be beneficial or harmful, but it would be different.

Photosynthesis proceeds through the reaction: [(Mellis, 2009)](#kix.icq8wh8vwj1a)

CO₂ + H₂O + 8 hv ⟶ (⅙) C₆H₁₂O₆ + O₂

The coefficients here are moles, so this means that with 8 moles of photons are needed for conversion of one mole (44 grams) of CO₂ and one mole (18 grams) of H₂O into a sixth of a mole (30 grams) of C₆H₁₂O₆ biomass and one mole (32 grams) of O₂.

One way to measure the efficiency is to measure the evolved oxygen for given levels of sunlight. At low light levels, the green alga chlorella vulgaris is able to achieve 84% efficiency at using photons to generate oxygen, absorbing 9.5 moles of photons for each mole of evolved oxygen.

However the efficiency rapidly falls as the light intensity increases, eventually saturating at less than half full sunlight intensity and producing no more oxygen as the sunlight levels increase further [(Mellis, 2009:273)](#kix.icq8wh8vwj1a). This graph from the paper shows how saturation is reached in measurements of a wild-type microalgae

[Figure needs permission]

[Figure 65](#figur_oxygen_evolution_photosynthesis): Empirical data from wild-type microalgae. The vertical axis is the amount of oxygen produced per second by each mole of chlorophyll. It starts below zero because in the dark, respiration consumes about 3 mmol of oxygen / mol Chl / sec

The oxygen production increases linearly up to about 400 μmol m⁻² s⁻¹ of light, and then it saturates. After about 1000 μmol m⁻² s⁻¹ no more oxygen can be produced by increasing the light intensity. Full sunlight is 2200 to 2500 μmol m⁻² s⁻¹ (or 2.2 to 2.5 mmol m⁻² s⁻¹)

This is due to limitations in the speed of photosynthesis.

[ Figure 1 of [(Mellis, 2009:273)](#kix.icq8wh8vwj1a)]

There are other losses in cellular processes and inefficiencies in photosynthesis, with the result that only part of the energy from photosynthesis is converted into usable energy by the algae. The theoretical maximum is that 8-10% is converted into biomass in conditions of full sunlight [(Mellis, 2009:274)](#kix.icq8wh8vwj1a).

The best case scenarios in labs and small scale microalgal cultivation achieve 3% efficiency under normal illumination [(Mellis, 2009:274)](#kix.icq8wh8vwj1a).

This low efficiency is due to the large numbers of chlorophyll antenna molecules attached to each reaction center, to absorb the light, which means terrestrial life absorbs much more light than it can process at high light levels and then has to re-radiate it as heat or photoluminescence. A smaller antenna size with fewer molecules per reaction center means light can penetrate deeper into a culture at the same cell density and more of the light is used. The cultures for smaller antenna sizes use less chlorophyll, so are lighter green at the same cell density [(Schenk et al, 2008:37)](#kix.mmz0e9sayozd).

According to Mellis, it would be possible to increase the typical 3% efficiency of green algae another three fold, close to the theoretical maximum of 8 to 10% by truncating the light-harvesting chlorophyll antenna size [(Mellis, 2009).](#kix.icq8wh8vwj1a) Experiments back this up, though with smaller improvements (instead of tripling, they achieve modest increases of 55% to 60%) [(Kirst, 2014)](#kix.q4yfvw1zs2e7)

So, why do terrestrial microbes capture more light than they need, shading other cells even of their own species, that would be able to use the excess light? It might be to inhibit competition from other species, that at high light levels a phototroph captures light that would otherwise be used by competing phototrophs. Also a larger antenna size allows it to capture more light at lower light levels with lower cell densities [(Ort et al, 2015:8530)](#kix.5mxlf05z0e9a) [(Negi et al, 2020:15)](#kix.rh6eayh1dl2y).

Reducing light antenna size has a trade off. A small antenna with fewer chlorophyll molecules increases efficiency at high light levels but if the cell density is low it reduces the efficiency at low light levels.

However modified cells have been designed that adjust the antenna size depending on the light intensity so that they achieve high efficiency both at low and high light levels compared to wild-type strains, doubling and even tripling the yields of the wild-type strains [(Negi et al, 2020:15)](#kix.rh6eayh1dl2y).

A Martian photosynthetic organism would experience large changes in light levels with a need to capture light during dust storms if possible, and also to capture as much as possible during conditions of bright sunlight, so it might already have an adjustable antenna size.

There are many other points in this complex process of oxygenic photosynthesis where efficiencies can be increased in principle.

Photosynthesis using an alternative form of carbon fixation could have a faster kinetic rate. CO₂ assimilation is often limited by the low catalysis rate of Rubisco. One proposed theoretical synthetic form of oxygenic photosynthesis could be two to three times faster than the Calvin–Benson cycle [(Bar-Even et al, 2010)](#kix.7qxbe65ibjji).

Terrestrial photosynthesis rejects 50% of the incoming sunlight, mainly in the red part of the spectrum, leading to the distinctive “red edge”. The purple bacteria and lichens don’t have this “red edge” and Martian life would be likely to use red light like the purple bacteria, because of the high absorption of blue light by dust [(Kiang, 2007)](#kix.3cbxwf1wrteo).

Oxygenic photosynthesis goes through two photosystems, 1 and 2, and both use the same frequencies of light. The efficiency could be doubled by using red light for one of the two systems [(Blankenship et al, 2011:808)](#kix.pigu57k8z2kz).

Martian life might also be able to use the full range of the spectrum. Terrestrial seaweeds are dark brown in colour because they use accessory pigments like fucoxanthin to gather the blue-green component of light rejected by chlorophyll. These then transfer the energy to the chlorophyll and so to the photosynthetic reaction centers. They do this so that they can use sunlight at only 1% of surface levels and to use the blue-green light that passes through seawater [(Caron et al, 2001)](#kix.yvuehebdansk).

There is no need for terrestrial plants to do this because they already get more light than they can use for photosynthesis. However, a hypothetical Martian microbe with faster photosynthesis might find it useful to capture the full spectrum, especially in the low light levels on Mars. This would double its theoretical efficiency compared to terrestrial life.

Oxygenic photosynthesis also uses the Calvin cycle. This has evolved only once. All the organisms with the capability for oxygenic photosynthesis belong to a single clade, all evolved from a single hypothetical ancestor. This is the least efficient of the six known pathways for carbon fixation, both in terms of energy, and in terms of the number of electrons needed for each mole of fixed CO₂ [(Bains et al, 2016)](#whomxsyo94yn).

So, why is terrestrial oxygenic photosynthesis so inefficient? Perhaps it is just hard to evolve this form of carbon fixation? Bains et al suggest this may be a many pathways event. Perhaps oxygenic photosynthesis could evolve in many ways, but with very low probability of achieving all the necessary steps so terrestrial life only happened to evolve it once.

Bains et all suggest as a perhaps more plausible alternative, that it could be a "pulling up the ladder" event where once the niche was filled, a photosynthesizer not limited by the need for an electron donor such as sulfide, Fe(II) or hydrogen then it was hard for a new photosynthesizer to evolve again [(Bains et al, 2016)](#whomxsyo94yn).

Either explanation would let Martian photosynthesizers achieve a more efficient form of photosynthesis than we have today, by randomly arriving at more efficient photosynthesis, or they might have "pulled up the ladder" on a more efficient form of photosynthesis.

In short Martian photoautotrophs

* Would be likely to absorb red light and use it for photosynthesis, and may use the full range of visible light potentially doubling light to biomass conversion at low light levels compared to terrestrial blue-green algae.
* May have adjustable light antenna size in order to cope with fluctuations of sunlight in the Martian solar storms so permitting high efficiency at high light levels
* May have photosynthesis that achieves faster reactions than terrestrial photosynthesis through an accident of evolution or because Martian conditions favour it, permitting it to use more energy with a large antenna size
* May have more efficient carbon fixation for photosynthesis than the Calvin cycle in terms of the electrons needed or the energy needed per mole of fixed CO₂

Each of these separately could increase biomass yields and it might have several of them combined.

A Martian photoautotroph would only need a small improvement in efficiency compared to terrestrial life to be competitive with our photoautotrophs in the oceans, and there seem to be possibilities for major increases in efficiency. This Martian photoautotroph then might replace the natural species in our oceans.

This could be harmless, even beneficial in some situations if it is compatible with terrestrial biology. However differences in biology could make it inedible, accidentally toxic, etc.

## Example of a mirror life analogue of chroococcidiopsis, a photosynthetic nitrogen fixing polyextremophile

Many radically different forms of exobiology have been proposed such as XNA based life or life with different bases or amino acids [(Schmidt, 2010)](#kix.olm1b61u9vxl). However there is one possibility that is not speculative, but a clear widely accepted possibility for a radically different exobiology.

There is clear evidence that mirror life (with L DNA and D amino acids) is physically and biochemically possible, and some of the processes have been created in the laboratory [(Weidmann, 2019)](#kix.llk2fnqr853v). Some astrobiologists such as Church think it is possible that we may eventually be able to make synthetic mirror life ([Peplow, 2016](#Peplow2016)).

***Church’s ultimate goal, to make a mirror-image cell, faces enormous challenges. In nature, RNA is translated into proteins by the ribosome, a complex molecular machine. “Reconstructing a mirror-image of the ribosome would be a daunting task,” says Zhu. Instead, Church is trying to mutate a normal ribosome so that it can handle mirror-RNA.***

***Church says that it is anyone’s guess as to which approach might pay off. But he notes that a growing number of researchers are working on looking-glass versions of biochemical processes. “For a while it was a non-field,” says Church. “But now it seems very vibrant.”***

In 2021, Fan et all were able to synthesize the 775 amino acid chain of Pyrococcus furiosus DNA polymerase, a DNA copying enzyme used for PCR. Using this they were able to assemble a 1,500 chain mirror DNA sequence, a record at the time ([Fan et al, 2021](#Fan_2021)).

This suggests the possibility that Mars could have mirror life, or a mix of mirror and non mirror life.

A mirror analogue of chroococcidiopsis from Mars could flourish almost anywhere from Antarctic cliffs to the Atacama desert [(Bahl et al, 2011)](#kix.axc3vj9odk3) or from Sri Lankan reservoirs [(Magana-Arachchi et al, 2013)](#kix.ejspgahn01jm) to the Chinese sea [(Xu et al, 201q26:111)](#kix.2o5rxmoxb588), and form the foundation of a mirror ecosystem.

Chroococcidiopsis, which is one of our best analogs for a possible Martian polyextremophile is an ancient polyextremophile with numerous alternative metabolic pathways it can utilize, including nitrogen fixation, methanotrophy, sulfate reduction, nitrate reduction etc [(KEGG, n.d.)](#kix.pj8o7osp4x21), even able to grow in complete darkness using a hydrogen-based lithoautotrophic metabolism with viable populations found over 600 meters below the surface [(Puente-Sánchez et al, 2018)](#kix.gmhweu12q29m) and in another case 750 meters below the Atlantic sea bed [(Li et al, 2020)](#kix.xaj0jr23elda).

In the same way a mirror Martian polyextremophile might retain numerous metabolic pathways from its evolutionary history on Mars that it could use to colonize diverse habitats on Earth. The Martian history would include hydrothermal vents, oxygen rich lakes, and almost any climate condition it could encounter on Earth as well as some conditions not present here naturally such as ultra low temperatures and ultra low atmospheric pressures and far higher levels of UV and ionizing radiation than life encounters on Earth.

Mirror starches, proteins and many fats would be largely indigestible to normal life [(Dinan et al, 2007)](#kix.8ecw6j7s9pbi) which might give these microbes a competitive advantage.

So mirror life from Mars would slowly spread and consume ordinary organics, and transform it into mirror organics. Eventually terrestrial microbes would adapt and we'd end with a mix of mirror and ordinary microbes each able to use the opposite sense of organics – but these would be different biochemistries, different capabilities.

The proportion of mirror and ordinary microbes would be hard to predict, but it could be mainly mirror organics in a worst case.

Higher life couldn't evolve fast enough to make use of the mirror organics and it may well also interfere with its metabolism. Eventually over millions of years Earth's biosphere might wel be enhanced as multicellular life evolves again able to use both types of organics and maybe we can accelerate that with genetic manipulation but it’s not a legacy we'd want to leave to our descendants.

If, after mirror life were to spread through the terrestrial biosphere, until a significant fraction of the microbes in some habitats consisted of largely inedible mirror life, possibly also accidentally toxic to terrestrial life or producing allergens, it seems unlikely that our ecosystems would continue to function in the same way.

## Example of mirror life nanobacteria spreading through terrestrial ecosystems

A mirror nanobacteria would have the same survival advantages in the wild as other nanobacteria due to its small size [(Ghuneim et al, 2018)](#kix.6av2wm9nvy6g) including a selection advantage in microhabitats with low nutrient concentrations because of the large surface to volume ratio, and selection advantage in the presence of large secondary consumers that preferentially prey on larger microbes. They would also not be infected by terrestrial phages - in this case that would be impossible because of the mirror biochemistry. [(Davies et al, 2009)](#kix.yborthmzo25j).

It is enough for a mirror nanobacteria to find some initial niche on Earth where it can survive in low numbers. Of course it wouldn't need to remain a nanobacteria in size after it escapes containment. Indeed the small size could be a response to low nutrient availability in the original habitat.

A Martian mirror nanobacteria could be present at a low level in the terrestrial environment for some time, until it makes the necessary adaptations to terrestrial conditions to start to spread widely through terrestrial biomes. It could adapt to novel terrestrial environments through varying gene expression, expressing latent capabilities it already has. Martian life could also be related to Earth life in the distant past. If so, it could rapidly take up capabilities from terrestrial life via gene transfer agents to help them to adapt to environments they encounter on our planet. This can happen overnight in seawater transferring capabilities between microbes that are far apart genetically [(Maxmen, 2010)](#kix.ixvz10mxikde).

Microbes would also develop new capabilities through evolution. This progresses rapidly in microbes with short generation times.

These changes could happen many years after a microbe of mirror life escapes from the facility. As an example of such a process, in the E. coli long-term evolution experiment, it took 20 years and 31,500 generations for e.coli to evolve the ability to use citrate in aerobic conditions [(Blount, 2008)](#kix.nq50fgqfwg99). One of the defining characteristics for E. Coli is that it tests negative in the citrate utilization test [(Sapkota, 2020)](#kix.mgoxacijiv90) [(EvoEd, n.d.)](#kix.cog94b3tjt7l)

This e.coli mutation to metabolize citrate occurred in only one of twelve initially identical strains, and was multi-step, historically contingent on previous mutations through to generation 20,000. In attempts to replay the mutation, the mutant cells couldn't arise in one step [(Lenski, 2017:2185)](#kix.nxug249rz14l).

A minimal size free living autotrophic cell, smaller than DNA based life, could still bring a novel biochemistry to Earth such as mirror life. Such life, if able to survive alongside terrestrial life in any habitat would then be able to evolve and adapt to terrestrial conditions. The long term effects of introducing a novel biochemistry as a permanent addition to Earth’s biosphere would be hard to predict.

This could happen even if the initial mirror nanobe seems to have no apparent cause for concern initially. Once Martian life is spread sufficiently widely, for instance in deserts, freshwater lakes, the sea or soil, or plant or animal microbiomes, this process would be impossible to stop.

So we should introduce microbes with a novel extraterrestrial biology to Earth with great caution, because of the speed of evolution, and the impossibility of controlling microbial evolution once released into the sea soil, air and other habitats that are present globally and interconnected through movement of water, wind, etc.

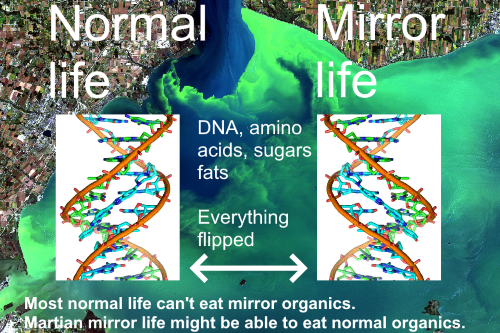
## Possibility of extraterrestrial Martian life setting up a “Diminished Gaia” on Earth

If Lovelock’s original Gaia hypothesis was true, then whatever the effects of returning extraterrestrial life to Earth, at least it would modify the planet to be close to optimally habitable for itself [(Lovelock, 1975)](#kix.reariez9j88k). As long as extraterrestrial life has similar requirements to terrestrial life, then by the strong Gaia hypothesis, it would keep Earth in a close to optimally habitable state for us too.

However, we suggested earlier that Mars could be an example of a planet with a “Swansong biosphere” where life made the planet less habitable than it would be without life (see [above](#_brwfiu3mn2bf)). Whether or not Mars is such a planet, the proposal leads to the possibility that introduction of extraterrestrial life could also introduce a novel homeostasis that even physically in terms of atmospheric composition, temperature etc, maintains Earth at a state significantly less habitable for us than it is now which for the purposes of this article we could call “Diminished Gaia”

We will start with a suggestion by Kasting. In a discussion of the need to be careful in experiments in biological engineering to try to make mirror life, he has suggested that mirror photosynthetic microbes with no predators could rapidly sequester CO₂ from the atmosphere depleting it for terrestrial life over a period of centuries (Kasting, cited in [Bohannon, 2010](#msx5f5igvnly)). C3 plants would no longer be able to survive once levels drop to below 10 to 60 ppm depending on the CO₂ compensation point of the plant, the point where more CO₂ is lost through photorespiration than gained through photosynthesis. Land life would be severely depleted except for C4 plants like maize and sugarcane which retain the CO₂ from photorespiration and would still be able to grow at close to 0 ppm [(Gerhart et al, 2010:679)](#kix.gx6bsirnprs9).

If mirror life somehow got the isomerases needed to convert normal organics to mirror organics, and break down normal fats, sugars and proteins, it could slowly convert familiar edible matter into mirrored molecules that normal life can’t digest ([Bohannon, 2010](#msx5f5igvnly)).



[Figure 66](#figur_mirror_life): Normal life, Mirror life, DNA, amino acids, sugars, fats, everything flipped. Most normal life can’t eat mirror organics. Martian mirror life might be able to eat normal organics.

Background image from [(NOAA, n.d.cwcu),](#kix.73mkfspkv7qy) DNA spiral from [(Pusey, 2012)](#kix.5wke44plkdgc)

Mars life might have this capability already. Martian life might metabolize the achiral sugars from meteorite infal [(Frantseva et al, 2018)](#kix.43cshwr9iept) ([Goetz et al, 2016:247](#kix.5ee0degz9iqz))l, or Mars might have life in both forms, mirror and non mirror life.

Perhaps the C4 plants also would be destroyed in the process, if they have no defences against mirror life. They might be directly consumed, or conversion of organics to mirror organics might make the soil, water, or the environment uninhabitable to them.

Extrapolating further, the climate would cool down to a new global ice age and slowly over tens of thousands of years oxygen levels in the atmosphere would also be reduced. Both in terms of temperature and atmospheric composition this new “Swansong Gaia” might be significantly less habitable to life. It would also be a self maintaining homeostasis. Any increase in CO₂ levels would lead to more of the mirror life cyanobacteria which would then sequester the CO₂ until it is less habitable again.

This would be a stable end point if evolution is ignored. However, it would not be the end of the process as far as life is concerned. Secondary mirror life consumers would be likely to evolve eventually, or it might be that they were accidentally imported from Mars along with the original mirror life primary producers. Some terrestrial microbes would be likely to develop the ability to metabolize mirror organics, with their short generation time. Some small multicellular organisms with short generation times might also develop the ability to metabolize mirror organics.

The outcome might depend on how fast these secondary consumers evolve and what their properties are. If this was later at a point with low oxygen levels, these might be methanogens, Though methane has greater warming potential than CO₂, it is removed from the atmosphere rapidly, unless the atmosphere is already reducing.

This might be an alternative equilibrium state for Earth with methanogens, cyanobacteria and methanotrophs with an atmosphere of a mix of nitrogen, methane and low levels of oxygen.

If such an end state was possible, it would be maintained under homeostasis but would be significantly less habitable.

In this way, in the very worst case of unfortunate non beneficial interactions, an accidental introduction of Martian life to our biosphere might transform Earth’s self reinforcing “Gaia”, into a self limiting “Diminished Gaia” which over millennia and millions of years reduces the habitability of our planet, not only to terrestrial life but to all forms of life.

Humans would surely intervene in some way in this process, for instance by bioengineering or by paraterraforming. With modern technology we would not go extinct, but this might be the worst case without intervention.

Other similar Swansong Gaia interactions could be imagined that could be set up by accidentally introducing extraterrestrial life.

The result would not be as limited as the Martian swansong biosphere hypothesis on a significantly less habitable planet, but would have reduced surface biomass and greatly reduced ecosystem complexity and far less species diversity compared to the current terrestrial biosphere.

## Worst case scenario where terrestrial life has no defences to an alien biology - humans survive by ‘paraterraforming’ a severely diminished Gaia

The physicist Claudius Gros looks at a clash of interpenetrating biospheres in his paper on a "Genesis project" to develop ecospheres on transiently habitable planets. Gros reasons that the key to functioning of the immune system of multicellular organisms, plants or animals, is recognition of “non-self”. He presumes that biological defense mechanisms evolve only when the threat is actually present and they don’t evolve to respond to a never encountered theoretical possibility [(Gros, 2016)](#kix.hwnfjqjxs7me).

*“How likely is it then, that ‘non-self’ recognition will work also for alien microbes?"*

*"Here we presume, that general evolutionary principles hold. Namely, that biological defense mechanisms evolve only when the threat is actually present and not just a theoretical possibility. Under this assumption the outlook for two clashing complex biospheres becomes quite dire."*

*"In the best case scenario the microbes of one of the biospheres will eat at first through the higher multicellular organisms of the other biosphere. Primitive multicellular organisms may however survive the onslaught through a strategy involving rapid reproduction and adaption. The overall extinction rates could then be kept, together with the respective recovery times, 1–10 Ma, to levels comparable to that of terrestrial mass extinction events."*

*"In the worst case scenario more or less all multicellular organism of the planet targeted for human settlement would be eradicated. The host planet would then be reduced to a microbial slush in a pre-cambrian state, with considerably prolonged recovery times. The leftovers of the terrestrial and the indigenous biospheres may coexist in the end in terms of ‘shadow biospheres’ "*

In such a worst case, where terrestrial life is naive and offers no resistance when eaten by Martian life, after a clash with life from an alien biosphere, almost all multicellular organisms on Earth could be eradicated. All that would be left would be some small rapidly evolving organisms.

This is an argument similar to the worst cases of Lederberg, Rummel and Sagan [*(Lederberg, 1999b)*](#kix.ar87fg72xwf2) [(Sagan, 1973:162)](#kix.urfjjsuep509) [(Meltzer, 2012)](#kix.cewdeelxmotf).

Even in this scenario, it would be possible to preserve higher life in enclosed habitats protected by use of technology. The habitats could have self contained biospheres based on plants grown for food, and oxygen, which in turn take up carbon dioxide and water from humans. This seems feasible as we have already designed almost completely self-sustaining habitats that should work in space, a more challenging situation [(Salisbury et al, 1997)](#kix.z752zjh2x4aq).

So long as our seed banks were protected from the invasive Martian life, whatever it is, we could gradually re-establish plant life inside these habitats too, and populate our habitats with any animal life rescued from deteriorating ecosystems. The seed banks preserve most plant species (apart from some tropical plants such as mangoes which can’t be preserved for long as seeds). Eventually much of the world could be covered in expanding joined together habitats in a process similar to paraterraforming. Perhaps a similar process would work for parts of the sea bed too, and the sea shore

In this way, at least some humans could survive any of these scenarios. However in this worst cases, our biosphere would be severely affected, for a significant period of time.

This scenario and some of the previous ones such as the introduction of mirror life may seem like a scene from a science fiction book or movie. Hopefully that is exactly what they are. Hopefully these are not future possibilities.

However, the idea of returning a sample from Mars itself would seem a science fiction scenario as recently as the early 1960s. We are entering a future where what used to be science fiction is becoming a reality, and we have to seriously consider real world outcomes from such scenarios. Unlike a movie script, we can’t rewrite this story to a happy ending if we don’t like the outcome.

Our intuitions about what is credible or incredible based on past experience can easily lead us astray in novel situations like this, never encountered by any previous human civilization.

## Worst case where alien life unrecognized by terrestrial immune systems spreads to pervade all terrestrial ecosystems

Humans wouldn't go extinct in such a scenario, as we would have time to recognize what is happening and build habitats to survive in. Also, we would be able to preserve much of the Earth’s biodiversity including all the plants with preservable seeds (which is most of them). However such a paraterraformed Earth would severely diminish life prospects for several generations.

Eventually life outside the habitats would reach an equilibrium, with small microscopic single cell and multicellular terrestrial lifeforms able to evolve fast enough to take advantage of the new microbial environments. Over millions of years, perhaps faster with assistance from humans, there would be higher life forms again able to survive in an environment with both kinds of biology. Perhaps humans also could artificially adapt our progeny to survive outside the habitats or find ways to supplement their own immune systems so that they are protected from the extraterrestrial microbes that our naive immune systems don’t recognize as life. But essentially this process would turn Earth into an alien planet for macroscopic terrestrial biology in its current (original) form.

Although we have technology we could use to survive this scenario today, it would have been much harder with the early technology of the 1960s. The first “bubble boy” David Vetter who lived his life in an isolation room was born in 1971 [(Gannon, 2012)](#kix.8v7dxpl8qbq3). Without experience of such technology, it would be that much harder for 1960s humans to survive back contamination of Earth’s biosphere with life that our biology is not able to protect itself against naturally.

We can't know, but we may be lucky with our Moon, that there was no extraterrestrial life there. This might be an extinction risk that extraterrestrials have already encountered at a similar technology level to 1960s humans. If an intelligent alien species returned alien life to their planet with inadequate planetary protection, at the level of technological development of the Apollo mission, they could go extinct. They might not manage to develop the technology for self-sustaining habitats in time to keep out the alien microbes. It’s not impossible that this has already made some other alien intelligent species extinct on one of the billions of exoplanets in our galaxy or in the billions of other galaxies in the observable universe.

# **Could Martian microbes be harmless to terrestrial organisms?**

It is striking that identified human microbial diseases are all bacteria or eukaryotes (e.g fungi). Earth’s third domain of life, the archaea, are not known to cause diseases in humans, animals or plants. The archaea could be implicated as opportunistic pathogens in some diseases like tooth decay, and diverticulosis, but the evidence is circumstantial. The archaea are present but it’s not clear they are a cause [(Kumondorova et al, 2019)](#kix.b1n6ejnld573) [(Chong, 2017)](#kix.bptd3sxzi2pa).

Whether or not there are genuine archaeal diseases, the experience of almost complete harmlessness of the archaea suggests it is possible that Martian microbes could also be harmless to terrestrial life, or almost completely harmless. An entire domain of life from Mars could perhaps be harmless, even beneficial, to terrestrial life. After all, a microbe normally has no incentive to harm its host. Although this is not true for all diseases (polio, and smallpox are examples or diseases that have never evolved to be less deadly), for most microbes, keeping its host alive is its priority and harming its host is maladaptive [(Chong, 2017)](#kix.bptd3sxzi2pa).

Interestingly, archaea are more closely related to animals and plants than bacteria, though less closely related to them than fungi. It seems that an evolutionary distance for Martian microbes would be no protection, nor would evolutionary closeness be protection either.

That leads to an interesting question, if we find a new domain of life on Mars that we believe may be harmless to terrestrial life, how could we prove it? How could we prove the archaea to be harmless, in a hypothetical scenario where we introduce them to Earth from Mars for the first time this century? It wouldn't be possible to test interactions exhaustively, though some of the most important interactions could perhaps be tested in experiments, also how would one predict how it could evolve?

This is a question we may have to address at some point in the future, for instance if we find related life on Mars but in a new domain not yet present on Earth.

## Enhanced Gaia - could Martian life be beneficial to Earth’s biosphere?

So far we’ve focused on situations where biosphere collisions are harmful, since the topic is planetary protection, so we need to focus on scenarios where there is indeed a need to protect Earth. However we should also recognize that the introduction of extraterrestrial life to our biosphere could also be beneficial, as Rummel mentioned in his foreword to “When Biospheres Collide” [(Meltzer, 2012)](#kix.cewdeelxmotf)

We have examples from multicellular life to show that invasive species aren’t always harmful. Schlaepfer et al did a survey of invasive species and in their table 1 they find many non native species that are actually beneficial. Some were deliberately introduced for their value for conservation, but many of the best examples were introduced unintentionally [(Schlaepfer et al, 2011).](#kix.kcy21xrpyb64)

Schlaepfer doesn’t list any microbial examples. What could benign interactions with terrestrial life look like for Martian microbes? Here are a few suggestions:

* More efficient photosynthetic life from Mars could increase the rate of sequestration of CO₂ in the sea and on land, improve soil organic content, and perhaps help with reduction of CO₂ levels in the atmosphere
* More efficient photosynthesis could increase the productivity of oceans
* Most of the surface layers of our oceans are deserts, except near to the coasts, because of the limitation of nitrogen, phosphorus, iron and silica (needed for diatom shells) [(Bristow et al, 2017)](#9mwlcto9tvof). If extraterrestrial life has different nutrient requirements, it may be able to inhabit these deserts and form the basis of an expanded food web.
* Martian microbes could be better at nitrogen fixation, phosphorus and iron mobilization, and so improve our soils, and help with crop yields as endophytes. Just as Martian microbes could enter the human microbiome, they could also enter plant microbiomes as endophytes and those interactions need not be harmful, many could be beneficial. [(Afzal et al, 2019)](#kix.g23z69lvyy50)
* New forms of yeast could be of interest in the food industry [(Sarmiento et al, 2015)](#kix.dj7mpnduv3vb).
* Martian life could increase species richness by gene transfer to Earth microbes, leading to more biodiverse microbial populations.
* Martian extremophiles could colonize microhabitats in deserts and eroded landscapes barely habitable to terrestrial life, helping with reversal of desertification
* More efficient Martian microbes might be useful to generate biofuels from sunlight and water [(Schenk et al, 2008)](#kix.mmz0e9sayozd)
* Martian life might be accidentally toxic and control harmful microbes or insects
* Martian life might aid digestion or enter into other beneficial forms of symbiosis.
* Martian life could produce beneficial bioactive molecules as part of the human microbiome. These could include molecules that are antiviral, antibacterial, antifungal, insecticides, molecules that kill cancer cells, immunosuppressants, and antioxidants - we get all of those from beneficial microbes that are already in our microbiome.  
   [(Borges et al, 2009)](#kix.mncej25eo55).
* It could add a new domain of life with almost entirely beneficial interactions similarly to the Archaea
* It could add new forms of multicellular life based on a different biochemistry, or multicellular life in a different domain of life from the eukaryotes, with a more ancient common ancestor.

However even if introducing terrestrial life is largely beneficial we still need caution. There would be not just one encounter in one ecosystem. Martian conditions may well favour polyextremophiles able to survive in a wide range of conditions.

Chroococcidiopsis is perhaps our best analogue for a Martian cyanobacteria and it is a polyextremophile and found in many habitats throughout the world. Also the microbes would evolve eventually, and perhaps quickly, or change gene expression, and eventually find new habitats that they can colonize.

Maybe some of these encounters would be beneficial in some ecosystems, while other ecosystems are degraded, possibly even by the same interactions with the same microbe. Similarly for organisms, some organisms may be benefited and others harmed.

The same Martian microbe may also have both harmful and beneficial effects on the same organism, or in the same ecosystem. Generally there might well be a mix of some beneficial and some harmful interactions.

On the other hand the interactions could all be beneficial. To take an example, our planet is not necessarily optimal for global biomass [(Kleidon, 2002)](#kix.n5t4lx4zw5dw). Perhaps extraterrestrial life with additional capabilities could do the opposite of triggering a Swansong Gaia.

Return of Martian life might create a new enhanced Gaia system that has significantly more surface biomass and biodiversity than the one we have today. It might even add new beneficial domains of life like the archaea or a new form of multicellularity which only enhances the diversity of our biosphere.

We have nothing by way of previous experience to guide us here.

Amongst a million extraterrestrial civilizations that return a sample from a nearby biosphere with limited technological capabilities to contain it, we don’t know how many would find they have harmed the biosphere of their home world. It might be that

* it is never seriously harmful, it usually leads to an enhanced Gaia, and is almost always a beneficial process.
* Or even that most extraterrestrial biospheres are seriously degraded after their first unsterilized sample return from a nearby independently evolved biosphere

There is no way to know.

# [A simple titanium sphere could contain an unsterilized sample for safe return to Earth’s surface even with the technology of 1969 - but how do you open this “Pandora's box”?](#h_a_simple_titanium_Pandoras_box)

We were lucky that our nearest destination for space exploration, the Moon, was not inhabited by an alien biochemistry. Suppose we had applied the Apollo guidelines correctly, and submitted them to a proper peer review. Back in the 1960s we didn’t have the scientific understanding necessary for a safe sample return.

In an alternate timeline where the Apollo guidelines went through legal review, a likely decision in 1969 was that human quarantine can't protect Earth for the reasons explained in: : [Complexities of quarantine for technicians accidentally exposed to sample materials](#h_complexities_of_quarantine).

In this alternate timeline the US would likely have done a robotic sample return first before sending humans to the Moon. In our timeline this was achieved a little over a year later with the Soviet mission Luna 16, the first robotic sample return from outside of Earth [(NASA, 2018luna)](#kix.qm44jws63esw).

We would have thought our robotic sample return procedures were safe in 1969, but they wouldn’t have been. Back then we didn’t have the knowledge of extremophiles and the limits of size for life needed to contain alien life. Even in 2009 we didn’t have modern understanding of the limits of size as we saw in: [First restricted (potentially life bearing) sample return since Apollo, however, science reviews in 2009 and 2012 have lead to increasing requirements on such a mission – especially as the result of discovery of the very small starvation mode nanobacteriaia](#h_increasing_requirements)

However, even with the technology of the 1960s, we ***could*** have returned an unsterilized sample to Earth’s surface with a zero risk of any harm to our biosphere. One way would be to seal it within a spherical shell of titanium, thick enough to be unbreachable during re-entry. If we never opened it once it reached the surface, Earth’s biosphere would be protected, for as long as it remained intact.

Spherical fuel tanks from rockets typically survive re-entry into our atmosphere undamaged. This is because of the high area to mass ratio, the high melting point of titanium of 1,668 °C, and the resistance to ablation of a spherical structure.



[Figure 67](#figur_titanium_tank), A sample return in a titanium sphere would be totally safe, but how then do we open the sphere? Top right image shows a titanium sphere that survived re-entry. Top left image shows Pandora trying to close the box that she opened in the Greek legend.

Main image - Genesis return capsule on the ground after it crashed [(NASA, 2008grcg)](#kix.kc8x09bna6wh).

Top left, Opening Pandora’s box [(Church, n.d.)](#kix.s6smhjtgzg3n)

Top right - space ball after re-entry - probably from the equipment module of Gemini 3, 4 or 5. [(Daderot, 2017)](#kix.r7h1nxrsqxfy)

We can do the same today. Enclose the samples in a sealed titanium sphere, and it can then be delivered safely to the Earth’s surface, so long as the outer surface is sterilized, or had no chain of contact with the Martian surface. However, if we wish to open the sample, and study it within our own biosphere, containment is far harder.

How do we open the sphere to study its contents? There doesn’t seem to be any way to do this that guarantees this same high level of certainty that we can protect the biosphere of Earth [(Ammann et al, 2012:25)](#qa4nethlmcdw).

*It is not possible to demonstrate that the return of a Mars sample presents no appreciable risk of harm*

There is nothing in the basic physics to prevent study of an unsterilized sample of an unknown alien biology on the Earth’s surface with no appreciable risk of harm. If we had 100% perfect nanoscale filters we could do it - so long as we can also replace them when needed with no appreciable risk of escape of a nanoscale particle, and so long as we can eliminate any appreciable risk of human error, accidents and malicious damage.

However, though we can take many precautions, it seems that our technology needs to be developed further before we can study a sample within our biosphere with the same level of biosafety that we would achieve for a sample return in a sealed titanium sphere.

At least we can’t achieve such levels of containment in a normal biosafety laboratory design even with improvements to the filters. I have a proposal below for a radically different form of laboratory that may be way to achieve titanium sphere levels of containment for a biosafe laboratory that might be worth considering, see:

* [Proposal: a sketch for a biosafe laboratory on Earth designed for 100% containment of even nanoscale mirror life using telerobotics, a sump heated to 300°C with heat and vacuum stable light oil, and built in heat sterilization at end of life of the facility - could this be a safe way to open “Pandora’s box”?](#h_proposal_biosafe_pandoras_box)

But following Amman et al, let’s assume for now that we use normal biosafety laboratory designs and that we can’t achieve the perfect safety of a titanium sphere. The question then is whether the level of safety we can achieve is sufficient.

# **[Which variation on the precautionary principle is appropriate for a Mars sample return?](#h_which_variation_precautionary)**

The precautionary principle was developed to help deal with some of the new unprecedented challenges faced by humans. The aim is to help guide decision making in situations (like a Mars sample return) where we have to make decisions although we don’t yet know the potential effects of our actions and where some possible outcomes could be severe. This is one variation on it:

*When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.*

*"In this context the proponent of an activity, rather than the public, should bear the burden of proof.*

*"The process of applying the Precautionary Principle must be open, informed and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives,* ***including no action****."*

[*(Raffensperger, 1998)*](#kix.x6cpe7y84lv1)

There are many other variations on this principle. The European Space Foundation study considered four variations on the precautionary principle [(Ammann et al, 2012:25)](#qa4nethlmcdw) following an analysis of the principle by Stewart [(Stewart, 2002)](#kix.i6axx1j5e276)

* **Non-preclusion Precautionary Principle**: Scientific uncertainty should not automatically preclude regulation of activities that pose a potential risk of significant harm.•
* **Margin of Safety Precautionary Principle**: Regulatory controls should incorporate a margin of safety; activities should be limited below the level at which no adverse effect has been observed or predicted.
* **Best Available Technology Precautionary Principle**: Activities that present an uncertain potential for significant harm should be subject to best technology available requirements to minimise the risk of harm unless the proponent of the activity shows that they present no appreciable risk of harm.
* **Prohibitory Precautionary Principle**: Activities that present an uncertain potential for significant harm should be prohibited unless the proponent of the activity shows that they present no appreciable risk of harm

The ESF ruled out the non-preclusion variation since the potential negative impact on the biosphere can’t be discarded, and neither the public or policy makers would accept a program without controls. They ruled out the margin of safety variation because the consequences can’t be estimated and there are no previous observations that we can use to predict adverse effects.

The ESF then ruled out the Prohibitory Precautionary Principle. The reasoning here may be less compelling than the reasoning for excluding the other versions of the principle. They explain that it is impossible to demonstrate that the sample return produces no appreciable risk of harm. If we used the Prohibitory variation this would lead to cancellation of the MSR mission, so they argued that we can’t use it [(Ammann et al, 2012:25)](#qa4nethlmcdw).

*It is not possible to demonstrate that the return of a Mars sample presents no appreciable risk of harm. Therefore, if applied, the Prohibitory Precautionary Principle approach would simply lead to the cancellation of the MSR mission.*

*Based on Stewart’s structure, the only model relevant to apply the Precautionary Principle would be the Best Available Technology Precautionary Principle.*

However Stewart, elsewhere in that same paper, suggests that there may be situations where prohibition may be needed. This is possible since society places very high value on the environment and its protection [(Stewart, 2002:15)](#kix.i6axx1j5e276).

*In critiquing strong versions of PP [Precautionary Principle], this essay does not argue that stringent preventive environmental regulation should never be adopted. … As society places a very high value on the environment and its protection, stringent preventive regulation of uncertain environmental risks is often justified and appropriate.*

In his conclusion he discusses whether there may be criteria we can use to decide which of the precautionary principles apply in any given situation, and if they exist, suggest they need to be identified and justified [(Stewart, 2002:48)](#kix.i6axx1j5e276):

*...If there are indeed criteria, consistent with PP premises, to guide selective application of the PP regulatory prescriptions and a balancing approach so as to avoid unduly rigid and costly regulation, those criteria need to be identified and justified.*

Stewart doesn’t attempt to outline criteria to use to decide between the variations on the principle. Instead presents this as a challenge for proponents of the Precautionary Principles to resolve.

So, should we use the Best Available Technology principle or the Prohibitory principle and can we develop criteria to help decide which version to use? This is an ethical decision, and not a decision for scientists or engineers to make for others without a voice in the decision. As Randolph put it [(Randolph, 2009:292)](#xs0gwy1vf9ff).

*While NASA and other space agencies have certainly maintained due diligence in protecting against back contamination, there remains a significant moral issue that I have not seen addressed in any of the literature.*

*The risk of back contamination is not zero. There is always some risk. In this case, the problem of risk - even extremely low risk - is exacerbated because the consequences of back contamination could be quite severe.* ***Without being overly dramatic, the consequences might well include the extinction of species and the destruction of whole ecosystems****. Humans could also be threatened with death or a significant decrease in life prospects*

***In this situation, what is an ethically acceptable level of risk, even if it is quite low? This is not a technical question for scientists and engineers. Rather it is a moral question concerning accepting risk.***

*Currently, the vast majority of the people exposed to this risk do not have a voice or vote in the decision to accept it. Most of the literature on back contamination is framed as a discourse amongst experts in planetary protection. Yet, as I've already argued, space exploration is inescapably a social endeavor done on behalf of the human race. Astronauts and all the supporting engineers and scientists work as representatives of all human persons...*

The ESF study’s mandate had an underlying assumption that the mission will happen as they were tasked with recommending a level of assurance to enable it in their mandate: [(Ammann et al, 2012:1)](#qa4nethlmcdw).

***“Recommend the level of assurance for the exclusion of an unintended release of a potential Mars life form into the Earth’s biosphere for a Mars Sample Return mission”***

This is why the only version of the principle available to them was the Best Available Technology

However, there is no such mandate for the legal process. The legal process is therefore likely to involve discussion of Stewart's question, to attempt to outline criteria for when the prohibitory version of the principle applies. We will look at one possible criterion for applying the Prohibitory version in the next section.

## Formulating Sagan’s statement that “we cannot take even a small risk with a billion lives” as a criterion for the prohibitory version of the precautionary principle

One possible criterion for applying the prohibitory principle is that it always applies when worst cases include severe degradation of the biosphere of Earth, or impact severely on large numbers of human beings. There can hardly be a clearer example of this than a worst case that can impact on the lives or livelihoods of a billion people. As Carl Sagan once put it [(Sagan, 1973:130)](#kix.urfjjsuep509)

*The likelihood that such pathogens exist is probably small, but we cannot take even a small risk with a billion lives.*

It is likely that some members of the general public and some of the experts involved in the discussions have similar views to Sagan on this matter. The criterion might be:

***Sagan’s criterion:*** *If it is impossible to show that there is no appreciable risk of significant harm to the lives or livelihoods of a billion people the Prohibitory version of the Precautionary Principle must always be used*

Here the threshold of a billion is arbitrary - but the exact figure may not matter. Any mission that has even a very minute risk of large-scale modification of the terrestrial biosphere will potentially endanger lives or livelihoods of at least a billion people.

There may well be other situations where we also need to apply the prohibitory principle. It would be a sufficient but not a necessary condition, as logicians put it.

If, for instance, it is impossible to show that there is less than one chance in a million that half a billion people die in some future proposed scientific experiment we surely still use the Prohibitory version, but there is no need to try to define an exact lower threshold here.

The suggestion is, we always use the Prohibitory version of the principle if Sagan's criterion can’t be met applies.

During the legal process for a Mars sample return, we can expect proposals along lines like this, and public discussion of whether Sagan’s criterion should be used (or something similar). It seems not impossible that a criterion similar to Sagan’s criterion is adopted as a result of the legal review. If that is the outcome, no unsterilized return will be permitted until we know enough to guarantee that this particular experiment is risk free, at least to the level where there is no appreciable risk that a billion people can be seriously adversely affected by the mission.

This idea doesn't seem to have been considered in the planetary protection literature - that after legal review we might adopt something like Sagan's criterion, or that criteria adopted during legal review could lead to the decision to adopt the Prohibitory version of the Precautionary principle. However, given that Carl Sagan had this view, others of influence in the debates may too. Synthetic biologists have already expressed similar views for their discipline, as we’ll see in the next section.

## A requirement for similar levels of safety to those used for experiments with synthetic life would lead to the Prohibitory version of the Precautionary Principle and make unsterilized sample return impossible with current technology and current understanding of Mars

Synthetic biology already permits the creation of inheritable synthetic life such as life with hachimoji DNA [(Hoshika et al, 2019)](#kix.7yh9gckbgm8u). They make sure that this is safe by designing nucleotides that depend on chemicals only available in the laboratory.

Synthetic biologists have suggested that a safety mechanism to contain synthetic life should be many orders of magnitude safer than any contemporary biosafety device.

Schmidt puts it like this [(Schmidt, 2010)](#kix.olm1b61u9vxl)zzz

*The ultimate goal would be a safety device with a probability to fail below 10−40, which equals approximately the number of cells that ever lived on earth (and never produced a non-DNA non-RNA life form). Of course, 10−40 sounds utterly dystopic (and we could never test it in a life time), maybe 10−20 is more than enough. The probability also needs to reflect the potential impact, in our case the establishment of an XNA ecosystem in the environment, and how threatening we believe this is.*

*The most important aspect, however, is that the new safety mechanism should be several orders of magnitude safer than any contemporary biosafety mechanism.*

Though Schmidt’s paper doesn't make a connection with the legal principle, in effect this is an application of the Prohibitory version of the Precautionary Principle as mentioned above [(Ammann et al, 2012:25)](#qa4nethlmcdw) [(Stewart, 2002)](#kix.i6axx1j5e276).

* **Prohibitory Precautionary Principle**: Activities that present an uncertain potential for significant harm should be prohibited unless the proponent of the activity shows that they present no appreciable risk of harm

(see [Which variation on the precautionary principle is appropriate for a Mars sample return?](#h_which_variation_precautionary) above)

It seems not impossible that such a view might prevail in legal discussions of a Mars sample return too. It has similar risks of returning unfamiliar life with the potential for *“the establishment of an XNA ecosystem in the environment”*.

If this is the legal outcome, it is for us, as proponents of the activity, to find a way to do it safely. The question then becomes, can we preserve the science value of the mission while running no appreciable risk of harm to Earth, similar to the risks from escape of synthetic life from a lab, at this level of a billion people’s lives or livelihoods seriously harmed?

When the ESF study stated that it would be impossible to demonstrate no appreciable risk of harm for a Mars sample return facility, this was based on an analysis of the risks. The main categories of risk listed in the study are [(Ammann et al, 2012:33)](#qa4nethlmcdw) :

* *A break-up of the container during atmospheric entry (due to a design fault or sabotage),*
* *An unsuccessful full sterilisation of the Earth Entry Capsule, potentially having Mars particles attached to its outside surfaces,*
* *Damage to the vehicle due to heavy impact with the Earth,*
* *Escape of material during transport or from the laboratory*

There are many examples of escapes of pathogens from conventional biosafety laboratories that were thought to be safe for those pathogens [(Furmanski, 2014)](#kix.6iaomexgyqa7). It’s often because of human error. Also it can be equipment failure with unexpected failure modes, like the gloves for the Apollo samples [(Meltzer, 2012:485)](#kix.cewdeelxmotf) [(Meltzer, 2012:241)](#kix.cewdeelxmotf) , or a problem with the design or construction of the facility.

The risk of laboratory escape could also include such external events as a small plane or helicopter crashing into the facility, a terrorist attack, theft, or arson, that someone burns the facility down.

If we have to use the Prohibitory version of the Precautionary Principle, it is probably impossible to eliminate those risks to a sufficient level of assurance with current technology.

But see:

* [Proposal: a sketch for a biosafe laboratory on Earth designed for 100% containment of even nanoscale mirror life using telerobotics, a sump heated to 300°C with heat and vacuum stable light oil, and built in heat sterilization at end of life of the facility - could this be a safe way to open “Pandora’s box”?](#h_proposal_biosafe_pandoras_box)

## Origins of the one in a million “gold standard” – as originally proposed it was 1 in 100 million and EPA uses numbers between 1 in 10,000 and 1 in 10 million – with administrative discretion - no magic number can substitute for informed and thoughtful consideration, working with the public

Kelly et al ([Kelly, 1991](#b_Kelly_1991)) traced the one in a million criterion back to a 1961 article by Mantel et al which proposed a 1 in 100 million chance of developing cancer as a criterion for the purpose of discussion ([Mantel et al, 1961](#b_Mantel_1961)). When asked by Kelly why he chose this figure he replied ***"We just pulled it out of a hat"*** ([Kelly, 1991](#b_Kelly_1991)). The FDA adopted this 1 in 100 million criterion in 1973 but by the time the final rule was issued it became 1 in a million. This became the "maximum lifetime risk that is essentially zero," or the level below which no further regulatory consideration would be given regarding the safety of residues of a carcinogenic animal drug.

Graham [(Graham, 1993)](#b_Graham_1993) says that in practice, EPA recommends a range of risk levels from 1 in 100,000 to 1 in 10 million, and sometimes approves at a level of 1 in 10,000. EPA's air office tries to reduce the risk to as many people as possible to 1 in a million and the maximally exposed individual to 1 in 10,000.

Graham says that there are many factors involved in a decision such as the risk of the exposed population, the resource cost and the scientific quality of risk assessments and concludes (Graham, 1993):

Administrative discretion is necessary to weight these factors on a case-by-case basis. No magic risk number can substitute for informed and thoughtful consideration by accountable officials who work with the public to make balanced decisions.

Kelly says that acceptability of a risk is properly made by those exposed to the hazard, or their health officials. It’s not scientifically derived or a decision that can be made by outsiders to the process. The acceptability is based on many factors.

The general consensus in the literature is that "acceptability" of a risk is a judgment decision properly made by those exposed to the hazard or their designated health officials. It is not a scientifically derived value or a decision made by outsiders to the process. Acceptability is based on many factors, such as the number of people exposed, the consequences of the risk, the degree of control over exposure, and 40 or so other factors.

This is similar to Randolph’s point mentioned above [(Randolph, 2009:292)](#xs0gwy1vf9ff)

***In this situation, what is an ethically acceptable level of risk, even if it is quite low? This is not a technical question for scientists and engineers. Rather it is a moral question concerning accepting risk.***

The EPA science advisory board lists some of the factors in 1990, including ([EPA, 1990:10](#b_EPA_1990))

Number of people and other organisms exposed to he risk

* likelihood of the environmental problem actually occurring
* severity of effects including economic losses and other damages if it does occur
* length of time over which the problem is caused, recognized and mitigated
* extent of the geographical area affected by it.

The EPA science advisory board likens the extra expense needed for precautions against long-term and widespread environmental problems to an insurance premium([EPA, 1990:10](#b_EPA_1990))

"some long-term and widespread environmental problems should be considered relatively high-risk even if the data on which the risk assessment is based are somewhat incomplete and uncertain. Some risks are potentially so serious, and the time for recovery so long, that risk reduction actions should be viewed as a kind of insurance premium and initiated in the face of incomplete and uncertain data. The risks entailed in postponing action can be greater than the risks entailed in taking inefficient or unnecessary action."

## What counts as "no appreciable risk"? Needs to be decided by ethics not science, but science can help clarify discussion - idea of expected number of people severely affected

In the prohibitory version of the precautionary principle, "appreciable risk" is left undefined. These things can't be decided on purely scientific grounds, it depends on ethical systems. These can vary by country and by religious or for philosophical reasons. Randolph gave this as one reason why it's important to have ethicists from a wide range of backgrounds involved in the decision process early on.

So, we can't decide this scientifically but we can break down the problem to provide a clearer framework for decision making. The Drake equation gives an approach that may be helpful.

We need to work out, what is an acceptable probability for "appreciable level of risk"? Is it 1 in a billion, 1 in a trillion, or even higher? Some synthetic biologists have come up with numbers far greater than a trillion there [cite]

One proposal by Nick Bostron for a scenario like this is to use the expected number of deaths or people severely affected in a typical worst case. Bostrom has suggested for large scale permanent effects we also need to look at future generations. So considered that way, a single release of mirror life could impact on the lives of not only us but all future generations on Earth.

Take one example, if human civilization expands to a trillion people and lasts for a million future generations, introducing mirror life impacts on the home planet of a quintillion people (10^18) who no longer can enjoy a planet free of mirror life.

So then, we need to replace the one in a billion level to one in a sextillion (10^24) to reduce the expected level of harm to equivalent to a biosafety laboratory which is handling pathogens that couldn't cause harm for future generations in the same way.

This is just one proposed way of thinking about such ideas. Again it would be for dialog, if we need to take account of future generations in this way. But it can help clarify thought.

Many accidental releases from biosafety laboratories don't lead to any deaths or severe impacts. So it's not about multiplying the worst case scenario deaths by the one in a million per facility with the aim to achieve an expected number of deaths.

We can also use this in a comparative way, to aim to achieve comparable assurances to current biosafety facilities. If a one in a million chance of escape is permitted for a case where escape could in a typical worst case severely impact on the lives of, say, 1000 people, it would need to be a 1 in a trillion chance if the worst case is the same level of risk of impact on a billion people to reduce the expected number of deaths to the same level as for an experiment that risks impacting on a 1000 people.

Some jobs and some forms of recreation have far higher levels of risk, such as test pilots, construction industry, base jumping. However the difference there is that it is a choice for the people who take those risks. Most people wouldn’t choose such a high risk job or recreation

Currently there are 59 BSL-4 laboratories operating or planned [(Lentzos et al, 2021),](#b_Lentzos_2021) with more than 50 of those operational [(Goad, 2021).](#b_Goad)

Even with a comparatively small number of facilities, there are releases even with that 1 in a million chance of release. However these are usually through human error rather than issues in the lab design or protocols. Example, in 2003 in Taiwan, SARS was released from a BSL4 facility through human error. The technician found a spill in a cabinet and instead of filling it with hydrogen peroxide and waiting for some hours as was the normal procedure, he wiped it with ethanol, and put his head into the cabinet to do this. He did this because the standard procedure would make him late for a conference [(Demaneuf, 2020)](#b_Demaneuf_2020)

Similar incidents might happen in a BSL-4 laboratory for a Mars sample return, especially since the technicians might well think it is unlikely to contain life and relax or skip procedures as happened often with the lunar sample returns. The recommendation of two years training before the sample return would hopefully eliminate this, but if we need the higher level of assurance of no appreciable risk this is harder to achieve.

## Adaptive approach - return an unsterilized sample to Earth’s biosphere only when you know what is in it

The process outlined in this article in the section [**Recommendation** to return a sample for teleoperated ‘in situ’ study above Geosynchronous Equatorial Orbit (GEO) in the Laplace plane, where particles in a ring system would orbit](#h_Recommendation_GEO) may be a solution. In summary:

1. **If preliminary studies suggest the chance of viable life in the sample is small, we sterilize it** with the equivalent of several millions or tens of millions of years of Mars surface ionizing radiation to be sure, return it to Earth, and study it in terrestrial labs as an unrestricted sample return.
2. **If preliminary studies suggest a significant possibility of viable life in the sample, we return it to above GEO**, sterilize some sections of the sample for return to Earth and study the rest telerobotically in orbit.   
     
   Our discoveries about the sample then determine what we do next.
3. **If viable life is found, then precautions are taken appropriate for whatever is discovered.** This can range from returning the sample unsterilized with no action needed to protect Earth, for instance in the case of an early pre-Darwinian form of life that has been shown to be no match for terrestrial life, through to perhaps total prohibition of returning it to Earth with current levels of technology, if what we find is a mirror-life nanobe.

This process not only enables us to examine an unsterilized sample far sooner than would be legally possible through attempts to return it directly to the Earth’s surface, it also does so in a way that never at any stage runs any appreciable risk of harm.

There is no appreciable risk involved to the biosphere of Earth. There is also no appreciable risk for ourselves, or any of the other organisms that inhabit our planet.

This then can be a template for future sample returns from Europa, Enceladus, or any other location in our solar system that might have non terrestrial life.

## **[Proposal:](#h_proposal_biosafe_pandoras_box)** [a sketch for a biosafe laboratory on Earth designed for 100% containment of even nanoscale mirror life using telerobotics, a sump heated to 300°C with heat and vacuum stable light oil, and built in heat sterilization at end of life of the facility - could this be a safe way to open “Pandora’s box”?](#h_proposal_biosafe_pandoras_box)

We saw that [(Ammann et al, 2012:25)](#qa4nethlmcdw) said it’s impossible to demonstrate that a Mars sample return presents no appreciable risk of harm.

*It is not possible to demonstrate that the return of a Mars sample presents no appreciable risk of harm. Therefore, if applied, the Prohibitory Precautionary Principle approach would simply lead to the cancellation of the MSR mission.*

However, with studies of xenobiology in the labs they do hope to achieve high levels of containment as we saw [(Schmidt, 2010)](#kix.olm1b61u9vxl)

*The ultimate goal would be a safety device with a probability to fail below 10−40, which equals approximately the number of cells that ever lived on earth (and never produced a non-DNA non-RNA life form). Of course, 10−40 sounds utterly dystopic (and we could never test it in a life time), maybe 10−20 is more than enough. The probability also needs to reflect the potential impact, in our case the establishment of an XNA ecosystem in the environment, and how threatening we believe this is.*

*The most important aspect, however, is that the new safety mechanism should be several orders of magnitude safer than any contemporary biosafety mechanism.*

With a Mars sample return we can’t use the same methods xenobiologists plan to use, to design the life itself so it can’t survive outside the laboratory.

But perhaps we need to look at this more closely. Could there be a way that we might be able to achieve 100% containment on Earth to the same degree of safety as an orbital facility above GEO?

This is my proposal for a way to do this, which also uses present day technology, so that the facility build can start right away. This is not yet peer reviewed. But perhaps NASA might be intrigued and look into it? It could be used for a comparison study to get an idea of how much it would cost to return a sample to Earth that’s 100% safe.

It would cost a fair bit more than their current plans. However a plus side is that it is mostly a one off cost. The facility could then be used for all future sample returns from around the solar system – that is if it can indeed be done in a way that is truly 100% safe.

The aim would be to make a design that can be approved in advance by all interested agencies and international organizations. This could be a sufficient guarantee to start on the build even before the legal process is underway.

Then the sample can be returned in the early 2030s as NASA could start the legal process with a high level of confidence that their design can withstand all legal challenges.

My aim here is to show that such a design may be feasible, but not to try to minimize costs. So this design will be over engineered and can surely be done with less cost.

The first step is to return the samples to a safe orbit in the Laplace plane above GEO as in the section: zzz

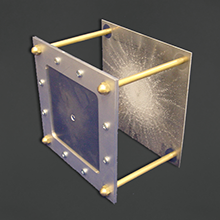
* [The Laplace plane is easy of access via low energy transfer of an Earth Return Vehicle from Mars to above GEO using either a Distant Retrograde orbit or LL2 halo orbit as intermediary](#h_laplace_plane)

This ensures that no contamination can get from the receiving satellite to Earth. xxx

Then the sample is enclosed in a presterilized titanium sphere that can be inspected from the outside, as described above in [A simple titanium sphere could contain an unsterilized sample for safe return to Earth’s surface even with the technology of 1969 - but how do you open this “Pandora's box”?](#h_a_simple_titanium_Pandoras_box)

For extra precautions the titanium sphere is covered in a multi-layer Whipple shield to protect from space debris and micrometeorite impacts, or an aluminium honeycomb shield or foam shield.

This is the basic idea of the Whipple shield:



NASA describes the Whipple shield like this [(NASA, n.d.sd)](#b_NASA_ndsd)

***“The Whipple bumper shocks the projectile and creates a debris cloud containing smaller, less lethal, bumper and projectile fragments. The full force of the debris cloud is diluted over a larger area on the spacecraft rearwall”***

More advanced designs have replaced the Whipple shield in many modern spacecraft. These other possibilities they mention include a honeycomb sandwich, metallic foam panel and a compressible foam used for the proposed Mars Module shield for future Mars missions.

For the Mars sample return, a honeycomb sandwich or metallic foam might be easier to use, as it would give a simple way to enclose a spherical container.

Only a large meteoroid could penetrate it, larger than any meteoroid that has impacted on the ISS. For additional assurance, acoustic sensors could be used to detect impacts, and the sample returned on an orbit that is biased away from Earth’s atmosphere and then a thruster used to bias it to the impact trajectory if there are no detected impacts in the few hours of the return journey from GEO to Earth’s atmosphere.

A large sphere will quickly slow down during re-entry and never reach temperatures that could melt titanium.

For additional protection to prevent heating of the sample, and reduce terminal velocity, it could be protected with a spherical ballute, as suggested for crew emergency re-entry vehicles. This is not needed to protect Earth’s biosphere, but will help to prevent heating of the sample, also will reduce the terminal velocity as it falls through the atmosphere, and the shock of impact as it hits the ground, and can help keep the interior at the cold temperatures of the Martian surface.

This is a design that was engineered to allow a human being to return safely from space without a parachute so should enable a reasonably soft landing for the sample ([Jones et al. 2004)](#b_jones_2004).

Diagram

Description automatically generated

[Figure ??](#figur_LAS_msr): Design for an inflatable spherical ballute for an emergency crewed atmospheric-entry vehicle. zzz

ESA demonstrated an inflatable ballute for re-entry in 2000 ([Marraffa et al, 2000](#b_Marraffa_2000)). This was a partial success, because of impact with the ballute by one of the components that didn’t separate cleanly, there was some localized heating to 200 ° C but the ballute remained inflated, and the interior temperature wasn’t changed ([Marraffa et al, 2000](#b_Marraffa_2000)).

For the next stage, to transfer the sample to the research laboratory, we use the mature technology for black box flight recorders. These use insulating materials to make sure that they can survive an aircraft crash.

These can withstand ([ATSB, n.d.)](#b_ATSB_nd):

* + *an impact producing a 3,400-g deceleration for 6.5 milliseconds (equivalent to an impact velocity of 270 knots and a deceleration or crushing distance of 45 cm)*
  + *a penetration force produced by a 227 kilograms (500 pounds) weight which is dropped from a height of 3 metres (10 feet)*
  + *a static crush force of 22.25 kN (5,000 pounds) applied continuously for five minutes*
  + *a fire of 1,100 degrees Celsius for 60 minutes.*

So, before transport the returned capsule is enclosed in insulating materials and a final outer shell similarly to a black box. Perhaps the Whipple shield could be designed to double as heat insulation for this stage.

The facility itself is built inside a decommissioned nuclear bunker so that there is no possibility of harm even by a direct hit by a plane or explosives, nuclear weapons or a meteorite impact up to 10s of meters in diameter.

The aim is to design the facility to be safe even for hazards like mirror life which can never be released during our lifetime or even during the lifetimes of any future generations on Earth. So, there needs to be a way to sterilize the sample and the entire facility when the facility is decommissioned.

So the facility is built inside an oven capable of dry heat to 300°C. This oven is designed so that it can be maintained externally, with the lab inside the oven. This means that the oven can be turned on at any time if there is some breach of containment that can’t be resolved in any other way.

300°C is enough to destroy most of the nucleobases and amino acids in minutes. For details see

* [Design specifications for 100% sterile rovers for fast safe astrobiological surveys throughout the solar system](#h_Design_100pc_sterile_rovers) (below)

So, when the facility is decommissioned, after all the science is done, the entire facility is heated to 300°C for as long as needed - it could be heat sterilized for six months if that was thought necessary.

To get the sample container into the facility - the only concern at this stage is terrestrial contamination. There should be no terrestrial contamination inside the titanium sphere, and it would be possible to unpack everything down to the titanium sphere outside the facility.

The titanium sphere would be cleaned first with ethanol, then placed inside the airlock. Once in the airlock, the outside of it can be treated with carbon dioxide snow (which is ideal for cleaning flat surface, removing all organics), and hydrogen peroxide or in whatever way is thought necessary to remove any traces of contamination with Earth life.

It would then be opened inside the facility using telerobotically controlled equipment to cut it open.

The simplest way to design the facility is as a hermetically sealed facility which doesn’t need any airlocks. Instead it is built with everything that will ever be needed to study the sample inside the facility, including everything that will ever be needed to repair the equipment, similarly to the design of a space mission to another planet.

Once the sample is placed inside the facility, it is hermetically sealed from the outside. All the work after that is done telerobotically, and nothing leaves the facility until the end of life when the entire facility is sterilized.

The advantage of building even a hermetically sealed facility on Earth rather than placing it in orbit or sending it to Mars would be to include heavy equipment such as particle accelerators.

However – in the forwards direction, we may need to bring in new equipment, replacement parts, reagents, growth media etc. In this direction, the aim is to make sure they are free of any terrestrial life.

In the backwards direction we need to be able to remove fragments of the original samples, and perhaps other materials e.g. growth media with mirror life in it for analysis in terrestrial labs. This time the aim is to make sure that it is sterile of any life that could harm Earth’s biosphere - we could still analyse sterilized mirror life after ionizing radiation.

We also need to remove any equipment that is no longer functional, packaging and so on.

To move materials in and out with no risk of release to Earth’s biosphere, the design uses two airlocks kept at positive pressure and a sump.

Mercury boils at 356.7°C. Big equipment could be pushed through a mercury sump and out of the building. However the density of mercury would make it hard to push objects through it and the vapors are toxic.

So, instead, this proposed design uses a vacuum stable high temperature oil such as Pentane X2000 which is used in space applications.

Pentane X2000 has a fire point of 335 C and flash point of 315 C (flash point is when the vapour from the oil has a risk of igniting). Density 0.85, vapor pressure 10-12 torr (13- 16 millibars) so it can be used in vacuum conditions with almost no loss of oil through evaporation [(Venier et al., 2003)](#b_Verner_2003)

Text

Description automatically generated

[Figure ??](#figur_LAS_msr): the LAS fully robotic floor plan for a Mars sample receiving facility placed inside an oven for end of laboratory lifetime sterilization of the facility and accessed via two airlocks and a sump for 100% containment of even mirror life nanobes.  
Sketch of telerobitic facility Credit NASA / LAS [(Hsu, 2009)](#bxtircq5lfhs)

Photo of Cultybraggan nuclear bunker ([Clark, 2009](#b_Clark_2009))

The oil sump is kept at a constant 300°C – this ensures that no viable spores can survive in it. It’s also irradiated constantly with ionizing radiation from cobalt gamma ray emitters placed in the oil, or X-rays or both. zz

The airlocks are also irradiated constantly with ionizing radiation or X-rays or both, and cycled with carbon dioxide snow to make sure that no biofilms can form in them. The oil in the sump is replenished from outside while keeping it at 300°C throughout.

Any materials to be removed are placed into the inner airlock. This is then pressurized to a positive pressure to keep out any mirror life and the pump’s outlet into the airlock is then sealed – the pump doesn’t operate beyond that point. The pump for pressurizing the inner airlock is operated from inside the facility, with no air connection with the outside.

Similarly the outer airlock is pressurized to a positive pressure and sealed with no air connection from the outer airlock to the inside.

In this way there is no way for air to pass between the inside and the outside of the facility.

For large objects that aren’t heat sensitive, the object is placed in one airlock and the airlocks are heated to 300°C to sterilize both the airlocks and the object of any amino acids or organic matter.

The object is then moved through the oil sump to the outer airlock and then both airlocks allowed to cool down – but the oil sump is kept at 300°C to remain as an impenetrable barrier to mirror life and covered with an insulating cover between uses.

The same method is used in the opposite direction to bring any objects into the facility that aren’t heat sensitive.

For heat sensitive objects, e.g. growth media for a simple example, first they need a heat insulating container which is sterilized at 300°C along with the airlocks – and then everything is allowed to cool down.

The heat sensitive object is then placed into one of the airlocks, which is then pressurized above atmospheric pressure, and sterilized with ionizing radiation, X-rays, and carbon dioxide snow (for flat surfaces / optical components) as appropriate to minimize impact on the heat sensitive object inside the heat insulating container while thoroughly sterilizing it of martian or terrestrial life depending on the direction it's moved.

For the carbon dioxide snow see:

* [Carbon dioxide snow sterilization – final 100% sterilization stage for pre-cleaned components that doesn’t need high temperatures but can remove even trace amounts of organics from surfaces – especially useful for microsats and microrovers / gliders](#h_CO2_snow)

The object is then placed in the heat insulating container, all this done telerobotically. The rest of the procedure is as before.

Both airlocks pressurized, heated to 300 C, then the container is then moved through the oil sump which remains at 300°C to the other airlock and then removed.

As before, this works in the same way in both directions.

The whole process would be automated with security fail safes so that no human being can override the process.

If there needs to be a way to override this lockout, perhaps for maintenance, this could be done using security keys that are not made available to the technicians who operate the facility normally so that there is no possibility of anyone trying to take shortcuts.

Instead, staff would need to call in an independent technician who has no involvement in the experiment, who has no motive to rush proceedings. They would then override the airlock opening mechanism, for instance if it gets stuck and can't be opened normally.

In the worst case, if an issue arises in the mechanisms that can’t be fixed in a way that preserves biological containment, experiments continue but nothing can be moved in or out any more and in worst case, if necessary the facility is decommissioned and heat sterilized.

If it becomes clear early on that the design is acceptable to everyone, it might be possible for NASA to start the build on a facility like this well before the end of the legal process, perhaps as early as 2024.

That would leave perhaps the same 9 years estimate for the build and the sample could be returned by 2033. However this assumes everything goes smoothly without any delays.

It would be important to communicate to the public clearly from the start of the legal process, to explain why the plans eliminate any appreciable risk of harm. To do this, it’s important to have the plans independently scrutinized by multiple experts in all the relevant agencies - the CDC, WHO, FAO, etc at an early stage, ideally before starting the legal process.

Pre-vetting like this by multiple experts would help make it clear in communications with the public that it is not just NASA's plan but is a coordinated plan of world experts in all relevant agencies that they all agree it would work. They would all need to agree that this means that there is no appreciable risk of harm to the Earth’s biosphere.

Even in this case 2033 seems to be optimistic, as there would be likely to be delays with such a complex new facility never built before. However, it seems an idea that deserves consideration that could perhaps be completed by the 2030s, would lead to a much simpler accelerated legal process.

It would be understandable if such an elaborate facility is not suitable for Perseverance's samples. However, it could be used later on for other samples from Mars or Europa and other locations.

Perhaps some day we find confirmed exotic life such as mirror life in our solar system. If so, at some point we will surely need a facility like this on Earth to study it, unless by then we have such advanced facilities in space that we never need to return the samples to Earth.

# **Early life or life precursors on Mars, such as protocells or Woese’s pre-Darwinian cells, could be very vulnerable in the forwards direction - legal protection is weak, but strengthened by the laws for backwards protection of Earth**

Just as terrestrial life may be vulnerable in the backwards direction, so might Mars life be vulnerable in the forwards direction. An example worst case is an early form of life or a precursor for life on Mars, perhaps resembling the RNA only protocells studied at Szostak labs [(Szostak, 2016)](#kix.nyrkdupr5n5r). Although not yet capable of exact replication, such protocells would be of great interest to astrobiology.

Early pre-Darwinian life might also be especially vulnerable. Woese suggested that in early cells from before LUCA (Last Universal Common Ancestor) lateral transfer might have been the dominant way that genes were transferred between cells. He presents this as a data supported conjecture [(Woese, 2002)](#kix.gkm9a21o2b9s),

The LUCA according to this view can’t have been a single organism but rather a

***“loosely knit diverse conglomerate of primitive cells that evolved as a unit”***

These primitive cells would have swapped genes amongst each other readily. It’s also possible that cells might have had a shared metabolism, cross feeding each other metabolically too like a modern bacterial consortium. [(Woese, 1998)](#kix.3rfttbnyrex5) [(Doolittle, 2000](#kix.jqgsmdyryfsq)

For more on this see section:

* [Possibility of early discovery of extraterrestrial microbes of no risk to Earth](#h_poss_early_discovery) (above)

For the argument in the opposite direction, that life on Mars could be more complex than terrestrial life, see [Scenario: evolution on Mars evolves faster than on Earth because of an oxygen rich atmosphere and frequent freeze / thaws of oceans, leading to life of the same genomic complexity as Earth or even greater, and with multicellularity evolving early](#h_scenario_evolution_faster)

If early pre-Darwinian life still exists on Mars today, it might offer no resistance to colonizing Earth microbial life, and this could lead to gradual and complete extinction of all native life that uses the alien biochemistry as the terrestrial life colonizes its habitats.

Another alternative to complete extinction is that if Martian life is closely related to terrestrial life, it might also be able to take up genetic material from a dead terrestrial cell, which it might be able to replicate in some form, so transforming into some more complex intermediate form of life which is partly terrestrial and partly Martian in origin, Martian life but with some terrestrial genetic material incorporated in it, so that we could no longer study the original less complex early life, or at least not in a living cell.

In these scenarios, after the terrestrial life spreads through Mars, there would likely still be remains of early life left in organic deposits too salty or cold or dry or in other ways uninhabitable to terrestrial life and maybe even the life itself if it could inhabit conditions beyond the reach of terrestrial life. But anywhere on Mars that terrestrial life could inhabit, the life would be gone.

In the forwards direction from Earth to Mars the legal protection is weak, based on one clause in the Outer Space Treaty, article IX requiring States Party to the Treaty, to: [(Ireland, 1967)](#kix.gwjsftjvp0rm)

***“***pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to **avoid their harmful contamination*… and, where necessary, shall adopt appropriate measures for this purpose.”***

This clause doesn't specify what "harmful contamination" is. However, it has customarily been taken to include harm to the scientific experiments of other parties to the treaty. Forward contamination with terrestrial life, if it could spread through Mars, would harm experiments by other parties to the treaty to search Mars for present day Martian life..

The treaty continues that if a State

*“has reason to believe that an activity or experiment planned by it or its nationals in outer space …**could cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space…* ***it shall undertake appropriate international consultations before proceeding with any such activity or experiment.****”*

The space lawyer Laura Montgomery is of the view that in US law, this clause is only enforceable on entities that are acting as part of a national program like NASA. For private companies like SpaceX, she doesn't think it implies an obligation on the State to stop them from harmful contamination though she does agree that states have an obligation to inform other member states of their activities [(Montgomery, 2016)](#kix.8kmbd9wqdhd5) [(Klang et al, 2017)](#kix.v1ffxr4mn0jw).

To take an example, if Elon Musk had plans to send humans on a SpaceX Starship to Mars, risking a crash on Mars – all the space lawyers agree, including Montgomery, that the US would be obliged to tell all the other States party to the treaty about these plans. They are obliged to do this, because such a crash landing can potentially interfere with their scientific observations on Mars and their search for life, by introducing Earth microbes.

However, according to Mongtomery’s reading, that's as far as their obligation goes under the treaty. Montgomery does not think the US government would be obliged to stop him from doing it, not without more clarification. She says it would need to be clarified in Congress and expresses a hope that Congress would decide against this interpretation that the US government would have an obligation to stop him.

Another space lawyer, Pamela Meredith, disagrees. She is of the view that by the treaty, the United States is also responsible for ensuring compliance with the treaty by private companies such as SpaceX [(Klang et al, 2017)](#kix.v1ffxr4mn0jw).

However, whatever the outcome of that legal discussion, or any legislative work, as we have seen, the law is only weak in the forwards direction. In the backwards direction it is strong.

Elon Musk’s rockets are intended to shuttle back and forth between Mars and Earth. He could send missions in the forwards direction one way to Mars without triggering Earth's environmental laws. However a spaceship designed to carry 100 people is far too large and complex to be sterilized for a return mission from Mars to Earth.

If we need to protect Earth from Mars samples then Earth has to be protected from materials returned on these spaceships in the same way as for the Perseverance Mars samples. The methods used by the Apollo missions for the Moon can’t be used for astronauts returning from Mars, since the Apollo guidelines were rescinded and were never given any legal scrutiny. We saw that no period of quarantine would be enough to protect Earth from mirror life nanobes, say (see : [Complexities of quarantine for technicians accidentally exposed to sample materials](#h_complexities_of_quarantine) above). This suggests that we need to have a clear understanding of whether there is any life on Mars that we might return to Earth accidentally, and the exobiology of Mars before we can send humans there, at least if they are going to return to Earth at some point.

Also, we need a clear understanding of Martian exobiology for the forward direction too, irrespective of the legal situation. At least, we do, if we value science and if it is indeed possible that we discover something as vulnerable to terrestrial biology as early life, maybe even Woese's transformable cells. We also need a clear understanding of Martian exobiology to decide whether or not it is safe to send humans to Mars in the forwards direction. Once we have a clear enough understanding of the exobiology of Mars (if any) to send astronauts there safely we may also have a clear enough understanding to at least know what we are doing if we make early life on Mars extinct, and make informed decisions about whether to preserve it / conserve it in habitats on Mars, or outside of Mars, or even to preserve early life over the entire planet.

Elon Musk, though he is so in favour of sending humans to Mars as quickly as possible, does care about the science impact of introducing Earth microbes to Mars.

Elon Musk was asked what he thought about Chris McKay’s suggestion that we should explore Mars in a biologically reversible way and if we find life there that we consider removing human presence to allow it to thrive [(McKay, 2009).](#b_McKay_2009) Elon Musk answered ([Musk, E., 2015](#b_Musk)):

A**. "Well it really doesn't seem like there is any life on Mars, on the surface at least, we are not seeing any sign of that. If we do find some sign of it, then for sure we need to understand what it is and try to ensure that we don't extinguish it, that's important.** But I think the reality is that there isn't any life on the surface of Mars. There may be microbial life deep underground, where it is shielded from radiation and the cold. So that's a possibility but in that case I think anything we do on the surface is really not going to have a big impact on the subterranean life.".

So, as one might expect from someone who values science himself, he does think it is important we don't extinguish any native Mars life.

# **The study “Safe on Mars” in 2002 proposed a mission similar to Perseverance to test whether it is safe to send astronauts to Mars – however with the modern more complex understanding of Mars, Perseverance’s sample won’t prove that astronauts are safe in Jezero crater**

It's understandable that prospective Mars astronauts and colonists want a mission with a single "Yes / no" test to discover if it is safe to send humans to Mars. This may not be as easy as it seems at first. As we’ve seen it would need to answer “Yes / no” to the question “Are there Martian mirror life nanobacteria on Mars or in Jezero crater”. See:

* [[Example of mirror life nanobacteria spreading through terrestrial ecosystems](#h_example_of_mirror_life)](#h_example_of_mirror) (above)

At first sight Perseverance’s sample return might seem to be the best way to do this. Indeed, the study ***“Safe on Mars”*** by the National Research Council in 2002 proposed that NASA establishes zones of minimal biological risk on Mars.

The suggestion was to send a precursor mission to determine if organic carbon is present. If organics were found, at or above the life-detection threshold, the suggestion was to use a sample return to find out if there is life present ([Board et al, 2002a](#kix.fph6gak1xp10), chapter [5](https://www.nap.edu/read/10360/chapter/7):[38](https://www.nap.edu/read/10360/chapter/7#38)). If no life was found in the sample returned from a region, it would be declared a safe place for humans to land.

However, though Curiosity found organics in 2014 [(JPL, 2014)](#p9voxfovte8s), the organics discovered so far are believed to come from meteorite impacts, and the search for life is far more complex than just investigating the first organics found on Mars. We now have a far more complex picture of Mars as covered earlier in the current paper, for instance in:

* [2015 review: maps can only represent the current incomplete state of knowledge for a specific time – with knowledge gaps on survival of terrestrial life in dust storms and potential for life to survive in habitats hard to detect from orbit - so can’t yet be used to identify which areas of Mars are of planetary protection concern in the forwards direction](#h_2015_maps)
* [Most samples from Jezero crater expected to be of no astrobiological interest - past biosignatures degraded - past and present day life low concentration, masked by abiotic organics, and patchy - especially challenging if Martian life never developed photosynthesis](#h_most_samples_patchy) and
* [Present day and past life may be patchy or inhabit millimeter scale features](#h_patchy_milliscale)

The reason ***“Safe on Mars”*** recommended a sample return as the best way to determine safety was because in 2002 they lacked instruments that could do in situ biosignature searches in 2002. The committee said that if such instruments became available they would have the advantage that they would not be limited by the small amount of material available to a sample return ([Board et al, 2002a](#kix.fph6gak1xp10), chapter [5](https://www.nap.edu/read/10360/chapter/7):[38](https://www.nap.edu/read/10360/chapter/7#38)).:

***"As stated above, there are currently no measurement techniques or capabilities available for such in situ testing. If such capabilities were to become available, one advantage is that the experiment would not be limited by the small amount of material that a Mars sample return mission would provide. What is more, with the use of rovers, an in situ experiment could be conducted over a wide range of locations."***

Indeed, at the time most of the instruments we could send to Mars for in situ testing for biosignatures were bulky and limited in capabilities. This was written only two years after the first sequencing of the human genome, which involved huge efforts, using many workstations, and was largely manual. Now we have handheld devices able to do end to end gene sequencing that you can hold in your hand. Other instruments have shrunk similarly. We have a miniaturized scanning electron microscope, superresolution microscope imagers to go beyond optical resolution, instrumetns

We now have greatly enhanced capabilities for in situ instruments, which are also low mass and have low power demands, as we saw in the section:

* [Modern miniaturized instruments designed to detect life in situ on Mars - could also be used to examine returned samples in an orbital telerobotic laboratory](#h_Modern_miniaturized_instruments)

***“Safe on Mars''*** *was* also written at a time when the possibility of present day life on the Mars surface was considered to be remote. At the time the surface was thought to have no possibilities for liquid water.

This was before

* the unexpected discovery in 2008 of perchlorates on Mars [(Hand, 2008)](#kix.9iwe09ylohj), which made brines possible at lower temperatures,
* the discovery in 2011 of the Recurring Slope Lineae or Warm Seasonal Flows [(McEwen, 2011)](#kix.ww6o6l5aa7a),
* the observations in 2014, of droplets on the legs of the Phoenix rover [(Gronstall, 2014)](#kix.lsnmx0t0aqsd),
* the temporary ultracold brines in the sand dunes discovered by Curiosity [(Martin-Torres et al, 2015)](#kix.c1m7hhbhkmn1),
* and many new suggestions for surface potential microhabitats, some of which we discussed in: [Could Perseverance’s samples from Jezero crater in the equatorial regions of Mars contain viable or well preserved present day life?](#h_could_samples_contain_viable_life)
* It was also published just a few months after the discovery of potential circadian rhythms in the reanalysis of the labelled release data from the Viking missions, in May 2002 (the Miller paper was from February 2002) [(Miller et al, 2002)](#kix.s9xdd9f9w2d6)

Based on what was known at the time, the authors of ***“Safe on Mars”*** were so certain that nothing of significance would be found, as the most likely outcome, that they suggested planning for a manned mission should go ahead, even before a sample can be returned. They expected the result of the first sample return to be favorable for a manned mission immediately after it ([Board et al, 2002a](#kix.fph6gak1xp10), chapter [5](https://www.nap.edu/read/10360/chapter/7):[41](https://www.nap.edu/read/10360/chapter/7#41)).

***There has been some concern that if a sample return is required, the planning for the first human mission to Mars may be delayed until a sample can be obtained. The committee believes that, even should a sample be required because organic carbon has been found, a baseline plan for a mission to Mars and even hardware development may still proceed under the assumption that a sample return will not find anything significant enough with regard to Martian biology to invalidate the baseline mission plan.***

***“Safe on Mars”*** is one of the main Mars related cites in the Decadal survey which in turn was the original motivation for the Mars sample return mission [(Board et al, 2012:15](#kix.3x8s1sakyp9f)7).

It is the only cite in the Decadal survey summary for the sentence:

***The elements of the Mars Sample Return campaign, beginning with the Mars Science Laboratory, will provide crucial data for landing significant mass, executing surface ascent and return to Earth, and identifying potential hazards and resources."***

One of the white papers for the next Decadal survey makes the same point as “Safe on Mars” that returned samples are critical for planetary protection protocols [(McSween et al, 2020)](#kix.okio4tk2u1yn):

***Returned samples are also critical for developing appropriate planetary protection protocols for both Mars and Earth.***

***“Breaking the chain of contact” when leaving Mars is technically achievable for robotic missions, but it is not possible for a crewed mission and potential biological hazards must be determined before humans go to Mars.***

Sample returns will indeed be needed at a later stage, if we discover life, to learn more about its capabilities. However, sadly, Perseverance mission is not going to settle questions about the safety for Earth’s biosphere or astronauts of any present day life on Mars, even in Jezero crater.

Perseverance is:

* **targeting a region of interest for past life rather than present day life** – it won’t be able to decide if there are other regions nearby such as RSLs that could produce spores in the dust. See [Could local RSL’s be habitable and a source of wind dispersed microbial spores? Both dry and wet mechanisms leave unanswered questions - may be a combination of both or some wet and some dry](#h_could_local_RSL)
* **is not equipped to search for biosignatures in situ, past or present**. See [Several studies by astrobiologists concluded we need capabilities to identify life in situ, for a reasonable chance to resolve central questions of astrobiology – if they are correct, this would also be necessary to show Mars is safe for Earth’s biosphere and for astronauts](#h_several_studies_in_situ)
* **is not searching for extant life in Jezero crater, for instance, won’t sample the expected brine layers in the Jezero crater sand dunes (which could be habitats for more capable Martian life) or much of the dirt, or salts**. See [Detection by Curiosity rover of liquid water as perchlorate brines in Gale crater sand dunes and similar conditions are predicted in Jezero crater dunes](#h_detection_liquid_water) and [How Martian life could make perchlorate brines habitable when they only have enough water activity at -70 °C – biofilms retaining water at higher temperatures - chaotropic agents permitting normal life processes at lower temperatures – and novel biochemistry for ultra low temperatures](#h_how_martian_life_could__habitable)
* **won’t return much by way of dust, which might potentially carry viable dust from distant parts of Mars** – it may have perhaps one sample of regolith, that may contain dust and whatever dust adheres to the outside of the sample tube walls, See: [Could Martian life be transported in dust storms or dust devils, and if so, could any of it still be viable when it reaches Perseverance?](#h_transported_dust_storms_dust_devils)

In short, the current sample return strategy doesn’t have a strong focus on extant life, and is not going to return samples from the most likely places to search for present day life even in Jezero crater such as the dirt, salty brine microhabitats or the Martian dust.

Perseverance is also not sufficiently sterilized to approach any region with potential microhabitats for terrestrial life, such as one of the Recurring Slope Lineae, if it finds one in Jezero crater.

In short, the selection of samples returned by Perseverance is not designed to give even a first idea of whether there might be extant life in Jezero crater.

The current paper suggested the ESF could increase the possibility of finding present day life in Jezero crater if they modify their rover to sample the dust and the brine

layers. It made several specific recommendations and proposals which could be considered to increase the possibility of returning extant life:

* [**Recommendation:** Extra sample of air and airfall dust to search for Martian life, assess forward contamination issues for terrestrial microbes, dust dangers for astronauts, and to return a random sample of wind-eroded rock from distant parts of Mars](#h_rec_air)
* [**Proposal:** magnets could be used to enhance dust collection](#h_proposal_magnets)
* [**Proposal:** to use the sample return capsule as a dust collector – keep it open to the atmosphere before adding the sample tubes](#h_proposal_sample_returjn_capsule_dust)
* [**Proposal:** by Jakosky et al from the 2020 NASA decadal survey to combine a dust sample with a compressed sample of the Martian atmosphere](#h_Proposal_Jakovsky)
* **[Recommendation:](#h_Recommendation_modify_ESA)** [modify ESA's sample fetch rover to grab a sample of the near surface temporary brine layers from sand dunes - perhaps Perseverance may be able to do this too with its regolith bit](#h_Recommendation_modify_ESA)

However these recommendations would still be just a first step. Though they could increase the chance of finding extant life, if it is present in Jezero crater, this wouldn’t be enough to prove Mars safe for humans, even in Jezero crater.

To take an example, if life is widespread in the dirt in Jezero crater, as the Viking results might suggest, we might have a reasonable chance of returning it in the first sample of dirt from Mars. If there are many spores in the dust, as for dust blown from terrestrial deserts, we might have a reasonable chance of finding it in the first sample of Martian dust returned from Mars.

However if there is no life in a few grams of dirt from Jezero crater, this only proves that this

particular sample is lifeless. It doesn’t prove that all the dirt in Jezero crater is lifeless, or even that dirt a few cms away from the sample is lifeless.

By analogy with terrestrial hyperarid deserts with microhabitats for life, there could be life in a patch of dirt or in the rocks just centimetres away from the samples selected for return, especially since Perseverance has minimal in situ life detection capabilities, as we saw in:

* [Most samples from Jezero crater expected to be of no astrobiological interest - past biosignatures degraded - past and present day life low concentration, masked by abiotic organics, and patchy - especially challenging if Martian life never developed photosynthesis](#h_most_samples_patchy) and
* [Present day and past life may be patchy or inhabit millimeter scale features](#h_patchy_milliscale)

It’s the same with the dust, if no life is detected in a returned sample of a few grams of dust,

this may let us obtain a first estimate of an upper bound on the number of viable spores or propagules blown around in the Martian dust, on the assumption that it is reasonably well mixed by the Martian dust storms.

However, a single sample of dust won’t prove that there are no viable propagules even in the dust in Jezero crater. Perseverance could easily miss wind blown dust streaks with viable spores, even from an RSL or other microhabitat in Jezero crater. Or the number of spores in the dust could be so low that a larger dust sample is needed to have a reasonable chance of returning them. The spores could also form and spread seasonally or even on longer cycles.

With Jakosky et al.’s experiment to collect dust in an air filter, it could be that if the experiment ran for a few more months it might have returned a viable spore.

So, how can we obtain reasonable assurance that Mars is safe for humans?

## To check safety of Mars for astronauts requires widespread in situ biosignature and life detection, and in situ tests of dust for spores and other propagules

With the complex understanding of Mars we have now, it is a possibility that even many lifeless samples returned from Mars, if selected according to the geology, may only find more and more patches of dust and drill sites on rocks on Mars that don't contain life.

Mars has a complex geology with a surface area similar to the total land area of Earth. If we do sample returns alone, with no in situ dedicated biosignature detection, it will be hard to do as much as a preliminary survey for life in the complex landscape of Mars since we don’t know where to focus our attention.

It’s the same with the dirt. It’s not practical to return enough material from Mars to do a survey using sample returns. In situ biosignature detection is a key to rapid progress. We can study far more samples on Mars than we could realistically return to Earth in the near future.

To give a vivid metaphor, if extant life on Mars is very rare, it would be like searching Earth for frog spawn. We could suspect that the best place to look for it is in marshes and ponds. But we could send many rovers to those habitats and if they can’t see the frog spawn and just return random samples of water they are highly unlikely to return it. If they can see the frog spawn they have a far higher chance of success. If we also know a bit about the habits of frogs and know the best time of year to look for the frog spawn, and where in a pond we are most likely to find it, we have an even better chance of success. Even so it may take a long time to find it, but we will find it faster than if we don’t have the capability to see it.

The current paper suggested that a few grams of dust returned from Mars could give a preliminary bound on the amount of life in the dust globally on Mars

* [**Recommendation:** Extra sample of air and airfall dust to search for Martian life, assess forward contamination issues for terrestrial microbes, dust dangers for astronauts, and to return a random sample of wind-eroded rock from distant parts of Mars](#h_rec_air)

That might have a reasonable chance of returning life, if Martian life spreads as spores in the dust and is reasonably widespread, or there are some habitats on Mars that produce large numbers of spores, or local habitats near to Jezero crater with the winds blowing towards the rover.

But if Martian life occurs in very low concentrations, or if it spreads only rarely in the dust, perhaps as fragments of biofilms not particularly adapted to dust dispersal, we may not find it for a long time using that method.

We also need in situ biosignature detection to get a first idea of the variety of habitats for life on Mars, for biosafety testing.

Then, if we are lucky, and somewhere in a half kilogram of samples we find a lifeform from Mars, all it does is give us evidence that a particular species occurs on Mars. It doesn't tell us much about any other species that might also occur on the planet and whether or not they also are safe for humans.

To take an example, if we discover normal non mirror life in a sample returned from Mars doesn’t prove that there is no mirror life on Mars. Mirror and non mirror life could co-exist on Mars or be adapted to different habitats from each other.

For another example, the presence of a familiar blue green algae would not be enough to rule out harmful fungal pathogens or a disease of biofilms able to invade human lungs.

The presence of familiar life can’t tell us much about the potential for unfamiliar life.

With the hypothesis that life on Earth originated from Mars, it is possible that there is both related and unrelated life on Mars.

It's interesting that life on Earth has so little diversity - with almost identical choices of nucleotides and of amino acids for all modern life. One solution is that terrestrial life originated on a planet with far more diversity and only one particular branch of life got to Earth, a branch of life that was either hardier or just lucky at the time of the panspermia.

That’s an example scenario where we might find both familiar and unfamiliar life on Mars. See

* [Early discovery of a familiar microbe from Mars such as chroococcidiopsis is not enough to prove the sample is safe - examples include familiar life with new capabilities, or mirror and non mirror life in the same sample](#h_early_discovery_familiar_microbe)

Another way Mars could have a mix of familiar and unfamiliar life is if life originated independently on Mars and some terrestrial life got from Earth to Mars in the early solar system when it was easier for life to be transferred during the huge impacts on Earth, and established itself in the Martian biosphere alongside the Martian originated life.

This could be a plausible scenario if terrestrial life evolved capabilities accidentally that let it be more resilient to planetary transfer via meteorite impacts than Martian life.

There may be some scenarios that would lead to an early positive decision of “Safe on Mars”. However we need caution here. If we return a vulnerable form of present day life such as an RNA world cell with no defenses against Earth life, we might swiftly decide that Earth life is problematic for Martian life in the forwards direction.

However, even such a discovery, that Martian life is very vulnerable to Earth life, would still not be enough by itself to show that Martian life is safe for Earth. The vulnerability could go both ways. As an example, there could be normal and mirror early life co-existing on Mars. The normal early life would be vulnerable to terrestrial life, but the mirror early life might be able to co-exist with it. Even early mirror life could be a risk for Earth.

To establish that terrestrial astronauts are safe on Mars in the positive direction requires much more evidence. Even the discovery of familiar life, perhaps a closely related blue green algae closely related to chroococcidiopsis would not establish the absence of mirror life, other forms of non terrestrial biology, opportunistic fungal pathogens, pathogens of biofilms, or other hazardous life on Mars.

It’s the same also with microhabitats. If we find an uninhabited microhabitat on Mars, this would not be enough to show that all the microhabitats on Mars are uninhabited since colonization of new microhabitats is likely to be extremely slow.

Small amounts of familiar life in the samples could also be contamination as we saw in:

* [[Limitations on cleanliness of the Mars sample tubes with estimated 0.7 nanograms contamination each for DNA and other biosignatures a per gram of returned rock sample and a roughly 0.02% possibility of a viable microbe in at least one of the tubes](#h_lim_cleannliness)](#_rbwqkwnbu7hc)

Mars could also have less evolved and more advanced life co-existing with each other, for instance, adapted to different habitats (early microbes with their smaller minimal size could be better adapted to deal with nutrient poor microhabitats), they could ignore each other as in the shadow biosphere hypothesis, play different mutually beneficial roles in the same microbial community, the early life could be parasitic or symbiotic with the more evolved life and so on.

## There is an asymmetry here - even discovery of extraterrestrial life of no risk to Earth in Jezero crater - such as pre-Darwinian life easily destroyed in microbial challenges with terrestrial life wouldn’t immediately prove the whole of Mars is safe for humans - while a single sample of a biohazard such as mirror life COULD be enough to prove Mars unsafe

Perhaps a discovery of easily destroyed transformable cells could show that Martian life in a sample returned from Jezero crater is safe for Earth as we saw in: [Possibility of early discovery of extraterrestrial microbes of no risk to Earth such as pre-Darwinian life as suggested by Weiss – if microbial challenge experiments show they are quickly destroyed by pervasive terrestrial microbes](#h_poss_early_discovery)

However, to show that the whole of Mars is safe, not just a returned sample we’d need to be very sure that it doesn’t co-exist with other potentially more hazardous life. Depending on how connected Mars is for transfer of life, there could be life at different stages of evolution co-existing on a complex Mars, for instance, recently evolved life in one habitat while another habitat in another part of Mars has ancient mirror life that still persists but hasn’t had time to spread to the habitat that is colonized by recently evolved life based on the complex picture of Mars we now have with potentially disconnected uninhabited habitats [(Cockell, 2014)](#kix.1w5s0x4py5zu):

This could be especially likely if the ancient Martian mirror life never developed photosynthesis or nitrogen fixation, see:

* [Most samples from Jezero crater expected to be of no astrobiological interest - past biosignatures degraded - past and present day life low concentration, masked by abiotic organics, and patchy - especially challenging if Martian life never developed photosynthesis or nitrogen fixation](#h_most_samples_patchy)

Also if it never developed specialized spores to survive transport in the dust storms.

There is a striking asymmetry here. It would take only one microbe that can harm astronauts or Earth’s biosphere, such as a mirror cyanobacteria or a potentially pathogenic fungus, to show that astronauts are not safe on Mars, or at least, can’t return safely to Earth.

However it's not so easy to show that astronauts are safe on Mars, which would require some understanding of the diversity of life on Mars. Indeed with modern understanding of the complex geology of Mars and its complex history of habitability, it’s not easy to find a scenario that would lead to an early decision that astronauts are safe on Mars as a whole or even in Jezero crater. This would require future missions dedicated to the task of finding out if Mars is safe for astronauts or Earth as one of the main objectives.

## [Several studies by astrobiologists concluded we need capabilities to identify life in situ, for a reasonable chance to resolve central questions of astrobiology – if they are correct, this would also be necessary to show Mars is safe for Earth’s biosphere and for astronauts](#h_several_studies_in_situ)

Several studies by astrobiologists have concluded that we need capabilities to identify life in situ, to have a reasonable chance of resolving central questions of astrobiology [(Paige, 2000)](#kix.jbi8mnfxz305), [(Bada et al, 2009)](#kix.b77th2810md), [(Davila et al, 2010](#kix.ngzkl9svh8bg)). A more recent update of “Safe on Mars” would surely conclude that the same capabilities are needed to resolve the question of whether astronauts are safe on Mars.

Paige et al., writing two years earlier than “Safe on Mars”, in 2000 argued that we don’t know where to go on Mars to get the samples we need to answer questions about past or present day life on Mars [(Paige, 2000)](#kix.jbi8mnfxz305).

***We don’t know where to go on Mars to get the samples we need to answer the life on Mars question ...***

They argued for a search in situ first for both past and present day life

***Phase 3. Deployment of Exobiologically-Focused Experiments, to provide detailed characterizations of the population of organic compounds, and to search for biomarkers of formerly living organisms, and extant life.***

***Phase 4. Robotic Return of Martian Samples to Earth, to improve the characterization of organic compounds, and to verify any evidence for biomarkers and extant life discovered in Phase 3.***

Bada et al, writing in 2009 in a white paper submitted to the 2012 Decadal review raised the same concern as Paige et al, [(Bada et al, 2009)](#kix.b77th2810md):

***… we do not yet know enough to intelligently select samples for possible return. In the best possible scenario, advanced instrumentation would identify biomarkers and define for us the nature of potential samples to be returned. In the worst scenario, we would mortgage the exploration program to return an arbitrary sample that proves to be as ambiguous with respect to the search for life as ALH84001."***

Bada et al. recommended that in situ searches should be highly sensitive to biosignatures at low parts per billion or parts per trillion. They give the example of the Atacama desert, where there is a huge variety in biosignatures at both the micro and macro scale and If the instruments are not sensitive enough, it would be easy to miss the signal of life altogether and return rocks with no life in them, even if there were sites only millimetres away with unambiguous signatures [(Bada et al, 2009:7)](#kix.b77th2810md):

***Field studies carried out in 2005 as part of Urey instrument development efforts have shown that in extremely arid locations like the Atacama Desert, variations in biodensity are incredibly pronounced on both the macroscale and microscale. If similar levels of biological heterogeneity were expected at one time on Mars, then it is probable that biosignatures could remain elusive during in situ investigation if instruments with inadequate sensitivity were utilized. Similarly, selection of a limited sample size could result in a null result for life detection during MSR missions and poses a high risk of ultimate failure.***

By analogy with their test missions in the Atacama desert, for the best chance of success, the instruments have to be sensitive to organics at levels that would not be detected by any of the instruments sent to Mars so far.

Davila et al, writing in 2010 stressed the importance of searching for present day and past life in situ to inform decisions about the samples to return, with the sample return at a later stage, saying [(Davila et al, 2010](#kix.ngzkl9svh8bg))

***Sample return would be most efficient and logical once we have information from a variety of environments, particularly if evidence of extant or extinct life is found at any of these sites"***

Bada et al. end their summary of the issues by saying [(Bada et al, 2009)](#kix.b77th2810md):

:

There are serious community reservations about a rush to commit valuable scientific resources and funding to MSR until a valid scientific discovery has been made to justify investment – the in situ detection of localized biosignatures and an attempt at characterization of spatial variability as a function of depth or mineralogy would make a strong case as a valid scientific rationale on which to pursue expensive sample return ambitions.

We feel that organic detection efforts over the next two decades via investment into advanced in situ robotic instrumentation are fundamental in support of a future intelligent MSR mission.

**Currently, MSR is regarded by much of the scientific community as largely weighted towards a technology demonstration as the rationale for good astrobiology will not be apparent until we discover more about our neighboring planet.**

With the single exception of “Safe on Mars”, all the papers I found stressed the importance of in situ searches first. As we saw in the previous two sections, “Safe on Mars” recommends sample return first only due to the bulky nature of the instruments we could send to Mars with the technology of the year 2000. With our new more complex understanding of Mars, a sample return like this can’t prove Mars safe for astronauts even in Jezero creater, see:

* [The study “Safe on Mars” in 2002 proposed a mission similar to Perseverance to test whether it is safe to send astronauts to Mars – however with the modern more complex understanding of Mars, Perseverance’s sample won’t prove that astronauts are safe in Jezero crater](#h_the_study_safe_on_mars)
* [To check safety of Mars for astronauts requires widespread in situ biosignature and life detection, and in situ tests of dust for spores and other propagules - though there is an asymmetry here, a single sample of a biohazard such as mirror life COULD be enough to prove Mars unsafe](#h_To_check_safety)

The Decadal review summing up doesn’t cite Bada et al.’s paper, or mention the conclusions presented in the paper, although it is listed in Appendix D in the list of papers submitted. The review relies instead on “Safe on Mars'' as one of its most cited sources [(Board et al., 2012:16, 63, 157)](#kix.3x8s1sakyp9f). It says [(Board et al., 2012:17)](#kix.3x8s1sakyp9f).

***The Mars community, in their inputs to the decadal survey, was emphatic in their view that a sample return mission is the logical next step in Mars exploration. Mars science has reached a level of sophistication such that fundamental advances in addressing the important questions above will come only from analysis of returned samples.***

The decision to return a sample from Mars as top priority may be the result of this heavy reliance on Safe on Mars, a single out of date source that supports this conclusion. It’s hard to see why a 2002 paper would be given so much weight over later papers based on a more modern understanding of Mars. Perhaps it’s because of its focus on evaluating the safety of Mars for human astronauts, which is a high priority for engineers and scientists who want to send astronauts to Mars?

## [Sample return as a valuable technology demo for astrobiology – and proposals to keep the first sample returns simple, a scoop of dirt or skimming the atmosphere to return micron sized dust samples](#h_sample_return_tehnology_demo)

The only astrobiologist I found to recommend an early sample return in the last two decades is Chris McKay [(NASA, n.d.cm)](#b_NASA_ndcm), and his proposal is a technology demo. In an interview with SpaceNews, he recommends we grab a sample of the Mars soil to show what we can do and return it to Earth. Spend one day on the surface. Design the simplest lowest cost way to return a sample from Mars, no Mars 2020, no rover. Just grab it and return [(David, 2015).](#b_David_L_2015)

"***The first thing is getting a mission that scoops up a bunch of loose dirt, puts it in a box and brings it back to Earth***. If I was an astronaut, what I would be worried about is not the rocks. It’s the dirt. The discovery [by NASA’s Phoenix lander] of perchlorate in the dirt is cause to worry. It’s toxic, and the second cause to worry is the fact that it took us so much by surprise. There was no prediction or premonition that there would be perchlorate in the soil. The fact that it took us completely by surprise makes me wonder if there are other surprises in the soil. In fact, I would be surprised if there are no other surprises. Bringing back dirt is easy because it’s everywhere you land. You don’t need precision landing. You don’t need a rover. You land, grab some dirt and launch it back to Earth. The ground time on Mars could be one day."

"...I’ve said for many years that the sample return should be motivated by a combination of human exploration and science. The science community, I think, does itself a disservice by taking the attitude that there will be just one sample return ever in the history of the universe, so it has to be perfect. And a sample return mission that falls short of perfect shouldn’t be considered. I don’t understand where the logic is behind that. Let’s make a first sample return a quick and easy sample grab, demonstrate the key technologies. It builds enthusiasm for the idea of round-trips to Mars. It would also make getting a second sample return easier, both programmatically and technically. That argument falls on deaf ears when I try and bring it up in the community."

One of his main concerns is that there is no alignment at present between the NASA Mars strategy and astrobiology. He covers this twice in the interview - near the beginning, and towards the end (emphasis mine):

"If we’re going to search for life, let’s search for life. I’ve been saying this to the point of exhaustion in the Mars community. The geologists win hands down as they are entrenched in the Mars program. The favorite trick is to form a committee to decide what to do. The people that are put on the committee, of course, are people who are funded to study rocks. So the committee recommends that we study rocks. They’ll say these rocks will give us the context of how to search for life on Mars. Then you say, well, that’s not right. But NASA Headquarters will say they asked the science community and they told us that this is what we ought to do. It’s kind of circular. The reason the committee told you that — it’s because you put a committee together of people who study rocks. It’s almost a Catch-22. "

"...Right now, ***as far as I’m concerned, there is no alignment between the Mars strategy and astrobiology***. What we have learned from studying Mars is that astrobiology has to go underground. You’ve got to start drilling. Curiosity has a drill and it had problems and we are now very cautious about using it. We’ve got to get back on that horse and send a bigger drill."

Chris McKay doesn’t suggest his "grab sample return of dirt from Mars" mission is likely to be of astrobiological interest. Rather he sees it as of interest for understanding the conditions in the current Mars dirt for future missions to the surface, and human missions particularly, as the dirt is thought to include chemicals harmful to humans.

Its interest for astrobiology would be as a technology demo to show we can return a sample from Mars, at a later stage, once we know how to select the samples intelligently.

China plans a similar approach, a little more complex, two rockets one to land, the other to retrieve the sample ([Jones, 2021)](#Jones_2021)

There's another even lower cost proposal, the "Sample collection to investigate Mars" or SCIM mission. The proposal is to dip into the Mars atmosphere during its dusty season, and pick up a sample of dusty air, to return to Earth. It would use a "free return" trajectory. As soon as it leaves Earth's vicinity, it's on a trajectory to skim the Mars atmosphere and return to Earth with only minor course corrections after that [(Leshing, 2002)](#b_Leshing_2002) [(Savage, 2002).](#Savage_2002)

[](https://www.youtube.com/embed/7WorhUTyURg?feature=oembed)

Video: [SCIM Mission to Mars narrated](https://www.youtube.com/embed/7WorhUTyURg?feature=oembed)

BoldlyGo is a Colorado based privately funded non profit. They have ambitious plans to raise a billion dollars for this and other scientific space projects, partly through wealthy philanthropists, for private exploration missions ([Billings, 2015](#b_Billings_2015)) ([Foust, 2014](#b_Foust_2014)).

This is mainly a geological mission. Laurie Leshing, one of the directors of the Boldly Go institute, interviewed by Space.com, says [(Tillman, 2014)](#b_Tillman_2014)

"Think of it as a microscopic average rock collection from Mars"

Only tiny micron scale rocks get that high into the atmosphere. However, the Stardust sample analysis has shown how much science return you can get from tiny samples. Papers continue to be published leading to new results about comets including the discovery in 2011 that some comets get warm enough for liquid water to form [(Berger et al, 2011).](#b_Berger_2011)

Such small dust particles high in the Martian atmosphere would be sterilized by the UV in the Martian atmosphere, and may have no planetary protection issues – or if they do they could be sterilized during the return mission with ionizing radiation which would have little effect on the geology as suggested in [Sterilized sample return as aspirational technology demonstration for a future astrobiology mission](#h_Sterilized_sample_return) (above).

The dirt in Chris McKay's proposal would also include some dust and larger particles that got there from distant parts of Mars during the dust storms, so her remark would apply to his idea as well.

In the current paper we argue that though returned samples will be essential eventually, the samples returned from Perseverance will not be sufficient to determine potential biological hazards of life on Mars, either for the astronauts or for Earth because of the variations in biodensity and the impossibility of sampling a diverse enough number of locations ex situ.

The issues are the same as for detecting life on Mars at all as outlined in the papers we cited [(Paige, 2000)](#kix.jbi8mnfxz305), [(Bada et al, 2009)](#kix.b77th2810md), [(Davila et al, 2010](#kix.ngzkl9svh8bg)).

If life is found in situ, returned samples from multiple habitats will be necessary to evaluate the biosafety.

The current paper argues that at this point the samples are sufficient only as a technological demo and to establish some of the parameters for a follow up in situ search and later sample returns.

If the reasoning in this section is accepted as correct, how can we resolve this issue quickly? This needs missions dedicated to the task as a high priority. Humans in the vicinity would help speed up the search considerably with their superior decision making capabilities, but we can’t send them to the Martian surface until we know that they will be safe on Mars. The current paper proposes that the solution is to do searches from orbit around Mars via telepresence.

# **[Resolving these issues with a rapid astrobiological survey, with astronauts teleoperating rovers from orbit around Mars](#h_resolving_issues)**

Mars can be explored robotically, and then telerobotically, with humans in orbit and on its two moons. This would involve both humans and robots, each doing what it does best, in a valued partnership. The astronauts would be involved in the search for life, controlling robots directly through telepresence and haptic feedback whenever there is a need for on the spot decisions using human intelligence. The robots are our collective sense organs on other planets. Torrence V. Johnson, Galileo Chief Scientist, put it like this in the foreword to Meltzer’s “Mission to Jupiter” [(Meltzer, 2007)](#kix.nfbetjdd3vdc)

*“There is always a tension in the national debate about how much robotic exploration (such as Galileo) we should do versus so-called human exploration (such as Apollo). This misses the point! What we call robotic exploration is in fact human exploration. The crews sitting in the control room at Jet Propulsion Laboratory as well as everyone out there who can log on to the Internet can take a look at what’s going on. So, in effect, we are all standing on the bridge of Starship Enterprise”*

SpaceX’s new technologies can greatly accelerate the pace of astrobiological exploration of Mars. We can send many rovers to Mars, our mobile sense organs in the solar system.

Once we have the capability, humans in orbit around Mars can direct the rovers on the surface of Mars via telepresence from orbit, with binocular vision and haptic feedback as for the HERRO study [(Oleson et al, 2013)](#kix.l8bu0gc28ggq) [(Valinia, 2012)](#kix.5vt0smtovomr) and the first part of the Lockheed Martin “Stepping Stones” to Mars [(Hopkins et al, 2011)](#kix.z16o9dm6gmye) [(Kwong et al 2011)](#kix.oeiydyocy8za) and Mars Base Camp [(Cichan et al, 2017)](#kix.8r93vmjpu4k4) studies as far as the human base camp on the moons of Mars exploring the surface via telepresence,

A picture containing transport, satellite

Description automatically generated

[Figure ??](#figur_Cernan_lunar_dust):

[NASA, 2012](#NASa_2012tchh) “Safely tucked inside orbiting habitat, space explorers use telepresence to operate machinery on Mars, even lobbing a sample of the Red Planet to the outpost for detailed study."

HERRO image of a tele-operated Centaur as an insert.

The sun-synchronous orbit proposed by HERRO is a spectacular one, comes in over the poles twice every Martian day and flies above opposite sides of Mars HERRO study [(Oleson et al, 2013)](#kix.l8bu0gc28ggq) [(Valinia, 2012)](#kix.5vt0smtovomr)

In this video, I use a futuristic spacecraft called the “Delta Flier” in Orbiter as that was the easiest way to do it in the program I used to make the video. Apart from that, it is the same as the orbit suggested for HERRO.

[](https://www.youtube.com/embed/BftmbvBd5m4?feature=oembed)

Video: [One Orbit Flyby, Time 100x: Mars Molniya Orbit Telerobotic Exploration in HERRO Mission](https://www.youtube.com/embed/BftmbvBd5m4?feature=oembed)

[Figure ??](#figur_Cernan_lunar_dust):

Most of it is speeded up 1000 times, the complete orbit would take 12 hours. I slow down to 100 times and 10 times during some of the close passes of Mars as otherwise it's just a blur as you go past as you see with the first time around. Uses the "Delta flier" a futuristic spacecraft from the Orbiter simulator

To set this up in the Orbiter simulator I used   
Orbit reference MARS   
Frame ref equator   
Epoch Current   
semimajor axis 12880   
Eccentricity 0.726451   
Inclination 116   
LAN 70   
LPe 70   
eps 272   
  
There the LAN, LPe and eps are guesses. Chosen so that it approaches on the sunny side but not sure if it approaches closest exactly at the point closest to the sun. The Eccentricity - I adjusted that until the periapsis was the same as given in the paper. Inclination and semimajor axis just as given in the paper ([Schmidt et al, 2012](#Schmidt_2012)).

And this is what it might look like from inside the spacecraft

A picture containing person, crowd

Description automatically generated

Composite of photo from the Cupola of the ISS ([Coleman, C, 2011](#Coleman_2011)) and Hubble photo of Mars ([Hubble, 2003](#Hubble_2003))

Our astronauts can also explore Phobos for the samples from throughout the history of Mars that are predicted to lie in its regolith as a result of impacts on early Mars. Our astrobiological understanding of Mars should expand rapidly in a few years once we can do this.

In this way humans and robots can work together to unravel the astrobiology of Mars in a way that avoids all possibility of such worst case consequences either for Earth, or for the astronauts themselves.

## [Value of telerobotic exploration for a planet with complex chemistry developed over billions of years – need for forward protection of uninhabited habitats](#h_value_of_lifeless_Mars)

This approach of exploring Mars from orbit first with tele-operated rovers and landers also avoids worst case consequences in the scenario of a lifeless Mars with uninhabited habitats  [(Cockell, 2014)](#kix.1w5s0x4py5zu). One might wonder, why is forward protection needed for uninhabited habitats? Does it matter if terrestrial life colonizes an uninhabited habitat on Mars?

The value of preserving uninhabited habitats, at least initially, is that if we can preserve their unique chemistry, at least for a while, it lets us study the effects of over 4 billion years of chemical evolution on another terrestrial planet in the absence of biology.

Prebiotic chemistry has value too. This could tell us much about the early prebiotic stages of evolution, and about the prospects of life around other planets in our galaxy. It can also help us to disentangle the effects of chemistry and of biology on our own planet by comparison with habitats in which only chemical reactions operate.

We can expect some of the astrobiological missions to yield initially ambiguous results as for Viking, since after all, it is our first ever astrobiological search anywhere. We can’t expect to get everything right at the first try. Scientific experiments often lead to ambiguous leads that need to be clarified. But with a vigorous program of exploration this should not be a problem.

The Europa Lander report set the requirement [(Hand et al, 2017)](#b_Hand_et_al_2017). ,

* *"Life-detection experiments should provide valuable information regardless of the biology results"*

We need to get away from this approach if we are going to have really serious in situ searches in our solar system. Many of the best astrobiological life detection instruments could not be sent with that requirement, or if they had some abiotic value, planetary geologists would not rank them high, judged according to their benefit for geochemical studies.

We should treat uninhabited habitats as an interesting potential discovery in their own right  [[(Cockell, 2014)](#kix.1w5s0x4py5zu).](https://docs.google.com/document/d/1QJgApnOW88OXgjuC7ktzaYiiE7UQHay2ihBWC9TARKw/edit#bookmark=kix.l7vg1blog2t6) On Earth, rocks from volcanoes, soon after they cool down, are inhabitable but uninhabited. Some regions of our harshest deserts don't have life, for instance gypsum pillars in the very driest areas of the Atacama desert, but that's because they are too dry for any Earth life. Just possibly Don Juan lake in Antarctica is uninhabited too - it has microbes but they probably don't grow there, but if so, it's because it is too salty for Earth life [NEEDS CITE].

If we only search for life once we know it is there, how can we expect to find life, unless it is an easily recognizable biofossil or macroscopic lifeform? A null result is of scientific value and can help focus the search [(Kite et al, 2018)](#b_Kite_2018). In addition a potential habitat with no life in it is also of scientific interest in itself

If we do discover a potential habitat in space, one which on Earth would be colonized by microbes, and get a null result from the life detection experiments, this might suggest an uninhabited habitat in space. This should be treated as a major discovery in its own right. It would be the first discovery in our solar system of what may be a common situation in our galaxy.

Places that are outside the normal range for Earth life are of astrobiological interest too, because we don't know of the limits for non Earth life. Is there life on Mars that can live in such habitats though Earth life can't? The answer to that is also interesting both ways, whether we find it, or don't. If Earth life hasn’t adapted to those conditions, maybe Mars life has?

## [Scenario of a pre-biotic uncontaminated Mars of great scientific value - microhabitats with autopoetic cells, Ostwald crystals breaking the mirror symmetry of organics, or naked genes, adsorbed on mineral particles with impenetrable membrane caps, but not yet quite life](#h_examples_prebiotic)

We can’t simulate in our laboratories the effect of millions, or billions of years of prebiotic chemistry on another world. Perhaps such habitats could have RNA and autopoetic cells [(Stano et al, 2010)](#kix.kagfxip2hrve) , but no life. Different habitable regions could differ in the type and complexity of the prebiotic chemistry, again in ways we can never simulate or study once the regions are taken over by Earth life.

Some of the habitats such as hydrothermal vents, fumaroles, or the liquid water in Richardson crater associated with the “spider” markings that form in spring on Mars might have complex chemistry of great interest. See:

* [Proposed surface microhabitats on Mars that could achieve higher densities of life and be a source for propagules in the dust – including brines that form rapidly when ice overlays salt at high latitudes, caves that vent to the surface, fumaroles, and fresh water melting around heated grains of dust trapped in ice layers through the solid state greenhouse effect](#h_proposed_surface_microhabitats)

Even the reactions of the dirt in the Viking experiments are hard to understand as chemistry and if they don’t have biological explanations may involve chemical reactions of interest to the origins of life.

* [Puzzles from the Viking landers – why some think Viking detected life already in the 1970s – evolved gases in the labelled release experiment offset from temperature fluctuations by as much as two hours, more typical of a circadian rhythm than a chemical reaction](#h_puzzles_from_viking)

To give a few examples, some of these “uninhabited habitats” might have autopoetic cells [(Stano et al, 2010)](#kix.kagfxip2hrve) and others Ostwald crystals [(Cartwright et al, 2007),](#kix.hvrp7vyptuh8) formed by crystallization of achiral organic solutions assisted by solution phase racemization [(Blackmond, 2010)](#kix.vlbwnlov1k2s). Or we might find ‘naked genes’ adsorbed on the surface of mineral particles, and perhaps with impermeable membrane caps ‘invented’ by the genetic system [(Leslie, 2004)](#kix.wpqo8wpceht9).

Some of these habitats might have one chirality and others the other chirality, and this could help to elucidate the origins of the homochirality of modern life.

We could study these processes actually in action, study naked genes as they are adsorbed on surfaces, growth of Ostwald crystals, or the activity of protocells in the native environment in which they developed.

If these habitats with prebiotic chemistry are habitable to Earth microbes, how long would they remain in a state suitable for study by astrobiologists and geochemists after infection by even one microbe or dormant spore capable of replicating in them?

Perhaps even an intact microbe or microbial spore is not needed. Infection with fragments of RNA or enzymes from Earth microbes could be enough to give protobionts in these habitats at a late stage in chemical evolution the missing key to become a simple form of replicating life. The resulting life could be interesting in its own right, but this process could erase all traces of the pre-existing protobionts, so that we never get to study them in their original state.

Study of the Martian meteorite NWA 5790 has revealed small vesicles that may provide bioreactors for early life to evolve even in the more recent Amazonian period on Mars [(Viennet et al, 2021)](#kix.7ba5uq4s07pb). Suppose they are, but life has not yet evolved? What a wonderful opportunity to study this process? There may be no other planet within light years to gain such insights from.

Mars could also have very early life, perhaps recently evolved in temporary surface habitats cut off from its deep hydrosphere as we discussed in the section. This earliest life could predate Darwinian evolution of cells based on Weiss’s idea of simple modifiable cells with no barriers to uptake of genetic material from other cells evolving through Lanarckian evolution with Darwinian evolution only of the genetic material itself:

* [Possibility of early discovery of extraterrestrial microbes of no risk to Earth](#h_poss_early_discovery)

In the best case (from the point of view of the study of early life) Mars could have multiple unconnected potential habitats, uninhabited and inhabited, preserving different stages of evolution from complex chemistry to life.

This would give a fine grained understanding of stages in the processes of development of life from non life. We could use present day Mars like a time machine to take us back to the early stages of life and perhaps get some idea of what happened on our own planet right at the beginning before life evolved.

If life is still at an extremely early stage of evolution on Mars with early life with modifiable cells, or prebiotic with life not yet evolved, it might be only a matter of time after the first human boots on Mars before introduced terrestrial life reigns supreme in all the habitats on such a world, both previously uninhabited and habited.

If we prioritize an astrobiological survey from orbit first, we may soon be able to make informed decisions about whether to send humans to the Mars surface. If the decision is then made to land astronauts on Mars, the astrobiological survey can help us to do it in a way that preserves the interest of native Martian complex chemistry, protocells, early life or complex life and is safe for our astronauts, and Earth itself.

Depending on our future plans, if the decision is made to colonize an early life or prebiotic Mars, at least we know in advance what we are doing.

The preliminary astrobiological survey would still give us an opportunity to "rescue" early life and prebiotic chemistry on Mars, to attempt to reproduce it, perhaps in space habitats outside of Mars, or there may be things we can do on the planet to protect small microcosms of uncontaminated Mars, even if just in small-scale habitats a few meters across, before the processes are erased on the rest of the planet itself.

Also, even if there is early or pre-biotic life on Mars, and we extinguish / destroy it, the measurements made during this survey would remain as a record for future humanity, thousands of years into our future of what Mars was like before we initiate the anthropocene geological era on Mars with surface processes altered by terrestrial biology.

We will also have many assets on the surface that we placed there to do the survey, of value to astronauts ,and in case that we decide to land humans there, we will have a better understanding of the Martian surface environment and the best place to build our bases.

The main thing is that we would make our decisions in knowledge of what we do. We’d avoid the situation of landing there, destroying early Mars and then having regret for what we destroyed. We’d be replacing pre-biotic or early life on Mars with terrestrial life in full knowledge of what we are doing and the consequences and preserving what we feel needs to be preserved for ourselves and for future generations.

## [Arthur C. Clarke’s story “Before Eden” exploring the theme of accidental extinction of extraterrestrial life in the forwards direction](#h_Arthur_c_Clarke_before_Eden)

Few science fiction authors tackled the theme of forward contamination of other parts of our solar system by Earth microbes, but there's one poignant sad story, by Arthur C. Clarke, ["Before Eden"](https://books.google.co.uk/books?id=JinIy94fhA8C&pg=PA60#v=onepage&q&f=false), published in [Amazing Stories, June 1961](http://www.isfdb.org/cgi-bin/title.cgi?41621). Back then, though they knew Venus was hot, scientists thought it was still possible that Venus could have water on its surface, perhaps at the top of its mountains.

A picture containing text, sign

Description automatically generated

[One of the covers for Arthur C. Clarke's "Before Eden"](https://archive.org/details/BeforeEden) -a poignant sad story about forward contamination of Venus, published in 1961 at a time when surface life there was still a remote scientific possibility. You can hear the complete story [read as an audio book here](https://archive.org/details/BeforeEden).

These adventurers are exploring a completely dry Venus, or so they think. Up to then (in the story), everyone thought Venus had no water, and was sterile of life. That was a natural thought, because the temperatures they encountered were always above the boiling point of water. But the heroes of the story are stranded near the not quite so hot South pole, and find mountainous cliffs there. On those mountains they find a dried up waterfall - and then - a lake!

“Yet for all this, it was a miracle—the first free water that men had ever found on Venus. Hutchins was already on his knees, almost in an attitude of prayer. But he was only collecting drops of the precious liquid to examine through his pocket microscope.... He sealed a test tube and placed it in his collecting bag, as tenderly as any prospector who had just found a nugget laced with gold. It might be – it probably was – nothing more than plain water. But it might also be a universe of unknown, living creatures on the first stage of their billion-year journey to intelligence....”

“...What they were watching was a dark tide, a crawling carpet, sweeping slowly but inexorably toward them over the top of the ridge. The moment of sheer, unreasoning panic lasted, mercifully, no more than a few seconds. Garfield’s first terror began to fade as soon as he recognised its cause....”

“… But whatever this tide might be, it was moving too slowly to be a real danger, unless it cut off their line of retreat. Hutchins was staring at it intently through their only pair of binoculars; he was the biologist, and he was holding his ground. No point in making a fool of myself, thought Jerry, by running like a scalded cat, if it isn’t necessary. ‘For heaven’s sake,’ he said at last, when the moving carpet was only a hundred yards away and Hutchins had not uttered a word or stirred a muscle. ‘What is it?’ Hutchins slowly unfroze, like a statue coming to life. ‘Sorry,’ he said. ‘I’d forgotten all about you. It’s a plant, of course. At least, I suppose we’d better call it that.’ ‘But it’s moving! ’ ‘Why should that surprise you? So do terrestrial plants. Ever seen speeded-up movies of ivy in action?’ ‘That still stays in one place – it doesn’t crawl all over the landscape.’ ”“‘Then what about the plankton plants of the sea? They can swim when they have to.’ Jerry gave up; in any case, the approaching wonder had robbed him of words... ”

“... ‘Let’s see how it reacts to light,’ said Hutchins. He switched on his chest lamp, and the green auroral glow was instantly banished by the flood of pure white radiance. Until Man had come to this planet, no white light had ever shone upon the surface of Venus, even by day. As in the seas of Earth, there was only a green twilight, deepening slowly to utter darkness. The transformation was so stunning that neither man could check a cry of astonishment. Gone in a flash was the deep, sombre black of the thickpiled velvet carpet at their feet. Instead, as far as their lights carried, lay a blazing pattern of glorious, vivid reds, laced with streaks of gold. No Persian prince could ever have commanded so opulent a tapestry from his weavers, yet this was the accidental product of biological forces. Indeed, until they had switched on their floods, these superb colours had not even existed, and they would vanish once more when the alien light of Earth ceased to conjure them into being...”

“...For the first time, as they relaxed inside their tiny plastic hemisphere, the true wonder and importance of the discovery forced itself upon their minds. This world around them was no longer the same; Venus was no longer dead – it had joined Earth and Mars. For life called to life, across the gulfs of space. Everything that grew or moved upon the face of any planet was a portent, a promise that Man was not alone in this universe of blazing suns and swirling nebulae. If as yet he had found no companions with whom he could speak, that was only to be expected, for the lightyears and the ages still stretched before him, waiting to be explored. Meanwhile, he must guard and cherish the life he found, whether it be upon Earth or Mars or Venus. So Graham Hutchins, the happiest biologist in the solar system, told himself as he helped Garfield collect their refuse and seal it into a plastic disposal bag. When they deflated the tent and started on the homeward journey, there was no sign of the creature they had been examining. That was just as well; they might have been tempted to linger for more experiments, and already it was getting uncomfortably close to their deadline. No matter; in a few months they would be back with a team of assistants, far more adequately equipped and with the eyes of the world upon them. Evolution had laboured for a billion years to make this meeting possible; it could wait a little longer.”

“...For a while nothing moved in the greenly glimmering, fog-bound landscape; it was deserted by man and crimson carpet alike. Then, flowing over the wind-carved hills, the creature reappeared. Or perhaps it was another of the same strange species; no one would ever know. It flowed past the little cairn of stones where Hutchins and Garfield had buried their wastes. And then it stopped. It was not puzzled, for it had no mind. But the chemical urges that drove it relentlessly over the polar plateau were crying: Here, here! Somewhere close at hand was the most precious of all the foods it needed – phosphorous, the element without which the spark of life could never ignite...” " ... And then it feasted, on food more concentrated than any it had ever known. It absorbed the carbohydrates and the proteins and the phosphates, the nicotine from the cigarette ends, the cellulose from the paper cups and spoons. All these it broke down and assimilated into its strange body, without difficulty and without harm. Likewise it absorbed a whole microcosm of living creatures—the bacteria and viruses which, on an older planet, had evolved into a thousand deadly strains. Though only a very few could survive in this heat and this atmosphere, they were sufficient. As the carpet crawled back to the lake, it carried contagion to all its world. Even as the Morning Star set its course for her distant home, Venus was dying. The films and photographs and specimens that Hutchins was carrying in triumph were more precious even than he knew. They were the only record that would ever exist of life’s third attempt to gain a foothold in the solar system. Beneath the clouds of Venus, the story of Creation was ended.”

How sad it would be if future explorers on Mars get glimpses of early forms of life on Mars, and they go extinct soon after they are discovered. Or indeed, even before, maybe they are extinct before anyone finds them, and all we find are traces of the signs of past life right up to the present but gone within a decade or two at the start of the Martian Anthropocene (if dust storms can spread terrestrial life throughout the planet).

## [Suggestion to develop design specifications for 100% sterile rovers for fast safe astrobiological surveys throughout the solar system based on research for Venus surface rovers](#h_Design_100pc_sterile_rovers)

Even a preliminary astrobiological survey is likely to require a large number of landers and rovers, to explore a wide variety of potential habitats, at least for a planet as complex as Mars. This increases the risk of forward contamination. Some authors have suggested that we relax planetary protection measures for our rovers, in order to study potential habitats on Mars rapidly, knowing that this is likely to introduce Earth life to them irreversibly [(Fairén et al, 2017)](#kix.uqumtmv14le8), Others suggest we still have time to send adequately sterilized rovers to the planet to learn something about astrobiology on Mars before humans get there [(Rummel et al, 2017)](#kix.he0kflo501ug)

This article proposes that we respond to the challenges by being more ambitious rather than less so in the field of planetary protection.

Our technology has advanced since the Viking landers. The Viking landers were baked for 112 °C for 30 hours, enough for a million-fold reduction of the originally low population [(Beauchamp, 2012)](#kix.kebgt1qylud6). As a result of research into a Venus lander, we now have preliminary specifications for a rover that can safely be baked at 200 - 300 °C for months.

This design of rover is based on commercial components including microprocessors and memory devices, that already function at 200 - 300 °C. They are used in oil wells, aviation and electric cars. Their heat resilience means they don't have to be cooled, and they can be placed closer to heat sources such as engines. This helps with cost, weight and most important, reliability [(Watson et al, 2012)](#kix.zqrftage3yi). Using these components along with high temperature mechanical components, sensors and cameras researchers have sketched out a design for a complete rover able to withstand temperatures of 300 °C (and then to survive at that temperature for long term missions on the surface of Venus with active cooling). This rover specification was developed as part of Venus Rover studies. The researchers propose that the same approach could be useful for planetary protection [(Sauder et al, 2017, section 6.2)](#kix.n59cqt9s3mjo).

The batteries and solar panels are best replaced by RTG’s (Radioisotope Thermal Generators) which can withstand high temperatures. Radio communication can be done with high temperature components and high temperature mechanical components are also possible.

Since these temperatures are only used for sterilization, the instruments do not have to operate at 200 - 300 °C. They just have to be able to survive heating at that temperature for several months on the journey to Mars. Once there, they would operate at normal temperatures. Future instruments to be deployed on this rover will need to use chips, solders and other components that work up to high enough temperatures for 100% sterilization.

With this rover specification, the whole spacecraft can be sterilized, as for Viking, but at a far higher temperature using modern more heat resistant electronics.

The simplest way to do this might be to use the spacecraft to heat itself during the journey out to Mars, to save the need to enclose it with a barrier before launch. If it uses an RTG as a source for power, this can also be used as a heat source too. Typically an RTG has an active cooling system or heat radiators. By disconnecting or regulating the active cooling, the RTG could heat the entire spacecraft during the journey out to any desired temperature.

Brian Wilcox has designed an ice melt probe for the Europan ocean which can be sterilized during the cruise phase, in this case at 500 °C, a temperature high enough to pyrolyze and decompose all large organics [(Wilcox, 2017:2)](#kix.ubiv50n5r668). The approach would be to have an inert gas circulate inside and outside the probe to maintain a nearly uniform temperature. It would be surrounded by a foil barrier which is also sterilized inside and out, and then the probe penetrates the foil barrier during deployment [(Wilcox, 2017:8)](#kix.ubiv50n5r668).

With such a high temperature as 500 °C, Brian Wilcox’s probe has no electronics on board, and is a simple remotely deployed probe. However at the significantly lower 300 °C, electronics can be used, and this seems to be a high enough temperature for protecting any native Martian life from terrestrial microbes, and also preventing forwards contamination by genetic sequences and proteins.

* 200 °C is enough to sterilize cells.
* At 250 °C the half life of the RNA bases under hydrolysis is between 1 and 35 minutes, with U the most stable, G and A of intermediate stability and C decomposing most rapidly.
* At 350 °C the half-lives are between 2 and 15 seconds (Levy et al, 1998).
* So long as some water vapour is available for hydrolysis of the bases, there is not likely to be any genetic material remaining by the time it reaches Mars after six months at 300 °C.
* 300 °C should be enough to destroy proteins too. Eight of the 20 amino acids, G, C, D, N, E, Q, R and H, have been proven to not just evaporate or liquify but to decompose at temperatures between 185 for Q (Glutamine) to 280 for H (Histamine) They were not able to completely characterize the gases emitted for the other twelve amino acids [(Weiss et al, 2018)](#kix.niag7hm91beo).

Once the design for such a rover has been developed, modifications of the basic design can be used anywhere in the solar system including Europa, Enceladus and other proposed locations to search for life.

This would greatly reduce the risk of contamination with terrestrial life. However, as with Wilcox’s probe, an issue is how to get the rover to the surface of Mars without adding microbial contamination from the rocket used to get it there, if we are aiming for truly 100% sterile rovers. This is easier for smaller spacecraft. As instruments get miniaturized we can do more with smaller rovers.

When microrovers need to enter an atmosphere, such as the Mars atmosphere, one approach is to pre-sterilize the entire reentry spaceship and enclose it in plastic before the launch. The plastic cover would simply burn away during re-entry exposing the sterile spacecraft inside.

Staehle et al. propose this method for their miniature paraglider to run piggyback on larger missions. It would re-entry as a parawing glider, capable of 10+ km of guided flight at a 3:1 glide ratio, with the entire spacecraft massing 10-20 kg including deployer and de-orbit propulsion  with science payload 1-2 kg and cost $20M reducing to $10M if 2-3 copies are made [(Staehle et al 2015)](#b_Staehl_2015)

A similar approach might be feasible for larger spacecraft too, by enclosing the entire spacecraft, aeroshell and parachute too, in a plastic cover that burns up in re-entry.

In our decisions about whether and how to protect Martian life from forwards contamination, we need to be able to evaluate not just what we would gain with humans on the surface, but also, what we would lose, if the trillions of microbes that travel with us extinguish native life on Mars.

There may be treasures of immense value, preserved on Mars for billions of years, and yet, vulnerable to destruction in just a few years if we are careless in our procedures to prevent forward contamination. The treasure of extraterrestrial life on Mars, if it exists, is as much a part of our common shared heritage as any of our artistic or architectural treasures preserved from ancient civilizations. This suggestion of 100% sterile rovers is a way to protect our heritage in the solar system.

### Ultra cleaning with [carbon dioxide snow sterilization – final 100% sterilization stage for pre-cleaned components that doesn’t need high temperatures but can remove even trace amounts of organics from surfaces – especially useful for microsats and microrovers / gliders](#h_CO2_snow)

This could be especially useful for highly sterilized rovers such as Steehle’s idea of a pre-sterilized microglider enclosed in a bag that burns up on entry to the Martian atmosphere mentioned in the last section [(Staehle et al 2015)](#b_Staehl_2015).

It is an alternative to such high temperatures as 300 °C is to use CO₂ snow. It is not enough to sterilize components on its own, but if the components are pre-cleaned using other methods it can kill any remaining dormant microbes from the surfaces, and not only that, decompose organics too.

Components for the ExoMars lander were partly sterilized using CO2 snow [(Fraunhaufer, 2015).](#b_Fraunhaufer_2015) It was also tested in 2015 as a method for sterilizing the James Webb mirror in case it got contaminated before the launch [(NASA, 2015sucs)](#b_NASA_2015sucs).

One advantage of CO2 snow is that it is especially easy to sterilize external surfaces of microsats, and microrovers / gliders, to the extent that there are no organics left. Of course this adds to the complexity of the mission. But if you value potential indigenous Mars life highly, it's worth it, to make sure we have no practical chance of making life there extinct.

The motivation here is that the external surfaces are most at risk of forward contamination. Especially if you are concerned about the possibility of transfer of complex molecules that it may be able to replicate to pre-biotic life, say then it’s best if you can eliminate all organics from Earth.

Carbon dioxide snow is one of the few techniques that removes everything, if it is used to sterilize a part that is already reasonably sterile. This is a new technique for spacecraft sterilization that was evaluated by ESA at one point [(Pagel at al, 2017).](#b_Pugel_2017)

It works especially well for flat components such as wafers and optical components. But it also works reasonably well for microgears [(Jantzen et al, 2018)](#b_Jantzen_2018).

The main difficulty is scaling it up to sterilize a complete spacecraft. Also, although it is great at removing micron scale contamination, it's not so good at dealing with complete microbes.

Neither NASA nor ESA have approved it for planetary protection [(Pagel at al, 2017).](#b_Pugel_2017) However it could be used as an additional method on top of methods already approved for final sterilization.

The great advantage of this is that it sterilizes at low temperatures, has no adverse effect on electronics, and also removes the organics completely if the robot starts off reasonably clean. It can also penetrate into tiny cracks and holes. It also has the additional advantage that it removes impurities that could interfere with the electronics.

If this method can be made 100% effective, you not only get no life on the spacecraft, but no DNA fragments or GTAs, or indeed, anything organic at all.

There are two ways to do it. One is to use supercritical liquid carbon dioxide, and enclose the instrument in a pressure vessel for small and delicate parts. The other way is to generate tiny particles of carbon dioxide snow which impact on the surfaces.

With the supercritical liquid method, the liquid carbon dioxide penetrates into tiny holes, dissolves the organics, and then, as it escapes as snow, it takes the organics with it, and changes back to gas, so leaving the spacecraft completely dry with no residue.

The pressurized supercritical method is:

* Inject CO₂ in a supercritical state. It behaves much like a liquid at 74 atmospheres upwards and 31 C.
* In this state, it dissolves organics readily
* It then forms snow which captures the organics and gets blown / sucked away.
* The snow evaporates rapidly into the gas state, leaving no residue
* Can be mixed with Hydrogen peroxide and other chemicals to increase effectiveness.
* Can be used even with sensitive electronics.
* It has been used to clean USB drives in testing and they functioned afterwards.
* Surface is left with no trace of organics, not even dead organisms.
* Doesn’t remove or inactivate spores unless it is combined with other methods to remove them [(Pagel at al, 2017).](#b_Pugel_2017)

The impacting snow method is what ESA are investigating and use already in an operating spacecraft clean room. It relies on tiny explosions of carbon dioxide snow to clean the spacecraft.

The method is to mix the CO₂ in advance with clean dry air, which triggers the formation of tiny snowflakes. These hit the spacecraft and penetrate into crevices. The spacecraft surfaces are relatively hot for the snowflakes. When they hit those "hot" surfaces, they suddenly expand 800 fold, in mini explosions, taking the organics and other matter away with them. The difference is that the CO₂ forms into snowflakes soon after it left the nozzle instead of on the surface [(Fraunhaufer, 2015)](#b_Fraunhaufer_2015) [(Giuliani et al, 2009: 3.2.3).](#b_Giulani_2009)

This could also be combined with other sterilization methods to reduce the levels even of organics that we bring to Mars. We could use this on Earth before or after a heat sterilization stage or ionizing radiation. A lander or rover could also take a container of CO₂ with it and use it for a final CO₂ snow sterilization stage on the surface of Mars after the landing, or extract carbon dioxide from the Mars atmosphere to use for an extra CO₂ snow sterilization stage after landing there.

# **Mars not habitable for humans in any ordinary sense of the word - less habitable than a plateau higher than Mount Everest, so high our lungs need a pressure suit to function – not significantly more habitable than the Moon**

Mars is not habitable in any ordinary sense of the word. The atmospheric pressure of 6 to 7 millibars is well below the Armstrong limit of [6.3%](https://www.google.com/search?client=firefox-b-d&q=47+mm+of+mercury+in+bars) where water and body fluids boil at body temperature [(Murray et al, 2013)](#kix.5lz8dej2gi95), so we would not be able to survive there even with bottled oxygen. The atmospheric pressure on Mars is too low for our lungs to function. We would go unconscious in seconds, and require a full body pressure suit to breathe.

Suppose we had a plateau on Earth, at a height of 45 kilometers [(NASA, n.d.ame)](#kix.wk3kttflfefk), five times higher than Mount Everest at 8,848.86 km [(Dwyer, 2020)](#kix.ah345s47n0t1). The pressure would be typical for Mars, but it would still be far more habitable than Mars.

We could survive on such a plateau simply by raising the pressure of the air inside habitats. On Mars colonists would have to generate all their own oxygen and scrub their habitats of the CO2 (possibly using plants or algae to do this). They would need to add some other gas such as nitrogen to the cabin atmosphere, as the CO2 in the Martian atmosphere raised to terrestrial pressures is lethal above 10% leading to rapid loss of consciousness and death, irrespective of how much oxygen there is [(IVHN, n.d.)](#kix.6f9xhftbglf1)

Colonists on Mars would also need extra protection from solar storms - even on such a high plateau on Earth we would have some protection due to Earth's magnetic field as for astronauts in the ISS. We also don't know what difference the lower Martian gravity makes to long term health, and then there's half the sunlight we get on Earth.

It would be far easier to colonize such a high plateau than Mars. Yet if such a plateau occurred on Earth, we would likely have few living there permanently except to extract resources or for scientific study. We don’t colonize most deserts, or the shallow continental shelves, which are far more habitable.

Then we have the problem of the dust.

## Dust as one of the greatest inhibitors to nominal operation on the Moon - and likely on Mars too

Lunar dust isn’t laced with perchlorates like the Martian dust, but it was still a major issue for lunar astronauts. They all reported difficulties with the dust [(Stubbs et al, 2007)](#kix.p7sfwz8gg7y).

Astronaut Eugene Cernan, the last man to walk on the Moon to date [(NASA, 2017rgc)](#kix.hb1hjfqzxw3c), described the lunar dust as one of the greatest inhibitors to a nominal operation on the Moon [(Levine, 2020)](#kix.ax4h179zgo2s):

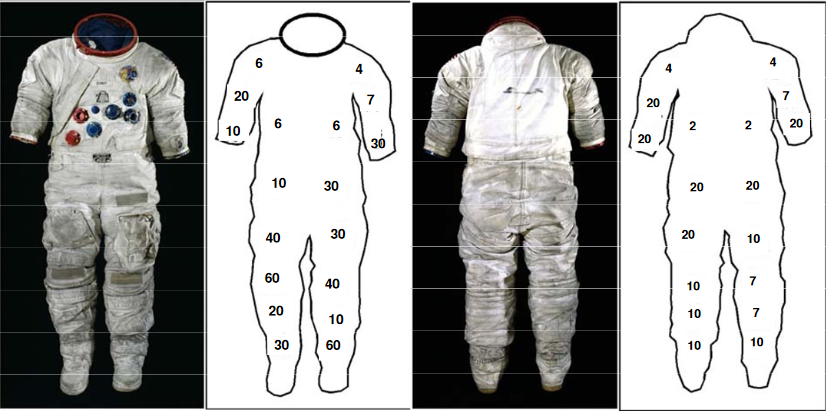
***“I think dust is probably one of the greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.***

***One of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and its restrictive friction-like action to everything it gets on., metal, no matter what it be and its restrictive friction-like action to everything it gets on,”***



[Figure 68](#figur_Cernan_lunar_dust): Gene Cernan inside the lunar module [(NASA, n.d.ecilm)](#kix.3riak3prfxf6). The dust got everywhere. He was particularly dusty because of an incident with a broken fender on the lunar rover [(Phillips, 2008)](#kix.wwmwsz3pjusf).

The lunar dust got embedded deep in the woven fabric of the suits causing significant damage after just three days EVA on the surface. The dirt got into the knees and the seat of the suit, and the upper arms too, perhaps when the astronauts supported themselves when they fell over on the lunar surface. This is something that needs to be considered in future lunar and Mars spacesuit designs [(Christoffersen et al, 2009)](#kix.tbuy0631dkon).



[Figure 69](#figur_Schmitt_lunar_dust): Concentrations of titanium (in units of 100 ppm) in the suit fabric for Jack Schmitt’s suit for Apollo 17. This seems to be a good tracer of the lunar dust.

Mars has worse dust problems than the Moon. For instance the Moon doesn’t have dust storms. Several times a decade dust storms on Mars block out the sunlight for weeks making surface conditions as dark as night.

Our rovers on Mars haven't yet travelled fast enough to create their own dust clouds but fast moving rovers or even people walking would throw the dust up into the air, as fine as cigarette ash, similarly to the arcs of dust thrown up by rovers on the moon.



[Figure 70](#figur_lunar_ballistic_dust): Clouds of lunar dust thrown up by the rover, during Apollo 16. On Mars the dust is as fine as this, but it would linger in the air and not fall back in ballistic arcs as it did on the Moon [(NASA, 1972)](#kix.f3n4mv4rlsm5).

Lunar dust falls back in ballistic arcs, in an atmosphere so thin it is classified as an exosphere rather than an atmosphere.

However, on Mars, some of the finest dust kicked up by astronauts or rovers would linger in the air for some time even in calm weather without winds.

Ignoring atmospheric drag, the ballistic arcs would be the same shape and height if the dust was kicked up one and a half times faster (calculated as sqrt(3.72/1.62) where 3.72 m/s² and 1.62 m/s² are for Mars gravity and the lunar gravity respectively) [(Hsu et al, 2012:455)](#kix.bxz2uojvsl78). The lunar rover was driving at around 10 km / hour [(Hsu et al, 2012)](#kix.bxz2uojvsl78), so as a rough estimate, a Mars rover driving at around 15 km / hour in similar conditions would produce similar height ballistic arcs to the lunar rover, though only for large particles.

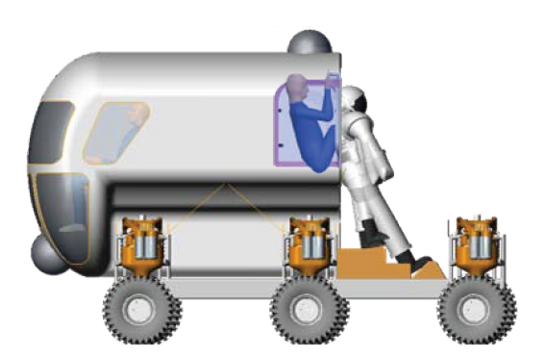
Dust of 1 mm diameter settles at a speed of about 5 meters per second [(Fuerstenau, 2006:Figure 1](#kix.kxdgk2p32x19)) so wouldn’t linger in the atmosphere for long in calm weather. However, a one micron particle will take half an hour to fall a meter in Martian conditions [(Fuerstenau, 2006:Figure 1](#kix.kxdgk2p32x19)), though it wouldn’t be thrown up so high as it would on the Moon.

The perchlorates in Martian dust, although useful as a resource for colonists to make fuel and oxygen, would also be potentially harmful. Perchlorates interfere with regulation of the thyroid gland (by impairing uptake of iodine).

Inhaling a few milligrams of Martian dust could exceed the recommended maximum daily dose for perchlorates (Reference dose or RfD) [(Davila et al, 2013)](#kix.gjzllhf89hy4). When the perchlorates are activated by ionizing radiation they may change to the more deadly chlorates and chlorites with some potential for more serious and immediate effects such as respiratory difficulties, headaches, skin burns, loss of consciousness and vomiting.

There are methods for dealing with this, used for dust suppression when mining uranium, lead or other heavy metal contaminated areas. But it adds to the complexity of Mars colonization [(Davila et al, 2013)](#kix.gjzllhf89hy4).

The challenges to keep the dust out impact on most aspects of a mission to the surface [(Rucker, 2017)](#kix.405gyjccoaq8). It can be done. The suitport may be a solution for the problem of dust inside habitats [(Boyle et al, 2013)](#kix.12f8hsvh88lb).



[Figure 71](#figur_suitport): Suitport illustration from [(Gernhard et al, 2008)](#kix.3znruuzay4) reduces loss of air when exiting or entering the rover and greatly reduces the dust problem.

None of this makes Mars settlement impossible, but Mars does not seem to be an optimal place to colonize for its own sake. There has to be another reason to take the tremendous efforts needed to colonize a place like this.

## [Planetary protection as an essential part of an ambitious, vigorous approach to human exploration - starting with exploration and settlement experiments on the Moon](#h_planetary_protection)

One way to explore the solar system in an ambitious, and yet responsible way is to focus human efforts on the moon to start with. The spacesuits and habitats designed for Mars also work on the Moon. Some of the challenges are similar, such as the dust, which may be easier to deal with on the Moon. Injured astronauts remain only a couple of days MEDEVAC from Earth and replaced damaged equipment can get to the explorers again in a matter of days.

Whatever we do further afield, the Moon is bound to be the main place tourists visit outside of Earth for the foreseeable future. It will be a science hub, it may become a hub for the maintenance and manufacture of spacecraft in the natural vacuum conditions and the low gravity for launch to orbit [(Schrunk et al, 2007)](#kix.swxxa9ibja43), and we saw that it is of astrobiological interest too in [**Potential for early discoveries of Martian life from samples of Martian meteorites preserved in ice at the lunar poles - likely pre-sterilised by natural processes sufficiently to protect Earth**](#h_pot_early_mars_life)

Once there are human settlers anywhere in our solar system, some will surely settle the Moon, either the vast lunar caves, or the peaks of almost eternal light at the lunar poles with near constant temperatures and nearby accessible lunar ice. There would be hotels on the Moon, tourists visiting, scientific bases and perhaps commercial exports from the Moon.

So why not start our settlement experiments on the Moon? Sending humans into space is hard. The Apollo astronauts were test pilots that made decisions in seconds with a cool head, in situations that would have swiftly killed less able astronauts. One example of this is when Apollo 10 tumbled during the test of the ascent stage from just above the lunar surface and they had seconds to act to identify and resolve the problem [(Evans, 2014)](#kix.bzh5ru59ihn8) [(Woods et al, 2018)](#kix.bhukf4tm3kog). Returning to the Moon is dangerous enough at present. We don’t need to look for other missions that are more exciting and dangerous than this.

The retired Canadian astronaut Chris Hadfield, former commander of the ISS, interviewed by New Scientist, put it like this [(Klein, 2017)](#u3b7o7mbthqd)

***"I think ultimately we’ll be living on the moon for a generation before we get to Mars. If the world and the moon were threatened and the only way to preserve our species was to launch from Earth, we could go to Mars with yesterday’s technology, but we would probably kill just about everybody on the way."***

***"It’s as if you and I were in Paris, paddling around in the Seine in little canoes saying, 'We’ve got boats, we’ve got paddles, let’s go to Australia!' Australia? We can barely cross the English Channel. We’re sort of in that boat in space exploration right now. A journey to Mars is conceivable but it’s still a lot further away than most people think."***

The Moon is not only safer, it's also a natural place to test and develop reliable technology that can later be used for multi-year missions throughout the solar system. A habitat that is self-sufficient for multiple years on the Moon, similarly to an interplanetary mission, would eliminate all the costs of re-supply from Earth. This is worth developing for its own sake as it would be a major saving for lunar exploration compared to one that needs to be supplied every three months like the ISS. In the process of learning to live on the Moon we learn to live on a voyage to another planet in a small spacecraft.

The Moon is of astrobiological interest too. It has the same meteorite flux as Earth, but in the conditions of the Moon we can recognize meteorites that fell billions of years ago. It should have meteorites from early Earth, Mars, Ceres and possibly Venus too. The amounts may be substantial.

According to one estimate, 7 ppm of the lunar surface materials are from Earth. A 10 km by 10 km region of the lunar surface may have 20 metric tons of materials from early Earth, including any fossils of early life. The materials transferred from Venus over the same area may amount to 1-30 kg and from Mars as much as 180 kg [(Armstrong et al, 2002)](#kix.1s7h8moj6fsp).

Some of these meteorites would still contain organics, preserved on the Moon at liquid nitrogen temperatures in the permanently shaded craters at its poles, a storehouse of cryopreserved samples of ancient chemistry and biology from the inner solar system. In this way we can study organics and perhaps even cryopreserved life from the early solar system, with no risk of forward or backwards contamination. The lunar caves are also of great interest and the Moon may have many surprises in store for us that we can’t yet anticipate.

Once our spacecraft are proven to be safe for long duration missions, this can then be followed by orbital missions to Mars and the telerobotic exploration of Mars in the context of a vigorous program of human exploration.

Perhaps the result of our astrobiological surveys is that we find early Martian life or even protocells, that mean we need to preserve Mars free from terrestrial life, for decades, to give enough time to understand what is there and study it from orbit, or indefinitely. Or perhaps we find mirror life or some other life form that is hazardous to return to Earth or our habitats.

If so, it's a discovery to treasure, not a reason to despair. As Carl Sagan put it in “Cosmos”, [(Sagan, 1980)](#fpxajasgc8h3)

***The existence of an independent biology on a nearby planet is a treasure beyond assessing, and the preservation of that life must, I think, supersede any other possible use of Mars.***

Race and Randolph suggest that human space explorers may have a moral obligation to respect the integrity of extraterrestrial ecosystems just as they do for terrestrial ecosystems we value (Race, 2002).

*While pragmatic concerns are important in maintaining the opportunity for future science study, a more fundamental and central rationale for a policy of non-interference or non-disturbance of an extraterrestrial ecosystem arises if ET life is found. Put simply, human space explorers may have a moral obligation to respect the integrity of extraterrestrial ecosystems just as they do those on Earth. It can be argued that extraterrestrial ecosystems should continue to function essentially the same as they did before their discovery by space explorers, following their natural evolutionary or development trajectory, whatever that might entail.*

Depending what we find, Martian life might be as valuable and interesting on the microbial scale as our tropical reefs or rainforests, and as we find out more about them and how their ecosystems work, even though only microbial, or maybe primitive multicellular life, we might value them in the same way that we value unique ecosystems on Earth.

If we do find mirror life on Mars, say, risking our astronauts and Earth’s biosphere, or the treasure of an independently originated life that we could easily have made extinct by mistake, we will know that it was a wise decision to do the telerobotic study from orbit first. There are many other places in our solar system for humans to explore in person, and perhaps eventually to settle.

As T Heppenheimer put it ([Heppenheimer, 1977](#kix.svod3vqs4byu):[chapter 2](https://space.nss.org/colonies-in-space-chapter-2-our-life-in-space/)):

***"Mars, the focus of so many hopeful dreams, might be bypassed. It will see its research centers for geology and other studies, but it appears to have few resources which cannot be had elsewhere. Even if it did, its gravity would make it costly to lift them out. Its atmosphere is just thick enough to prevent the use of a mass-driver. Yet the atmosphere is too thin to screen the solar ultraviolet or permit the use of aircraft for transportation.***

***Mars of the great volcanoes, Mars of the deserts, of the frosty nights and the whistling winds in the canyons—if it is to be colonized, it will be done as an afterthought in the history of the human reach into space. It may remain a vast dry land, far from the major centers of commerce or population, thinly populated and of interest mainly to the people that live there. Mars may be the Australia of future centuries."***

## The Moon has some potential for commercial exports – while there is no convincing case for commercial exports for Mars - and extant life on Mars, especially of novel biochemistry, could potentially be of great commercial value

The Moon has some potential for viable commercial exports including possibly platinum and ice for spacecraft, and could have a viable tourist industry [(Wingo, 2004)](#kix.98rcds3qlcem) [(Wingo, 2016)](#kix.hv3axcnej6z8) [(Spudis, 2016)](#kix.ovubz9obhggt) [(Schrunk et al, 2007)](#kix.swxxa9ibja43).

It is not easy to find similar exports for Mars because of the deeper gravity well than the Moon, and the distance, too far, at present for easy establishment of a viable tourist industry or other industries that require easy and safe transit within days instead of months.

The discovery of unfamiliar life on Mars could give the planet this commercial interest needed for long term settlement. This could be a reason to explore Mars telerobotically from orbit and start the first settlements in orbit.

Intellectual understanding of unfamiliar life on Mars could be the most valuable export from the planet, commercially as well as intellectually. Whether Mars has early life or advanced but different life like mirror life, or related life that has evolved for a few hundred million years on a different planet, it would be the only terrestrial planet within light years of travel that has life on it apart from Earth. Studying that life from orbit could be a motivation for space settlement in orbit around Mars.

Study of terrestrial extremophiles has led to enzymes that are widely used and are the basis of a billion dollar industry in extremophile enzymes

We can get some idea of the potential value of extraterrestrial life from the study of extremophiles which has lead to enzymes that are widely used [(Sarmiento et al, 2015)](#kix.dj7mpnduv3vb).

* in the $1 billion industry of enzymes for detergents - this is another application - they work at cold temperatures so removing the need for heating and saving energy.
* in the food industry, including bread making, fruit juices, for lactose free foods, for making syrups for wood pulp and paper processing
* in the textile, cement, cosmetic industries.
* in various research techniques for experts studying DNA and RNA

They are used to reduce costs, make the processes more eco friendly, reduce CO₂ emissions, enable more efficient faster processing, et.

The cold adapted enzymes are more active, so less of the enzyme is needed, and they can be used at lower temperatures, saving energy. The heat adapted enzymes are active and efficient at high temperatures, extreme pH values, high concentrations of the substrate, and high pressures. They are also highly resistant to organic solvents, and other things that stop enzymes working (denaturing agents). They are easier to separate during purification steps (because they don't break up) and they catalyze faster reactions.

Study of life from Mars could lead to many discoveries of a similar nature.

Indeed, discoveries from study of a novel biochemistry could be far more radical than these enzymes, with implications for pharmaceuticals, understanding processes in medicine, agriculture, nanotechnology, and many other fields. They may form materials with novel properties too (many materials we use in everyday life are the results of biology).

It’s impossible to know what the results would be. These lifeforms if they exist, and any discoveries that would flow from them, are part of our natural heritage as human beings living in our solar system.

## Discovery of extant life on Mars could lead to long term interest in the planet, including orbiting colonies using sterile robots as our mobile eyes and hands to explore the planet from orbit via telepresence, and perhaps develop it commercially too, making it more habitable for Martian life

It's impossible to know yet what we find on Mars. Perhaps we do find mirror life that’s hazardous to humans or to Earth’s biosphere. Or perhaps we find early life on Mars or some other form of life that’s vulnerable to extinction from competition with terrestrial life (similarly to the Arthur C. Clarke story for Venus). See

* [Planetary protection as an essential part of an ambitious, vigorous approach to human exploration - starting with exploration and settlement experiments on the Moon](#h_planetary_protection)
* [Arthur C. Clarke’s story “Before Eden” exploring the theme of accidental extinction of extraterrestrial life in the forwards direction](#h_Arthur_c_Clarke_before_Eden) (above)

If we do find hazardous life that can never be returned to Earth, or early life that we value as a treasure, or for some other reasons astronauts need to remain in orbit around Mars, it would still be possible to develop the surface of Mars commercially, and with commercial exports. Martian commerce could be done telerobotically too, using the methods of autonomous mining [(Mueller et al, 2012)](#kix.qel01gq6u5xk) [(Laguna, 2021)](#kix.pn9t0opd9xgc).

Several authors have suggested bootstrapping space exploration with seed factories that makes more equipment on the surface of the Moon or other destinations, and even a copy of itself [(Freitas et al, 1981)](#kix.k1fk1woltdz1) [(Kalil, 2014)](#kix.al7ek166v1xh) [(Metzger et al., 2013)](#kix.pm23tv2jcx9d).

This would also help with keeping the equipment on Mars sterile of terrestrial life, if this is needed. So long as the original seed factory is sterile, any equipment made on Mars made by the small seed factory of 100% sterile manufacturing robots and 3D printers would itself also be sterile. This could be a way to accelerate exploration or commercial use of Mars.

Chris McKay has discussed an approach he calls planetary ecosynthesis. If we do find a second genesis of life on Mars, biologically different from terrestrial life – it could be that the life still lingers in isolated refugia, but is headed towards future extinction.

In this scenario, we might decide not just to preserve it but to enhance conditions for growth and make Mars more habitable for Martian life, to whatever extent we can. He suggests this could greatly benefit humans, and more than outweigh any utilitarian value from attempts to make Mars itself more habitable for terrestrial life [(McKay, 2009).](#b_McKay_2009)

*Perhaps the most interesting and challenging case is that in which Mars has, or had, life and this life represents a distinct and second genesis.*

*I would argue that if there is a second genesis of life on Mars, its enormous potential for practical benefit to humans in terms of knowledge should motivate us to preserve it and to enhance conditions for its growth. Observations of Mars show that currently there is no global biosphere on that planet and if life is present it is in isolated refugia or dormant. It is possible that life present on Mars today is at risk of extinction if we do not alter the Martian environment so as to enhance its global habitability.*

*An appreciation for the potential utility and value of the restoration of a Martian biota does not depend on the assignment of intrinsic value to alternative lifeforms. The creation of a second biosphere using a second genesis of life could be of great utilitarian value for humans in terms of the knowledge derived ranging from basic biology to global ecology. And a case can be made that its’ value exceeds the opportunity cost of not establishing human settlements on Mars.*

The discovery of extant life could then, indirectly, lead to a long term interest in the planet and settlement of the Martian moons as well as settlements in orbits around Mars that are of especial value for studying the surface such as the orbit proposed for HERRO [(Oleson et al, 2013)](#kix.l8bu0gc28ggq) [(Valinia, 2012)](#kix.5vt0smtovomr). These would be a few of the many settlements in an expanding exploration throughout the solar system. Humans and robots would work together, the sterile robots on the surface as our mobile eyes and hands and the humans in orbit operating them for the decision making.

## This could be a stepping stone to human outposts or colonies further afield such as Jupiter’s Callisto or Saturn’s Titan, and settlements in self contained habitats throughout the solar system, spinning slowly for artificial gravity and built from materials from asteroids and comets

We could set our sights on eventually sending humans to Callisto in the Jupiter system. Callisto, the outermost of the larger moons of Jupiter has abundant resources of ice, organics from carbonaceous meteorites, and other resources, Callisto also has lower radiation levels than Mars and the same planetary protection classification as the Moon [(Adams et al, 2003)](#kix.lpul4lmggtyc) [(Kerwick 2012)](#kix.c80bxkhr4tav) [(McGuire et al, 2003)](#kix.rjyty14z9y3d)

Once we have faster interplanetary transport, Saturn’s moon Titan is an attractive target for a human base, since it is one of the few places in the solar system where a spacesuit is not needed. The temperatures are extremely low but this needs only thermal protection, essentially, high tech drysuits with the thermal protection only 7.5 cm thick, and batteries to heat a visor and gloves [(Nott 2009)](#kix.qzxviz9soi3w), due to its greater than Earth pressure atmosphere. Thermal protection is far easier to make and maintain than protection from vacuum conditions.

Titan has abundant wind and hydro power [(Hendrix et al, 2017)](#kix.f9quqd4jp00e), organics for making plastics, a stable environment and complete protection from ionizing radiation and large meteorites. Titan’s planetary protection status needs to be confirmed but forward and backward contamination of any native Titan life seems unlikely at such low temperatures. The main contamination risk would be of flows of liquid water (cryovolcanism). If liquid water is present, it would need careful study first, as this would provide a possible habitat for Earth life as well as a habitat that could have alien life that our astronauts and Earth need protection from [(Wohlforth et al, 2016a)](#kix.8tsi0n7gu4yg) [(Wohlforth et al, 2016b)](#kix.nod21z7ti8b3).

Whether any of these are easy places to live long term may depend on the gravity requirements for human health which are not yet known. However it is not yet known if the gravity on the Moon or Mars is suitable for human health long term either. It’s possible that they all need to be supplemented with the use of slow centrifuges spinning for artificial gravity during sleep, exercise etc.

If our aim is space settlement, planets may not necessarily be the obvious choice they seem to be. There is enough material in the asteroid belt to eventually build habitats with area the equivalent of a thousand times the surface land area of the Earth or more in the form of Stanford Torus type habitats and such habitats are more customizable to match human requirements. This is an observation that goes back to O'Neil in 1969 when he was teaching freshman physics, ([Heppenheimer, 1977](#kix.svod3vqs4byu):[chapter 2](https://space.nss.org/colonies-in-space-chapter-2-our-life-in-space/))

***The first answers they came up with indicated there was more than a thousand times the land area of Earth as the potential room for expansion. They concluded that the surface of a planet was not the best place for a technical civilization. The best places looked like new, artificial bodies in space, or inside-out planets.***

***The classical science-fiction idea, of course, is to settle on the surface of the moon or Mars, changing the conditions there as desired. It turned out that there were several things wrong with this, however. First, the solar system doesn’t really provide all that much area on the planets—a few times the surface area of Earth, at most. And in almost all cases the conditions on these planets are very hard to work with.***

There's far more potential for settlement in the asteroid belt than there is on either Earth or Mars, measured according to the available land area. In addition, settlers can choose whatever climate and even atmosphere, and gravity level that they like for the habitats.

Over the centuries, and millennia, settlers may be able to set up colonies out to Pluto and beyond, using thin film mirrors to concentrate the sunlight [(Johnson et al, 1977)](#kix.3wpfx4g5gxn8).

***"At all distances out to the orbit of Pluto and beyond, it is possible to obtain Earth-normal solar intensity with a concentrating mirror whose mass is small compared to that of the habitat.”***

# **Conclusion - legal process is both understandable and necessary**

I hope the considerations presented above show that we do need to take extreme care with a sample returned from Mars, at least until it is better characterized. This is not just bureaucratic red tape. There are sound reasons that require it, grounded in the need to protect human health, and the proper functioning of Earth’s biosphere.

The legal ramifications are far greater once we consider possibilities for extraterrestrial life, such as mirror life, to disrupt the entire biosphere of Earth. Almost all aspects of human life become relevant to the legal process.

We saw that it is possible that some formulation of Sagan’s criterion becomes legally required as a result of expert discussion of the worst case scenarios in the process of public scrutiny of the sample return plans.

If a version of Sagan’s criterion is applied, mission planners will need to be able to guarantee that the mission is risk free, at least to the level where there is no appreciable risk of large scale modification of the biosphere or harm to numbers of the order of a billion people or more. At our present state of knowledge we don’t know enough to give that assurance.

We saw that if any of the current published designs is used as a basis, relying on HEPA or ULPA filters, the design of the facility seems certain to be changed during the legal process. We saw that the technology to build the filters that are likely to be legally required doesn't exist yet. If such a radical redesign is needed at the end of the legal process this pushes the sample return into the 2040s and NASA is not permitted to take the level of risk with public funding.

The proposed solution to return samples to an extraterrestrial location such as above GEO avoids all these issues and has maximum flexibility. If there is no life in the sample or the life is soon shown to be harmless or easy to handle, it can be returned to Earth with only a few months extra delay compared to a sterilized return, with some sterilized samples returned immediately. If there is life and it is hazardous or potentially so, it can be studied in orbit around Earth

This could become the norm for any return of extraterrestrial biochemistry, whether from Mars, Europa, Enceladus, Ceres, or any other location. In this way the sample holding satellite above GEO could become the nucleus of a future extraterrestrial life receiving laboratory for our samples returned from anywhere in the solar system. This might become a general requirement for all missions returning samples that could contain life.

They would be returned to the orbital laboratory and studied telerobotically, until the capabilities of any life in the sample are well enough characterized to evaluate the risks. They can then be returned to Earth as soon as it is possible to demonstrate without reasonable doubt that they can be handled safely in a terrestrial facility, while any radically different biology such as mirror life is likely to be studied telerobotically in the orbital laboratory for the foreseeable future, requiring significant advances in technology before it can be studied safely directly on Earth.

This solution, to return unsterilized samples to above GEO, is not only a way to bypass legal complexities. This can be part of a measured step by step process that keeps Earth protected at all stages, while optimizing the science return and reducing the cost. This process also lets us protect our planet using the far more secure Prohibitory Precautionary Principle rather than the Best Available Technology Precautionary Principle.

This mission has an ethical dimension which requires wider participation in decision making than is usual for a space mission. We conclude that the complex legal process is both understandable and necessary.

# References (some quotations included to assist verification)

[Uses Harvard reference style, but in this draft, instead of a, b, c etc., I use unique ids like [(NASA, 2020tesgs](#kix.76qmy7dxcqdq)[)](#kix.6aisxl7zz0qc) - the idea is to search / replace these ids with a, b, c etc once the list is complete, after peer review]

## A

Abdo, J.M., Sopko, N.A. and Milner, S.M., 2020. [The applied anatomy of human skin: a model for regeneration](https://www.sciencedirect.com/science/article/pii/S2213909520300033#bib0020). Wound Medicine, 28, p.100179.

*Approximately every 28 days, fully differentiated cuboidal basal keratinocytes with large nuclei, abundant organelles, and a phospholipid membrane migrate apically from the basal layer through the spinous and granular layers [4]. During this turnover process, an accumulation of keratin and lipids ensues which then undergoes terminal differentiation to form the stratum corneum  
…  
Skin is an active immunological organ, and dysfunctional innate defenses have serious clinical implications. Products of the stratum corneum, including free fatty acids, polar lipids, and glycosphingolipids accumulate in the intercellular spaces and horny layer, exhibiting antimicrobial properties, and functioning as a first line of defense. Antimicrobial peptides (AMPs) exhibit potent and targeted resistance against a wide spectrum of common pathogens. When this barrier is breached, second lines of protection are provided by inflammatory cascades in the subepithelial tissue. Approximately sixteen AMPs have been shown to be expressed in the skin (Table 1)*

Abe, S., 2001, [Can Liquid Water Exist on Present-Day Mars?](https://nai.nasa.gov/articles/2001/3/26/can-liquid-water-exist-on-present-day-mars/) NASA Astrobiology Institute

Abdel-Nour, M., Duncan, C., Low, D.E. and Guyard, C., 2013. [Biofilms: the stronghold of Legionella pneumophila](http://www.mdpi.com/1422-0067/14/11/21660/htm). International journal of molecular sciences, 14(11), pp.21660-21675.

Abrevaya, X.C., Mauas, P.J. and Cortón, E., 2010. [Microbial fuel cells applied to the metabolically based detection of extraterrestrial life](https://arxiv.org/ftp/arxiv/papers/1006/1006.1585.pdf). *Astrobiology*, *10*(10), pp.965-971.

Adams, F.C. and Spergel, D.N., 2005. [Lithopanspermia in star-forming clusters](https://deepblue.lib.umich.edu/bitstream/handle/2027.42/63258/ast.2005.5.497.pdf?sequence=1). *Astrobiology*, *5*(4), pp.497-514.

Adams, R.B., Alexander, R.A., Chapman, J.M., Fincher, S.S., Hopkins, R.C., Philips, A.D., Polsgrove, T.T., Litchford, R.J., Patton, B.W. and Statham, G., 2003. [Conceptual design of in-space vehicles for human exploration of the outer planets](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040010797.pdf).

Afzal, I., Shinwari, Z.K., Sikandar, S. and Shahzad, S., 2019. [Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants](https://www.sciencedirect.com/science/article/pii/S0944501318304592). Microbiological research, 221, pp.36-49

Agle, D., 2022, [NASA’s Ingenuity in Contact With Perseverance Rover After Communications Dropout](https://mars.nasa.gov/technology/helicopter/status/379/nasas-ingenuity-in-contact-with-perseverance-rover-after-communications-dropout/)

Aldrin, B. and Warga, W., 2015. [*Return to earth*](https://www.amazon.com/Return-Earth-Buzz-Aldrin-ebook/dp/B017APD518). Open Road Media.

Allen, C.C., Albert, F.G., Combie, J., Bodnar, R.J., Hamilton, V.E., Jolliff, B.L., Kuebler, K., Wang, A., Lindstrom, D.J. and Morris, P.A., 1999. [Biological sterilization of returned Mars samples](https://mars.nasa.gov/mgs/sci/fifthconf99/6161.pdf).

Alberts B, Johnson A, Lewis J, et al. Molecular Biology of the Cell. 4th edition,2002,

New York: Garland Science; .[Cell Biology of Infection](https://www.ncbi.nlm.nih.gov/books/NBK26833/)

Allwood, A.C., Grotzinger, J.P., Knoll, A.H., Burch, I.W., Anderson, M.S., Coleman, M.L. and Kanik, I., 2009. [Controls on development and diversity of Early Archean stromatolites](https://www.pnas.org/content/106/24/9548). *Proceedings of the National Academy of Sciences*, *106*(24), pp.9548-9555.

Almeida, M.P., Parteli, E.J., Andrade, J.S. and Herrmann, H.J., 2008. [Giant saltation on Mars](https://www.pnas.org/content/pnas/105/17/6222.full.pdf). *Proceedings of the National Academy of Sciences*, *105*(17), pp.6222-6226.

Ambrogelly, A., Palioura, S. and Söll, D., 2007. [Natural expansion of the genetic code](https://www.researchgate.net/profile/Dieter_Soll/publication/6627120_Natural_expansion_of_the_genetic_code_Nat/links/54d8bdc40cf25013d03efd4e/Natural-expansion-of-the-genetic-code-Nat.pdf). Nature chemical biology, 3(1), pp.29-35.

American Chemical Society, 2015, [“Cyborg bacteria outperform plants when turning sunlight into useful compounds”](https://phys.org/news/2017-08-cyborg-bacteria-outperform-sunlight-compounds.html), Phys.org

*"A future direction, if this phenomenon exists in nature, would be to bioprospect for these organisms and put them to use,"*

Ammann, W., Barros, J., Bennett, A., Bridges, J., Fragola, J., Kerrest, A., Marshall-Bowman, K., Raoul, H., Rettberg, P., Rummel, J. and Salminen, M., 2012. [Mars Sample Return backward contamination–Strategic advice and requirements](https://science.nasa.gov/science-red/s3fs-public/atoms/files/ESF_Mars_Sample_Return_backward_contamination_study.pdf) - Report from the ESF-ESSC Study Group on MSR Planetary Protection Requirements.

Anbar, A.D. and Levin, G.V., 2012, June. [A Chiral Labelled Release Instrument for In Situ Detection of Extant Life](https://www.lpi.usra.edu/meetings/marsconcepts2012/pdf/4319.pdf). In *Concepts and Approaches for Mars Exploration* (Vol. 1679, p.4319)

Andrew, R.G., 2019, [NASA’s Curiosity Rover Finds Unexplained Oxygen on Mars](https://www.scientificamerican.com/article/nasas-curiosity-rover-finds-unexplained-oxygen-on-mars/), Scientific American

*On Earth, photosynthesis and respiration by living things cause tiny fluctuations in our planet’s otherwise steady oxygen concentration. We shouldn’t expect this on Mars, though. “That’s far out,” Telling says: Mars appears too inhospitable for a critical mass of life capable of sustaining either process. “It’s almost certainly going to be a nonbiological chemical reaction.”*

*Trainer herself does not rule out a biological explanation, but nevertheless underscores its unlikeliness. “People in the community like to say that it will be the explanation of last resort, because that would be so monumental,” she says. There are abiotic mechanisms aplenty, both known and unknown, to rule out first before leaping to any more sensational claims.*

Andrews, R.G., 2020, Rocks, Rockets and Robots: [The Plan to Bring Mars Down to Earth](https://www.scientificamerican.com/article/rocks-rockets-and-robots-the-plan-to-bring-mars-down-to-earth1/), Scientific American

*A single U.S. facility ticking all of these boxes could cost around $500 million, Dreier says. And it is not yet clear if others will be built in Europe*

*...*

*MSR’s masters are foregoing parachutes because the devices cannot be guaranteed to work, Vijendran says—something immortalized in 2004 by the solar-wind-particle-gathering Genesis mission, whose sample capsule broke open after an unintentional hard landing. In this case, it is simpler to build a rigid capsule that can withstand such a landing. “It just comes in, and, wham, it hits the ground,” Vago says. “That’s going to be an interesting one.”*

APOD, 2013, [Saturn from above](https://apod.nasa.gov/apod/ap131021.htm)

Anosova, I., Kowal, E.A., Dunn, M.R., Chaput, J.C., Van Horn, W.D. and Egli, M., 2015. [The structural diversity of artificial genetic polymers](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4756832/). *Nucleic acids research*, *44*(3), pp.1007-1021.

Archer, S.D., Lee, K.C., Caruso, T., Maki, T., Lee, C.K., Cary, S.C., Cowan, D.A., Maestre, F.T. and Pointing, S.B., 2019. [Airborne microbial transport limitation to isolated Antarctic soil habitats](https://researchcommons.waikato.ac.nz/bitstream/handle/10289/13245/Airblimits.pdf?sequence=42). *Nature microbiology*, *4*(6), pp.925-932. [Supplementary information](https://static-content.springer.com/esm/art%3A10.1038%2Fs41564-019-0370-4/MediaObjects/41564_2019_370_MOESM1_ESM.pdf)

Armstrong, J.C., Wells, L.E. and Gonzalez, G., 2002. [Rummaging through Earth's attic for remains of ancient lif](https://arxiv.org/pdf/astro-ph/0207316.pdf)e. *Icarus*, *160*(1), pp.183-196.

ATSB (Australian Transport Safety Beaureau), n.d., [Black box flight recorders fact sheet](https://skybrary.aero/sites/default/files/bookshelf/3679.pdf)

Avila-Herrera, A., Thissen, J., Urbaniak, C., Be, N.A., Smith, D.J., Karouia, F., Mehta, S., Venkateswaran, K. and Jaing, C., 2020. [Crewmember microbiome may influence microbial composition of ISS habitable surfaces](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0231838). PloS one, 15(4), p.e0231838.

## B

Bada, J.L., Aubrey, A.D., Grunthaner, F.J., Hecht, M., Quinn, R., Mathies, R., Zent, A. and Chalmers, J.H., 2009. [Seeking signs of life on Mars: In situ investigations as prerequisites to a sample return mission](http://mepag.jpl.nasa.gov/reports/decadal/JeffreyLBada_URS211530.pdf). Planetary science decadal survey White Paper, Scripps Institution of Oceanography, USA.

*"Two strategies have been suggested for seeking signs of life on Mars: The aggressive robotic pursuit of biosignatures with increasingly sophisticated instrumentation vs. the return of samples to Earth (MSR). While the former strategy, typified by the Mars Science Laboratory (MSL), has proven to be painfully expensive, the latter is likely to cripple all other activities within the Mars program, adversely impact the entire Planetary Science program, and discourage young researchers from entering the field."*

*"In this White Paper we argue that it is not yet time to start down the MSR path. We have by no means exhausted our quiver of tools, and we do not yet know enough to intelligently select samples for possible return. In the best possible scenario, advanced instrumentation would identify biomarkers and define for us the nature of potential sample to be returned. In the worst scenario, we would mortgage the exploration program to return an arbitrary sample that proves to be as ambiguous with respect to the search for life as ALH84001."*

Bada, J.L., Ehrenfreund, P., Grunthaner, F., Blaney, D., Coleman, M., Farrington, A., Yen, A., Mathies, R., Amudson, R., Quinn, R. and Zent, A., 2008. [Urey: Mars organic and oxidant detector](http://astrobiology.berkeley.edu/PDFs_articles/08UreySpaceSciRev.pdf). *Strategies of Life Detection*, pp.269-279.

Bahl, J., Lau, M.C., Smith, G.J., Vijaykrishna, D., Cary, S.C., Lacap, D.C., Lee, C.K., Papke, R.T., Warren-Rhodes, K.A., Wong, F.K. and McKay, C.P., 2011. [Ancient origins determine global biogeography of hot and cold desert cyanobacteria](https://www.nature.com/articles/ncomms1167). Nature communications, 2(1), pp.1-6.

Bak, E.N., Larsen, M.G., Jensen, S.K., Nørnberg, P., Moeller, R. and Finster, K., 2019. [Wind-driven saltation: an overlooked challenge for life on Mars.](https://www.researchgate.net/profile/Kai-Finster/publication/328837688_Wind-Driven_Saltation_An_Overlooked_Challenge_for_Life_on_Mars/links/5be5916fa6fdcc3a8dc8fc19/Wind-Driven-Saltation-An-Overlooked-Challenge-for-Life-on-Mars.pdf) Astrobiology, 19(4), pp.497-505.

*Spores in cavities will only be subjected to abrasion when the cavities crack open and the spores can get hit upon by a mineral particle. This process may be slow and explain the long tail of the number of surviving spores.The grain size of the regolith will likely affect the above-mentioned mechanisms and thus would have influence on the survival time of present microorganisms. We will address the effect of grain size in more detail in coming experiments.*

Bains, W. and Schulze-Makuch, D., 2016. [The cosmic zoo: the (near) inevitability of the evolution of complex, macroscopic life](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5041001/). Life, 6(3), p.25.

*Photosynthesis is primarily useful for providing energy for the reduction of environmental carbon ...*

*There are six known pathways for fixing carbon dioxide, of which the Calvin Cycle used in oxygenic phototrophs is the least efficient in terms of the energy and the reducing equivalents (electrons) required per mole of fixed CO₂ ...*

*However, the great advantage provided by oxygenesis was its capacity to liberate life from the need to find rare electron donors such as sulphide, hydrogen or Fe(II) to support the reduction of carbon dioxide, giving oxygenic photosynthesisers an advantage over all other forms of life ...*

*There are six known pathways for fixing atmospheric carbon, of which the Calvin Cycle used in oxygenic phototrophs is the least efficient in terms of the energy and the reducing equivalents (electrons)required per mole of fixed CO₂. Rubisco has a very low turnover for fixing carbon, and its carboxylase activity is compromised by opposing oxygenase activity that uses molecular oxygen to break down Ribulose-1,5-bisphosphate rather than fix CO₂ into it. Despite this, the first inventor of water-splitting was successful, and filled the niche ...*

*Oxygenesis evolved only once. There are two possible explanations for this. One is that it is a Random Walk process, requiring a sequence of unlikely evolutionary steps, which would not have evolved elsewhere. The hypotheses on the origins of oxygenesis above hint this may not be the case, but do not prove it. The other explanation is that the evolution of oxygenesis is a Many Paths process, one which has a high probability of occurring, but is also a Pulling Up the Ladder event, such that once oxygenesis evolved once that evolution removed the preconditions for its evolution again, in this case filling the niche of a photosynthesiser freed from limitation of an electron donor supply. The biochemistry of oxygenic photosynthesis points toward this second explanation.*

Bandfield, J.L., Glotch, T.D. and Christensen, P.R., 2003. [Spectroscopic identification of carbonate minerals in the Martian dust](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.720.8096&rep=rep1&type=pdf). Science, 301(5636), pp.1084-1087.

Baqué, M., Napoli, A., Fagliarone, C., Moeller, R., de Vera, J.P. and Billi, D., 2020. [Carotenoid Raman Signatures Are Better Preserved in Dried Cells of the Desert Cyanobacterium Chroococcidiopsis than in Hydrated Counterparts after High-Dose Gamma Irradiation](https://www.mdpi.com/2075-1729/10/6/83/htm). *Life*, *10*(6), p.83.

Bar-Even, A., Noor, E., Lewis, N.E. and Milo, R., 2010. [Design and analysis of synthetic carbon fixation pathways](https://www.pnas.org/content/107/19/8889). Proceedings of the National Academy of Sciences, 107(19), pp.8889-8894.

One such cycle, which is predicted to be two to three times faster than the Calvin–Benson cycle, employs the most effective carboxylating enzyme, phosphoenolpyruvate carboxylase, using the core of the naturally evolved C4 cycle. Although implementing such alternative cycles presents daunting challenges related to expression levels, activity, stability, localization, and regulation, we believe our findings suggest exciting avenues of exploration in the grand challenge of enhancing food and renewable fuel production via metabolic engineering and synthetic biology.

Battista, J.R., Earl, A.M. and Park, M.J., 1999. [Why is Deinococcus radiodurans so resistant to ionizing radiation?](https://www.researchgate.net/profile/John-Battista/publication/12830069_Why_is_Deinococcus_radiodurans_so_resistant_to_ionizing_radiation/links/598b2cfcaca272e57acaec24/Why-is-Deinococcus-radiodurans-so-resistant-to-ionizing-radiation.pdf). Trends in microbiology, 7(9), pp.362-365.

Baugh, R.F., 2017. [Murky Water: Cyanobacteria, BMAA and ALS](https://openaccesspub.org/jnrt/article/592). *Journal of Neurological Research and Therapy*, *2*(1), p.34.

Baumgartner, R.J., Van Kranendonk, M.J., Wacey, D., Fiorentini, M.L., Saunders, M., Caruso, S., Pages, A., Homann, M. and Guagliardo, P., 2019. [Nano− porous pyrite and organic matter in 3.5-billion-year-old stromatolites record primordial life](https://pubs.geoscienceworld.org/gsa/geology/article-abstract/47/11/1039/573756/Nano-porous-pyrite-and-organic-matter-in-3-5?redirectedFrom=fulltext). *Geology*, *47*(11), pp.1039-1043.

Baylor University College of Medicine (BUCM), 1967, [Comprehensive Biological Protocol for the Lunar Sample Receiving Laboratory Manned Spacecraft Center](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19680021536.pdf)

Beaty, D.W., Allen, C.C., Bass, D.S., Buxbaum, K.L., Campbell, J.K., Lindstrom, D.J., Miller, S.L. and Papanastassiou, D.A., 2009. [Planning considerations for a Mars sample receiving facility: Summary and interpretation of three design studies](https://authors.library.caltech.edu/53810/1/ast.2009.0339.pdf). Astrobiology, 9(8), pp.745-758.

Beaty, D.W., Grady, M.M., McSween, H.Y., Sefton‐Nash, E., Carrier, B.L., Altieri, F., Amelin, Y., Ammannito, E., Anand, M., Benning, L.G. and Bishop, J.L., 2019. [The potential science and engineering value of samples delivered to Earth by Mars sample return](https://onlinelibrary.wiley.com/doi/full/10.1111/maps.13232): International MSR Objectives and Samples Team (iMOST). *Meteoritics & Planetary Science*, *54*, pp.S3-S152.

Beauchamp, P., 2012. [Assessment of planetary protection and contamination control technologies for future planetary science missions](https://web.archive.org/web/20170808152222/https://solarsystem.nasa.gov/docs/PPCCTECHREPORT3.pdf).

Belbruno, E., Moro-Martín, A., Malhotra, R. and Savransky, D., 2012. [Chaotic exchange of solid material between planetary systems: implications for lithopanspermia](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3440031/). *Astrobiology*, *12*(8), pp.754-774.

Belbruno, E., 2018. [*Capture dynamics and chaotic motions in celestial mechanics: With applications to the construction of low energy transfers*](https://press.princeton.edu/books/hardcover/9780691094809/capture-dynamics-and-chaotic-motions-in-celestial-mechanics). Princeton University Press.

Benner, S. and Davies, P. , 2010,  [‘Towards a Theory of Life’](https://books.google.co.uk/books?id=OscgAwAAQBAJ&pg=PA27#v=onepage&q&f=false), in Impey, C., Lunine, J. and Funes, J. eds., *Frontiers of astrobiology*. Cambridge University Press.

Benner, S.A. and Kim, H.J., 2015, September. [The case for a Martian origin for Earth life.](https://ui.adsabs.harvard.edu/abs/2015SPIE.9606E..0CB/abstract) In *Instruments, Methods, and Missions for Astrobiology XVII* (Vol. 9606, p. 96060C). International Society for Optics and Photonics.

Benzerara, K., Skouri-Panet, F., Li, J., Férard, C., Gugger, M., Laurent, T., Couradeau, E., Ragon, M., Cosmidis, J., Menguy, N. and Margaret-Oliver, I., 2014. [Intracellular Ca-carbonate biomineralization is widespread in cyanobacteria](https://www.pnas.org/content/111/30/10933). *Proceedings of the National Academy of Sciences*, *111*(30), pp.10933-10938.

*Cyanobacteria are known to promote the precipitation of Ca-carbonate minerals by the photosynthetic uptake of inorganic carbon. This process has resulted in the formation of carbonate deposits and a fossil record of importance for deciphering the evolution of cyanobacteria and their impact on the global carbon cycle. Though the mechanisms of cyanobacterial calcification remain poorly understood, this process is invariably thought of as extracellular and the indirect by-product of metabolic activity. Here, we show that contrary to common belief, several cyanobacterial species perform Ca-carbonate biomineralization intracellularly.*

Berger, E.L., Zega, T.J., Keller, L.P. and Lauretta, D.S., 2011. [Evidence for aqueous activity on comet 81P/Wild 2 from sulfide mineral assemblages in Stardust samples and CI chondrites](https://meteoritegallery.com/wp-content/uploads/2014/04/Evidence-for-aqueous-activity-on-comet-81PWild-2-from-sul%EF%AC%81de-mineral-assemblages-in-Stardust-samples-and-CI-chondrites.pdf). Geochimica et Cosmochimica Acta, 75(12), pp.3501-3513. Press release from the University of Arizona: [Frozen Comet Had a Watery Past, UA Scientists Find](https://news.arizona.edu/story/frozen-comet-had-a-watery-past-ua-scientists-find)

Best, A. and Kwaik, Y.A., 2018. [Evolution of the arsenal of Legionella pneumophila effectors to modulate protist host](https://mbio.asm.org/content/9/5/e01313-18)s. *MBio*, *9*(5).

Bianciardi, G., Miller, J.D., Straat, P.A. and Levin, G.V., 2012. [Complexity analysis of the Viking labelled release experiments](http://central.oak.go.kr/repository/journal/11315/HGJHC0_2012_v13n1_14.pdf). International Journal of Aeronautical and Space Sciences, 13(1), pp.14-26.

Bilen, M., Dufour, J.C., Lagier, J.C., Cadoret, F., Daoud, Z., Dubourg, G. and Raoult, D., 2018. [The contribution of culturomics to the repertoire of isolated human bacterial and archaeal species](https://microbiomejournal.biomedcentral.com/articles/10.1186/s40168-018-0485-5#MOESM1). *Microbiome*, *6*(1), pp.1-11.

Biller, S.J., McDaniel, L.D., Breitbart, M., Rogers, E., Paul, J.H. and Chisholm, S.W., 2017. [Membrane vesicles in sea water: heterogeneous DNA content and implications for viral abundance estimates](https://www.nature.com/articles/ismej2016134). The ISME journal, 11(2), pp.394-404.

*These small, spherical, lipid membrane-bound structures typically range in size from ~20 to 200 nm diameter and provide a means for cells to interact with their environment over both spatial and temporal scales*

*Perhaps one of the most striking features of extracellular vesicles is that they can contain nucleic acids (Dorward et al., 1989; Valadi et al., 2007; Rumbo et al., 2011; Biller et al., 2014). DNA fragments of diverse sizes, ranging from hundreds of bp to >20 kb have been reported in vesicles from Gram-negative bacteria, Gram-positive bacteria, archaea and eukaryotes, and include genomic, plasmid and viral DNA (Dorward and Garon, 1990; Klieve et al., 2005; Soler et al., 2008; Biller et al., 2014; Gaudin et al., 2014; Jiang et al., 2014; Grande et al., 2015; Yáñez-Mó et al., 2015). As such, vesicles can function as vehicles of horizontal gene exchange (Yaron et al., 2000; Renelli et al., 2004; Klieve et al., 2005). Shotgun sequencing of vesicle-associated DNA from ocean samples has revealed sequences from diverse bacteria, archaea and eukaryotes (Biller et al., 2014), suggesting that vesicles could be an important mechanism mediating gene transfer among marine microbes.*

Billi, D., Staibano, C., Verseux, C., Fagliarone, C., Mosca, C., Baqué, M., Rabbow, E. and Rettberg, P., 2019a. [Dried biofilms of desert strains of Chroococcidiopsis survived prolonged exposure to space and Mars-like conditions in low Earth orbit](https://www.researchgate.net/profile/Cyprien-Verseux/publication/331027480_Dried_Biofilms_of_Desert_Strains_of_Chroococcidiopsis_Survived_Prolonged_Exposure_to_Space_and_Mars-like_Conditions_in_Low_Earth_Orbit/links/5ee9e56d299bf1faac5c948f/Dried-Biofilms-of-Desert-Strains-of-Chroococcidiopsis-Survived-Prolonged-Exposure-to-Space-and-Mars-like-Conditions-in-Low-Earth-Orbit.pdf). Astrobiology, 19(8), pp.1008-1017.

*Our results suggest that bacteria might indeed survive on Mars if shielded from UV, for instance by martian dust, since it is known that a few millimeters of soil is enough for UV protection (Mancinelli and Klovstad, 2000; Cockell and Raven, 2004). In view of the resistance of desert strain of Chroococcidiopsis to ionizing radiation (Billi et al., 2000; Verseux et al., 2017), the exposure in LEO to a total dose of 0.5 Gy of ionizing radiation did not affect biofilm survival. Hence, based on the dose of 76 mGy/year measured by the Curiosity rover at Gale Crater’s surface (Hassler et al., 2013), dried biofilms would survive on Mars more than half a decade. In addition, since the UV dose received in LEO corresponds to approximately 8 h under a Mars UV flux at the equator (Cockell et al., 2000), the speculated biofilm survival supports the possible dissemination of viable organisms. If carried, for instance, by winds at 5 m/sec (Gomez-Elvira et al., 2014) with the average flux mentioned above, they could travel more than 100km without dying. However, other factors found on Mars need to be taken into account so as to reduce the planetary protection risk, such as the presence of perchlorates that have been shown to be highly damaging to life (Wadsworth and Cockell, 2017)*

Billi, D., Verseux, C., Fagliarone, C., Napoli, A., Baqué, M. and de Vera, J.P., 2019b. [A desert cyanobacterium under simulated Mars-like conditions in low Earth orbit: implications for the habitability of Mars](https://www.researchgate.net/profile/Daniela-Billi/publication/331027480_Dried_Biofilms_of_Desert_Strains_of_Chroococcidiopsis_Survived_Prolonged_Exposure_to_Space_and_Mars-like_Conditions_in_Low_Earth_Orbit/links/5ca21364a6fdcc1ab5ba0613/Dried-Biofilms-of-Desert-Strains-of-Chroococcidiopsis-Survived-Prolonged-Exposure-to-Space-and-Mars-like-Conditions-in-Low-Earth-Orbit.pdf). *Astrobiology*, *19*(2), pp.158-169.

*In this experiment, survival of the Chroococcidiopsis strain occurred only with those cells that were mixed with martian regolith simulant and plated as thin layers (about 15–30 μm, corresponding to 4–5 cell layers).*

*… Our finding suggests that a putative microbial life-form at least as resistant to desiccation and radiation as the investigated desert cyanobacterium could withstand some exposure to UV on the martian surface.*

*… Our findings support the hypothesis that opportunistic colonization of protected niches on Mars, such as in fissures, cracks, and microcaves in rocks or soil, could have enabled life to remain viable while being transported to a new habitat*

Billings, L., 2015, Making Space for Everyone: [A Q&A with BoldlyGo's Jon Morse](https://www.scientificamerican.com/article/making-space-for-everyone-a-q-a-with-boldlygo-s-jon-morse), Scientific American

Blackmond, D.G., 2010. [The origin of biological homochirality](https://cshperspectives.cshlp.org/content/2/5/a002147.full.pdf). *Cold Spring Harbor perspectives in biology*, *2*(5), p.a002147.

Blackmond, D.G., 2019. [The origin of biological homochirality](https://cshperspectives.cshlp.org/content/11/3/a032540.full). *Cold Spring Harbor perspectives in biology*, *11*(3), p.a032540.

Blankenship, R.E., Tiede, D.M., Barber, J., Brudvig, G.W., Fleming, G., Ghirardi, M., Gunner, M.R., Junge, W., Kramer, D.M., Melis, A. and Moore, T.A., 2011. [Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement](https://www.researchgate.net/profile/Richard_Sayre/publication/51120946_Comparing_Photosynthetic_and_Photovoltaic_Efficiencies_and_Recognizing_the_Potential_for_Improvement/links/00463517eb44cd0891000000.pdf). *science*, *332*(6031), pp.805-809.

Blount, Z.D., Borland, C.Z. and Lenski, R.E., 2008. [Historical contingency and the evolution of a key innovation in an experimental population of Escherichia coli](https://www.nature.com/articles/ismej201769). Proceedings of the National Academy of Sciences, 105(23), pp.7899-7906.

Board, S.S. and National Research Council, 1999. *Size limits of very small microorganisms: proceedings of a workshop*. National Academies Press.

Board, S.S. and National Research Council, 2002a. [*Safe on Mars: Precursor measurements necessary to support human operations on the Martian surface*](https://books.google.co.uk/books?hl=en&lr=&id=OOs3oDSKj4oC). National Academies Press.

Board, S.S. and National Research Council, 2002b. [*The Quarantine and Certification of Martian Samples*](https://www.nap.edu/read/10138/chapter/7). National Academies Press.

Board, S.S. and National Research Council, 2009. *Assessment of planetary protection requirements for Mars sample return missions*. National Academies Press. [page 48](https://www.nap.edu/read/12576/chapter/7#48)

[5, Potential for Large Scale Effects](https://nap.nationalacademies.org/read/12576/chapter/7#48)

*"Despite suggestions to the contrary, it is simply not possible, on the basis of current knowledge, to determine whether viable Martian life forms have already been delivered to Earth. Certainly in the modern era, there is no evidence for large-scale or other negative effects that are attributable to the frequent deliveries to Earth of essentially unaltered Martian rocks. However the possibility that such effects occurred in the distant past cannot be discounted.”*

Board, S.S. and National Research Council, 2012. [*Vision and voyages for planetary science in the decade 2013-2022*](https://solarsystem.nasa.gov/resources/598/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022/). National Academies Press.

Board, S.S., European Space Sciences Committee and National Academies of Sciences, Engineering, and Medicine, 2015. [Review of the MEPAG report on Mars special regions](https://www.nap.edu/catalog/21816/review-of-the-mepag-report-on-mars-special-regions). National Academies Press.

[10](https://www.nap.edu/read/21816/chapter/4#10): *“****SR-SAG2 Finding 3-1:*** *Cell division by Earth microbes has not been reported below –18°C (255K).*

***“Revised Finding 3-1:*** *Cell division by Earth microbes has not been reported below –18°C (255K). The very low rate of metabolic reactions at low temperature result in doubling times ranging from several months to year(s). Current experiments have not been conducted on sufficiently long timescales to study extremely slow-growing microorganisms.”*

Boeder, P.A. and Soares, C.E., 2020, August. [Mars 2020: mission, science objectives and build. In Systems Contamination: Prediction, Control, and Performance 2020](https://www.researchgate.net/publication/343915302_Mars_2020_mission_science_objectives_and_build) (Vol. 11489, p. 1148903). International Society for Optics and Photonics.

Bohannon, J., 2010. [Mirror-image cells could transform science-or kill us all](https://www.wired.com/2010/11/ff_mirrorlife/). Wired, Accessed at: https://www.wired.com/2010/11/ff\_mirrorlife/

*Kasting: “After doing some rough calculations on the effects of a mirror cyanobacteria invasion, Jim Kasting isn’t sure which would kill us first—the global famine or the ice age. “It would quickly consume all the available nutrients,” he says. “This would leave fewer or perhaps no nutrients for normal organisms.” That would wipe out the global ocean ecology and starve a significant portion of the human population. As the CO₂ in the ocean was incorporated into inedible mirror cells, they would “draw down” CO₂ from the atmosphere, Kasting says. For a decade or two, you would have a cure for global warming. But Kasting predicts that in about 300 years the bugs would suck down half of Earth’s atmospheric CO₂. Photosynthesis of most land plants would fail. “All agricultural crops other than corn and sugar cane would die,” he says. (They do photosynthesis a little differently.) “People might be able to subsist for a few hundred years, but things would be getting pretty grim much more quickly than that.” After 600 years, we’d be in the midst of a global ice age. It would be a total evolutionary reboot—both Kasting and Church think mirror predators would evolve, but whatever life existed on Earth by that point wouldn’t include us..*

Bontemps, J, 2015, [Follow up: Signs of Ancient Life in Mars Rover Photos?](http://www.astrobio.net/mars/follow-signs-ancient-life-mars-rover-photos/) NASA Astrobiology Magazine

Borges, W.D.S., Borges, K.B., Bonato, P.S., Said, S. and Pupo, M.T., 2009. [Endophytic fungi: natural products, enzymes and biotransformation reactions](https://www.researchgate.net/profile/Warley_Borges/publication/233633077_Endophytic_Fungi_Natural_Products_Enzymes_and_Biotransformation_Reactions/links/550e1dbb0cf2ac2905aac539.pdf). Current Organic Chemistry, 13(12), pp.1137-1163.

Borojeni, I.A., Gajewski, G. and Riahi, R.A., 2022. [Application of Electrospun Nonwoven Fibers in Air Filters](https://www.mdpi.com/2079-6439/10/2/15/pdf?version=1644317375). Fibers, 10(2), p.15.

Boshuizen, H.C., Neppelenbroek, S.E., van Vliet, H., Schellekens, J.F., Boer, J.W.D., Peeters, M.F. and Conyn-van Spaendonck, M.A., 2001. [Subclinical Legionella infection in workers near the source of a large outbreak of Legionnaires disease](https://academic.oup.com/jid/article/184/4/515/810113?view=extract). *The Journal of infectious diseases*, *184*(4), pp.515-518.

Boston, P.J., 2010. [Location, location, location! Lava caves on Mars for habitat, resources, and the search for life](http://journalofcosmology.com/Mars130.html). *Journal of Cosmology*, *12*, pp.3957-3979.

Boudaugher-Fadel, M.K., 2018. [Evolution and geological significance of larger benthic foraminifera](https://www.jstor.org/stable/pdf/j.ctvqhsq3.4.pdf), UCL

Boyle, R.A., Lenton, T.M. and Williams, H.T., 2007. [Neoproterozoic ‘snowball Earth’glaciations and the evolution of altruism](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.330.5964&rep=rep1&type=pdf). *Geobiology*, *5*(4), pp.337-349.

Boxe, C.S., Hand, K.P., Nealson, K.H., Yung, Y.L. and Saiz-Lopez, A., 2012. [An active nitrogen cycle on Mars sufficient to support a subsurface biosphere](https://authors.library.caltech.edu/30213/1/Boxe2012p17592Int_J_Astrobiol.pdf). *International Journal of Astrobiology*, *11*(2), pp.109-115.

Boyle, R., Rodriggs, L.M., Allton, C., Jennings, M. and Aitchison, L.T., 2013. [Suitport feasibility-human pressurized space suit donning tests with the marman clamp and pneumatic flipper suitport concepts](https://core.ac.uk/download/pdf/42736689.pdf). In *43rd International Conference on Environmental Systems* (p. 3399).

Brazil, R., 2015, [The origin of homochirality](https://www.chemistryworld.com/features/the-origin-of-homochirality/9073.article), Chemistry World.

Bristow, L.A., Mohr, W., Ahmerkamp, S. and Kuypers, M.M., 2017. [Nutrients that limit growth in the ocean](https://www.sciencedirect.com/science/article/pii/S0960982217303287). *Current Biology*, *27*(11), pp.R474-R478.

Brown, G.D., Denning, D.W., Gow, N.A., Levitz, S.M., Netea, M.G. and White, T.C., 2012. [Hidden killers: human fungal infections](https://knowthecause.com/wp-content/uploads/2015/09/Brown10121FungiGHiddenKillers.pdf). *Science translational medicine*, *4*(165), pp.165rv13-165rv13.

Brown, J.R., 2003. [Ancient horizontal gene transfer](https://www.researchgate.net/profile/James_Brown43/publication/10922742_Ancient_Horizontal_Gene_Transfer/links/0046352e7c997bf67b000000/Ancient-Horizontal-Gene-Transfer.pdf). Nature Reviews Genetics, 4(2), p.121.

Bruno, K.A., Mathews, J.E., Yang, A.L., Frisancho, J.A., Scott, A.J., Greyer, H.D., Greyer, F.D., Greenaway, M.S., Cooper, G.M., Bucek, A. and Morales-Lara, A.C., 2019. [BPA alters estrogen receptor expression in the heart after viral infection activating cardiac mast cells and T cells leading to perimyocarditis and fibrosis](https://www.frontiersin.org/articles/10.3389/fendo.2019.00598/full). Frontiers in Endocrinology, 10, p.598.

Bryant, D.A. and Frigaard, N.U., 2006. [Prokaryotic photosynthesis and phototrophy illuminated](http://application.sb-roscoff.fr/download/fr2424/enseignement/master/OEM/2013/ephybio/six/Bryant%20et%20al%202006%20(prokaryotic%20photosyntheses).pdf). Trends in microbiology, 14(11), pp.488-496.

Bryson, P.D., 1996. *Comprehensive reviews in toxicology: for emergency clinicians*. CRC press. See [page 680](https://books.google.co.uk/books?id=f7009NkJv70C&pg=PA680)

BS, 2009, BS EN 1822-1:2009 [High efficiency air filters (EPA, HEPA and ULPA), Part 1: Classification, performance testing, marking](http://www.gttlab.com/uploads/soft/161025/EN1822-1-2009Highefficiencyairfilters(EPA,HEPAandULPA)Part1Classification,performance.pdf)

Burton, A.S., Stern, J.C., Elsila, J.E., Glavin, D.P. and Dworkin, J.P., 2012. [Understanding prebiotic chemistry through the analysis of extraterrestrial amino acids and nucleobases in meteorites](https://science.gsfc.nasa.gov/691/analytical/PDF/BurtonReview2012.pdf). Chemical Society Reviews, 41(16), pp.5459-5472.

Busso, N. and So, A., 2010. [Gout. Mechanisms of inflammation in gout](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2888190/). Arthritis research & therapy, 12(2), p.206.

Byrd, A.L., Belkaid, Y. and Segre, J.A., 2018. [The human skin microbiome](https://www.nature.com/articles/nrmicro.2017.157). *Nature Reviews Microbiology*, *16*(3), p.143.

## C

Cabrol, N.A., 2021. [Tracing a modern biosphere on Mars](https://www.researchgate.net/profile/Nathalie-Cabrol/publication/350115645_Tracing_a_modern_biosphere_on_Mars/links/60522519a6fdccbfeae91c6f/Tracing-a-modern-biosphere-on-Mars.pdf). Nature Astronomy, 5(3), pp.210-212.

CAIB, 2003, [Columbia Accident Investigation Board Report](http://web.archive.org/web/20100710232209/http://caib1.nasa.gov/news/report/), Volume III, [Appendix D.10, Debris recovery](http://web.archive.org/web/20161014213445/http://caib1.nasa.gov/news/report/pdf/vol2/part10.pdf)

Calaway, M.J., McCubbin, F.M., Allton, J.H., Zeigler, R.A. and Pace, L.F., 2017. [Mobile/Modular BSL-4 Facilities for Meeting Restricted Earth Return Containment Requirements](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001664.pdf)

Callaghan, J.O., [Europe’s first Mars rover delayed by two years](https://www.nature.com/articles/d41586-020-00746-6), Nature, 2020

Campanale, C., Massarelli, C., Savino, I., Locaputo, V. and Uricchio, V.F., 2020. [A detailed review study on potential effects of microplastics and additives of concern on human health](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7068600/). International Journal of Environmental Research and Public Health, 17(4), p.1212.

Capone, D.G., Popa, R., Flood, B. and Nealson, K.H., 2006. [Follow the nitrogen](https://www.researchgate.net/profile/Kenneth-Nealson/publication/7104708_Geochemistry_Follow_the_nitrogen/links/55db965508aed6a199ac63d2/Geochemistry-Follow-the-nitrogen.pdf). Science, 312(5774), pp.708-709.

Caron, L., Douady, D., de Martino, A. and Quinet, M., 2001. [Light harvesting in brown algae](http://www.vliz.be/imisdocs/publications/289162.pdf). *Cah Biol Mar*, *42*, pp.109-124.

Carrier, B.L., Bass, D., Gaubert, F., Grady, M.M., Haltigin, T., Harrington, A.D., Liu, Y., Martin, D., Marty, B., Mattingly, R. and Siljeström, S., 2019. [Science-Driven Contamination Control Issues Associated with the Receiving and Initial Processing of the MSR Samples](https://mepag.jpl.nasa.gov/reports/MSPG%20Contamination%20Control%20Report%20Final.pdf).

Carrier, B.L., Beaty, D.W., Meyer, M.A., Blank, J.G., Chou, L., DasSarma, S., Des Marais, D.J., Eigenbrode, J.L., Grefenstette, N., Lanza, N.L. and Schuerger, A.C., 2020. [Mars Extant Life: What's Next? Conference Report.](https://www.liebertpub.com/doi/pdfplus/10.1089/ast.2020.2237) ([html](https://www.liebertpub.com/doi/10.1089/ast.2020.2237))

*802: Future missions would therefore benefit from the development of instruments capable of direct and unambiguous detection of extant life in situ, and improvements are needed in capabilities for sample preparation to optimize biosignature detection. Spacecraft resources should support a sufficient number of sample analyses to support replicate analyses, positive and negative controls. Contamination control should be coupled with contamination knowledge so that Earth-sourced material can be eliminated as a possible source of any biological material discovered in Martian samples.*

Carter, 2001, ["Moon Rocks and Moon Gems"](https://www.archives.gov/publications/prologue/2001/winter/nasa-lunar-lab),

Cartwright, J.H., Piro, O. and Tuval, I., 2007. [Ostwald ripening, chiral crystallization, and the common-ancestor effect](http://imedea.uib-csic.es/~ituval/PAPERS/PRL98.pdf). *Physical review letters*, *98*(16), p.165501.

Casero, M.C., Ascaso, C., Quesada, A., Mazur-Marzec, H. and Wierzchos, J., 2020. [Response of endolithic Chroococcidiopsis strains from the polyextreme Atacama Desert to light radiation](https://www.frontiersin.org/articles/10.3389/fmicb.2020.614875/ful). Frontiers in microbiology, 11.

*Since cyanobacteria originated in the Precambrian era, when the ozone shield was absent, UVR has presumably acted as an evolutionary pressure leading to the development of different protection mechanisms (Rahman et al., 2014) including avoidance, the scavenging of ROS by antioxidant systems, the synthesis of UV-screening compounds, and DNA repair systems for UV-induced DNA damage and protein resynthesis (Rastogi et al., 2014a).*

CDC, n.d., [Haemophilus influenzae type b (Hib)](https://www.who.int/immunization/diseases/hib/en/)

Cecere, E., Petrocelli, A. and Verlaque, M., 2011. [Vegetative reproduction by multicellular propagules in Rhodophyta: an overvie](https://d1wqtxts1xzle7.cloudfront.net/51137109/Vegetative_reproduction_by_multicellular20161231-29593-yau2q6.pdf?1483254010=&response-content-disposition=inline%3B+filename%3DVegetative_reproduction_by_multicellular.pdf&Expires=1614959639&Signature=A-9PiSVqRCkdtmTidDurz4Y2EZeFCLv3sD7S9REndyla-~tnC0Epg2abz5Brv8ycScZbsM9YYYBploNQkgnypZt-6afnZB-5JQbpQi14z60dKBZz7ysu4phZ3gPOpTq-al959S2U6HlAVD8gISKdxIzDYoE3BHYGzmyc9ZgZO0PJZSfoe74IyJIyuw9s7xgLPrwtEzWvf2mYPamkdKoqenG8B-QG5wEg3pX7-xQEBfjsFG2FvulWqAtYo6JP66obbKRN366ltOjW670koyuobHNNQ5jrv6B51A-6iukbB7azTAPk2uvSOMICM0LREnTf0Jd1rAL-6VcLJml4rioZ1A__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA)w. *Marine Ecology*, *32*(4), pp.419-437.

Chan, Q.H.S., Stroud, R., Martins, Z. and Yabuta, H., 2020. [Concerns of organic contamination for sample return space missions](http://oro.open.ac.uk/70743/1/70743.pdf). *Space Sci. Rev*.

56: A key lesson learned from past sample return missions is that a certain level of terrestrial contamination is inevitable, despite the best efforts that were made to minimise it. While careful measures of contamination control are planned and implemented, future studies of mission returned samples should be aware of the pres-ence of different levels of terrestrial contamination, and employ state-of-the-art methods in order to distinguish extra-terrestrial organics from the inevitable terrestrial contamination.

Chan-Yam, K., Goordial, J., Greer, C., Davila, A., McKay, C.P. and Whyte, L.G., 2019. [Microbial activity and habitability of an Antarctic dry valley water track](https://www.liebertpub.com/doi/full/10.1089/ast.2018.1884). Astrobiology, 19(6), pp.757-770.

Chevrier, V.F., Rivera-Valentín, E.G., Soto, A. and Altheide, T.S., 2020. [Global Temporal and Geographic Stability of Brines on Present-day Mars](https://iopscience.iop.org/article/10.3847/PSJ/abbc14/pdf). The Planetary Science Journal, 1(3), p.64.

Chin, J.P., Megaw, J., Magill, C.L., Nowotarski, K., Williams, J.P., Bhaganna, P., Linton, M., Patterson, M.F., Underwood, G.J., Mswaka, A.Y. and Hallsworth, J.E., 2010. [Solutes determine the temperature windows for microbial survival and growth](http://www.pnas.org/content/107/17/7835.full). *Proceedings of the National Academy of Sciences*, *107*(17), pp.7835-7840.

Chojnacki, M., Banks, M. and Urso, A., 2018. [Wind‐driven erosion and exposure potential at Mars 2020 rover candidate‐landing sites](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017JE005460). Journal of Geophysical Research: Planets, 123(2), pp.468-488.

Chong, J., 2017, [Comment: Archaea: closet pathogens?](https://microbiologysociety.org/publication/past-issues/archaea/article/comment-archaea-closet-pathogens.html), Issue Archaea, Microbiology Today Magazine,

Christoffersen, R. and Lindsay, J.F., 2009. [Lunar dust effects on spacesuit systems: insights from the Apollo spacesuits](https://www.si.edu/content/MCIImagingStudio/papers/Lunar%20Dust%20Effects%20Spacesuit%20Systems.pdf). Johnson Space Center.

Church, F.S., n.d. [Opened up a Pandora's box](https://commons.wikimedia.org/wiki/File:Opened_up_a_Pandora%27s_box.jpg)

Cichan, T., Bailey, S.A., Antonelli, T., Jolly, S.D., Chambers, R.P., Clark, B. and Ramm, S.J., 2017. [Mars Base Camp: An Architecture for Sending Humans to Mars](https://www.liebertpub.com/doi/full/10.1089/space.2017.0037). *New Space*, *5*(4), pp.203-218.

Clark, B., 2009, [Cultybraggan nuclear bunker](https://www.geograph.org.uk/photo/1483182)

Cleland, C.E., 2019. [The Quest for a Universal Theory of Life: Searching for Life as we don't know it](https://books.google.co.uk/books?id=eqCsDwAAQBAJ) (Vol. 11). Cambridge University Press.

Cockell, C.S., 2008. [The Interplanetary Exchange of Photosynthesis](https://www.researchgate.net/profile/Charles_Cockell/publication/5937888_The_Interplanetary_Exchange_of_Photosynthesis/links/0c960530632bf30e20000000.pdf). *Origins of Life and Evolution of Biospheres*, *38*(1), pp.87-104.

Cockell, C.S., Kaltenegger, L. and Raven, J.A., 2009. [Cryptic photosynthesis—extrasolar planetary oxygen without a surface biological signature](https://arxiv.org/ftp/arxiv/papers/0809/0809.3990.pdf). *Astrobiology*, *9*(7), pp.623-636.

Cockell, C.S., 2014. [Trajectories of Martian habitability](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3929387/). Astrobiology, 14(2), pp.182-203.

Cockell, C.S., Harrison, J.P., Stevens, A.H., Payler, S.J., Hughes, S.S., Kobs Nawotniak, S.E., Brady, A.L., Elphic, R.C., Haberle, C.W., Sehlke, A. and Beaton, K.H., 2019a. [A low-diversity microbiota inhabits extreme terrestrial basaltic terrains and their fumaroles: implications for the exploration of Mars](https://www.liebertpub.com/doi/pdfplus/10.1089/ast.2018.1870). *Astrobiology*, *19*(3), pp.284-299.

Cockell, C.S. and McMahon, S., 2019b. [Lifeless Martian samples and their significance](https://www.researchgate.net/profile/Charles_Cockell/publication/333588068_Lifeless_Martian_samples_and_their_significance/links/5e6aa808458515e555763b87/Lifeless-Martian-samples-and-their-significance.pdf). Nature Astronomy, 3(6), pp.468-470.

Cockell, C.S., McMahon, S., Lim, D.S., Rummel, J., Stevens, A., Hughes, S.S., Nawotniak, S.E.K., Brady, A.L., Marteinsson, V., Martin-Torres, J. and Zorzano, M.P., 2019c. [Sample Collection and Return from Mars: Optimising Sample Collection Based on the Microbial Ecology of Terrestrial Volcanic Environments](https://link.springer.com/article/10.1007/s11214-019-0609-7). *Space Science Reviews*, *215*(7), p.44.

Coleman, C, 2011, [Russian cosmonaut Dmitri Kondratyev (left), Expedition 27 commander; and Italian Space Agency/European Space Agency astronaut Paolo Nespoli in the Cupola, use still cameras to photograph the topography of points on Earth. Picture taken by 3rd crew member, Cady Coleman](https://commons.wikimedia.org/wiki/File:ISS-27_Dmitri_Kondratyev_and_Paolo_Nespoli_photograph_the_Earth_through_the_Cupola.jpg)

Collinge, J., Whitfield, J., McKintosh, E., Beck, J., Mead, S., Thomas, D.J. and Alpers, M.P., 2006. [Kuru in the 21st century—an acquired human prion disease with very long incubation periods](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.400.9503&rep=rep1&type=pdf). The Lancet, 367(9528), pp.2068-2074.

*We identified 11 patients with kuru from July, 1996, to June, 2004, all living in the South Fore. All patients were born before the cessation of cannibalism in the late 1950s. The minimum estimated incubation periods ranged from 34 to 41 years. However, likely incubation periods in men ranged from 39 to 56 years and could have been up to 7 years longer. PRNP analysis showed that most patients with kuru were heterozygous at polymorphic codon 129, a genotype associated with extended incubation periods and resistance to prion disease*

Colombo, C. and Gkolias, I., 2017. [Analysis of orbit stability in the geosynchronous region for end-of-life disposal](https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/864/SDC7-paper864.pdf). In *7th European Conference on Space Debris, ESA/ESOC* (pp. 1-14). ESA

Compton, W.D., 1989. [Where no man has gone before: A history of Apollo lunar exploration missions](https://books.google.co.uk/books?id=nSisnCa2NcIC) (Vol. 4214). US Government Printing Office. Pages [145](https://books.google.co.uk/books?id=nSisnCa2NcIC&pg=PA145)-[146](https://books.google.co.uk/books?id=nSisnCa2NcIC&pg=PA146):

Congressional Research Service, 2021, [National Environmental Policy Act: Judicial Review and Remedies](https://crsreports.congress.gov/product/pdf/IF/IF11932)

Conley, C (2016), interviewed by Straus, M., for National Geographic, [*Going to Mars Could Mess Up the Hunt for Alien Life*](http://news.nationalgeographic.com/2016/09/mars-journey-nasa-alien-life-protection-humans-planets-space/). Available at: <https://www.nationalgeographic.com/news/2016/09/mars-journey-nasa-alien-life-protection-humans-planets-space/> (accessed 1 July 2020)

*From the perspective of planetary protection, Conley is also concerned about terrestrial organisms that can absorb water from the air. She recalls fieldwork she did in the Atacama Desert in Chile, which is one of the driest places on Earth, with less than 0.04 inch of rain a year.*

*Even in this dessicated place, she found life: photosynthetic bacteria that had made a home in tiny chambers within halite salt crystals. There’s a small amount of water retained inside the halite and, at night, it cools down and condenses both on the walls of the chambers and on the surface of the organisms that are sitting there.*

Cooper, G. and Rios, A.C., 2016. [Enantiomer excesses of rare and common sugar derivatives in carbonaceous meteorites](https://www.pnas.org/content/113/24/E3322.long). Proceedings of the National Academy of Sciences, 113(24), pp.E3322-E3331.

Cooper, G.M., Hausman, R.E. and Hausman, R.E., 2007. [*The cell: a molecular approach*:The Molecular Composition of cells](https://www.ncbi.nlm.nih.gov/books/NBK9879/) (Vol. 4, pp. 649-656). Washington, DC: ASM press.

Correia, A.M., Ferreira, J.S., Borges, V., Nunes, A., Gomes, B., Capucho, R., Gonçalves, J., Antunes, D.M., Almeida, S., Mendes, A. and Guerreiro, M., 2016. [Probable person-to-person transmission of Legionnaires’ disease](http://repositorio.insa.pt/bitstream/10400.18/3439/1/Correia_et_al_2016.pdf). *New England Journal of Medicine*, *374*, pp.497-498.

Cortesão, M., Fuchs, F.M., Commichau, F.M., Eichenberger, P., Schuerger, A.C., Nicholson, W.L., Setlow, P. and Moeller, R., 2019. [Bacillus subtilis spore resistance to simulated Mars surface conditions](https://www.frontiersin.org/articles/10.3389/fmicb.2019.00333/full). *Frontiers in microbiology*, *10*, p.333.

Cousins, C.R. and Crawford, I.A., 2011. [Volcano-ice interaction as a microbial habitat on Earth and Mars](https://research-repository.st-andrews.ac.uk/bitstream/handle/10023/8744/AST_2010_0550R2Cousins_forCE.pdf). Astrobiology, 11(7), pp.695-710.

COSPAR, 2011. [COSPAR Planetary Protection Policy, 20 October 2002, as amended to 24 March 2011](http://www.physics.rutgers.edu/~ajbaker/honors292/COSPAR_Planetary_Protection_Policy_v3-24-11.pdf), COSPAR/IAU Workshop on Planetary Protection.

Cowen, L.E., Sanglard, D., Howard, S.J., Rogers, P.D. and Perlin, D.S., 2015. [Mechanisms of antifungal drug resistance](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4484955/). Cold Spring Harbor perspectives in medicine, 5(7), p.a019752.

Cox, P.A., Banack, S.A., Murch, S.J., Rasmussen, U., Tien, G., Bidigare, R.R., Metcalf, J.S., Morrison, L.F., Codd, G.A. and Bergman, B., 2005. [Diverse taxa of cyanobacteria produce β-N-methylamino-L-alanine, a neurotoxic amino acid](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC555964/). *Proceedings of the National Academy of Sciences*, *102*(14), pp.5074-5078.

Craven, E., Winters, M., Smith, A.L., Lalime, E., Mancinelli, R., Shirey, B., Schubert, W., Schuerger, A., Burgin, M., Seto, E.P. and Hendry, M., 2021. [Biological safety in the context of backward planetary protection and Mars Sample Return: conclusions from the Sterilization Working Group](https://www.cambridge.org/core/journals/international-journal-of-astrobiology/article/biological-safety-in-the-context-of-backward-planetary-protection-and-mars-sample-return-conclusions-from-the-sterilization-working-group/B541CA22933846952EC723FD2514B6F4" \t "_blank). *International Journal of Astrobiology*, *20*(1), pp.1-28.

Creamer, J.S., Mora, M.F. and Willis, P.A., 2017. [Enhanced resolution of chiral amino acids with capillary electrophoresis for biosignature detection in extraterrestrial samples](https://pubs.acs.org/doi/pdf/10.1021/acs.analchem.6b04338). *Analytical chemistry*, *89*(2), pp.1329-1337.

Crisler, J.D.; Newville, T.M.; Chen, F.; Clark, B.C.; Schneegurt, M.A., 2012. *["Bacterial Growth at the High Concentrations of Magnesium Sulfate Found in Martian Soils"](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3277918)*. Astrobiology. **12** (2): 98–106

Cronin, J.R. and Pizzarello, S., 1983. [Amino acids in meteorites](https://pubmed.ncbi.nlm.nih.gov/11542462/). Advances in Space Research, 3(9), pp.5-18.

Crotts, A.P., 2007. [Lunar Outgassing, Transient Phenomena and The Return to The Moon, III: Observational and Experimental Techniques](https://iopscience.iop.org/article/10.1088/0004-637X/707/2/1506/pdf). *arXiv preprint arXiv:0706.3954*.

Crotts, A.P., 2008. [Lunar outgassing, transient phenomena, and the return to the Moon. I. Existing data](https://iopscience.iop.org/article/10.1086/591634/pdf). *The Astrophysical Journal*, *687*(1), p.692.

Crotts, A.P. and Hummels, C., 2009. [Lunar outgassing, transient phenomena, and the return to the Moon. II. Predictions and tests for outgassing/regolith interactions](http://user.astro.columbia.edu/%7Earlin/TLP/paper2.pdf). *The Astrophysical Journal*, *707*(2), p.1506.

***Section 3.1 final para:*** *Simply scaling by the time between molecular collisions, corresponding to a 125 m diameter ice patch at φ = 0, we find at the base of the regolith a 160 m patch at φ = 26◦ (Aristarchus Plateau), 580 m at φ = 51◦.6 (Plato), 2.3 km at φ = 65◦ (10% polar cap), and an essentially divergent value, 522 km at φ = 82◦ (1% polar cap). If in fact the regolith layer is much deeper than suspected, the added depth of low diffusivity dust significantly increases the patch area: 170 m at φ = 26◦, 830 m at φ = 51◦.6, and 4 km at φ = 65◦.*

***Section 3.3:*** *In the Moon’s formation temperatures of proto-Earth and progenitor impactor material in simulations grow to thousands of Kelvins, sufficient to drive off the great majority of all volatiles, but these are not necessarily the only masses in the system. Either body might have been orbited by satellites containing appreciable volatiles, which would likely not be heated to a great degree and which would have had a significant probability of being incorporated into the final moon. Furthermore, there is recent discussion of significant water being delivered to Earth/Moon distances from the Sun in the minerals themselves (Lunine et al. 2007, Drake & Stimpfl 2007), and these remaining mineral-bound even at high temperatures up to 1000K (Stimpfl et al. 2007). The volume of surface water on Earth is at least 1.4 × 109 km3, so even if the specific abundance of lunar water is depleted to 10−6 terrestrial, one should still expect over 1010 tonnes endogenous to the Moon, and it is unclear that later differentiation would eliminate this. This residual quantity of water would be more than sufficient to concern us with the regolith seepage processes outlined above.*

Czaja, A.D., Beukes, N.J. and Osterhout, J.T., 2016. [Sulfur-oxidizing bacteria prior to the Great Oxidation Event from the 2.52 Ga Gamohaan Formation of South Africa](http://eps.harvard.edu/files/eps/files/czaja_etal_2016_geology.pdf). *Geology*, *44*(12), pp.983-986. See also Czaja interviewed for University of Cincinnati by Melanie Schefft, 2016, [Life before oxygen](http://magazine.uc.edu/editors_picks/recent_features/bacteria.html),

“And this discovery is helping us reveal a diversity of life and ecosystems that existed just prior to the Great Oxidation Event, a time of major atmospheric evolution.”

## D

Dadachova, E. and Casadevall, A., 2008. [Ionizing radiation: how fungi cope, adapt, and exploit with the help of melanin](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2677413/). Current opinion in microbiology, 11(6), pp.525-531.

Daderot, 2017, [Oregon Space Ball, probably from the equipment module of Gemini 3, 4, or 5 mission, titanium](https://commons.wikimedia.org/wiki/File:Oregon_Space_Ball,_probably_from_the_equipment_module_of_Gemini_3,_4,_or_5_mission,_titanium_-_Oregon_Air_and_Space_Museum_-_Eugene,_Oregon_-_DSC09749.jpg) - Oregon Air and Space Museum - Eugene, Oregon

Dance, A., 2020, [The search for microbial dark matter](https://www.nature.com/articles/d41586-020-01684-z), Nature

Daubar, I.J., Atwood‐Stone, C., Byrne, S., McEwen, A.S. and Russell, P.S., 2014. [The morphology of small fresh craters on Mars and the Moon](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2014JE004671). *Journal of Geophysical Research: Planets*, *119*(12), pp.2620-2639.

David, L., 2015, [Q&A with Chris McKay, Senior Scientist at NASA Ames Research Center](https://spacenews.com/qa-with-chris-mckay-senior-scientist-at-nasa-ames-research-center/), SpaceNews

David, L., 2017, [Mars Flows: A Recurring Controversy](https://www.leonarddavid.com/mars-flows-a-recurring-controversy/), [Leonard David's](https://www.leonarddavid.com/leonard-david-bio/) "Inside Outer Space" blog (space journalist).

Davidson, M, 2004, “[Mars Fossils, Pseudofossils or Problematica](http://aix1.uottawa.ca/~weinberg/mars/)?”

Davies, P.C., Benner, S.A., Cleland, C.E., Lineweaver, C.H., McKay, C.P. and Wolfe-Simon, F., 2009. [Signatures of a shadow biosphere](http://asdf.m.ffame.org/pubs/Signatures%20of%20a%20Shadow%20Biosphere.pdf). Astrobiology, 9(2), pp.241-249.

Davies, P., 2014, [The key to life on Mars may well be found in Chile](https://www.theguardian.com/commentisfree/2012/aug/03/life-mars-chile), The Guardian

Davila, A.F., Willson, D., Coates, J.D. and McKay, C.P., 2013. [Perchlorate on Mars: a chemical hazard and a resource for humans](https://www.researchgate.net/publication/242525435_Perchlorate_on_Mars_A_chemical_hazard_and_a_resource_for_humans). *Int. J. Astrobiol*, *12*(04), pp.321-325.

Day, M. and Dorn, T., 2019. [Wind in Jezero crater](https://static1.squarespace.com/static/57db29c93e00bef0b17748bd/t/5cb12965e79c70e52f181d51/1555114343331/Day_et_al-2019-Geophysical_Research_Letters.pdf), Mars. Geophysical Research Letters, 46(6), pp.3099-3107.

Deacon, J., 2016. [The microbial world: airborne microorganisms](http://archive.bio.ed.ac.uk/jdeacon/microbes/airborne.htm). Edinburgh: University of Edinburgh.

Debus, A., 2004, April. [Planetary Protection: Organisation, Requirements and Needs for Future Planetary Exploration Missions](http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?db_key=AST&bibcode=2004ESASP.543..103D&letter=0&classic=YES&defaultprint=YES&whole_paper=YES&page=105&epage=105&send=Send+PDF&filetype=.pdf). In *Tools and Technologies for Future Planetary Exploration* (Vol. 543, pp. 103-114).

Deighton B., 2016, [Life could exist on Mars today, bacteria tests show](https://ec.europa.eu/research-and-innovation/en/horizon-magazine/life-could-exist-mars-today-bacteria-tests-show), Horizon, EU research and Innovation Magazine

Demaneuf, G., 2020. [The Good, the Bad and the Ugly: a review of SARS Lab Escapes](C://Users/rober/Downloads/GBU_article-2.pdf).

Deo, P.N. and Deshmukh, R., 2019. [Oral microbiome](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6503789/): Unveiling the fundamentals. *Journal of oral and maxillofacial pathology: JOMFP*, *23*(1), p.122.

Desroches, T.C., McMullin, D.R. and Miller, J.D., 2014. [Extrolites of Wallemia sebi, a very common fungus in the built environment](https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12100). Indoor air, 24(5), pp.533-542.

de Vera, J.P., Schulze-Makuch, D., Khan, A., Lorek, A., Koncz, A., Möhlmann, D. and Spohn, T., 2014. [Adaptation of an Antarctic lichen to Martian niche conditions can occur within 34 days](http://elib.dlr.de/97969/1/Vera%20et%20al%202014.pdf). *Planetary and Space Science*, *98*, pp.182-190. See also summary Koh Xuan Yang, 2014, [Adaptation of Antarctic Lichens to Conditions on Mars](http://beyondearthlyskies.blogspot.co.uk/2014/10/adaptation-of-antarctic-lichens-to.html), Beyond Earthly Skies

Devincenzi, D.L. and Bagby, J.R., 1981. [Orbiting quarantine facility. The Antaeus report](https://ntrs.nasa.gov/citations/19820012351)., NASA.

Dhami, N.K., Reddy, M.S., Mukherjee, A., 2013. [Biomineralization of calcium carbonates and their engineered applications: a review](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3810791/). *Frontiers in microbiology*, *4*, p.314.

DiBiase, R.A., Limaye, A.B., Scheingross, J.S., Fischer, W.W. and Lamb, M.P., 2013. [Deltaic deposits at Aeolis Dorsa: Sedimentary evidence for a standing body of water on the northern plains of Mars](https://authors.library.caltech.edu/39420/1/jgre20100.pdf). *Journal of Geophysical Research: Planets*, *118*(6), pp.1285-1302. NASA / MARS Exploration program announcement: [A Martian Coastal Delta Environment?](https://mars.nasa.gov/resources/5428/a-martian-coastal-delta-environment/)

Dinan, F.J. and Yee, G.T., 2007. [An adventure in stereochemistry: Alice in mirror image land](https://www.saddleback.edu/faculty/jzoval/worksheets_tutorials/ch13worksheets/Alice%20in%20Mirror%20Image%20Land%20Worksheet%20and%20Key.pdf). New York: National Center for Case Study Teaching in Science, University at Buffalo, State University of New York.

DLR, n.d., [The topography of Jezero crater – landing site of NASA's Mars 2020 mission](https://www.dlr.de/content/en/articles/news/2020/03/20200929_topography-of-jezero-crater.html)

Doolittle W. F., 2000, [Uprooting the Tree of Life](http://faculty.bennington.edu/~sherman/comp.%20anim.%20physiol./readings/uprooting%20the%20tree%20of%20life.pdf), Scientific American

*As Woese has written, “The ancestor cannot have been a particular organism, a single organismal lineage. It was communal, a loosely knit, diverse conglomeration of primitive cells that evolved as a unit, and it eventually developed to a stage where it broke into several distinct communities, which in their turn become the three primary lines of descent [bacteria, archaea and eukaryotes].” In other words, early cells, each having relatively few genes,differed in many ways. By swapping genes freely, they shared various of their talents with their contemporaries. Eventually this collection of eclectic and changeable cells coalesced into the three basic domains known today. These domains remain recognizable because much (though by no means all) of the gene transfer that occurs these days goes on within domains.*

Doyle, A., 2014, [Mapping Amino Acids to Understand Life's Origins](https://www.astrobio.net/origin-and-evolution-of-life/mapping-amino-acids-to-understand-lifes-origins/), NASA Astrobiology magazine.

Doyle, A., 2017, [Ancient Lake On Mars Was Hospitable Enough To Support Life](https://www.astrobio.net/news-exclusive/ancient-lake-mars-hospitable-enough-support-life/), NASA Astrobiology magazine

Drake, H., Åström, M.E., Heim, C., Broman, C., Åström, J., Whitehouse, M., Ivarsson, M., Siljeström, S. and Sjövall, P., 2015. [Extreme 13 C depletion of carbonates formed during oxidation of biogenic methane in fractured granite](https://www.nature.com/articles/ncomms8020). *Nature communications*, *6*, p.7020.

Duda, V.I., Suzina, N.E., Polivtseva, V.N. and Boronin, A.M., 2012. [Ultramicrobacteria: formation of the concept and contribution of ultramicrobacteria to biology](https://www.researchgate.net/profile/Valentina-Polivtseva/publication/234279647_Ultramicrobacteria_Formation_of_the_Concept_and_Contributionof_Ultramicrobacteria_to_Biology/links/55829f2b08ae1b14a0a134fc/Ultramicrobacteria-Formation-of-the-Concept-and-Contribution-of-Ultramicrobacteria-to-Biology.pdf). *Microbiology*, *81*(4), pp.379-390.

Dundas, C.M., McEwen, A.S., Chojnacki, M., Milazzo, M.P., Byrne, S., McElwaine, J.N. and Urso, A., 2017. [Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water](https://www.nature.com/articles/s41561-017-0012-5). *Nature Geoscience*, *10*(12), p.903

Dunlop, R.A., Cox, P.A., Banack, S.A. and Rodgers, K.J., 2013. [The non-protein amino acid BMAA is misincorporated into human proteins in place of L-serine causing protein misfolding and aggregation](http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0075376). *PloS one*, *8*(9), p.e75376.

Du Toit, A., 2019. [Expanding diversity of the human microbiom](https://www.nature.com/articles/s41579-019-0154-0#citeas)e.*Nat Rev Microbiol* **17,** 126

Dutt, P. [A review of low-energy transfers](https://link.springer.com/article/10.1007/s10509-018-3461-4?shared-article-renderer). *Astrophys Space Sci* **363,** 253 (2018). <https://doi.org/10.1007/s10509-018-3461-4>

Dwyer, C., 2020, [Everest Gets A Growth Spurt As China, Nepal Revise Official Elevation Upward](https://www.npr.org/2020/12/08/944152693/everest-gets-a-growth-spurt-as-china-nepal-revise-official-elevation-upward), NPR

## E

Eberl, L., Molin, S. and Givskov, M., 1999. [Surface motility of Serratia liquefaciens](https://jb.asm.org/content/jb/181/6/1703.full.pdf) MG1. Journal of bacteriology, 181(6), pp.1703-1712.

ECDC, n.d., [Facts about variant Creutzfeldt-Jakob disease](https://www.ecdc.europa.eu/en/vcjd/facts), European Centre for Disease Prevention and Control

*In a recent study of French vCJD cases, the incubation period has been estimated to be around 13 years (95% CI: 9,7-17,9 years)*

Edwards, C.S. and Piqueux, S., 2016. [The water content of recurring slope lineae on Mars](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL070179). *Geophysical Research Letters*, *43*(17), pp.8912-8919. NASA press release: [Test for Damp Ground at Mars' Seasonal Streaks Finds None](https://www.nasa.gov/feature/jpl/test-for-damp-ground-at-mars-seasonal-streaks-finds-none)

Elliott, T.A. and Gregory, T.R., 2015. What's in a genome? [The C-value enigma and the evolution of eukaryotic genome content](https://royalsocietypublishing.org/doi/full/10.1098/rstb.2014.0331). Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1678), p.20140331.

Elsila, J.E., Callahan, M.P., Dworkin, J.P., Glavin, D.P., McLain, H.L., Noble, S.K. and Gibson Jr, E.K., 2016[. The origin of amino acids in lunar regolith samples](https://www.sciencedirect.com/science/article/pii/S0016703715005906). *Geochimica et Cosmochimica Acta*, *172*, pp.357-369. Press release: [New NASA study reveals origin of organic matter in Apollo lunar samples](https://phys.org/news/2015-10-nasa-reveals-apollo-lunar-samples.html)

EMW, ISO 29463 - [New test standard for HEPA Filters](https://www.emw.de/en/filter-campus/iso29463.html) At: <https://www.emw.de/en/filter-campus/iso29463.html> Accessed on 7 July 2020

*In 1998* [*EN 1822*](https://www.emw.de/en/filter-campus/filter-classes.html) *came into effect. This was the first standard, which established a filter classification system for* [*HEPA filters*](https://www.emw.de/en/products/hepa-air-filters/) *based on filtration process theory. EN 1822 also introduced the evaluation criterion MPPS (Most Penetrating Particle Size). MPPS is the particle size at which the air filter has its lowest arrestance. Not just a whim of nature, MPPS relates directly to physical mechanisms in the* [*filtration process*](https://www.emw.de/en/filter-campus/theory-of-particle-filtration.html)*.*

*The U.S. takes a different approach for filter classification of HEPA filters. The mother of all test procedures for these filters in the U.S. is MIL-STD-282, which was introduced in 1956. Other test procedures include e.g. IEST-RP-CC001 and IEST-RP-CC007. Each test procedure specifies certain particle sizes at which efficiency is evaluated. Depending on the filter class evaluated, this is done at 0.3 µm, 0.1 - 0.2 µm or 0.2 - 0.3 µm.*

Engineering ToolBox, 2003. [Young's Modulus - Tensile and Yield Strength for common Materials](https://www.engineeringtoolbox.com/young-modulus-d_417.html) [online].

Eninger, R.M., Honda, T., Reponen, T., McKay, R. and Grinshpun, S.A., 2008. [What does respirator certification tell us about filtration of ultrafine particles?](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6800048/). Journal of occupational and environmental hygiene, 5(5), pp.286-295.

EPA (US Environmental Protection Agency). Science Advisory Board, 1990. [Reducing risk: Setting priorities and strategies for environmental protection](https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000PNG1.TXT).

EPA, n.d., [What is the National Environmental Policy Act?](https://www.epa.gov/nepa/what-national-environmental-policy-act)

EPA, n.d.pwio., [Partnering with International Organizations](https://www.epa.gov/international-cooperation/partnering-international-organizations).

European Commission, n.d., [Health and Safety at Work](https://ec.europa.eu/social/main.jsp?catId=148).

ESA, 2018, [Mars sample return](https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Mars_sample_return), accessed at: <https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Mars_sample_return>, accessed on 17 July 2020.

ESA, 2019op, [Oxia Planum](https://exploration.esa.int/web/mars/-/54724-oxia-planum), at: https://exploration.esa.int/web/mars/-/54724-oxia-planum (accessed 2 July 2020)

ESA, 2019edu, [The ExoMars drill unit](https://exploration.esa.int/web/mars/-/43611-rover-drill)

ESA, 2020, [Sample Fetch Rover for Mars Sample Return campaign](https://www.esa.int/ESA_Multimedia/Videos/2020/02/Sample_Fetch_Rover_for_Mars_Sample_Return_campaign)

ESA, n.d.GEO, [Geostationary Orbit](https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#GEO)

ESA, n.d.LFM, [Life Marker Chip](http://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Life_marker_chip)

ESA, n.d.MET, [METERON project](https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Automation_and_Robotics/METERON_Project), available at: <https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Automation_and_Robotics/METERON_Project>, accessed on 11 July 2020

ESA, n.d.MS, [ESA member states](https://www.esa.int/About_Us/Corporate_news/Member_States_Cooperating_States)

ESA, n.d.SDM, [Space debris mitigation: the case for a code of conduct](https://www.esa.int/Enabling_Support/Operations/Space_debris_mitigation_the_case_for_a_code_of_conduct)

EU, 2001, [Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment](https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32001L0042&from=EN)

Eugster, O., Busemann, H., Lorenzetti, S. and Terribilini, D., 2002. [Ejection ages from krypton‐81‐krypton‐83 dating and pre‐atmospheric sizes of Martian meteorites](https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1945-5100.2002.tb01033.x). *Meteoritics & Planetary Science*, *37*(10), pp.1345-1360.

Evans, B., 2014[,'Weaving Up the Freeway': The Triumph of Apollo 10 (Part 4)](https://www.americaspace.com/2014/05/19/weaving-up-the-freeway-the-triumph-of-apollo-10/)

See also transcript: https://history.nasa.gov/afj/ap10fj/as10-day5-pt20.html

EvoEd, n.d, [E. coli Citrate Use](http://www.evo-ed.org/Pages/Ecoli/), Cases for Evolution Education

## F

Fairén, A.G., Parro, V., Schulze-Makuch, D. and Whyte, L., 2017. [Searching for life on Mars before it is too late](http://online.liebertpub.com/doi/full/10.1089/ast.2017.1703). *Astrobiology*, *17*(10), pp.962-970.

Fajardo-Cavazos, P., Morrison, M.D., Miller, K.M., Schuerger, A.C. and Nicholson, W.L., 2018. [Transcriptomic responses of Serratia liquefaciens cells grown under simulated Martian conditions of low temperature, low pressure, and CO 2-enriched anoxic atmosphere](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3582281/). Scientific reports, 8(1), pp.1-10.

Fan, C., Deng, Q. and Zhu, T.F., 2021. [Bioorthogonal information storage in l-DNA with a high-fidelity mirror-image Pfu DNA polymerase](https://www.nature.com/articles/s41587-021-00969-6). *Nature Biotechnology*, *39*(12), pp.1548-1555.

For popular account see Addison, R, 2021, [Mirror image enzyme constructs longest ever mirror DNA strand](https://www.chemistryworld.com/news/mirror-image-enzyme-constructs-longest-ever-mirror-dna-strand/4014122.article), Chemistry world

Fang, J., 2010. Animals thrive without oxygen at sea bottom. *Nature*, *464*(7290), pp.825-826.

Faure, E., Not, F., Benoiston, A.S., Labadie, K., Bittner, L. and Ayata, S.D., 2019. [Mixotrophic protists display contrasted biogeographies in the global ocean](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6461780/). *The ISME journal*, *13*(4), pp.1072-1083.

Fischer, E., Martinez, G., Elliott, H.M., Borlina, C. and Renno, N.O., 2013, December. [The Michigan Mars Environmental Chamber: Preliminary Results and Capabilities](https://www.researchgate.net/publication/283504377_The_Michigan_Mars_Environmental_Chamber_Preliminary_Results_and_Capabilities). In AGU Fall Meeting Abstracts (Vol. 2013, pp. P41C-1928).

Fischer, E., Martínez, G.M., Elliott, H.M. and Rennó, N.O., 2014. [Experimental evidence for the formation of liquid saline water on Mars](https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/2014GL060302). *Geophysical research letters*, *41*(13), pp.4456-4462.

Fisk, M., Popa, R., Bridges, N., Renno, N., Mischna, M., Moores, J. and Wiens, R., 2013. [Habitability of Transgressing Mars Dunes](http://www.lpi.usra.edu/meetings/lpsc2013/pdf/1434.pdf). *Geochimica et Cosmochimica Acta*, *67*, pp.3871-3887.

Fournier, G.P., Moore, K.R., Rangel, L.T., Payette, J.G., Momper, L. and Bosak, T., 2021. [The Archean origin of oxygenic photosynthesis and extant cyanobacterial lineages](https://royalsocietypublishing.org/doi/10.1098/rspb.2021.0675). *Proceedings of the Royal Society B*, *288*(1959), p.20210675. Press release from MIT: [Zeroing in on the origins of Earth’s “single most important evolutionary innovation”](https://news.mit.edu/2021/photosynthesis-evolution-origins-0928)

Foust, J., 2014, [Nonprofit Organization Seeks To Raise a Billion Dollars To Fund Space Science Missions](https://spacenews.com/40865nonprofit-organization-seeks-to-raise-a-billion-dollars-to-fund-space/), SpaceNews

Foust, J., 2020, [Taking on the challenge of Mars sample return](https://www.thespacereview.com/article/3930/1), The Space Review

*“Only recently, with the reality of a Mars Sample Return project, have we started to revisit and think in depth about implementation of backwards planetary protection,” said Lisa Pratt, NASA’s planetary protection officer. The last time NASA seriously thought about backwards planetary protection, she noted at the MEPAG meeting, was during the Apollo program a half century ago.*

*...*

*A concept review and development milestone known as Key Decision Point (KDP) A are scheduled before the end of the current fiscal year.*

*“We’re not prepared to discuss that at this point in time,” Watzin said when asked at the MEPAG meeting for the cost of the overall program. “As we go forward into KDP-A, we’ll have to start talking about that. Towards the end of this fiscal year is when we’ll be ready to have that conversation.”*

Foust, J., 2021, [The multi-decade challenge of Mars Sample Return](https://spacenews.com/the-multi-decade-challenge-of-mars-sample-return/), Space News

*That schedule was too aggressive for the independent panel. “The schedules required to support launches in 2026 were substantially shorter than the actual experience from recent, somewhat similar programs,” like Mars 2020 and Curiosity, Thompson said.*

*Under a revised schedule recommended by the panel, the lander mission would launch in 2028. The orbiter could launch in either 2027 or 2028, since its use of electric propulsion gives it the flexibility to pursue alternative trajectories. That revised schedule would delay the return of the samples until 2033.*

*At the same time, the study warned about delaying the missions beyond 2028 [because of risk of landing before a global dust storm with solar power issues]*

*...*

*It also recommended looking at adding a radioisotope thermoelectric generator (RTG) to the lander, or at least the lander with the MAV, to ensure sufficient power and to keep the rocket’s propulsion system from getting too cold.*

Fox, S. and Strasdeit, H., 2017. [Inhabited or uninhabited? Pitfalls in the interpretation of possible chemical signatures of extraterrestrial life](https://www.frontiersin.org/articles/10.3389/fmicb.2017.01622/full). Frontiers in Microbiology, 8, p.1622

*Examples of such “molecular fossils” are 1.64 Ga old carotenoid derivatives (Lee and Brocks, 2011) and degradation products of chlorophylls and hemes (geoporphyrins; Callot and Ocampo, 2000) which have been reported, for example, from ∼500 Ma old oil shales (Serebrennikova and Mozzhelina, 1994). Hence, the extraordinary stability of certain molecular fossils opens the prospect of detecting chemical traces of life on other planets and moons even if it became extinct a long time ago.*

*It is highly unlikely that a natural abiotic process generates long chain molecules that have precisely defined lengths, ordered sequences, and homochiral building blocks. Therefore, proteins and nucleic acids can certainly be regarded as strong chemical biosignatures.*

*Low to moderate enantiomeric excesses, as they occur, for example, in meteoritic α,α-dialkyl amino acids (Pizzarello and Cronin, 2000), are definitely not indicative of a biological origin.*

*On the other hand, a lack of enantiopurity can be a false-negative result because the initial enantiopurity could have been lost by racemization, a process well-known for the proteinogenic L-amino acids (Bada and Schroeder, 1975; Bada, 1985). Furthermore, one should not discard the possibility that an extraterrestrial organism synthesizes both enantiomers. In fact, terrestrial bacteria produce diverse D-amino acids (e.g., D-Ala, D-Glu, D-Leu, D-Met, D-Phe, and D-Tyr) which have effects on the peptidoglycan of the cell wall, both directly by incorporation into the polymer and indirectly by regulating enzymes that synthesize and modify peptidoglycan (Höltje, 1998; Lam et al., 2009). Another intriguing example from terrestrial life is the simultaneous presence of L- and D-isovaline in some fungal peptides (Degenkolb et al., 2007).*

*No natural non-biological processes that generate them have been observed in nature, but there are some indications that, at least in rare instances, natural abiotic compounds might be enantiopure. For example, there is a single case where, under laboratory conditions, a small enantiomeric excess of an amino acid was amplified to near enantiopurity (>99%; Klussmann et al., 2006). This amino acid was serine under solid–liquid equilibrium conditions in water at the eutectic point. However, for all other amino acids tested, enantiopurity was not achieved. Also, this mechanism will not work with chiral compounds that crystallize as conglomerates (i.e., mixtures of pure L and pure D crystals). Because of the special conditions and compounds necessary, it is unclear if this physical process is relevant to the generation of enantiopurity (i.e., enantiomeric excesses near 100%) in extraterrestrial environments.*

Fraeman, A, 2020, [Sols 2819-2821: Movin' Right Along in Search of Good Sights and Good Rocks](https://mars.nasa.gov/msl/mission-updates/sols-2819-2821-movin-right-along-in-search-of-good-sights-and-good-rocks/) , NASA.

Frantseva, K., Mueller, M., ten Kate, I.L., van der Tak, F.F. and Greenstreet, S., 2018. [Delivery of organics to Mars through asteroid and comet impacts](https://arxiv.org/pdf/1803.03270.pdf). Icarus, 309, pp.125-133.

Franz, H.B., Kim, S.T., Farquhar, J., Day, J., Economos, R.C., McKeegan, K.D., Schmitt, A.K., Irving, A.J. and Hoek, J., 2014. ["Isotopic Links between Atmospheric Chemistry and the Deep Sulphur Cycle on Mars](http://www.nature.com/nature/journal/v508/n7496/full/nature13175.html). *Nature*, *508*(7496), pp.364-368. [Press release: Meteorites Yield Clues to Red Planet’s Early Atmosphere](https://cmns.umd.edu/news-events/features/2088)

Franz, H.B., Mahaffy, P.R., Webster, C.R., Flesch, G.J., Raaen, E., Freissinet, C., Atreya, S.K., House, C.H., McAdam, A.C., Knudson, C.A. and Archer, P.D., 2020. [Indigenous and exogenous organics and surface–atmosphere cycling inferred from carbon and oxygen isotopes at Gale crater](http://www-personal.umich.edu/~atreya/Articles/indigenous.pdf). *Nature Astronomy*, *4*(5), pp.526-532.

Fraser, C.I., Terauds, A., Smellie, J., Convey, P. and Chown, S.L., 2014. [Geothermal activity helps life survive glacial cycles](https://www.pnas.org/content/111/15/5634#T1). Proceedings of the National Academy of Sciences, 111(15), pp.5634-5639. Press release [Volcanoes provided ice-age refuge for Antarctic biodiversity](https://www.antarctica.gov.au/magazine/issue-26-june-2014/science/volcanoes-provided-ice-age-refuge-for-antarctic-biodiversity/)

[G](https://www.antarctica.gov.au/magazine/issue-26-june-2014/science/volcanoes-provided-ice-age-refuge-for-antarctic-biodiversity/)

Fraunhaufer, 2015, [Space probes: sterile launch into outer space](https://www.fraunhofer.de/en/press/research-news/2015/august/space-probes-sterile-launch-into-outer-space.html)

*"The method originates from the USA, and is used to remove paint from aircraft fuselage. A powerful jet of frozen carbon dioxide (CO₂) crystals, about the size of a rice kernel, blasts the paint right off the metal. The researchers made this crude instrument substantially more refined. Instead of CO₂ pellets, they use carbon dioxide snow to work on each individual component – from the highly sophisticated aluminum workbench to the ring washers. Here’s the rub: the beam that the jet emits is additionally accelerated with a blast of CDA (clean dry air) that encases it. This is how it penetrates into every nook and cranny, removing even the minuscule pollutant. As soon as the tiny snowflakes hit the relatively hot surface, they become gaseous, causing their volume to explosively expand 800-fold. The detonation pressure completely sweeps away every single bit of dust, even fingerprints which the cold gas had just turned brittle. “This approach involves a dry process that does not warp surfaces. When cleaning, these can be gently treated with CO₂. That makes it unnecessary to apply heat or chemicals,” Gommel says when explaining the advantages of this method.* "

Freitas, R.A., and Zachary, W.B., 1981, May. [A self-replicating, growing lunar factory](http://www.rfreitas.com/Astro/GrowingLunarFactory1981.htm). In 4th Space manufacturing; Proceedings of the Fifth Conference (p. 3226).

Friedland, N., Negi, S., Vinogradova-Shah, T., Wu, G., Ma, L., Flynn, S., Kumssa, T., Lee, C.H. and Sayre, R.T., 2019. [Fine-tuning the photosynthetic light harvesting apparatus for improved photosynthetic efficiency and biomass yield](https://www.nature.com/articles/s41598-019-49545-8). *Scientific reports*, *9*(1), pp.1-12.

Fuerstenau, S.D., 2006. [Solar heating of suspended particles and the dynamics of Martian dust devils](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006GL026798). Geophysical research letters, 33(19).

Furmanski, M., 2014. [Laboratory Escapes and “Self-fulfilling prophecy” Epidemics](https://armscontrolcenter.org/wp-content/uploads/2016/02/Escaped-Viruses-final-2-17-14-copy.pdf). Center for Arms Control and Nonproliferation.

## G

Galletta, G., Bertoloni, G. and D'Alessandro, M., 2010. [Bacterial survival in Martian conditions](https://arxiv.org/abs/1002.4077). *arXiv preprint arXiv:1002.4077*.

Gannon, R., 1962. [Life in a Germfree World](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3477854/#f122). *Popular Science*, *90*.

Garcia-Descalzo, L., Gil-Lozano, C., Muñoz-Iglesias, V., Prieto-Ballesteros, O., Azua-Bustos, A. and Fairén, A.G., 2020. [Can Halophilic and Psychrophilic Microorganisms Modify the Freezing/Melting Curve of Cold Salty Solutions? Implications for Mars Habitability](https://www.liebertpub.com/doi/pdf/10.1089/ast.2019.2094). Astrobiology, 20(9), pp.1067-1075.

Garcia‐Pichel, F. and Belnap, J., 1996. [Microenvironments and microscale productivity of cyanobacterial desert crusts](https://onlinelibrary.wiley.com/doi/abs/10.1111/j.0022-3646.1996.00774.x) 1. Journal of phycology, 32(5), pp.774-782.

Gaskin, J.A., Jerman, G., Gregory, D. and Sampson, A.R., 2012, March. [Miniature variable pressure scanning electron microscope for in-situ imaging & chemical analysis](https://ieeexplore.ieee.org/abstract/document/6187064/). In *Aerospace Conference, 2012 IEEE* (pp. 1-10). IEEE.

Geiling, N., 2013, [Did Life Come to Earth From Mars?](https://www.smithsonianmag.com/science-nature/did-life-come-to-earth-from-mars-2378085/), Smithsonian mag

*“RNA is the key to the ribosome, which is what makes proteins. There’s almost no question that RNA, which is a molecule involved in catalysis, arose before proteins arose,” Benner explains. The difficulty is that for RNA to assemble into long strands–which is needed for genetics – you can’t have the assembly taking place in water. “Most people think that water is essential for life. Very few people understand how corrosive water is,” Benner says. For RNA, water is extremely corrosive – bonds cannot be made within water, preventing long-strands from forming.*

*However, Benner says that these paradoxes can be resolved with the help of two very important groups of minerals. The first are borate minerals. Borate minerals–which contain the element boron–prevent life’s building blocks from devolving into tar if incorporated into organic compounds. Boron, as an element, is seeking electrons to make itself stable. It finds these in oxygen, and together the oxygen and boron form the mineral borate. But if the oxygen boron finds is already bonded to carbohydrates, the carbohydrates linked with boron form a complex organic molecule dotted with borate that’s less resistant to decomposition.*

*The second group of minerals that come into play involve those that contain molybdate, a compound that consists of molybdenum and oxygen. Molybdenum, more famous for its conspiratorial relation to the Douglas Adams classic A Hitchhiker’s Guide to the Galaxy than for its other properties, is crucial, because it takes the carbohydrates that borate stabilized, bonds to them and catalyzes a reaction which rearranges them into ribose: the R in RNA.*

Gerhart, L.M. and Ward, J.K., 2010. [Plant responses to low [CO₂] of the past](https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x). New Phytologist, 188(3), pp.674-695.

Gernhardt, M.L. and Abercromby, A.F., 2008. [Health and safety benefits of small pressurized suitport rovers as EVA surface support vehicles](https://web.archive.org/web/20100213221815/http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080014281_2008013625.pdf).

Ghuneim, L.A.J., Jones, D.L., Golyshin, P.N. and Golyshina, O.V., 2018. N[ano-sized and filterable bacteria and archaea: biodiversity and function](https://www.frontiersin.org/articles/10.3389/fmicb.2018.01971/full). Frontiers in microbiology, 9, p.1971.

See section Selective Pressures for Small Size

Gibson Jr, E.K., McKay, D.S., Thomas-Keprta, K.L., Wentworth, S.J., Westall, F., Steele, A., Romanek, C.S., Bell, M.S. and Toporski, J., 2001. [Life on Mars: evaluation of the evidence within Martian meteorites ALH84001, Nakhla, and Shergotty](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.539.6004&rep=rep1&type=pdf). Precambrian research, 106(1-2), pp.15-34.

Gibson, E.K., McKay, D.S., Thomas-Keprta, K.L., Clemett, S.J. and White, L., 2012. [Nature of Reduced Carbon in Martian Meteorites](https://ntrs.nasa.gov/citations/20120012511). Meteoritics and Planetary Science Supplement, 75, p.5306.

Gilvarry, J.J., 1964a. [The possibility of a pristine lunar life](https://www.sciencedirect.com/science/article/abs/pii/0022519364900517). Journal of Theoretical Biology, 6(3), pp.325-346.

Gilvarry, J.J., 1964b. [The possibility of a primordial lunar life](https://books.google.co.uk/books?hl=en&lr=&id=t8zYBAAAQBAJ&oi=fnd&pg=PA179). in Mamikunian, G. and Briggs, M.H. eds., 2013. Current aspects of exobiology. Elsevier.

GIPA (Gamma Industry Processing Alliance) and IIA (International Irradiation Association), 2018. [A Comparison of Gamma, E-beam, X-ray and Ethylene Oxide Technology for the Industrial Sterilization of Medical Devices and Healthcare Products](http://large.stanford.edu/courses/2018/ph241/goronzy2/docs/gipa-aug17.pdf), 1–49.

Gladman, B., Dones, L., Levison, H.F. and Burns, J.A., 2005. [Impact seeding and reseeding in the inner Solar System](http://www.ucolick.org/~laugh/kobe/projects/astrobio.pdf). *Astrobiology*, *5*(4), pp.483-496.

Goad, M., n.d. [A New Interactive Map Reveals Where the Deadliest Germs Are Studied](https://schar.gmu.edu/news/2021-07/new-interactive-map-reveals-where-deadliest-germs-are-studied), George Mason University

(by visual count, I make it 7 not operational yet out of 59 mapped)

Goetz, W., Brinckerhoff, W.B., Arevalo, R., Freissinet, C., Getty, S., Glavin, D.P., Siljeström, S., Buch, A., Stalport, F., Grubisic, A. and Li, X., 2016. [MOMA: the challenge to search for organics and biosignatures on Mars. International Journal of Astrobiology](https://www.researchgate.net/publication/305311049_MOMA_The_challenge_to_search_for_organics_and_biosignatures_on_Mars), 15(3), pp.239-250

Golombek, M., Balaram, J., Maki, J., Williams, N., Grip, H., and Aung, M., 2020, [Mars helicopter on the 2020 rover mission](https://www.hou.usra.edu/meetings/lpsc2020/pdf/2096.pdf), 51st Lunar and Planetary Science Conference

Goodsell, D., 2000, [PDB101: Molecule of the Month: Ribosomal Subunits](https://pdb101.rcsb.org/motm/10), RCSB Protein Data Bank

Goodsell, D.S., 2004. [Catalase. Molecule of the Month](http://pdb101.rcsb.org/motm/57). RCSB Protein Data Bank. *Retrieved,(2007)-02-11*.

*Fortunately, cells make a variety of antioxidant enzymes to fight the dangerous side-effects of life with oxygen. Two important players are superoxide dismutase, which converts superoxide radicals into hydrogen peroxide, and catalase, which converts hydrogen peroxide into water and oxygen gas. The importance of these enzymes is demonstrated by their prevalence, ranging from about 0.1% of the protein in an Escherichia coli cell to upwards of a quarter of the protein in susceptible cell types. These many catalase molecules patrol the cell, counteracting the steady production of hydrogen peroxide and keeping it at a safe level.*

Goordial, J., Davila, A., Lacelle, D., Pollard, W., Marinova, M.M., Greer, C.W., DiRuggiero, J., McKay, C.P. and Whyte, L.G., 2016. [Nearing the cold-arid limits of microbial life in permafrost of an upper dry valley](https://www.nature.com/articles/ismej2015239), Antarctica. *The ISME journal*, *10*(7), pp.1613-1624.

*Soils from the hyper-arid core of the Atacama Desert have cell numbers and culturable counts similar to University Valley permafrost (*[*Supplementary Table S3*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4918446/#sup1)*), but small, viable microbial communities are activated and detected when Atacama soils are wetted (*[*Navarro-González et al., 2003*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4918446/#bib22)*;* [*Crits-Christoph et al., 2013*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4918446/#bib6)*). Our results suggest that microorganisms in the University Valley permafrost soils analysed here are not exposed to sufficiently long and frequent clement conditions to allow for metabolism or growth. Instead, our results suggest that a fundamental threshold may be crossed in some University Valley permafrost soils, where the combination of permanently subfreezing temperatures, low water activity, oligotrophy and age are severely constraining the evolution of functional cold-adapted organisms*

*Very low microbial biomass was found by direct microscopic cell counts (1.4−5.7 × 10^3 cells per g soil) in both the dry and ice-cemented permafrost using DTAF stain as described by Steven et al. (2008). Comparatively, 2 orders of magnitude higher cell counts (1.2−4.5 × 10^5 cells per g soil) were detected in the active layer and permafrost soils from the Antarctic Peninsula.*

Gopinath, P.M., Saranya, V., Vijayakumar, S., Meera, M.M., Ruprekha, S., Kunal, R., Pranay, A., Thomas, J., Mukherjee, A. and Chandrasekaran, N., 2019. [Assessment on interactive prospectives of nanoplastics with plasma proteins and the toxicological impacts of virgin, coronated and environmentally released-nanoplastics](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6586940/). Scientific reports, 9(1), pp.1-15.

Gordon, E., Mouz, N., Duee, E. and Dideberg, O., 2000. [The crystal structure of the penicillin-binding protein 2x from Streptococcus pneumoniae and its acyl-enzyme form: implication in drug resistance](https://www.sciencedirect.com/science/article/pii/S0022283600937409). *Journal of molecular biology*, *299*(2), pp.477-485.

Gough, R.V., Rapin, W., Martínez, G.M., Meslin, P.Y., Gasnault, O., Schröder, S. and Wiens, R.C., 2020, March. [Possible Detection of Water Frost by the Curiosity Rover](https://www.hou.usra.edu/meetings/lpsc2020/pdf/2205.pdf). In Lunar and Planetary Science Conference (No. 2326, p. 2205).

Grady, M.M., 2020. [Exploring Mars with Returned Samples](http://oro.open.ac.uk/70747/1/11214_2020_Article_676.pdf). Space Science Reviews, 216, article no.51

*The MSR mission currently being planned will return limited amounts of sample, mainly rocks. It is not scheduled to collect airfall dust, which is the material required in relatively large quantities for testing. However, the returned tubes, which will have been exposed on the Martian surface for around 10 years,will almost certainly be covered in dust - and it is possible that this material might be suitable for the abrasion testing. What is likely to be more useful, though, is that collection and characterization of the airfall dust from the exterior surfaces of the sample tubes will help in production of a high-quality dust simulant. The grain size, shape, angularity, composition and density of the airfall dust will be replicated and large quantities synthesised, enabling large-scale testing of engineering systems to be undertaken.*

...

*The disadvantages of removing a sample from its environment prior to analysis revolve around changes that might occur because the sample is no longer in thermal or redox equilibrium with its surroundings.*

Graham, J., 1993. [Risk in perespective: The legacy of one in a million](https://cdn1.sph.harvard.edu/wp-content/uploads/sites/1273/2013/06/The-Legacy-of-One-in-a-Million-March-1993.pdf). Harvard Center for Risk Analysis, Risk Perspective, 1, pp.1-2.

"Although some observers see value in "bright-line" levels of acceptable risk, history suggests that acceptable risk will ultimately be defined on a case-by-case basis. Key decision factors such as the risk of he exposed population, the resource cost of meeting risk targets, and the scientific quality of risk assessments vary enormously from one decision context to another.

Administrative discretion is necessary to weight these factors on a case-by-case basis. No magic risk number can substitute for informed and thoughtful consideration by accountable officials who work with the public to make balanced decisions.

Gramling, J., Meyer, M., Braun, B., 2021 [Explore Mars Sample Return - presentation to the MEPAG](https://mepag.jpl.nasa.gov/meeting/2021-01/04_MEPAG%201_2021%20V5.pdf) (Powerpoint)

Greenberg, R. and Tufts, B.R., 2001. [Macroscope: Infecting Other Worlds](https://www.jstor.org/stable/27857494). *American Scientist*, *89*(4), pp.296-299.

*"As long as the probability of people infecting other planets with terrestrial microbes is substantially smaller than the probability that such contamination happens naturally, exploration activities would, in our view, be doing no harm. We call this concept the natural contamination standard."*

Grimont, P.A. and Grimont, F., 1978. [The genus serratia](https://www.researchgate.net/profile/Patrick_Grimont/publication/226092360_The_Genus_Serratia/links/0c960531489b4c2785000000/The-Genus-Serratia.pdf). Annual Reviews in Microbiology, 32(1), pp.221-248.

Gronstall, A., 2014, [Liquid Water from Ice and Salt on Mars](https://www.astrobio.net/mars/liquid-water-ice-salt-mars/), NASA astrobiology magazine.

Gros, C., 2016. [Developing ecospheres on transiently habitable planets: the genesis project](https://link.springer.com/article/10.1007/s10509-016-2911-0). *Astrophysics and Space Science*, *361*(10), p.324.

Grotzinger, J.P., 2013. [Habitability, Taphonomy, and Curiosity's Hunt for Organic Carbon](https://www.planetary.org/blogs/guest-blogs/2013/20131221-habitability-taphonomy-and-curiositys-hunt-for-organic-carbon.html?referrer=http://www.quora.com/Is-Mars-worth-mining-for-Earth-purposes), Planetary Society.

Grotzinger, J.P., 2014. [Habitability, Organic Taphonomy, and the Sedimentary Record of Mars](https://www.hou.usra.edu/meetings/8thmars2014/pdf/1175.pdf). *LPICo*, *1791*, p.1175.

Grove, G.L. and Kligman, A.M., 1983. [Age-associated changes in human epidermal cell renewal](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.977.3844&rep=rep1&type=pdf). Journal of Gerontology, 38(2), pp.137-142.

Giuliani, M., Amerio, E., Lobascio, C., Saverino, A. and Guarnieri, V., 2009. [Contamination Control Approach for Exomars Mission](http://esmat.esa.int/materials_news/isme09/pdf/6-Contamination/S8%20-%20Giuliani.pdf). In *11th ISME International Symposium on Materials in a Space Environment (September 2009)*.

*The most promising candidate as Ultra Cleaning Technique appears to be the CO2 Snow Cleaning: this process removes micron and submicron particulates and hydrocarbon-based contamination by means of a snow stream confined in a N2 jet, impinging onto the surfaces to be cleaned. It is non-destructive, nonabrasive, residue-free, based upon the expansion of either liquid or gaseous carbon dioxide through an orifice. The contamination layer is removed by means of the synergic effects of the nucleation of small dry ice particles and a high velocity gas carrier stream. Upon impact with a dirty surface, the dry ice media removes particles by momentum transfer, local sublimation of CO2 snow which traps and carries away the contamination and also thanks to the thermal tension induced by the CO2 snow jet, which freezes the contamination layer. Finally, the high-velocity gas blows the contaminants away.*

Gülgönül, Ş. and Sözbir, N., 2018, November. [Propellant Budget Calculation Of Geostationary Satellites](https://www.researchgate.net/publication/329074503_Propellant_Budget_Calculation_of_Geostationary_Satellites). In 6th International Symposium on Innovative Technologies in Engineering and Science 09-11 November 2018 (ISITES2018 Antalya-Turkey). See table 2 Apogee Maneuver Firing (AMF) delta v 1495.7 m/s.

Gyollai, I., Polgari, M., Bérczi, S., Gucsik, A. and Pál-Molnár, E., 2019. [Mineralized biosignatures in ALH-77005 Shergottite-Clues to Martian Life?](https://www.degruyter.com/document/doi/10.1515/astro-2019-0002/html). Open Astronomy, 28(1), pp.32-39.

## H

Haberle, R.M., McKay, C.P., Schaeffer, J., Cabrol, N.A., Grin, E.A., Zent, A.P. and Quinn, R., 2001. [On the possibility of liquid water on present‐day Mars](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2000JE001360). *Journal of Geophysical Research: Pl*

Hales, T.C., 1998. [An overview of the Kepler conjecture](https://arxiv.org/pdf/math/9811071.pdf). arXiv preprint math/9811071

Hales, T., Adams, M., Bauer, G., Dang, T.D., Harrison, J., Le Truong, H., Kaliszyk, C., Magron, V., McLaughlin, S., Nguyen, T.T. and Nguyen, Q.T., 2017. [A formal proof of the Kepler conjecture](https://www.cambridge.org/core/services/aop-cambridge-core/content/view/78FBD5E1A3D1BCCB8E0D5B0C463C9FBC/S2050508617000014a.pdf/a-formal-proof-of-the-kepler-conjecture.pdf). In *Forum of mathematics, Pi* (Vol. 5). Cambridge University Press.

Hand, E., 2008, [Perchlorate found on Mars](https://www.nature.com/news/2008/080806/full/news.2008.1016.html), Nature

Hand, K.P., Murray, A.E., Garvin, J.B., Brinckerhoff, W.B., Christner, B.C., Edgett, K.S., Ehlmann, B.L., German, C.R., Hayes, A.G., Hoehler, T.M., Horst, S.M., Lunine, J.I., Nealson, K.H., Paranicas, C., Schmidt, B.E., Smith, D.E., Rhoden, A.R., Russell, A.R., Russell, M.J., Templeton, A.S., Willis, P.A., Yingst, R.A., Phillips, C.B., Cable, M.L., Craft, K.L., Hofmann, A.E., Northeim, T.A., Pappalardo, R.P., and the Project Engineering Team, 2017: [Report of the Europa Lander Science Definition Team](https://solarsystem.nasa.gov/docs/Europa_Lander_SDT_Report_2016.pdf).

Hansen, J.R., 2012. [First Man: The Life of Neil A. Armstrong](https://books.google.co.uk/books?id=rMS6JFuLgx4C). Simon and Schuster.

Hartmann, W.K. 2004, [Isochrons for Martian Crater Populations of Various Ages](https://www.psi.edu/epo/isochrons/chron04a.html), [Page 2](https://www.psi.edu/epo/isochrons/chron04b.html)

Hartmann, W.K. and Daubar, I.J., 2017. Martian cratering 11. [Utilizing decameter scale crater populations to study Martian history.](https://onlinelibrary.wiley.com/doi/full/10.1111/maps.12807) *Meteoritics & Planetary Science*, *52*(3), pp.493-510.

Hassler, D.M., Zeitlin, C., Wimmer-Schweingruber, R.F., Ehresmann, B., Rafkin, S., Eigenbrode, J.L., Brinza, D.E., Weigle, G., Böttcher, S., Böhm, E. and Burmeister, S., 2014. [Mars’ surface radiation environment measured with the Mars Science Laboratory’s Curiosity rover](https://authors.library.caltech.edu/42648/1/RAD_Surface_Results_paper_SCIENCE_12nov13_FINAL.pdf). *science*, *343*(6169).

Hays, L.E., Graham, H.V., Des Marais, D.J., Hausrath, E.M., Horgan, B., McCollom, T.M., Parenteau, M.N., Potter-McIntyre, S.L., Williams, A.J. and Lynch, K.L., 2017. [Biosignature preservation and detection in Mars analog environments](https://www.liebertpub.com/doi/full/10.1089/ast.2016.1627). Astrobiology, 17(4), pp.363-400.

*Improved instrumentation on rovers that might detect and identify a diversity of potential in situ biosignatures, including ancient organic molecular biosignatures, designed with the ability to differentiate biotic and abiotic signals in micro- or macrostructures. Instrumentation could also be better attuned to the unique complications of biosignature preservation on Mars (e.g., deeper drilling to access potentially better preserved organics)*

*The fluorescence spectrometers on SHERLOC can detect condensed carbon and aromatic organics by deep UV-induced fluorescence, and SHERLOC's Raman spectrometer will allow classification of aromatic and aliphatic organics. Raman spectrometry can also be used to detect minerals relevant to aqueous chemistry. While these measurements would allow us to identify reduced carbon compounds, there may not be sufficient structural information to distinguish between a biological signal and extraterrestrial organic input.*

*A major knowledge gap that will directly impact our ability to choose an appropriate landing site is what terrestrial analog environments might look like—what the biosignature signals might be—if photosynthetic microorganisms had not evolved and instead the environments were only inhabited by chemosynthetic microorganisms*

*4.4. Strategies and priorities*

*In many of the environments discussed, there is a dichotomy between habitability and preservation—many of the conditions that make an environment more habitable are destructive to one or more of the biosignatures of interest. For example, fluid flow in the subsurface of hydrothermal environments helps create the redox gradients that support communities that inhabit the outflow channel. Fluids are also essential for lithification and the associated decrease in permeability essential for long-term preservation. Preservation is enhanced by rapid burial and mineral precipitation that encases and lithifies biological materials in less permeable matrices—in these cases, silica from hydrothermal environments, or silica-enriched aqueous environments, is an important material for preservation. However, these same fluids can degrade biosignatures such as mineralogy, chemistry, and micro- and macrostructures. One strategy for astrobiological exploration has to be to seek out a “sweet spot” where these two balance each other so that long-term preservation is possible. This sweet spot may occur as conditions change through time.*

Hayward, A.C., Fragaszy, E.B., Bermingham, A., Wang, L., Copas, A., Edmunds, W.J., Ferguson, N., Goonetilleke, N., Harvey, G., Kovar, J. and Lim, M.S., 2014. [Comparative community burden and severity of seasonal and pandemic influenza: results of the Flu Watch cohort study](https://www.thelancet.com/journals/lanres/article/PIIS2213-2600(14)70034-7/fulltext). The Lancet Respiratory Medicine, 2(6), pp.445-454. Popular account: NHS, 2014, [Three-quarters of people with flu have no symptoms](https://www.nhs.uk/news/medical-practice/three-quarters-of-people-with-flu-have-no-symptoms/)

Head, J.N., Melosh, H.J. and Ivanov, B.A., 2002. [Martian meteorite launch: High-speed ejecta from small craters](https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1945-5100.2002.tb01033.x). *Science*, *298*(5599), pp.1752-1756.

*Page 1355: Nishiizumi et al. (1986) found that all cosmogenic nuclide data indicate that the shergottites were ejected from>3 m depth. This conclusion was supported by Reedy (1989) stating that the Shergottite-Nakhdite-Chassignite group meteorites (SNCs), especially the shergottites, must have been buried >5 m in any previous parent object (corresponding to a shielding depth of >I500 glcm²)*

Heinz, J., Krahn, T. and Schulze-Makuch, D., 2020. [A new record for microbial perchlorate tolerance: fungal growth in NaClO4 brines and its implications for putative life on Mars](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7281446/). Life, 10(5), p.53.

Heinz, J., Schulze‐Makuch, D. and Kounaves, S.P., 2016. [Deliquescence-induced wetting and RSL-like darkening of a Mars analogue soil containing various perchlorate and chloride salts](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016GL068919%20and%20resistant%20to%20the%20stress%20of%20saltation.). Geophysical research letters, 43(10), pp.4880-4884.

Heinz, P., Geslin\*, E. and Hemleben, C., 2005. [Laboratory observations of benthic foraminiferal cysts](https://www.researchgate.net/profile/Emmanuelle_Geslin/publication/235927029_Laboratory_observations_of_benthic_foraminiferal_cysts/links/55cb13f208aeca747d6a0083/Laboratory-observations-of-benthic-foraminiferal-cysts.pdf). *Marine Biology Research*, *1*(2), pp.149-159.

Hiesinger, H. and Head III, J.W., 2006. [New views of lunar geoscience: An introduction and overview](https://pdfs.semanticscholar.org/8b8e/b3ccdbd3c373c6f2678088b90be27b34ade7.pdf). *Reviews in mineralogy and geochemistry*, *60*(1), pp.1-81.

Hendrickson, R., Urbaniak, C., Minich, J.J., Aronson, H.S., Martino, C., Stepanauskas, R., Knight, R. and Venkateswaran, K., 2021. [Clean room microbiome complexity impacts planetary protection bioburden](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8643001/). *Microbiome*, *9*(1), pp.1-17.

Hendrix, A.R. and Yung, Y.L., 2017. [Energy Options for Future Humans on Tita](https://arxiv.org/ftp/arxiv/papers/1707/1707.00365.pdf)n. *arXiv preprint arXiv:1707.00365*.

Heninger, S.J., Anderson, C.A., Beltz, G. and Onderdonk, A.B., 2009. [Decontamination of Bacillus anthracis spores: Evaluation of various disinfectants](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2957119/). Applied Biosafety, 14(1), pp.7-10.

*The present study compares the efficacy of various disinfectants against Bacillus anthracis spores. While Bleach Rite® and 10% bleach reduce spore numbers by 90% within 10 minutes, a long contact time is required for complete disinfection.*

*As shown in Table 2, when a sample containing 100,000 spores was analyzed, either Bleach Rite® or 10% bleach was able to dramatically reduce (<0.0001% remaining) the number of viable spores at the earliest time point, and no viable spores were detected after 20 minutes of treatment. Complete sterilization was not attained until 20 minutes post-inoculation due to 1 cfu being present at 10 minutes in the 10% bleach-treated groups.*

Heppenheimer, T.A., 1977. [Colonies in Space](https://space.nss.org/colonies-in-space-chapter-2-our-life-in-space/).

Hirakata, Y., Hatamoto, M., Oshiki, M., Watari, T., Araki, N. and Yamaguchi, T., 2020. [Food selectivity of anaerobic protists and direct evidence for methane production using carbon from prey bacteria by endosymbiotic methanogen](https://www.nature.com/articles/s41396-020-0660-0#:~:text=Anaerobic%20protists%20are%20major%20predators%20of%20prokaryotes%20that%20affect%20the,4%2C5%2C6%5D.). The ISME Journal, 14(7), pp.1873-1885.

Hoff, B., Thomson, G. and Graham, K., 2007. [Ontario: Neurotoxic cyanobacterium (blue-green alga) toxicosis in Ontario](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1780230/). *The Canadian Veterinary Journal*, *48*(2), p.147.

Hoffman, N. and Kyle, P.R., 2003, July. [The ice towers of Mt. Erebus as analogues of biological refuges on Mars](https://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3105.pdf). In Sixth International Conference on Mars (p. 3105).

Hogle, J.M., 2002. [Poliovirus cell entry: common structural themes in viral cell entry pathways](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1500891/). Annual Reviews in Microbiology, 56(1), pp.677-702.

Holson, D.A.. 2015, [Ackee Fruit Toxicity](https://emedicine.medscape.com/article/1008792-overview), Medscape - Emergency medicine

Horne, W.H., Volpe, R.P., Korza, G., DePratti, S., Conze, I.H., Shuryak, I., Grebenc, T., Matrosova, V.Y., Gaidamakova, E.K., Tkavc, R. and Sharma, A., 2022. [Effects of Desiccation and Freezing on Microbial Ionizing Radiation Survivability: Considerations for Mars Sample Return.](https://www.liebertpub.com/doi/pdf/10.1089/AST.2022.0065?fbclid=IwAR3b2cGbAu_2Wu9bFHYTfUblARsZRIkFExalSwY5gSMDa2ubEGei7uNPobc) *Astrobiology*.

Hopkins, J.B. and Pratt, W.D., 2011, September. [Comparison of Deimos and Phobos as destinations for human exploration, and identification of preferred landing sites](http://csc.caltech.edu/references/Hopkins-Phobos-Deimos-Paper.pdf). In *AIAA Space 2011 Conference & Exposition, Long Beach* (pp. 27-29).

Horgan, B.H., Anderson, R.B., Dromart, G., Amador, E.S. and Rice, M.S., 2020. [The mineral diversity of Jezero crater: Evidence for possible lacustrine carbonates on Mars](https://www.sciencedirect.com/science/article/pii/S0019103518306067). Icarus, 339, p.113526.

Horvath, D.G., Moitra, P., Hamilton, C.W., Craddock, R.A. and Andrews-Hanna, J.C., 2020. [Evidence for geologically recent explosive volcanism in Elysium Planitia](https://arxiv.org/ftp/arxiv/papers/2011/2011.05956.pdf.), Mars. arXiv preprint arXiv:2011.05956

Hoshika, S., Leal, N.A., Kim, M.J., Kim, M.S., Karalkar, N.B., Kim, H.J., Bates, A.M., Watkins, N.E., SantaLucia, H.A., Meyer, A.J. and DasGupta, S., 2019. [Hachimoji DNA and RNA: A genetic system with eight building blocks](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6413494/). Science, 363(6429), pp.884-887

Hospodsky D, Yamamoto N, Nazaroff W, Miller D, Gorthala S, Peccia J. [Characterizing airborne fungal and bacterial concentrations and emission rates in six occupied children’s classrooms](https://onlinelibrary.wiley.com/doi/abs/10.1111/ina.12172). Indoor air. 2015;25(6):641–52.

Houtkooper, J.M. and Schulze-Makuch, D., 2006. [A possible biogenic origin for hydrogen peroxide on Mars: the Viking results reinterpreted](https://arxiv.org/ftp/physics/papers/0610/0610093.pdf). *arXiv preprint physics/0610093*.

Hsu, H.W. and Horányi, M., 2012. [Ballistic motion of dust particles in the Lunar Roving Vehicle dust trails](https://www.researchgate.net/profile/Mihaly-Horanyi/publication/258468670_Tracking_Lunar_Dust_-_Analysis_of_Apollo_Footage/links/54a02cb30cf257a6360215d3/Tracking-Lunar-Dust-Analysis-of-Apollo-Footage.pdf). American Journal of Physics, 80(5), pp.452-456.

Hsu, J., 2009, [Keeping Mars Contained](https://web.archive.org/web/20200516104239/http:/www.astrobio.net/news-exclusive/keeping-mars-contained/), NASA Astrobiology Magazine.

Hu, R., Kass, D.M., Ehlmann, B.L. and Yung, Y.L., 2015. [Tracing the fate of carbon and the atmospheric evolution of Mars](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4673500/). *Nature communications*, *6*, p.10003.

Hubble, 2003, [Photograph of Mars taken by the Hubble Space Telescope during opposition in 2003](https://commons.wikimedia.org/wiki/File:Mars_23_aug_2003_hubble.jpg).

Huber, H., Hohn, M.J., Rachel, R., Fuchs, T., Wimmer, V.C. and Stetter, K.O., 2002. A new phylum of Archaea represented by a nanosized hyperthermophilic symbiont. *Nature*, *417*(6884), pp.63-67

Huesing, J., Sutherland, O., Geelen, K., Vijendran, S., Alves, J., Edwards Jr, C.D., Muirhead, B.K., Lock, R.E., Nicholas, A.K., Umland, J.W. and Nairouz, B., 2019. [Engineering the Earth Return Orbiter Concept for a potential Mars Sample Return Campaign](https://www.hou.usra.edu/meetings/ninthmars2019/pdf/6347.pdf). *LPICo*, *2089*, p.6347.

Hurowitz, J.A., Grotzinger, J.P., Fischer, W.W., McLennan, S.M., Milliken, R.E., Stein, N., Vasavada, A.R., Blake, D.F., Dehouck, E., Eigenbrode, J.L. and Fairen, A.G., 2017. [Redox stratification of an ancient lake in Gale crater](https://repository.si.edu/bitstream/handle/10088/32598/201741CE.pdf), Mars. *Science*, *356*(6341).

Hutzler, A., Kilic, E., Langevin, P., Ellis, J.S., Bennett, A. and Ferrière, L., 2017, July. [EURO-CARES Extraterrestrial Sample Curation Facility: Architecture as an enabler of science](https://ttu-ir.tdl.org/bitstream/handle/2346/73091/ICES_2017_323.pdf). 47th International Conference on Environmental Systems. [EURO-CARES](http://www.euro-cares.eu/)

Ikumapayi, U.N., Kanteh, A., Manneh, J., Lamin, M. and Mackenzie, G.A., 2016. [An outbreak of Serratia liquefaciens at a rural health center in The Gambia](https://scholar.google.com/scholar?cluster=4770786288665771581&hl=en&as_sdt=0,5). The Journal of Infection in Developing Countries, 10(08), pp.791-798.

## I

Ireland, N., 1967. [Treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies.](https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html)

IVHN (International Volcanic Hazard Network), n.d. [Carbon Dioxide (CO₂ )](https://www.ivhhn.org/information/information-different-volcanic-gases/carbon-dioxide)

## J

Jacob, D.J., 1999. [Introduction to atmospheric chemistry](https://acmg.seas.harvard.edu/education/introduction-atmospheric-chemistry) (12th edition updated 2021)

Jacob, D.E., Wirth, R., Agbaje, O.B.A., Branson, O. and Eggins, S.M., 2017. [Planktic foraminifera form their shells via metastable carbonate phases](https://www.nature.com/articles/s41467-017-00955-0#ref-CR2). *Nature communications*, *8*(1), pp.1-9.

Planktic foraminifera are among the most important calcifying organisms in the open ocean, contributing as much as half the particulate CaCO3 exported from the surface ocean annually (ca. 2.9 Gt CaCO3 yr−1)

Jakosky, B., Amato, M., Atreya, S., Des Marais, D., Mahaffy, P., Mumma, M., Tolbert, M., Toon, B., Webster, C. and Zurek, R., 2021. [Scientific value of returning an atmospheric sample from Mars](https://assets.pubpub.org/fljl7iiz/51617915355905.pdf). Bulletin of the AAS, 53(4).

In the implementation involving gas compression, existing technology could be utilized. For example, MOXIE on Mars 2020 uses an Air Squared compressor (2.3 kg, 100 W) designed for large gas amount, flow rates; a miniature scroll pump by Creare (350 g, 5W) developed for Mars under SBIR. The compressor could be mounted on the lander and not be a part of sample-canister mass that is returned to Earth; for example, it could utilize a solenoid release/separation mechanism, with Schrader-like input valve in series with microvalve seal. Airborne dust also could be collected with addition of 3 valves and a dust filter (Figure 6). After gas reservoir is filled and reservoir valves closed, large volumes of Mars air would be pumped through filter to collect and trap dust and its valves closed.

With consideration of upcoming Mars-targeted missions, we conclude that gas collected in a newly designed and purpose-built valved sample-tube sized vessel, which could be flown on either SFR or SRL, would be considered of higher priority than either the head space gas or a sealed M2020 sample tube. Conceptually, this vessel would require no more physical space to return than a sealed empty sample tube and alleviate concerns about the manufacturing and history of a non-purpose-built vessel, and the valving would provide a more robust mechanism for sealing the vessel and testing the seal upon return.

Jantzen, S., Decarreaux, T., Stein, M., Kniel, K. and Dietzel, A., 2018. [CO2 snow cleaning of miniaturized parts](https://www.sciencedirect.com/science/article/abs/pii/S014163591730507X). *Precision Engineering*, *52*, pp.122-129.

Javaux, E.J., 2019. [Challenges in evidencing the earliest traces of life](https://www.nature.com/articles/s41586-019-1436-4). *Nature*, *572*(7770), pp.451-460.

Jheeta, S., 2013. [Horizontal gene transfer and its part in the reorganisation of genetics during the LUCA epoch](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4187132/) .[Life (Basel)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4187132/), 3(4): 518–523.

*“What are the mechanisms by which HGT occurs? Currently these include: transduction, a process whereby a viral capsule is used to transfer genetic material from one cell to another; conjugation, a process exhibited by microbes during which a plasmid or a small piece of a plasmid from one donor cell is transferred to another recipient cell (Prof. Matxalen Llosa—see summary report); transformation, which occurs when a competent cell takes up a “naked” strands of nucleic acid from the environment—such strands of nucleic acids may not necessarily have been exuded by living entities (e.g., mitochondrion genes transferred to eukaryote chromosomes), they could also be from recently dead cells, as well as from long extinct organisms; gene transfer agents (GTA), which are bacteriophage-like particles containing random cellular genomic segments intended for transduction to another living recipient cell; and membrane vesicle transfer (MVT), in which small membrane sacs emanating from the surface of a cell contain genetic material for transfer to another living recipient cell.”*

Jiang, X., Musyanovych, A., Röcker, C., Landfester, K., Mailänder, V. and Nienhaus, G.U., 2011. [Specific effects of surface carboxyl groups on anionic polystyrene particles in their interactions with mesenchymal stem cells](https://pubs.rsc.org/--/content/articlelanding/2011/nr/c0nr00944j/unauth#!divAbstract). *Nanoscale*, *3*(5), pp.2028-2035.

Johnson, J.R., Grundy, W.M. and Lemmon, M.T., 2003. [Dust deposition at the Mars Pathfinder landing site: Observations and modeling of visible/near-infrared spectra](https://www.sciencedirect.com/science/article/abs/pii/S0019103503000848). Icarus, 163(2), pp.330-346.

*Two-layer models were run assuming both linear and nonlinear dust accumulation rates, and suggest that RCT dust optical depth at the end of the 83-sol mission was 0.08 to 0.16, or on the order of 5- to 10-μm thickness for plausible values for dust porosity and grain size. These values correspond to dust fall rates of about 20–45 μm per Earth year, consistent with previous studies of dust deposition on Mars*

Johnson, R.D. and Holbrow, C.H. eds., 1977. [*Space settlements: A design study*](https://settlement.arc.nasa.gov/75SummerStudy/Table_of_Contents1.html) (Vol. 413). Scientific and Technical Information Office, National Aeronautics and Space Administration.

*"At all distances out to the orbit of Pluto and beyond, it is possible to obtain Earth-normal solar intensity with a concentrating mirror whose mass is small compared to that of the habitat.”*

[*chapter 7*](https://settlement.arc.nasa.gov/75SummerStudy/Chapt7.html)

Johnson, S.S., Mischna, M.A., Grove, T.L. and Zuber, M.T., 2008. [Sulfur‐induced greenhouse warming on early Mars](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007JE002962). *Journal of Geophysical Research: Planets*, *113*(E8).

Jones, A., 2021, [China is planning a complex Mars sample return mission](https://spacenews.com/china-is-planning-a-complex-mars-sample-return-mission/), SpaceNews

Jones, J., Hall, J. and Wu, J.J., 2004. [*Inflatable Emergency Atmospheric-Entry Vehicles*](https://ntrs.nasa.gov/api/citations/20110020421/downloads/20110020421.pdf) (No. NPO-40156). See also [press release](https://www.techbriefs.com/component/content/article/tb/pub/briefs/mechanics-and-machinery/1823)

Joyce, G.F., 2007. [A glimpse of biology's first enzyme](https://science.sciencemag.org/content/315/5818/1507.full). Science, 315(5818), pp.1507-1508.

Joyce, G.F. and Szostak, J.W., 2018. [Protocells and RNA self-replication](https://molbio.mgh.harvard.edu/szostakweb/publications/Szostak_pdfs/Szostak_Joyce_CSHL_PerspectBiol_2018.pdf.pdf). *Cold Spring Harbor Perspectives in Biology*, *10*(9), p.a034801.

JPL, 2003 [Stardust, NASA’s comet sample return mission - comets and the question of life](https://stardust.jpl.nasa.gov/science/life.html) available at: <https://stardust.jpl.nasa.gov/science/life.html> (Accessed 2 July 2020)

JPL, 2014, [How NASA Curiosity Instrument Made First Detection of Organic Matter on Mars](https://www.jpl.nasa.gov/news/how-nasa-curiosity-instrument-made-first-detection-of-organic-matter-on-mars)

JPL, 2016, [NASA Weighs Use of Rover to Image Potential Mars Water Sites](https://www.jpl.nasa.gov/news/news.php?feature=6542), available at: <https://www.jpl.nasa.gov/news/news.php?feature=6542>, accessed on: July 18, 2020

JPL, 2017ncr NASA's [Curiosity Rover Sharpens Paradox of Ancient Mars](https://www.jpl.nasa.gov/news/nasas-curiosity-rover-sharpens-paradox-of-ancient-mars)

JPL, 2021, [My Favorite Martian Image: Helicopter Scouts Ridge Area for Perseverance](https://www.jpl.nasa.gov/news/my-favorite-martian-image-helicopter-scouts-ridge-area-for-perseverance)

JPL, 2021s, [SHERLOC’S view of Organics Within Garde Abrasion Patch](https://www.jpl.nasa.gov/images/pia25042-sherlocs-view-of-organics-within-garde-abrasion-patch)

Jull, A.J.T., Eastoe, C.J., Xue, S. and Herzog, G.F., 1995. [Isotopic composition of carbonates in the SNC meteorites Allan Hills 84001 and Nakhla. Meteoritics](https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1029/96JE03111), 30(3), pp.311-318.

Jung, P., Baumann, K., Lehnert, L.W., Samolov, E., Achilles, S., Schermer, M., Wraase, L.M., Eckhardt, K.U., Bader, M.Y., Leinweber, P. and Karsten, U., 2020. [Desert breath—How fog promotes a novel type of soil biocenosis, forming the coastal Atacama Desert’s living skin](https://onlinelibrary.wiley.com/doi/full/10.1111/gbi.12368). Geobiology, 18(1), pp.113-124.

## K

Kahn, R., 1985. [The evolution of CO₂ on Mars](https://www.sciencedirect.com/science/article/pii/0019103585901162). *Icarus*, *62*(2), pp.175-190.

Kakoi, M., Howell, K.C. and Folta, D., 2014. [Access to Mars from Earth–Moon libration point orbits: manifold and direct options](https://ntrs.nasa.gov/api/citations/20150000152/downloads/20150000152.pdf). *Acta Astronautica*, *102*, pp.269-286.

Kalil, 2014, [Bootstrapping a Solar System Civilization](https://obamawhitehouse.archives.gov/blog/2014/10/14/bootstrapping-solar-system-civilization), White House

Kapoor, G., Saigal, S. and Elongavan, A., 2017. [Action and resistance mechanisms of antibiotics: A guide for clinicians](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5672523/). *Journal of anaesthesiology, clinical pharmacology*, *33*(3), p.300

Karman, T., Miliordos, E., Hunt, K.L., Groenenboom, G.C. and van der Avoird, A., 2015. [Quantum mechanical calculation of the collision-induced absorption spectra of N2–N2 with anisotropic interactions](https://repository.ubn.ru.nl/bitstream/handle/2066/144982/144982.pdf?sequence=1). *The Journal of Chemical Physics*, *142*(8), p.084306.

KEGG, n.d., [Metabolic pathways - Chroococcidiopsis thermalis](https://www.genome.jp/kegg-bin/show_pathway?cthe01100+Chro_2988), Kyoto Encyclopedia of Genes and Genomes

Kelly, K.E. and Cardon, N.C., 1991. [The Myth of 10-6 as a Definition of Acceptable Risk: Or," in Hot Pursuit of Superfund's Holy Grail".](https://www.heartland.org/publications-resources/publications/the-myth-of-10-6-as-a-definition-of-acceptable-risk) Environmental Toxicology International, Incorporated.

Kerwick, T.B., 2012. [Colonizing Jupiter's Moons: An Assessment of Our Options and Alternatives](http://www.environmental-safety.webs.com/Galileo_WaS_Journal.pdf). *Journal of the Washington Academy of Sciences*, pp.15-26.

Kiang, 2007, [The Color of Life, on Earth and on Extrasolar Planets](https://web.archive.org/web/20160118212625/https://www.giss.nasa.gov/research/briefs/kiang_01/), NASA science briefs

https://web.archive.org/web/20160118212625/https://www.giss.nasa.gov/research/briefs/kiang\_01/

*Its distinct impacts on the spectral signature of our planet are, most significantly, oxygen in the atmosphere and the surface reflectance spectrum of land plants. The latter is notable not only for a "green bump" but also a "red edge", the steep contrast between absorbance by chlorophyll in the red and high reflectance of plant leaves in the near-infrared (NIR). However, purple bacteria perform photosynthesis with NIR radiation and produce no oxygen, and lichens do not have a strong red edge. Scientists still puzzle over why plants are green, because it seems this wastes the light where our Sun produces the most energy.*

Kim, H.J., Kim, H.N., Raza, H.S., Park, H.B. and Cho, S.O., 2016. [An intraoral miniature X-ray tube based on carbon nanotubes for dental radiography.](https://www.sciencedirect.com/science/article/pii/S1738573316000437) *Nuclear Engineering and Technology*, *48*(3), pp.799-804.*,*

*The tube voltage is 50 kV and the electron beam current is 200 μA in the calculation.*

Kim, J.P., Kim, J.H., Kim, J., Lee, S.N. and Park, H.O., 2016. [A nanofilter composed of carbon nanotube-silver composites for virus removal and antibacterial activity improvement.](https://www.sciencedirect.com/science/article/abs/pii/S1001074215004180) Journal of Environmental Sciences, 42, pp.275-283.

Kinch, K.M., Bell III, J.F., Goetz, W., Johnson, J.R., Joseph, J., Madsen, M.B. and Sohl‐Dickstein, J., 2015. [Dust deposition on the decks of the Mars Exploration Rovers: 10 years of dust dynamics on the Panoramic Camera calibration targets](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014EA000073). Earth and Space Science, 2(5), pp.144-172.

*At the Spirit landing site, half the year is dominated by dust deposition, the other half by dust removal, usually in brief, sharp events. At the Opportunity landing site the Martian year has a semiannual dust cycle with dust removal happening gradually throughout two removal seasons each year.*

*On Spirit there is a yearly pattern with steady dust deposition throughout roughly the colder half year from late southern summer to late southern winter, which encompasses the Martian aphelion, and overall dust removal during the warmer and windier perihelion season from late southern winter to late southern summer.*

*On Opportunity ... the overall variation between highs and lows is smaller, and there are two periods of overall dust deposition and two periods of overall dust removal every year. The deposited dust thickness peaks once in the middle of the northern hemisphere spring. This peak recurs very regularly 6 times. ... There is also a peak roughly in the middle of the southern spring. This peak is clear in the first year, but the pattern becomes more irregular later in the mission and is entirely absent in the last year.*

King, H., n.d., [Mohs Hardness Scale](https://geology.com/minerals/mohs-hardness-scale.shtml), Geology.com

Kirschvink, J.L., Weiss, B.P. and Beukes, N.J., 2006. Boron, ribose, and a Martian origin for terrestrial life. GeCAS, 70(18), pp.A320-A320

Kirschvink, J., 2013, [Boron, Ribose, and a Martian Origin for Terrestrial Life](https://video.ias.edu/dreams-kirschvink) - Institute for Advanced Study Video Lectures

Kirst, H., Formighieri, C. and Melis, A., 2014. [Maximizing photosynthetic efficiency and culture productivity in cyanobacteria upon minimizing the phycobilisome light-harvesting antenna size](https://www.sciencedirect.com/science/article/pii/S0005272814005362). *Biochimica et Biophysica Acta (BBA)-Bioenergetics*, *1837*(10), pp.1653-1664.

Kite, E.S., Mischna, M.A., Daswani, M.M. 2014, [Quantifying the effect of Mars obliquity on the intermittency of post-Noachian surface liquid water](http://geosci.uchicago.edu/~kite/doc/HW_2014_Quantifying_the_Intermittency_of_Mars_Surface_Habitability_BUDGET_DETAILS_REMOVED.pdf), proposal for submission to ROSES – Habitable Worlds 2014

Kite, E.S. and Mayer, D.P., 2017. [Mars sedimentary rock erosion rates constrained using crater counts, with applications to organic-matter preservation and to the global dust cycle.](https://arxiv.org/ftp/arxiv/papers/1610/1610.02748.pdf) *Icarus*, *286*, pp.212-222.

Kite, E.S., Gaidos, E. and Onstott, T.C., 2018. [Valuing life detection missions](https://arxiv.org/ftp/arxiv/papers/1802/1802.09006.pdf). *arXiv preprint arXiv:1802.09006*.

Klang, J. and Barron, T., 2017. [Space Law Then, Now, and in the Future: A Conversation with Pamela Meredith and Laura Montgomery](https://www.kmazuckert.com/publications/space/ABA_AirSpaceLawyer_v030n04_Meredith_Montgomery.pdf). *The Air and Space Lawyer*, *30*(4), pp.1-18.

**LM:** Pamela and I disagree on this, but there’s a provision in the Outer Space Treaty, Article VI, which says that each country must supervise and authorize the activities of its nongovernmental entities. This is not a self-executing provision, and the U.S. Supreme Court has held that a non-self-executing treaty is not domestically enforceable. ...

**PM:** I disagree with Laura on this. Article VI of the Outer Space Treaty provides that all state parties to the treaty are responsible for their activities in outer space, whether they’re carried out by government agencies or private companies. Countries are required to subject private companies within their jurisdiction that engage in space activities to an authorization requirement and continuing supervision. So, the United States is responsible for compliance with the Outer Space Treaty by our private companies or entities that go into space.

Klusman, R.W., Luo, Y., Chen, P., Yung, Y.L. and Tallapragada, S., 2022. [Seasonality in Mars atmospheric methane driven by microseepage, barometric pumping, and adsorption](https://www.sciencedirect.com/science/article/pii/S0019103522001889" \l "bb0345). Icarus, p.115079.

Kleidon, A., 2002. [Testing the effect of life on Earth's functioning: how Gaian is the Earth system?](https://link.springer.com/content/pdf/10.1023/A:1014213811518.pdf). *Climatic Change*, *52*(4), pp.383-389.

Klein, A., 2017, interview with Christ Hadfield, ["We should live on the moon before a trip to Mars"](https://www.newscientist.com/article/2144864-chris-hadfield-we-should-live-on-the-moon-before-a-trip-to-mars/)*,* New Scientist

Klingler, J.M., Mancinelli, R.L. and White, M.R., 1989. [Biological nitrogen fixation under primordial Martian partial pressures of dinitrogen](http://www.ncbi.nlm.nih.gov/pubmed/11537369). *Advances in Space Research*, *9*(6), pp.173-176.

Klussmann, M., Iwamura, H., Mathew, S.P., Wells, D.H., Pandya, U., Armstrong, A. and Blackmond, D.G., 2006. [Thermodynamic control of asymmetric amplification in amino acid catalysis](https://www.nature.com/articles/nature04780). *Nature, 441(7093),* pp.621-623*.*

Kminek, G. and Bada, J.L., 2006. [The effect of ionizing radiation on the preservation of amino acids on Mars](https://www.researchgate.net/profile/Jeffrey_Bada/publication/222819214_The_effect_of_ionizing_radiation_on_the_preservation_of_amino_acids_on_Mars/links/5c1c0f61299bf12be38eedf5/The-effect-of-ionizing-radiation-on-the-preservation-of-amino-acids-on-Mars.pdf). *Earth and Planetary Science Letters*, *245*(1-2), pp.1-5.

* Kminek et al’s paper uses more than double the radiation levels now known from Curiosity, 200 mGy instead of 76 mGy for surface radiation but the reasoning is the same

Kminek, G., Fellous, J.L., Rettburg, P., Moissl-Eichinger, C., Sephton, M.A., Royle, S.H., Spry, A., Yano, H., Chujo, T., Margheritis, D.B. and Brucato, J.R., 2019. [The international planetary protection handbook](https://spiral.imperial.ac.uk/bitstream/10044/1/75039/4/1-s2.0-S1752929819300647-main%20%281%29.pdf). See: section "Case Study Planetary Protection Category V Unrestricted Earth Return: Hayabusa-1&2"

Knoll, A, 2013, interviewed by Adams, C. [One Man on Mars: An interview with Dr. Andrew Knoll](http://sitn.hms.harvard.edu/flash/2013/space-knoll/)

Kok, J.F., 2010. [Difference in the wind speeds required for initiation versus continuation of sand transport on Mars: Implications for dunes and dust storms.](https://arxiv.org/ftp/arxiv/papers/1002/1002.1346.pdf) Physical Review Letters, 104(7), p.074502.

Koonin, E.V., 2014. [Carl Woese's vision of cellular evolution and the domains of life](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4008548/). *RNA biology*, *11*(3), pp.197-204.

Korr, M., 2020. [Mary Mallon: First Asymptomatic Carrier of Typhoid Fever](https://search.proquest.com/openview/b536a8e243370d01edfceccee5aab225/1?pq-origsite=gscholar&cbl=24126). Rhode Island Medical Journal, 103(4), pp.73-73.

Krisko, A. and Radman, M., 2013. [Biology of extreme radiation resistance: the way of Deinococcus radiodurans](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3685888/). Cold Spring Harbor perspectives in biology, 5(7), p.a012765.

*The desiccated bacteria are constituents of the dust occasionally blown up by the winds into the atmosphere and stratosphere. where bacteria from different geographic origins mix while being exposed to UVC light 100 to 1000 times more intense than on Earth’s surface. They eventually rehydrate when falling back on Earth with the rain and snow (this is how Francois-Xavier Pellay in our laboratory collects robust bacteria) and—depending on their genomic constitution—develop, or not, in the ecological niches into which they happen to fall. Indeed, the most efficient cellulose degraders are deinococci found growing in the waist of the wood-sawing industry (Deinove, pers. comm.).*

*The resistance of D. radiodurans is not exclusive to radiation and desiccation but extends also to many toxic chemicals and conditions. Therefore, Dra is called a polyextremophile, a robust “generalist,” to be distinguished from specialized extremophiles with an evolutionary redesign of their proteome (e.g., proteins purified from thermophiles are thermostable in vitro). Unlike specialized extremophiles, Dra does not thrive on extreme conditions—indeed, it does not grow while desiccated or when heavily* irradiated—but it can reproduce under standard growth conditions after recovering from damage inflicted by chronic moderate, or acute intense, exposures to cytotoxic conditions.

Kuhlman, K.R., Venkat, P., La Duc, M.T., Kuhlman, G.M. and McKay, C.P., 2008. [Evidence of a microbial community associated with rock varnish at Yungay, Atacama Desert](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2007JG000677), Chile. *Journal of Geophysical Research: Biogeosciences*, *113*(G4).

Kumar, V., van de Veerdonk, F.L. and Netea, M.G., 2018. Antifungal immune responses: emerging host–pathogen interactions and translational implications. Genome medicine, 10(1), pp.1-3.

Kumondorova, A. and Serkan, İ.K.İ.Z., 2019. [Archaea and their potential pathogenicity in human and animal diseases](https://dergipark.org.tr/en/download/article-file/899423). Journal of Istanbul Veterinary Sciences, 3(3), pp.79-84.

Kumpitsch, C., Koskinen, K., Schöpf, V. and Moissl-Eichinger, C., 2019. The microbiome of the upper respiratory tract in health and disease. *BMC biology*, *17*(1), p.87.

Kun, Á., 2021. [Maintenance of Genetic Information in the First Ribocell](http://real.mtak.hu/139999/1/RibozymeBook-AdamKun-05.pdf). Ribozymes, 1, pp.387-417.

Kwong, J., Norris, S.D., Hopkins, J.B., Buxton, C.J., Pratt, W.D. and Jones, M.R., 2011, September. [Stepping stones: exploring a series of increasingly challenging destinations on the way to mars](https://arc.aiaa.org/doi/abs/10.2514/6.2011-7216). In *AIAA Space 2011 Conference, Long Beach, CA* (pp. 27-29).

## L

Laborator Ecole Polytechnique Fédérale de Lausanne, 2014, [Traces of Martian biological activity could be locked inside a meteorite](https://www.eurekalert.org/news-releases/889851), Eureka alert

Lachance, J.C., Rodrigue, S. and Palsson, B.O., 2019. [Synthetic biology: minimal cells, maximal knowledge](https://elifesciences.org/articles/45379). *Elife*, *8*, p.e45379.

Laguna, J., 2021, [How reliable wireless communication is driving autonomous mining](https://www.ivtinternational.com/features/how-reliable-wireless-communication-is-driving-autonomous-mining.html), International Vehicle Technology

Lakdawalla, E, 2014, [Curiosity update, sols 645-661: Driving, driving, driving](https://www.planetary.org/blogs/emily-lakdawalla/2014/06161423-curiosity-update-sols-645-661.html), Planetary Society

Lane, N., 2015. *The vital question: energy, evolution, and the origins of complex life*. WW Norton & Company, [page 49](https://books.google.co.uk/books?id=IfJYBQAAQBAJ&pg=PT49).

*"Microbes are not equivalent to large animals: their population sizes are enormously larger, and they pass around useful genes (such as those for antibiotic resistance) by lateral transfer, making them very much less vulnerable to extinction. There is no hint of any microbial extinction even in the aftermath of the Great Oxygenation Event. The 'oxygen holocaust', which supposedly wiped out most anaerobic cells, can't be traced at all; there is no evidence from either phylogenetics or geochemistry that such an extinction ever took place. On the contrary, anaerobes prospered."*

Lanza, N.L., Fischer, W.W., Wiens, R.C., Grotzinger, J., Ollila, A.M., Cousin, A., Anderson, R.B., Clark, B.C., Gellert, R., Mangold, N. and Maurice, S., 2014. [High manganese concentrations in rocks at Gale crater, Mars](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014GL060329). *Geophysical Research Letters*, *41*(16), pp.5755-5763.

Popular exposition: [Nina Lanza](https://astronomy.com/authors/nina-lanza), [How a weird Mars rock may be solid proof of an ancient oxygen atmosphere](https://astronomy.com/news/2016/07/how-a-weird-mars-rock-may-be-solid-proof-of-an-ancient-oxygen-atmosphere), Astronomy magazine

Lanza, N.L., Wiens, R.C., Arvidson, R.E., Clark, B.C., Fischer, W.W., Gellert, R., Grotzinger, J.P., Hurowitz, J.A., McLennan, S.M., Morris, R.V. and Rice, M.S., 2016. [Oxidation of manganese in an ancient aquifer, Kimberley formation, Gale crater, Mars](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL069109). *Geophysical Research Letters*, *43*(14), pp.7398-7407.

Latgé, J.P., 1999. [Aspergillus fumigatus and aspergillosis](https://scholar.google.com/scholar_url?url=http://cmr.asm.org/content/12/2/310.full&hl=en&sa=T&oi=gsb-gga&ct=res&cd=0&ei=0sS-WovXCMK1mAGjh5LQBw&scisig=AAGBfm1LpPRudw3-i5PXvXsD6H1BB4pWpQ). *Clinical microbiology reviews*, *12*(2), pp.310-350.

Lauterbach, M.A., 2012. [Finding, defining and breaking the diffraction barrier in microscopy–a historical perspective](https://link.springer.com/article/10.1186/2192-2853-1-8). *Optical nanoscopy*, *1*(1), p.8.

Lebeaux, D., Chauhan, A., Rendueles, O. and Beloin, C., 2013. [From in vitro to in vivo models of bacterial biofilm-related infections](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4235718/). *Pathogens*, *2*(2), pp.288-356.

Lederberg, J. 1959, [letter to J.B.S. Haldane](https://profiles.nlm.nih.gov/ps/access/BBAEAF.pdf)

*"Just as I started to write this letter I realized there might have  
been a substantial connection between its import and the occasion of  
my visit to you November 6, 1957….*

*“It must have been around this time surely that I began to think of the scientific consequences of lunar and planetary probes. … I have in mind the quite tangible possibility of contamination by terrestrial organisms of the surfaces of Mars and Venus, unless stringent precautions are taken to sterilize any vehicles sent there...."*

Lederberg, J., 1999a. [Paradoxes of the host-parasite relationship](https://profiles.nlm.nih.gov/ps/access/BBGNMY.pdf). *ASM News*, *65*(12).

Lederberg, J., 1999b. [Parasites face a perpetual dilemma](https://profiles.nlm.nih.gov/ps/access/BBGNMX.pdf). *ASM News*, *65*(2).

Lee, J.J., 2020, [Newfound desert soil community lives on sips of fog](https://www.sciencenewsforstudents.org/article/newfound-desert-soil-community-lives-on-sips-of-fog), Science news for students

Leflaive, J. and Ten‐hage, L.O.Ï.C., 2007. [Algal and cyanobacterial secondary metabolites in freshwaters: a comparison of allelopathic compounds and toxins](https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2427.2006.01689.x). *Freshwater Biology*, *52*(2), pp.199-214.

Lenardon, M.D., Munro, C.A. and Gow, N.A., 2010. [Chitin synthesis and fungal pathogenesis](https://www.sciencedirect.com/science/article/pii/S1369527410000639). *Current opinion in microbiology*, *13*(4), pp.416-423.

Lenski, R.E., 2017. [Experimental evolution and the dynamics of adaptation and genome evolution in microbial populations](https://www.nature.com/articles/ismej201769). The ISME journal, 11(10), pp.2181-2194.

*P 2185: “Although Cit+mutants were very rare, the replays showed that genetic context mattered: neither the ancestor norany clone that had been isolated before generation 20,000 produced any Cit+mutants, but 17 mutants arose from later clones. Thus, the origin of this new function was historically contingent; that is, the propensity to evolve the Cit+phenotype depended on one or more previous changes.”*

Lentzos, F. and Koblentz, G.D., 2021, The Conversation, [Fifty-nine labs around world handle the deadliest pathogens – only a quarter score high on safety](https://theconversation.com/fifty-nine-labs-around-world-handle-the-deadliest-pathogens-only-a-quarter-score-high-on-safety-161777)

Lerman, L., 2004. [DO Martian BLUEBERRIES HAVE PITS?… ARTIFACTS OF Martian WATER PAST](https://www.lpi.usra.edu/meetings/earlymars2004/pdf/8063.pdf). emge, p.8063.

Lerner, L, 2019, [Salt deposits on Mars hold clues to sources of ancient water](https://news.uchicago.edu/story/salt-deposits-mars-hold-clues-sources-ancient-water), University of Chicago news.

Leshin, L.A., 2002, May. Sample Collection for Investigation of Mars (SCIM): [Mars Sample Return Within This Decade](https://ui.adsabs.harvard.edu/abs/2002AGUSM.P51A..11L/abstract). In AGU Spring Meeting Abstracts (Vol. 2002, pp. P51A-11).

Leslie E, O., 2004. Prebiotic chemistry and the origin of the RNA world. *Critical reviews in biochemistry and molecular biology*, *39*(2), pp.99-123.

*"A scenario that I personally find attractive is one in which the very first replicators were 'naked genes' adsorbed on the surface of mineral particles, and in which impermeable membrane caps were 'invented' by the genetic system as it became metabolically competent. Escape from the mineral surface, enabled by the development of a closed spherical membrane would occur at a relatively late stage in evolution"*

Leso, V., Fontana, L. and Iavicoli, I., 2018. [Nanomaterial exposure and sterile inflammatory reactions](https://pubmed.ncbi.nlm.nih.gov/29959027/). Toxicology and Applied Pharmacology, 355, pp.80-92.

Leung, N.H., Xu, C., Ip, D.K. and Cowling, B.J., 2015. [The fraction of influenza virus infections that are asymptomatic: a systematic review and meta-analysis](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4586318/). Epidemiology (Cambridge, Mass.), 26(6), p.862.

Leung, W.W.F. and Sun, Q., 2020. [Charged PVDF multilayer nanofiber filter in filtering simulated airborne novel coronavirus (COVID-19) using ambient nano-aerosols](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7194611/). *Separation and Purification Technology*, *245*, p.116887.

Levin, G.V. and Straat, P.A., 1981. [Antarctic soil no. 726 and implications for the Viking labelled release experiment](http://www.gillevin.com/Mars/Reprint92-scan_images/Reprint92-scan.htm). Journal of Theoretical Biology, 91(1), pp.41-45.

Levin, G.V. and Straat, P.A., 2016. [The case for extant life on Mars and its possible detection by the Viking labelled release experiment](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6445182/). *Astrobiology*, *16*(10), pp.798-810.

Levine, J.S., 2020. [Lunar Dust and Its Impact on Human Exploration: Identifying the Problems.](https://www.lpi.usra.edu/announcements/artemis/whitepapers/2012.pdf) *The Impact of Lunar Dust on Human Exploration*, *2141*, p.5007.

Li, J., Mara, P., Schubotz, F., Sylvan, J.B., Burgaud, G., Klein, F., Beaudoin, D., Wee, S.Y., Dick, H.J., Lott, S. and Cox, R., 2020. [Recycling and metabolic flexibility dictate life in the lower oceanic crust](https://www.nature.com/articles/s41586-020-2075-5#ref-CR20). *Nature*, *579*(7798), pp.250-255.

Levy, J.S., Fassett, C.I., Holt, J.W., Parsons, R., Cipolli, W., Goudge, T.A., Tebolt, M., Kuentz, L., Johnson, J., Ishraque, F. and Cvijanovich, B., 2021. Surface boulder banding indicates [Martian debris-covered glaciers formed over multiple glaciations](https://www.pnas.org/doi/10.1073/pnas.2015971118). *Proceedings of the National Academy of Sciences*, *118*(4). Press release[: Colgate Planetary Geologist Publishes Groundbreaking Analysis of Mysterious Martian Glaciers](https://www.colgate.edu/news/stories/colgate-planetary-geologist-publishes-groundbreaking-analysis-mysterious-martian)

Lewis, K.W., Aharonson, O., Grotzinger, J.P., Kirk, R.L., McEwen, A.S. and Suer, T.A., 2008. [Quasi-periodic bedding in the sedimentary rock record of Mars](https://ntrs.nasa.gov/api/citations/20150008374/downloads/20150008374.pdf). *science*, *322*(5907), pp.1532-1535. [Press release Caltech Researchers Find Ancient Climate Cycles Recorded in Mars Rocks](https://www.caltech.edu/about/news/caltech-researchers-find-ancient-climate-cycles-recorded-mars-rocks-1494)

Lingam, M. and Loeb, A., 2020. [Potential for liquid water biochemistry deep under the surfaces of the moon, mars, and beyond](https://iopscience.iop.org/article/10.3847/2041-8213/abb608#apjlabb608s2). *The Astrophysical Journal Letters*, *901*(1), p.L11.

Liu, Y., Wu, X., Zhao, Y.Y.S., Pan, L., Wang, C., Liu, J., Zhao, Z., Zhou, X., Zhang, C., Wu, Y. and Wan, W., 2022. [Zhurong reveals recent aqueous activities in Utopia Planitia](https://www.science.org/doi/10.1126/sciadv.abn8555), Mars. *Science Advances*, *8*(19), p.eabn8555.

*Hydrated sulfates may form through notable acid weathering of dust and sand inside the ice deposit when volcanic aerosols dissolve in the thin films of water to create acidic solutions (*[*36*](https://www.science.org/doi/10.1126/sciadv.abn8555#core-R36)*); however, this process has difficulty explaining the duricrust features. Therefore, one scenario that we prefer is that the predepositional regolith underwent cementation and lithification during the rising or infiltration of briny groundwater to form the observed platy rocks (*[*Fig. 5*](https://www.science.org/doi/10.1126/sciadv.abn8555#F5)*). The salt cements (e.g., sulfates or opaline silica) precipitate from the groundwater in the capillary fringe zone, where active evaporation and accumulation can occur (*[*37*](https://www.science.org/doi/10.1126/sciadv.abn8555#core-R37)*). Episodic fluctuation of the groundwater table may further thicken the indurated section and result in a fine-layered structure. After evaporation, the regolith overlying the duricrust is subject to deflation and erosion, while the duricrusts are resistant to aeolian erosion (*[*38*](https://www.science.org/doi/10.1126/sciadv.abn8555#core-R38)*). In this scenario, kilometer-scale briny groundwater may have been episodically active and interacting with the colluvium at the landing site. Alternatively, aqueous minerals such as hydrated silica have been observed to be associated with flow features and pitted cones elsewhere in the northern plains (*[*12*](https://www.science.org/doi/10.1126/sciadv.abn8555#core-R12)*), and the observed mineralogy and duricrust in this work may have some generic link with the pitted cones in the vicinity of the rover (*[*Fig. 1*](https://www.science.org/doi/10.1126/sciadv.abn8555#F1)*), which requires further investigation by the Tianwen-1 orbiter and Zhurong rover*

*The hydrated minerals and widespread salt cementations imply the presence of briny liquid water in the subsurface, which may have been generated by melting the ground ice during temporary climate perturbations (e.g., volcanism and impacts).*

*Specifically, possible dike swarms responsible for landform formation or recent volcanism from the Elysium region could have been a heat source for maintaining the groundwater system or melting the ice. Alternatively, local transient liquid water under current climate condition may be responsible for local melting of subsurface ground ice, forming indurated duricrust, in which case the water-rock interaction and the spatial extent would be limited.*

*Determining the mineralogy and spatial extent of the platy rocks in future traverse would provide clues to distinguish different climate conditions for these water activities. Regardless of the potential heat source, the in situ observations manifest recent aqueous activities on Mars, suggesting that the cold and dry late Amazonian epoch may have been episodically punctuated by short-duration climatic warming events that result in melting of ground ice at latitude less than 30°N. The in situ identification of such environments points to a more active Amazonian surface hydrosphere for Mars than previously considered.*

Lin, Y., El Goresy, A., Hu, S., Zhang, J., Gillet, P., Xu, Y., Hao, J., Miyahara, M., Ouyang, Z., Ohtani, E. and Xu, L., 2014. [NanoSIMS analysis of organic carbon from the Tissint Martian meteorite: Evidence for the past existence of subsurface organic‐bearing fluids on Mars](https://documents.epfl.ch/groups/e/ep/epflmedia/www/20141201_Tissint/Tissint_FullTextArticle.pdf). *Meteoritics & Planetary Science*, *49*(12), pp.2201-2218.

Lindensmith, C.A., Rider, S., Bedrossian, M., Wallace, J.K., Serabyn, E., Showalter, G.M., Deming, J.W. and Nadeau, J.L., 2016. [A submersible, off-axis holographic microscope for detection of microbial motility and morphology in aqueous and icy environments](http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0147700). *PloS one*, *11*(1), p.e0147700.

Liu, J., Li, B., Wang, Y., Zhang, G., Jiang, X. and Li, X., 2019. [Passage and community changes of filterable bacteria during microfiltration of a surface water supply](https://www.sciencedirect.com/science/article/pii/S016041201930772X). *Environment international*, *131*, p.104998

Lock, R.E., Bailey, Z.J., Kowalkowski, T.D., Nilsen, E.L. and Mattingly, R.L., 2014, March. [Mars Sample Return Orbiter Concepts Using Solar Electric Propulsion for the Post-Mars 2020 Decade](https://www.researchgate.net/profile/Zachary_Bailey/publication/269300438_Mars_Sample_Return_Orbiter_concepts_using_Solar_Electric_Propulsion_for_the_post-Mars2020_decade/links/55955d6708ae21086d206431.pdf). In *2014 IEEE Aerospace Conference* (pp. 1-10). IEEE.

Lovelock, J.E. and Margulis, L., 1974. [Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis](https://www.tandfonline.com/doi/pdf/10.3402/tellusa.v26i1-2.9731). *Tellus*, *26*(1-2), pp.2-10.

Lovelock, J.E., 1975. [Thermodynamics and the recognition of alien biospheres](http://www.jameslovelock.org/thermodynamics-and-the-recognition-of-alien-biospheres/). *Proceedings of the Royal Society of London. Series B. Biological Sciences*, *189*(1095), pp.167-181.

## M.

McDaniel, L.D., Young, E., Delaney, J., Ruhnau, F., Ritchie, K.B. and Paul, J.H., 2010. [High frequency of horizontal gene transfer in the oceans](https://www.researchgate.net/profile/Kim-Ritchie/publication/47369923_High_Frequency_of_Horizontal_Gene_Transfer_in_the_Oceans/links/5578554908ae752158703436/High-Frequency-of-Horizontal-Gene-Transfer-in-the-Oceans.pdf). *Science*, *330*(6000), pp.50-50.

McDermott, J.M., Seewald, J.S., German, C.R. and Sylva, S.P., 2015. [Pathways for abiotic organic synthesis at submarine hydrothermal fields](https://www.pnas.org/content/pnas/112/25/7668.full.pdf). Proceedings of the National Academy of Sciences, 112(25), pp.7668-7672.

McEwen, A.S., Ojha, L., Dundas, C.M., Mattson, S.S., Byrne, S., Wray, J.J., Cull, S.C., Murchie, S.L., Thomas, N. and Gulick, V.C., 2011. [Seasonal flows on warm Martian slopes](http://science.sciencemag.org/content/333/6043/740). *Science*, *333*(6043), pp.740-743.

McGuire, M.L., Borowski, S.K., Mason, L.M. and Gilland, J., 2003. [High power MPD nuclear electric propulsion (NEP) for artificial gravity HOPE missions to Callisto](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040005901.pdf).

McKay, C.P., Pollack, J.B. and Courtin, R., 1991. [The greenhouse and antigreenhouse effects on Titan](https://www.science.org/doi/10.1126/science.11538492). *Science*, *253*(5024), pp.1118-1121. NASA press release [Scientists discover anti-greenhouse effect on Titan](https://www.nasa.gov/home/hqnews/1991/91-143.txt).

McKay, C.P., 2009. [Planetary ecosynthesis on Mars: restoration ecology and environmental ethics.](https://web.archive.org/web/20200401190045/https:/esseacourses.strategies.org/EcosynthesisMcKay2008ReviewAAAS.pdf) *Exploring the origin, extent, and future of life: Philosophical, ethical, and theological perspectives*, pp.245-260.

McKay, C., (2015) interviewed by David, L. for Space News [Q&A with Chris McKay, Senior Scientist at NASA Ames Research Center](https://spacenews.com/qa-with-chris-mckay-senior-scientist-at-nasa-ames-research-center/). Available at: <https://spacenews.com/qa-with-chris-mckay-senior-scientist-at-nasa-ames-research-center/>

McKay, C.P., 2010. [An origin of life on Mars](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2845199/). *Cold Spring Harbor Perspectives in Biology*, *2*(4), p.a003509.

McKay, D.S., Gibson, E.K., Thomas-Keprta, K.L., Vali, H., Romanek, C.S., Clemett, S.J., Chillier, X.D., Maechling, C.R. and Zare, R.N., 1996. [Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001](http://lunar.earth.northwestern.edu/courses/438/search.life.pdf). *Science*, *273*(5277), pp.924-930.

*“These surfaces also display small regularly shaped ovoid and elongated forms ranging from about 20 to 100nm in longest dimension. Similar textures containing ovids have been found on the surface of calcite concretions grown from Pleistocene groundwater in southern Italy, where they are interpreted as nanobacteria that have assisted the calcite precipitation”*

McMahon, S., Bosak, T., Grotzinger, J.P., Milliken, R.E., Summons, R.E., Daye, M., Newman, S.A., Fraeman, A., Williford, K.H. and Briggs, D.E.G., 2018. [A field guide to finding fossils on Mars](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6049883/#jgre20942-sec-0011title). *Journal of Geophysical Research: Planets*, *123*(5), pp.1012-1040.

McMahon, S., Parnell, J., Ponicka, J., Hole, M. and Boyce, A., 2013. [The habitability of vesicles in martian basal](https://academic.oup.com/astrogeo/article/54/1/1.17/194320)t. Astronomy & Geophysics, 54(1), pp.1-17.

McNeil, D.G., 2020, [Inside China’s All-Out War on the Coronavirus, New York Times](https://www.nytimes.com/2020/03/04/health/coronavirus-china-aylward.html).

McSween, H.Y., 1997. [*Evidence for life in a Martian meteorite?*](https://www.geosociety.org/gsatoday/archive/7/7/pdf/i1052-5173-7-7-1.pdf). Geological Society of America.

McSween, H.Y., Grady, M.M., McKeegan, K., Beaty, D.W. and Carrier, B.L., 2020. [Why Mars Sample Return is a Mission Campaign of Compelling Importance to Planetary Science and Exploration.](http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/214-598b3c6f1442d89985f444c9124c0f16_McSweenHarryY.pdf) White Paper for the Survey.

Magana-Arachchi, D.N. and Wanigatunge, R.P., 2013. [First report of genus Chroococcidiopsis (cyanobacteria) from Sri Lanka: a potential threat to human health](https://scholar.google.com/scholar?cluster=7725054431080211508). *Journal of the national science foundation of Sri Lanka*, *41*(1).

Mahlen, S.D., 2011. [Serratia infections: from military experiments to current practice](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3194826/). *Clinical microbiology reviews*, *24*(4), pp.755-791.

Makarova, K.S., Aravind, L., Wolf, Y.I., Tatusov, R.L., Minton, K.W., Koonin, E.V. and Daly, M.J., 2001. [Genome of the extremely radiation-resistant bacterium Deinococcus radiodurans viewed from the perspective of comparative genomics](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC99018/). *Microbiology and molecular biology reviews*, *65*(1), pp.44-79.

*More recently, it has been proposed that adaptation could also occur in permafrost or other semifrozen conditions where cryptobiotic microbes with extremely long generation times could be selected with metabolic processes able to repair the unavoidable accumulation of background radiation-induced DNA damage*

Maki, T., Lee, K.C., Kawai, K., Onishi, K., Hong, C.S., Kurosaki, Y., Shinoda, M., Kai, K., Iwasaka, Y., Archer, S.D. and Lacap‐Bugler, D.C., 2019. [Aeolian dispersal of bacteria associated with desert dust and anthropogenic particles over continental and oceanic surfaces](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JD029597). Journal of Geophysical Research: Atmospheres, 124(10), pp.5579-5588.

Mancinelli, R.L., 1993, personal communication with D. Thomas at NASA Ames Research center, cited in Thomas, D., 1995, [Biological aspects of the ecopoesis and terraformation of Mars: Current perspectives and research](https://s3.amazonaws.com/academia.edu.documents/5281196/1995_Thomas_48_415-418.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1522874944&Signature=G4jffUdXqwiHPq6YNKyAxkSWANg%3D&response-content-disposition=inline%3B%20filename%3DBiological_aspects_of_the_ecopoeisis_and.pdf), Journal of the British Interplanetary Society, vol 48, pp 415 - 418,

*“Additional unpublished research revealed nitrogen fixation by a variety of microorganisms at pN of 0.2 mbar - the current partial pressure of nitrogen in the Mars atmosphere.”*

Mangus, S. and Larsen, W., 2004. [Lunar Receiving Laboratory Project History](https://www.lpi.usra.edu/lunar/documents/lunarReceivingLabCr2004_208938.pdf).

Mantel, N. and Bryan, W.R., 1961[. “Safety” testing of carcinogenic agents](https://academic.oup.com/jnci/article-abstract/27/2/455/907154?redirectedFrom=PDF). Journal of the National Cancer Institute, 27(2), pp.455-470.

Margulis, L. and Lovelock, J.E., 1974. [Biological modulation of the Earth's atmosphere](https://www.sciencedirect.com/science/article/abs/pii/001910357490150X). *Icarus*, *21*(4), pp.471-489.

*We review the evidence that the Earth's atmosphere is regulated by life on the surface so that the probability of growth of the entire biosphere is maximized.*

Marraffa, L., Kassing, D., Baglioni, P., Wilde, D., Walther, S., Pitchkhadze, K. and Finchenko, V., 2000. [Inflatable re-entry technologies: flight demonstration and future prospects](https://www.esa.int/esapub/bulletin/bullet103/marraffa103.pdf). *ESA bulletin*, pp.78-85.

Martínez, J.L., 2012[. Natural antibiotic resistance and contamination by antibiotic resistance determinants: the two ages in the evolution of resistance to antimicrobials](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3257838/). Frontiers in microbiology, 3, p.1.

Martínez, G.M. and Renno, N.O., 2013. [Water and brines on Mars: current evidence and implications for MSL](https://link.springer.com/article/10.1007/s11214-012-9956-3). *Space Science Reviews*, *175*(1-4), pp.29-51. Section numbers refer to the pdf rather than the online html version of the article.

Martín-Torres, F.J., Zorzano, M.P., Valentín-Serrano, P., Harri, A.M., Genzer, M., Kemppinen, O., Rivera-Valentin, E.G., Jun, I., Wray, J., Madsen, M.B. and Goetz, W., 2015. [Transient liquid water and water activity at Gale crater on Mars.](https://www.nature.com/articles/ngeo2412) *Nature Geoscience*, *8*(5), p.357. Summary:  ["Evidence of liquid water found on Mars (BBC)](http://www.bbc.co.uk/news/science-environment-32287609). NASA press release: [NASA Mars Rover's Weather Data Bolster Case for Brine](https://www.nasa.gov/jpl/msl/nasa-mars-rovers-weather-data-bolster-case-for-brine) and University of Copenhagen press release, [Mars might have liquid water](https://www.nbi.ku.dk/english/news/news15/mars-might-have-liquid-water/), quotes Morten Bo Madsen, associate professor and head of the Mars Group at the Niels Bohr Institute at the University of Copenhagen. :

*“We have discovered the substance calcium perchlorate in the soil and, under the right conditions, it absorbs water vapour from the atmosphere. Our measurements from the Curiosity rover’s weather monitoring station show that these conditions exist at night and just after sunrise in the winter. Based on measurements of humidity and the temperature at a height of 1.6 meters and at the surface of the planet, we can estimate the amount of water that is absorbed. When night falls, some of the water vapour in the atmosphere condenses on the planet surface as frost, but calcium perchlorate is very absorbent and it forms a brine with the water, so the freezing point is lowered and the frost can turn into a liquid. The soil is porous, so what we are seeing is that the water seeps down through the soil. Over time, other salts may also dissolve in the soil and now that they are liquid, they can move and precipitate elsewhere under the surface,” explains Morten Bo Madsen, associate professor and head of the Mars Group at the Niels Bohr Institute at the University of Copenhagen.*

Matthews, D., Jones, H., Gans, P., Coates, S. and Smith, L.M., 2005. [Toxic secondary metabolite production in genetically modified potatoes in response to stress](https://www.ncbi.nlm.nih.gov/pubmed/16190629). Journal of Agricultural and Food Chemistry, 53(20), pp.7766-7776.

Mattingly, R, 2010, [Mission Concept Study, Planetary Science Decadal Survey, MSR Orbiter Mission (Including Mars Returned Sample Handling)](https://www.nap.edu/resource/13117/App%20G%2008_Mars-Sample-Return-Orbiter.pdf)

Maxmen, A., 2010. [Virus-like particles speed bacterial evolution](https://www.nature.com/news/2010/100930/full/news.2010.507.html). *Nature doi*:*10.1038/news.2010.507*

Mégarbane, B., Borron, S.W. and Baud, F.J., 2005. [Current recommendations for treatment of severe toxic alcohol poisonings.](https://www.semanticscholar.org/paper/Current-recommendations-for-treatment-of-severe-M%C3%A9garbane-Borron/2634afbfda7553fb76f78b5dd827145bebe9fcba) Intensive care medicine, 31(2), pp.189-195.

Melis, A., 2009. [Solar energy conversion efficiencies in photosynthesis: minimizing the chlorophyll antennae to maximize efficiency](https://ehsanzadeh.iut.ac.ir/sites/ehsanzadeh.iut.ac.ir/files/files_course/rue-antennae2009.pdf). *Plant science*, *177*(4), pp.272-280.

Meltzer, M., 2007. [Mission to Jupiter: a history of the Galileo project](https://history.nasa.gov/sp4231.pdf). *NASA STI/Recon Technical Report N*, *7*.

Meltzer, M., 2012. [When Biospheres Collide: A History of NASA's Planetary Protection Programs](https://www.nasa.gov/pdf/607072main_WhenBiospheresCollide-ebook.pdf). Government Printing Office, After Splashdown: Plans To Safely Transport the Apollo Astronauts, Command Module, and Samples to the Recovery Ship, Page 217 and following

Meringer, M., Cleaves, H.J. and Freeland, S.J., 2013. [Beyond terrestrial biology: Charting the chemical universe of α-amino acid structures](https://pubs.acs.org/doi/abs/10.1021/ci400209n). Journal of chemical information and modeling, 53(11), pp.2851-2862.

Merino, N., Aronson, H.S., Bojanova, D.P., Feyhl-Buska, J., Wong, M.L., Zhang, S. and Giovannelli, D., 2019. [Living at the extremes: extremophiles and the limits of life in a planetary context](https://www.frontiersin.org/articles/10.3389/fmicb.2019.00780/ful). *Frontiers in microbiology*, *10*, p.780.

Meteoritical Bulletin Database,2021, [Search the Meteoritical bulletin database](https://www.lpi.usra.edu/meteor/metbull.php) :

[Martian meteorites](https://www.lpi.usra.edu/meteor/metbull.php?sea=&sfor=names&ants=&nwas=&falls=&valids=&stype=contains&lrec=50&map=ge&browse=&country=All&srt=name&categ=Martian+meteorites&mblist=All&rect=&phot=&strewn=&snew=0&pnt=Normal%20table&dr=&page=1): [Martian meteorites in Antarctica](https://www.lpi.usra.edu/meteor/metbull.php?sea=Antarctica&sfor=places&ants=&nwas=&falls=&valids=&stype=contains&lrec=50&map=ge&browse=&country=All&srt=name&categ=Martian+meteorites&mblist=All&rect=&phot=&strewn=&snew=0&pnt=Normal%20table&dr=&page=0): [All meteorites in Antarctica](https://www.lpi.usra.edu/meteor/metbull.php?sea=Antarctica&sfor=places&ants=&nwas=&falls=&valids=&stype=contains&lrec=50&map=ge&browse=&country=All&srt=name&categ=All&mblist=All&rect=&phot=&strewn=&snew=0&pnt=Normal%20table&dr=&page=1) : [Doubtful meteorites in Antarctica](https://www.lpi.usra.edu/meteor/metbull.php?sea=Antarctica&sfor=places&ants=&nwas=&falls=&valids=&stype=contains&lrec=50&map=ge&browse=&country=All&srt=name&categ=Doubtful+meteorites&mblist=All&rect=&phot=&strewn=&snew=0&pnt=Normal%20table&dr=&page=0)

Metzger, P.T., Muscatello, A., Mueller, R.P. and Mantovani, J., 2013. [Affordable, rapid bootstrapping of the space industry and solar system civilization](https://ascelibrary.org/doi/abs/10.1061/(ASCE)AS.1943-5525.0000236). *Journal of Aerospace Engineering*, *26*(1), pp.18-29.

Mileikowsky, C., Cucinotta, F.A., Wilson, J.W., Gladman, B., Horneck, G., Lindegren, L., Melosh, J., Rickman, H., Valtonen, M. and Zheng, J.Q., 2000. [Natural transfer of viable microbes in space: 1. From Mars to Earth and Earth to Mars.](https://d1wqtxts1xzle7.cloudfront.net/48941006/icar.1999.631720160918-20137-1ec9ewk-with-cover-page-v2.pdf?Expires=1669390222&Signature=AJk-yC7smzTLqE4hLw~OrJBs6YAqyarbuIy~73jyrVkYHAXHTlLn6wPPeA4~gcA8yDqM1~Js7fN3F6NaO~j-5sfrHs~vcXD8Gbalw24QSrREtYYhFC9mt12UlkjoyckDPBCMz5bV~FrNwVoQ6pjIw8qpDVuxdpYTBo-~KRRDlZcQm9VJUvn6De7cme22A7VYQ~6I-T8R9dJGjOmuGycpZ86IGUHwFuZaGI5r3s9qezqkH5SQo9EheK~i7vw0gZ9A8r1-Y-ln4FVi9dm8cvp053QuDcTrBvQE88zhBSERvuR0J~4bj2ytrRavLm5XMAqVIBUKr2l519rbO6oJ4NGeFQ__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA) *Icarus*, *145*(2), pp.391-427.

*page 419: Category 1: Small and medium-sized meteoroids (with radii from 2 to 80 cm and masses from 0.1 kg to~6:5 tons (if 𝜌≈3g/cm3). These meteoroids provide no shielding against the galactic cosmic rays, on the contrary they increase the dose rates caused by unshielded GCR by the creation of more particles in-side the meteoroids. However, they could still serve as vehicles for viable transfers from Mars to Earth lasting 1 million years* for D. radiodurans R1 and 0.3 million years for B. subtilis (wild type) if DNA decay is not limiting.

Miller, J.D., Straat, P.A. and Levin, G.V., 2002, February. [Periodic analysis of the Viking lander Labelled Release experiment](http://www.gillevin.com/Mars/Reprint119-Miller-Straat-Levin-FINAL_files/Reprint119-Miller-Straat-Levin-FINAL.htm). In *Instruments, Methods, and Missions for Astrobiology IV* (Vol. 4495, pp. 96-108). International Society for Optics and Photonics.

*A temperature-regulated change in CO2 solubility could at least partially account for the amplitude of the LR oscillation. However, the HT oscillation phase leads the LR oscillation by as much as two hours, an unusual circumstance if this were simply a chemical oscillation driven by thermal fluctuation.*

*(Admittedly there is uncertainty concerning the delay between change in temperature at the head end assembly, perhaps one inch over the 0.5 cc soil sample, and soil sample temperature per se. However, a two-hour lag seems quite long for what is presumably a convective and radiative process. Similarly, thermal-induced movement of gas between the soil sample and the beta detector requires only about 20 minutes.)*

*Furthermore, the LR oscillation does not slavishly follow the thermal variation; rather, it seems that the LR rhythm is extracted from the HT oscillation, while high frequency noise is not. This is very common in terrestrial organisms in which a low frequency periodic stimulus (i.e., a zeitgeber) such as a 12:12 light/dark cycle can entrain a circadian rhythm, while high frequency transients in the same stimulus are ignored (e.g., turning on the light in the bathroom at night for a minute or two does not alter normal entrainment to the light/dark cycle).*

*Furthermore, there is abundant evidence that as little as a 2º C temperature cycle can entrain circadian rhythms in terrestrial organisms such as lizards, fruit flies, and bread molds and entrainment can be preferential to the diminution phase of the temperature cycle, in analogy to the temperature fall that occurs at sunset on Mars).*

Ming, X. and Shijie, X., 2009. [Exploration of distant retrograde orbits around Moon](http://ming). *Acta Astronautica*, *65*(5-6), pp.853-860.

Minton, K.W., 1994. [DNA repair in the extremely radioresistant bacterium Deinococcus radiodurans](https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1365-2958.1994.tb00397.x). Molecular microbiology, 13(1), pp.9-15.

Miteva, V.I. and Brenchley, J.E., 2005. [Detection and isolation of ultrasmall microorganisms from a 120,000-year-old Greenland glacier ice core](https://aem.asm.org/content/aem/71/12/7806.full.pdf). *Applied and Environmental Microbiology*, *71*(12), pp.7806-7818.

Möhlmann, D., 2005. [Adsorption water-related potential chemical and biological processes in the upper Martian surface](https://www.researchgate.net/publication/7390930_Adsorption_Water-Related_Potential_Chemical_and_Biological_Processes_in_the_Upper_Martian_Surface#pf3). *Astrobiology*, *5*(6), pp.770-777.

Möhlmann, D.T.F., 2009, June. [Liquid Interfacial and Melt-Water in the Upper Sub-Surface of Mars](https://www.lpi.usra.edu/meetings/hydrous2009/pdf/4001.pdf). In Workshop on Modeling Martian Hydrous Environments (Vol. 1482, p. 48).

Mojarro, A., Hachey, J., Tani, J., Smith, A., Bhattaru, S., Pontefract, A., Doebler, R., Brown, M., Ruvkun, G., Zuber, M.T. and Carr, C.E., 2016, October. [SETG: nucleic acid extraction and sequencing for in situ life detection on Mars](https://www.hou.usra.edu/meetings/ipm2016/pdf/4095.pdf). In *3rd International Workshop on Instrumentation*

*for Planetary Mission* (Vol. 1980).

Mojarro, A., Jin, L., Szostak, J.W., Head, J.W. and Zuber, M.T., 2020. [In search of the RNA world on Mars](https://www.biorxiv.org/content/biorxiv/early/2020/02/28/2020.02.28.964486.full.pdf). BioRxiv.

Montgomery, L., 2016, [Planetary Protection and Its Applicability to the Private Sector](http://groundbasedspacematters.com/index.php/2016/10/03/planetary-protection-and-its-applicability-to-the-private-sector/), Law Offices of Laura Montgomery.

Moore, N.C., 2014, [Martian salts must touch ice to make liquid water, study shows](http://www.ns.umich.edu/new/releases/22274-martian-salts-must-touch-ice-to-make-liquid-water-study-shows), Michigan news.

Morozova, Daria; Möhlmann, Diedrich; Wagner, Dirk (2006). [*"Survival of Methanogenic Archaea from Siberian Permafrost under Simulated Martian Thermal Conditions"*](http://epic.awi.de/14473/1/Mor2006e.pdf) (PDF). Origins of Life and Evolution of Biospheres. **37** (2): 189–200

Mosca, C., Rothschild, L.J., Napoli, A., Ferré, F., Pietrosanto, M., Fagliarone, C., Baqué, M., Rabbow, E., Rettberg, P. and Billi, D., 2019. [Over-expression of UV-damage DNA repair genes and ribonucleic acid persistence contribute to the resilience of dried biofilms of the desert cyanobacetrium Chroococcidiopsis exposed to Mars-like UV flux and long-term desiccation](https://www.frontiersin.org/articles/10.3389/fmicb.2019.02312/full#ref51). Frontiers in microbiology, 10, p.2312.

*Dried-rewetted biofilms and dried-UV-irradiated-rewetted biofilms were tested for respiration by monitoring the INT reduction by dehydrogenases after 72 h of rehydration. The INT staining revealed 30 and 10% of alive cells with insoluble red formazan spots in the cytoplasm of dried-rewetted biofilms and dried-UV-irradiated-rewetted biofilms, respectively,*

*After 7 years of air-drying, Chroococcidiopsis not only avoided genome degradation but preserved at least a sub-set of mRNAs and 16S ribosomal RNA.*

*... In the present work, the occurrence of survivors in dried biofilms and dried-UV-irradiated biofilms was proved by growth after transfer into liquid BG-11 medium (not shown) and by INT reduction after 72 h of rewetting.*

*Reshaping the boundaries of Chroococcidiopsis desiccation and UV tolerance has implications in the search for extra-terrestrial life since it contributes to defining the habitability of Mars and planets orbiting other stars. In fact, the UV dose used here corresponds to that of a few hours at Mars’s equator (Cockell et al., 2000). Hence, considering that survivors occurred in the bottom layers of the biofilms (Baqué et al., 2013), it might be hypothesized that if a biofilm life form ever appeared during Mars’s climatic history, it might have been transported in a dried state under UV radiation, from niches that had become unfavorable to niches that were inhabitable (Westall et al., 2013). The reported survival also suggests that intense UV radiation fluxes would not prevent the presence of phototrophic biofilms or their colonizing of the landmass of other planets.*

Mueller, R.P. and Van Susante, P.J., 2012. [A review of extra-terrestrial mining robot concepts](https://ntrs.nasa.gov/api/citations/20120008777/downloads/20120008777.pdf). Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments, pp.295-314.

Mulkidjanian A.Y. (2015) [Abiotic Photosynthesis](https://link.springer.com/referenceworkentry/10.1007%2F978-3-662-44185-5_4). In: Gargaud, M., Amils, R. and Cleaves, H.J. eds., 2011. Encyclopedia of astrobiology (Vol. 1). Springer Science & Business Media.

Muñoz-Dorado, J., Marcos-Torres, F.J., García-Bravo, E., Moraleda-Muñoz, A. and Pérez, J., 2016. [Myxobacteria: moving, killing, feeding, and surviving together](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4880591/). *Frontiers in microbiology*, *7*, p.781.

Murray, D.H., Pilmanis, A.A., Blue, R.S., Pattarini, J.M., Law, J., Bayne, C.G., Turney, M.W. and Clark, J.B., 2013. [Pathophysiology, prevention, and treatment of ebullism](https://www.researchgate.net/profile/Jonathan-Clark-10/publication/235754706_Pathophysiology_Prevention_and_Treatment_of_Ebullism/links/57cf6ffb08ae057987ac0dcc/Pathophysiology-Prevention-and-Treatment-of-Ebullism.pdf). Aviation, space, and environmental medicine, 84(2), pp.89-96.

Musk, E., 2015, Elon Musk interview AGU 2015 Conference San Francisco at [30 minutes](https://youtu.be/WwFa3nk1V0I?t=1804)

## N

Nakai, R., 2020. [Size matters: ultra-small and filterable microorganisms in the environment.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7308576/) *Microbes and environments*, *35*(2), p.ME20025.

Nakajima, Y., Yoshizawa, S., Nakamura, K., Ogura, Y., Hayashi, T. and Kogure, K., 2017. [Draft Genome Sequences of Tersicoccus phoenicis DSM 30849T, Isolated from a Cleanroom for Spacecraft Assembly, and Tersicoccus sp. Strain Bi-70, Isolated from a Freshwater Lake](https://journals.asm.org/doi/full/10.1128/genomeA.00079-17). Genome Announcements, 5(13), pp.e00079-17.

Nakamiya, M., Yamakawa, H., Scheeres, D.J. and Yoshikawa, M., 2010. [Interplanetary transfers between halo orbits: connectivity between escape and capture trajectories](https://arc.aiaa.org/doi/abs/10.2514/1.46446?journalCode=jgcd). *Journal of guidance, control, and dynamics*, *33*(3), pp.803-813.

National Academies of Sciences, Engineering, and Medicine. 2020. [*Assessment of the Report of NASA's Planetary Protection Independent Review Board*](https://www.nap.edu/catalog/25773/assessment-of-the-report-of-nasas-planetary-protection-independent-review-board). Washington, DC: The National Academies Press. https://doi.org/10.17226/25773.

NASA, 1969, [President Nixon visits Apollo 11 crew in quarantine](https://www.flickr.com/photos/nasacommons/7876061882/), NASA in the Commons, Flickr

NASA, 1972, [Apollo 16 lunar rover "Grand Prix"](https://www.youtube.com/watch?v=X30z82aeSHw) (stabilized). Frame is from [1:11](https://youtu.be/X30z82aeSHw?t=71)

NASA, 1995, photograph [AS11-40-5927](https://www.history.nasa.gov/alsj/a11/AS11-40-5927HR.jpg) from [Apollo 11 image library](https://www.history.nasa.gov/alsj/a11/images11.html).

NASA, 1997, PIA00571: [Ice on Mars Utopia Planitia Again](https://photojournal.jpl.nasa.gov/catalog/PIA00571)

NASA, 2001, [TNA World, NASA Astrobiology magazine](https://www.astrobio.net/origin-and-evolution-of-life/tna-world/)

NASA, 2004, [Mars Exploration Rover , Mars facts](https://mars.nasa.gov/internal_resources/825/)

Spirit’s landing site: 14.57°S and 175.47°E. Opportunity: 1.5°S, 354.47°E.

NASA, 2005odt, [Opportunity Discovers Tiny Craters on Mars](https://www.nasa.gov/vision/universe/solarsystem/mer-04272005.html), accessed at <https://www.nasa.gov/vision/universe/solarsystem/mer-04272005.html>, accessed on July 18, 2020

NASA, 2005npr, [NPR 8020.12D, Planetary Protection Provisions for Robotic Extraterrestrial Missions](https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8020_012D_&page_name=Preface). Washington , DC: Office of Safety and Mission Assurance

NASA, 2005ppp. [Planetary protection provisions for robotic extraterrestrial missions](https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8020_012D_&page_name=Chapter5). NPR 8020.12 C.

NASA, 2008grcg, [Genesis Return Capsule on the Ground](https://www.nasa.gov/mission_pages/genesis/multimedia/genesisrecov090804-2.html)

NASA, 2008mfosm, [Morning Frost on the Surface of Mars](https://www.nasa.gov/multimedia/imagegallery/image_feature_1160.html)

NASA, 2011cit, [Changes in Tilt of Mars' Axis](https://www.nasa.gov/mission_pages/msl/multimedia/pia15095.html)

NASA, 2011itii, NID 7120.99: [NASA Information Technology and Institutional Infrastructure Program and Project Management Requirements](http://nodis3.gsfc.nasa.gov/OPD_docs/NID_7120_99_.pdf),

NASA, 2012fdg, [NASA Facilities Design Guide](https://www.hq.nasa.gov/office/codej/codejx/Assets/Docs/NASA_Facilities_Design_Guide_Final_Submittal_-_8_8_124.pdf)

NASA, 2012tchh, [Telerobotics Could Help Humanity Explore Space](https://sservi.nasa.gov/articles/telerobotics-could-help-humanity-explore-space/)

NASA, 2013ach, [Apollo 11 comes home](https://www.nasa.gov/sites/default/files/images/372772main_GPN-2000-001212_full.jpg).

NASA, 2013stmgc, [Steady Temperatures at Mars' Gale Crater](https://mars.nasa.gov/resources/5206/steady-temperatures-at-mars-gale-crater/)

NASA, 2014fpr, [NPR 8820.2G Facility Project Requirements](https://nodis3.gsfc.nasa.gov/npg_img/N_PR_8820_002G_/N_PR_8820_002G_.pdf)

NASA, 2015, [Mars - Viking 1 Lander](https://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vl1_11d128.html)

NASA, 2015sucs, [Scientists using CO₂ snow cleaning to clean a test mirror](https://www.nasa.gov/image-feature/goddard/engineers-clean-mirror-with-carbon-dioxide-snow)

NASA, 2016hmossf, [How Mold on Space Station Flowers is Helping Get Us to Mars](https://www.nasa.gov/mission_pages/station/research/news/flowers)

NASA, 2016rssys, [NASA Rover's Sand-Dune Studies Yield Surprise](https://www.jpl.nasa.gov/news/nasa-rovers-sand-dune-studies-yield-surprise)

NASA, 2016tmsom [The Mysterious Smell of Moondust](https://science.nasa.gov/science-news/science-at-nasa/2006/30jan_smellofmoondust)

NASA, 2017, [A guide to Gale crater](https://mars.nasa.gov/resources/20328/a-guide-to-gale-crater/) (video)

NASA, 2017rgc, [Remembering Gene Cernan](https://www.nasa.gov/astronautprofiles/cernan/)

NASA, 2018, [M2020 Candidate Landing Site Data Sheets JEZERO CRATER](https://www.nature.com/articles/s41598-018-35946-8) available at: <https://www.nature.com/articles/s41598-018-35946-8> accessed on 17 July 2020

NASA, 2018luna, [Luna 16](https://solarsystem.nasa.gov/missions/luna-16/in-depth/)

NASA, 2019merm, ["Mars Exploration Rover Mission: All Opportunity Updates"](http://mars.nasa.gov/mer/mission/status_opportunityAll.html).

NASA, 2019nsfl, [NASA Searches for Life from the Moon in Recently Rediscovered Historic Footage](https://www.nasa.gov/ames/lunar-biology-lab)

NASA, 2019aaasi, [Arctic and Antarctic Sea Ice: How Are They Different?](https://climate.nasa.gov/blog/2861/arctic-and-antarctic-sea-ice-how-are-they-different/)

NASA, 2019ya, [50 Years Ago: Hornet + 3 – The Recovery of Apollo 11](https://www.nasa.gov/feature/50-years-ago-hornet-3-the-recovery-of-apollo-11)

NASA, 2020mhts, [Mars helicopter Tech Specs](https://mars.nasa.gov/technology/helicopter/#Tech-Specs), accessed at: <https://mars.nasa.gov/technology/helicopter/#Tech-Specs>, accessed on: July 18, 2020.

NASA, 2020cfmsr, [Concepts for Mars Sample Return](https://mars.nasa.gov/mars-exploration/missions/mars-sample-return/), at <https://mars.nasa.gov/mars-exploration/missions/mars-sample-return/> (accessed 2 July 2020)

NASA, 2020msros, [Mars Sample Return Orbiting Sample Container Concept Model](https://mars.nasa.gov/resources/24911/mars-sample-return-orbiting-sample-container-concept-model/), accessed at: https://mars.nasa.gov/resources/24911/mars-sample-return-orbiting-sample-container-concept-model/, accessed on: July 22, 2020

NASA, 2020nebmsr, [NASA Establishes Board to Initially Review Mars Sample Return Plans](https://mars.nasa.gov/news/8737/nasa-establishes-board-to-initially-review-mars-sample-return-plans)

NASA, 2020plpk [Mars 2020 Perseverance Landing Press Kit](https://www.jpl.nasa.gov/news/press_kits/mars_2020/landing/mission/)

NASA 2020prls, Perseverance Rover's Landing Site: [Jezero Crater](https://mars.nasa.gov/mars2020/mission/science/landing-site/), <https://mars.nasa.gov/mars2020/mission/science/landing-site/> (accessed 2 July 2020)

NASA, 2020prst, [Perseverance Rover Sample Tubes](https://www.nasa.gov/feature/jpl/a-martian-roundtrip-nasas-perseverance-rover-sample-tubes)

NASA, 2020sonr, [Summary of NASA Responses to Mars Sample Return Independent Review Board Recommendations](https://www.nasa.gov/sites/default/files/atoms/files/nasa_esa_mars_sample_return_irb_report.pdf)

*D-1: NASA and ESA should replan the baseline MSR program for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch continuing to be studied for feasibility and potential benefits.*

*NASA Response: NASA partially concurs with this recommendation. The MSR team will continue to examine the 2026, 2027 and 2028 launch opportunities during Phase A, while working to maintain current schedules to mature the design and retire risk as quickly as possible during Phase A, while also working to minimize program impacts due to COVID.*

*C-3:This study should be augmented to include a strong focus on potential Radioisotope Thermoelectric Generator(RTG)incorporation on either a single-lander or two-lander approach, to achieve the following benefits:Type1 launch option in 2028 Possible longer surface timeline RTG-sourced heating of the MAV   
NASA Response: NASA concurs with this recommendation*

NASA, 2020tesgs, [The Extraordinary Sample-Gathering System of NASA's Perseverance Mars Rover](https://mars.nasa.gov/news/8682/the-extraordinary-sample-gathering-system-of-nasas-perseverance-mars-rover/).

NASA, 2021nmttm, [NASA Moves to the Next Phase in a Campaign to Return Mars Samples to Earth](https://scitechdaily.com/nasa-moves-to-the-next-phase-in-a-campaign-to-return-mars-samples-to-earth/), SciTechDaily

NASA, 2021mpb, Marscopter press briefings.

Marscopter altitude: **Bob Balaram** says looking at 10 meters, limited by the range of the laser altimeter. MiMi Aung says 600 to 700 meters.

[1:01:32](https://youtu.be/JM_2hmdRnfQ?t=3692) from: [After NASA's Historic First Flight: Ingenuity Mars Helicopter Update Streamed live on 19 Apr 2021](https://youtu.be/JM_2hmdRnfQ)

Maximum separation: **MiMi Aung:** "The vehicles can be apart up to a kilometer or further ... The signal to noise ratio is extremely good. We can go beyond 1 kilometer distance."

[33:41](https://www.youtube.com/watch?v=BAlXe-U0ws4&t=2021) from: [NASA’s Ingenuity Mars Helicopter’s Next Steps (Media Briefing) Streamed live on 30 Apr 2021](https://youtu.be/BAlXe-U0ws4)

Distance for a single flight: **Bob Balaram:** “I think a total of 600 meters is not unreasonable. 2 minutes flight at 5 meters per second is a possibility. That’s probably where we'll see how well it does, and if there is more margin we can use for the flights. That's probably a good place to think of the limit.”

[1:01:20](https://youtu.be/BAlXe-U0ws4?t=3680) from: [NASA’s Ingenuity Mars Helicopter’s Next Steps (Media Briefing) Streamed live on 30 Apr 2021](https://youtu.be/BAlXe-U0ws4)

NASA, 2021prmtl, [Perseverance Rover, Mission Timeline › Landing](https://mars.nasa.gov/mars2020/timeline/landing/)

NASA, 2021wnpr, Watch NASA’s Perseverance Rover Land on Mars, Thomas Zurbukin at [14:45](https://youtu.be/gm0b_ijaYMQ?t=885)

***Macy Ragsdale:*** *Is anything alive on Mars?*

***Thomas Zurbuchen (NASA associate administrator):*** *That's a question i ask myself, is anything alive there, and frankly at the surface where we're going right now with Perseverance we do not believe there's anything alive right there, because of the radiation that's there, it's chilling cold and there's really no water there. But guess what we think that three billion years ago this looked like a stream that you may see on earth and frankly a lot more similar than Earth but water with a magnetic field just like the earth with an atmosphere and the question is at that time three billion years ago were there single cell organisms just off the type that developed on earth so is there life on on Mars overall we don't know but where we're going right now we're really looking for ancient life and that's what we're so excited about.*

NASA, 2022mpfs, [Fact Sheet Proposed Action](https://downloads.regulations.gov/NASA-2022-0002-0002/attachment_5.pdf), [MSR PEIS Fact Sheets](https://www.regulations.gov/document/NASA-2022-0002-0002)

NASA, 2022msr, [public comments](https://www.regulations.gov/document/NASA-2022-0002-0001), MSR, PEIS

NASA, 2022smsr [The Safety of Mars Sample Return](https://downloads.regulations.gov/NASA-2022-0002-0002/attachment_7.pdf), [MSR PEIS Fact Sheets](https://www.regulations.gov/document/NASA-2022-0002-0002)

*Such a Mars sample receiving facility would have design and sample handling requirements equivalent to those of biological safety laboratories used for research studies of infectious diseases. The well-established safety protocols and engineering controls used to isolate hazardous biological materials in such laboratories address issues that are very similar to those involved in Mars sample return. At this time, there are several options under study for implementing a Mars sample receiving facility.*

NASA, 2022nepa, [National Environmental Policy Act; Mars Sample Return Campaign](https://downloads.regulations.gov/NASA-2022-0002-0001/content.pdf) Federal Register / Vol. 87, No. 73 / Friday, April 15, 2022 / Notices

*The general scientific consensus is that the Martian surface is too inhospitable for life to survive there today. It is a freezing landscape with no liquid water that is continually bombarded with harsh radiation.*

*Scientists are interested in returning samples that may reveal what the Martian environment was like billions of years ago, when the planet was wetter and may have supported microbial life.*

*There is no current evidence that the samples collected by the Mars 2020 mission from the first few inches of the Martian surface could contain microorganisms that would be harmful to Earth’s environment.*

*Nevertheless, out of an abundance of caution and in accordance with NASA policy and regulations, NASA would implement measures to ensure that the Mars samples are contained (with redundant layers of containment) so that they could not impact humans or Earth’s environment, and the samples would remain contained until they are examined and confirmed safe for distribution to terrestrial science laboratories. NASA and its partners would use many of the basic principles that biological laboratories use today to contain, handle, and study materials that are known or suspected to be dangerous.*

NASA, 2022nic, [NASA Invites Comment on Initial Plans for Mars Sample Return Program](https://www.nasa.gov/press-release/nasa-invites-comment-on-initial-plans-for-mars-sample-return-program)

*NASA will consider all comments received during the scoping process in the subsequent development of the MSR Draft Environmental Impact Statement, which is currently scheduled to be released for public comment later this year.*

NASA, 2022wip, [*"Where is Perseverance?"*](https://mars.nasa.gov/mars2020/mission/where-is-the-rover/). Mars 2020 Mission Perseverance Rover

NASA, n.d.ame, [Atmosphere](https://marsed.asu.edu/mep/atmosphere), Mars Education

NASA, n.d.cls, [Curiosity's Landing Site: Gale Crater](https://mars.nasa.gov/msl/timeline/prelaunch/gale-crater/)

NASA, n.d.cm, [Chris McKay, at NASA Ames](https://www.nasa.gov/content/chris-mckay/)

NASA, n.d.dan, [Dynamic Albedo of Neutrons (DAN)](https://mars.nasa.gov/msl/spacecraft/instruments/dan/), see also archived page for scientists: [Dynamic Albedo of Neutrons (DAN)](https://web.archive.org/web/20210224030220/https://mars.nasa.gov/msl/spacecraft/instruments/dan/for-scientists/)

NASA, n.d.ecilm, [Eugene Cernan in Lunar Module](https://www.nasa.gov/content/images-of-astronaut-gene-cernan)

NASA, n.d.hsp, [Health Stabilization Program](https://www.nasa.gov/sites/default/files/atoms/files/health_stabilization_program_technical_brief_ochmo_021020.pdf)

NASA, n.d. mbtn, [Mars, by the numbers](https://solarsystem.nasa.gov/planets/mars/by-the-numbers/) surface area 144,371,391km2. This seems to be based on the volumetric mean radius of 3389.5 kilometers as 4\*pi\*3389.5^2. See [NASA n.d. Mars Fact Sheet](https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html)/ Since a sphere has the minimum surface area to volume ratio of any spheroid then the Martian area is at least this much.

NASA, n.d.mfs, [Mars Fact sheet](https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html)

NASA, n.d.monm, [Map of NASA's Mars Landing Sites](https://mars.nasa.gov/resources/24729/map-of-nasas-mars-landing-sites/)

NASA, n.d.MOXIE [MOXIE](https://mars.nasa.gov/mars2020/spacecraft/instruments/moxie/), and [MOXIE for scientists](https://mars.nasa.gov/mars2020/spacecraft/instruments/moxie/for-scientists/).

NASA, n.d. MSASL, [Martian seasons and solar longitude](http://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html) at: <http://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html> accessed on July 17, 202

NASA, n.d. PRLS, [Perseverance Rover's Landing Site: Jezero Crater](https://mars.nasa.gov/mars2020/mission/science/landing-site/), accessed at <https://mars.nasa.gov/mars2020/mission/science/landing-site/>, accessed on 17 July 2020.

NASA, n.d.sd, [Shield Development](https://hvit.jsc.nasa.gov/shield-development/)

NASA, n.d.,SEH,, [System Engineering Handbook](https://www.nasa.gov/seh/index.html), see particularly

2.5 [Cost Effectiveness considerations](https://www.nasa.gov/seh/2-5-cost-effectiveness-considerations#Fig2-5-1https://www.nasa.gov/seh/2-5-cost-effectiveness-considerations)

3.3 [Project Pre-Phase A: Concept Studies](https://www.nasa.gov/seh/3-3-project-pre-phase-a-concept-studies)

3.4 [Project Phase A: Concept and Technology Development](https://www.nasa.gov/seh/3-4-project-phase-a-concept-and-technology-development)

3.5 [Project Phase B: Preliminary Design and Technology Completion](https://www.nasa.gov/seh/3-5-project-phase-b-preliminary-design-and-technology-completion)

NASA, n.d.WiC, [Curiosity: Mission: Where is the rover?](https://mars.nasa.gov/msl/mission/where-is-the-rover/)

Curiosity landing site: 137.44°E, 4.589°S

NASA, n.d.WiP, [Where is Perseverance?](https://mars.nasa.gov/mars2020/mission/where-is-the-rover/)

Perseverance landing site: 18.45°N 77.45°E,

NASA, n.d. WISO, [What is Surface Operations?](https://mars.nasa.gov/mars2020/timeline/surface-operations/)

*drills core samples from about 30 promising rock and “soil” (regolith) targets and caches them on the Martian surface (Objective C)*

Naseem, M., Osmanoglu, Ö. and Dandekar, T., 2020. [Synthetic Rewiring of Plant CO₂ Sequestration Galvanizes Plant Biomass Production](https://www.sciencedirect.com/science/article/pii/S0167779919303142). *Trends in Biotechnology*, *38*(4), pp.354-359.

*The CETCH cycle requires less energy to operate than other aerobic CO₂ -fixation pathways. One limitation of CETCH is the production of glyoxylate, a less active metabolic intermediate that requires acetyl-CoA (AcCoA) or propanoyl-CoA [*[*3*](https://www.sciencedirect.com/science/article/pii/S0167779919303142#bb0015)*] for conversion into other metabolites. Also, glyoxylate is not well connected to other metabolic pathways. Despite functional impediments associated with any synthetically designed pathway, CETCH is the most efficient artificial cycle that fixes (in vitro) several-fold more CO₂ than does the natural CBB. The incorporation of CETCH-based enoyl-CoA carboxylase/reductases (ECRs) should be an excellent alternative to the native Calvin cycle. It can sequester approximately 80 CO₂ molecules per second (in vitro) compared with RuBisCO, which fixes two to five CO₂ molecules per second in plants.*

National Research Council. 2009. [Assessment of Planetary Protection Requirements for Mars Sample Return Missions (Report)](http://www.nap.edu/openbook.php?record_id=12576&page=28). p. 59.

"*It has been estimated that the planning, design, site selection, environmental reviews, approvals, construction, commissioning, and pre-testing of a proposed SRF will occur 7 to 10 years before actual operations begin. In addition, 5 to 6 years will likely be required for refinement and maturation of SRF-associated technologies for safely containing and handling samples to avoid contamination and to further develop and refine biohazard-test protocols. Many of the capabilities and technologies will either be entirely new or will be required to meet the unusual challenges of integration into an overall (end-to-end) Mars sample return program.*"

National Center for Biotechnology Information, 2022g, [PubChem Compound Summary for CID 750 ,Glycine](https://pubchem.ncbi.nlm.nih.gov/compound/Glycine)

National Center for Biotechnology Information, 2022t, [PubChem Compound Summary for CID 6305, Tryptophan](https://pubchem.ncbi.nlm.nih.gov/compound/Tryptophan). Retrieved May 20, 2022 from <https://pubchem.ncbi.nlm.nih.gov/compound/Tryptophan>.

Nealson, K.H., Inagaki, F. and Takai, K., 2005. [Hydrogen-driven subsurface lithoautotrophic microbial ecosystems (SLiMEs): do they exist and why should we care?](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1078.4608&rep=rep1&type=pdf). *Trends in microbiology*, *13*(9), pp.405-410.

Negi, S., Perrine, Z., Friedland, N., Kumar, A., Tokutsu, R., Minagawa, J., Berg, H., Barry, A.N., Govindjee, G. and Sayre, R., 2020. [Light regulation of light‐harvesting antenna size substantially enhances photosynthetic efficiency and biomass yield in green algae](https://lodgbot.com/wp-content/uploads/2020/05/13May20-The-Plant-Journal-Algae-photosynthesis-improvement.pdf). *The Plant Journal*.

*page 15: The NC-77 transgenic line, however, had a three-fold increase in bio-mass yield compared with wild-type. This increased bio-mass production in NC transgenics with adjustable light harvesting antenna sizes, however, raises the question why have algae and plants evolved large, less effi-cient, fixed light-harvesting antenna systems that oversaturate downstream electron transfer processes during most (80%) of the day. In mixed species environments, the abil-ity to shade or reduce the light available to competing spe-cies may offer a selective advantage, because limiting light availability to other species would reduce their growth rates and presumably their fitness (Zhuet al., 2008; Ortet al., 2015). Species competing for light are clearly impacted by shading as plant canopies close or as algal cultures reach high cell densities. Thus, having large light-harvesting antenna systems may reduce light availability for competitors and enhance fitness for plants or algae thatshade competitors as is the case in high-density algal cul-tures. In addition, plants living lower in the canopy or algae growing deeper in the water column often experi-ence very low light conditions.*

*Having a large light-harvesting antenna would allow photosynthesis and growth at light intensities that could not support the growth of algae with smaller antenna sizes optimized for growth at higher light intensities. In fact, algae that grow at extreme depths in the oceans have among the largest light-harvesting antenna sizes known in photosynthetic organisms (Yamazakiet al., 2005).*

Neukum, G., Jaumann, R., Hoffmann, H., Hauber, E., Head, J.W., Basilevsky, A.T., Ivanov, B.A., Werner, S.C., Van Gasselt, S., Murray, J.B. and McCord, T., 2004.. [Recent and episodic volcanic and glacial activity on Mars revealed by the High Resolution Stereo Camera](https://www.astroarts.org/downloads/pdfs/3121.pdf). *Nature*, *432*(7020), pp.971-979.

New York Times, 2015, [Mars Curiosity Browser Tracker](https://archive.nytimes.com/www.nytimes.com/interactive/science/space/mars-curiosity-rover-tracker.html#sol1059).

Nicholson, W.L., 2009. [Ancient micronauts: interplanetary transport of microbes by cosmic impacts](http://fire.biol.wwu.edu/cmoyer/zztemp_fire/biol345_F10/papers/Nicholson_lithopanspermia_TIM10.pdf). *Trends in microbiology*, *17*(6), pp.243-250.

Nicholson, W.L., Krivushin, K., Gilichinsky, D. and Schuerger, A.C., 2013. [Growth of Carnobacterium spp. from permafrost under low pressure, temperature, and anoxic atmosphere has implications for Earth microbes on Mars](https://www.pnas.org/content/110/2/666.short). Proceedings of the National Academy of Sciences, 110(2), pp.666-671.

Nicolau, M., Picault, N. and Moissiard, G., 2021. [The Evolutionary Volte-Face of Transposable Elements: From Harmful Jumping Genes to Major Drivers of Genetic Innovation](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8616336/). Cells, 10(11), p.2952

NIH, n.d. [Research on Microbial Biofilms](http://grants.nih.gov/grants/guide/pa-files/PA-03%E2%80%93047.htm).

Niles, P.B., Boynton, W.V., Hoffman, J.H., Ming, D.W. and Hamara, D., 2010. [Stable isotope measurements of Martian atmospheric CO₂ at the Phoenix landing site](http://web.gps.caltech.edu/classes/ge140a/Stable_Isotope_W19/Problem_Sets_files/Niles2010.pdf). science, 329(5997), pp.1334-1337. Press release: [Phoenix Mars Lander Finds Surprises About Planet’s Watery Past](https://news.arizona.edu/story/phoenix-mars-lander-finds-surprises-about-planet-s-watery-past) (University of Arizona)

Niles, P.B., Catling, D.C., Berger, G., Chassefière, E., Ehlmann, B.L., Michalski, J.R., Morris, R., Ruff, S.W. and Sutter, B., 2013. [Geochemistry of carbonates on Mars: implications for climate history and nature of aqueous environments](http://faculty.washington.edu/dcatling/Niles2012_CarbonatesOnMarsReview.pdf). Space Science Reviews, 174(1), pp.301-328.

Nisbet, E., Zahnle, K., Gerasimov, M.V., Helbert, J., Jaumann, R., Hofmann, B.A., Benzerara, K. and Westall, F., 2007. [Creating habitable zones, at all scales, from planets to mud micro-habitats, on Earth and on Mar](https://www.researchgate.net/profile/J_Helbert/publication/227269386_Creating_Habitable_Zones_at_all_Scales_from_Planets_to_Mud_Micro-Habitats_on_Earth_and_on_Mars/links/02e7e5391aa497b7f8000000.pdf)s. *Space science reviews*, *129*(1-3), pp.79-121

NOAA, n.d.cwcu, [Can we clean up, stop, or end harmful algal blooms?](https://oceanservice.noaa.gov/facts/hab-solutions.html)

NOAA, n.d.witd, [What is the difference between photosynthesis and chemosynthesis?](https://oceanexplorer.noaa.gov/facts/photochemo.html)

Noell, A.C., Fisher, A.M., Takano, N., Fors-Francis, K., Sherrit, S. and Grunthaner, F., 2016, October. Astrobionibbler: [In Situ Microfluidic Subcritical Water Extraction of Amino Acids](https://www.hou.usra.edu/meetings/ipm2016/pdf/4059.pdf). In *3rd International Workshop on Instrumentation for Planetary Mission* (Vol. 1980).

*anets*, *106*(E10), pp.23317-23326.

Noffke, N., 2015. [Ancient sedimentary structures in the< 3.7 Ga Gillespie Lake Member, Mars, that resemble macroscopic morphology, spatial associations, and temporal succession in terrestrial microbialites](http://s-t-a-t.faafoundation.org/471325/research-library/miscellaneous/ast-2E2014-2E1218.pdf). *Astrobiology*, *15*(2), pp.169-192.

Noffke, N., Christian, D., Wacey, D. and Hazen, R.M., 2013. [Microbially induced sedimentary structures recording an ancient ecosystem in the ca. 3.48 billion-year-old Dresser Formation, Pilbara, Western Australia](http://online.liebertpub.com/doi/pdfplus/10.1089/ast.2013.1030). Astrobiology, 13(12), pp.1103-1124.

Nolan, K., 2008. Mars: A cosmic stepping stone. In *MARS A Cosmic Stepping Stone* (pp. 105-115). Springer, New York, NY. For the triple point feedback suggestion see [page 137](https://books.google.co.uk/books?id=bW1h6SbxzxQC&pg=PA137).

Nott, J., 2009. [Titan: a distant but enticing destination for human visitor](https://www.researchgate.net/publication/26883114_Titan_A_Distant_But_Enticing_Destination_for_Human_Visitors)s. *Aviation, space, and environmental medicine*, *80*(10), pp.900-901.

Nyquist, L.E., Bogard, D.D., Shih, C.Y., Greshake, A., Stöffler, D. and Eugster, O., 2001. [Ages and geologic histories of Martian meteorites](https://www.researchgate.net/profile/Otto-Eugster/publication/225856700_Ages_and_Geologic_Histories_of_Martian_Meteorites/links/0deec524ec770d956b000000/Ages-and-Geologic-Histories-of-Martian-Meteorites.pdf). In *Chronology and evolution of Mars* (pp. 105-164). Springer, Dordrecht.

## O

Ocampo, C., 2005. [Trajectory analysis for the lunar flyby rescue of AsiaSat-3/HGS-1](https://nyaspubs.onlinelibrary.wiley.com/doi/abs/10.1196/annals.1370.021). Annals of the New York Academy of Sciences, 1065(1), pp.232-253.

Ojha, L., Wilhelm, M.B., Murchie, S.L., McEwen, A.S., Wray, J.J., Hanley, J., Massé, M. and Chojnacki, M., 2015. [Spectral evidence for hydrated salts in recurring slope lineae on Mars](http://astronomy.nmsu.edu/berdis/Ojha_etal.pdf). *Nature Geoscience*, *8*(11), p.829.

Oldenburg, K., 2019, [Mars Sample Return overview infographic](https://www.esa.int/ESA_Multimedia/Images/2019/05/Mars_Sample_Return_overview_infographic), ESA

Oleson, S.R., Landis, G.A., McGuire, M.L. and Schmidt, G.R., 2013. [HERRO mission to Mars using telerobotic surface exploration from orbit](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130011281.pdf)

Olsen, S.J., Chang, H.L., Cheung, T.Y.Y., Tang, A.F.Y., Fisk, T.L., Ooi, S.P.L., Kuo, H.W., Jiang, D.D.S., Chen, K.T., Lando, J. and Hsu, K.H., 2003. [Transmission of the severe acute respiratory syndrome on aircraft](https://www.nejm.org/doi/full/10.1056/NEJMoa031349). *New England Journal of Medicine*, *349*(25), pp.2416-2422.

O'Malley-James, J.T., Greaves, J.S., Raven, J.A. and Cockell, C.S., 2013. [Swansong biospheres: refuges for life and novel microbial biospheres on terrestrial planets near the end of their habitable lifetimes](https://arxiv.org/abs/1210.5721). *International Journal of Astrobiology*, *12*(2), pp.99-112.

O'Malley-James, J.T., Cockell, C.S., Greaves, J.S. and Raven, J.A., 2014. [Swansong biospheres II: The final signs of life on terrestrial planets near the end of their habitable lifetimes](https://arxiv.org/abs/1310.4841). *International Journal of Astrobiology*, *13*(3), pp.229-243.

O'Malley-James, J.T., 2014. [*Life at the end of worlds: modelling the biosignatures of microbial life in diverse environments at the end of the habitable lifetimes of Earth-like planets*](https://core.ac.uk/download/pdf/30318019.pdf) (Doctoral dissertation, University of St Andrews).

Onstott, T.C., Ehlmann, B.L., Sapers, H., Coleman, M., Ivarsson, M., Marlow, J.J., Neubeck, A. and Niles, P., 2019. [Paleo-rock-hosted life on Earth and the search on Mars: a review and strategy for exploration](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6786346/). Astrobiology, 19(10), pp.1230-1262.

A critical nutrient to the expansion of both subsurface and surface life on any planet is the availability of nitrogen as an aqueous species. On Earth, microorganisms evolved the ability to fix N2 into ammonia with the development of nitrogenase to overcome this constraint. Nitrogenases, Nif proteins, are complex enzymes, utilizing iron, molybdenum, and/or vanadium, that exist in both bacterial and archaeal domains. Phylogenetic comparison of genes that comprise nitrogenases and a complement of proteins required for their regulation indicate that nitrogenases emerged in anoxic sulfidic environments on Earth within obligate anaerobic thermophilic methanogens and were transferred to obligate anaerobic clostridia (Boyd et al., 2015), both common subsurface microorganisms. As Nif proteins were adopted first by the aerobic diazotrophic lineage Actinobacteria and then by the more recently evolved aerobic Proteobacterial and Cyanobacterial lineages, the Nif protein suite became more complex to protect the core MoFe-bearing proteins from O2 (Boyd et al., 2015). Although it is not clear whether the emergence of the more complex protein occurred prior to or after the Great Oxidation Event, it is certain that the ancestral protein emerged in an anoxic environment when the demands for aqueous nitrogen species exceeded the abiotic supply. The implications for martian ecosystems are that nitrogenase would have also likely emerged within an anaerobic subsurface environment, not in the oxic surface environment.

Experiments on the effects of low pN2 on diazotrophic nitrogen-fixing soil bacteria have shown that they could grow in N2 partial pressures of 5 mbar but not 1 mbar (Klingler et al., 1989). This result suggests that further experiments on wild-type species are required to determine whether the evolution of pN2 in the martian atmosphere was a significant deterrent to the expansion of early life, especially after Mars lost most of its atmosphere. Analyses of the nitrogen budget and of nitrogen cycling from deep subsurface environments in South Africa indicate that the pN2 is higher at depth than on the surface, that most of this N2 originates from the rock formations through nitrogen cycling, and that N2 is being actively fixed in the subsurface by microbial communities (Silver et al., 2012; Lau et al., 2016b). Given the presence of a cryosphere barrier to diffusion on Mars, the nitrogen availability and perhaps even the pN2 of subsurface brines are likely to be higher there than on the martian surface.

…

*Meter-sized Fe(II)-rich carbonate/iron oxide concretions (Fig. 4) are found in Jurassic sandstone deposits of southwest Colorado that were formed at hundreds of meters' depth between 2 and 0.5 Ma as the Colorado River Basin was uplifted (McBride et al., 2003; Loope et al., 2010). Similar-sized ferroan calcite and siderite concretions occur in Late Paleocene/Early Eocene Wasatch Group sandstones, and siderite nodule-bearing cores from the formation (Lorenz et al., 1996) yielded thermophilic Fe(III)-reducing bacteria that were capable of producing prodigious quantities of siderite (Roh et al., 2002). In subaqueous systems unconstrained by rock matrix, authigenic carbonate mounds at CH4 and hydrocarbon seeps, formed from carbon mobilized by methane- and alkane-oxidizing microorganisms (Greinert et al., 2001; Formolo et al., 2004; Ussler and Paull, 2008), can be hundreds of meters tall and more than a kilometer wide (Klaucke et al., 2008).*

OpenClipArt, n.d., [Etiquette CD rom](https://commons.wikimedia.org/wiki/File:Etiquette_cd-rom_01.svg)

Oren, A., Bardavid, R.E. and Mana, L., 2014. [Perchlorate and halophilic prokaryotes: implications for possible halophilic life on Mars](https://pubmed.ncbi.nlm.nih.gov/24150694/). *Extremophiles*, *18*(1), pp.75-80.

Orosei, R., Lauro, S.E., Pettinelli, E., Cicchetti, A., Coradini, M., Cosciotti, B., Di Paolo, F., Flamini, E., Mattei, E., Pajola, M. and Soldovieri, F., 2018. [Radar evidence of subglacial liquid water on Mars](https://science.sciencemag.org/content/361/6401/490). *Science*, *361*(6401), pp.490-493.

Ort, D.R., Merchant, S.S., Alric, J., Barkan, A., Blankenship, R.E., Bock, R., Croce, R., Hanson, M.R., Hibberd, J.M., Long, S.P. and Moore, T.A., 2015. [Redesigning photosynthesis to sustainably meet global food and bioenergy demand](https://www.pnas.org/content/pnas/112/28/8529.full.pdf). *Proceedings of the national academy of sciences*, *112*(28), pp.8529-8536.

*page 8530: A principal limitation of efficient photosynthesis is that organisms absorb more light in full sunlight than they can use productively. The reason seems clear: high absorptivity provides effective capture at low light intensities, such as at dawn and dusk and on cloudy days, and it obviates competition from other phototrophs by absorbing the light before they do.*

Osman, S., Peeters, Z., La Duc, M.T., Mancinelli, R., Ehrenfreund, P. and Venkateswaran, K., 2008. [Effect of shadowing on survival of bacteria under conditions simulating the Martian atmosphere and UV radiation](http://aem.asm.org/content/74/4/959.full). *Applied and Environmental Microbiology*, *74*(4), pp.959-970.

## P

Paige, D.A., 2000, July. [Mars exploration strategies: Forget about sample return](http://www.lpi.usra.edu/meetings/robomars/pdf/6199.pdf). In *Concepts and Approaches for Mars Exploration* (p. 243).

Parfrey, L.W., Lahr, D.J., Knoll, A.H. and Katz, L.A., 2011. [Estimating the timing of early eukaryotic diversification with multigene molecular clocks](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3158185/). *Proceedings of the National Academy of Sciences*, *108*(33), pp.13624-13629.

Parnell, J., Brolly, C., Spinks, S. and Bowden, S., 2016. [Metalliferous biosignatures for deep subsurface microbial activity](https://link.springer.com/article/10.1007%2Fs11084-015-9466-x). Origins of Life and Evolution of Biospheres, 46(1), pp.107-118.

Parro, V., de Diego-Castilla, G., Moreno-Paz, M., Blanco, Y., Cruz-Gil, P., Rodríguez-Manfredi, J.A., Fernández-Remolar, D., Gómez, F., Gómez, M.J., Rivas, L.A. and Demergasso, C., 2011. [A microbial oasis in the hypersaline Atacama subsurface discovered by a life detector chip: implications for the search for life on Mars](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3242637/). *Astrobiology*, *11*(10), pp.969-996.

Pasini, D., 2014, April. [Panspermia Survival Scenarios for Organisms that Survive Typical Hypervelocity Solar System Impact Events](http://adsabs.harvard.edu/abs/2014EPSC....9...68P). In *European Planetary Science Congress* (Vol. 9).

Pavlov, A.K., Kalinin, V.L., Konstantinov, A.N., Shelegedin, V.N. and Pavlov, A.A., 2006. [Was Earth ever infected by Martian biota? Clues from radioresistant bacteria](https://biochem.wisc.edu/sites/default/files/labs/cox/pdfs/38.pdf). *Astrobiology*, *6*(6), pp.911-918

Peplow, M., 2016. [Mirror-image enzyme copies looking-glass DNA](https://www.nature.com/articles/nature.2016.19918). *Nature News*, *533*(7603), p.303.

Pérez-Brocal, V., Latorre, A. and Moya, A., 2011. [Symbionts and pathogens: what is the difference?](https://www.uv.es/biodiver/pdfs/PerezBrocal2013-2.pdf). In *Between pathogenicity and commensalism* (pp. 215-243). Springer, Berlin, Heidelberg.

Pfaller, M.A. and Diekema, D.J., 2004. [Rare and emerging opportunistic fungal pathogens: concern for resistance beyond Candida albicans and Aspergillus fumigatus](https://jcm.asm.org/content/jcm/42/10/4419.full.pdf). Journal of clinical microbiology, 42(10), pp.4419-4431.

*The field of medical mycology has become an extremely challenging study of infections caused by a wide and taxonomically diverse array of opportunistic fungi.*

*The message to both clinicians and clinical microbiologists is that there are no uniformly nonpathogenic fungi: any fungus can cause a lethal infection in a sufficiently immunocompromised host and should never be dismissed out of hand as a contaminant.*

Phillips, C.R., 1974. [The planetary quarantine program: Origins and achievements, 1956-1973](https://ntrs.nasa.gov/api/citations/19750006598/downloads/19750006598.pdf) (Vol. 4902). Scientific and Technical Information Office, National Aeronautics and Space Administration.

Phillips, T., 2008, [Moondust and Duct Tape](https://science.nasa.gov/science-news/science-at-nasa/2008/21apr_ducttape)

Pikuta, E.V., Hoover, R.B., Klyce, B., Davies, P.C. and Davies, P., 2006, September. [Bacterial utilization of L-sugars and D-amino acids](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/6309/63090A/Bacterial-utilization-of-L-sugars-and-D-amino-acids/10.1117/12.690434.short). In *Instruments, Methods, and Missions for Astrobiology IX* (Vol. 6309, p. 63090A). International Society for Optics and Photonics.

Pikuta, E.V. and Hoover, R.B., 2010, September. [Utilization of alternate chirality enantiomers in microbial communities](https://www.researchgate.net/profile/Elena_Pikuta/publication/253435043_Utilization_of_alternate_chirality_enantiomers_in_microbial_communities/links/552c37a10cf29b22c9c443d9.pdf). In *Instruments, Methods, and Missions for Astrobiology XIII* (Vol. 7819, p. 78190P). International Society for Optics and Photonics.

Pikuta, E.V., Menes, R.J., Bruce, A.M., Lyu, Z., Patel, N.B., Liu, Y., Hoover, R.B., Busse, H.J., Lawson, P.A. and Whitman, W.B., 2016. [Raineyella antarctica gen. nov., sp. nov., a psychrotolerant, d-amino-acid-utilizing anaerobe isolated from two geographic locations of the Southern Hemisphere](http://riquim.fq.edu.uy/archive/files/6dc14dcd6641d2e6d706d6f3e5923446.pdf). *International journal of systematic and evolutionary microbiology*, *66*(12), pp.5529-5536.

Pires, F. 2015, [“Mars liquid water: Curiosity confirms favorable conditions”](http://ns.umich.edu/new/releases/22815-mars-liquid-water-curiosity-confirms-favorable-conditions), Michigan news.

*"Life as we know it needs liquid water to survive. While the new study interprets Curiosity's results to show that microorganisms from Earth would not be able to survive and replicate in the subsurface of Mars, Rennó sees the findings as inconclusive. He points to biofilms—colonies of tiny organisms that can make their own microenvironment."*

Pires, P. and Winter, O.C., 2020. [Location and stability of Distant Retrograde Orbits around the Moon](https://academic.oup.com/mnras/article-abstract/494/2/2727/5817352?redirectedFrom=PDF). *Monthly Notices of the Royal Astronomical Society*, *494*(2), pp.2727-2735.

Pla-García, J., Rafkin, S.C.R., Martinez, G.M., Vicente-Retortillo, Á., Newman, C.E., Savijärvi, H., de la Torre, M., Rodriguez-Manfredi, J.A., Gómez, F., Molina, A. and Viúdez-Moreiras, D., 2020. [Meteorological predictions for Mars 2020 Perseverance rover landing site at Jezero crater](https://link.springer.com/article/10.1007/s11214-020-00763-x). *Space science reviews*, *216*(8), pp.1-21.

Poch, O., Istiqomah, I., Quirico, E., Beck, P., Schmitt, B., Theulé, P., Faure, A., Hily-Blant, P., Bonal, L., Raponi, A. and Ciarniello, M., 2020. [Ammonium salts are a reservoir of nitrogen on a cometary nucleus and possibly on some asteroid](https://arxiv.org/ftp/arxiv/papers/2003/2003.06034.pdf)s. Science, 367(6483), p.eaaw7462. Researcher's announcement: [Cometary nitrogenous salts tell about the Solar System’s history](https://thesciencebreaker.org/breaks/earth-space/cometary-nitrogenous-salts-tell-about-the-solar-systems-history)

Comentary: [Finding comets’ hidden nitrogen](https://cen.acs.org/physical-chemistry/astrochemistry/Finding-cometshidden-nitrogen/98/web/2020/03)

Pray, L., 2008. [Transposons, or jumping genes: Not junk DNA](https://www.nature.com/scitable/topicpage/transposons-the-jumping-genes-518/). *Nature Education*, *1*(1), p.32.

Preva, n.d., [Preva Dental X-ray System](https://www.midmark.com/docs/librariesprovider2/pdfs/00-02-1576-rev-za1-preva-user-manual.pdf?sfvrsn=3ac0e91c_4)

*The maximum momentary line current (less than 5 s) of the Preva is 10 A when operated on 120 V (1.2 kW). Operation at higher input voltage will reduce the maximum current (5 A at 240 V). The technique factors producing the maximum momentary line current are 65 kV, 7 mA, 2 s*

PubChem, n.d., [Bisphenol A](https://pubchem.ncbi.nlm.nih.gov/compound/Bisphenol-A#datasheet=LCSS.), Retrieved October 15, 2020 from <https://pubchem.ncbi.nlm.nih.gov/compound/Bisphenol-A#datasheet=LCSS>.

Puente-Sánchez, F., Arce-Rodríguez, A., Oggerin, M., García-Villadangos, M., Moreno-Paz, M., Blanco, Y., Rodríguez, N., Bird, L., Lincoln, S.A., Tornos, F. and Prieto-Ballesteros, O., 2018. [Viable cyanobacteria in the deep continental subsurface](https://www.pnas.org/content/pnas/115/42/10702.full.pdf). *Proceedings of the National Academy of Sciences*, *115*(42), pp.10702-10707

Pugel, B., Popescu, S. and Madad, S., 2020. [Restricted and Uncontained: Health Considerations in the Event of Loss of Containment During the Restricted Earth Return of Extraterrestrial Samples](https://www.liebertpub.com/doi/abs/10.1089/hs.2019.0088). Health security, 18(2), pp.132-138.

Pugel, D.B., Rummel, J.D. and Conley, C., 2017, March. [Brushing your spacecraft's teeth: A review of biological reduction processes for planetary protection missions](https://ntrs.nasa.gov/api/citations/20170002044/downloads/20170002044.pdf). In *2017 IEEE Aerospace Conference* (pp. 1-10). IEEE.

[Pusey, C., 2012,](https://commons.wikimedia.org/wiki/File:1DNA.gif) DNA groove animation based on PDB [1DNH](http://www.rcsb.org/structure/1DNH)

## Q

Quinn, R.C., Martucci, H.F., Miller, S.R., Bryson, C.E., Grunthaner, F.J. and Grunthaner, P.J., 2013. [Perchlorate radiolysis on Mars and the origin of Martian soil reactivity](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3691774/). *Astrobiology*, *13*(6), pp.515-520.

## R

Race, M. S., 1996, [Planetary Protection, Legal Ambiguity, and the Decision Making Process for Mars Sample Return](https://web.archive.org/web/20100619123320/http://salegos-scar.montana.edu/docs/Planetary%20Protection/AdvSpaceResVol18(1-2).pdf) Adv. Space Res. vol 18 no 1/2 pp (1/2)345-(1/2)350

Race, M.S. and Randolph, R.O., 2002. [The need for operating guidelines and a decision making framework applicable to the discovery of non-intelligent extraterrestrial life](https://www.bestlibrary.org/sc9/files/ethics_space.pdf). *Advances in Space Research*, *30*(6), pp.1583-1591

Race, M. R., Johnson, J.E., Spry, J.A., Siegel, B., Conley, C., 2015, [Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions Workshop Report](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160012793.pdf), NASA Ames Research Center

*"Obviously, the current understanding of microbe survival in Mars dust environments remains uncertain and represents an important knowledge gap"*(page 34)

Raffensperger, C., 1998, [The Wingspread Consensus Statement on the Precautionary Principle](https://web.archive.org/web/20010622225811/http://www.sehn.org/wing.html)

Rahman, M.A., Sinha, S., Sachan, S., Kumar, G., Singh, S.K. and Sundaram, S., 2014. [Analysis of proteins involved in the production of MAA׳ s in two Cyanobacteria Synechocystis PCC 6803 and Anabaena cylindrica](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4135294/). Bioinformation, 10(7), p.449.

Randolph, R. 2009, [Chapter 10, A Christian Perspective](https://books.google.co.uk/books?id=TljowmgtdcYC&pg=PA292), in Bertka, C.M. ed., 2009. Exploring the Origin, Extent, and Future of Life: Philosophical, Ethical and Theological Perspectives (Vol. 4),. Cambridge University Press.

Ranjan, S., 2017. [The UV Environment for Prebiotic Chemistry: Connecting Origin-of-Life Scenarios to Planetary Environments](https://dash.harvard.edu/bitstream/handle/1/41142052/RANJAN-DISSERTATION-2017.pdf?sequence=1) (Doctoral dissertation).

193:

*Meteorite analysis has detected boron in Martian clays, important for abiogenesis since borate minerals can stabilize ribose and catalyze other prebiotic chemistry reactions (see Stephenson et al. 2013 and sources therein). Mars may also have enjoyed greater availability of prebiotically important phosphate than Earth (Adcock et al. 2013). Climate models suggest liquid water was transient on Mars (Wordsworth et al. 2013b), which suggests the evidence of wet/dry cycles. Such cycles are useful for prebiotic chemistry: aqueous eras are beneficial for the formation of biotic monomers, while dry eras tend to concentrate feedstock molecules and aid monomer polymerization (Benner & Kim 2015), relevant to the formation of nucleotides and amino acids (Patel et al. 2015). Finally, the putative dryness of Mars and the potential acidity of its early aqueous environment owing to dissolved carbonic acid from a CO₂ -dominated atmosphere, suggest molybdate, which is suggested to catalyze formation of prebiotically important sugars such as ribose, may have been stable on Mars (Benner & Kim 2015; Benner et al. 2010). Hence, there is growing interest in the possibility that prebiotically important molecules may have been produced on Mars (Benner 2013), and even the hypothesis that life may have originated on Mars and been seeded to Earth (Kirschvink & Weiss 2002; Gollihar et al. 2014; Benner & Kim 2015)*

Redd, N.T., 2015, [How Much Contamination is Okay on Mars 2020 Rover?](http://www.astrobio.net/mars/how-much-contamination-is-okay-on-mars-2020-rover/), NASA Astrobiology magazine

Renno, N., 2014, [How liquid water forms on Mars](https://www.youtube.com/watch?v=iLWv9UGwjdE), YouTube video, [University of Michigan Engineering](https://www.youtube.com/channel/UCSvOdBJgMnTYsK-cZIGZSYQ) (transcript from [1:48 onwards](https://youtu.be/iLWv9UGwjdE?t=108))

Rettberg, P., Anesio, A.M., Baker, V.R., Baross, J.A., Cady, S.L., Detsis, E., Foreman, C.M., Hauber, E., Ori, G.G., Pearce, D.A. Pearce, D.A. and Renno, N.O., 2016. [Planetary protection and Mars special regions—a suggestion for updating the definition.](https://scholarworks.montana.edu/xmlui/bitstream/handle/1/13172/17-014_Planetary_Protection_and_Mars_A1b.pdf?sequence=1&isAllowed=y)

Richardson, T.L., 2019. [Mechanisms and pathways of small-phytoplankton export from the surface ocean](https://www.researchgate.net/profile/Tammi_Richardson/publication/326334015_Mechanisms_and_Pathways_of_Small-Phytoplankton_Export_from_the_Surface_Ocean/links/5e172957a6fdcc28376390eb/Mechanisms-and-Pathways-of-Small-Phytoplankton-Export-from-the-Surface-Ocean.pdf). *Annual Review of Marine Science*, *11*, pp.57-74.

Richmond, J.Y. and McKinney, R.W., 2000. [Primary containment for biohazards: selection, installation and use of biological safety cabinets](https://www.who.int/ihr/training/laboratory_quality/3_cd_rom_bsc_selection_use_cdc_manual.pdf).

Roberts, D. and Marks, R., 1980. [The determination of regional and age variations in the rate of desquamation: a comparison of four techniques](https://core.ac.uk/download/pdf/82322877.pdf). Journal of Investigative Dermatology, 74(1), pp.13-16. See figures 3-4.

Rodriguez, J.A.P., Fairén, A.G., Tanaka, K.L., Zarroca, M., Linares, R., Platz, T., Komatsu, G., Miyamoto, H., Kargel, J.S., Yan, J. and Gulick, V., 2016. [Tsunami waves extensively resurfaced the shorelines of an early Martian ocean](https://www.nature.com/articles/srep25106). *Scientific reports*, *6*(1), pp.1-8.

Rosengren, A.J. and Scheeres, D.J., 2014. [Laplace plane modifications arising from solar radiation pressure](https://iopscience.iop.org/article/10.1088/0004-637X/786/1/45). The Astrophysical Journal, 786(1), p.45.

Rosengren, A.J., Scheeres, D.J. and McMahon, J.W., 2013. [Long-term dynamics and stability of GEO orbits: the primacy of the Laplace plane](https://www.researchgate.net/profile/Aaron_Rosengren/publication/287471546_Long-term_dynamics_and_stability_of_GEO_orbits_The_primacy_of_the_laplace_plane/links/56795cf308ae0d45249b34ab.pdf). In Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, South Carolina, Paper AAS (pp. 13-865).  
  
Also as Rosengren, A.J., Scheeres, D.J. and McMahon, J.W., 2014. [The classical Laplace plane as a stable disposal orbit for geostationary satellites](http://commercialspace.pbworks.com/w/file/fetch/88916768/Rosengren,%20Scheeres%202014.pdf). Advances in Space Research, 53(8), pp.1219-1228.

Roth, V.R., Arduino, M.J., Nobiletti, J., Holt, S.C., Carson, L.A., Wolf, C.F.W., Lenes, B.A., Allison, P.M. and Jarvis, W.R., 2000. [Transfusion‐related sepsis due to Serratia liquefaciens in the United States](https://onlinelibrary.wiley.com/doi/abs/10.1046/j.1537-2995.2000.40080931.xw4vwk/darpa-repair-satellite-rsgs). Transfusion, 40(8), pp.931-935.

Rothschild, L.J., 1995. [A “cryptic” microbial mat: A new model ecosystem for extant life on Mars](https://www.sciencedirect.com/science/article/abs/pii/S027311779980088X). Advances in Space Research, 15(3), pp.223-228.

Rothschild, L.J. and Giver, L.J., 2002. [Photosynthesis below the surface in a cryptic microbial mat](https://www.researchgate.net/publication/231914776_Photosynthesis_below_the_surface_in_a_cryptic_microbial_mat). *International Journal of Astrobiology*, *1*(4), p.295.

Rucker, M., 2017. [Dust storm impacts on human Mars mission equipment and operations.](https://core.ac.uk/download/pdf/84914099.pdf)

Rummel, J., Race, M., Nealson, K., ["No Threat? No Way"](https://www.planetary.org/planetary-report/tpr-2000-6), The Planetary Report Nov/Dec. 2000

Contains:

* ***A Case for Caution*** by John Rummel, NASA'S planetary protection officer at the time, and previously, NASA senior scientist for Astrobiology
* ***Hazardous Until Proven Otherwise***, by Margaret Race, a biologist working on planetary protection and Mars sample return for the SETI Institute and specialist in environment impact analysis
* ***Practical Safe Science*** by Kenneth Nealson, Director of the Center of Life Detection at NASA's JPL at the time.

Rummel, J.D., Race, M.S., DeVinenzi, D.L., Schad, P.J., Stabekis, P.D., Viso, M. and Acevedo, S.E., 2002. [A draft test protocol for detecting possible biohazards in Martian samples returned to Earth](https://explorers.larc.nasa.gov/HPMIDEX/pdf_files/07_MSRDraftTestProtocol.pdf).

*Pages 94-5: Questions about the adequacy of the SRF to maintain the new life form must also be addressed, including the possible need to add equipment, change operations, review emergency plans, or upgrade the facilities because of what has been found.*

*Concerns about security should also be reconsidered, especially in view of the potential disruptive activities of any terrorists or ‘radical’ groups that may be opposed to sample return. The advisability of allowing distribution of untested sample material outside the SRF2684* may need to be reconsidered, as well.

*Plans should be developed well in advance in order to avoid a frenzied, reactive mode of communications between government officials, the scientific community, the mass media, and the public. Any plan that is developed should avoid a NASA-centric focus by including linkages with other government agencies, international partners, and external organizations, as appropriate. It will also be advisable to anticipate the kinds of questions the public might ask, and to disclose information early and often to address their concerns, whether scientific or non-scientific.  
...*

*Evaluations of the proposal should be conducted both internal and external to NASA and Centre National d’Etudes Spatiale (CNES) and the space research communities in the nations participating in the mission. An ethical review should be conducted at least at the level of the Agencies participating and these reviews made public early in the process (in France, the national bioethics committee, Comité Consultatif National d'Ethique pour les Sciences de la Vie et de la Santé, CCNE, is the appropriate organization). The final protocol should be announced broadly to the scientific community with a request for comments and input from scientific societies and other interested organizations. Broad acceptance at both lay public and scientific levels is essential to the overall success of this research effort.*

In the long term, the discovery of extraterrestrial life, whether extant or extinct, in situ or within returned sample materials, will also have implications beyond science and the SRF per se. Such a discovery would likely trigger a review of sample return missions, and plans for both robotic and human missions. Legal questions could arise about ownership of the data, or of the entity itself, potentially compounded by differences in laws between the United States and the countries of international partners. In any event, ethical, legal and social issues should be considered seriously. Expertise in these areas should be reflected in the membership on appropriate oversight committee(s).

Page 101: **Communications** Unusual or unprecedented scientific activities are often subject to extreme scrutiny at both the scientific and political levels. Therefore, a communication plan must be developed as early as possible to ensure timely, and accurate dissemination of information to the public about the sample return mission, and to address concerns and perceptions about associated risks. The communication plan should be pro-active and designed in a manner that allows the public and stakeholders to participate in an open, honest dialogue about all phases of the mission with NASA, policy makers, and international partners. Risk management and planetary protection information should be balanced with education/outreach from the scientific perspective about the anticipated benefits and uncertainties associated with Mars exploration and sample return.

The communication plan should also address how the public and scientific community will be informed of results and findings during Life Detection and Biohazard testing, including the potential discovery of extraterrestrial life. Because of the intense interest likely during initial sample receipt, containment, and testing, procedures and criteria should be developed in advance for determining when and how observations or data may be designated as “results suitable for formal announcement.” Details about the release of SRF information, the management of the communication plan, and its relationship to the overall communications effort of the international Mars exploration program should be decided well in advance of the implementation of this protocol.

Rummel, J.D., Beaty, D.W., Jones, M.A., Bakermans, C., Barlow, N.G., Boston, P.J., Chevrier, V.F., Clark, B.C., de Vera, J.P.P., Gough, R.V. and Hallsworth, J.E., 2014. [A new analysis of Mars “special regions”: findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2)](https://www.researchgate.net/profile/David_Beaty/publication/268444482_A_new_analysis_of_Mars_Special_Regions_findings_of_the_second_MEPAG_Special_Regions_Science_Analysis_Group_SR-SAG2/links/547c9b0b0cf27ed9786229dd.pdf)

Rummel, J. D., Conley C. A, 2017,.[Four fallacies and an oversight: searching for Martian life](http://online.liebertpub.com/doi/full/10.1089/ast.2017.1749) *Astrobiology*, *17*(10), pp. 971-974.

Rummel, J.D. and Conley, C.A., 2018. [Inadvertently Finding Earth Contamination on Mars Should Not Be a Priority for Anyone](https://www.liebertpub.com/doi/abs/10.1089/ast.2017.1785?journalCode=ast). *Astrobiology*, *18*(2), pp.108-115.

Rutkin, A., 2014. [X-ray medicine blasts off to space](https://www.newscientist.com/article/2004086-first-medical-x-ray-scanner-heads-for-space-station/). *New scientist*, (2974), p.14.

## S

Sagan, C, 1961. [Organic matter and the Moon](https://www.nap.edu/download/18476)., National Academy of Sciences.

[*Page 23*](https://www.nap.edu/read/18476/chapter/5#23)*: It is remarkable that the depth at which surviving lunar organic matter is expected to be localized (section II) is just the depth at which temperatures appear to be optimum for familiar organisms (section IV). At such temperatures and depths, some moisture should be expected, arising from meteoritic and organic bound water. Watson, Murray and Brown (1961) have recently pointed out that ice could have been retained on permanently shaded areas of the Moon. These circumstances provide all the survival requirements of many terrestrial organisms - water and their metabolites, appropriate temperature, and negligible radiation. That autochthons evolving with the changing environment could also survive under these conditions is far from inconceivable.*

Sagan, C., Levinthal, E.C. and Lederberg, J., 1968. [Contamination of Mars](https://profiles.nlm.nih.gov/ps/access/BBABJH.ocr). *Science*, *159*(3820), pp.1191-1196.

*"The prominent dust storms and high wind velocities previously referred to imply that aerial transport of contaminants will occur on Mars. While it is probably true that a single unshielded terrestrial microorganism on the Martian surface ... would rapidly be enervated and killed by the ultraviolet flux, ... The Martian surface material certainly contains a substantial fraction of ferric oxides, which are extremely strongly absorbing in the near ultraviolet. ... A terrestrial microorganism imbedded in such a particle can be shielded from ultraviolet light and still be transported about the planet."*

*…*

*"A single terrestrial microorganism reproducing as slowly as once a month on Mars would, in the absence of other ecological limitations, result in less than a decade in a microbial population of the Martian soil comparable to that of the Earth's. This is an example of heuristic interest only, but it does indicate that the errors in problems of planetary contamination may be extremely serious."*

Sagan, C., 1973, [*The Cosmic Connection - an Extraterrestrial Perspective*](https://www.e-reading.life/bookreader.php/148581/Sagan_-_The_Cosmic_Connection___An_Extraterrestrial_Perspective.pdf)

*I reach this conclusion reluctantly. I, myself, would love to be involved in the first manned expedition to Mars. But an exhaustive program of unmanned biological exploration of Mars is necessary first****. The likelihood that such pathogens exist is probably small, but we cannot take even a small risk with a billion lives.*** *Nevertheless, I believe that people will be treading the Martian surface near the beginning of the twenty-first century.*

Sagan, C., 1977. [Reducing greenhouses and the temperature history of Earth and Mars](https://www.nature.com/articles/269224a0). *Nature*, *269*(5625), pp.224-226.

Sagan, C., 1980., *Cosmos: The Story of Cosmic Evolution, Science and Civilisation*

full quote:

*The surface area of Mars is exactly as large as the land area of the Earth. A thorough reconnaissance will clearly occupy us for centuries. But there will be a time when Mars is all explored; a time after robot aircraft have mapped it from aloft, a time after rovers have combed the surface, a time after samples have been returned safely to Earth, a time after human beings have walked the sands of Mars. What then? What shall we do with Mars?*

*There are so many examples of human misuse of the Earth that even phrasing this question chills me. If there is life on Mars, I believe we should do nothing with Mars. Mars then belongs to the Martians, even if the Martians are only microbes. The existence of an independent biology on a nearby planet is a treasure beyond assessing, and the preservation of that life must, I think, supersede any other possible use of Mars.*

Sagan, C., 1997. [Pale blue dot: A vision of the human future in space](http://www.planetary.org/explore/space-topics/earth/pale-blue-dot.html). Random House Digital, Inc..

Sakai, H., Tanaka, T. and Itoh, T., 2007. [Birth and death of genes promoted by transposable elements in Oryza sativa](https://www.sciencedirect.com/science/article/abs/pii/S0378111906007104). *Gene*, *392*(1-2), pp.59-63.

Sakimoto, K.K., Wong, A.B. and Yang, P., 2016. [Self-photosensitization of nonphotosynthetic bacteria for solar-to-chemical production](http://nanowires.berkeley.edu/wp-content/uploads/2016/01/Science-2016-Sakimoto-74-7.pdf). *Science*, *351*(6268), pp.74-77.

Sakon, J.J. and Burnap, R.L., 2005, March. [A Further Analysis of Potential Photosynthetic Life on Mars](https://www.lpi.usra.edu/meetings/lpsc2005/pdf/2120.pdf). In *36th Annual Lunar and Planetary Science Conference* (Vol. 36).

Sakon, J.J. and Burnap, R.L., 2006. [An analysis of potential photosynthetic life on Mars. *International Journal of Astrobiology*](https://www.cambridge.org/core/journals/international-journal-of-astrobiology/article/an-analysis-of-potential-photosynthetic-life-on-mars/7E87D8A6D505F4055573F1FDA7F38F39), *5*(2), pp.171-180.

Salisbury, F.B., Gitelson, J.I. and Lisovsky, G.M., 1997. [Bios-3: Siberian experiments in bioregenerative life support](https://watermark.silverchair.com/47-9-575.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAagwggGkBgkqhkiG9w0BBwagggGVMIIBkQIBADCCAYoGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMAn30iIATHHfo3IzKAgEQgIIBW5cJ0jDcFk88OpPF03DGC7GoFnIizdVd7i6LEefG4HorO5QRi_NEhuqBtEEIJeqcAQokndkxx6tdiNzc1Bp6pReVMsInwTXaDnWjt6mxN_evtUMJyrR2lWVekbDR-PCEgTUPWQZyHl-s6ubsGFBXZQgg92pEKTWwaSp-WF8HBaEsgGooudYpmZyknzz_eCnN1M-ErYH36l977XZP91PAUzrhQI6PKQFsisfSvL2nWXQTmXzhpBIFUja1H-EPIMKTf-sQ1-Wpo8TbXADCJ9OJKo34_PXu672XSHILdb2gaHQFePAQjuBxkB6WEKU1yU0XDOPQxFBTl9hHnSjPivshzpryOAxoCL3rOPAYDTmqlLNuyCKfvzeDyGEMTYR1Rvj8OG7r8S71ZNuNuvmdAum3EdsGnUC1g7dmH1BXL30XTK5zyyppX8pqgWEt1b_FYxq7wLdO83D49fLPki7E). *BioScience*, *47*(9), pp.575-585.

Salvatore, J.O. and Ocampo, C.A., DirecTV Group Inc, 2000. [Free return lunar flyby transfer method for geosynchronous satellites having multiple perilune stages](https://patentimages.storage.googleapis.com/fe/c3/3c/3806a58caa778b/US6149103A.pdf). U.S. Patent 6,149,103.

See Table 1, final row, delta v 1230.6 m/s. This patent is based on the rescue mission for the HGS-1 geostationary satellite using a lunar flyby described in [(Ocampo, 2005)](#kix.dhfxkcwvvr1s)

Sapkota, A, 2020, [Citrate Utilization Test- Principle, Procedure, Results, Uses](https://microbenotes.com/citrate-utilization-test-principle-procedure-and-result-interpretation/#result-interpretation-of-citrate-utilization-test), Microbe Notes

Sarmiento, F., Peralta, R. and Blamey, J.M., 2015. [Cold and hot extremozymes: industrial relevance and current trends](https://www.frontiersin.org/articles/10.3389/fbioe.2015.00148/full). *Frontiers in bioengineering and biotechnology*, *3*, p.148.

*While isolating psychrophilic strains would likely provide a better analog for the Martian surface, the generation times are prohibitively slow for research purposes in such exploratory experiments*

Sauder, J., Hilgemann, E., Johnson, M., Parness, A., Hall, J., Kawata, J. and Stack, K., 2017. [Automation Rover for Extreme Environments](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170002798.pdf).

Savage, D., 2002, [NASA selects four Mars scout mission concepts for study](https://www.nasa.gov/home/hqnews/2002/02-238.txt)

Scanlon, K.E., Head, J.W., Wilson, L. and Marchant, D.R., 2014. [Volcano–ice interactions in the Arsia Mons tropical mountain glacier deposits](https://www.sciencedirect.com/science/article/pii/S0019103514002164). *Icarus*, *237*, pp.315-339. Press release: Stacey, K., 2014, [A habitable environment on Martian volcano?](https://news.brown.edu/articles/2014/05/mars), Brown university.

Schlaepfer, M.A., Sax, D.F. and Olden, J.D., 2011. [The potential conservation value of non‐native species](http://depts.washington.edu/oldenlab/wordpress/wp-content/uploads/2013/03/ConservationBiology_2011b_replies.pdf). *Conservation Biology*, *25*(3), pp.428-437.

Scharf, C., 2016, [How the Cold War Created Astrobiology, Life, death, and Sputnik](http://nautil.us/issue/32/space/how-the-cold-war-created-astrobiology-rp), Nautilus Magazine.

Schenk, P.M., Thomas-Hall, S.R., Stephens, E., Marx, U.C., Mussgnug, J.H., Posten, C., Kruse, O. and Hankamer, B., 2008. [Second generation biofuels: high-efficiency microalgae for biodiesel production](https://www.researchgate.net/profile/Ben_Hankamer/publication/43498856_Second_Generation_Biofuels_High-Efficiency_Microalgae_for_Biodiesel_Production/links/0c96051cc124e949e7000000.pdf). *Bioenergy research*, *1*(1), pp.20-43.

*page 37: Normal wild-type algae have large chlorophyll-bindingLHCII antenna systems and consequently the culture is dark green. Cell lines with small LHCII antenna systems yield cultures which are a much lighter green at the same cell density (Fig.7a). In the wild-type case, algal cells at the illuminated surface of the bioreactor that are exposed to high light levels capture the bulk of the light, but waste upto∼90% of the energy as fluorescence and heat [122,134].*

*As a result the wild-type cells located deeper in the culture are exposed to ever decreasing levels of light the further they are from the illuminated surface (see“Open PondSystems”section). These shaded cells are prevented from capturing enough solar energy to drive photosynthesis efficiently. This in turn drastically reduces the efficiency of the overall culture.In contrast, small antenna cell lines with reduced LHCIIlevels have the advantage that they improve the light penetration into the bioreactor (Fig.7a) and better match itto the energy requirements of each photosynthesizing cell. Thus small antenna cells at the bioreactor surface absorb only the light that they need, largely eliminating fluores-cence of excess energy. This in turn allows more light (i.e.the light wasted in wild-type as fluorescence and heat) to penetrate into the bioreactor so that even cells deeper in the culture have a near optimal exposure to light*

Schentag, J.J., Akers, C., Campagna, P. and Chirayath, P., 2004. [SARS: Clearing the Air. In *Learning from SARS: Preparing for the Next Disease Outbreak*](https://www.ncbi.nlm.nih.gov/books/NBK92445/)*: Workshop Summary*. National Academies Press (US).

*HEPA Filtration is the “Best Available Control Technology” at 99.99 percent at 0.3-micron efficiency level and is “Generally Accepted Control Technology” at 99.97 percent at 0.1-micron efficiency level. The added feature of the new 0.1-micron advanced filters is the “gel” seal and micro fiberglass construction that allows combining these filters with UV light disinfection. HEPA filters combined with charcoal and prefilters are the highest approved filters available for NIOSH-certified respirators.*

Schilling, G., 2015, [Are We Martians After All?](https://www.sciencemag.org/news/2013/08/are-we-martians-after-all), AAS Science

Schirber, M, 2013 [Searching for Organics in a Nibble of Soil](https://web.archive.org/web/20130221043653/http:/www.astrobio.net/exclusive/5325/searching-for-organics-in-a-nibble-of-soil) NASA Astrobiology Magazine

Schmidt, G., Landis, G. and Oleson, S., 2012, March. [HERRO missions to Mars and Venus using telerobotic surface exploration from orbit](file:///C:\Users\rober\Downloads\Schmidt,%20G.,%20Landis,%20G.%20and%20Oleson,%20S.,%202012,%20March.%20HERRO%20missions%20to%20Mars%20and%20Venus%20using%20telerobotic%20surface%20exploration%20from%20orbit.%20In%20AIAA%20Space%202011%20Conference%20&%20Exposition%20(p.%207343)). In *AIAA Space 2011 Conference & Exposition* (p. 7343).

Schmidt, M., 2010. [Xenobiology: a new form of life as the ultimate biosafety tool](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2909387/). *Bioessays*, *32*(4), pp.322-331.

Schmidt, M.E., Ruff, S.W., McCoy, T.J., Farrand, W.H., Johnson, J.R., Gellert, R., Ming, D.W., Morris, R.V., Cabrol, N., Lewis, K.W. and Schroeder, C., 2008. [Hydrothermal origin of halogens at Home Plate, Gusev crater.](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007JE003027) *Journal of Geophysical Research: Planets*, *113*(E6).

Schorghofer, N., Williams, J.P., Martinez‐Camacho, J., Paige, D.A. and Siegler, M.A., 2021. [Carbon dioxide cold traps on the moon](https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL095533). *Geophysical Research Letters*, *48*(20), p.e2021GL095533.

Schrunk, D., Sharpe, B., Cooper, B.L. and Thangavelu, M., 2007. [*The moon: Resources, future development and settlement*.](https://www.amazon.com/Moon-Development-Settlement-Colonization-Exploration/dp/0387360557#reader_0387360557) Springer Science & Business Media.

Schuerger, A.C., Ulrich, R., Berry, B.J. and Nicholson, W.L., 2013. [Growth of Serratia liquefaciens under 7 mbar, 0 C, and CO₂-enriched anoxic atmospheres](https://scholar.google.com/scholar_url?url=https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3582281/&hl=en&sa=T&oi=gsb-gga&ct=res&cd=0&d=4888033286252311022&ei=uhYsX5K1NsKwmAH6vamoDA&scisig=AAGBfm33vWBwyW1GGHlgGoU960xu_KSNUg). Astrobiology, 13(2), pp.115-131

Schuerger, A.C. and Nicholson, W.L., 2016. [Twenty species of hypobarophilic bacteria recovered from diverse soils exhibit growth under simulated Martian conditions at 0.7 kPa](https://www.researchgate.net/profile/Andrew_Schuerger/publication/241433918_Synergistic_Effects_of_Low_Pressure_Low_Temperature_and_CO2_Atmospheres_Inhibit_the_Growth_of_Terrestrial_Bacteria_Under_Simulated_Martian_Conditions/links/5b804e55299bf1d5a724cdd3/Synergistic-Effects-of-Low-Pressure-Low-Temperature-and-CO2-Atmospheres-Inhibit-the-Growth-of-Terrestrial-Bacteria-Under-Simulated-Martian-Conditions.pdf). *Astrobiology*, *16*(12), pp.964-976.

Schuyler, A., Warner, N.H., Derick, B., Rogers, A.D. and Golombek, M.P., 2020, March. [Crater Morphometry on the Dark-Toned Mafic Floor Unit at Jezero Crater, Mars: Comparisons to a Known Basaltic Lava Plain at the InSight Landing Site](https://www.hou.usra.edu/meetings/lpsc2020/pdf/1608.pd). In Lunar and Planetary Science Conference (No. 2326, p. 1608).

Schulze-Makuch, D. and Houtkooper, J.M., 2010a. [A perchlorate strategy for extreme xerophilic life on Mars.](https://meetingorganizer.copernicus.org/EPSC2010/EPSC2010-308.pdf) *EPSC Abstracts*, *5*, pp.EPSC2010-308.

Schulze-Makuch, D. and Houtkooper, J.M., 2010b. "[Making a Splash on Mars (about how water is unstable over most of Mars and close to boiling point of water in the Hellas basin)](https://science.nasa.gov/science-news/science-at-nasa/2000/ast29jun_1m)" — [*NASA Science*](https://en.wikipedia.org/wiki/NASA), June 29, 2000

Schwandt, C.S., Lofgren, G.E. and McKay, G.A., 2004. [Evidence for exclusively inorganic formation of magnetite in Martian meteorite ALH84001](ftp://ftp.impmc.upmc.fr/pub/users/benzerar/Magnetites/GoldenAmMin_04.pdf.pdf). American Mineralogist, 89(5-6), pp.681-695.

Schwendner, P. and Schuerger, A.C., 2020. [Exploring microbial activity in low-pressure environments](https://www.researchgate.net/profile/Andrew_Schuerger/publication/338756181_Exploring_Microbial_Activity_in_Low-pressure_Environments/links/5e8f65f2a6fdcca789062381/Exploring-Microbial-Activity-in-Low-pressure-Environments.pdf). *Astrobiology: Current, Evolving, and Emerging Perspectives, Caister Academic Press, Norfolk, UK, doi*, *10*(9781912530304.07).

Schwieterman, E.W., Reinhard, C.T., Olson, S.L., Ozaki, K., Harman, C.E., Hong, P.K. and Lyons, T.W., 2019. [Rethinking CO Antibiosignatures in the Search for Life Beyond the Solar System](https://iopscience.iop.org/article/10.3847/1538-4357/ab05e1/pdf). *The Astrophysical Journal*, *874*(1), p.9.

Sczepanski, J.T. and Joyce, G.F., 2014. [A cross-chiral RNA polymerase ribozyme](https://www.nature.com/articles/nature13900). Nature, 515(7527), pp.440-442.

Sieber, J.R., McInerney, M.J., Plugge, C.M., Schink, B. and Gunsalus, R.P., 2010. [Methanogenesis: syntrophic metabolism](https://link.springer.com/referenceworkentry/10.1007/978-3-540-77587-4_22). In *Handbook of Hydrocarbon and Lipid Microbiology*.

Sehnal, D., Rose, A.S., Koča, J., Burley, S.K. and Velankar, S., 2018, June. Mol\*: towards a common library and tools for web molecular graphics. In MolVa: Workshop on Molecular Graphics and Visual Analysis of Molecular Data, Brno, Czech Republic. Eurographics. doi:10.2312/molva.20181103, [3ZD5 the 2.2 A structure of a full-length catalytically active hammerhead ribozyme](https://www.rcsb.org/structure/3ZD5), RCSB PDB

Sella, S.R., Vandenberghe, L.P. and Soccol, C.R., 2014. [Life cycle and spore resistance of spore-forming Bacillus atrophaeus](http://www.sciencedirect.com/science/article/pii/S0944501314000597). *Microbiological research*, *169*(12), pp.931-939.

Serôdio, J., Cruz, S., Cartaxana, P. and Calado, R., 2014. [Photophysiology of kleptoplasts: photosynthetic use of light by chloroplasts living in animal cells](https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.2013.0242). *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1640), p.20130242.

Shaheen, R., Niles, P.B., Chong, K., Corrigan, C.M. and Thiemens, M.H., 2015. [Carbonate formation events in ALH 84001 trace the evolution of the Martian atmosphere](https://www.pnas.org/content/112/2/336). Proceedings of the National Academy of Sciences, 112(2), pp.336-341.

Shahrzad, S., Kinch, K.M., Goudge, T.A., Fassett, C.I., Needham, D.H., Quantin‐Nataf, C. and Knudsen, C.P., 2019. [Crater statistics on the dark‐toned, mafic floor unit in Jezero Crater, Mars](https://static-curis.ku.dk/portal/files/243150816/2018GL081402.pdf). *Geophysical Research Letters*, *46*(5), pp.2408-2416

Shannon, D.M., 2006[. Elemental analysis as a first step towards “following the nitrogen” on Mars](http://sites.google.com/site/derekshannon/DShannon_Thesis_Full.pdf). University of Southern California.

Sharov, A.A., 2006. [Genome increase as a clock for the origin and evolution of life](https://biologydirect.biomedcentral.com/articles/10.1186/1745-6150-1-17). *Biology Direct*, *1*(1), pp.1-10.

Sharov, A.A. and Gordon, R., 2013. [Life before earth](https://arxiv.org/ftp/arxiv/papers/1304/1304.3381.pdf). *arXiv preprint arXiv:1304.3381*.

Shea, G., 2019, [NASA Program/Project Life Cycle](https://www.nasa.gov/seh/3-project-life-cycle), Systems Engineering Handbook, NASA, accessed at: <https://www.nasa.gov/seh/3-project-life-cycle> , Accessed on: August 18, 2020.

Shekhtman, L., 2019, [With Mars methane mystery unsolved, Curiosity serves scientists a new one: Oxygen](https://www.nasa.gov/feature/goddard/2019/with-mars-methane-mystery-unsolved-curiosity-serves-scientists-a-new-one-oxygen/)

Shen, J., Zerkle, A.L. and Claire, M.W., 2021[. Nitrogen Cycling and Biosignatures in a Hyperarid Mars Analog Environment](https://www.liebertpub.com/doi/pdf/10.1089/ast.2021.0012). Astrobiology.

Shirley, J.H., 2015. [Solar System dynamics and global-scale dust storms on Mars](https://www.researchgate.net/publication/273398220_Solar_System_dynamics_and_global-scale_dust_storms_on_Mars). *Icarus*, *251*, pp.128-144.

Shih P.M., Hemp J., Ward L.M., Matzke N.J., and Fischer W.W. (2017) [Crown group Oxyphotobacteria postdate the rise of oxygen](https://onlinelibrary.wiley.com/doi/am-pdf/10.1111/gbi.12200). Geobiology 15:19–29

*P10: Our cross-calibrated analyses estimate the divergence of Oxyphotobacteria and Melainabacteria to have occurred ca. 2.5-2.6 Ga (Table 3). This result is consistent with the hypothesis that stem group Oxyphotobacteria evolved oxygenic photosynthesis after their divergence from the Melainabacteria, relatively close in time to the rise of oxygen.*

Sholes, S.F., Krissansen-Totton, J. and Catling, D.C., 2019. [A maximum subsurface biomass on Mars from untapped free energy: CO and H₂ as potential antibiosignatures](https://arxiv.org/abs/1811.08501). Astrobiology, 19(5), pp.655-668.

Singer, E., 2014, [New Twist Found in the Story of Life’s Start](https://www.quantamagazine.org/chiral-key-found-to-origin-of-life-20141126), Quanta Magazine

Singh, R., Bhadouria, R., Singh, P., Kumar, A., Pandey, S. and Singh, V.K., 2020. [Nanofiltration technology for removal of pathogens present in drinking water](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7173494/). In Waterborne Pathogens (pp. 463-489). Butterworth-Heinemann.

Sivasubramaniam, R. and Douglas, R., 2018. [The microbiome and chronic rhinosinusitis](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6251963/). *World journal of otorhinolaryngology-head and neck surgery*, *4*(3), pp.216-221.

Sleep, N.H. and Bird, D.K., 2007. [Niches of the pre‐photosynthetic biosphere and geologic preservation of Earth's earliest ecology](http://faculty.washington.edu/dcatling/ASTBIO502/Sleep2007_PrePhotosyntheticBiosphere.pdf). Geobiology, 5(2), pp.101-117.

Smith, M.D. and Guzewich, S.D., 2019. [The Mars Global Dust Storm of 2018](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190027303.pdf).

Solden, L., Lloyd, K. and Wrighton, K., 2016. [The bright side of microbial dark matter: lessons learned from the uncultivated majority.](https://www.sciencedirect.com/science/article/pii/S1369527416300558#bib0345) *Current opinion in microbiology*, *31*, pp.217-226.

Soler, Z.M. and Schlosser, R.J., 2012. [The role of fungi in diseases of the nose and sinuses](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3904040/). *American journal of rhinology & allergy*, *26*(5), pp.351-358.

Spaulding, S.A., Kilroy, C.A.T.H.Y. and Edlund, M.B., 2010. [Diatoms as non-native species](https://www.researchgate.net/profile/Sarah_Spaulding/publication/232666319_Species_within_the_Genus_Encyonema_Kutzing_Including_Two_New_Species_Encyonema_reimeri_sp_nov_and_E_nicafei_sp_nov_and_E_stoermeri_nom_nov_stat_nov/links/02e7e51ddd414216aa000000/Species-within-the-Genus-Encyonema-Kuetzing-Including-Two-New-Species-Encyonema-reimeri-sp-nov-and-E-nicafei-sp-nov-and-E-stoermeri-nom-nov-stat-nov.pdf). *The diatoms: applications for the environmental and earth sciences*, pp.560-569.

Spudis, P.D., 2016. [The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources](https://www.amazon.com/Value-Moon-Explore-Prosper-Resources/dp/1588345033/tag=space041-20). Smithsonian Institution.

 Staehle, R.L., Spangelo, S., Lane, M.S., Aaron, K.M., Bhartia, R., Boland, J.S., Christensen, L.E., Forouhar, S., de la Torre Juarez, M., Trawny, N. and Webster, C.R., 2015. [Multiplying Mars lander opportunities with MARSdrop microlanders](https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3237&context=smallsat). 29th Annual AIAA/USU Conference on Small Satellites

Stamenković, V., Ward, L. M., Mischna. M., Fischer. W. W.. "[O2 solubility in Martian near-surface environments and implications for aerobic life](https://www.nature.com/articles/s41561-018-0243-0)" — [*Nature*](https://en.wikipedia.org/wiki/Nature), October 22, 2018 - see also Vlada Stamenkovic. "[Origins of Life & Habitability - authors website with bibliography - and author shared link to the article](http://habilabs.com/life/)", sharing is via [Nature Sharedit](https://www.springernature.com/gp/researchers/sharedit) — [*Habilabs*](https://en.wikipedia.org/wiki/Habilabs)

Stano, P. and Luisi, P.L., 2010. [Chemical Approaches to Synthetic Biology-From Vesicles Self-Reproduction to Semi-Synthetic Minimal Cells](https://mitpress.mit.edu/sites/default/files/titles/alife/0262290758chap27.pdf). In *ALIFE* (pp. 147-153).

Steinle, L., Knittel, K., Felber, N., Casalino, C., de Lange, G., Tessarolo, C., Stadnitskaia, A., Damsté, J.S.S., Zopfi, J., Lehmann, M.F. and Treude, T., 2018. [Life on the edge: active microbial communities in the Kryos MgCl 2-brine basin at very low water activity](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5956074/). The ISME journal, 12(6), pp.1414-1426.

Stern, J.C., Sutter, B., Freissinet, C., Navarro-González, R., McKay, C.P., Archer, P.D., Buch, A., Brunner, A.E., Coll, P., Eigenbrode, J.L. and Fairen, A.G., 2015. [Evidence for indigenous nitrogen in sedimentary and aeolian deposits from the Curiosity rover investigations at Gale crater](https://www.pnas.org/content/pnas/112/14/4245.full.pdf), Mars. *Proceedings of the National Academy of Sciences*, *112*(14), pp.4245-4250.

See also NASA press release: [Curiosity Rover Finds Biologically Useful Nitrogen on Mars](https://www.jpl.nasa.gov/news/news.php?feature=4516)

Stern, S.A., 1999. [The lunar atmosphere: History, status, current problems, and context.](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1999RG900005) Reviews of Geophysics, 37(4), pp.453-491.

Stewart, R.B., 2002. [Environmental regulatory decision making under uncertainty](http://www.cserge.ucl.ac.uk/Stewart.pdf). Research in Law and Economics, 20, pp.71-126.

Steigerwald, B., 2019, [New Insight into How Much Atmosphere Mars Lost](https://www.nasa.gov/feature/goddard/2019/mars-lost-atmosphere)

Stillman, E, 2018, Chapter 2 - [Unraveling the Mysteries of Recurring Slope Lineae](https://books.google.co.uk/books?id=2aRBDwAAQBAJ&pg=PA69&lpg=PA69&) in Soare, R.J., Conway, S.J. and Clifford, S.M. eds., 2018. *Dynamic Mars: Recent and Current Landscape Evolution of the Red Planet*. Elsevier.

[*Page 81*](https://books.google.co.uk/books?id=2aRBDwAAQBAJ&pg=PA81#v=onepage&q&f=false)*: “No proposed RSL mechanism can adequately describe all the observations … We suggest RSLs that are scored excellent and very good and sites that do not typographically preclude aquifer fed springs are likely caused by a wet-dominated mechanism while numerous other sites are caused by dry granular flow”*

Stöffler, D., Horneck, G., Ott, S., Hornemann, U., Cockell, C.S., Moeller, R., Meyer, C., de Vera, J.P., Fritz, J. and Artemieva, N.A., 2007. [Experimental evidence for the potential impact ejection of viable microorganisms from Mars and Mars-like planets](https://www.sciencedirect.com/science/article/pii/S0019103506004143). *Icarus*, *186*(2), pp.585-588.

Strange, N., Landau, D., McElrath, T., Lantoine, G. and Lam, T., 2013. [Overview of mission design for NASA asteroid redirect robotic mission concept.](http://planetary.s3.amazonaws.com/assets/pdfs/20140623_ARRM_Mission_Design_IEPC.pdf)

Stromberg, J.M., Parkinson, A., Morison, M., Cloutis, E., Casson, N., Applin, D., Poitras, J., Marti, A.M., Maggiori, C., Cousins, C. and Whyte, L., 2019. [Biosignature detection by Mars rover equivalent instruments in samples from the CanMars Mars Sample Return Analogue Deployment](https://core.ac.uk/download/pdf/224801185.pdf). Planetary and Space Science, 176, p.104683.

*The most prominent and conclusive organic biosignature observed is the presence of chlorophyll and carotene detected in the UV-VIS-NIR and Raman spectra in samples S3 and S4 … However, apart from the carotene and chlorophyll absorption features below ~800 nm, there are no other indications of organic compounds observed in the reflectance spectra of any of the samples. While this most likely evidence of present endolithic life, the detection of such molecules may have implications for Mars as they have been shown to be somewhat stable under Martian surface conditions. However, this stability and preservation potential is dependent on their endolithic habitat, and so detection requires a fresh surface exposed by abrasion (e.g., RAT (rock abrasion tool)) or sample crushing.*

Stubbs, T.J., Vondrak, R.R. and Farrell, W.M., 2007. [Impact of dust on lunar exploration](https://www.nasa.gov/centers/johnson/pdf/486014main_StubbsImpactOnExploration.4075.pdf).

Sultanpuram, V.R., Mothe, T., Chintalapati, S. and Chintalapati, V.R., 2016. Tersicoccus solisilvae sp., nov., [a bacterium isolated from forest soil](https://www.microbiologyresearch.org/content/journal/ijsem/10.1099/ijsem.0.001470). International Journal of Systematic and Evolutionary Microbiology, 66(12), pp.5061-5065.

Summons, R.E., Sessions, A.L., (co-chairs), Allwood, A.C., Barton, H.A., Beaty, D.W., Blakkolb, B., Canham, J., Clark, B.C. and Dworkin, J.P. (2014 Organic Contamination Panel), 2014. [Planning considerations related to the organic contamination of Martian samples and implications for the Mars 2020 rover.](https://authors.library.caltech.edu/53814/1/ast.2014.1244.pdf)

Summons, R.E., Amend, J.P., Bish, D., Buick, R., Cody, G.D., Des Marais, D.J., Dromart, G., Eigenbrode, J.L., Knoll, A.H. and Sumner, D.Y., 2011. [Preservation of martian organic and environmental records: final report of the Mars Biosignature Working Group](https://dash.harvard.edu/bitstream/handle/1/13041033/66876195.pdf?sequence=2&isAllowed=y). *Astrobiology*, *11*(2), pp.157-181.

Swindle, T.D., Atreya, S., Busemann, H., Cartwright, J.A., Mahaffy, P.R., Marty, B., Pack, A. and Schwenzer, S.P., 2021. [Scientific Value of Including an Atmospheric Sample as part of Mars Sample Return](https://www.liebertpub.com/doi/pdfplus/10.1089/AST.2021.0107). Astrobiology, (ja).

***(2) Collecting gas in a newly-designed, valved, sample-tube-sized vessel that is flown on either the Sample Fetch Rover (SFR) or the Sample Retrieval Lander (SRL)***

***...***

***The triple oxygen isotope composition of atmospheric CO2, O2, H2O, and CO would provide a unique picture of Martian atmospheric photochemistry and allow an understanding of the anomalous signatures in Martian minerals and water.***

Szostak, J., 2016, [“On the Origin of Life”](http://molbio.mgh.harvard.edu/szostakweb/publications/Szostak_pdfs/Szostak_2016_MedicinaB.pdf), MEDICINA (BuenosAires) 2016; 76, 199-203 and [Szostak lab summary](http://molbio.mgh.harvard.edu/szostakweb/)

Szostak, J.W., 2017. [The narrow road to the deep past: in search of the chemistry of the origin of life](https://onlinelibrary.wiley.com/doi/pdf/10.1002/anie.201704048). *Angewandte Chemie International Edition*, *56*(37), pp.11037-11043.

## T

Tarnas, J.D., Mustard, J.F., Lollar, B.S., Bramble, M.S., Cannon, K.M., Palumbo, A.M. and Plesa, A.C., 2018. [Radiolytic H2 production on Noachian Mars: implications for habitability and atmospheric warming](https://www.sciencedirect.com/science/article/abs/pii/S0012821X18305326). Earth and Planetary Science Letters, 502, pp.133-145. Press release: [Ancient Mars had right conditions for underground life, new research suggests](https://www.brown.edu/news/2018-09-24/radiolysis)

Tarnas, J.D., Mustard, J.F., Lin, H., Goudge, T.A., Amador, E.S., Bramble, M.S., Kremer, C.H., Zhang, X., Itoh, Y. and Parente, M., 2019. [Orbital identification of hydrated silica in Jezero crater,](https://core.ac.uk/download/pdf/275574665.pdf) Mars. Geophysical Research Letters, 46(22), pp.12771-12782.

*The likelihood of detected silica to host biosignatures is highly dependent on the geochemical conditions of its formation environment. We have proposed 9 hypotheses for the origin of hydrated silica in Jezero crater, including primary volcanism,diagenesis via fluid infiltration of the olivine-rich or deltaic units, authigenic formation in a lacustrine environment, detrital transport of material formed authigenically in the Jezero watershed, or transport to Jezero crater via aeolian processes.*

Till, J.L., Guyodo, Y., Lagroix, F., Morin, G., Menguy, N. and Ona-Nguema, G., 2017. [Presumed magnetic biosignatures observed in magnetite derived from abiotic reductive alteration of nanogoethite](https://www.sciencedirect.com/science/article/pii/S1631071317300093). Comptes Rendus Géoscience, 349(2), pp.63-70.

Tillman, N.T., 2014, [Incredible Technology: Private Mars Mission Could Return Samples by 2020](https://www.space.com/26255-private-mars-sample-return-mission-2020.html), Space.com

Todar, K., 2006. [Todar's online textbook of bacteriology](http://textbookofbacteriology.net/index.html).

See [Bacterial Defense against Phagocytosis](http://textbookofbacteriology.net/antiphago.html)

*-In L. pneumophila, as with the chlamydia, some structural feature of the bacterial cell surface, already present at the time of entry (ingestion), appears to modify the membranes of the phagosomes, thus preventing their merger with lysosomal granules. In Legionella, it is known that a single gene is responsible for the inhibition of phagosome lysosome fusion.*

*… Legionella pneumophila enters mononuclear phagocytes by depositing complement C3b on its surfaces and using that host protein to serve as a ligand for binding to macrophage cell surfaces. After ingestion, the bacteria remain in vacuoles that do not fuse with lysosomes, apparently due to the influence of soluble substances produced by the bacteria.*

Toner, J.D. and Catling, D.C., 2016. [Water activities of NaClO4, Ca (ClO4) 2, and Mg (ClO4) 2 brines from experimental heat capacities: water activity> 0.6 below 200 K](https://faculty.washington.edu/dcatling/Toner2016_WaterActivity_Perchlorates_at_Low_T.pdf). *Geochimica et Cosmochimica Acta*, *181*, pp.164-174

Topputo, F. and Belbruno, E., 2015. [Earth–Mars transfers with ballistic capture](https://arxiv.org/pdf/1410.8856.pdf). *Celestial Mechanics and Dynamical Astronomy*, *121*(4), pp.329-346.

Tornabene, L.L., Moersch, J.E., McSween Jr, H.Y., McEwen, A.S., Piatek, J.L., Milam, K.A. and Christensen, P.R., 2006. Identification of large (2–10 km) rayed craters on Mars in THEMIS thermal infrared images: Implications for possible Martian meteorite source regions. *Journal of Geophysical Research: Planets*, *111*(E10).

Trainer, M.G., Wong, M.H., Mcconnochie, T.H., Franz, H.B., Atreya, S.K., Conrad, P.G., Lefèvre, F., Mahaffy, P.R., Malespin, C.A., Manning, H.L. and Martín‐Torres, J., 2019. [Seasonal variations in atmospheric composition as measured in Gale Crater](https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019JE006175), Mars. *Journal of Geophysical Research: Planets*, *124*(11), pp.3000-3024. See also [Supporting information](https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029%2F2019JE006175&file=jgre21250-sup-0001-2019JE006175-SI.pdf)

*Surprisingly, however, we have found that O₂ does not demonstrate the predictable seasonal behavior of the other major components. Surface O₂ measurements by SAM yield abundances that vary between 1300 and 2200 ppmv; when corrected for the annual global mean pressure, O₂ varies from 1300 to 1900 ppmv. Despite large instrument backgrounds, these are the first precise in situ measurements of O2, revealing a surprising seasonal and interannual variation that cannot be accounted for in current chemical models. Though Mars has the potential to generate significant O₂ release due to abundances of oxidants in/at its surface, the mechanisms by which O₂ could be quickly generated and then quickly destroyed are completely unknown. As with all surprising results, we hope that continued in situ, experimental, and theoretical results may shed light on this intriguing observation.*

Treiman, A.H., n.d., [Fossil Life in ALH 84001?](https://www.lpi.usra.edu/lpi/meteorites/life.html)

Turbet, M. and Forget, F., 2019. [The paradoxes of the Late Hesperian Mars ocean](https://www.nature.com/articles/s41598-019-42030-2). Scientific reports, 9(1), pp.1-5.

## U

UN, 1945, [Constitution of the United Nations Food and Agriculture Organization (FAO)](https://www.jus.uio.no/english/services/library/treaties/14/14-01/food-organization.xml)

United Nations, 2020, [Press Briefing: Coronavirus Outbreak (COVID - 19):](https://youtu.be/1vwshXayRQE) WHO Update (25 February 2020) at [10:80](https://youtu.be/1vwshXayRQE?t=608)

Urbaniak, C., Massa, G., Hummerick, M., Khodadad, C., Schuerger, A. and Venkateswaran, K., 2018. [Draft genome sequences of two Fusarium oxysporum isolates cultured from infected Zinnia hybrida plants grown on the international space station](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5958250/). Genome announcements, 6(20).

Urbaniak, C., van Dam, P., Zaborin, A., Zaborina, O., Gilbert, J.A., Torok, T., Wang, C.C. and Venkateswaran, K., 2019. [Genomic Characterization and Virulence Potential of Two Fusarium oxysporum Isolates Cultured from the International Space Station](https://msystems.asm.org/content/msys/4/2/e00345-18.full.pdf). MSystems, 4(2).

Uhran, B., Conley, C. and Spry, J.A., 2019. [Updating Planetary Protection Considerations and Policies for Mars Sample Return](https://www.sciencedirect.com/science/article/abs/pii/S0265964618300833). Space Policy, 49, p.101322.

USFWS, n.d., [Formation of ice wedges in permafrost](https://media.arcus.org/album/wildreach-graphics/3401), Polar Archive

USGS, n.d., [Resources on Isotopes](https://wwwrcamnl.wr.usgs.gov/isoig/res/funda.html)

## V

Vago, J.L., Westall, F., Coates, A.J., Jaumann, R., Korablev, O., Ciarletti, V., Mitrofanov, I., Josset, J.L., De Sanctis, M.C., Bibring, J.P. and Rull, F., 2017. [Habitability on early Mars and the search for biosignatures with the ExoMars Rover](https://www.liebertpub.com/doi/full/10.1089/ast.2016.1533). *Astrobiology*, *17*(6-7), pp.471-510.

*However, the likelihood of a cold surface scenario does not constitute a serious obstacle for the possible appearance of life, as extensive subglacial, submerged, and emerged volcanic/hydrothermal activity would have resulted in numerous liquid water-rich settings. The right mixture of ingredients, temperature and chemical gradients, organic molecule transport, concentration, and fixation processes could have been found just as well in a plethora of terrestrial submarine vents as in a multitude of vents under (maybe) top-frozen martian bodies of water.*

Vaishampayan, P., Moissl-Eichinger, C., Pukall, R., Schumann, P., Spröer, C., Augustus, A., Roberts, A.H., Namba, G., Cisneros, J., Salmassi, T. and Venkateswaran, K., 2013. [Description of Tersicoccus phoenicis gen. nov., sp. nov. isolated from spacecraft assembly clean room environments](https://www.researchgate.net/profile/Cathrin-Sproeer/publication/233886394_Description_of_Tersicoccus_phoenicis_gen_nov_sp_nov_isolated_from_spacecraft_assembly_clean_room_environments/links/00b4952a57200ea850000000/Description-of-Tersicoccus-phoenicis-gen-nov-sp-nov-isolated-from-spacecraft-assembly-clean-room-environments.pdf). International journal of systematic and evolutionary microbiology, 63(Pt\_7), pp.2463-2471.

Valinia, A., Garvin, J.B., Vondrak, R., Thronson, H., Lester, D., Schmidt, G., Fong, T., Wilcox, B., Sellers, P. and White, N., 2012. [Low-Latency Telerobotics from Mars Orbit: The Case for Synergy Between Science and Human Exploration](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120013068.pdf).

Valtonen, M., Nurmi, P., Zheng, J.Q., Cucinotta, F.A., Wilson, J.W., Horneck, G., Lindegren, L., Melosh, J., Rickman, H. and Mileikowsky, C., 2008. [Natural transfer of viable microbes in space from planets in extra-solar systems to a planet in our solar system and vice versa](https://arxiv.org/ftp/arxiv/papers/0809/0809.0378.pdf). *The Astrophysical Journal, 690(1), p.210.*

*From our discussion above, it is clear that exchanges of bacteria between planets in different solar systems are only possible during the birth cluster stage of the systems in question. As the number of life-carrying bodies received by the Earth may have been in thousands, so also other planets in other stellar systems may have received their life from other members of our original star cluster, or even from a single source, the Earth.Thus the limited form of lithopanspermia inside a star cluster is possible, while the stronger version of life spreading through the whole Galaxy from a single source could not happen via mechanisms described in this work. But life-carrying bodies originating from our solar system may have found their way to our original neighbours, and that all conditions being optimal, life seeded by our system could have spread to many other solar systems.Here in our solar system our common ancestor cell most probably originated either on the Earth or on Mars. We cannot say for sure which one since there has been millions of potentially life-carrying transfers between these two planets.The GAIA mission will perhaps be able to locate the members of the birth cluster of the Sun while the SIM and DARWIN missions will be able to detect planets around them and search for signs of life in the planets. Even before these missions, the currently ongoing search for life in Mars may already give an indication how likely it is that life is transported between planets by natural means.*

van Heereveld, L., Merrison, J., Nørnberg, P. and Finster, K., 2017. [Assessment of the Forward Contamination Risk of Mars by Clean Room Isolates from Space-Craft Assembly Facilities through Aeolian Transport-a Model Study](https://www.researchgate.net/publication/305656209_Assessment_of_the_Forward_Contamination_Risk_of_Mars_by_Clean_Room_Isolates_from_Space-Craft_Assembly_Facilities_through_Aeolian_Transport_-_a_Model_Study). *Origins of Life and Evolution of Biospheres*, *47*(2), pp.203-21

[n-to-questions-about-covid-19-and-viral-load/](https://www.sciencemediacentre.org/expert-reaction-to-questions-about-covid-19-and-viral-load/), accessed on: July 28, 2020

*“The minimal infective dose is defined as the lowest number of viral particles that cause an infection in 50% of individuals (or ‘the average person’). For many bacterial and viral pathogens we have a general idea of the minimal infective dose but because SARS-CoV-2 is a new pathogen we lack data. For SARS, the infective dose in mouse models was only a few hundred viral particles. It thus seems likely that we need to breathe in something like a few hundred or thousands of SARS-CoV-2 particles to develop symptoms. This would be a relatively low infective dose and could explain why the virus is spreading relatively efficiently.*

van Schaik, W. (2020) interviewed by Science Media Centre, expert reaction to questions about COVID-19 and viral load, accessed at: [https://www.sciencemediacentre.org/expert-reacti](https://www.sciencemediacentre.org/expert-reaction-to-questions-about-covid-19-and-viral-load/)

Vellinger, J.C., Barton, K., Faget, P., Todd, P. and Boland, E., 2016. [Rodent bone densitometer on the International Space Station: Instrument design and performance](https://ui.adsabs.harvard.edu/abs/2016cosp...41E1994V/abstract). cosp, 41, pp.F5-1.

*The commercial software package controls four paired-energy exposures, 80 and 35 kV*

Venier, C.G., Jones Jr, W.R., Jansen, M.J. and Marchetti, M., 2003, September. [Comparative physical and tribological properties of three Pennzane® fluids, SHF X-1000, SHF X-2000, and SHF X-3000](https://adsabs.harvard.edu/full/2003ESASP.524..337V/0000340.000.html). In 10th European Space Mechanisms and Tribology Symposium (Vol. 524, pp. 337-340).

Viennet, J.C., Bernard, S., Guillou, C.L., Sautter, V., Grégoire, B., Jambon, A., Pont, S., Beyssac, O., Zanda, B., Hewins, R. and Remusat, L., 2021. [Martian Magmatic Clay Minerals Forming Vesicles: Perfect Niches for Emerging Life?](https://www.liebertpub.com/doi/pdfplus/10.1089/ast.2020.2345). Astrobiology.

Vincent, J.F. and Wegst, U.G., 2004. [Design and mechanical properties of insect cuticle](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1090.7026&rep=rep1&type=pdf). *Arthropod structure & development*, *33*(3), pp.187-199.

Vicente-Retortillo, Á., Martínez, G.M., Renno, N., Newman, C.E., Ordonez-Etxeberria, I., Lemmon, M.T., Richardson, M.I., Hueso, R. and Sánchez-Lavega, A., 2018. [Seasonal deposition and lifting of dust on Mars as observed by the Curiosity rover](https://www.nature.com/articles/s41598-018-35946-8). *Scientific reports*, *8*(1), pp.1-8.

*We show that the amount of dust accumulated on the sensor follows a seasonal cycle, with net dust removal during the perihelion season until Ls ~ 300°, and net dust deposition until the end of the aphelion season (Ls ~ 300°–180°)*

Vítek, P., Edwards, H.G.M., Jehlička, J., Ascaso, C., De los Ríos, A., Valea, S., Jorge-Villar, S.E., Davila, A.F. and Wierzchos, J., 2010. [Microbial colonization of halite from the hyper-arid Atacama Desert studied by Raman spectroscopy](http://rsta.royalsocietypublishing.org/content/368/1922/3205#ref-36). *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, *368*(1922), pp.3205-3221.

## W

Wadowsky, R.M., Wolford, R., McNamara, A.M. and Yee, R.B., 1985. [Effect of temperature, pH, and oxygen level on the multiplication of naturally occurring Legionella pneumophila in potable water.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC238529/) *Applied and environmental microbiology,* 49(5), pp.1197-1205..

Wadsworth, J. and Cockell, C.S., 2017. [Perchlorates on Mars enhance the bacteriocidal effects of UV light](https://www.nature.com/articles/s41598-017-04910-3)). *Scientific reports*, *7*(1), pp.1-8.

Wagner, S., 2006. [*The Apollo experience lessons learned for constellation lunar dust management*](https://www.hq.nasa.gov/alsj/TP-2006-213726.pdf) (No. JSC-CN-10841).

Walker, R.C, 2019, [Sponges on Mars? We ask Stamenković about their oxygen-rich briny seeps model](https://encyclopediaofastrobiology.org/wiki/Sponges_on_Mars%3F_We_ask_Stamenkovi%C4%87_about_their_oxygen-rich_briny_seeps_model) - expanded verson of Wikinews article [Simple animals could live in Martian brines: Wikinews interviews Vlada Stamenković](https://en.wikinews.org/wiki/Simple_animals_could_live_in_Martian_brines:_Wikinews_interviews_planetary_scientist_Vlada_Stamenkovi%C4%87) , WikiNews

Wall, M., 2018, ["Salty Martian Water Could Have Enough Oxygen to Support Life"](https://www.space.com/42210-mars-brines-oxygen-support-life.html)

— [*Space.com*,](https://en.wikipedia.org/wiki/Space.com)

Warmflash, D., Larios-Sanz, M., Jones, J., Fox, G.E. and McKay, D.S., 2007. [Assessing the Biohazard Potential of Putative Martian Organisms for Exploration Class Human Space Missions](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070030011.pdf).

*Indeed, not even all infectious human pathogens—let alone non-infectious pathogens— on Earth require a multicellular, macroscopic host to evolve harmful capabilities.*

*July, 1976, the month that VL1 [Viking Lander 1] landed on theMartian surface, was also the month of the outbreak of Legionnaires’ disease at the American Legion convention in Philadelphia.*

*The cause, Legionella pneumophila, is a facultative, Gram-negative rod that is one of several human pathogens now known to be carried in the intracellular environments of protozoan hosts. L. pneumophila can also persist, even outside of any host, as part of biofilms.*

*In essence, all that a potentially infectious human pathogen needs to emerge and persist is to grow and live naturally under conditions that are similar to those that it might later encounter in a human host. On Mars, these conditions might be met in a particular niche within the extracellular environment of a biofilm, or within the intracellular environment of another single-celled Martian organism. It is important to note the numerous biofilms observed aboard the Mir space station, which were found on surfaces and within water plumbing. These films were often multi-species and included bacteria, fungi, and protozoa.*

*To be sure, the genetic similarity between humans and protozoa is much greater than could be expected between humans and the Martian host of a Martian microbe.*

*However, the L. pneumophila example does bring into question the rationale of the need for host-pathogen coevolution. Even in the context of a planetary bio-sphere that is limited to single-celled life, and even where there is unlikely to have been a co-evolution between agent and host organism, the possibility of infectious agents, even an invasive type, cannot be ruled out.*

Watson, J. and Castro, G., 2012. [High-temperature electronics pose design and reliability challenges](https://www.analog.com/en/analog-dialogue/articles/high-temperature-electronic-pose-design-challenges.html). Analog Dialogue, 46(2), pp.3-9.

Webster, C.R., Mahaffy, P.R., Flesch, G.J., Niles, P.B., Jones, J.H., Leshin, L.A., Atreya, S.K., Stern, J.C., Christensen, L.E., Owen, T. and Franz, H., 2013. [Isotope ratios of H, C, and O in CO₂ and H2O of the Martian atmosphere](https://repository.si.edu/bitstream/handle/10088/58163/260.full.pdf?isAllowed=y&sequence=1). Science, 341(6143), pp.260-263.

Weidmann, J., Schnölzer, M., Dawson, P.E. and Hoheisel, J.D., 2019. [Copying life: synthesis of an enzymatically active mirror-image DNA-ligase made of D-amino acids](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1636439/). *Cell chemical biology*, *26*(5), pp.645-651.

Weinmaier, T., Probst, A.J., La Duc, M.T., Ciobanu, D., Cheng, J.F., Ivanova, N., Rattei, T. and Vaishampayan, P., 2015. [A viability-linked metagenomic analysis of cleanroom environments: eukarya, prokaryotes, and viruses](https://microbiomejournal.biomedcentral.com/articles/10.1186/s40168-015-0129-y). Microbiome, 3(1), pp.1-14.

Weiss, I.M., Muth, C., Drumm, R. and Kirchner, H.O., 2018. [Thermal decomposition of the amino acids glycine, cysteine, aspartic acid, asparagine, glutamic acid, glutamine, arginine and histidine](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5807855/). *BMC biophysics*, *11*(1), p.2. For the decomposition temperatures see [Table 1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5807855/table/Tab1/?report=objectonly)

Westall , 2013, [Habitability of other planets and satellites - Habitability and Survival](https://books.google.com/books?id=VYjEBAAAQBAJ&pg=PA192)

Westall, F., Loizeau, D., Foucher, F., Bost, N., Betrand, M., Vago, J. and Kminek, G., 2013. [Habitability on Mars from a microbial point of view](https://hal-insu.archives-ouvertes.fr/file/index/docid/866015/filename/ast.2013.1000-1.pdf). Astrobiology, 13(9), pp.887-897.

Westall, F., Foucher, F., Bost, N., Bertrand, M., Loizeau, D., Vago, J.L., Kminek, G., Gaboyer, F., Campbell, K.A., Bréhéret, J.G. and Gautret, P., 2015. [Biosignatures on Mars: what, where, and how? Implications for the search for Martian life](https://www.liebertpub.com/doi/pdfplus/10.1089/ast.2015.1374). *Astrobiology*, *15*(11), pp.998-1029.

WhiteHouse, 1977, [NSC-25: Scientific or Technological EXperiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space](https://irp.fas.org/offdocs/pd/pd25.pdf)

WHO, 2007. [Legionella and the prevention of legionellosis](https://www.who.int/water_sanitation_health/publications/legionella/en/).

WHO, 2019, [Leprosy, Key facts](https://www.who.int/news-room/fact-sheets/detail/leprosy), accessed at: <https://www.who.int/news-room/fact-sheets/detail/leprosy> Accessed on: July 18, 2020

WHO, 2003, [Laboratory Biosafety Manual Second Edition (Revised)](https://www.who.int/csr/resources/publications/biosafety/Labbiosafety.pdf)

WHO, 2014, [Haemophilus influenzae type b (Hib)](https://www.who.int/immunization/diseases/hib/en/)

WHO, 2020wic, [1st WHO Infodemiology Conference](https://www.who.int/news-room/events/detail/2020/06/30/default-calendar/1st-who-infodemiology-conference)

WHO, 2020tosi, [Transmission of SARS-CoV-2: implications for infection prevention precautions](https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions), Science Brief

Wickett, R.R. and Visscher, M.O., 2006. [Structure and function of the epidermal barrier](https://www.ajicjournal.org/article/S0196-6553(06)00950-3/fulltext). American journal of infection control, 34(10), pp.S98-S110.

*In SC [stratum corneum] that is desquamating at its normal rate, corneocytes persist in the SC for approximately 2 weeks, depending on body site, before being shed into the environment. On average, about one layer of corneocytes is shed each day from the surface and replaced by keratinocytes at the SG. The corneocytes that are shed each day can have a significant bacterial load and may be a source of contamination of the environment.*

Wierzchos, J., Ríos, A.D.L. and Ascaso, C., 2012. [Microorganisms in desert rocks: the edge of life on Earth](https://digital.csic.es/bitstream/10261/133795/1/Int%20Microbiol.%2015(4)%20173-83%20(2012).pdf).

Williams, J.P., Pathare, A.V. and Aharonson, O., 2014. [The production of small primary craters on Mars and the Moon](https://www.sciencedirect.com/science/article/pii/S001910351400133X#b0120). *Icarus*, *235*, pp.23-36.

Wilcox, B.H., Carlton, J.A., Jenkins, J.M. and Porter, F.A., 2017, March. [A deep subsurface ice probe for Europa](https://www.researchgate.net/profile/Fletcher-Porter/publication/317702124_A_deep_subsurface_ice_probe_for_Europa/links/5eb20507299bf18b9599969c/A-deep-subsurface-ice-probe-for-Europa.pdf). In 2017 IEEE Aerospace Conference (pp. 1-13). IEEE.

Wingo, D., 2004. [*Moonrush: Improving life on earth with the moon's resources*](https://www.amazon.com/Moonrush-Improving-Earth-Resources-Apogee/dp/1894959108/) Burlington: Apogee Books.

Wingo, D., 2016. [Site selection for lunar industrialization, economic development, and settlement](https://www.amazon.com/Value-Moon-Explore-Prosper-Resources/dp/1588345033/tag=space041-20). New Space, 4(1), pp.19-39.

Winn, W.C., 1988. [Legionnaires disease: historical perspective](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC358030/pdf/cmr00055-0072.pdf). *Clinical Microbiology Reviews*, *1*(1), pp.60-81.

Witze, A., 2018. [There's water on Mars! Signs of buried lake tantalize scientists](https://www.nature.com/articles/d41586-018-05795-6). *Nature*, *560*(7716), pp.13-15

Woese, C., 1998. [The universal ancestor](http://www.pnas.org/content/95/12/6854.long). *Proceedings of the national academy of Sciences*, *95*(12), pp.6854-6859.

*There are different ways of looking at such a community of progenotes. On the one hand, it could have been the loose-knit evolutionary (genetic) community just discussed. On the other, it could have been more like a modern bacterial consortium, with cells cross-feeding one another not only genetically but also metabolically. Cell–cell contacts would have facilitated both processes. In both views of the community, the latter in particular, it is not individual cell lines but the community of progenotes as a whole that survives and evolves. It was such a community of progenotes, not any specific organism, any single lineage, that was our universal ancestor—a genetically rich, distributed, communal ancestor.*

Woese, C.R., 2002. [On the evolution of cells](http://www.pnas.org/content/99/13/8742). *Proceedings of the National Academy of Sciences*, *99*(13), pp.8742-8747.

*“Aboriginal cell designs are taken to be simple and loosely organized enough that all cellular componentry can be altered and/or displaced through HGT, making HGT the principal driving force in early cellular evolution. Primitive cells did not carry a stable organismal genealogical trace. Primitive cellular evolution is basically communal. The high level of novelty required to evolve cell designs is a product of communal invention, of the universal HGT field, not intralineage variation. It is the community as a whole, the ecosystem, which evolves. The individual cell designs that evolved in this way are nevertheless fundamentally distinct, because the initial conditions in each case are somewhat different. As a cell design becomes more complex and interconnected a critical point is reached where a more integrated cellular organization emerges, and vertically generated novelty can and does assume greater importance.”*

Wohlforth, C., Hendrix, A.R., 2016a, [Let’s Colonize Titan](https://blogs.scientificamerican.com/guest-blog/lets-colonize-titan/), Scientific American

Wohlforth, C., Hendrix, A.R., 2016b, [Beyond Earth: Our Path to a New Home in the Planets](https://books.google.co.uk/books?id=WBycCwAAQBAJ&dq), Knopf Doubleday Publishing Group

WolfmanSF, 2019, [Hachimoji DNA base pairs](https://en.wikipedia.org/wiki/File:Hachimoji_DNA_base_pairs.gif) and [Hachimoji RNA base pairs](https://en.wikipedia.org/wiki/File:Hachimoji_RNA_base_pairs.gif)

Wolfram, J., 2018, [Apollo 11 Splashdown footage highlighting Navy Frogmen's role,](https://www.youtube.com/watch?v=snCNhgY6r5o)

Woods, D., Wheeler, R., Roberts, I., 2018, [Day 5 part 20: A surprise at staging](https://history.nasa.gov/afj/ap10fj/index.html), The Apollo 10 Flight Journal

Wordsworth, R., Kalugina, Y., Lokshtanov, S., Vigasin, A., Ehlmann, B., Head, J., Sanders, C. and Wang, H., 2017. [Transient reducing greenhouse warming on early Mars](https://arxiv.org/pdf/1610.09697.pdf). *Geophysical Research Letters*, *44*(2), pp.665-671. Press release [Bursts of methane may have warmed early Mars](https://www.seas.harvard.edu/news/2017/01/bursts-methane-may-have-warmed-early-mars)

## X

Xu, Z., Chen, Y., Meng, X., Wang, F. and Zheng, Z., 2016. [Phytoplankton community diversity is influenced by environmental factors in the coastal East China Sea](https://www.tandfonline.com/doi/pdf/10.1080/09670262.2015.1107138). *European Journal of Phycology*, *51*(1), pp.107-118.

*Abstract: Surface seawater was collected in four different seasons in the coastal East China Sea adjacent to the Yangtze River Estuary and phytoplankton community diversity was analysed using rbc L genetic markers.*  
*page 111: The cyanobacterium Chroococcidiopsis sp. was widely represented in the tree, accounting for 14%, 7%, 3% and 7% of total clones in spring, summer, autumn and winter, respectively*

## Y

Yan, J., Grantham, M., Pantelic, J., De Mesquita, P.J.B., Albert, B., Liu, F., Ehrman, S., Milton, D.K. and EMIT Consortium, 2018. [Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community](https://www.pnas.org/content/115/5/1081). Proceedings of the National Academy of Sciences, 115(5), pp.1081-1086. Popular account: Paddock, C., 2018, ['Just breathing' is enough to spread flu](https://www.medicalnewstoday.com/articles/320690), Medical news Today

Yano, H., Chujo, T. JAXA/ISAS, [Case Study Planetary Protection Category V Unrestricted Earth Return: Hayabusa-1&2](http://pposs.org/wp-content/uploads/2017/03/14.-PPOSS-Case-Study-category-V-H.-Yano.pdf) Japan and the Hayabusa-1 and Hayabusa-2 Teams

Yeager, C.M., Lanza, N.L., Marti-Arbona, R., Teshima, M., Lingappa, U.F. and Fischer, W.W., 2019. Terrestrial Rock Varnish: Implications for Biosignatures on Mars. *LPICo*, *2108*, p.5060.

Yocum, R.R., Rasmussen, J.R. and Strominger, J.L., 1980. [The mechanism of action of penicillin. Penicillin acylates the active site of Bacillus stearothermophilus D-alanine carboxypeptidase.](https://www.ncbi.nlm.nih.gov/pubmed/7372662) *Journal of Biological Chemistry*, *255*(9), pp.3977-3986.

Yong, C.Q.Y., Valiyaveetill, S. and Tang, B.L., 2020. [Toxicity of microplastics and Nanoplastics in mammalian systems](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7084551/). International Journal of Environmental Research and Public Health, 17(5), p.1509.

Yung, Y.L., Chen, P., Nealson, K., Atreya, S., Beckett, P., Blank, J.G., Ehlmann, B., Eiler, J., Etiope, G., Ferry, J.G. and Forget, F., 2018. [Methane on Mars and habitability: challenges and responses](https://www.liebertpub.com/doi/full/10.1089/ast.2018.1917). Astrobiology, 18(10), pp.1221-1242.

## Z

Zakharova, K., Marzban, G., de Vera, J.P., Lorek, A. and Sterflinger, K., 2014. [Protein patterns of black fungi under simulated Mars-like conditions](https://www.nature.com/articles/srep05114). *Scientific reports*, *4*, p.5114.

Zhang, N. and Cao, H., 2020. [Enhancement of the antibacterial activity of natural rubber latex foam by blending It with chitin](https://www.mdpi.com/1996-1944/13/5/1039/htm). *Materials*, *13*(5), p.1039.

Zhang, Y., Ptacin, J.L., Fischer, E.C., Aerni, H.R., Caffaro, C.E., San Jose, K., Feldman, A.W., Turner, C.R. and Romesberg, F.E., 2017. [A semi-synthetic organism that stores and retrieves increased genetic information](https://www.nature.com/articles/nature24659). *Nature*, *551*(7682), pp.644-647..

Zhou, B. and Shen, J., 2007. Comparison Of HEPA/ULPA Filter Test Standards Between America And Europe. In *Proceedings of Clima*.

Zubrin, R. ["Contamination From Mars: No Threat"](http://www.freerepublic.com/focus/f-news/516795/posts), The Planetary Report July/Aug. 2000, P.4–5

Zurbuchen, T.H., 2019. [NASA Response to Planetary Protection Independent Review Board Recommendations](https://apps.dtic.mil/sti/pdfs/AD1085135.pdf).

ZZ2, 2014, [A small pile of Martian regolith simulant JSC MARS-1A](https://en.wikipedia.org/wiki/File:Martian_regolith_simulant_-_pile.JPG), Wikimedia commons

# Figure permissions

Copyright rules for: [NASA](https://sti.nasa.gov/disclaimers/#.YGHyaD_TVQI)

[Figure 1](#fig_mars_sample_return): ESA

[Figure 2](#fig_swab_bleach): NASA

[Figure 3](#fig_Sagan_lunar_habitat): Own work, incorporates NASA photograph of Apollo 11 lunar landing module Eagle.

[Figure 4](#fig_SEM_microbe): [Creative commons](https://www.sciencedirect.com/science/article/pii/S016041201930772X)

[Figure 5](#fig_ESF_containment): ESF

[Figure 6](#fig_sample_containment): NASA

[figure 7](#fig_double_wall_system): NASA / FLAD

[Figure 8](#fig_EURO_CARES_text): ESF (screenshot from page circling misquoted number)

[Figure 9](#fig_ESF_text): ESF

[Figure 10](#fig_coronavirus_carrier): [unrestricted research re-use granted for as long as Elsevier COVID-19 resource center remains active](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7194611/).

[Figure 11](#fig_ribozyme): [Free of all copyright restrictions](https://www.rcsb.org/pages/policies)

[Figure 12](#fig_ALH84001_nanobe): [AAS: Science](https://science.sciencemag.org/content/273/5277/924.abstract) [Figure needs permission, redraw or new source]

[Figure 13](#fig_project_costs_NASA): NASA

[Figure 14](#fig_quarantine_issues): NASA

[Figure 15](#fig_Zinnia_mold): NASA

[Figure 16](#fig_LAS_msr): NASA / LAS

[Figure 17](#fig_sterilized_msr): ESA

[Figure 18](#fig_amino_acid_ionizing_radiation): Earth and Planetary Science Letters [article](https://www.sciencedirect.com/science/article/abs/pii/S0012821X06002123) [Figure needs permission, redraw or new source]

[Figure 19](#fig_carbon_nanotupe_X_ray): [Science Direct](https://www.sciencedirect.com/science/article/pii/S1738573316000437): [Figure needs permission, redraw or new source]

[Figure 20](#fig_endoliths_Mars): [Creative commons](http://revistes.iec.cat/index.php/IM/article/view/65855) cc by 3.0

[Figure 21](#fig_CO_isotope_processes)*: Nature Astronomy* [Figure needs permission, redraw or new source]

[Figure 22](#fig_lifeless_sample_return): Nature [Figure needs permission, redraw or new source]

[Figure 23](#fig_viking_circadian_rhythms): [Figure needs permission]

[Figure 24](#fig_viking_circadian_rhythms_smoother): [Figure needs permission]

[Figure 25](#fig_curiosity_brines): [Nature Geoscience](https://www.researchgate.net/journal/Nature-Geoscience-1752-0908) [figure needs permission]

[Figure 26](#fig_curiosity_water_activity): [Nature Geoscience](https://www.researchgate.net/journal/Nature-Geoscience-1752-0908) [figure needs permission]

[Figure 27](#fig_REMS_surface_temp_to_200): NASA

[Figure 29](#fig_cfu_low_pressure):[Astrobiology](https://www.liebertpub.com/doi/abs/10.1089/ast.2016.1587) [Figure needs permission]

[Figure 30](#fig_UV_Mars_storm): NASA

[Figure 31](#fig_foraminiferal_cysts): [Marine Biology Research](https://www.tandfonline.com/doi/abs/10.1080/17451000510019114?tab=permissions&scroll=top) [Figure needs permission]

[Figure 32](#fig_saltation): NASA; the bounce was sketched by hand to approximate the shape of a typical bounce from figure 2b of Almeida et al [(Almeida et al, 2020)](#kix.p083jl9pyr3j)

[Figure 33](#fig_phoenix_droplets): NASA

[Figure 34](#fig_fossil_microbial_mat) :[Astrobiology](https://www.liebertpub.com/doi/full/10.1089/ast.2014.1218) [Figure needs permission]

[Figure 35](#fig_cone_shaped_stromatolite): [PNAS](https://www.pnas.org/content/106/24/9548) [Figure needs permission]

[Figure 36](#fig_ALH84001_namobes2): [NASA](https://apod.nasa.gov/apod/ap960807.html)

[Figure 37](#fig_chiral_meteorite_amino_acids): [Chemical Society Reviews](https://pubs.rsc.org/en/content/articlelanding/2012/cs/c2cs35109a/unauth) [Figure needs permission]

[Figure 38](#fig_chiral_meteorite_sugars): [PNAS](https://www.pnas.org/content/113/24/E3322.long) [Figure needs permission]

[Figure 39](#fig_crater_age): Own work

[Figure 40](#fig_small_crater_degradation) [HiRISE](https://www.uahirise.org/media/usage.php) NASA/JPL/University of Arizona

[Figure 41](#fig_organics_radiolysis_survival): [ScienceDirect](https://www.sciencedirect.com/science/article/abs/pii/S0019103516305425) [Figure needs permission]

[Figure 42](#fig_rotary_sampler): [Nature microbiology](https://www.nature.com/articles/s41564-019-0370-4) [Figure needs permission or another source]

[Figure 43](#fig_MAHLI_REMS_dust): NASA

[Figure 44](#fig_Viking_digging_tool): NASA

[Figure 45](#fig_Orbiting_Sample_Container_with_regolith): NASA, [CC by 3.0](https://en.wikipedia.org/wiki/File:Martian_regolith_simulant_-_pile.JPG), [public domain](https://commons.wikimedia.org/wiki/File:Etiquette_cd-rom_01.svg)

[Figure 46](#fig_swansong_gaia): NASA

[Figure 47](#fig_curiosity_oxygen_excess): NASA

[Figure 48](#fig_inverse_correlation_oxygen_dust): [CC by 4.0](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JE006175)

[Figure 49](#fig_telerobotic_msr): ESA

[Figure 50](#fig_Laplace_plane): NASA

[Figure 51](#fig_HAMR_Laplace_inclination): [COSPAR](http://commercialspace.pbworks.com/w/file/fetch/88916768/Rosengren,%20Scheeres%202014.pdf) - [COSPAR grants permission for reuse](https://cosparhq.cnes.fr/publications/advances-in-space-research-asr/)

[Figure 52](#fig_HAMR_Laplace_parameter_space): [COSPAR](http://commercialspace.pbworks.com/w/file/fetch/88916768/Rosengren,%20Scheeres%202014.pdf) - [COSPAR grants permission for reuse](https://cosparhq.cnes.fr/publications/advances-in-space-research-asr/)

[Figure 53](#fig_HAMR_Laplace_eccentricity): [COSPAR](http://commercialspace.pbworks.com/w/file/fetch/88916768/Rosengren,%20Scheeres%202014.pdf) - [COSPAR grants permission for reuse](https://cosparhq.cnes.fr/publications/advances-in-space-research-asr/)

[Figure 54](#fig_DRO_sample_capture): [IEEE](https://www.infona.pl/resource/bwmeta1.element.ieee-art-000006836477/tab/summary) [Figure needs permission]

[Figure 55](#fig_LL2_halo_sample_capture): [Acta Astronautica](https://www.sciencedirect.com/science/article/abs/pii/S0094576514002094) [Figure needs permission]

[Figure 56](#fig_double_halo_sample_capture): [Acta Astronautica](https://www.sciencedirect.com/science/article/abs/pii/S0094576514002094) [Figure needs permission]

[Figure 57](#fig_uninhabited_habitat_meteorite_impact): [Astrobiology](https://www.liebertpub.com/doi/abs/10.1089/ast.2013.1106) [Figure needs permission, redraw or new source]

[Figure 58](#fig_DNA_alternatives): [CC by 4.0](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4756832/)

[Figure 59](#fig_base_pairing_systems): [CC by 4.0](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4756832/)

[Figure 60](#fig_Hachimoji): [AAS Science](https://science.sciencemag.org/content/363/6429/884.abstract) [Figure needs permission] - Redrawn CC by 4.0

[Figure 61](#fig_codons_reassignment): Nature Chemical Biology [Figure needs permission, redraw or new source]

[Figure 62](#fig_coronated_polystyrene): [CC by 4.0](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6586940/)

[Figure 63](#fig_coalescing_coronated_polystyrene): [CC by 4.0](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6586940/)

[Figure 64](#fig_polystyrene): [Nanoscale](https://pubs.rsc.org/--/content/articlelanding/2011/nr/c0nr00944j/unauth#!divAbstract) [Figure needs permission, or new source]

[Figure 65](#fig_oxygen_evolution_photosynthesis): [Elsevier](https://www.sciencedirect.com/science/article/abs/pii/S0168945209001861) [Figure needs permission]

[Figure 66](#fig_mirror_life): NASA / USGS [(background image)](http://nasa/USGS), [free of all copyright restrictions](https://www.rcsb.org/pages/usage-policy) (DNA spiral)

[Figure 67](#fig_titanium_tank): NASA / Creative Commons

[Figure 68](#fig_Cernan_lunar_dust): NASA

[Figure 69](#fig_Schmitt_lunar_dust): NASA

[Figure 70](#fig_lunar_ballistic_dust): NASA

# Highlights of what’s new in this article

[needs updating]

The planetary protection literature already covers the issue of the length of quarantine period for an astronaut or technician (Carl Sagan observed that the latency period of leprosy is measured in decades), and the ethical issue of keeping an astronaut or technician in quarantine when they have a sudden life threatening condition potentially caused by extraterrestrial materials.

However I found no previous mention of asymptomatic carriers, like typhoid Mary [(Korr, 2020)](#kix.i3u68r56h0sy) as an issue for the use of human quarantine to protect Earth from extraterrestrial life. Also I found no mention of the need for quarantine to contain life that is not pathogenic of humans but could cause problems for other terrestrial lifeforms, or the need for quarantine to contain unfamiliar biology such as mirror life that could have adverse effects on the terrestrial ecosystems. This article concludes that there seems to be no way to contain such hazards using human quarantine, unless we know what is in the sample and what its capabilities are. This conclusion seems to be new.

See

* [[Complexities of quarantine for technicians accidentally exposed to sample materials](#h_complexities_of_quarantine)](#h_complexities_of_quarantine)

In discussions of worst case scenarios for return of extraterrestrial life, I have seen no previous study of the effects of returning mirror life.

See

* [Example of mirror life nanobacteria spreading through terrestrial ecosystems](#h_example_of_mirror_life)

Several of the other worst case scenarios I look at here seem to be new to the planetary protection literature. See for instance:

* [Possibility of extraterrestrial Martian life setting up a “Diminished Gaia” on Earth](#_kuefq6e917l6)
* [Worst case scenario where terrestrial life has no defences to an alien biology - humans survive by ‘paraterraforming’ a severely diminished Gaia](#_p8mguenm8mn)

I found no previous mention of the observation that NASA would need to know what they need to build before they can start the build process, and that since they won’t be able to overrule objections as they did for Apollo, this won’t be known until they complete the legal process. As a result the timescale for a sample return in this article is longer than in previous studies.

See

* [NASA procedural requirements for mission planners - they need to have a clear vision of the problems and how they can be solved before key point A](#_xla39n7rhqn1)

Previous work has proposed that the reason that Mars is close to the cold arid limit of life with its atmosphere close to the triple point of water could be due to processes such as abiotic photosynthesis with up to several bars of CO₂ sequestered in the Martian dust alone. However I found no previous mention of the idea that this could be the result of biology and biotic photosynthesis.

Previous work has looked at the possibility of swansong biospheres, also at an anti-gaia where life makes a planet gradually less inhabitable until it makes itself extinct. However I found no previous mention of the idea of combining both of those in a swansong gaia, where life maintains the atmosphere at close to the triple point of water, never making itself extinct, for billions of years. and can do so over a wide range of emissions scenarios for the volcanoes.

See

* [Suggestion of a self perpetuating “Swansong Gaia” maintaining conditions slightly above minimal habitability for billions of years - as a way for early life to continue through to present day Mars](#h_suggestion_swansong_Gaia)

This is relevant to the topic of this article because processes to keep the atmosphere at slightly above minimal habitability for billions of years add to the possibilities for returning viable life in the sample.

Previous articles have suggested returning extraterrestrial life to low Earth orbit or to the Moon, but I found no previous discussion of returning it to the Laplace “ring” plane above GEO.

See

* [**Recommendation** to return a sample for teleoperated ‘in situ’ study above Geosynchronous Equatorial Orbit (GEO)](#h_Recommendation_GEO)

Previous articles suggest sterilizing extraterrestrial samples with gamma rays. However I found no previous discussion of using nanoscale X-ray emitters for sterilization during the six months return flight from Mars to Earth.

See:

* [Suggestion to use nanoscale X-ray emitters for sterilization](#_qmz83mcmqrxs)

There are many proposals for sample receiving facilities. However I wasn’t able to find any that correctly cited the ESF 2012 requirement that release of a single particle of 0.05 microns is not permitted under any circumstances. The EURO CARES design cites this study but due to an unfortunate typo, the design is for a one in a million chance of release of a sample of 0.1 microns, per particle, which would not comply.

See:

* [Order of magnitude typo in cite for EURO-CARES sample return facility design - ESF study’s probability < 10⁻⁶ is for unsterilised particles of 0.01 μm not 0.1 μm](#_mdfjnmunzqky)

Previous studies all look at HEPA and ULPA filters. This seems to be the first to notice that these filters don’t comply with the ESF recommendations, and that new technology is needed if these recommendations become legal requirements

See

* [Filter technology innovations needed for 0.05 μm standard - HEPA and ULPA filters are not adequate](#_f0mc527l4mw4)

This seems to be the first study to consider the available technology and observe that even the best experimental filters in laboratories such as an experimental filter to attempt to contain the smallest droplets with individual SARS - CoV2 viruses don’t yet comply with the ESF recommendation

See

* [[Example of best available nanofilter technology from 2020, not yet commercially available, filters out 88% of ambient aerosol particles at 0.05 microns - far short of the ESF requirement to filter out 100% at this size – though the ESF requirement at 0.05 microns can be met with nanoparticles in water under high pressure](#_wxhe1kvuyput)](#h_nanofilter)

Previously Chris McKay suggested grabbing a sample of dirt as a low cost sample return mission. However I found no previous suggestion to modify the ESA sample fetch rover to add a sample of dirt on top of the rock samples from Perseverance.

* [Possible use of Perseverance - or modification of ESA’s Sample Fetch Rover to return samples from shallow sand dune subsurface](#_9e0adi3zubdd)

Previous articles have looked at the effect of UV on transfer of life in the dust, however I found no discussion of the possibility that native Martian life could evolve to cover itself in nanoparticles of iron oxides to protect its propagules from UV light, in a process similar to the agglutinated external sediment cysts built by some foraminifera in the sea.

See

* [Could Martian life be transported in dust storms or dust devils, and if so, could any of it still be viable when it reaches Perseverance?](#h_transported_dust_storms_dust_devils)

I found no previous suggestion to add empty sample tubes with magnets in the neck to the ESA fetch rover, to be left on the surface to collect dust from dust storms and dust devils while the rover fetches the Perseverance samples..

See

* [**Recommendation:** Extra sample of air and airfall dust to search for Martian life, assess forward contamination issues for terrestrial microbes, dust dangers for astronauts, and to return a random sample of wind-eroded rock from distant parts of Mars](#h_rec_air)
* [**Proposal:** magnets could be used to enhance dust collection](#h_proposal_magnets)
* [**Proposal:** to use the sample return capsule as a dust collector – keep it open to the atmosphere before adding the sample tubes](#h_proposal_sample_returjn_capsule_dust)

I have found no previous papers on sampling the dust in dust storms to search for traces of distant inhabited habitats perhaps thousands of kilometers away, such as happens on Earth with terrestrial transfer of spores in dust storms from deserts. Also I can’t find any suggestion that spores from such habitats could explain the Viking results. See:

* [Searching for distant inhabited habitats on Mars through presence or absence of one originally living cell per gram – a rough first estimate assuming uniform mixing throughout Mars for a first estimate requires life to cover between 114,000 and 1,140 square kilometers with densities of life in the dust similar to an Antarctic RSL analogue in cell count, but less than a tenth of a square kilometer if any reach a billion cells per gram – these figures can be higher if any source habitats with high densities of cells are closer to the rover with uneven mixing](#h_Searching_for_distant_habitats_dust)

The idea of using the Marscopter or the Perseverance rover itself to look for young craters within reach of Perseverance excavated to a depth of several meters in the last few thousand years seems to be new to this article.

See

* [Proposal to use Marscopter or observations by Perseverance from a high elevation to search for recently excavated small craters for less degraded organics from early Mars](#_2bzb19kzv667)

Carl Sagan said of a Mars sample return:

*The likelihood that such pathogens exist is probably small, but we cannot take even a small risk with a billion lives.*

However I can’t find previous studies that elaborate on this and connect it with insights from synthetic biology to suggest that the legal process of a sample return would be likely to consider the need for higher standards of containment than for a normal biosafety laboratory.

See

* [Formulating Sagan’s criterion and variations on the precautionary principle - which one is appropriate for a Mars sample return?](#_fp1s7mhe7n2d)

The suggestion that one possible outcome of the legal process is that the mission can’t go ahead seems to be new to this article.

See

* [A requirement for similar levels of safety to those used for experiments with synthetic life would lead to the Prohibitory version of the Precautionary Principle and make unsterilized sample return impossible with current technology and current understanding of Mars](#h_any_requirement_similar_synthetic_life)

The suggestion that Mars could have life that can never make safe contact with Earth’s biosphere is an unstated background to the planetary protection literature, but this article may be first to state this clearly.

I think this may be the first paper to say explicitly that the worst case scenarios include situations where we can never return life from Mars to Earth, and where quarantine of astronauts can’t protect Earth, for instance if Mars has mirror life. At present we have no way to prove that any unfamiliar biology on Mars would be safe for Earth’s biosphere.

See

* [Similar considerations apply to astronauts returning from Mars - in some scenarios such as mirror Martian life, astronaut quarantine would be insufficient to protect Earth’s biosphere](#h_astronaut_mirror_life)

There have been several proposals to study Mars telerobotically from orbit, but the more detailed suggestion that we need to complete a rapid preliminary astrobiological survey of Mars from orbit first before we can make properly informed decisions about sending humans to the surface seems to be new.

See

* [Resolving these issues with a rapid astrobiological survey of Mars, tele-operating rovers from orbit](#_k25tnylg2ekh)

The proposal to use the technology for a Venus lander to construct heat sterilized 100% sterile rovers to explore Mars is not new to this article but the detailed discussion is new, especially the proposal that we need to develop a specification for 100% sterile rovers before we start large scale exploration of Mars from orbit. Such a specification and designs based on it will greatly simplify planetary protection for exploring Mars and other potential locations for life like Europa and Enceladus.

See

* [Design specifications for 100% sterile rovers for fast safe astrobiological surveys throughout the solar system](#_4f9mmbuo6v1t)

The aim in this article is to try to anticipate some of the issues that will be raised in the future, as experts from disciplines like epidemiology, synthetic biology, the engineering of filters, and ethicists and lawyers examine NASA’s recommendation:s. Many new points in this article come as a result of widening the literature examined to cover these fields.

For details about some of the other points that may be new, see:

* [What is new to the planetary protection literature in this article](#_v3mk32itl19x) below.

Do please contact me if you know of previous work on these topics, thanks!

# Outline - and what’s new in this article

[needs updating]

Much of this paper is an application of material from the wider scientific literature that so far hasn’t been applied to the problems involved in planetary protection.

**“New presentation”** means a new take on the literature, organized to make comparisons easier, shed light on connections.

**“Summarizes:”** means it summarizes the literature

**“Expands”** means it summarizes the literature but with extra details or suggestions

**“Recommendation”** means a recommendation for future missions.

**“New”** means to the best of my knowledge, the material is new to the published literature about planetary protection. To give one example, to my knowledge, the issue of symptomless superspreaders has never previously been discussed in the context of planetary protection but is widely discussed in epidemiology.

**“original”** means original research, such as the proposal of a Martian swansong Gaia.

Many of these matters may have been discussed informally and not published previously. If the reader knows of any previous publication of any of these points - including preprints, or video presentations or discussions - do say and I will cite it. Thanks!

This section is primarily to assist reviewers. However it may also be of interest to readers too, as an outline and to show what is new in the article.

[Mid edit, sections marked (...) need to be written]

[**No legal precedent for a restricted sample return with “potential for adverse changes to the environment of Earth” (Apollo guidelines had no peer review)**](#_xkd93xv99557)

**Summarizes:** Perseverance has landed on Mars, the legal process hasn’t started yet, and there is no legal precedent.

[Apollo procedures didn’t protect Earth even according to the Interagency Committee on Back Contamination (ICBC) that advised NASA A](#_tj6p37ygj9f7)

**Summarizes:**NASA was able to overrule objections in 1969, but would not be able to do so today.

[Comet and asteroid sample returns are straightforward - but are unrestricted sample returns - sterilized during collection - or Earth has a similar natural influx](#h_Comet_and_asteroid)

**Summarizes**: we have already done comet and asteroid sample returns but they were straightforward because there was no back contamination risk.

[Controversial 2019 recommendation to classify parts of Mars as category II, similar to the Moon, in forward direction](#_jc8iush5q1j7)

**Summarizes:** Stern et al.’s recommendation to classify regions of Mars as Category II like the Moon in the forwards direction, yet restricted category V in the backward direction, similarly to the situation for the Moon in 1969. They base this on the report by Rummel et al. from 2014.

* [2015 review: maps can only represent the current incomplete state of knowledge for a specific time – with knowledge gaps on survival of terrestrial life in dust storms and potential for life to survive in habitats hard to detect from orbit - so can’t yet be used to identify which areas of Mars are of planetary protection concern in the forwards direction](#h_2015_maps)

**Summarizes:** Board (2015) which was not cited by Stern et al. criticises Rummel et al. and concludes that before a Category II classification of parts of Mars we need to complete knowledge gaps on transfer of terrestrial life in the dust storms, and potential for life to survive in microhabitats on Mars not easily detected from orbit.

[2015 review: maps can only represent the current incomplete state of knowledge for a specific time – with knowledge gaps on survival of terrestrial life in dust storms and potential for life to survive in habitats hard to detect from orbit - so can’t yet be used to identify which areas of Mars are of planetary protection concern in the forwards direction](#h_2015_maps)

**Summarizes:** NAS 2020 review says the category system applies to a mission not a target and makes criticisms similar to Board et al in 2015 of attempts to categorize regions of Mars using maps.

[Why we may need to protect Earth from backward contamination even if it turns out that forward contamination is unlikely or impossible - example of Sagan’s proposed habitat on the Moon](#_on4osbov63dz)

**New presentation:** The Apollo missions attempted to protect Earth from backwards contamination of and didn’t protect the Moon from forward contamination. It’s interesting to look into how this was possible and ask whether such a situation could arise on Mars for future missions

This is possible if

1. Native habitats for Martian life can’t be colonized with terrestrial life (e.g. too cold for terrestrial life), OR
2. Contamination with terrestrial life spreads only with great difficulty over thousands of years from one part to another of the Martian surface.

[Comparison of the Moon as understood in 1969 with Mars as we understand it today](#_9nd42ridv6j1)

**New presentation** - the idea of comparing the situation in 1969 with Mars as we understand it today in this direct point by point way may be new.

[**First restricted sample return since Apollo - with proposed microhabitats and no natural way for any life from surface layers to reach Earth**](#_kiftltovmy6p)

**Summarizes:** some of the proposed microhabitats such as the RSLs, the puzzling Viking results and discusses Greenberg’s natural contamination principle.

[First restricted (potentially life bearing) sample return since Apollo, however, science reviews in 2009 and 2012 have lead to increasing requirements on such a mission – especially as the result of discovery of the very small starvation mode nanobacteria](#h_increasing_requirements)

**Summarizes:** ESF study found a theoretical minimum size for terrestrial life which also matched the scanning electron micrographs of nanobacteria that passed through a 0.1 micron nanofilter

[By European Space Foundation study (2012), particles larger than 0.05 μm in diameter are not to be released under any circumstances](#_3js02w62qkf0)

**Summarizes:** requirements from the 2012 ESF study

The three proposed methods of containing samples in a Mars sample receiving facility, BSL-4 in a clean room, clean room in a BSL-4 and triple wall - with examples for each design

**Summarizes:** some of the proposed sample receiving facility designs

[Order of magnitude typo in cite for EURO-CARES sample return facility design - ESF study’s probability < 10⁻⁶ is for unsterilised particles of 0.01 μm not 0.1 μm while 100% containment is required for particles of 0.05 μm](#_mdfjnmunzqky)

**New:** Order of magnitude typo in the EURO-CARES cite of the ESF report - they cite the requirement as a one in a million chance of containing a particle with diameter greater than 0.1 µm. The ESF report discusses a one in a million chance for a particle with diameter greater than 0.01 µm.

This one in a million figure also refers to the chance of a release of a single particle at this size over the lifetime of the facility, and EURO-CARES treats it as a probability per particle.

The ESF study has a requirement of 100% containment at 0.05 μm.

The papers on sample receiving facility designs don’t seem to have picked up on this requirement, but it would be brought up in the legal process.

[Filter technology innovations needed for 0.05 μm standard - HEPA and ULPA filters are not adequate](#_f0mc527l4mw4)

**New:** HEPA and ULPA filters used for biosafety level IV facilities don’t comply with the requirements of the ESF sample return study.

[[Example of best available nanofilter technology from 2020, not yet commercially available, filters out 88% of ambient aerosol particles at 0.05 microns - far short of the ESF requirement to filter out 100% at this size – though the ESF requirement at 0.05 microns can be met with nanoparticles in water under high pressure](#_wxhe1kvuyput)](#_wxhe1kvuyput)

**New:** discussion of whether a suitable filter can be made with current technology. Experimental nanofilters can filter out 100% of particles at this size for water treatment but have significant maintenance challenges.

For aerosols the best available technology seems to be represented by a proposed filter in development in 2020 capable of filtering out individual SARS-Cov2 particles as small as 0.06 µm. This filter, which is “state of the art” and not yet available commercially, is only able to filter out 88% of particles at 0.05 µm, far short of the 100% requirement of the ESF study.

The technology doesn’t seem to exist yet.

[Need for maintenance for future 0.05 μm compliant filters](#_aufdkljm0dkh)

**Summarizes:** Equipment needs to be maintained and filters need regular replacement.

**New:** nanofilters for removing 0.05 μm aerosol particles are likely to be challenging to maintain and replace safely.

[ESF study’s recommendation for regular review of the size limits](#h_ESF_regular_review)

**Expands:** - the ESF study said regular review is needed. By 2020, eight years later, another review is certainly required since the minimum size was reduced from 250 nm to 50 nm / 10 nm in just three years from 2009 to 2012.

[Scientific developments since 2012 relevant to review of 0.05 µm / 0.01 µm size limits](#_4kt6j3orab8b)

**Expands:** Discussion of the possibility of an RNA world microbe with a diameter of only 0.014 µm. This is mentioned in the 1999 limitations of size report as a possible interpretation of the ALH84001 meteorite nanoscale features, but got little attention since then.

The new suggestion in this article is that small microbes with a novel biochemistry such as mirror life could be better able to compete with larger terrestrial organisms. New research into synthetic life since the ESF study in 2012 might lead a review to reconsider the possibility of small RNA world microbes in the sample.

[Priority early on in legal process to decide on filter requirements and to outline future technology to achieve this standard](#_93ji66cqejk)

(...)

[Need for advanced planning and oversight agency set up before start of the legal process](#_v23hp14dpnnx)

(...)

[NASA procedural requirements for mission planners to develop a clear vision of the problems and show how the solution will be feasible and cost-effective before key decision point A because of significant costs involved in modifying designs after the build starts](#_xla39n7rhqn1)

Summarizes existing literature

[Potential changes in requirements as a result of the legal process](#_8v7pce832u7s)

(...)

[Minimum timeline: 2 years to develop consensus legal position, 6-7 years to file Environmental Impact Statement, 11 years to build sample return facility](#h_MinimumTimeline)

(...)

[[Need for legal clarity before build starts - NASA has reached keypoint A for the budget for entire program, but can’t know what they will be legally required to build for the facility.](#h_need_for_legal_clarity)](#_pdvvj8y2sqjl)

(...)

[[Need for legal clarity before launch of ESA’s Earth Return Orbiter, Earth Entry Vehicle, and NASA’s Mars Ascent Vehicle.](#h_need_for_legal_clarity_earth_return)](#_3ku6cvvx8agc)

(...)

[Likely legal requirement for facility to be ready to receive samples well before unsterilized samples return to Earth](#_2ixeoo5rp3q7)

(...)

[Legal process likely to extend well beyond 6 years with involvement of CDC, DOA , NOAA, OSHA etc, legislation of EU and members of ESA, international treaties, and international organizations like the World Health Organization](#h_legal_process_likely)

(...)

[**Public health challenges responding to release of an extraterrestrial pathogen of unfamiliar biology**](#_h3xlihwvoz0)

Summarizes existing literature

[**Complexities of quarantine for technicians accidentally exposed to sample materials**](#h_complexities_of_quarantine)

(...)

[Vexing issue of authorizations to remove technicians from quarantine to treat life threatening medical incidents in hospital](#_i5u77k7ag6jk)

**Expands**: covers the ethical issues for human quarantine mentioned in Meltzer et al of balancing an uncertain risk of planetary protection against a certainty that an individual's life can be saved. Gives examples and discusses how it is ethically understandable that preventing risk of death or serious injury to an individual has the highest priority - but it then negates most of the value of quarantine.

[Example of technician in quarantine with acute respiratory distress and symptoms similar to Legionnaires’ disease](#_yga1rhqn8rpx)

**New:** This is already in planetary protection discussions - but the suggestion that a Martian pathogen of human lungs could also be symptomless in some individuals like some cases of Legionnaires’ disease may be new.

[Arbitrariness of technician’s quarantine period for an unknown pathogen](#_tzbdyck03mo4)

(...)

[How do you quarantine a technician who could be a symptomless super-spreader of an unknown Martian pathogen?](#_tu1phnn2a9h)

**New:** Symptomless super-spreader carriers (like Typhoid Mary). This doesn’t seem to be discussed previously in the planetary protection literature.

[Martian microbes could participate harmlessly or even beneficially in the human microbiome but harm other terrestrial organisms when the technician exits quarantine - example of wilting Zinnia on the ISS](#_dwfiy8grncyn)

**New:** That alien life could become part of the human microbiome, and remain harmless to humans then harm other creatures or the biosphere on leaving quarantine.

The idea of alien life becoming part of the human microbiome in quarantine may be new.

[What if mirror life becomes part of the technician’s microbiome?](#_c4x8f4hxlkj0)

**New:** That the human microbiome could support mirror-life nanobacteria - especially if it is pre-adapted to use non mirror organics on Mars.

[Survival advantages of mirror life competing with terrestrial life that can’t metabolize mirror organics](#_27aq7y25n4kx)

**New:** That mirror-life nanobacteria from Mars may be preadapted to metabolize non mirror organics   
  
This could be from adaptation to use racemic mixtures of organics from meteoritic and comet infall, or the result of co-existing with non mirror life on Mars.

Examining advantages of a mirror-life nanobacteria to survive in the wild on Earth even if its biochemistry is simpler than any terrestrial life (similarly to the arguments used in favour of nanobes in a shadow biosphere).

[Similar considerations apply to astronauts returning from Mars - in some scenarios such as mirror Martian life, astronaut quarantine would be insufficient to protect Earth’s biosphere](#_287ajdtckwy)

(...)

[Telerobotics as a solution to all these human quarantine issues](#_hq85xokbn43c)

(...)

[Zubrin's arguments in: "Contamination from Mars: No Threat" and the response of planetary protection experts in "No Threat? No Way":](#_46cr20rbmp4w)

(...)

[**These complexities arise due to need to contain almost any conceivable exobiology**](#_se5oz9sa1i6j)

(...)

[**Sterilized sample return as aspirational technology demonstration for a future astrobiology mission**](#h_Sterilized_sample_return)

(...)

[[Level of sterilization needed similar to ~100 million years of Martian surface ionizing radiation - and would leave present day life and past life still recognizable - if recognizable without sterilization](#_2oqtgaj3wac7)](#h_level_sterilization)

[s](#_2oqtgaj3wac7)

(...)

[Suggestion to use nanoscale X-ray emitters for sterilization](#_qmz83mcmqrxs)

(...)

[Effects of gamma radiation on rock samples - and need to test X-rays](#_dkbd7p7vhaw5)

(...)

**Why it’s a major challenge to find samples from Jezero crater to help decide central questions in astrobiology until we can send in situ life detection instruments - most past biosignatures will be degraded beyond recognition – nearly all organics on Mars are expected to be abiotic - past and present day life is expected to be low in concentration and patchy in distribution – and all this is especially challenging if Martian life never developed photosynthesis or nitrogen fixation**

(...)

[Perseverance’s target, an ancient delta in Jezero crater - high potential - but need to manage expectations - with limited in situ biosignature detection, samples not likely to resolve central questions in astrobiology](#_c06p2zao6zvk)

(...)

[Limitations on cleanliness of the Mars sample tubes with estimated 0.7 nanograms contamination each for DNA and other biosignatures per gram of returned rock sample, and a roughly 0.02% possibility of a viable microbe in at least one of the tubes](#h_lim_cleannliness)

(...)

[Modern miniaturized instruments designed to detect life in situ on Mars - could also be used to examine returned samples in an orbital telerobotic laboratory](#h_Modern_miniaturized_instruments)

(...)

[**Could Perseverance’s samples from Jezero crater in the equatorial regions of Mars contain viable or well preserved present day life?**](#h_could_samples_contain_viable_life)

(...)

[Detection by Curiosity rover of liquid water as perchlorate brines in Gale crater sand dunes and similar conditions are predicted in Jezero crater dunes](#h_detection_liquid_water)

**Expands:** Discussion of the brine layer found in sand dunes by Curiosity. Although too cold for terrestrial life, I argue that it is potentially habitable by martian life with lower temperature limits than terrestrial life using chaotropic agents, or biofilms or both. Nilton Renno briefly mentioned the idea of a biofilm making this layer habitable in an interview but it hasn’t had much attention. This increases the potential for returning native life from Jezero crater.

[Experiments with black yeasts, fungi and lichens in Mars simulation conditions suggest life could use the night time humidity directly without liquid water](#h_experiments_black_yeasts)

**Summarizes:** Discussion of experiments in the ability of some fungi and lichens to metabolize in the presence of the high night time humidity but without liquid water, in Mars surface conditions of high UV and low atmospheric pressure and extreme variations in temperature. This possibility again can’t be ruled out, and more experiments are needed.

Not much seems to have been done by way of published research in the last few years

[Surface conditions of ionizing radiation, UV radiation, cold and chemical conditions don’t rule out the presence of life](#_qbomwrudqbj7)

(...)

[Sources of nitrogen on Mars as potential limiting factor – unless Martian life can fix nitrogen at 0.2 mbar](#h_sources_of_nitrogen)

**Expands:** Discussion of the possibility of nitrogen fixation in the present day Martian atmosphere even with its low levels of nitrogen - which could contribute to habitability for present day life. Experiments so far have shown that this is possible at terrestrial atmospheric pressure and Martian partial pressures of nitrogen. If this is possible it expands habitability of the Martian near subsurface. This possibility can’t be ruled out and needs experiments on low pressure nitrogen fixation in Mars simulation chambers.

[Could Martian life be transported in dust storms or dust devils, and if so, could any of it still be viable when it reaches Perseverance?](#h_transported_dust_storms_dust_devils)

(...)

[Native Martian propagules (spore aggregates or hyphal fragments) could be up to half a millimeter in diameter, and evolve extra protection such as a shell of agglutinated iron oxide particles or chitin](#h_Native_Martian_propagules)

(...)

[Potential for spores and other propagules from nearby or distant regions of Mars similarly to transfer of spores from the Gobi desert to Japan](#_kdyk9up638hw)

**New:** Suggestion that if Martian life is wind dispersed, it may be dispersed seasonally during the dust storm seasons. Spore formation may also be triggered by the low light levels of a dust storm.   
  
Suggestion for year round sample collection of the dust to search for seasonal wind dispersed spores, e.g. with one sample tube left open to the dust for a Martian year. A null result here would also be significant and it would also help with studies of the survivability of terrestrial microbes as the composition and chemical composition of the dust is also likely to vary seasonally and in dependence on storms.

[Searching for distant inhabited habitats on Mars through presence or absence of one originally living cell per gram – a rough first estimate assuming uniform mixing throughout Mars for a first estimate requires life to cover between 114,000 and 1,140 square kilometers with densities of life in the dust similar to an Antarctic RSL analogue in cell count, but less than a tenth of a square kilometer if any reach a billion cells per gram – these figures can be higher if any source habitats with high densities of cells are closer to the rover with uneven mixing](#h_Searching_for_distant_habitats_dust)

(...)

[Could local RSL’s be habitable and a source of wind dispersed microbial spores? Both dry and wet mechanisms leave unanswered questions - may be a combination of both or some wet and some dry](#h_could_local_RSL)

**Summarizes:** Discussion of the Recurring Slope Lineae (RSLs). Though the dry formation model gets most publicity neither the dry nor the wet models are able to explain all the features, for instance the dry formation model is currently unable to explain seasonality and resupply. There may be elements of both models or some may be formed in one way and some in the other. This makes it an open question whether the RSLs are potentially habitable to present day life.

[**Could Perseverance find well preserved past life? Knoll criterion and difficulties of recognizing life by its structures**](#_brwfiu3mn2bf)

**New:** Suggestion that early Martian life might lack nitrogen fixation may be new (an obvious suggestion but not mentioned before AFAIK). Previous studies have already suggested it might lack photosynthesis, and might never have evolved it.  
  
 This is relevant for the search for past life in Jezero crater as it would be much less common if there is no nitrogen fixation as well as no photosynthesis

Summarizes:

**• issues with recognizing past life as life**

**• likely ambiguity of returned samples of past life**

**• abiotic chiral imbalances in some meteorites**

**• abiotic C13 depletion**

**• likely presence in returned samples of micron and nanoscale features** that resemble microbes and may be associated with organics

**• Infall of organics from meteorites, comets and interplanetary dust and indigenous processes** such as abiotic photosynthesis making it hard to distinguish abiotic and biotic organics

**• Degradation of past life by racemization, reactive chemicals, etc.**

[Perseverance could detect distinctive biosignatures like chlorophyll and carotene - but only for exceptionally well preserved life](#h_perseverance_could_detect_chlorophyll)

(...)

[**Recommendations to increase the chance of returning present day life, unambiguous past life, and other samples of astrobiological interest by adapting ESA’s Sample Fetch Rover and Perseverance caching strategies**](#_drq89oose4bw)

**New:** Specific recommendations for additional samples that Perseverance and the ESA fetch rover could take, that could increase the astrobiological interest.

[Young craters within 90 days travel of the landing site - to search for past life less damaged by cosmic radiation - near certainty of a crater of 16 to 32 meters in diameter less than 50,000 years old](#_vctrprx8w5u1)

**New:** Recommendation to search for young (< 10 million years old) craters in Jezero crater more than 2 meters deep within the region accessible by Perseverance.

**Original research:** calculation of the probability of craters of various sizes and ages within reach of Perseverance for drives of various lengths in days

[Probability of a new crater within reach of Perseverance forming during the mission](#_w4m4h8ozphlp)

**Original research:** calculation of probability of craters of various sizes forming in the next 4 or 10 years within reach of Perseverance.

[Dating young craters from orbit through fresh appearance with sharp rim](#_1l0srgglbe91)

**Summarizes:** research into how the appearance of a crater changes due to erosion

**Original research:** there aren’t enough craterlets of 10 cm upwards to use to identify the youngest craters of up to 32 meters.

[Recommendation to use Marscopter or observations by Perseverance from a high elevation to search for recently excavated small craters for less degraded organics from](#_2bzb19kzv667) early Mars

(...)

[Exposure of organics through wind erosion - for samples of less degraded past life](#h_exposure_organics_wind_erosion)

(...)

* [**Recommendation:** Extra sample of air and airfall dust to search for Martian life, assess forward contamination issues for terrestrial microbes, dust dangers for astronauts, and to return a random sample of wind-eroded rock from distant parts of Mars](#h_rec_air)

**New:** Leaving a sample tube uncapped during a dust storm or indeed for an entire season before adding rock samples on top, or collect samples using vacuum spore collectors

[Value to astrobiology of samples of the brine layers found by Curiosity in sand dunes at depths of 0 to 15 cms - to search for present day life](#_2iwhmajunqhu)

(...)

[Possible use of Perseverance - or modification of ESA’s Sample Fetch Rover to return samples from shallow sand dune subsurface](#_9e0adi3zubdd)

**New:** Suggestion to attempt to sample the brine layer found by Curiosity

Placing a pile of regolith or sand dune dust in the sample return capsule on top of a plate placed over the sample tubes before sealing it for return to Earth or in the base of the capsule - which might help resolve the controversies about the Viking labelled release experiment and give us a sample of regolith

[**Suggestion of a self perpetuating “Swansong Gaia” maintaining conditions slightly above minimal habitability for billions of years - as a way for early life to continue through to present day Mars**](#_md8f75hyofko)

**New:** Suggestion of a self perpetuating Martian "Swansong Gaia" where feedback processes, unlike those on Earth, keep the planet perpetually at a very low level of habitability, but not quite sterile  
  
Such feedbacks would include photosynthetic life cooling down the planet by removing CO₂ in balance with volcanic emissions keeping it at close to the triple point for water.   
  
Previous explanations for the atmospheric pressure so close to the triple point have involved abiotic processes for maintaining pressure close to the triple point, including abiotic photosynthesis.   
  
The new suggestion is that it could also be caused by biology. This suggestion, if true, increases the potential for present day life at low levels, barely detectable but still present. If true it also increases the possibility of present day surface or near surface life that has remained there since life first evolved on Mars

[Methanogens as part of the cycle with a warming effect limited by the response of photosynthesis in a Swansong Gaia](#_w000n5uck2n9)

(...)

[Self limiting methanogens, methanotrophs, and Fe(III)-reducing bacteria maintaining a subsurface Swansong Gaia hydrology](#_ew8jyqninat5)

(...)

[Could seasonal oxygen be a possible signal of photosynthesis maintaining a Swansong Gaia homeostasis on Mars?](#_lzmkpbjprkhu)

(...)

[How does this Swansong Gaia compare with the original “Gaia hypothesis?”.](#_xnzrvmigmtfd)

(...)

[Potential limits on the biomass of a Swansong Gaia on Mars using the amounts of free CO and H₂ in the atmosphere](#_xnkj4yfjaylg)

(...)

[Testing the “Swansong Gaia” hypothesis](#_y8zjv32xbzy)

(...)

[**Recommendation to return a sample for teleoperated ‘in situ’ study above Geosynchronous Equatorial Orbit (GEO)**](#h_Recommendation_GEO)

**New:** Recommendation to return unsterilized samples to above GEO.

Advantages include

* that it is far in delta v from either Earth or the Moon,
* that it is suitable for low latency telepresence from Earth.
* The article suggests using the Laplace plane at an inclination of 7.2 degrees to the equatorial plane, a similar point of equilibrium to Saturn’s ring plane. This minimizes dispersion of any high area to mass ratio (HAMR) materials shed by the sample containing satellite.

The Moon, and LEO have been suggested before but above GEO seems to be a new suggestion

[Return to within the Laplace plane above GEO to contain debris in event of an off nominal explosion or other events](#_u6rda2g1xrg9)

(...)

[Low energy transfer of an Earth Return Vehicle from Mars to above GEO](#_flib5ihr0y4g)

(...)

[Preliminary study of the returned sample above GEO](#_6doc0sfjbdcc)

(...)

[Studying life telerobotically in orbit above GEO](#_7tytnuk25o44)

(...)

[Possibility of early discovery of extraterrestrial microbes of no risk to Earth](#h_poss_early_discovery)

(...)

[Early discovery of a familiar terrestrial microbe on Mars is not enough to prove sample is safe without more research](#_95b5ooobkldt)

**New:** Warning that the presence of closely related terrestrial life in the sample does not rule out the possibility of simultaneous presence of novel biology.   
  
As a specific example, a mirror cyanobacteria might co-habit the same microbiomes with non-mirror cyanobacteria, perhaps with both descended from a chirality indifferent early form of life based on something similar to Joyce's enzyme.   
  
This may be especially likely with Benner’s hypothesis that life originated on Mars. Mars might have greater biodiversity than terrestrial life, including perhaps multiple independently evolved life chemistries, and branches of life, only some of which have got to Earth via panspermia.

[Possibility of discovery of high risk extraterrestrial microbes needing extreme caution](#_d765msr1bx3c)

(...)

[Could Martian life have got to Earth on meteorites? Our Martian meteorites come from at least 3 m below the surface in high altitude regions of Mars](#h_could_Martian_life_have_got_to_Earth)

**Expands:** surface layers of dust, salt, and brines, which are most habitable and most likely to have life, are not able to get into the ejecta after a typical asteroid impact. This point is not original but it is seldom emphasized. This greatly reduces the possibility of meteorite transfer of life during the three billion years of the present drier Amazonian period on Mars.

[Has life from Mars caused mass extinctions on Earth in the past?](#_w18lxh14foya)

**Expands:** Discussion of whether Martian life could have caused the Great Oxygenation event on Earth. This expands on a statement in the 2009 NRC study that the possibility of past life from Mars causing mass extinctions on Earth can't be ruled out. They don't give an example; an example helps make the discussion more concrete.

[Potential diversity of extraterrestrial life based on alternatives to DNA such as RNA, PNA, TNA, additional bases and an additional or different set of amino acids](#h_potential_diversity_et_life)

(...)

[**Could present day Martian life harm terrestrial organisms?**](#_90r679e00r6y)

**New:** Detailed discussion of example worst case scenarios, such as sequestration of CO₂ by a mirror life ocean dwelling photoautotroph that has no secondary consumers. Although such worst case scenarios have had some discussion for laboratory safety for synthetic biology, such example worst case scenarios don't seem to be mentioned in planetary protection discussions yet.

**New:** Possibility that extraterrestrial fungi could infect humans with invasive biofilms. Opportunistic fungi kill an estimated 1.5 million people worldwide every year.

**New:** Possibility that antifungals and antibiotics have no effect on a novel biochemistry.

[Could a Martian originated pathogen be airborne or otherwise spread human to human?](#_mjy48ylbinho)

(...)

[Microplastics and nanoplastics as an analogue for cells of alien life entering our bodies unrecognized by the immune system.](#_c04xtjg7bmog)

**New:** Discussion of permeability of the human body to microplastics and nanoplastics and exploration of whether it could be similarly permeable to alien live with a novel biochemistry not recognized by the immune system

[Exotoxins, protoxins, allergens and opportunistic infection](#_nv8m95nwa6eh)

**New:** Possibility that extraterrestrial fungi and other microbes could also be allergens

[Accidental similarity of amino acids forming neurotoxins such as BMAA](#_hzzu3tos299k)

**New:** Suggestion that novel amino acids may be misincorporated similarly to BMAA and may be neurotoxins for Earth life by causing protein folding anomalies. The article proposes as a hypothesis that this might be a common occurrence for a biosphere collision with a biochemistry that has a radically different vocabulary of amino acids,

[Martian microbes better adapted to terrestrial conditions than terrestrial life, example of more efficient photosynthesis](#h_Martian_microbes_better_adapted)

New: Discussion of impact on our biosphere of cyanobacteria more efficient at photosynthesis than terrestrial life

[Example of a mirror life analogue of chroococcidiopsis, a photosynthetic nitrogen fixing polyextremophile](#h_example_of_mirror_life_analogue)

(...)

[[Example of mirror life nanobacteria](#h_example_of_mirror_life)](#_kj1pr29b8qxs)

(...)

[Possibility of extraterrestrial Martian life setting up a “Diminished Gaia” on Earth](#_kuefq6e917l6)

(...)

[Worst case scenario where terrestrial life has no defences to an alien biology - humans survive by ‘paraterraforming’ a severely diminished Gaia](#_p8mguenm8mn)

**New:** Discussion of the effects on Earth’s biosphere if a novel biochemistry becomes established, to the point where the number of microbes in an ecosystem of the novel biochemistry are the same as for terrestrial biochemistry, within orders of magnitude

**New:** Discussion of paraterraforming a degraded biosphere in worst case scenario

[Worst case where alien life unrecognized by terrestrial immune systems spreads to pervade all terrestrial ecosystems](#_9t3at4mgnlzi)

**New:** Discussion of the possibility of novel introduced life evolving or changing gene expression after release from a sample handling facility  
**New:** Discussion of the possibility of life that is initially maladapted developing the capabilities to spread widely, after first establishing small populations on Earth

[Could Martian microbes be harmless to terrestrial organisms?](#h_Could_Martian_microbes)

(...)

[Enhanced Gaia - could Martian life be beneficial to Earth’s biosphere?](#_qg4dre3vy8vr)

**New:** Discussion of potential beneficial effects of introducing extraterrestrial biology - most discussion focuses only on the negative effects and the potential for beneficial effects needs to be mentioned.

[A simple titanium sphere could contain an unsterilized sample for safe return to Earth’s surface - but how do you open this “Pandora's box”?](#_imt6dv36x0tk)

(...)

[**Variations on the precautionary principle - which is appropriate for a Mars sample return?**](#_fp1s7mhe7n2d)

(...)

[Formulating Sagan’s statement that “we cannot take even a small risk with a billion lives” as a criterion for the prohibitory version of the precautionary principle](#_e0vzd0xwbzsw)

**New:** Suggestion that the use of the Best Available Technology version of the Precautionary Principle in the ESF study could be challenged in a legal review. Formulation of Sagan's statement that “we cannot take even a small risk with a billion lives” - as a criterion that if the potential worst case scenario impacts on the lives or livelihoods of of the order of a billion people or more, we should always use the Prohibitory version of the Precautionary principle rather than the Best Available Technology version

**New:** Suggestion that the legal review may lead to more stringent requirements than anticipated by mission planners, and that it is not guaranteed that a legal review would approve any unsterilized return. If something resembling Sagan’s criterion becomes established in law as a requirement, then we can’t currently provide this certainty. A return of an unsterilized sample to a non terrestrial facility would then be the legally required standard for future sample return of extraterrestrial biology at the early stages when we are not yet able to prove it is safe for Earth.

**New:** One possible outcome of the legal process is a decision that an unsterilized sample can’t be returned until it can be handled in such a way that there is no appreciable risk of adverse effects on Earth’s environment - i.e. that it is required to use the Prohibitory rather than the Best Available Technology version of the Precautionary Principle in this situation.  
  
**New:** The conclusion might also be that even a minute risk of severe impact on the lives or livelihoods of a billion people always counts as “appreciable risk”. This is referred to as “Sagan’s Criterion” as it is based on a statement he made.

The authors of the 2012 ESF study say “*It is not possible to demonstrate that the return of a Mars sample presents no appreciable risk of harm.”*

If this is the outcome of the legal process, the sample would need to be sterilized or returned to some other location not connected to Earth’s biosphere to fulfill the legal requirements.

[A requirement for similar levels of safety to those used for experiments with synthetic life would lead to the Prohibitory version of the Precautionary Principle and make unsterilized sample return impossible with current technology and current understanding of Mars](#h_any_requirement_similar_synthetic_life)

(...)

[Adaptive approach - return an unsterilized sample to Earth’s biosphere only when you know what is in it](#_qtpt6qowfe1f)

(...)

[Vulnerability of early life on Mars in forwards direction - legal protection is weak, but strengthened by the laws for backwards protection of Earth](#h_vulnerability_early_life)

(...)

[Why Mars sample returns are no longer enough to prove astronauts are "Safe on Mars" or safe in Jezero crater - with the modern more complex understanding of Mars](#_nrm1zt3alb7)

(...)

[To check safety of Mars for astronauts requires widespread in situ biosignature and life detection, and in situ tests of dust for spores and other propagules - though a single sample of a biohazard such as mirror life COULD be enough to prove Mars unsafe](#_10rh8sqhumhb)

(...)

Resolving these issues with a rapid astrobiological survey, with astronauts teleoperating rovers from orbit around Mars

(...)

[Value of telerobotic exploration for a planet with complex chemistry developed over billions of years, but no life](#_l06mtkyk3pfy)

(...)

[Design specifications for 100% sterile rovers for fast safe astrobiological surveys throughout the solar system](#_4f9mmbuo6v1t)

(...)

[Mars less habitable than a plateau higher than Mount Everest, so high our lungs need a pressure suit to function](#_nywdspjuqul)

(...)

[Dust as one of the greatest inhibitors to nominal operation on the Moon - and likely on Mars too](#h_dust_as_one)

(...)

[Planetary protection as an essential part of an ambitious, vigorous approach to human exploration](#_nywdspjuqul)

(...)

[**Conclusion - legal process is both understandable and necessary**](#_1zy6z1urmm8)

(...)