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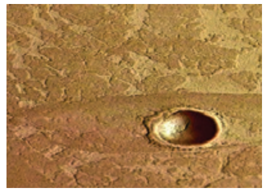

A living Mars?

The possibility of a living Mars is deeply ingrained in popular culture. The observations of the astronomer Percival Lowell, and his interpretation that these canals were built to channel melt-water from the polar regions down to the dying cities and farms huddled around the equator, are well known. Even into the 1960s, textbooks were being published that explained the temporal variation in surface brightness as due to the seasonal spread of vegetation. Martians are the science-fiction writer's alien invader of choice, from the heat-ray-wielding tripods of H.G. Wells to the bulbous-headed aggressors of Tim Burton's 1996 film *Mars Attacks*. With the armada of robotic probes currently orbiting and roving across the red planet, Mars has never been so forefront in the public eye. Much of this interest is focussed on the possibility that our planetary neighbour has supported an independent genesis of life, and that in certain regions it may remain habitable even to this day. A selection of some of the most recent results and discoveries concerning the astrobiological potential of Mars are discussed.

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Life, as we understand it, has three fundamental requirements. Firstly, water is needed to serve as a solvent, allowing biochemical reactions to proceed, and raw materials and waste products to diffuse into and outside the cell. To accomplish this, water must be in its liquid state, which in turn defines the pressure and temperature regimes within which life can be active. Secondly, the molecular components of life, DNA/RNA, proteins, fatty membranes, are built from carbon polymers, and so the presence of organic chemistry is also necessary. Thirdly, life requires an external energy source to drive its chemical reactions and maintain its extraordinary level of complexity. Terrestrial life is ingeniously diverse in the environmental energy sources it can tap, supporting itself on sunlight (and possibly even geothermal light at deep sea vents), decomposition of organic compounds, or running inorganic redox reactions reminiscent of geology. On Mars, with the availability of redox gradients providing inorganic energy and possibility of an early environment conducive for photosynthesis on the surface, this third requirement is probably the least limiting.

The possibility of life based on exotic biochemistry, using solvents other than water or non-carbon-based polymers, has been mooted to relax the limitations of the first two requirements of extra-terrestrial life. But we cannot even begin to understand how such a scenario might support chemistry complex enough for life, and there are reasons to suspect that water and carbon-based foundations are optimal for biology, at least for the conditions prevalent on a terrestrial planet like Earth or Mars. So for the moment, it makes most sense to search for life as terrestrially known, rather unknown, and this means hunting for regions on Mars with the potential for liquid water and complex organic chemistry.

These are the requirements for the sustaining of life, but we understand very poorly what conditions and prerequisites are necessary to support prebiotic chemistry and the origin of life. Fierce debate rages whether life on Earth emerged in sunlit surface pools, or around hydrothermal vents in the sea floor, or perhaps even within the deep subsurface crust. In the absence of this understanding then, the search for life beyond Earth is currently directed towards locations where conditions are thought to be compatible with the survival of terrestrial life in all its extreme forms.

The Martian environment

Contrary to the impression that might be gleaned from the popular press, the presence of water on Mars

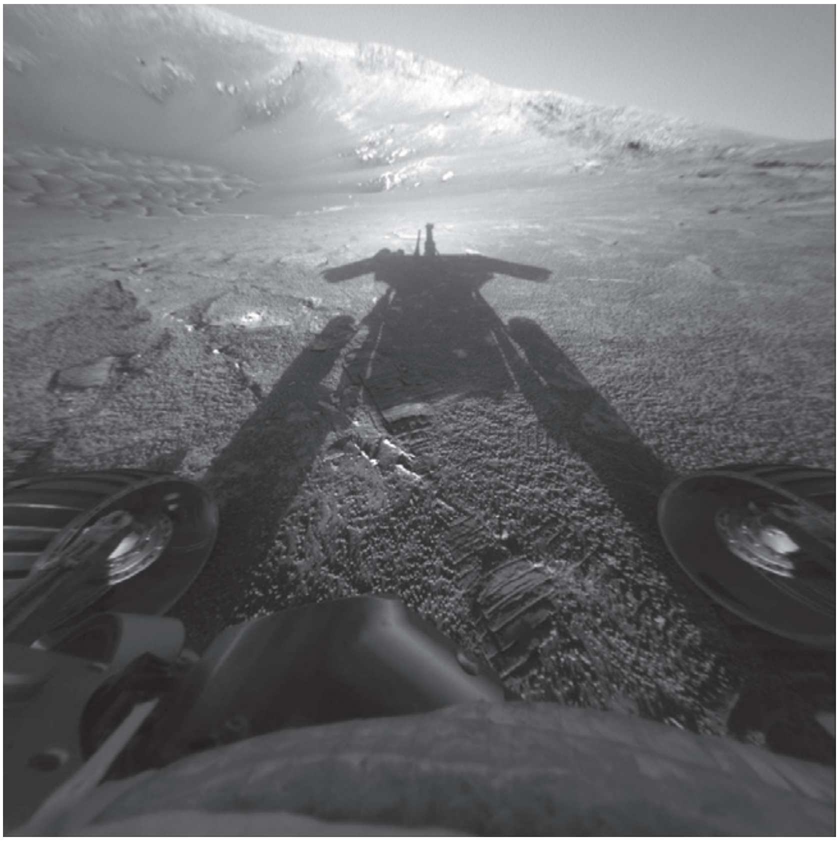

Fig. 1. *Opportunity* snaps its own shadow after finding evidence of ancient water on the Meridiani plains. (Image: Mars Exploration Rover Mission, JPL, NASA.).

has been beyond doubt for years. We can see great volumes of water ice in the polar caps. The big question remains, however, as to what is the history of *liquid* water on Mars.

The satellite images sent back from the Viking orbiters in the 1970s show tantalizing hints of liquid flow on a massive scale: great channels tens of kilometres across that must have been formed by catastrophic floods. Images of the southern highlands show dendritic valley networks, and many craters contain concentric rings of sedimentation presumably deposited by the drying-out of lakes. Water was thought to be the most likely candidate, but convincing proof of the long-term action of liquid water was not finally gathered until a few years ago, with the arrival on the red planet of the twin NASA rovers *Spirit* and *Opportunity*. *Opportunity*, shown in Fig. 1, discovered several independent threads of evidence that interweave to tell the story of a large sea of water covering the plains of Meridiani over millions of years. But this sea, and the valley networks, date to a period very early in Martian history; a time when climatic conditions must have been very different to now. Mars seems to have lost the vast majority of its early atmosphere, leaving a miniscule surface pressure and freezing cold temperatures without the insulation of a significant greenhouse effect. Water is unstable as a liquid throughout most of Mars' surface, and is either frozen solid or sublimes away into the atmosphere to collect at the poles.

Today, Mars is a freeze-dried desert, and the prospects for any life that may have emerged during the warmer primordial climate remaining active near the rusty surface seem slim indeed. Extremely cold-tolerant terrestrial organisms, known as psychrophiles, have been found growing and dividing at –12 °C in Alaskan sea ice. This is possible because even though the bulk of the water is frozen, channels of concentrated brine remain liquid and provide a micro-environment suitable for continued microbial activity. Some researchers have even cited evidence for protein synthesis and 'maintenance metabolism' down to –20 °C. Permafrost is believed to lie within meters of the Martian surface at high latitudes, but the temperature is permanently below –40 °C and so it is thought that any near-surface life, if it is indeed based on biochemistry comparable to the terrestrial system, will be held dormant for geological periods of time.

Surface hazards

The Martian surface, denuded of an atmospheric overcoat, appears to be extremely hostile to life for a number of other reasons beyond the limited availability of liquid water. The Viking landers could not detect the slightest whiff of organics, down to the parts-per-billion level, from their samples of soil. Even in the absence of a biosphere, prebiotic chemistry can produce simple organics, and a limited amount are expected to have been delivered from exogenous sources by cometary and meteoritic in-fall. A carbonaceous chondrite that fell in Murchison, Australia, in 1969 has been found to contain a rich repository of organics: amino acids, sugars, and nucleotide bases used in DNA. The failure of Viking to detect any organics (within the sensitivity of their instruments, although some authors have pointed out that the spacecraft would still overlook the equivalent of tens of millions of cells per gram of soil) implies that some process must be destroying these expected molecules.

The Earth's surface is protected today from the harsh ultraviolet radiation of the sun by the ozone layer, itself a direct result of the action of life, and both early Earth and Mars may have received protection from a photochemical smog in the air. Present-day Mars has no such shielding, and the surface is bathed in hazardous rays hundreds of times more intense than the Earth. Although this UV poses a direct danger to organisms trying to make a living photosynthesizing on the surface, cells hidden within cracks and crevices of rocks, so-called cryptoendoliths, could receive enough light to grow but with the UV filtered out. Perhaps more importantly, the constant flood of UV over billions of years is believed to have built up a substantial concentration of oxidants in the Martian topsoil. This harsh chemical environment would destroy any organic molecules, ripping apart the vital building blocks of life, and explain the *Viking* null result.

Calculations of how deep this oxidizing layer extends are hard to constrain, but, unless well-preserved deep inside rocks, life is unlikely to remain within the loose Martian topsoil. A further environmental hazard is the constant rain of cosmic radiation beating down on the surface—particles accelerated by solar flares and supernova throughout the galaxy. Unlike Earth, Mars receives no significant shielding from a dense atmosphere or global magnetic field, and this energetic radiation penetrates metres underground. Dormant organisms held cryopreserved in the Martian subsurface permafrost would be unable to repair the cellular damage inflicted by this radiation, and so even life safely below the oxidizing layer may be steadily destroyed over geological time.

So any life right on the Martian surface is exposed to a range of harsh environmental insults. This near-subsurface environment of the top few metres of Martian dust and regolith is of great importance because it is the region we will be able to access for the foreseeable future. The *Viking* landers scooped up topsoil and could find no convincing signs of life, past or present. Digging beneath the layer affected by chemical oxidants and cosmic radiation is now a prime concern for astrobiology, and the deepest drill planned for an up-coming probe is the 2 m segmented shaft of *ExoMars*, currently being designed by the European Space Agency. Within this accessible region, constrained by our current technological capability, life is likely to be limited in its survival over the aeons of time since the primordial warmer, wetter, Mars. That is not to say that we could not detect signs of its previous existence; many biosignatures such as fossils, distinctive organic molecules or biases in isotope ratios may remain in the soil billions of years after life fell extinct. However, the Holy Grail for astrobiology is to discover living life: cells that could be recovered and studied in a Petri dish, and it is this more stringent goal that will be focussed on for the moment.

An active biosphere?

If the exposed Martian surface is so inclement for life, the natural thought would be to look deeper underground. The terrestrial subsurface is extensively colonized by microbial ecosystems, and some researchers estimate the living mass of this deep biosphere to even exceed that of the sunlit surface ecosystems. Many of these organisms are heterotrophic, subsisting off water percolating down from the surface ecosystems, rich in photosynthetically-derived organics. But there are also examples of microbial ecosystems believed to be entirely isolated from the sun and photosynthetic production, chemoautotrophs self-reliant in terms of both energy and organic building blocks. One such case is a formation of basaltic rock lying about a kilometre beneath the Columbia river basin in Washington State, USA. This was formed by a series of large floods of volcanic lava across the surface around ten million years ago. The rock is rich in reduced iron, which reacts slowly with aquifer water to release hydrogen. Chemoautotrophic archaea oxidize this hydrogen, passing the freed electron to dissolved carbon dioxide and so fixing it to produce organic molecules. The products of this inorganic reaction are water and methane gas, and so such chemoautotrophs are methanogens. The assemblages of these anaerobic primary producers and the heterotrophs that feed off them have been called Subsurface Lithotrophic Microbial Ecosystems, or SLiMEs.

Such ecosystems on Earth represent a good model for possible extraterrestrial habitats. Firstly, they are viable deep beneath a potentially hostile surface as they are not dependent on the organics or oxidants produced by photosynthesis. They also do not require geothermal hotspots to drive them, unlike the deep sea hydrothermal vents also considered as potential astrobiological habitats, and can be supported simply by a slab of reduced basaltic rock bathed in aquifer water with dissolved carbon dioxide. Such subsurface environments are likely to be common on any terrestrial planet, such as Mars, which has exhibited volcanism at any period in its history.

The deepest that life has yet been discovered on Earth is within a Swedish borehole 5.3 km beneath the surface. Even at these crushing depths, there are ample water-filled cracks and crevices within rocks to host microbial communities. It is thought that there is no survival limit for depth *per se*, so long as the ambient temperature does not become sterilizing. The heterotrophic bacteria at the bottom of the Swedish borehole coped with an ambient temperature of more than 70 °C. The highest temperature that can be tolerated by terrestrial organisms is the 121 °C record set by an archaeal hyperthermophile isolated from the scorching plumes of hydrothermal vents. This temperature threshold is reached at different depths depending on the local thickness of crust, but can be as much as 10 km down in some sedimentary rock formations.

In some ways, the Martian crust would provide an event better environment for a deep biosphere than Earth. Its crust has been unmodified by plate tectonics, and so retains a high degree of brecciation from the primordial pummelling of the heavy bombardment. The Martian regolith is likely to be sufficiently porous to a great depth. At some depth beneath the frozen surface the ambient temperature will become warm enough to support pockets of liquid water. The minimum depth that this occurs, which depends on parameters including the salinity of groundwater and the Martian geothermal gradient, and the maximum depth that the permafrost layer penetrates into the regolith, is hard to model. The hope is that these two regions will overlap in the subsurface, with the bottom of the cryosphere thawed to produce aquifers of liquid, habitats for a Martian deep biosphere, possibly at around 4 km depth in equatorial regions.

MARSIS is an instrument aboard the Mars Express orbiter, a powerful radar system able to penetrate many kilometres underground and resolve subsurface structures. The device has already made a number of astounding discoveries, including the buried bottoms of hidden craters, but the announcement that astrobiologists are really waiting for is the detection of the tell-tale reflection off a liquid water surface deep within the crust – the signature of an underground aquifer suitable for a Martian SLiME. MARSIS ought to be able to detect just such a layer of liquid water fairly easily in the top 1–2 km, and possibly as deep as 5 km underground, but no candidate locations have yet been found.

Although MARSIS has yet to spot a suitable aquifer, tentative evidence supporting a Martian SLiME has already been collected. Mars Express also carries an infrared spectrometer, and using this instrument, low levels of methane in the Martian atmosphere have been discovered. The distribution of this methane is not even, which would suggest the existence of localized sources. The presence of methane is particularly interesting because it ought to be rapidly photolyzed and destroyed, being completed scrubbed out of the atmosphere on the order of centuries. This means that whatever process produced the methane must have operated very recently, and may be still currently active. As discussed above, the SLiME microbes in Earth's deep biosphere release methane as a waste product of their autotrophic metabolism, and so this faint wisp of Martian methane has certainly attracted the attention of astrobiologists. The methane can of course also be explained without invoking biology: abiotic sources such as low levels of volcanism or the release of gas from hydrate-rich ice have been proposed. However, these geological sources would in themselves be surprising since no current geothermal activity has yet been observed on Mars.

One way of resolving the debate over the source being biotic or abiotic would be to examine the ratio of carbon isotopes in the methane. The chemical processes of life, driven by enzymes, tend to favour the lighter isotope of contributing atoms over heavier isotopes (since they move faster). Photosynthesis, for instance, fixes atmospheric carbon dioxide into carbohydrates that are enriched with ^{12}C relative to ^{13}C. If the Martian methane were biogenic in origin, it would be expected to be similarly depleted in ^{13}C. Such determination of the isotopic composition is not possible with current instruments at Mars, but coupled with a more precise pin-pointing of the sources on the surface this would be a very interesting experiment for the future. There are several problems with using isotope biases as evidence for biological activity, however. For example, detecting any biological perturbation to the isotope ratio implies that you know the original ratio to a high degree of accuracy, and enrichment of ^{12}C can also be caused by geological processes if they operate at low temperature.

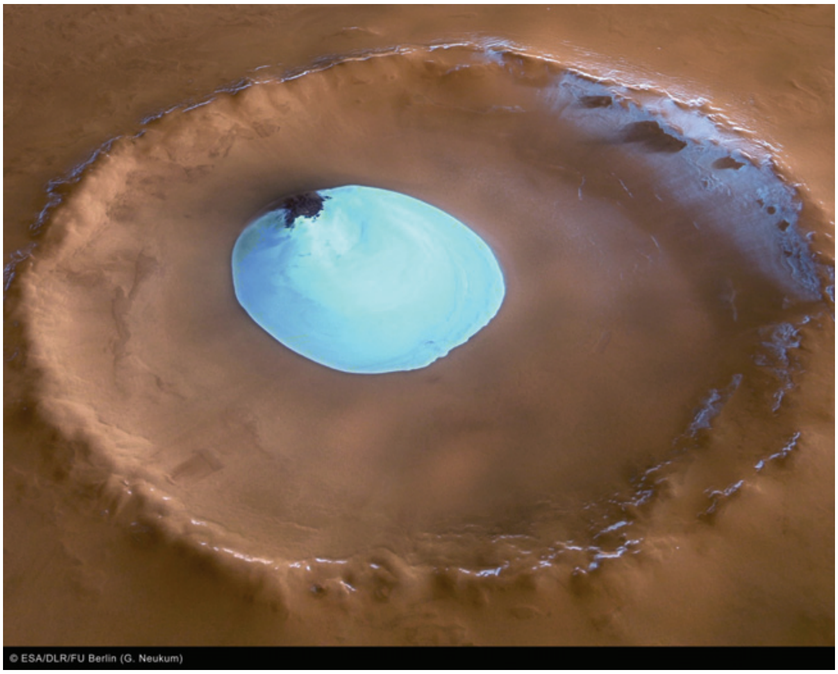

Fig. 2. Water ice on the floor of a crater near the Martian North pole. (Image: ESA/DLR/FU Berlin, G. Neukum).

Where to look?

Over the course of this article, the present-day Martian surface conditions have been discussed with respect to the requirements for life as we understand it, as well as the potential for even a current biosphere deep underground. Considering these issues it is almost certainly true that were life to have emerged on Mars it would be more likely to be surviving in active ecosystems deep in the crust than in the near subsurface. Gaining access to any such deep biosphere is undeniably difficult, however, and drilling boreholes to sample from kilometres down is unlikely to be feasible with robotic probes, and would require industrial-scale machinery and human supervision. With this in mind, where would be the best spots on the surface to search for signs of life in the near future? What follows is a shopping list of sorts, of locations that astrobiologists would like to visit in search of signs of extraterrestrial life.

The most obvious locations to try first are those where the presence of liquid water has been inferred during the early epochs of Martian history, or even much more recently. These include the dried riverbeds of the valley networks in the southern highlands or within the deposits at the bottom of ancient crater lakes. Larger craters showing signs of ancient lakes are particularly enticing targets because the impact could have set-up a hydrothermal system at the bottom of the lake capable of supporting an ecosystem even as the water's surface froze over. Figure 2 shows an image snapped from orbit of water ice covering the floor of a crater near the North Pole of Mars.

The long-lived aqueous environment of Meridiani Planum, as pieced-together by *Opportunity*, also presents an astrobiological opportunity, if not for prebiotic chemistry and the emergence of life, then perhaps its subsequent colonisation and persistent habitation. Rio Tinto is a drainage system in south-western Spain believed to be comparable to the ancient water of Meridiani in terms of its high acidity and mineralogy. This river, despite its extreme pH and concentration of heavy metal ions, is inhabited by diverse bacteria and archaea microbes, and supports the idea of the Meridiani basin being a habitable environment on early Mars. Many different biosignatures may remain in the once-sodden sediments of this plain, including microscopically-identifiable fossils of cells, biogenic complex organic molecules, or isotropic biases, but will require another probe to follow *Opportunity*'s lead with appropriate instruments to gather such evidence.

Other exciting targets include locations on Mars that are believed to have flown with liquid water in much more modern times. Few people could surely have missed the announcements in December 2006 of photographic evidence that gullies coursing down the sides of impact craters have flowed with fluid at some point between December 2001 and April 2005. The 'before' and 'after' shots were taken by *Mars Global Surveyor* and clearly show the appearance of light-coloured deposits, thought to be frost or salt, along the floor and banks of gullies in two different craters. The interpretation supported by many researchers is that these crater gullies have flowed with liquid water, not in ancient epochs, but right now, and present an extremely exciting prospect for life near Mars' surface. *Mars Global Surveyor* has also found a number of impact craters that were created within the last few years. Searching the bottom of very recent impact craters is attractive because it represents a method for accessing deep beneath the surface without needing extensive drilling equipment, and provides material that has not been exposed to the surface hazards, such as chemical oxidation, for very long.

One other site of great interest is within Elysium, near the Martian equator. Lying upon these plains appear to be great blocks of dusty pack-ice, striking evidence of a frozen sea, as shown in Fig. 3. Not only is this putative expanse of water estimated to be comparable in size and depth to the North Sea, but from the scarcity of craters it also appears to be extremely young—having gushed out on to the Martian surface only about five million years ago (exposed ice near the equator is expected to steadily sublime away into the atmosphere). If this interpretation of orbital images turns out to be correct, then this frozen sea is perhaps the most promising astrobiological target on the surface of Mars. It represents a large sample of liquid water that has flowed up from deeper beneath the Martian surface, and like the bottom of recent impact craters has not been exposed to surface hazards very long. The hope is that this water may contain Martian microbes that have been conveniently cryo-preserved and can be recovered by probes drilling down into the ice.

Planetary protection

Many of these potential habitats, however, are also potentially extremely problematic for surface exploration and astrobiological surveying. The issue is one of 'planetary protection', and the fact that the most interesting locations for astrobiology, i.e. those with near-surface water, are *ipso facto* also the riskiest locations to attempt exploration. The concern is the possibility of contaminating such locations with Earth's biota and thus confusing identification of the very evidence being searched for in the first place. Martian landers to date have had a notoriously poor success rate, with *Mars Polar Lander* and *Beagle 2* both recently crashing onto the red planet. The problem is that a failure during the landing sequence would cause the probe to fall uncontrollably into the region of special interest, excavating its own impact crater

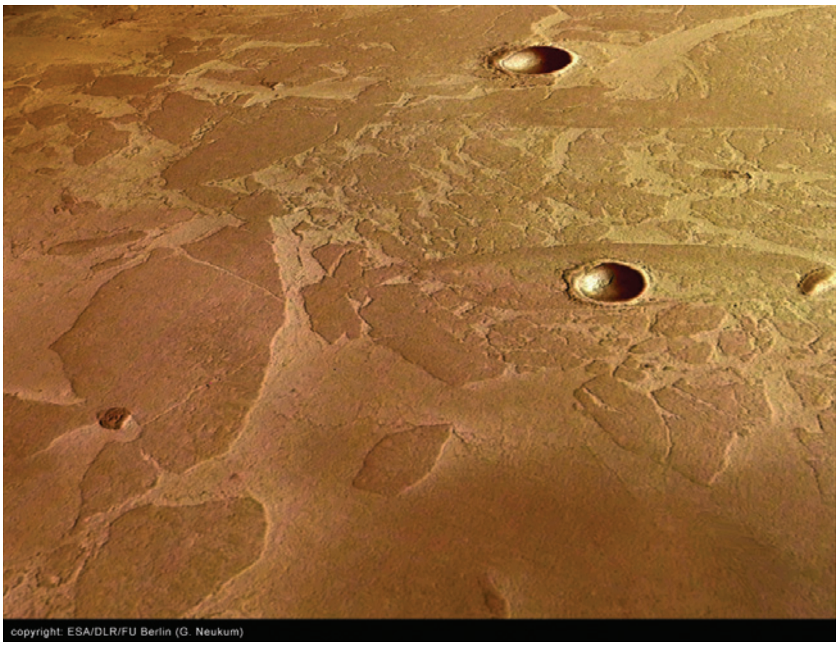

Fig. 3. A frozen sea on the surface of Mars at the plains of Elysium? (Image: ESA/DLR/FU Berlin G. Neukum).

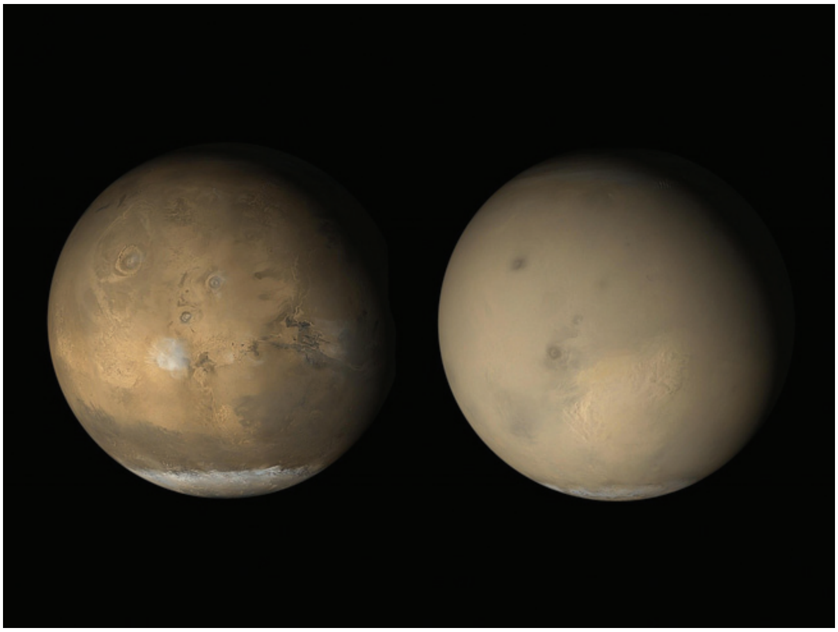

Fig. 4. Two images of Mars taken just 50 days apart in 2001, showing the development of a global dust storm.

and maybe melting the local permafrost long enough for terrestrial contamination microbes to survive and grow upon the surface. There is the argument, therefore, that we should not even attempt to visit the sorts of locations listed above until we can expect a near-100 per cent reliability of both our probes landing systems and our capability to completely sterilize any equipment sent to the Martian surface. On the other hand, Fig. 4 demonstrates Mars' ability to generate global storms, redistributing surface dust (and thus also delivered contagion) across its entire face, and so is it defensible to consider any location upon Mars to be an acceptable site to risk landing on? Or have we already delivered a sufficient bioload from Earth that attempts to now protect certain special regions would be like closing the barn door behind the bolting horse? These issues are especially important considering the current plans to send humans to Mars, in that adequate sterilization will be practically impossible.

Suggestions for further reading

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Lewis Dartnell has recently published an introductory book on astrobiology, called *Life in the Universe: A Beginner's Guide*. It is reviewed in this issue on page 79.