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The search for life in our Solar System and the implications for science and society

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The search for another type of life in the Solar System addresses the fundamental question of life in the Universe. To determine if life forms we discover represent a second genesis, we must find biological material that would allow us to compare that life to the Earth's phylogenetic tree of life. An organism would be alien if, and only if, it did not link to our tree of life. In our Solar System, the worlds of interest for a search for life are Mars, Europa, Enceladus and, for biochemistry based on a liquid other than water, Titan. If we find evidence for a second genesis of life, we will certainly learn from the comparative study of the biochemistry, organismal biology and ecology of the alien life. The discovery of alien life, if alive or revivable, will pose fundamentally new questions in environmental ethics. We should plan our exploration strategy such that we conduct biologically reversible exploration. In the long term we would do well, ethically and scientifically, to strive to support any alien life discovered as part of an overall commitment to enhancing the richness and diversity of life in the Universe.

Keywords: life; second genesis; astrobiology; Mars; Europa; Enceladus

1. Introduction

Over the long history of human thought, a persistent theme has been a desire to understand our place in the cosmos and understand if experiences on Earth are representative of things beyond. An early point of view, which held that the Earth was a special place in the cosmic scheme, has given way to a principle of mediocrity—the view that Earth is typical. From astronomical research we know that our Galaxy is a typical spiral type, that the Sun is a typical star and that many stars have planets. Our expectation is that Earth-like worlds are common. But we have no insight yet if the principle of mediocrity applies equally to biology. Is life common or is life on Earth singular? To answer that question, we look and we listen. But, so far, 'naught there was a-stirring in the still, dark night'. In this paper, I review the project of life search in the other worlds of our Solar System, covering the motivations, the prospects and the implications for science and society.

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2. Why are we searching?

We are searching for a second example of life to determine empirically if life is common in the Universe.

Everything we know about life is based on studies of life on Earth. Unfortunately, there is only one type of life on Earth—all life forms on Earth have a common biochemical basis and genetic history. The fundamental question for astrobiology is the search for a different type of life—a second genesis.

If we find another example of life and have established that it had an independent origin, then we would know that life is common in the Universe. If life started twice in our Solar System we can then be certain that life is not a fluke but a natural outcome of planetary environments. A primal philosophical and scientific question will have been answered.

In addition to establishing that life is common in the Universe, the discovery of a second genesis would provide a second example of biochemistry that could be studied. All known life on Earth shares common biochemical and genetic systems. These include the 20 protein amino acids, adenosine triphosphate (ATP), deoxyribonucleic acid (DNA), ribonucleic acid (RNA), the coding for proteins, etc. With only one example to study, we are unable to determine which aspects of biochemistry are universal and which aspects are mere accidents of Earth history. Much might be learned from a comparative study of two different types of biochemistry, both capable of life. A practical and near-term approach to search for a second genesis of life is to find and characterize organic material. Biology is distinguishable from chemistry in that it selects some organic molecules and uses them in preference to other, chemically similar, molecules.

3. What are we searching for?

We are searching for the biological remains of alien life, be it dead or alive. Biological material is required to see how life elsewhere relates to the Earth's tree of life. If life is not on our tree of life, then it is, by definition, alien.

The search for life on other worlds, and on Mars in particular, has often focused on a search for fossils. However, fossils may tell us that there was life present but will not tell us if that life is indeed a second genesis representing an independent origin of life. To conduct the search, we need to find biologically produced organic material, also called biomarkers.

To determine if life discovered on another world represents a second genesis will require that we compare that life to the phylogenetic tree of all life on the Earth. The operative question can be phrased as: Is this life on our tree of life? If the answer to this question is yes, then this life is not alien even if it is found on another world. We now appreciate that rocks and possibly biological material can be exchanged between planets. Thus life on Mars and Earth may be related and thus on the same tree of life. At one time, the term 'alien life' referred to any life from another planet; now we realize that life on another planet may be the same type of life as we know from Earth. The term 'alien life' now refers to an organism that is not on our tree of life, regardless of what planet it is on. Alien life might even be here on the Earth [1–3].

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To compare samples of possibly alien life to our tree of life requires that we have biological material. The tree of life is based on the genetic relationship between life forms and is derived from DNA or RNA sequence comparisons. Phylogenetic trees can also be derived from protein sequences, which effectively are a record of the encoding DNA.

4. Where to search

In our Solar System, the worlds of interest for a search for life are Mars, Europa, Enceladus and, for non-water liquid, Titan.

Observations of life on the Earth indicate that the common ecological requirement for life is liquid water. Energy, carbon and other elements are needed as well, but these are accessed in different forms by different organisms. Thus, the search for life in planetary environments can be currently conducted as a search for liquid water habitats—past and present (e.g. [4]).

While several other worlds in the Solar System have evidence for past or present liquid water, Mars is usually foremost in terms of interest to astrobiology. There is persuasive evidence that Mars had stable liquid water in its past, and suggestive evidence that some liquid water activity may occur even under current conditions. Figure 1 shows Nanedi Vallis, a 2.5 km-wide canyon in the Xanthe Terra region of Mars. This sinuous canyon has a channel on the floor that may have been the bed of the river responsible for the erosion. This image is the best evidence we have that some of the fluvial features on Mars were carved by liquid water in stable flow on the surface for an extended interval [5].

The current conditions on Mars are not compatible with the stable flow of liquid water. The surface temperatures are low, averaging $-60°C$, and more importantly the surface pressures are close to the triple point of water, 610 Pa. At lower elevations in the Northern Plains, the pressures are up to approximately 1500 Pa, while in the Southern Highlands, the pressures are well below 610 Pa. At these low pressures, water boils at low temperatures—at the triple point, freezing and boiling coincide. The result of the low pressure on Mars is that liquid water has a narrow range for possible stability [6,7].

Thus, the evidence of liquid water in the past on Mars implies that the atmosphere was considerably thicker and somewhat warmer. The atmospheric pressure must have been more than 10 times the present value in order to stabilize liquid water, and mean temperatures may have been 20°C warmer [8–10]. The details of the atmospheric composition and greenhouse effect are unclear, and current climate models do not seem to be able to provide a self-consistent scenario for the warming of the early Martian atmosphere [11–13]. Despite the difficulties of the theoretical climate models, the evidence of liquid water on the surface of Mars in the past is strong and directly motivates a search for evidence of life.

The first, and to date only, direct search for life on Mars was done by the *Viking* missions. Each of the two landers carried three biology experiments to the surface of Mars to search for metabolic activity in samples from the top few centimetres of the Martian soil. The pyrolytic release experiment [14] was based on the assumption that Martian life would have the capability to incorporate radioactively labelled carbon dioxide in the presence of sunlight (i.e. photosynthesis). The labelled release (LR) experiment [15] sought to

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Figure 1. Liquid water in the past on Mars. *Mars Global Surveyor* image showing Nanedi Vallis of Mars. Image covers an area 9.8 km by 18.5 km; the canyon is about 2.5 km wide. This image is the best evidence we have that some of the fluvial features on Mars were carved by liquid water in stable flow on the surface for an extended interval. Photo from NASA/Malin Space Sciences.

detect life by the release of radioactively labelled carbon initially incorporated into organic compounds in a nutrient solution. The gas exchange experiment (GEx) [16] was designed to determine if Martian life could metabolize and exchange gaseous products in the presence of water vapour and in a nutrient solution. The *Viking* biology instruments all yielded evidence of activity. Two results were of particular interest. In the GEx, the soil released O_2 upon humidification [16] in amounts ranging from 70 to 770 nmol cm^{-3}. Heating the sample to 145°C for 3.5 h reduced the amount of O_2 released by about 50 per cent. There was a slow evolution of CO_2 when nutrient solution was added to the soil. The LR experiment indicated the rapid release of CO_2, followed by a prolonged slow release of CO_2, from radioactively labelled carbon in a nutrient solution. The effect was completely removed by heating to 160°C for 3 h, partially destroyed at 40–60°C, and relatively stable for short periods at 18°C, but lost after long-term

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storage at 18°C. Another key instrument on the *Viking* landers was the GCMS (gas chromatograph/mass spectrometer), which searched for organics in the soil. The most surprising result of the *Viking* soil analysis was the inability to detect organics in surface samples, and from samples below the surface (maximum depth sampled was about 10 cm) [17,18].

The results of the LR experiment were particularly controversial because they agreed with preflight expectations of a biological reaction. If considered alone, the LR results would be consistent with life on Mars. However, when the *Viking* biology experiments are considered together with the lack of organics as determined by the GCMS, the most probable explanation for the observed reactivity is chemical, not biological, activity (for a review, see [19,20]; for an opposite view, see [21]). The probable cause of this chemical activity is the presence in the Martian soil of one or more photochemically produced oxidants such as H_2O_2 (e.g. [22]).

However, Navarro-Gonzalez *et al.* [23] suggested that oxidants in the Martian soil would have destroyed any organics in the sample on Mars during the thermal processing step before analysis by the GCMS. The discovery by the *Phoenix* mission of perchlorate at concentrations of approximately 0.5 per cent in the Martian soil [24] greatly strengthens this possibility. While completely stable and unreactive at Martian soil temperatures, perchlorate decomposes and releases highly reactive Cl and O species at temperatures of approximately 330°C [25]. Thus, if there were perchlorates in the *Viking* soils, as expected based on the *Phoenix* results, then organics at levels of many tens of parts per million could have been present in the soil and destroyed upon heating in the GCMS protocol [26]. Thus, the question of organics in the soil on Mars is wide open, and one of the main arguments against a biological interpretation of the LR results has been removed.

As discussed above, if we find life on Mars, we seek to know how that life relates to the tree of life on the Earth. This requires that we have organic samples of Martian life, not just fossils or traces. There are several sites on Mars where we might find biological material. If the *Viking* LR results do indicate life present on Mars in the soil, rather than some chemical oxidant, then the problem of access to biology is easily solved: biological material is alive in the surface soil. Another possible source of active biology would be subsurface aquifers; however, none have yet been detected. Suitable organic material, albeit probably dead, might be found preserved in minerals, salts or frozen in ice. Smith & McKay [27] review these possible sources of biological samples and conclude that the ancient permafrost in the Southern Highlands may be the best site to recover biological remains of Martian life.

The main difficulty with Mars as a target for the search for a second genesis is its proximity to Earth and the possibility that these two planets have exchanged biological material. It is now established that many of the meteorites found on Earth have come from Mars [28]. Furthermore, studies of the magnetic domains within one of these meteorites by Weiss *et al.* [29] have shown that interior temperatures do not necessarily exceed the survival limits of micro-organisms. This shows that it is possible that life from Mars was carried to Earth, and the other way as well. Thus, it may well be that life on Mars shares a common origin with life on the Earth, and we must look further in the Solar System to find a second genesis.

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However, the very meteorites from Mars that suggest that life may have been transferred from Mars to Earth, or vice versa, provide material from Mars that can be investigated now. While there is contamination from Earth sources in these meteorites (e.g. [30,31]), there is clearly also organic material from Mars [32] and possible evidence for biological processes in the form of magnetite, as recently suggested by Thomas-Keprta *et al.* [33].

In the outer Solar System, there are two worlds that potentially have subsurface liquid water: Europa and Enceladus. Europa is a large moon of Jupiter with an icy surface. The surface has features that appear to indicate ice floating on water. These include linear cracks, icebergs and fractured ice rafts (e.g. [34,35]). The evidence that the subsurface water is still present comes from the magnetic disturbance that Europa makes as it moves through Jupiter's magnetic field. The disturbance indicates a slightly conductive global ocean [36]. In the water of Europa's ocean, there may be life [37].

Enceladus is a small icy moon of Saturn, with a radius of only 252 km. *Cassini* data have revealed about a dozen or so jets of fine icy particles emerging from the south polar region of Enceladus [38]. The jets have also been shown to contain simple organic compounds, and the south-polar region is bathed in excess heat coming from below [39,40]. These jets are evidence for activity driven by some geophysical energy source, but the nature of the energy source remains unclear, as does the source of the ice and water vapour. However, it is possible that a liquid water environment exists beneath the south-polar cap, which may have been a site for the origin of life and in which plausible ecosystems might exist [41]. Several theories for the origin of life on Earth would apply to Enceladus. These are: (i) origin in an organic-rich mixture, (ii) origin in the redox gradient of a submarine vent, and (iii) panspermia. There are at least three microbial ecosystems on Earth that provide analogues for possible ecologies on Enceladus because they do not rely on sunlight, oxygen or organics produced at the surface by photosynthesis [41]. Two of these ecosystems are found deep in volcanic rock and the primary productivity is based on the consumption by methanogens of hydrogen produced by rock reactions with water. The third ecosystem is found deep below the surface in South Africa and is based on sulphur-reducing bacteria consuming hydrogen and sulphate, both ultimately produced by radioactive decay.

As a target for future orbiter or sample return missions, Enceladus rates high because fresh samples of interest are jetting into space ready for collection. Detailed *in situ* analysis of the organics in the plume may indicate if biological sources are involved [41]. A definitive analysis will probably require a sample return.

Titan, the largest moon of Saturn, is the only moon with a thick atmosphere. The atmosphere is composed of N_2 and approximately 5 per cent CH_4, with a surface pressure that is 1.5 times Earth sea-level pressure. The surface temperature is approximately 95 K and at this low temperature CH_4 condenses to a liquid on the surface. Thus, Titan is unusual in that it is the only world in the Solar System other than Earth that has a widespread liquid on its surface. On Titan this liquid is not H_2O as it is on Earth, but rather it is a mixture of CH_4 and C_2H_6 in lakes of various sizes predominantly in the northern polar regions [42]. Benner *et al.* [43] suggested that liquid hydrocarbons on the surface of Titan could be a suitable solution for biological processes.

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Table 1. Free energies of hydrogenation on Titan and Earth.

		free energy, $-\Delta G$ (kJ per mole of CH_4)
reaction on Titan[a]	$C_2H_2 + 3H_2 = 2CH_4$	167
	$C_2H_6 + H_2 = 2CH_4$	28
	solid organics + H_2 = solid organics + CH_4	54
Earth methanogens[b]		10–40

[a]McKay & Smith [44].
[b]Kral *et al.* [45], Hoehler *et al.* [46].

Energy is also available. Photochemical processes in Titan's atmosphere produce organic molecules, including C_2H_2, C_2H_6 and solid organics. McKay & Smith [44] calculated that the organics in the atmosphere could be a source of energy when combined with atmospheric H_2, yielding CH_4. The energy released is more than the minimum energy required by methanogens on Earth. This comparison is made in table 1. Kral *et al.* [45] found that the minimum energy needed for methanogens was $\Delta G = -40$ kJ per mole of CH_4. An even lower value was deduced by Hoehler *et al.* [46], who put the limit for metabolizing H_2 by methanogens on Earth at $\Delta G = -10.6 \pm 0.7$ kJ per mole of CH_4 at 0.1 MPa and 22°C. As shown in table 1, the energy available on Titan is from 54 to 167 kJ mol^{-1}.

Thus it is possible that there may be life forms living in liquid methane on Titan consuming organic molecules and hydrogen [44,47]. Such life would clearly represent a different origin of life than Earth life. If life on Titan survives in liquid CH_4 and C_2H_6 it could be widespread on the surface and could have global effects on the atmosphere. McKay & Smith [44] computed that if the metabolic rates of such life on Titan were high enough it would cause depletion in the mixing ratio of H_2 in the lower atmosphere.

5. How to search

A practical and near-term approach to search for a second genesis of life is to find and characterize organic material. Biology is distinguishable from chemistry in that it selects some organic molecules and uses them in preference to other, chemically similar, molecules.

A practical approach to determining if a collection of material collected on another world is of biological origin is to look for a selective pattern of organic molecules similar to, but not necessarily identical with, the selective pattern of biochemistry in life on the Earth [48]. Some biochemists (e.g. [49]) argue that life everywhere will use the same set of biomolecules as life on the Earth. This would imply that there is only one peak in the fitness landscape of biochemistry. Even in the case that all biological systems converge on the same biochemistry, there may still be variations between life forms due to chirality of molecules. Life on Earth uses L (left-handed) amino acids in proteins and D (right-handed) sugars in DNA and polysaccharides. Life is possible that is exactly similar in all

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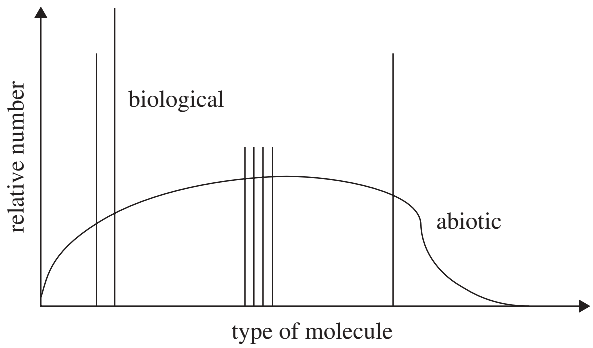

Figure 2. Schematic of the difference between biogenic and non-biogenic distributions of organic material. Non-biological processes produce smooth distributions of organic material illustrated here by the curve. Biology, in contrast, selects and uses only a few distinct molecules, which together form a functional set, shown here as spikes (e.g. the 20 left-handed amino acids as a set for constructing proteins). Analysis of a sample of organic material from another world may indicate a biological origin if it shows such selectivity. Figure from McKay [48].

biochemical respects to life on Earth except that it has D instead of L amino acids in its proteins and/or L instead of D sugars. However, it is also possible that there are a variety of fundamentally different functional sets of biomolecules that can support life. Even if life on another world has the same biochemistry and the same chiral choices as life on Earth, it may still not map onto the Earth's tree of life if its genetic coding is different from the universal coding seen in life on the Earth—a different language written in the same alphabet.

McKay [48] labelled this pattern of biological selection as the 'Lego principle'. The biological polymers that construct life on Earth are the proteins, the nucleic acids and the polysaccharides. These are built from repeated units of the 20 L amino acids, the five nucleotide bases and the D sugars—in analogy with the Lego blocks in the children's toys. The use of only certain basic molecules allows life to be more efficient and selective. Evolutionary selection on life anywhere is likely to result in the same selective use of a restricted set of organic molecules.

The question of the number of possible biochemistries consistent with life can only be answered by the study of naturally occurring alien life forms, or by the construction of other life forms in the laboratory. It terms of the search for life in our Solar System, it is important to note that a characteristic biogenic pattern of organic molecules would persist even after an organism is dead (figure 2).

6. Scientific implications

If we find evidence for a second genesis of life, we will certainly learn from the comparative study of the biochemistry, organismal biology and ecology of the alien life.

Even if an alternative life is based on carbon and water, it may have a different biochemical system. The number of distinct macromolecules that can be constructed from carbon is combinatorial, and thus very large. It may well be that life with a different origin and different history uses a different set of

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carbon-based molecules for its genetic and structural functions, rather than the DNA/RNA and proteins used for these functions by life as we know it. Having a second example of biochemistry would allow us to compare and contrast two biochemical systems both capable of sustaining life. From this comparative study, we might begin to understand which features of Earth biochemistry are universal and which features are particular to the historical developments on Earth.

In addition to comparisons at the biochemical level, it would be interesting to compare the cell structure and organization. Even more broadly, if we can observe or re-create entire ecosystems based on alien life, the potential for comparison is greatly expanded. In the widest sense, an alien biosphere composed of alien organisms using a different pattern of biomolecules gives the greatest scope for scientific return by comparison.

In addition to the biochemical, organismal and ecological levels, comparing life as we know it to a second genesis may help to address questions related to understanding the tree of life itself. One example question in this category is the fact that, of the two domains of life that are entirely microbial, only one (the bacteria) cause disease. The other domain (the archaea) are found in our intestines (about 1% of the human intestinal microbes are archaea) and in many ways are more similar to eukaryotes than bacteria. The archaea are also more closely related on the tree of life to eukaryotes than are bacteria. Yet, there is no known disease or infection caused by archaeal micro-organisms. A complete understanding of this may require an overall understanding of the tree of life that will most easily come with having another type of life to compare with.

7. Societal implications

The discovery of alien life, if alive or revivable, will pose fundamentally new questions in environmental ethics. Ethically and scientifically, we would do well to strive to support any alien life discovered as part of an overall commitment to enhancing the richness and diversity of life in the Universe.

The current field of astrobiology differs from other disciplines in space science in one fundamental way: astrobiology explicitly includes the question of what is the future of life in the Universe? This should motivate us to consider the long-term goal for human choices and actions with respect to life in the Universe. Human choices, while they should be informed by science, depend on ethical, economic and broad societal considerations. McKay [50] has suggested that the long-term goal for astrobiology should be to enhance the richness and diversity of life in the Universe and that our choices and actions should reflect this goal.

McKay [50] suggests that, while life is not the only source of value in the natural world, it is unique in that it is something of value that can be preserved, but it can also be spread without limit. If life has value then humans can create value and spread value as they spread life. In this sense, a focus on enhancing life connects to the deeply seated motivation for humans to be active creators, or co-creators, helping to shape and guide the existing creation and contributing to its diversity [50].

While human action can contribute to life, it can also cause damage if unchecked. A relevant and current example is the biological contamination associated with exploration of potentially biological worlds like Mars. The search

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for life on Mars poses a logical dilemma: how to search for life without contaminating Mars with life from Earth. Such contamination poses two dangers. First, the search for life on Mars may give positive results because of life carried from Earth. Secondly, alien life forms native on Mars may be endangered by competition with transplanted Earth life.

Mars is interesting because it may have had life in the past and because it may be a place for life in the future. However, we are uncertain of the current biological state of Mars. There are at least three possibilities: (i) there is life on Mars that is distinctly different from life on Earth—a second genesis; (ii) there is life on Mars that is genetically related to life on Earth; and (iii) there is no life on Mars. Each of these possibilities implies distinctly different scenarios for how we can best explore Mars. Until we know which of these possibilities is correct, we must explore Mars in a way that keeps our options open with respect to future life.

One solution to this dilemma is that we must explore Mars in a way that is biologically reversible. Exploration is biologically reversible if it is possible and practicable to remove all life forms carried to Mars by that exploration. Because of the high ultraviolet and oxidizing conditions on the surface of Mars, the robotic and human exploration of the planet can be done in a way that is biologically reversible. We must be able to undo ('ctrl Z') our contamination of Mars if we discover a second genesis of life [51–53].

It has been proposed that re-creating a biosphere on Mars (e.g. [54]) based on indigenous life, or, lacking indigenous life, based on Earth life, would contribute to expanding the richness and diversity of life in the Universe [52,53]. The societal issues associated with re-creating life on Mars have been discussed in terms of assuming both that life has intrinsic value and alternatively that it has only instrumental value [55]. The concept of assigning intrinsic value to life forms is perhaps most clearly stated in the first two tenets of deep ecology [56,57]:

- The well-being of non-human life on Earth has value in itself. This value is independent of any instrumental usefulness for limited human purposes.
- Richness and diversity in life forms contribute to this value and are a further value in themselves.

When applied to Mars [58], these principles argue that a biologically rich Mars is of more value than the fascinating but dead world we see today. Furthermore, a Martian biosphere populated by a second type of life would contribute to more diversity than one populated by transplants from Earth.

We know from observations of Mars that it does not have a rich global biosphere. Thus, if there is Martian life it is either dormant or surviving within some limited refugia. We do not know what would be the fate of that life if Earth organisms either were to colonize these existing refugia or were to be present as Mars was warmed in the first step of planetary restoration. It might be that co-habitation of Earth life and an alien type of Martian life is possible. However, the facts of biological competition for resources would seem to indicate that one form would dominate and drive the other to extinction. Thus, it would seem that the notion of the intrinsic worth of life and diversity of life would dictate that we will not allow contact between Martian life and Earth life until the implications of such contact are fully understood.

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It is important to note that the basis for the ethical issues does not come from assigning intrinsic value to microbes *per se*. On Earth, we freely kill micro-organisms. The focus of the ethical concern is for a second type of life capable of independent biological and evolutionary development. This is true even if the specific organisms involved are only microbes.

8. Conclusion

The spacecraft exploration of the Solar System has opened up many new worlds to astrobiological investigation. Missions to Mars and Europa are in the works, and plans are afoot for further missions to Enceladus and Titan.

The search for alien life on the other worlds of our Solar System and the scientific knowledge we may gain from such a discovery is a challenge and an opportunity for the current age of space exploration. How we search, what we find and how we respect and promote life in all its richness and diversity will set the pattern for the years to come.

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