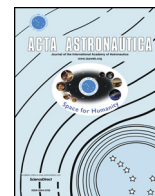




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Why planetary and exoplanetary protection differ: The case of long duration genesis missions to habitable but sterile M-dwarf oxygen planets

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ABSTRACT

Time is arguably the key limiting factor for interstellar exploration. At high speeds, flyby missions to nearby stars by laser propelled wafersats taking 50–100 years would be feasible. Directed energy launch systems could accelerate on the other side also crafts weighing several tons to cruising speeds of the order of 1000 km/s ($c/300$). At these speeds, superconducting magnetic sails would be able to decelerate the craft by transferring kinetic energy to the protons of the interstellar medium. A tantalizing perspective, which would allow interstellar probes to stop whenever time is not a limiting factor. Prime candidates are in this respect Genesis probes, that is missions aiming to offer terrestrial life new evolutionary pathways on potentially habitable but hitherto barren exoplanets.

Genesis missions raise important ethical issues, in particular with regard to planetary protection. Here we argue that exoplanetary and planetary protection differ qualitatively as a result of the vastly different cruising times for payload delivering probes, which are of the order of millennia for interstellar probes, but only of years for solar system bodies. Furthermore we point out that our galaxy may harbor a large number of habitable exoplanets, M-dwarf planets, which could be sterile due to the presence of massive primordial oxygen atmospheres. We believe that the prospect terrestrial life has in our galaxy would shift on a fundamental level in case that the existence of this type of habitable but sterile oxygen planets will be corroborated by future research. It may also explain why our sun is not a M dwarf, the most common star type, but a medium-sized G-class star.

1. Introduction

Space exploration is confronted inherently with the extended travel times needed to traverse the voids of space extending between earth and the destination. In addition to travel times, key limiting factors are cost considerations and the time devoted to mission development and design. The latter is in particular the case for further away destinations, such as missions to the outer solar system. Typically examples of past and future missions are here the Voyager crafts [1], the Europa Clipper [2] and missions searching for life in the subglacial waters of ice moons [3]. Is there however a maximal planning horizon societies would be willing to support? It is not uncommon for projects involving large-scale scientific or technology development tasks to span decades. Long-term collaborative efforts, like the ITER fusion reactor [4], are nevertheless more often than not accompanied by continuous controversies concerning the ultimate effort to utility ratio, with a central reason being the rational to discount future rewards [5]. It is hence unlikely that explorative space missions taking centuries or even millennia to complete would ever survive the initial cost-to-benefit evaluation. The situation may however change for endeavors not designed for their

usefulness in terms of science data or other return values. This will be the case, as we argue here, for Genesis missions aiming to establish an ecosphere of unicellular lifeforms on potentially habitable but hitherto barren exoplanets.

2. The utility vs. realizability dilemma of deep space exploration

Solar system traveling times are long, but somewhat manageable. The recent surge of interest in directed energy launching systems [6] has presented us on the other side with the prospect that interstellar space missions may become realizable within several decades. The development of mission scenarios for interstellar probes has hence left the realm of fusion-size spaceships [7,8], becoming instead a question of pros and cons. We argue here that two types of interstellar probes may be considered, fast data return probes and comparatively slow Genesis crafts.

2.1. Data gathering by fast flyby probes

Directed energy launch systems may accelerate wafersat spacecrafts

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weighing a few gram up to 20% of the speed of light [9], at least modulo a substantial technology development effort. Wafer-sized interstellar probes capable of reaching the nearest stars within several decades may hence be employed, as envisioned by the Breakthrough Starshot Initiative [10], for science data return missions. The technical challenges, ranging from material issues [11], the stability at launch [12], to the interaction of a relativistic spacecraft with electromagnetic forces [13], and with the interstellar medium [14], are immense, but not insurmountable.

Interstellar science probes need to be fast, as data return missions taking centuries would not be considered worth the investment. Flyby missions are consequently the only viable option. Decelerating with the aim to enter solar or planetary orbits involves on a practical level the transfer of the kinetic energy to either the photons of the target star or to the ionized particles of the interstellar medium. Solar sail deceleration, the first method, is however not possible when the craft travels at relativistic speeds; the probe would have bypassed the target star long before coming to a stop. For the second method, magnetic sails weighing of the order of several hundreds tons would be necessary [15]. To accelerate a craft of that size to close to the speed of light is however beyond launch infrastructures potentially realizable within the next generations. The same holds for active deceleration of massive spaceships by TW-sized solar-system based laser beams [16]. Interstellar science probes are consequently realizable only if they are fast, viz when limited to flyby investigations.

2.2. Payload delivery by slow interstellar crafts

Fast and slow are highly relative terms in the realm of space travel. The Voyager spaceprobes cruise at speeds of the order of 20 km/s, which is high with respect to everyday's velocities, but slow when it comes to interstellar distances. Here we consider an interstellar spacecraft to be 'slow' when cruising roughly 50 times faster than the Voyager probes, at 1000 km/s, which corresponds to 1/300 of the speed of light. The millennia needed to reach the nearest stars at such a velocity exceed typical human planing horizons by far, which implies that it is not possible to assess the potential benefits of slow interstellar missions with standard utility criteria. A slow craft has on the other hand enough time at its disposal to decelerate via magnetic braking, that is by transferring momenta to the interstellar protons [17]. It has been estimated in this regard, that the magnetic field created by a 1.5 ton superconducting loop with a radius of 50 km would be able of doing the job [15]. Magnetic sails are moreover self-deploying, as wires with opposite currents repel each other. Slow interstellar spacecrafts are hence suited for delivering ton-sized payloads to far away destinations.

Slow interstellar ton-sized crafts may be launched, importantly, by the same directed energy launch systems envisioned for fast flyby missions, with the reduced velocity trading off the increased weight [18]. Comparatively slow, that is non-relativistic interstellar crafts, could be accelerated alternatively by the type of advanced ion engines that are being developed within NASA's evolutionary Xenon thruster (NEXT) effort [19,20]. Laser arrays of the order of 100 MW would be used in this case not to propel a reflecting light-sail, but to power the solar cells of the craft [21]. A conversion rate of 70%, potentially achievable when the sail performance is tuned to the laser frequency, would then be enough to power 70 MW lithium-fueled gridded ion thrusters [22].

Overall we are confident that interstellar spaceprobes entering solar or planetary orbit on arrival are potentially realizable, albeit at the cost of prolonged mission times. Less likely seem in contrast the perspective that fast probes could decelerate, independently of the technique envisioned for the braking maneuver.

2.3. Interstellar deceleration

The lack of an in-place infrastructure implies, on arrival, that it is

substantially more challenging to decelerate an interstellar craft than to speed it up in first place. This is in especially true when the craft is fast and when mission durations should be kept within human planing horizons. Given enough time, and a magnetic sail of substantial size [15,23,24], braking from the protons of the interstellar medium is however feasible, as discussed in the previous sections.

Regarding solar sails, it has been proposed that graphene may be the optimal candidate material [25], both for launching an interstellar probe and for braking from the photons of the target star [26]. Physically, a graphene monolayer is characterized by an ultra-low areal mass density of $7.4 \cdot 10^{-7}$ kg/m², a negligible reflectivity and a flat absorption coefficient $A_\omega = \pi\alpha \approx 0.023$, as resulting from the Dirac cone, where $\alpha = e^2/(\hbar c) \approx 1/137$ is the fine structure constant [27]. Assuming that the properties of a graphene monolayer could be improved by about a factor 100 without a corresponding weight increase, namely to reflectivity values of 99.99%–99.999%, a fast interstellar craft could decelerate at α -Centauri using stellar photon pressure [26], at least as a matter of principle. How to realize the required performance boost is presently however unclear.

The field of a magnetic sail is produced by a large superconducting loop. Alternatively one may consider an electric sail [28], which consists of electrically charged structures of similar extensions. In this case it is the electric field of the charged craft that reflects the protons of the interstellar medium [17]. It would however be a challenge for an interstellar craft to power the electron gun needed to maintain the required potential difference between the craft and the surrounding rarefied medium. Electric sails may however be advantageous for solar system application, as their performance decays only as $1/r$, as a function of the distance to the sun, and not as $1/r^2$, as for solar sails [29].

2.4. The slow path from prokaryotes to eukaryotes

Payload delivering interstellar crafts come with cruising times of a few millennia, at least, that is with timescales that may seem extraordinary long to human planning horizons. A handful of millenia are on the other hand irrelevant from the perspective of evolutionary processes. On earth it took about one billion years, that is until the end of the archean genetic expansion [30], to develop modern prokaryotes, viz bacteria, and another billion years for the basis of all complex life, eukaryotic cells, to emerge [31]. It is not a coincidence, that higher life forms are made of eukaryotic and not of prokaryotic cells, but a consequence of the energy barrier that prevents prokaryotic cells to support genomes of eukaryotic size [32]. The massive genomes necessary for the coding of complex eukaryotic morphologies are typically four to six orders of magnitude larger than the genetic information encoding prokaryotic life [33].

The emergence of eukaryotic cells has been on earth the key bottleneck along the route from uni-cellular to multi-cellular and morphological complex life. Taking the timescale of terrestrial evolutionary processes as a reference, we may hence postulate that exobiological lifeforms could need similar time spans, if at all, to evolve to complexity levels comparable to terrestrial eukaryotic life [34]. There are moreover arguments for the possibility, as discussed further below, that a relatively high percentage of potentially habitable planets may harbor either no life at all, or only lifeforms equivalent in complexity below that of modern terrestrial bacteria. A payload of single-cell eukaryotes, either as germs or in terms of codings for an onboard gen laboratory, would hence be a valuable payload for slow cruising Genesis probes destined to habitable but otherwise barren exoplanets. Operationally, instead of landing, the Genesis probe would carry out the seeding process from orbit via the retrograde expulsion of micro-sized drop capsules. The goal would be in the end to lay the foundations for a self-developing ecosphere of initially unicellular organisms [35].

3. The case for habitable but sterile oxygen planets

A Genesis probe should comply with planetary protection considerations and target only certain types of potentially habitable planets [36]. One possibility is that the candidate planet is only transiently habitable, that is for time spans that are too short for complex single- or multi-cellular life to develop [35]. Examples for causes for limited habitability are orbital instabilities of the hosting planetary system and geological disruptions due to the absence of plate tectonics [35]. Of interest in this respect are furthermore planets orbiting brown dwarfs [37], that is failed stars having 13–75 times the mass of Jupiter. The mass of brown dwarfs is too low for hydrogen fusion, the energy source of main-sequence stars, with the consequence that the star cools progressively by radiative dissipation of its initial reservoir of thermal energy. Depending on the mass of the star, on the orbital distances of the planets and on other parameters, like the impact of gravitational and atmospheric tides, a given brown-dwarf planet could remain habitable for periods ranging from a few hundred million years to a few billion years [37]. Brown dwarf planets are hence interesting Genesis candidate planets.

3.1. Abiotic oxygen buildup in the runaway greenhouse state of young M-dwarf planets

Stars with a mass greater than about 0.075 the mass of the sun are heavy enough to produce energy via hydrogen burning. A well known example is the Trappist-1 system [38], a system composed of seven earth-sized planets orbiting a M-dwarf star at distances that are either within or close to the nominal habitable zone. The mass of the central star is in this case about 0.08 the mass of the sun, which is not a coincidence. Estimates show [39], that a majority of rocky habitable zone planets is expected to orbit M dwarfs, that is low-mass stars like Trappist-1.

M dwarfs are characterized by an extended Kelvin Helmholtz contraction time, which is the time it takes for a protostar to reach the main sequence by shedding its initial reservoir of gravitational energy radiatively. The Kelvin Helmholtz timescale extends from about 10 million years for sun-like stars to several hundred million years for late M dwarfs [40]. Planets orbiting low mass stars at a distance corresponding to the main-sequence habitable zone will hence experience an extended initial runaway greenhouse state induced by the increased irradiation from the initially substantially larger host star. With the ending of the Kelvin Helmholtz contraction of the central star the atmosphere of the planet cools correspondingly.

In the initial greenhouse state the stratosphere is wet. The UV radiation of the host star leads in this stage to the photodissociation of water, and with it to the loss of hydrogen to space, with the oxygen staying mostly behind [41]. Depending on the initial reservoir, several earth oceans worth of water may be lost altogether [42]. For the habitable-zone planets of the Trappist-1 system the resulting buildup of abiotic oxygen has been estimated to reach partial pressures of 350–490 bars [43]. It is presently not clear to which extent the buildup of abiotic oxygen during the Greenhouse state is countered by redox reactions resulting from the interaction of the atmosphere with a magma ocean [44]. It is likely that the final oxygen content of the atmosphere is reduced, but still substantial. Primordial oxygen partial pressures of several bars and more may hence be a common feature of rocky M-dwarf planets.

3.2. Are oxygen planets sterile?

The chemical environments of oxygen planets, that is of planets disposing of a substantial amount of primordial atmospheric oxygen, are expected to differ substantially from the one of archaic earth. The origins of life on earth are yet not understood [45], it is however clear that abiogenesis may occur only in microstructured chemo-physical

reaction environments [46] that are driven by a sustained energy source [47], as realized within the alkaline hydrothermal vent scenario [48]. Potential birthing places of life such as submarine alkaline vents are conjectured furthermore to be characterized by steep electrochemical concentration gradients [49], as a necessary precondition for the emergence of prebiotic vectorial reaction pathways. Primordial oxygen, when present, could disrupt however the formation of these electronchemical disequilibria [50]. An important point in this context is a well-known relationship between oxygen and cellular energy,¹ namely that the synthesis of the chemical constituents of cells, like amino acids, bases and lipids, from glucose and ammonium, demands about 13 times more energy per cell in the presence of O₂ than in the absence of oxygen [51,52]. It is hence conceivable that the emergence of life could be preempted on otherwise habitable M-dwarf planets by the presence of primordial oxygen. A substantial amount of future research effort is clearly warranted in order to corroborate, or to disprove this presumption. In case, we would live in a galaxy where habitable but sterile planets abound. Oxygen planets would then be prime candidates for Genesis missions.

4. Planetary vs. exoplanetary protection

An endeavor aiming to endow other planets with life raises a series of ethical issues. From a utilitarian perspective it may be considered in fact unethical to allocate a substantial amount of resources to projects not contributing to the overall welfare of humanity [53]. We will not pursue this argument further, focusing instead on two key aspects of planetary protection.

4.1. Planetary protection for human benefit

Planetary protection had been formulated historically with the exploration of the solar system in mind [54]. Back contamination needs to be avoided, clearly, such that “*earth is protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from another planet*”. Space exploration should be carried out, furthermore, in a manner that does not jeopardize “*the conduct of scientific investigations of possible extraterrestrial life forms, precursors and remnants*”. Human benefit considerations have hence been, as these formulations of the planetary protection policy of the International Committee on Space Research (COSPAR) show, the core original rationale for avoiding not only backward, but also forward contamination [55].

The very existence of extraterrestrial life is a subject of debate. Remote sensing attempts, like the detection of extrasolar life via a direct or indirect spectral analysis of exoplanetary atmospheres [56], will be carried out in the next years. In situ investigations of extrasolar life are in contrast unlikely to be ever undertaken. On one side because the delivery of the required landing modules by slow-cruising interstellar probes would take millennia. The second point is that we may expect science to progress within the intervening centuries to a point that would allow for a near to full understanding of the possible routes to abiogenesis and of the spectra of possible lifeforms. Another aspect is that computer experiments can be anticipated to advance to a point that would allow, eventually, to retrace the geophysical evolution of a given non-solar planetary system in detail, possibly when supplemented by flyby observations. Relatively little could be added in this case by additional in situ investigations. Protecting the rudimentary biosphere of an exoplanet for science purposes is hence not as relevant as it is for solar system bodies.

4.2. Ethically grounded planetary protection

Common ethical imperatives are ambiguous when human activities

¹ W. F. Martin, private communication.

impact higher but non-human life forms, in particular with regard of the relative relevance of anthropocentric and non-anthropocentric values [57]. There is however a deeply rooted common-sense notion that humanity should protect life forms of a certain level of complexity, at least whenever possible. This notion withstands the Darwinian nihilist viewpoint [58], attributing instead value to life per se [59].

Taking the evolution of terrestrial biota as a reference [30,35], we may classify non-solar ecosystems into four categories: primitive-prokaryotic, prokaryotic, unicellular eukaryotic and multi-cellular eukaryotic, viz complex life. For terrestrial life it is custom to attribute value nearly exclusively to complex life, viz to animals and plants. Killing a few billion bacteria while brushing teeth does not cause, to give an example, moral headaches. The situation changes however when it comes to extrasolar life, for which we may attribute value also to future evolutionary pathways. This is a delicate situation. Is it admissible to bring eukaryotes to a planet in a prokaryotic state, superseding such indigenous life with lifeforms having the potential to develop into complex ecologies? Our prevalence to attribute value predominately to complex lifeforms would suggest that this would be ethically correct [58,59], in particular if we could expect our galaxy to harbor large numbers of planets in prokaryotic states. Endowing a selected number of exoplanets with the possibility to evolve higher life forms would in this case not interfere with the evolution of yet simple life forms on potentially billions of other planets.

Genesis missions would comply with the common-sense norm to attribute value to complex lifeforms, the very rational to undertake them in first place, and abort whenever the target planet harbors life that can be detected from orbit. Considering the case of Mars, it is however clear that it will be hard to rule out unambiguously the existence of ecospheres of exceedingly low bioproductivity. Protocols regulating the necessary level of confidence are hence needed. It would be meaningful to embargo the entire extrasolar system in case that complex life would be detected by flyby probes on one of its planets.

5. Discussion & outlook

The recent advent of directed energy launch concepts demonstrates that interstellar space probes may become realizable within the foreseeable future [60]. The technical challenges involved are daunting. An example is the development of self-healing electronics [61], that is of circuits that would be capable to withstand decades to millennia of cosmic bombardment [62]. It is hence important to assess and to classify the range of possible interstellar missions. The first option is a high speed flyby mission by gram-sized wafersats that have been accelerated to a sizable fraction of the speed of light [18], say 20%. Here we have pointed out that the directed energy launch systems envisioned for fast flyby missions would be suited to launch in addition payload delivering probes cruising at reduced velocities of typical 1000 km/s. These probes would weigh of the order of several tons, in particular due to the weight demands of the magnetic sail that would be needed for braking off the interstellar medium [15]. The long arrival times of a minimum of several thousand years require however an in depth analysis of the rational for carrying out this kind of comparatively slow-cruising interstellar missions. One possibility would be the Genesis project [35], which proposes to initiate the development of pre-cambrian ecospheres of unicellular organisms on transiently habitable exoplanets.

We have pointed out, in addition, that the existence of habitable but sterile oxygen planets would alter radically our view of our cosmic neighborhood, in particular from the perspective of interstellar mission planing. The number of potentially habitable M-dwarf planets has been estimated to be substantial [63], with the consequence that it is not implausible that a rich biosphere might be detected eventually on a nearby M-dwarf planet via remote sensing. Biosphere compatibility considerations suggest in this case that we should not consider in-situ investigations of exoplanets teeming with life [35], with the reason

being that such an endeavor could be catastrophic for the indigenous biosphere.

The situation changes, in contrast, if the target habitable planet contains a substantial amount of primordial atmospheric oxygen and if primordial oxygen preempts the emergence of life. Habitable oxygen planets would then be sterile. Oxygen, which is otherwise a preconditions for multi-cellular and hence complex life to thrive, is expected to be generated in vast amounts during the initial runaway greenhouse state occurring during the extended Kevin Helmholtz contraction phase of nominally habitable late M dwarfs planets [42]. It is presently not known if the resulting primordial oxygen atmosphere, which may differ drastically from planet to planet in volume [44], would inhibit life to originate in first place. The existence of habitable but sterile oxygen planets, that is of worlds that would offer terrestrial life nearly unlimited grounds for the pursue of new evolutionary pathways, would revolutionize in any case our view of our galactic neighborhood.

The initial Kevin Helmholtz contractions phase of yellow G-class stars like our sun is relatively short, typically of the order of several million years. Potentially habitable planets orbiting not a M dwarf, but G stars, are hence not forced to go through an extended initial Greenhouse state, even though they can enter one, like Venus, as a consequence of the final orbital parameters. One may speculate whether this circumstance is the reason why earth is not orbiting a red M dwarf, the most frequent star type of the galaxy, but a star type which is substantially less common, a yellow G star.

Regarding the difference between the protection of solar system bodies and exoplanets we have pointed out that the extended time scales necessary for an in-situ exploration of exoplanets changes the rational. Financing a deep-space mission taking several millenia cannot be justified along the lines of solar system exploration, viz for the advancement of science. It is interesting in this context to connect to the ongoing controversy [64], whether the hypothetical counterfactual of planetary protection, “*You protect what you want to study, but you cannot study what you protect.*”, does impede the search for life on Mars [65]. Protecting life on exoplanets for the sake of science is in analogy not a valid rational, as it could be studied in any case only on time scales far exceeding standard human planning horizons.

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