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Unrestricted Earth Return, Planetary Protection and the Wisdom of the Precautionary Principle

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Abstract

We live in a new era of space exploration where robotic spacecraft can be sent out to deep space and retrieve samples of our moon, planets, and icy moons for direct return to Earth. These sample return missions are now mounted by diverse international space agencies as well as private industry, but without international planetary protection protocols necessary to prevent a back contamination event involving any alien microbes. The organizations that allow for these missions (Category V) to proceed are the Committee on Space Research (COSPAR) and the Space Studies Board (SSB), which has been allowing Unrestricted Earth Return (hereafter UER) from samples of Small Solar System Bodies such as comets and asteroids. These samples are brought directly to Earth-based laboratories for study without any of them being certified to handle harmful or deadly pathogenic organisms if these are found. Although little is decisively known about the potential of comet and asteroid samples to contain harmful pathogens, the decision to allow UER's is based on the "assumption" based on a possibly incorrect scientific opinion that comets and asteroids are indeed dead lifeless objects. The rationale for this assumption is centered on the estimated 4700 metric tons of Interplanetary Dust Particles (IDP's) from comets and asteroids that settle to the surface of Earth each year without having any substantial evidence of adverse global effects that we are aware of and therefore is considered "biosphere safe". But is it? We ourselves have good reason to challenge this assertion. Moreover, SSB recommendations point out that while the risk of back contamination from UER missions is very low, it is not zero.

Keywords

Planetary Protection, Back Contamination, Astrobiology, Panspermia, Comets, Asteroids, Unrestricted Earth Return

1. Introduction

Evidence for cometary panspermia via the transport of microbes by comets to other celestial objects (planets and moons) has been available since 1986 [1] [2] along with newly obtained information from four UER missions that now call into question the wisdom of allowing UER missions [3] in the first place. The Precautionary Principle is defined as a broad epistemological, philosophical and legal approach to innovations with the potential for causing harm when definitive scientific knowledge on the matter is lacking. This scientific principle is at the heart of International Space Law, which was drafted by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and opened for signatures in January 1967. In Article 9 of the document, it says:

In the exploration and use of outer space, including the moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall 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 also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the moon and other celestial bodies, may request consultation concerning the activity or experiment.

"*States Parties to the Treaty shall 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 also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.*"

Interplanetary Dust Particles (IDP) entering the Earth's atmosphere producing meteor showers such as the Perseids, Geminids and Leonids originate from cometary and asteroidal dust particles that form a huge pancake-like disk around the Sun known as the zodiacal cloud. A study of the zodiacal light spectra from this cloud was found to draw a parallel to observations made with the European Space Agency's (ESA) Rosetta spacecraft of cometary dust particles in the coma of comet 67P [4]. A more recent study [5] using high-resolution spectra obtained from Rosetta spacecraft of comet 67P has detected the spectrum of Dimethyl Sulfide (DMS), a terrestrial atmospheric gas thought to be only produced by marine and fresh water phytoplankton and photosynthetic bacteria living in Earth's lakes and oceans.

A previous study published in 2018 [6] by a group of Russian planetary scientists who analyzed cosmic dust samples that were collected from the surface of the illuminator (window) on the outside of the International Space Station (ISS) were found to contain bacteria some of which were still viable. A DNA sequence of one of the bacteria belonged to the genus *Mycobacteria* and was genetically similar to "species found in Barents and Kara seas' coastal zones". The authors of this research paper attributed two possibilities for the presence of marine bacterial DNA on the ISS: One possibility is the unlikely transfer of terrestrial organisms from the stratosphere into the ionosphere with an ascending branch of the global electric circuit. The second possibility was that the exterior of the ISS bacteria had an ultimate space origin, perhaps as the ISS accumulated interplanetary dust particles containing microorganisms in its 400 km orbit around Earth as the Earth itself traveled in its orbit around the sun passing through the zodiacal cloud composed cometary dust and bacteria left behind from their outgassing tails.

The problem of back contamination

Because of the potential risk of altering the global micro-organism balance of Earth's biosphere with an unknown extraterrestrial invasive species or even harmful prebiotic chemicals, NASA's Planetary Protection (PP) policy for a potential Mars Sample Return mission has been hotly debated for decades [7]. This is particularly relevant now as we plan to return samples of Mars directly to Earth sometime in the 2030's [8]. This PP policy also applies to the eventual Earth return of material from a number of icy moons such as Europa (from Jupiter) and Enceladus (from Saturn) that are suspected of having oceans of water under icy crusts. The discovery of these oceans was made after observations of vast geyser systems of liquid water-ice spewing out from fissures in the crusts of these moons. Such sample return missions as are being planned are designated as Restricted Earth Return Missions [9] because of the possibility they may contain indigenous microbes. Therefore reasonable questions regarding the unrestricted Earth return of comets and some asteroids are: Why aren't they considered as Restricted Earth Return (hereafter RER) missions, like the icy moons of Jupiter and Saturn? Comets and some asteroids share similarities to the icy moons of Jupiter and Saturn only in miniature as they vent dust, gas and water ice into space from fissures in their surfaces, so why are they deemed lifeless based on assumption?

Missions are placed into different categories based on a concern for the target of the mission and the type of mission envisioned:

Category I: Applies to missions to targets thought to be of no biological interest, such as Earth's moon and Jupiter's moon Io, with no associated planetary protection requirements.

Category II: Applies to missions to targets with minimal biological interest but of intrinsic interest for the study of chemical evolution, requiring documentation to ensure planetary protection goals are met.

Category III: Applies to missions that are for fly-by and orbiters not intended to land or impact the surface.

Category IV: Applies to missions that have landed craft and make direct contact with targets of significant biological interest. Subsections for landed craft to Mars with and without life detection experiments and include whether or not landing or traveling to a "special region" where water may be present and the temperature range is suitable to sustain life.

Category V: Applies to all missions that make contact with another solar system body and then return to Earth, with additional constraints to guarantee the safety of Earth's biosphere. These missions can be designated as "unrestricted Earth return" or "restricted Earth return."

At this time, recommendations for RER missions are envisioned to be curated and examined in a high-level not-yet-designed Biosafety Level-4 or higher laboratory combined with a state-of-the-art ISO Class 5 clean room [10].

On the other hand, PP policies allowing for UER missions lack the mandatory quarantine and sterilization procedures that RER missions will have [11], nor are they required to be examined in any specially designed Biosafety-4 labs to safely handle any potentially biohazardous samples. The questions to be asked are clear: Since the value seen with UER missions is that it allows for faster economic analyses in already established research facilities, is it worth the expense to forego biosafety concerns? Can the scientific value of UER's be limited if some of the samples become contaminated with terrestrial microorganisms?

To date, there have been four UER missions: One mission to a comet 81P/Wild-2 and three to asteroids Itokawa, Ryugu and Bennu.

The NASA Stardust mission was the first successful UER mission to a comet. Stardust was launched in 1999 and landed safely back on Earth on January 15th, 2006 and returned samples captured in aerogel from the cloud of dust that surrounds the nucleus of the comet as the Stardust spacecraft as it flew through. Analysis of 81P/Wild 2 dust grains has shown that liquid water existed inside the comet at some point in its history and was determined by the research team after finding the copper iron sulfide mineral "cubanite" that can only form when exposed to heated groundwater to 99 degrees Fahrenheit (210 degrees Celsius). This new information contradicted the theory that cometary ice is always in a state of deep freeze. It was hypothesized the interior of 81P/Wild-2 was warm enough to melt ice, but remained cool enough to form the mineral cubanite [12]. There was only one of two heat sources responsible for this—the first being collisions with other celestial objects, which in turn would generate water that allowed the sulfides to form quickly. The other possibility was radioactive decay.

The Japanese led Hayabusa 1 mission (JAXA) was launched May 9, 2003, flown to the near-Earth S-type asteroid 25,143 Itokawa and returned samples to Earth on June 13, 2010. Analysis revealed the first evidence for extraterrestrial amino acids in asteroidal material and the first-ever measurements of hydrated minerals contained in samples from the surface of an asteroid. These hydrated minerals had a hydrogen isotopic composition that was indistinguishable from Earth's oceans suggesting that asteroids like S-type Itokawa may have played an important role in the formation of the oceans on Earth [13].

Japan launched a second Hayabusa-2 mission to the carbon-rich asteroid Ryugu and returned samples to Earth on December 6, 2020 where the sample capsule was opened at the curation facility of JAXA (Japan Aerospace Exploration Agency), Sagamihara, Japan. Studies of samples from Ryugu, confirmed the presence of dimethyl sulfide (DMS) alongside other organic compounds like polycyclic aromatic hydrocarbons (PAHs). During curation the activities researchers were startled to find an abundance of rods and filaments that changed with time and proposed the growth and decline of a "terrestrial" prokaryote population with a generation time of 5.2 days and this was defined as a rapid biological contamination event [14]. Conversely, since Hayabusa 2 was a UER mission to what scientific opinion considered a "lifeless asteroid", there was no Precautionary Principle in place nor indeed any way to rule out a back-contamination event. It raised the spectre of a reverse contamination scenario where unanticipated extraterrestrial microbes could rapidly escape and multiply in our biosphere.

Genge *et al.* in their important paper stated:

*If indigenous extraterrestrial organisms were discovered in an asteroid it would, therefore, have profound implications for the timescales of the origins and evolution of life. Furthermore, it would imply that life could be delivered to the surface of all the terrestrial planets by primitive impactors. Considering the profound nature of these implications exceptionally strong evidence would be required to demonstrate the indigenous nature of microorganisms in asteroid materials, which the current study suggests is highly likely to be compromised by the potential for contamination…*furthermore they recommended:

*The rapid colonization of Ryugu sampleA*0180 *by terrestrial organisms suggests that extra-planetary organic matter could allow the survival of microbial life on the surface of other planets and sustain ecosystems in environments where indigenous metabolic energy sources are scarce. Thus, both inbound and outbound missions to celestial bodies should be reassessed for contamination control and planetary protection procedures.*

In 2016 NASA launched its OSIRIS-REx mission to retrieve samples of the asteroid Bennu. It landed back on Earth in 2023 where samples were analyzed in clean rooms at the Johnson Space Center in Houston. One of the key findings from Bennu was that it was dominated by clay minerals, particularly serpentine and mirrored the type of rock found at mid-ocean ridges on Earth [15] again showing a connection between asteroids as deliverers of water to the Earth.

However, on September 08, 2023 the current acting NASA Planetary Protection Officer Nick Benardini said:

"*The OSIRIS-REx* (*mission to asteroid Bennu*) *sample return is classified as an unrestricted Earth-return so there don't need to be any protocols put in place from a public safety and Planetary Protection perspective…Due to this type of target body having only some of the key formational and evolutionary organic molecules necessary for life*, *there is no chance that the sample from Bennu could contain living organisms*."

The debate on the occurrence of dimethyl sulfide (DMS)—abiotic or biotic?

On Earth, the sulfur-bearing gas "dimethyl sulfide (DMS; C_2H_6S)" is an important component of Earth's atmosphere produced by a few classes of ocean dwelling marine and lacustrine phytoplankton, mainly the Dinophyceae (dinoflagellates) and the Prymnesiophyceae (which includes the coccolitnophores). However, DMS production is also known from members of the Chrysophyceae and the Bacillariophyceae family of diatoms that are found in sea ice and glaciers. DMS is also a naturally occurring product of sulfur-rich organics known to accumulate in anoxic environments such as marine and lacustrine sediments and through the process of diagenesis is incorporated into the sedimentary rock record as shales and coal.

It is because of this association with photosynthetic life on Earth, that DMS is now thought to be a reliable biosignature gas to look for in the habitable-zone of exoplanets that also show spectral evidence for liquid water oceans and a hydrogen-dominated atmosphere [16]. Thus this new class of exoplanets called a "Hycean world" is defined as a temperate ocean-covered world with an H2-rich atmosphere. The planet was discovered using the transit method of observing possible exoplanets in hundreds of distant stars with Kepler Space Telescope and in 2015 found K2-18 b orbiting in the habitable-zone around its parent star—a small red dwarf star known as K2-18 approximately 120 light-years away in the constellation Leo. Because K2-18 b was found to be 8.6 times more massive than earth, it is called a trans-Neptunian planet similar to the size of the planet Neptune in our solar system. K2-18 b's atmosphere was analyzed by a team of international astronomers using archived data from NASA's Hubble Space Telescope WFC3 camera from 2016 and 2017. The data revealed the likely presence of icy clouds in its atmosphere. The team published a 2019 paper [17] concluding that their observations demonstrate that habitable-zone exoplanets with the right conditions for liquid water can be analyzed with state-of-the-art telescopes such as the James Webb Space Telescope.

As interest in exoplanet planet K2-18 b continued to grow it prompted astronomers from the UK and USA on September 8th 2023 to publish new findings from the NIRISS and NIRSpec instruments on James Webb Space Telescope in the 0.9 - 5.2 μm range looking for carbon-bearing molecules. They discovered abundant CH_4 and CO_2 along with the non-detection of ammonia (NH_3) which the team interpreted as being consistent with chemical predictions for an ocean under a temperate H2-rich atmosphere. The spectrum also suggested they may have also detected dimethyl sulfide (DMS), which was predicted by [18] to be an observable biomarker. However the UK/US researchers stated in their paper that further validation is needed to confirm the presence of DMS in the atmosphere of K2-18 b [19].

The suggestion that DMS could be used as a possible biomarker for biological activity on the planet K2-18b caught the attention of a team of astronomers from the University of Bern in Switzerland who for two years studied comet 67P with the high-resolution mass spectrometer DFMS on the ESA's Rosetta spacecraft. The team found the signal of dimethyl sulfide (DMS) in comet 67P coma and concluded that since comets are assumed (wrongly in our view) to be "lifeless", it called into question the usefulness of DMS as a biosignature gas. Their results were presented to the 2024 European Geosciences Union in Vienna, Austria and afterward in a scientific paper [20].

DMS on Mars, the interstellar medium and asteroid Ryugu

It is also interesting to note that DMS was detected when NASA's Curiosity rover's GC/MS analysis of gases released from a mudstone rock in Gale Crater (a former ancient lakebed) was consistent with the presence of thiophene (C_4H_4S), methylthiophenes (C_5H_6S), methanethiol (CH_4S), and dimethyl sulfide (C_2H_6S) [21].

Following the discovery of dimethyl sulfide (DMS; CH_3SCH_3) signatures in comet 67P a February 2025 paper submitted by Miguel Sanz-Novo *et al.* to The Astrophysical Journal Letters reported the first detection of DMS in an interstellar cloud during the exploration of an ultra-deep molecular line survey performed toward the Galactic center molecular cloud G + 0.693 − 0.027 with the Yebes 40 m and IRAM 30 m telescopes [22]. Again as in other previous papers the authors report their discovery as having an abiotic origin. However, is this persistence due to the rejection that lyophilized microbial life forms and its chemistry cannot survive in molecular clouds?

DMS presence on asteroid Ryugu:

According to current research, dimethyl sulfide (DMS) has also been detected on asteroids, specifically in samples from the asteroid Ryugu, indicating that this molecule, often considered a biosignature due to its primary production by life on Earth, can also be formed through non-biological processes in space, raising questions about its reliability as a sole indicator of life on other planets; the discovery was made by analyzing samples collected by the Hayabusa2 spacecraft [23].

While the jury is still out on whether dimethyl sulfide in comets, asteroids, exoplanets and the interstellar cloud near the center of our galaxy is the result of abiotic or biotic chemistry, a recent 2024 paper by Edmund R. R. Moody *et al. The* *nature of the last universal common ancestor and its impact on the early Earth system* published in the journal Nature Ecology and Evolution [24] seems to point to call into question whether life is a cosmic phenomenon. In their abstract it says:

"*The nature of the last universal common ancestor* (*LUCA*), *its age and its impact on the Earth system have been the subject of vigorous debate across diverse disciplines*, *often based on disparate data and methods. Age estimates for LUCA are usually based on the fossil record*, *varying with every reinterpretation. The nature of LUCA*'*s metabolism has proven equally contentious*, *with some attributing all core metabolisms to LUCA*, *whereas others reconstruct a simpler life form dependent on geochemistry. Here we infer that LUCA lived* 4.2 *Ga* (4.09 - 4.33 *Ga*) *through divergence time analysis of pre-LUCA gene duplicates*, *calibrated using microbial fossils and isotope records under a new cross-bracing implementation*".

The age of the earth for LUCA in this paper at 4.09 - 4.33 Ga has been previously postulated to be the maximum-age bound based on the time of the Moon-forming impact (4510 million years ago (Ma) ± 10 Myr) which would have effectively sterilized Earth's precursors, Tellus and Theia. Since the earth would have still been in a molten state at this early stage, questions of whether LUCA might have a cosmic origin should be examined.

Overwhelming rationale for the cosmic theory of life

The implied assumption in the rejection of planetary protection protocols for bringing back samples that are procured from asteroids, comets and planets is that there is no chance whatsoever of such samples containing "live" or potentially hazardous biological material. The most recent studies of material recovered from asteroids Bennu and Ryugu, in our view, casts serious doubts on this assumption.

In the case of the recovered fragment of Ryugu a wide range of microorganisms were discovered within its porous matrix, but all these have been declared as having most likely to have arisen from terrestrial contamination [25].

Although we cannot absolutely rule out such a claim, the possibility of microbial spores having pre-existed within a loosely aggregated fragment of a once "living" comet or asteroid remains, in our view, the far more likely option.

Discovery of bacteria on ISS

One of the most dramatic instances of the recovery of cometary microorganisms from space is contained in the 2018 report by a team of Russian cosmonauts claiming the recovery of a variety of and rare so-called extremophilic microorganisms from the outside of the International Space Station (ISS) [26]. The ISS orbits the Earth at a height of 400 km effectively precluding the origin of this microbial entity from the Earth. Analysis of all the relevant data in this case seems to confirm that the recovered organisms are exceedingly unlikely to have originated from the surface of the Earth. The presence of bacterial DNA was shown by the method of nested PCR with primers specific to DNA of the genus *Mycobacteria*, DNA of the strains of capsular bacteria *Bacillus*, and DNA encoding 16S ribosomal RNA. The results of amplification followed by sequencing and phylogenetic analysis indicated the presence of the bacteria of the genus *Mycobacteria* and the extreme bacterium of the genus *Delftia* in the samples of cosmic dust. All claims of terrestrial contamination, which are coarsely used, appears to be untenable, thus providing the clearest direct proof thus far of cometary microorganisms entering the Earth's vicinity and splashing on the windows of the ISS [27].

The prevailing philosophy in space science as well as biology is to reject or ignore all the arguments that have been presented over the last half century challenging the standard theory of life's origins in a primordial soup of organic molecules on the Earth. A recent study suggesting that the last universal common ancestor of life on Earth (LUCA) is a diverse microbial community rather than a single microbe adds further to the case for a non-terrestrial origin of life. Moreover, this event of Earth-bound origination is now "inferred" to have occurred 4.2 billion years ago. This is during the Hadean geological epoch when the Earth's impact-riddled surface would have been far too inhospitable for even organic molecules to survive [28].

In present-day biology the information contained in enzymes—the arrangements of 20 biological amino acids into folded chains—plays a crucial role, and this information is transmitted via the coded ordering of nucleotides in DNA. In a hypothetical RNA world that may have predated the DNA-protein world, RNA is posited to serve a dual role as both enzyme and genetic transmitter. If a few ribozymes are regarded as essential precursors to all life, one could attempt to make an estimate of the probability of the assembly of a simple ribozyme which is composed of some 300 bases. This probability turns out to be 1 in 4^{300}, which is equivalent to 1 in 10^{180}—which already defines an event that can hardly be supposed to happen even once in the entire history of the universe. A similar calculation for the ordering of amino acids in a minimal set of bacterial enzymes gives an even more ridiculous probability—1 in 10^{5000} with plausible assumptions [29]. It is such numerical arguments that initially drove Hoyle and N. C. Wickramasinghe [30] to the conclusion that the emergence of life had of necessity to be a cosmic phenomenon, a possibly unique event in the cosmos, which itself may have existed for an infinite length of time if the most recent research is to be taken into account.

2. Conclusions

By the early 1980's N. C. Wickramasinghe, Fred Hoyle and many collaborators had accumulated enough evidence from astronomy to claim that the chemical make-up of cosmic dust judged by the way they absorbed light over near infrared wavelengths in particular was uncannily similar to bacteria and viruses [31]. The fashionable point of view, however, is to assert without any proof that organic chemistry is occurring everywhere, and the resulting chemicals happen perchance to match exactly the spectral behavior of desiccated bacteria! Furthermore, it is maintained against all the odds that terrestrial life originated in a geological instant in situ on the Earth, after organic molecules from space came to be delivered possibly by the agency of comets. The European Space Agency's Rosetta Mission to comet 67P/C-G has provided the most detailed observations that satisfy all the consistency checks for biology and the theory of cometary panspermia [32].

The weight of evidence favors the survival of bacteria under interstellar conditions at any rate to the extent that viable interstellar transfers of microbial life between star systems are inevitable. Even more inevitable would be the transfer of life between bodies in a single planetary system such as our own solar system, over a long-enough timescale, we would expect intermingling between habitable locations to define a connected ecosystem. With new robotic space missions like the Europa Clipper on its way to look for evidence of life in the water-ice plumes emanating from the moons of Jupiter and Saturn, along with newly published constraints [33] on biosignature gases dimethyl sulfide (DMS) and dimethyl disulfide (DMDS) in the atmosphere of exoplanet K2-18 b with high abundance (10 ppmv) while using the James Webb Space Telescope, we live with a new world-view that is fast emerging at the present time and to ignore it or devalue its implications would be irresponsible. In relation to the present context of planetary protection protocols rejection of a vast body of evidence implying the almost certain existence of adapted microorganisms within habitable regions of other solar-system bodies—comets, asteroids, planets including Mars—would be short-sighted and dangerous to say the least. When the entire biosphere hangs in the balance, it is adventuristic to the extreme to bring unknown microbial life or extremely resilient extremophiles to Earth's environment. While there is a chance it would do no harm, that is not the point. Unless we can rule out the chance that it might do harm, we should carefully plan planetary protection protocols in line with such a course.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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