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RESEARCH ARTICLE

Solid grains ejected from terrestrial exoplanets as a probe of the abundance of life in the Milky Way

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Abstract

Searching for extrasolar biosignatures is important to understand life on Earth and its origin. Astronomical observations of exoplanets may find such signatures, but it is difficult and may be impossible to claim unambiguous detection of life by remote sensing of exoplanet atmospheres. Here, another approach is considered: collecting grains ejected by asteroid impacts from exoplanets in the Milky Way and then travelling to the Solar System. The optimal grain size for this purpose is around 1 μm, and though uncertainty is large, about 10^5 such grains are expected to be accreting on Earth every year, which may contain biosignatures of life that existed on their home planets. These grains may be collected by detectors placed in space, or extracted from Antarctic ice or deep-sea sediments, depending on future technological developments.

Contents

Introduction

The abundance of life in the universe is poorly known (Lineweaver and Davis 2002; Spiegel and Turner 2011; Kipping 2020). In the Drake equation (Vakoch and Dowd 2015), the probability f_l of life in any form appearing on a habitable planet may not be of order unity. Instead, it may be so small that Earth is the only planet that harbours life in the observable universe (13.8 billion light-year radius in light travel distance), though many abiogenesis events may have occurred in the total volume of an inflationary universe (Totani 2020). Knowing f_l quantitatively is crucially important to get a hint about the completely unknown processes of abiogenesis, and it can be constrained by searching for extraterrestrial signatures of life. If there is no life of a different origin than ours in the Solar System, we need to search for extrasolar biosignatures, which can be probed by astronomical observations of nearby exoplanet atmospheres (see Kiang *et al.* 2018, for a review). However, any candidate biosignature is likely to be controversial, given that even oxygen (a representative biomarker in exoplanet atmospheres) can be generated abiologically (Meadows *et al.* 2018; Bains and Petkowski

2021; Meadows *et al.* 2022; Smith and Mathis 2022). Search for extra terrestrial intelligence may find unambiguous extrasolar technosignatures, but it is sensitive only to intelligent life, which may be much less abundant than primitive life forms. Thus it is uncertain whether we will obtain an irrefutable constraint on f_l in the future by methods proposed so far. Here, another approach of directly sampling extrasolar biosignatures of primitive life or microbes is considered.

Ejection of rocks and grains from terrestrial planets

Meteorites of Martian origin found on Earth demonstrate that material has been exchanged between planets in the Solar System. These rocks are thought to have been ejected from their home planets by giant impact events of asteroids. The possibility of living microbes on such ejecta migrating to other planets has been discussed in the literature as the panspermia hypothesis (Nicholson 2009, for a review). Rocks ejected from Earth or Mars eventually fall onto planets after $\sim 10^{6-7}$ yrs stay in orbits, but 10–20% of these are ejected from the Solar System by interaction with the giant planets (Gladman 2000; Melosh 2003). This implies the possibility of interstellar transfer of living organisms, but previous studies found negligibly small success probabilities (Melosh 2003; Wallis and Wickramasinghe 2004; Valtonen *et al.* 2008; Adams and Napier 2022). Interstellar panspermia is limited not only by large distances to nearby stars, but also by the survival time of organisms in space ($\sim 10^{5-7}$ yrs, Valtonen *et al.* 2008; Wesson 2010) and the minimum rock size ($\gtrsim 10$ kg, Valtonen *et al.* 2008; Adams and Napier 2022) to protect microbes during the journey.

However, if our purpose is to capture these ejecta particles after travelling to Earth as a search of extrasolar biosignatures, these constraints do not apply[1] . We do not need living organisms, but the existence of life in exoplanets can be probed by remains of microbes, microfossils, minerals produced by biological activities (biominerals), or any other signatures of past biological activities (e.g. concentration of biological molecules or isotopic ratios) (Cavalazzi and Westall 2018). The mineralogical diversity of Earth is larger than Venus or Mars, which is thought to be due to the presence of life (Hazen *et al.* 2008; Cataldi *et al.* 2017). Then smaller rocks or grains are more favourable, because particle flux would be larger and hence a higher detection probability is expected. It is reasonable to consider grains larger than the minimum size of bacteria ($\sim 1\,\mu$m), so that direct biosignatures (remains or microfossils) can be contained.

Typically, the total mass of ejecta in a single meteorite impact is about 10^{-3} of the impactor mass, and total mass ejection rate from a terrestrial planet has been estimated at 10^{4-5} kg/yr in the Solar System for ejecta mass larger than ~ 10 kg (Wallis and Wickramasinghe 2004; Napier 2004; Valtonen *et al.* 2008). It should be noted that these estimates were made for panspermia studies and take into account the conditions under which microorganisms can survive the launch (temperatures $< 100\text{C}^\circ$ and shock pressure $P < 1$ GPa). The estimate is likely to increase for our purpose because the weaker condition (preservation of biosignatures) is sufficient. If we impose only the condition of nonmolten ejecta, the estimate may increase by a factor of 10–60 (Cataldi *et al.* 2017). Here we conservatively present the following calculations based on the 10^{4-5} kg/yr rate. Small ejecta particles may not escape the planet if they are decelerated as they pass through the atmosphere. However, the impact would produce high-velocity vapour and particle plume which blows a hole through the atmosphere, and then small particles may also be ejected (Melosh 1988; Wallis and Wickramasinghe 2004).

Mass/size distribution of ejected rocks or grains, dN/dm (number of ejecta per unit ejecta mass m), is expected to be broad. When rocks on a planet's surface break up by dynamic fragmentation following an impact, fragment mass distribution is $dN/dm \propto m^{-\alpha}$ with $\alpha \sim 2$ (Melosh *et al.* 1992). When a rock is ejected into space, smaller grains or soils can also be pushed out by the rock, whose total mass is comparable to the rock. The mass/size distribution may further be altered by collisions in interplanetary space. Since the collisional disruption time is shorter than 10^{6-7} yrs for grains smaller than 1 cm

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[1] Cataldi *et al.* (2017) considered the possibility of remotely detecting these ejecta bound in their home planetary system by astronomical observations from Earth.

(Leinert *et al.* 1983), they are converted into smaller grains during the typical residence time in interplanetary space. The mass distribution of asteroids is a result of such collisional cascades, and it is also a power-law with $\alpha \sim 2$ (Dermott *et al.* 2001). Therefore, it is reasonable to expect an ejecta supply rate $d\dot{N}/dm$ into interplanetary space to be a power-law with $\alpha \sim 2$. In this case, the total ejecta mass per logarithmic interval of m, $m\, d\dot{N}/d(\ln m) = m^2\, d\dot{N}/dm$ is constant against m. Then, in a wide range of m, the total ejecta mass supply rate is $\sim 10^4$ kg/yr in an interval of $m_l < m < m_u$ with $m_u/m_l = e = 2.718\ldots$, and it would be increased by a factor of at most 10 when a wider mass range (e.g., $m_u/m_l = 10^5$) is considered.

Travels in interplanetary and interstellar space

It is necessary to examine whether micron-sized grains can be ejected from the Solar System, because such small grains are affected by non-gravitational processes in interplanetary space, in contrast to larger bodies (Dermott *et al.* 2001; Koschny *et al.* 2019). Magnetic fields are not important for grains larger than 1 μm, but the Poynting-Robertson (PR) drag time is shorter than the collisional time for grains smaller than 100 μm. Then particles smaller than 1 cm will spiral into the Sun within 10^6 yrs by collisional disruption and subsequent PR drag, but collisions are still effective during the inspiral to produce even smaller micron-sized grains. Solar radiative pressure is greater compared to gravity for smaller grains, and the two forces are comparable at ~ 1 μm size. Grains of this size are then ejected from the Solar System as “beta meteoroids” (Zook and Berg 1975; Dermott *et al.* 2001), and consequently a significant fraction of originally 1–10^4 μm ejecta will eventually escape from the Solar System as micron-sized grains (Leinert *et al.* 1983; Napier 2004; Wesson 2010). In the following, it is assumed that the Solar System is typical among planetary systems in the Milky Way, and grains about 1 μm in diameter ($m \sim 10^{-12}$ g for a spherical grain of density $\sim$3g cm^{-3}) that were originally on a planet’s surface are ejected from a planetary system into interstellar medium (ISM) at a total mass ejection rate of $\dot{M}_{\rm ej} = 10^4$ kg/yr.

Micron-sized grains may be damaged or destroyed during interstellar travel. Conventional theoretical estimates of the lifetime of interstellar dust particles are relatively short ($\sim 0.1 - 1$ Gyr, Jones *et al.* 1997). However, these estimates are highly uncertain, and such short lifetime conflicts with the observed dust abundance and dust production time scales in the Milky Way as well as distant galaxies (Jones and Nuth 2011; Rowlands *et al.* 2014; Ferrara and Peroux 2021). About ten times longer lifetime is then favourable, and some theoretical studies support this possibility (Slavin *et al.* 2015; Marínez-González *et al.* 2019). Furthermore, micron-sized grains considered here are larger than the general interstellar dust grains responsible for the extinction of light from astronomical objects (5–250 nm, Mathis *et al.* 1977; Grün and Landgraf 2000). Such large grains are decoupled from ISM gas and smaller grains, resulting in a longer lifetime (Grün and Landgraf 2000; Frisch and Slavin 2003; Slavin *et al.* 2004; Hirashita *et al.* 2016). Therefore, the interstellar lifetime of micron-sized grains, τ_{is}, could be comparable with the age of the Solar System or the Milky Way ($\tau_{is} \sim$1–10 Gyr), though further studies are necessary for a more quantitative estimate.

Exoplanetary grain flux to Earth

Now we can estimate the interstellar density $\rho_{ej} = \dot{M}_{ej}\, n_* f_{hp}\, \tau_{is}$ of the micron-sized grains ejected from habitable terrestrial planets in the Milky Way, where n_* is the number density of Sun-like stars and f_{hp} is the fraction of stars having a habitable planet. Here, the spatial distribution of the grains is assumed to be the same as that of stars, and the evolution of the Milky Way (e.g., star formation history) is not taken into account, but such a simple treatment is sufficient for this work. Adopting $n_* = 0.03$pc^{-3} (for stars in the solar neighbourhood heavier than $\sim 0.3 M_\odot$, Bovy 2017), $f_{hp} = 0.1$ (Lissauer *et al.* 2014), and $\tau_{is} = 10$ Gyr, ρ_{ej} is found to be 1.0×10^{-41} g cm^{-3}, which is $\sim 10^{14-15}$ times smaller than dust density in typical ISM of a hydrogen number density $n_H \sim 0.3$ cm^{-3} (Grün and Landgraf 2000) and a dust-to-gas mass ratio of 0.01 (Tricco *et al.* 2017). The radial migration of stars in the Milky

Way disk is estimated to be more than 1 kpc for a time scale of a few Gyrs (Frankel *et al.* 2018; Lian *et al.* 2022), and hence the grains observed at one location is a mixture of a considerable fraction of the Galaxy, in contrast to astronomical observations of nearby exoplanets.

The density ρ_{ej} can be converted into particle flux $F_{ej} = \rho_{ej}\,\langle v\rangle/(4\pi m)$ per steradian, where $\langle v\rangle$ is the mean velocity of grains. Motion of micron-sized grains are affected by solar radiation when entering the Solar System, but *in situ* spacecraft measurements indicate that the flux of interstellar dust grains of $m \sim 10^{-12}$ g is not reduced at a distance of about 1 au from the Sun (Grün *et al.* 1997). Then the micron-sized grains from terrestrial exoplanets are accreting on Earth directly from ISM at a rate of $A_\oplus = 4\pi F_{ej}\pi r_\oplus^2 \sim 1.6 \times 10^3$ particles every year, where $r_\oplus$ is the Earth radius. Here, $m = 10^{-12}$ g and $\langle v\rangle = 40$ km/s (for the Maxwell distribution with one-dimensional velocity dispersion $\sigma_v = 25$ km/s, Cox 2013) are adopted, assuming that the grain velocity distribution in ISM is the same as stars in the solar neighbourhood.

The rate $A_\oplus$ may further be increased if we consider gravitational capture of grains by interaction with giant planets in the Solar System. Mainly low-velocity objects are captured and bound to the Solar System by a cross section $\sigma_c\,(v) = \sigma_0\,(v/v_c)^{-2}[1 + (v/v_c)^2]^{-2}$, where $\sigma_0 = 2.32 \times 10^5 \mathrm{au}^2$ and $v_c = 0.42$ km/s (Adams and Napier 2022). A fraction $f_\oplus \sim 10^{-4}$ of the captured objects are expected to hit Earth before they are lost from interplanetary space (Melosh 2003; Adams and Napier 2022). Then the accretion rate $A_\oplus$ is enhanced by a factor of $\eta_c = \langle\sigma_c v\rangle f_\oplus/(\pi r_\oplus^2\langle v\rangle) \sim 10^2$ compared with direct hitting from ISM, and thus $A_\oplus \sim 1.6 \times 10^5\ \eta_{c,2}$ particles per year, where $\eta_{c,2} \equiv \eta_c/10^2$. It should be noted that the estimate of η_c (especially $f_\oplus$) is highly uncertain, which is considering only gravitational interactions. Radiative pressure and the PR drag effect may change this estimate.

These grains from terrestrial exoplanets can be collected by detectors placed in space, utilizing a low-density capture media like silica aerogel that enables capture of hypervelocity particles with mild deceleration and hence minimal damage to biosignatures (Westphal *et al.* 2014; Yamagishi *et al.* 2021). A very large total effective area (hopefully comparable to Earth, or $\sim 10^3$ km^2 to expect one particle detection per year) is necessary to detect these particles, but it may be possible in the future, depending on technological developments and humanity's advance into space. A single large detector is not necessary, but a large number of small and low-cost detectors would be more realistic. Large space telescopes in the next generation cost more than 10 billion USD (NASEM of USA 2021), targeting indirect biosignatures in exoplanet atmospheres. It would be interesting to think about what can be done at the same cost to search for direct biosignatures by collecting grains from exoplanets.

Another collecting method may be to search on Earth for these exoplanet grains. Cosmic dust particles smaller than 10–100 μm survive atmospheric entry without severe heating (Koschny *et al.* 2019), and hence biosignatures are not seriously damaged by the entry process. Such micrometeorites have been collected from Antarctic snow or ice (Yada *et al.* 2004; Rojas *et al.* 2021). The accretion rate $A_\oplus$ estimated above implies that $10^9\ \eta_{c,2}$ grains from exoplanets are embedded in the entire Antarctic ice (1.4×10^7 km^2 area and 2500 m mean depth corresponding to an accumulation time of $\sim 3 \times 10^5$ yr, Kawamura *et al.* 2017), or $10^2\ \eta_{c,2}$ grains in an area of 1 km^2. Cosmic dust particles have also been collected in deep-sea sediments, where low accumulation rates and long exposure times allow extraterrestrial particles to collect in high concentrations (Brownlee 1985). For a typical accumulation rate (2×10^{-6} m/yr), about $10^4\ \eta_{c,2}$ grains from exoplanets can be collected from deep-sea clay of 1 m depth (corresponding to 5×10^5 yr) in a 100 km^2 area. It is worth investigating the best locations and strategies to collect these extremely rare particles on Earth by future technologies.

Uncertainties and issues for future consideration

It is clear that there are large uncertainties (probably a few orders of magnitude or more in total) in the flux estimate of exoplanet dust particles in this work, at various stages of launch from the home planets, escape from the home exoplanetary systems, travel in interstellar space, and capture by the Solar System and by Earth. However, the estimate is large enough to make the future detection of such exoplanetary particles a realistic possibility, and merits further study.

Another important issue not discussed here is whether biosignatures are preserved until the exoplanet particles reach Earth. They may be damaged at various stages, including launches from the home planets, exposure to radiation and cosmic rays in interstellar space, entry to Earth, and weathering in Earth environments. Microbial carcasses would be most vulnerable to damage, while microfossils and biominerals would be more likely to be preserved. It is important to investigate and choose the best biosignatures for this purpose, which should be abundant on terrestrial planets harbouring life and identifiable after a long travel from their home.

Identifying grains of extrasolar origin would not be easy after eliminating the possibility of terrestrial or Solar-System origin. Grains detected directly from interstellar space may be identified by their orbits. Extrasolar particles scattered by giant planets and then bound to the Solar System may be difficult to distinguish from particles ejected from Earth, even if they contain biosignatures. Long residence times in interstellar space inferred from cosmic ray and radiation exposure would be useful, because grains ejected from Earth would be lost in $\sim 10^7$ yrs like interplanetary dust particles. Identification would be even more difficult for particles collected on Earth. Extraordinary biosignatures that are quite different from known Earth life, as well as anomalous isotope ratios and/or mineralogical compositions, are expected to be helpful in identifying biosignatures of extrasolar particles. Finding even just one such particle would have an immense impact on the origin of life studies.

More quantitative considerations are beyond the scope of this paper and require experimental studies by experts in various fields. Given the possibility of getting biosignatures in direct samples from exoplanets, further research in this direction is recommended.

Conflict of interest. None.

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