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Chaotic exchange of solid material between planetary systems: implications for lithopanspermia

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Abstract

We examine a low energy mechanism for the transfer of meteoroids between two planetary systems embedded in a star cluster using quasi-parabolic orbits of minimal energy. Our study addresses whether life on Earth could have been transferred to other planetary systems in the solar system's birth cluster and vice versa. We conclude that lithopanspermia is an open possibility if life had an early start. (Detailed discussion in Belbruno et al. 2012, Astrobiology, in press).

1. Introduction

The probability of transfer between the stars in the solar local neighborhood is extremely low because of the high relative velocities of the stars and the low stellar densities [1]. However, the majority of stars are born in stellar clusters with larger stellar densities and smaller relative velocities, increasing the transfer probabilities [2]. We explore a very low energy mechanism first described by [3] in the mathematical context of a class of nearly parabolic trajectories in the restricted three-body problem. The escape velocities of these parabolic-type trajectories are very low ($\sim$ 0.1 km/s), substantially smaller than the mean relative velocity of stars in the cluster, and the meteoroid weakly escapes the planetary system (after it passes near the largest planet in the system) by slowly meandering away. Weak capture is the reverse process. Weak transfer takes places between two "chaotic layers" around each star, created by the gravitational perturbations from the most massive planet in the planetary system and from the rest of the cluster stars.

2. Results

Using Monte Carlo simulations we estimate the transfer probability. We adopt the average cluster properties inferred for the Solar birth cluster [4], with N = 4300 members, a total mass of 3784 $M_\odot$ and a cluster scale length of 3.78 pc, with an expected lifetime of 322.5 Myr (ranging from 135–535 Myr, for N = 1000–10000). We sample 5 million trajectories finding the following transfer probabilities: $1.5{\cdot}10^{-3}$ (for transfers from 1 $M_\odot \rightarrow$ 1 $M_\odot$), $0.5{\cdot}10^{-3}$ (1 $M_\odot \rightarrow$ 0.5$M_\odot$) and $1.2{\cdot}10^{-3}$ (0.5 $M_\odot \rightarrow$ 1$M_\odot$) (for comparison, [2] found capture probabilities of $\sim 10^{-6}$ for mean ejection speeds of $\sim$ 5 km/s, typical of hyperbolic ejecta of the solar system).

Adopting parameters from the minimum mass solar nebula [5], considering a range of planetesimal size distributions derived from observations of asteroids and KBOs and theoretical coagulation models [6,7,8], and taking into account the results from Oort Cloud formation models [9] for the fraction of planetesimals that are subject to weak escape from the early solar system, we estimated the number of meteoroids that may have been delivered to the weak stability boundary of the solar system over the lifetime of the Sun's birth cluster. Using this number and the probability of the weak capture of meteoroids on weakly escaping orbits, we calculated the number of weak transfer events from the early solar system to the nearest star in the cluster, assuming it is a solar-type and harbors a planetary system. This number depends strongly on the adopted planetesimal size distribution. We find that, for the cases where the power law size distribution at the small sizes ($dN/dD \propto D^{-q_2}$ for $D < D_0$) has index $q_2 = 3.5$, the expected number of weak transfer events between two solar type stars is of the order of 10^{14}–$3{\cdot}10^{16}$; for a shallow size distribution ($q_2 = 1.1$) the number is of the order of 10^4. We conclude that solid material could have been transferred in significant quantity from the solar system to other solar-type stars in its birth cluster via the weak transfer mechanism described here.

We now discuss how much material originating from the Earth's crust may have been available for weak transfer. We assume that as a consequence of the heavy bombardment that took place before the cluster dispersed, l km of the Earth surface was ejected, with a total mass of $M_{\rm B} \sim 3 \cdot 10^{24} \cdot l({\rm km})$ g. Adopting a power-law distribution, $dN/dm \propto m^{-\alpha}$, with α = 5/3, m_1 = 10 kg and $m_2 = 10^{-9}$ $M_\oplus$ (corresponding to objects 10 km in size), this total mass would be distributed in $\sim 2 \cdot 10^{15} \cdot l({\rm km})$ bodies. A significant fraction of these fragments would have been ejected on hyperbolic orbits, i.e. beyond the domain of weak escape. To estimate how many of these bodies may have populated the weak stability boundary, we use the Oort Cloud formation efficiency of $\sim 1\%$ [9], resulting in $\sim 2 \cdot 10^{13} \cdot l({\rm km})$ bodies with a terrestrial origin that may have been subject to weak escape. Assuming only 1% of the ejected Earth material remained weakly shocked (allowing microorganisms to survive), we get that $\sim 2 \cdot 10^{11} \cdot l({\rm km})$ life-bearing rocks with an Earth origin may have been subject to weak escape. Using the weak capture probability derived above, $1.5 \cdot 10^{-3}$, we estimate that the total number of lithopanspermia events between the Earth and the nearest solar-type star in the cluster may have been of the order of $3 \cdot 10^{8} \cdot l({\rm km})$, where l is the depth of the Earth's crust in km that was ejected.

We now discuss the time constrains focussing on two key aspects: (a) whether there is evidence that life may have arisen on Earth before the cluster dispersed, and (b) the survival of life to the hazards of outer space during the timescales relevant to weak transfer. Regarding the first issue, the high oxygen isotope ratio, $^{18}O/^{16}O$, of detrital zircons suggests that liquid water was circulating in the upper crust of the Earth when the solar system was only 288 Myr old [10] or even 164 Myr old [11], indicating that habitable conditions may have allowed life to emerge during this period. In this case the "window of opportunity" for life-bearing rocks to be transferred to another planetary system in the cluster opens by the time liquid water was available and ends by the cluster dispersal time, $T_{\rm cluster} \sim$ 135–535 Myr [4]. Within this timeframe, there was a mechanism that allowed large quantities of rocks to be ejected from the Earth: the ejection of material resulting from the impacts at Earth during the heavy bombardment of the inner solar system, that ended when the solar system was approximately 770 Myr old. The second time constrain is the survival of microorganisms to the hazards of radiation during their long journey in outer space. [12] used a computer model to account for the effects of Galactic cosmic rays and for the effects of natural radioactivity in meteorites characteristic of Earth and Mars, finding maximum survival times that range from about 12–15 Myr (for sizes of $<$ 0.03 m) to 400–500 Myr (for sizes 2.33–2.67 m). These need to be compared to the transfer timescales associated with the weak transfer mechanism, of the order of tens of millions of years, implying that the survival of microorganisms could be viable via meteorites exceeding $\sim$ 1 m in size.

The discussion above assesses the possibility that life on Earth could have been transferred to other planetary systems when the Sun was still embedded in its stellar birth cluster. But could life on Earth have originated beyond the boundaries of our solar system? Our results indicate that, from the point of view of dynamical transport efficiency, life-bearing extra-solar planetesimals could have been delivered to the solar system via the weak transfer mechanism if life had a sufficiently early start in other planetary systems, before the solar maternal cluster dispersed. An early microbial biosphere, if it existed, likely survived the LHB. Thus, both possibilities remain open: that life was "seeded" on Earth by extra-solar planetesimals or that terrestrial life was transported to other star systems, via dynamical transport of meteorites.

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