Research Paper

Lithopanspermia in Star-Forming Clusters

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ABSTRACT

This paper considers the lithopanspermia hypothesis in star-forming groups and clusters, where the chances of biological material spreading from one solar system to another is greatly enhanced (relative to action in the field) because of the close proximity of the systems and lower relative velocities. These effects more than compensate for the reduced time spent in such crowded environments. This paper uses ~300,000 Monte Carlo scattering calculations to determine the cross sections $\langle \sigma_{cap} \rangle$ for rocks to be captured by binaries and provides fitting formulae for other applications. We assess the odds of transfer as a function of the ejection speed v_{eject} and number N_* of members in the birth aggregate. The odds of any given ejected meteoroid being recaptured by another solar system are relatively low, about $1:10^3$–10^6 over the expected range of ejection speeds and cluster sizes. Because the number of ejected rocks (with mass $m > 10$ kg) per system can be large, $N_R \sim 10^{16}$, virtually all solar systems are likely to share rocky ejecta with all of the other solar systems in their birth cluster. The number of ejected rocks that carry living microorganisms is much smaller and less certain, but we estimate that $N_B \sim 10^7$ rocks can be ejected from a biologically active solar system. For typical birth environments, the capture of life-bearing rocks is expected to occur $N_{bio} \approx 10$–16,000 times (per cluster), depending on the ejection speeds. Only a small fraction ($f_{imp} \sim 10^{-4}$) of the captured rocks impact the surfaces of terrestrial planets, so that $N_{lps} \approx 10^{-3}$–1.6 lithopanspermia events are expected per cluster (under favorable conditions). Finally, we discuss the question of internal versus external seeding of clusters and the possibility of Earth seeding young clusters over its biologically active lifetime. Key Words: Panspermia—Origin of life—Interstellar meteorites. Astrobiology 5, 497–514.

INTRODUCTION

THE QUESTION OF WHETHER LIFE can be spread from one solar system to another is of long standing interest to astrobiology. Previous estimates (*e.g.*, Melosh, 2003) have suggested that the odds of both meteoroid and biological transfer

are exceedingly low. However, such estimates have been determined for the conditions in the local galactic neighborhood, *i.e.*, in the field. The odds of transfer increase in more crowded environments. Although the vast majority of stars currently reside in the field, most stars form within small groups or clusters, rather than in isolation

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(*e.g.*, Lada and Lada, 2003; Porras *et al.*, 2003; see also Adams and Myers, 2001). Since the time scale for planet formation and the time that young stars are expected to live in their birth clusters are roughly comparable, about 10–30 million years (Myr), debris from planet formation has a good chance of being transferred from one solar system to another. A related question is whether biologically active material can be transferred from one system to another. Because of the destructive effects of ultraviolet (UV) radiation, and other hardships of deep space, current thinking suggests that biological material must be encased in rock in order to survive the transfer process. The required rock mass is often taken to be $m > 10$ kg (Horneck, 1993; Nicholson *et al.*, 2000; Benardini *et al.*, 2003; Melosh, 2003), though better transfer odds can be obtained if this mass is smaller (Napier, 2004). As a result of the required UV shielding, this mechanism is generally called lithopanspermia. Suppose that life can be seeded into one solar system in a young cluster, by way of either direct biogenesis or a chance encounter with bio-invested material from outside the birth aggregate. Subsequent dynamical interactions among the constituent solar systems can then allow life to spread throughout the birth cluster. The goal of this work is to estimate the likelihood of such transfer.

The transfer of rocks between planets within a solar system is a well-established phenomenon. Researchers on Earth regularly find and study martian meteorites (McSween, 1985), and the dynamics of such transfer have been well studied (*e.g.*, Gladman, 1997; Dones *et al.*, 1999; Mileikowsky *et al.*, 2000). The transfer of rocky material between solar systems is more difficult but should still take place. The exchange of life-bearing meteorites between solar systems is unlikely to occur between field stars (Melosh, 2003) because of the high relative velocities and low stellar density. As we show here, however, in young stellar groups and clusters, where most stars form, the stellar densities are higher, and the relative velocities are lower. These properties increase the odds of transfer. Furthermore, previous estimates of capture cross sections have focused on single stars; most stars live in binary systems, and the capture cross sections for binaries are greatly enhanced.

In this paper, we present a comprehensive evaluation of the lithopanspermia mechanism in star-forming groups and clusters. We first perform a series of numerical calculations to estimate the distributions of ejection speeds for rocks exiled from their solar systems and discuss the distribution of rock sizes and masses. We next consider the dynamics of young groups and clusters, and estimate the optical depth for ejected rocks to be recaptured by other solar systems. To make such estimates, we calculate the capture cross sections using a Monte Carlo technique and a large ensemble (~300,000) of numerical experiments to sample the parameter space. Putting all of these components together, we estimate the expected number of rocks to be recaptured, the expected number of life-bearing rocks to be transferred, and finally the expected number of successful lithopanspermia events (per cluster). Note that clusters are not guaranteed to have any of their member solar systems develop life during the 10–100 Myr that they remain bound. As a result, this paper calculates the odds of lithopanspermia events only for those clusters that produce at least one living system.

LITHOPANSPERMIA IN GROUPS AND CLUSTERS

Ejection of rocky bodies from a solar system

One can think of each solar system in the cluster as a source of rocky debris. In other words, each solar system produces a mass outflow rate of rocky material. Our present solar system contains about 50 Earth masses ($M_{\oplus}$) of rocky bodies, with most of the mass residing in the cores of the Jovian planets. The early solar nebula contained 50–100 $M_{\oplus}$ of heavy elements. Here, we parameterize the heavy element content M_Z of nascent solar systems as

$$M_Z = F_0 M_{\oplus} \qquad (1)$$

where we expect $F_0 = 50$–200 for typical systems.

Since planets form within solar systems on time scales of roughly $t_p = 10$ Myr (Lissauer, 1993), and since some fraction f_e of the rocky material will be ejected during the course of planet formation and subsequent dynamical evolution of the system, the mean mass loss rate (in rocks) from a young solar system is given by

$$\left\langle \frac{dM}{dt} \right\rangle = \frac{f_e F_0 M_{\oplus}}{t_p} \qquad (2)$$

Numerical studies (Dones *et al.*, 1999; see also Melosh, 2003) suggest that about one-third of the

material not locked up in planets will be ejected from a given solar system containing giant planets (such as Jupiter and Saturn). Since planet formation is unlikely to be 100% efficient, we might expect one-third of the initial material to be left over, and one-third of that to be ejected (with a good fraction of the remainder accreted by the central star), so that $f_e \approx 1/10$. Since the times scales for planet formation are roughly the same as the lifetimes for small stellar clusters (Binney and Tremaine, 1987), this process has time to grind towards completion while the cluster remains intact, and hence each solar system contributes a mass $M_R = f_e F_0 M_\oplus$ of rocky material to its birth aggregate. A conservative benchmark value for this mass scale is thus $M_R \approx M_\oplus$, with a corresponding mass loss rate of $\langle dM/dt \rangle \approx 10^{-7}$ $M_\oplus$ year$^{-1} \approx 2 \times 10^{13}$ g s^{-1}. This mass loss rate may seem large. For comparison, the mass equivalent loss due to solar radiation escaping from our solar system is $\dot{m} = L_\odot/c^2 \approx 4 \times 10^{12}$ g s^{-1}, only about five times smaller.

The speeds of rocks ejected from a solar system depend on their initial location (the depth of the stellar gravitational potential well) and the mass of the scattering body (the depth of its gravitational potential well). When biologically active rocks are removed from the surface of their parent planet through impacts, they can either be directly ejected from the solar system or left in orbit (about the central star) where they are subsequently ejected by other solar system bodies. As representative examples of this latter process, we have performed three ensembles of scattering calculations to sample the possible ejection speeds. In these three-body experiments, a small rocky body and a companion (either a giant planet or star) are placed in orbits about a primary star with mass $M_* = 1.0\ M_\odot$. The companion is taken to have a moderately eccentric orbit, whereas the rocks are given initial semi-major axes and eccentricities so that the orbits bring the bodies near each other (sometimes orbit-crossing). Specifically, the rocks have eccentricities randomly drawn from the interval [0,0.5] and semi-major axes $a = \zeta a_C$, where a_C is the semi-major axis of the companion and ζ is a log-random variable selected from the range $\log_{10} \zeta \in [-1,1]$. The simulations are co-planar and are integrated using a Bulirsch–Stoer scheme.

The resulting distributions of ejection speeds are shown in Fig. 1 for three representative cases: a Jupiter-like planet (with the mass of Jupiter and semi-major axis $a_C = 5$ AU), a Neptune-like planet (with the mass of Neptune and $a_C = 30$ AU), and a 0.1 $M_\odot$ binary companion with $a_C = 42$ AU (near the peak of the binary period distribution). The distribution of ejection speeds is similar for the two planetary cases, with median values $v_{eject} = 5.4$ km s^{-1} (5.8 km s^{-1}) and mean values $\langle v_{eject} \rangle = 6.2 \pm 2.7$ km s^{-1} (6.1 $\pm$ 1.3 km s^{-1}) for giant planet analogs of Jupiter (Neptune). These results are in good agreement with previous work that found ejection speeds of $v_{eject} \approx 5 \pm 3$ km s^{-1} for rocky bodies scattering out of a solar system because of perturbations from Jupiter (Melosh, 2003). The distribution of ejection speeds for the stellar companion has a somewhat smaller median ($v_{eject} = 4.8$ km s^{-1}) and mean ($\langle v_{eject} \rangle = 5.0 \pm 2.5$ km s^{-1}) values; more significantly, the distribution is wider and has substantial support at smaller ejection speeds. Additional simulations (not shown here) indicate that rocky ejecta from solar systems with smaller primaries will generally have lower ejection speeds. We note that solar systems can have a wide variety of architectures (*e.g.*, Levison *et al.*, 1998; Levison and Agnor, 2003), including planetary systems encircled by binary companions (*e.g.*, David *et al.*, 2003), so that an even wider distribution of ejection speeds remains possible.

Distribution of rock sizes and masses

For a given mass in rocky material, we need to specify its mass distribution. The distribution of interplanetary bodies has been discussed previously, and the differential mass distribution generally takes a power-law form:

$$\frac{dN}{dm} = Bm^{-\alpha} \qquad (3)$$

where B is the normalization constant. The slope α has a canonical value of about 1.83 for systems dominated by collisions (see, *e.g.*, Hughes and Daniels, 1982; Napier, 2001) and about 1.67 for rocks hitting the atmosphere of Earth (Schroeder, 1991). We assume here that the distribution of rocky bodies in a forming solar system has this general form, although the normalization (which sets the total mass in rocky material) can vary from system to system. The distribution can be normalized by requiring a fixed total mass M_R in rocky bodies, *i.e.*,

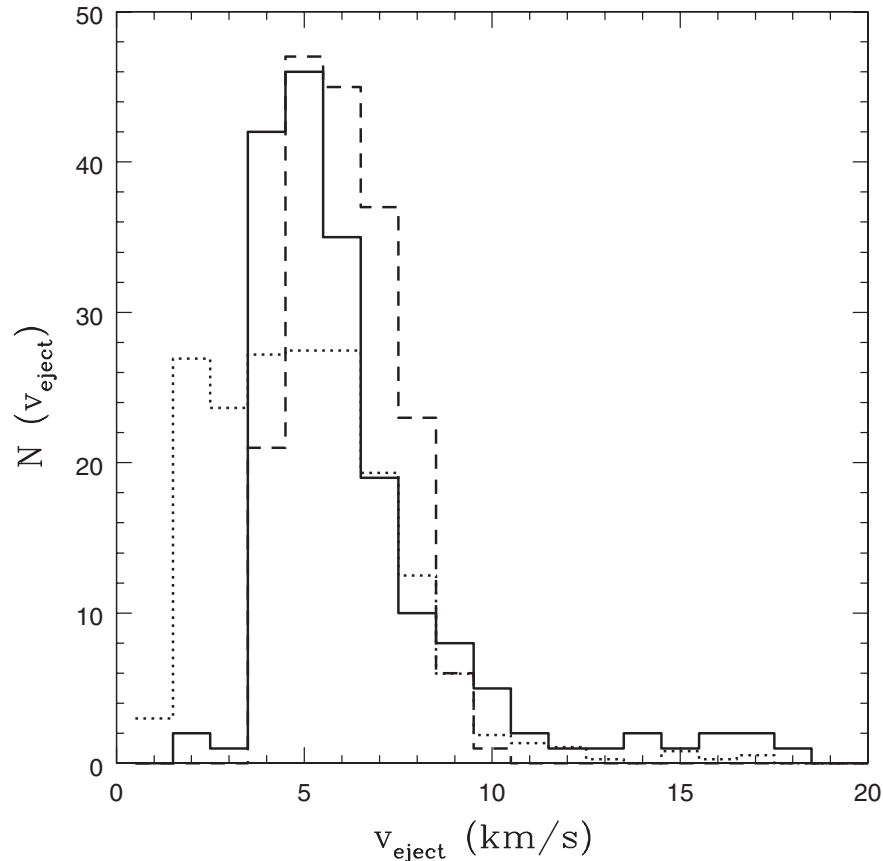$$M_R = B \int dm\ m^{-(\alpha-1)} \qquad (4)$$

FIG. 1. Ejection speeds for rocky bodies removed from a solar system. The solid curve shows the distribution of ejection speeds for rocky bodies on Jupiter-crossing orbits. The dashed curve shows the corresponding distribution of ejection speeds for rocky bodies on Neptune-crossing orbits. The dotted curve shows the distribution of ejection speeds for a stellar companion with mass $M_* = 0.1\ M_\odot$ and with semi-major axis $a = 42$ AU (near the peak of the binary period distribution). All three distributions of ejection speed shown here have the same normalization.

To keep the integral from diverging, we introduce an upper mass cutoff m_2 and thereby obtain

$$B = (2 - \alpha)M_R m_2^{-(2-\alpha)} \tag{5}$$

Similarly, to keep the number of rocky bodies from diverging, we must impose a lower mass cutoff m_1. For distributions of this type, namely with indices in the range $1 < \alpha < 2$, essentially all of the mass resides in the upper end of the range, whereas all of the rocky bodies, by number, reside in the lower end of the range. In this setting, we are only interested in bodies larger than the minimum size/mass required to shield biological material. This lower mass limit m_1 is often taken to be 10 kg (Melosh, 2003), though alternate values have been suggested (Napier, 2004). For given values of the upper and lower mass scales, the total number N_R of bodies with mass $m > m_1$ thus becomes

$$N_R = \frac{2 - \alpha}{\alpha - 1} \frac{M_R}{m_1^{(\alpha-1)}\ m_2^{(2-\alpha)}} \tag{6}$$

For one set of typical values—$\alpha = 5/3$, $m_1 = 10$ kg, $m_2 = 0.1\ M_\oplus$, and $M_R = M_\oplus$ (Melosh, 2003)—the total number of rocky bodies becomes $N_R \approx 10^{16}$. For an alternate set of values—$\alpha = 11/6$ and $m_1 = 10^4$ kg (Napier, 2004)—we obtain $N_R \approx 8 \times 10^{16}$.

Life-bearing rocks

Only some fraction of the material ejected from the solar system will be biologically active (seeded with spores or other biological material). We denote this fraction as f_B, so that the total amount (per system) of biologically active material is $f_B N_R$. Although the fraction f_B is not well determined, it is significant that many bacteria—those known as extremophiles—are well suited

to survival in harsh conditions. In particular, the bacterium *Deinococcus radiodurans* seems almost designed for space travel—it can withstand extreme doses of radiation, cold, and oxidation damage, and can survive for long periods without water (*e.g.*, Minton, 1994; Battista, 1997; White *et al.*, 1999).

Previous papers have estimated the minimum mass m_B required for biologically active material to survive in deep space and found that $m_B \approx 10$ kg (Horneck, 1993; Nicholson *et al.*, 2000); this value motivates our choice of lower mass cutoff $m_1 = m_B$. As a result, the maximum number of biologically active units that could be provided by a single solar system would be N_R if all the rocks were biologically active. As discussed above, N_R is $\sim 10^{16}$, although this number is uncertain and varies from system to system. Nonetheless, this value provides a good starting point.

Unfortunately, the effectiveness of panspermia depends sensitively on the lower mass limit m_B for life to survive in rocks. If the mass scale is much lower (*e.g.*, Napier, 2004), then the steep distribution function (Eq. 3) implies an enormous increase in the number of available missiles. On the other hand, life-bearing rocks that are captured by other solar systems and land on terrestrial planets are subject to another peril: The microorganisms must survive the landing. Small rocks burn up in the atmosphere and/or reach temperatures too high for life to survive. Larger rocks will make it through the atmosphere and can have interior temperatures low enough for life to survive, but such large rocks tend to have violent impacts with the planetary surface. These impacts can also heat up the rocks and cause the destruction of biological material contained within. Some data on this issue exist: The observed mass distributions of meteorites on the Antarctic ice (Huss, 1990) do not flatten out for masses greater than about 100 g, which implies that the meteoroids larger than 100 g have a good chance of surviving their fall through the atmosphere. The 10-kg rocks considered here should thus be safe (see also Wells *et al.*, 2003). Microorganisms in larger rocks have an even greater chance of survival. Meter-sized bodies reach modest terminal speeds (for an atmosphere of terrestrial density), and experimental data indicate that bacteria can survive the landing (*e.g.*, Burchell *et al.*, 2001, 2004; Mastrapa *et al.*, 2001).

We also need an estimate of the fraction f_B of ejected rocks that carry biological material. Suppose, for example, that life is seeded on a large terrestrial planet in the system. It is reasonable to suppose that life would quickly spread over the surface and into the planet down to depth ℓ of a few kilometers. As an optimistic benchmark scenario, we can assume that the mass $3(\ell/R_E)M_\oplus \sim 10^{-3}M_\oplus$ is biologically active and blasted away from the surface by the intense early bombardment phase of that solar system. If this mass is broken up into $m_B = 10$-kg pieces, then the number of life-bearing rocks would be $N_B \sim 10^{20}$. However, it would be more likely for the mass to be broken up into a range of sizes, *e.g.*, distributed according to the considerations of the previous section. In this case, the number of biologically active rocks would be $N_B \approx 1.5(\ell/R_E)M_\oplus/(m_1{}^2m_2)^{1/3} \sim 10^{13}$.

The number of biologically active rocks has been estimated previously (*e.g.*, Melosh, 2003; Wallis and Wickramasinghe, 2004). As another benchmark, Melosh (2003) has estimated that about 15 rocks per year (above the minimum mass m_B) should be ejected from the surfaces of terrestrial planets because of impacts (see also Melosh and Tonks, 1994; for a more detailed discussion of boulder ejection, see Wallis and Wickramasinghe, 2004.) Over the time scale of 10 Myr considered here, a terrestrial planet with life would contribute $N_B \sim 10^7$ life-bearing rocks. Taken together, these considerations suggest that the number of life-bearing rocks lies in the range $N_B = 10^7$–10^{14}, with the lower end of the range being strongly favored. We take $N_B = 10^7$ as our standard value for the remainder of this paper. Notice, however, that a smaller minimum mass m_B (for biological protection) implies a larger number of rocks N_R and a larger number of life-bearing rocks N_B. Since both values scale proportional to $m_B{}^{-2/3}$, if m_B were as small as 142 g (the mass of a baseball), then the number of life-bearing rocks would be larger by a factor of ~ 17. On the other hand, during the late heavy bombardment of Earth, large impacts may have led to a sterilization of the planet, at least on the surface. As a result, the number of biologically active rocks could be much smaller than the numbers quoted above.

Dynamical scattering interactions in groups and clusters

Stars—and hence solar systems—form in groups and clusters with a range of sizes, but a

large fraction are born in stellar aggregates within the size range $N_* = 100$–$1{,}000$. A cluster with N_* members has a typical radius of $R = R(N_*) = 1$ pc $(N_*/100)^{1/2}$, where this formula follows from a fit to the data presented in Lada and Lada (2003) and Carpenter (2000). The average starting number density n_{*0} of solar systems in the birth cluster is given by

$$n_{*0} = \frac{N_*}{4(\pi/3)R^3} \approx \frac{750 \text{ pc}^{-3}}{\pi N_*^{1/2}} \qquad (7)$$

The effective "scattering optical depth" τ for interactions between a passing body and a member of the cluster is given by the integral

$$\tau = \int n_*\langle\sigma\rangle v\,dt \qquad (8)$$

where $\langle\sigma\rangle$ is the cross section for interaction—in this case, the cross section for a solar system to capture a passing piece of rock.

The scattering optical depth depends on the speeds at which rocks are ejected from their solar systems. For ejection speeds less than (or comparable to) the velocity dispersion of the cluster, the rocks are dynamically bound and will orbit within the gravitational potential well of the cluster for many crossing times. In the opposite limit, high-speed rocks only experience a single crossing time before passing out of the cluster. As shown in *Ejection of rocky bodies from a solar system*, rocky bodies scattered by Jupiter and Neptune are expected to have ejection speeds $v_{\rm eject} \approx 3$–9 km s^{-1}, somewhat larger than the typical velocity dispersion $v_{\rm cls} \approx 1$ km s^{-1} for a small cluster. As a result, many of the rocks will reside in the high-speed regime with $v \sim 5$ km s^{-1}. Because the solar systems themselves are moving with relative speeds $v \approx v_{\rm cls} \sim 1$ km s^{-1}, and because the scattering optical depth is a decreasing function of v, using the velocity scale $v_{\rm cls}$ results in the largest possible scattering optical depth τ, *i.e.*, an upper limit on the efficacy of transfer.

For rocks that are bound to the cluster, we can "evaluate" the optical depth integral by writing it in the form

$$\tau = F_R n_{*0}\,v_0 t_{R0}\langle\sigma\rangle \qquad (9)$$

where the subscript "0" refers to the values at the beginning of the cluster's life. The time scale t_{R0} is the initial value of the dynamical relaxation time. The total effective lifetime of the cluster is then given by the time scale $F_R t_{R0}$. Dynamical

studies (see Binney and Tremaine, 1987) indicate that clusters have total lifetimes of 50–100 times the initial relaxation times. During this time, however, the number density n_* and typical speeds v of the solar systems decrease substantially. We thus need to take lifetime factor F_R to be somewhat smaller, $F_R \approx 10$. The starting relaxation time is given by

$$t_{R0} = \frac{R}{v_0}\,\frac{N_*}{10 \log N_*} \qquad (10)$$

and the effective optical depth of interaction becomes

$$\tau \approx \frac{3F_R N_*^2\langle\sigma\rangle}{40\pi R^2 \log N_*} \approx 24\frac{N_*}{\log N_*}\,\frac{\langle\sigma\rangle}{(1 \text{ pc})^2} \qquad (11)$$

This quantity will generally be less than unity, and thus represents the probability that a given piece of rock will be captured by some solar system in the cluster, during the time interval for which the cluster remains intact.

A related quantity is the optical depth of interaction $\tilde{\tau}$ for a given solar system to capture any piece of rock from an alien solar system. This second optical depth is given by the same integral form

$$\tilde{\tau} = \int n_{\rm rock}\,\langle\sigma\rangle v\,dt \qquad (12)$$

where $n_{\rm rock}$ is the number density of rocky bodies that the solar system encounters. The remaining quantities are the same as before (Eq. 9). In this case, we assume that each solar system ejects (on average) a given number N_R of rocks, and that the velocity distribution of these rocky bodies follows that of the stars (which should be the case for low-speed ejections since both populations are living in the same gravitational potential well). As a result, one expects that $n_{\rm rock} \approx (N_R/N_*)n_*$ and hence $N_*\tilde{\tau} = N_R\tau$, where this latter quantity is the expected number of capture events for the entire group/cluster.

For rocks with higher initial velocities, the total path length sampled by a passing rock is on the order of one crossing length, *i.e.*, $\int v\,dt \approx R$. The scattering optical depth is thus given by

$$\tau = n_*\langle\sigma\rangle R = \frac{3N_*\langle\sigma\rangle}{4\pi R^2} \approx 24\,\frac{\langle\sigma\rangle}{(1 \text{ pc})^2} \qquad (13)$$

Because of the manner in which the cluster sizes R scale with stellar membership N_*, the scattering optical depth τ is nearly independent of the cluster richness. This optical depth in the high-

speed limit is smaller than that of the low-speed limit by a factor of $N_*/\log N_*$ and also has a smaller cross section (which is a sharply decreasing function of v_{eject}—see the following section).

Interaction cross sections

The optical depths for interactions derived above can be applied to a wide variety of events provided that the cross section for the event is known. In this context, we are interested in two separate but related issues: the capture of passing rocky bodies by other solar systems (which are mostly binaries), as well as the possibility that the rocky body strikes the surface of a terrestrial planet. The cross section for this process can thus be written in the form

$$\langle \sigma \rangle = \langle \sigma_{\text{cap}} \rangle f_{\text{imp}} \quad (14)$$

where $\langle \sigma_{\text{cap}} \rangle$ is the capture cross section and f_{imp} is the fraction of captured rocks that strike the surface of a terrestrial planet in the system.

We have calculated the capture cross sections $\langle \sigma_{\text{cap}} \rangle$ using a scattering code developed previously (Laughlin and Adams, 2000; Adams and Laughlin, 2001) to study the dynamics of solar systems interacting with binaries [most star systems are binary (see Abt, 1983)]. In this context, we perform a series of calculations to study the capture of rocky bodies by binary star systems. Individual encounters are treated as three-body problems in which the equations of motion are integrated using a Bulirsch–Stoer scheme. We separate out the semi-major axis of the binary from the other variables (see below) and write the capture cross section $\langle \sigma_{\text{cap}} \rangle$ in terms of the integral

$$\langle \sigma_{\text{cap}} \rangle \equiv \int_0^\infty f_{\text{cap}}(a)(4\pi a^2)p(a)\, da \quad (15)$$

where a is the semi-major axis of the binary orbit and $p(a)$ is the distribution of a [determined from the observed distribution of binary periods (see Kroupa, 1995)]. This treatment includes only those interactions within the predetermined area $4\pi a^2$ (more distant encounters are neglected because they have little effect). The function $f_{\text{cap}}(a)$ represents the fraction of encounters that result in capture.

Dynamical encounters between a given rock and a field binary are described by 10 input pa-rameters (see Laughlin and Adams, 2000). These variables include the binary semi-major axis a, the stellar masses m_{*1} and m_{*2}, the eccentricity ε_{b} and the initial phase angle ℓ_{b} of the binary orbit, the asymptotic velocity v_∞ of the rock relative to the center of mass, the angles θ, ψ, and ϕ (which describe the impact direction and orientation), and finally the impact parameter h of the encounter.

To compute the fraction of captures $f_{\text{cap}}(a)$ and the corresponding cross sections, we perform a large number of numerical experiments using a Monte Carlo scheme to select the input parameters. The binary eccentricities are sampled from the observed distribution (Duquennoy and Mayor, 1991). Masses of the two binary components are drawn separately from an initial mass function consistent with the observed initial mass function (in particular, the form advocated by Adams and Fatuzzo, 1996). The impact parameters h are chosen randomly within a circle of radius $2a$ centered on the binary center of mass. The impact velocities at infinite separation v_∞ are sampled from a Maxwellian distribution with a given dispersion σ_v. Here, we calculate the cross sections as a function of the dispersion σ_v. For low ejection speeds, the rocks are bound to the cluster, and the relevant velocity dispersion is determined by the gravity of the cluster ($\sigma_{\text{c}} \approx v_{\text{cls}} \approx 1$ km s^{-1}). For higher ejection speeds, the rocks are not necessarily bound, and the relevant velocity dispersion is given by the dynamics of the ejection process (see Fig. 1).

Using the methodology described above, we have performed approximately 300,000 numerical experiments to sample the parameter space. The resulting cross sections are shown in Fig. 2 as a function of the velocity dispersion σ_v. Figure 2 also presents a fit to the cross sections, where the fitting function has the form

$$\langle \sigma_{\text{cap}} \rangle = (51{,}900 \text{ AU}^2)\, v_{\text{kms}}^{-1.79} \\ \exp[-0.235(\ln v_{\text{kms}})^2] \quad (16)$$

where v_{kms} is the velocity dispersion in units of km s^{-1}.

The capture cross sections calculated here are much greater than those used in the previous study of Melosh (2003) for two reasons: (1) Most stars reside in binary systems, and binarity increases the interaction cross sections. The work of Melosh (2003) used a Jupiter-mass companion, although the cross sections increase with companion mass; an extrapolation of those results
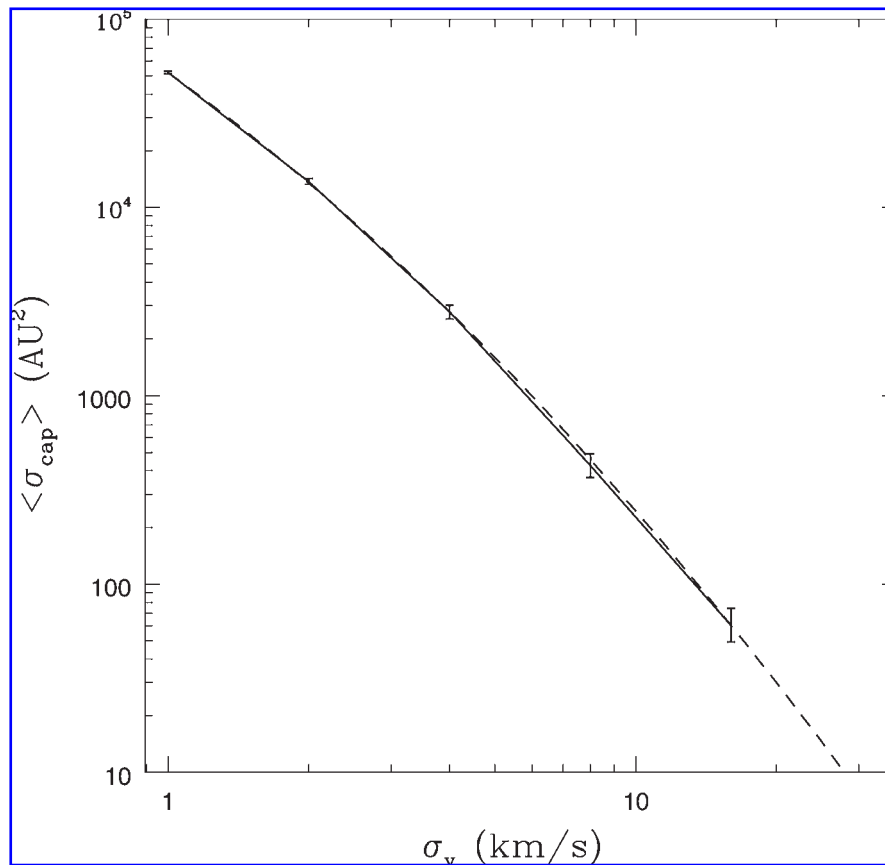
FIG. 2. Capture cross section for rocks interacting with binary star systems. The cross section $\langle \sigma_{cap} \rangle$ is shown as a function of the velocity dispersion σ_v. Typical star-forming groups and clusters have $\sigma_v \approx 1$ km s^{-1}, corresponding to the left end of the curve; stars in the field have $\sigma_v \approx 20$–40 km s^{-1}, corresponding to the right side of the curve. Rocks that are scattered out of solar systems display a range of ejection speeds (roughly spanning the range shown here), depending on the location in their solar system from which they are ejected. The solid curve shows the result of our numerical simulations; the error bars depict the 1 SD errors resulting from the Monte Carlo scheme used to sample the input parameter space. The dashed curve shows an analytic fit to the cross section (see text).

leads to estimates compatible with those calculated here (see also Laughlin and Adams, 2000; Adams and Laughlin, 2001). (2) The cross sections are sensitive to the relative velocity of the interacting systems. In a young cluster this velocity scale is only $\sigma_v \sim 1$ km s^{-1} and the ejection speeds $v_{eject} \sim 5$ km s^{-1}; both values are much smaller than the velocity dispersion of field stars where σ_v is ~ 20–40 km s^{-1}.

Although binarity increases the interaction cross sections, binary systems have a lower probability of supporting stable planetary orbits in their habitable zones, and the companion can inhibit terrestrial planet formation. These effects are surprisingly modest: Over 50% of binary systems are wide enough to allow for Earth-like planets to remain stable over the current 4.6 billion years (Gyr) age of the solar system (David *et al.*, 2003). The reason for this large fraction of viable sys-

tems is that most binaries are wide, with the peak of the binary period distribution at $P_b \approx 10^5$ days (Duquennoy and Mayor, 1991). Such orbits are wide enough ($a \sim 42$ AU for a solar mass primary) to allow stable orbits in the terrestrial region, as well as a stable "Jupiter" with semimajor axis $a = 5$ AU. For this same reason, most binary companions do not inhibit the formation of terrestrial planets (Quintana *et al.*, 2002; Quintana, 2004).

Transfer probabilities

Given the above considerations, we can now evaluate the odds for rocks to be ejected by one solar system and captured by another. The odds of life-bearing rocks being transferred can be determined similarly. Note that the results depend rather sensitively on the ejection speeds for rocks

expelled from a solar system. In order to cover the range of possibilities, we discuss both the low-speed limit and the high-speed limit. In the low-speed limit, defined as when the ejection speed v_{eject} is less than the stellar velocity dispersion v_{cls} in the cluster, the relative speed of interaction between rocks and solar systems is determined by the stellar motions and hence $v = v_{cls} = \sim 1$ km s^{-1}. In the high-speed limit, the ejection speeds are larger than relative speeds between solar systems, and v_{eject} determines the relative speeds for capture interactions ($v_{eject} \approx 5$ km s^{-1} for many solar systems as illustrated by Fig. 1). Because $v \approx 1$ km s^{-1} represents an upper limit on the scattering optical depth (see *Dynamical scattering interactions in groups and clusters)*, we define a fiducial cross section $\langle \sigma \rangle_1 \equiv 52{,}000$ AU$^2 \approx \pi(129$ AU$)^2$, as found numerically for $\sigma_v = 1$ km s^{-1}. To allow for easy scaling of our results, we also define a reduced cross section $\langle \tilde{\sigma} \rangle \equiv \langle \sigma_{cap} \rangle / \langle \sigma \rangle_1$. The velocity dependence of $\langle \tilde{\sigma} \rangle$ is given by Eq. 16 and by Fig. 2.

In the low-speed limit, the effective optical depth of interaction (per rock) becomes

$$\tau \approx (3 \times 10^{-5}) \, \frac{N_*}{\log N_*} \, \langle \tilde{\sigma} \rangle \qquad (17)$$

where we expect $\langle \tilde{\sigma} \rangle \approx 1$. The typical stellar population for a clustered star formation region is about $N_* = 300$, so $\tau \approx 0.0016$, and the number of rocks needed to get a capture event is about $\tau^{-1} \approx 630$.

In the high-speed limit, the rocks only stay in the cluster for one crossing time and the effective optical depth for interactions becomes

$$\tau \approx (3 \times 10^{-5}) \, \langle \tilde{\sigma} \rangle \qquad (18)$$

where $\langle \tilde{\sigma} \rangle \ll 1$. For a typical ejection speed $v_{eject} = 5$ km s^{-1}, for example, the reduced cross section $\langle \tilde{\sigma} \rangle \approx 0.0305$, and the scattering optical depth is $\tau \approx 10^{-6}$. In other words, only about one out of a million rocks are recaptured.

The total number of capture events in the entire cluster is given by $N_{cap} = N_R \tau$, where N_R is $\sim 10^{16}$ (see *Distribution of rock sizes and masses*). For the low-speed limit $N_{cap} \approx 10^{13}$, and for the high-speed case with $v_{eject} = 5$ km s^{-1}, $N_{cap} \approx 10^{10}$. As a result, the solar systems in a typical birth aggregate will experience billions to trillions of capture events, where "capture events" are the capture of rocky bodies from a single given solar system. It is possible—and even likely—that every solar system will contribute $N_R \sim 10^{16}$ rocky bodies to the cluster environment. As a result, essentially every solar system in a cluster can share rocky material with all of the other solar systems in its birth aggregate.

The number of life-bearing rocks is far lower than the total and has a large uncertainty. Since the origin of life is presumably a rare event in contexts where panspermia is of interest, we expect that at most one solar system would (initially) become biologically active and capable of seeding the rest of its birth cluster. We thus consider only one system as the source of bioactive rocks. Keep in mind, however, that not all clusters are guaranteed to develop life. As a result, the number of successful lithopanspermia events calculated here should be multiplied by the fraction f_{cl} of clusters that contain at least one living system (independent of panspermia). For our benchmark value $N_B = 10^7$, the number of captured life-bearing rocks is $N_{bio} \approx 16{,}000$ over the entire cluster in the limit of low ejection speeds. On average, every solar system would capture about 50 life-bearing rocks from the parent system. For higher ejection speeds (here, $v_{eject} = 5$ km s^{-1}), $N_{bio} \approx 10$, and only one out of 30 solar systems in a typical birth cluster is expected to capture biologically active rocks. Nonetheless, some transfer of life-bearing rocks is likely to occur within young star clusters.

Although the capture of life-bearing rocks is necessary to spread life from one planet to another, it is not sufficient. A captured rock must eventually find its way from its initial orbit (that resulting from the capture process) to the surface of a suitable terrestrial planet. The probability f_{imp} for a captured rock to strike a terrestrial planet is generally very small. Melosh (2003) has performed a series of simulations to estimate this quantity and finds that the probability of impact over the entire age of our solar system (4.5 Gyr) is only about $f_{imp} \sim 10^{-4}$. The probability of impact on a large rocky moon, in orbit about a giant planet, is somewhat smaller, $f_{imp} \sim 10^{-5}$. As a working benchmark value, we adopt $f_{imp} \sim 10^{-4}$.

In this setting, however, the biologically active rocks are often captured while the solar systems are young and hence still in the process of building planets. These systems are extremely active, and collisions are common. The life-bearing rocks have a much better chance (compared with the case of mature solar systems) of colliding with other debris and infecting them with spores. Although a life-bearing rock will collide with many

other rocky bodies, the efficiency of transfer (from rock to rock) is not known. In the long run, a large fraction of the total rocky content of a solar system will become incorporated into surviving bodies—giant planets, moons, terrestrial planets, or asteroids—so any infected rocks have a good chance of seeding life on larger bodies. This effect will act to make the quantity f_{imp} larger than that calculated previously for more mature solar systems. Our adopted fiducial value ($f_{imp} \sim 10^{-4}$) should thus be considered as a lower limit to the transfer efficiency. In addition to rocky bodies, comets provide another useful vehicle for the transfer of biologically active material. As an added advantage, when comets pass through the atmosphere of an Earth-like planet, they tend to disintegrate into dust and can thereby deposit biological material in a viable state (*e.g.*, Narlikar *et al.*, 2003). For further discussion regarding the survival of microorganisms during infall, see Hoyle *et al.* (1999).

As described above, the expected number of captured rocks that are potentially biologically active is $N_{bio} = 10$–16,000 per cluster, depending mostly on the ejection speeds. Over this range, the expected number of biologically active rocks from a parent solar system that impact the surfaces of (potentially habitable) terrestrial planets in other solar systems is about 0.001–1.6 per cluster. With these odds, biological transfer within a typical birth aggregate is quite possible.

The discussion thus far determines the likelihood of biologically active rocks being transferred from a living solar system to the surface of a potentially habitable planet in another system. In practice, however, only a fraction f_{seed} of these rocks will lead to seeding of the new world. The difficulties associated with atmospheric entry, crashing onto the surface, and the necessity of landing in a nutrient-rich location will lead to many failed attempts. This additional probability factor, which cannot be calculated within the scope of this paper, must be folded into any global assessment of the odds of lithopanspermia.

These results are summarized in Fig. 3, which shows the expected number of lithopanspermia events $N_{lps} = \tau f_{imp} N_B$ as a function of mean ejection speed $\langle v_{eject} \rangle$. In this context, the velocity dispersion that determines the capture cross sections (see Fig. 2) is given by the maximum of the mean ejection speed $\langle v_{eject} \rangle$ and the cluster velocity dispersion v_{cls}. The effects of varying the cluster size N_* are illustrated by the three curves (for $N_* = $ 100, 300, and 1,000). At low velocities $v_{eject} < v_{cls}$,

the ejected rocks are bound to the cluster, and the expected number of lithopanspermia events is maximized; in this limit, larger clusters produce higher numbers N_{lps} of expected events. At high speeds $v_{eject} > v_{cls}$, and the ejected rocks are unbound and generally pass through the cluster only once. In this limit, the effects of larger N_* (which increases the density of target solar systems) are nearly canceled by the effects of increasing the cluster size R, so the optical depth for scattering interactions (and hence N_{lps}) is independent of cluster membership N_*. Although Eqs. 11 and 13 depict the transition between the low and high velocity regimes as a step function, the actual transition will not be as sharp. At intermediate ejection speeds $v_{eject} \sim 2$–3 km s^{-1}, some rocks will remain in the cluster for several crossing times; in addition, some systems ($\sim 10\%$) reside in the cluster core where the gravitational potential is deeper than average, perhaps by a factor of ~ 10 (Binney and Tremaine, 1987), so higher ejection speeds are required for the rocks to become unbound. As a result, the transition from the low-speed limit to the high-speed limit has been smoothed out in Fig. 3 (with a transition width of 1 km s^{-1}).

Long-term biological transformation of a cluster

The discussion thus far has focused on the first 10 Myr of evolution, comparable to (but somewhat less than) the expected lifetimes for embedded groups and clusters. Although the majority of clusters will disperse after 10–20 Myr (*e.g.*, Lada and Lada, 2003), some fraction (roughly 10%) will remain bound for longer periods of time (100–500 Myr). In such environments, life has more time to spread throughout the cluster. This subsection considers the general transformation of a cluster from a nonliving state to one in which all of the solar systems support life. Although most stellar aggregates will not live long enough to complete this transition, this process is important in long-lived clusters.

We assume here that the total number of stars N_* remains constant over the time span of interest. Let N_D be the number of nonliving solar systems and N_L the number of living ones ($N_D + N_L = N_*$). The infection rate Γ—the rate at which living systems can transfer life-bearing rocks to terrestrial planets in nonliving systems—is given by

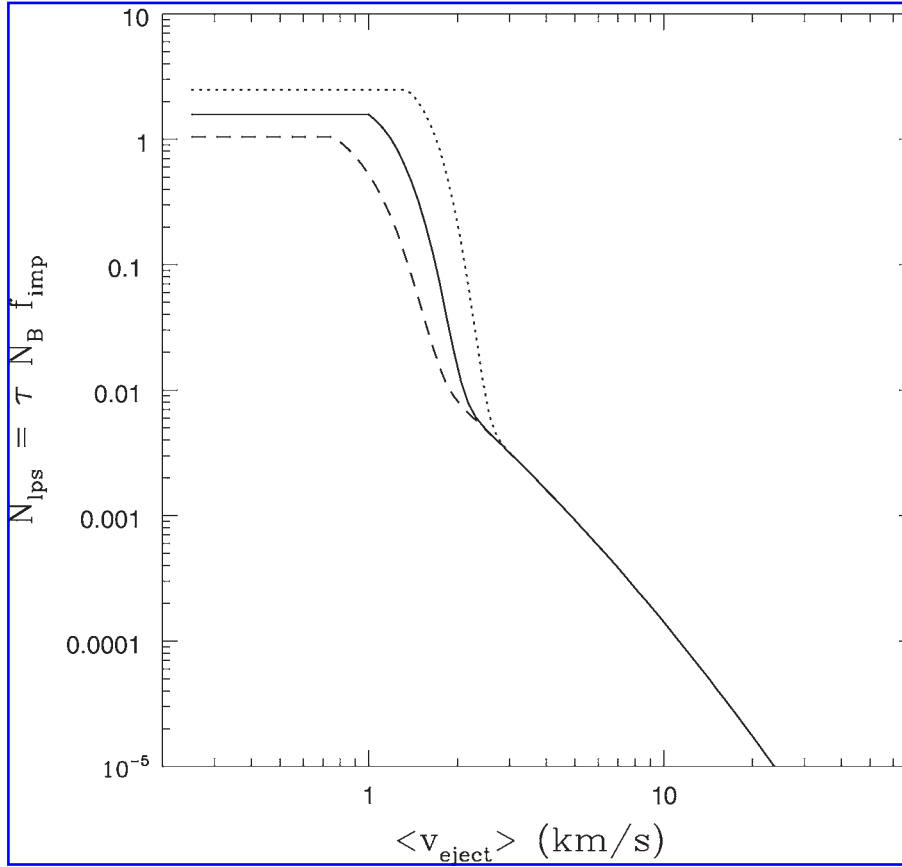$$\Gamma = \langle \sigma \rangle v n_B \qquad (19)$$

FIG. 3. Expected number of lithopanspermia events per cluster. The three curves show the expected number of successful instances of biological transfer as a function of the mean ejection speed $\langle v_{eject} \rangle$. The capture cross sections are a function of velocity dispersion σ_v, which is set by the maximum of the mean ejection speed $\langle v_{eject} \rangle$ and the cluster velocity dispersion v_{cls}. The solid curve shows the number of events expected for a typical group/cluster with $N_* = 300$ members. The dashed curve corresponds to $N_* = 100$, and the dotted curve corresponds to $N_* = 1,000$.

where n_B is the number density of life-bearing rocks in the cluster at a given time. The transition from nonliving to living systems is described by the differential equation

$$\frac{dN_D}{dt} = -\Gamma N_D = -\langle \sigma \rangle v n_B N_D \qquad (20)$$

The number density of life-bearing rocks n_B depends on the number of living systems in the cluster and on how long they have been alive. If every living system provides $\gamma \approx 15$ rocks per year to the cluster, the population of life-bearing rocks obeys the equation

$$\frac{dn_B}{dt} = \gamma n_*(1 - f_D) \qquad (21)$$

where $f_D \equiv N_D/N_*$ is the fraction of nonliving solar systems. We can combine Eqs. 20 and 21 to obtain

$$\frac{d}{dt}\left(\frac{1}{f_D}\frac{df_D}{dt}\right) = -n_*\langle \sigma \rangle v \gamma (1 - f_D) \qquad (22)$$

The time scale t_0 on which the fraction f_D (and hence $f_L = 1 - f_D$) evolves is given by

$$t_0 \equiv (n_*\langle \sigma \rangle v \gamma)^{-1/2} \approx 6.3 \text{ Myr} \\ (N_*/300)^{1/4}\langle \tilde{\sigma} \rangle^{-1/2} (v/1 \text{ km s}^{-1})^{-1/2} \qquad (23)$$

where we have used $f_{imp} = 10^{-4}$ and scaled the result using typical values in the second (approximate) equality. The fraction of nonliving systems in the cluster thus obeys the equation

$$\frac{d}{d\tilde{t}}\left(\frac{1}{f_D}\frac{df_D}{d\tilde{t}}\right) = -(1 - f_D) \qquad (24)$$

where the dimensionless time $\tilde{t} = t/t_0$. The solution for the fraction $f_L = (1 - f_D)$ of living systems as a function of dimensionless time is shown in Fig. 4. As formulated here, the solution can only depend on the initial condition $f_L(0)$, where we take the starting time to be when the first solar system in the group develops life. Figure 4 shows
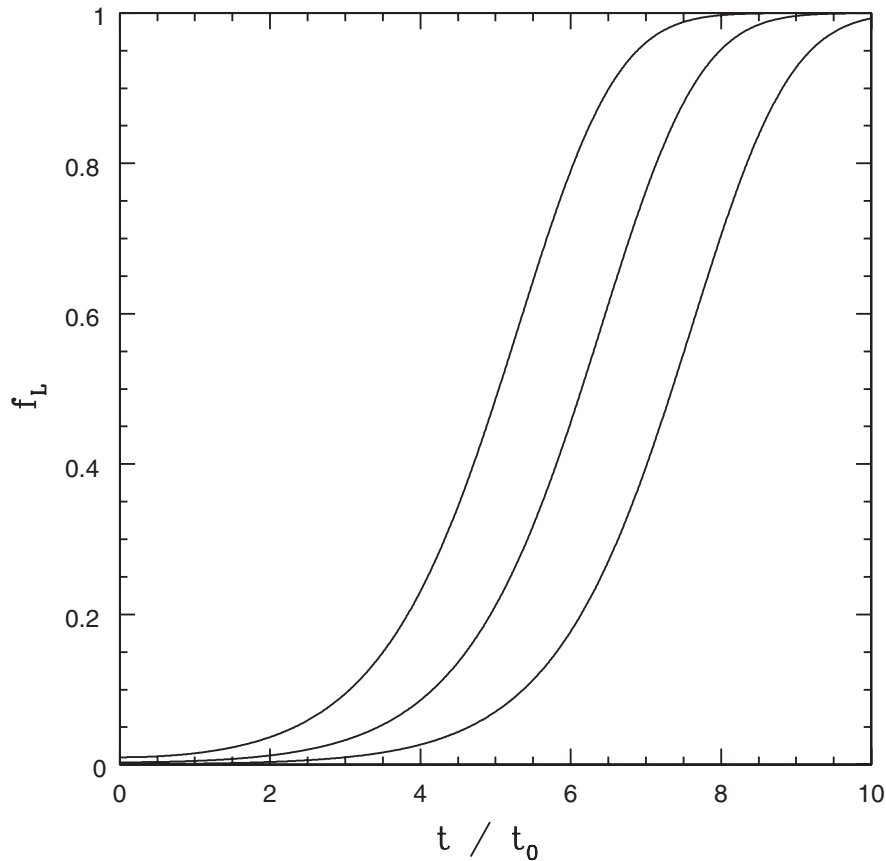
FIG. 4. Fraction of solar systems that contain life as a function of dimensionless time. The three curves show the result for different starting conditions, *i.e.*, $f_L(t = 0) = 1/N_*$ with $N_* = 100$, 300, and 1,000 (from left to right).

the solutions for three starting conditions, $f_L(t = 0) = 1/N_*$, with $N_* = 100$, 300, and 1,000. In smaller groups, the fraction f_L of living systems is larger at the initial time, so the curve for $f_L(t)$ increases faster for smaller N_*. Figure 5 shows the evolution in terms of physical variables—the larger clusters produce many more living systems in the end (as expected), though the times scales are somewhat longer. Notice that for typical values of N_*, the time required for a cluster to make the transition to fully living ($f_L \rightarrow 1$) is longer than the expected lifetimes of these systems.

Time scales for lithopanspermia in clusters

The basic scenario for lithopanspermia in clusters is outlined above. To complete the discussion, we must examine the time scales involved in the process. These time scales should be compared with the cluster lifetimes, which are expected to be of order 10–100 Myr, with considerable variation (Lada and Lada, 2003; Porras *et al.*, 2003).

The time required for biologically active rocks to be ejected from the parent solar system is probably the most important bottleneck in the process. For example, previous work has shown that the time required for martian ejecta to be removed from a solar system like our own is typically 30–50 Myr (Gladman *et al.*, 1996; Melosh, 2003), where the minimum time for ejection is about 4 Myr. The median ejection time falls to only a few Myr when Jupiter is placed at the orbit of Mars; extrapolation of Fig. 3 from David *et al.* (2003) indicates that such a solar system architecture would allow the Earth-like planet to remain stable for (roughly) 200 Myr, longer than typical cluster lifetimes ($\sim$100 Myr) and long enough for biological transfer to occur. Since solar systems are expected to have a wide variety of architectures, the time required for biologically active rocks to be ejected will vary greatly from system to system. In some cases, the rocks may not be ejected before the biologically active system leaves the cluster, and the lithopanspermia process will suffer from an added inefficiency.
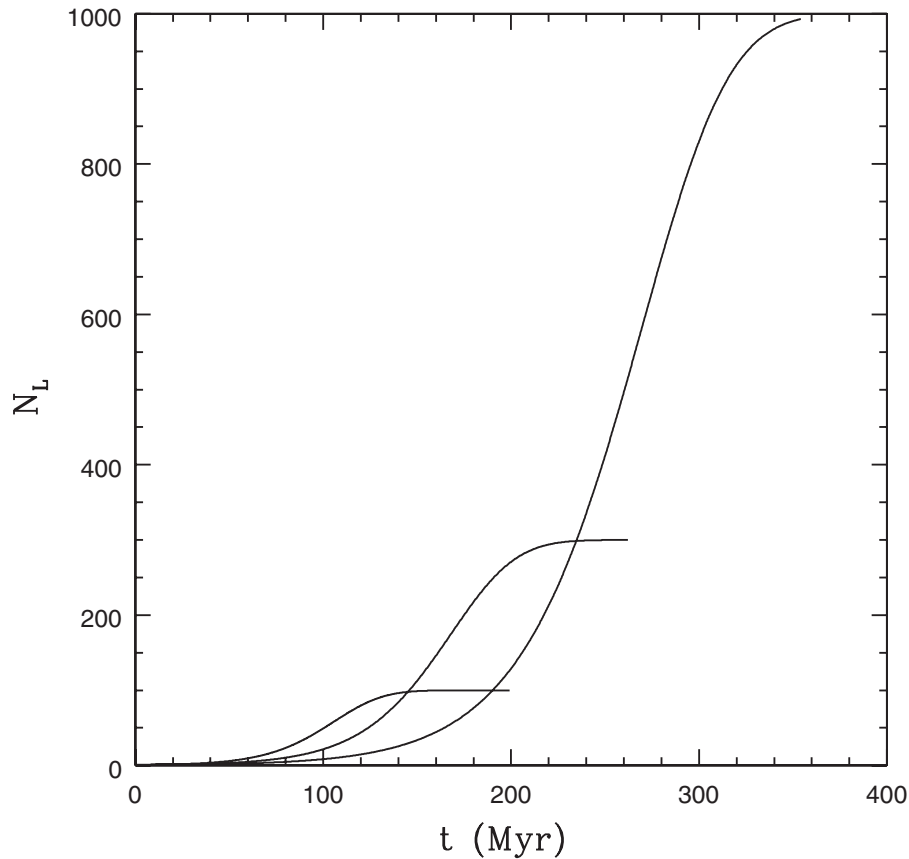
FIG. 5. Number of solar systems that contain life as a function of physical time (in Myr). The three curves show the result for different starting conditions, for clusters with $N_* = 100$, 300, and 1,000. Each curve asymptotically approaches N_* in the long time limit.

The time required for ejected rocks to travel from system to system is relatively short (compared with the other time scales of interest). The ejection speeds lie in the range 1–10 km s^{-1}, and the cluster size is of order 1 pc. The corresponding travel times thus fall in the range 0.1–1 Myr, short enough not to be an issue.

Erosion poses yet another potential problem facing biologically active rocks in space. For example, in the present Zodiacal cloud, a meter-sized rock can be eroded on the relatively short time scale of 0.02–0.23 Myr, where this time scale depends sensitively on the relative speed between the rocks and the eroding medium (see Napier, 2004). This time scale estimate is shorter than the time required for rocks to be ejected from the solar system. Since younger systems contain even more gas and can drive more severe erosion, this effect introduces another inefficiency into the panspermia process.

Lithopanspermia involves another rather long time scale. After a rock is captured by another so-lar system, a great deal of time passes before the rock lands on the surface of a terrestrial planet in the new system. The distribution of these time scales has been calculated previously (Melosh, 2003). Most rocks are re-ejected (leading to the small fraction $f_{imp} \sim 10^{-4}$) with a median time of about 60 Myr. Although this time scale is comparable to (or perhaps longer than) the cluster lifetime, it is not a major obstacle for panspermia: The new solar system can seed itself over a longer time scale, as long as the biologically active rocks are not stripped out of the system as the cluster disperses.

Of course, the most important, and most uncertain, time scale is that required for life to develop in one of the member solar systems. Unfortunately, this time scale remains largely unknown.

CONCLUSIONS

In this paper, we have reconsidered the hypothesis of lithopanspermia in the context of

young, clustered star-forming regions. In this environment, the conditions are different from those considered previously (namely in the field) in several respects: (1) The density of solar systems is much greater, and the relative velocities are lower—these qualities tend to enhance the transfer of any biologically active rocks that are present. (2) The systems live in the cluster for only 10–100 Myr, so the time scales available for transfer are shorter. (3) We also consider the fact that most stars reside in binaries; binarity increases the cross sections for the capture of passing meteoroids but also decreases the range of parameter space available for habitable planets. In the early formative phases of the solar system, rocky debris and bombardment are much more common, which also enhances transfer. However, the background UV radiation fields are stronger in regions of clustered star formation, and hence biological cargo is in greater danger.

Summary of results

1. We have calculated the cross sections $\langle \sigma_{cap} \rangle$ for rocky bodies to be captured by binary star systems (which make up the majority of solar systems). To determine each cross section, we use a Monte Carlo technique to sample the range of binary parameters, interaction geometries, and interaction speeds (for a given velocity dispersion σ_v). The resulting cross section is a steeply decreasing function of the velocity dispersion (see Fig. 2) and can be fit with a simple analytic form (see Eq. 16). The resulting capture cross sections can be used in a wide variety of other applications.

2. Within typical star-forming regions, the probability of any given ejected rock being recaptured by another solar system is relatively low. The effective optical depth for this interaction is sensitive to the ejection speed of the rock from its original solar system. Over the expected range of clusters with $N_* = 30$–1,000, the capture optical depth $\tau \approx 0.0003$–0.0043 in the limit where the mean ejection speed is less than or comparable to the velocity dispersion of the stars in the cluster. For a higher mean ejection velocity $\langle v_{eject} \rangle$ of ~5 km s^{-1}, the optical depth is much lower, $\tau \approx 10^{-6}$. In both limits, however, most rocks ejected from forming solar systems are not recaptured.

3. The total number N_R of ejected rocks per solar system is large, and the number of capture events N_{cap} per cluster is given by $N_{cap} \approx N_R \tau$. Given the order of magnitude estimate N_R ~10^{16}, every cluster will experience billions to trillions of capture events. Essentially all solar systems in a given birth aggregate are enriched (polluted) by rocks from other solar systems. In other words, the sharing of rocky material among young solar systems is inevitable.

4. The number N_B of biologically active rocks ejected from a living solar system is estimated to be N_B ~10^7 over the time spent in the birth aggregate (with considerable uncertainty). For clusters in which at least one system develops life, the number N_{bio} of capture events for biologically active rock (per cluster) is given by $N_{bio} \approx N_B \tau$. In the low-speed limit, the number of biologically active rocks captured (per cluster) is about N_{bio} ~16,000. This value is a steeply decreasing function of the rock ejection speed and reduces to $N_{bio} \approx 10$ (per cluster) for the benchmark value $\langle v_{eject} \rangle = 5$ km s^{-1}. If a solar system gives rise to life within a birth aggregate, then it is likely to transfer life-bearing rocks to the other solar systems in the aggregate. (Note that only a fraction of clusters will develop life and thus be capable of spreading it through the mechanism considered here.)

5. Only a fraction of the captured rocks that are biologically viable will strike the surface of a terrestrial planet and thereby complete the lithopanspermia process. Previous studies estimated this fraction to be f_{imp} ~10^{-4}. In general, the number of lithopanspermia events is given by $N_{lps} \approx f_{imp} N_B \tau$. In the limit of low ejection speeds, only one or two lithopanspermia events are expected in a typical birth cluster. For higher speeds, $\langle v_{eject} \rangle \approx 5$ km s^{-1}, the expected number of successful lithopanspermia events per cluster is ~10^{-3}, and the odds of successful lithopanspermia are about 1 out of 1,000. These general results are shown in Fig. 3. A related quantity is the effective efficiency of lithopanspermia, which is relatively low, *i.e.*, $\varepsilon_{lps} \equiv N_{lps}/N_* \approx 3 \times 10^{-6}$–$5 \times 10^{-3}$.

The numbers quoted here apply only to those clusters that develop life and implicitly assume that all rocks that land on habitable planets will spread life. Neither of these assumptions is guaranteed to hold. To assess the global probability of lithopanspermia, one must take into account that only a fraction f_{cl} of clusters will develop life

while they remain intact and only a fraction f_{seed} of rocks that land on suitable planets will be successful in establishing life.

External versus internal seeding

In any panspermia scenario, a key bottleneck is the origin of life in the first place. Of course, if the spontaneous origin of life were sufficiently common, there would no need for any panspermia mechanism to explain the presence of life, though biological transfer would still be of interest. In the present context, an important issue is whether life is more likely to arise spontaneously within a birth cluster or be captured from the outside. To make a quantitative assessment, we assume that life will arise with probability p for any given solar system within a time span of 10 Myr. Solar systems forming within a group or cluster (which remains intact for about 10 Myr) will thus create life with probability p. The probability P_C of a birth aggregate with N_* systems giving rise to life spontaneously is thus $P_C \approx N_* p$.

For comparison, we must estimate the probability of the birth cluster capturing life-bearing rocks from the outside. The optical depth for capture is given by $\tau = n\sigma_T \ell$, where n is the number density of life-bearing rocks, σ_T is the capture cross section of the entire cluster, and $\ell = vt$ is the effective path length. Since v is ~40 km s^{-1} and t is ~10 Myr, the path length ℓ is ~400 pc. In the solar neighborhood, the number density of stars $n_* \approx 0.04$ pc^{-3}. If we assume that solar systems are biologically viable for ~10 Gyr, then individual systems will create life with probability $1,000p$. The density of solar systems that give rise to life is $1,000n_*p \approx 40p$ pc^{-3}. If each living solar system ejects 15 life-bearing rocks per year (see Life-bearing rocks), the density of life-bearing rocks is $n \sim 6 \times 10^{12}p$ pc^{-3}. The capture cross section for the entire cluster is approximately $N_*\langle\sigma(40 \text{ km s}^{-1})\rangle$, where the cross section for an individual solar system to capture a high-speed rock is $\langle\sigma(40 \text{ km s}^{-1})\rangle \approx 3$ AU^2 (see Eq. 16). The probability of the cluster capturing life-bearing rocks is thus $\tau = n\sigma vt \approx 180,000N_*p$ (per cluster). To compare with our estimate for the spontaneous rise of life, we must take into account the fact that only a fraction f_{imp} of the life-bearing rocks captured in this manner eventually strike the surface of a terrestrial planet and make a successful transfer. For the benchmark value f_{imp} ~10^{-4}, the probability of a cluster being seeded

from the outside is $P_C \approx 18N_*p$. These results suggest that a young cluster is more likely to capture life from outside than to give rise to life spontaneously. Once seeded, the cluster provides an effective amplification mechanism to infect other members.

This formalism also provides an estimate of the probability that Earth has transferred life to other solar systems. This issue is especially pertinent because Earth is the one planet where we know that life developed. We consider the case of continued ejection of life-bearing rocks over the age of the solar system, so we use conditions relevant to the field. The optical depth for a rock (from Earth) being captured by another solar system is given by $\tau = n_*\sigma_v(\Delta t)$, where $n_* \approx 0.04$ pc^{-3}, $v \approx 40$ km s^{-1}, $\Delta t \approx 4$ Gyr, and $\sigma(40 \text{ km s}^{-1}) \approx 3$ AU^2. With these values, the optical depth for capture is $\tau \approx 4.6 \times 10^{-7}$. Following the same approximation scheme developed earlier, we assume that the Earth ejects about 10 life-bearing rocks per year and thus ejects $N_B \approx 4 \times 10^{10}$ such rocks during the time over which life has existed. Putting these two results together, we find that $N_B\tau/2 \approx 9,000$ life-bearing rocks will be captured by other solar systems (where we have included the factor of 2 to account for the fact that the rocks that are ejected first have a longer travel time). Using the standard fraction $f_{imp} \approx 10^{-4}$ for the number of captured rocks that make their way onto the surface of a habitable planet, the expected number of transfer events is about 0.9. In other words, these results suggest that life on Earth can be transferred to *one* other habitable world in another solar system. This value reflects the steady-state transfer rate of life from our solar system to others. In addition, our planet is thought to have experience a period of "late heavy bombardment" from about 4.4 to 3.8 Gyr ago, when a large number of additional life-bearing rocks could be ejected into space. This epoch implies an enhancement in the transfer rate [and will be the subject of a forthcoming paper (G. Laughlin, personal communication)].

Discussion and future work

This paper shows that young star clusters provide an efficient means of transferring rocky material from solar system to solar system. If any solar system in the birth aggregate supports life, then many other solar systems in the cluster can capture life-bearing rocks. Only a fraction of these

systems will feed biologically active rocks onto the surfaces of terrestrial planets, however, so the odds of successful lithopanspermia are low. In the limit of low-speed ejecta, only a few systems per cluster are expected to be biologically seeded through this mechanism, though the efficiency is reasonably high (about $\varepsilon_{\text{lps}} \approx 0.005$). If the origin of life is relatively common and life-bearing rocks can be ejected at low speeds, then dynamical interactions in stellar birth clusters would provide an effective mechanism for spreading life.

This paper has explored the possibility that young clusters can lead to greater efficiency of panspermia. However, these cluster environments also present additional hazards for the transfer of biological material. One obstacle is the increased levels of radiation at UV wavelengths. Previous work on this subject has shown that the radiation fields in small clusters (those with a few hundred members) are generally not strong enough to affect circumstellar disks and planet formation (*e.g.*, Adams and Laughlin, 2001; Adams *et al.*, 2004), though a definitive assessment of the consequences for biological material remains to be done. Further, the radiation fields increase steeply with increasing cluster size N_* so that sufficiently large clusters will present substantial hazards. Another potential issue is that of supernovae. Since only about three out of every 1,000 stars are massive enough to end their lives in a supernova explosion, such events are rare in small clusters (Adams and Laughlin, 2001). Furthermore, the most massive stars tend to live near the cluster centers, so that the majority of stars will be ~1 pc away (see Adams and Myers, 2001).

In the discussion thus far, we have estimated the likelihood of lithopanspermia events using conservative values for the input parameters. The resulting odds of life being carried from solar system to solar system are high enough to be tantalizing, but not high enough to guarantee transfer. It is interesting to see what might happen with more optimistic estimates. Consider the case of low ejection speeds so that the velocity dispersion of solar systems in the cluster determines the cross section, *i.e.*, $\sigma_v \approx v_{\text{cls}} \approx 1$ km s^{-1} and hence $\langle \sigma \rangle \approx 1$. In this case, the interaction optical depth $\tau = 3 \times 10^{-5} N_* / \log N_*$. Next we assume that the lower mass limit for spores to survive is $m_B = 142$ g (the mass of a baseball) so that $N_B \approx 1.7 \times 10^8$, and the efficiency of transfer is enhanced because of the extreme collisional activity of planet formation so that $f_{\text{imp}} \approx 10^{-3}$. We also assume that life-bearing rocks that land on suitable planets will successfully spread life so that $f_{\text{seed}} = 1$. With these values, the expected number of lithopanspermia events (per cluster) is $N_{\text{lps}} \approx 5.1 N_* / \log N_*$ over the fiducial 10 Myr time scale. In this limit, life can be transferred to every solar system in a group with $N_* = 100$. In a larger cluster with $N_* = 1,000$, 75% of the systems would become infected with life over the nominal 10 Myr time period; however, larger clusters remain intact much longer and have additional time to transfer biological material from system to system. As a result, optimistic circumstances allow a cluster, once biologically seeded, to transfer life to the majority of its solar systems through the process of lithopanspermia.

To further our understanding of the lithopanspermia mechanism, additional calculations must be performed. One important quantity is the fraction f_{imp} of captured material that falls onto the surfaces of habitable planets. This paper follows previous authors and uses the estimate $f_{\text{imp}} \approx 10^{-4}$. Starting with the locations of captured rocks from the binary capture simulations, a large ensemble of dynamical calculations should be performed to determine f_{imp}. A related issue is that, for sufficiently young solar systems, biologically active rock can be captured while the planets are still being assembled. During the planet formation epoch, rock–rock collisions are common, and spores could (in principle) be transferred from rock to rock, leading to an enhancement in the effective value of f_{imp}. Another important quantity is the minimum mass necessary for biological material to survive in space. In the setting of a young cluster, the travel time is much lower than in the field (only ~1 Myr compared with many Gyr), but the radiation fields are more intense. And finally, the number of biologically active rocks ejected by a given living planet should be estimated with greater precision.

ACKNOWLEDGMENTS

ABBREVIATIONS

Gyr, billion years; Myr, million years; UV, ultraviolet.

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