Transfer of Rocks between Planetary Systems: Panspermia Revisited

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ABSTRACT

Motivated by the recent discovery of interstellar objects passing through the solar system, and by recent developments in dynamical simulations, this paper reconsiders the likelihood for life bearing rocks to be transferred from one planetary system to another. The astronomical aspects of this lithopanspermia process can now be estimated, including the cross sections for rock capture, the velocity distributions of rocky ejecta, the survival times for captured objects, and the dynamics of the solar system in both its birth cluster and in the field. The remaining uncertainties are primarily biological, i.e., the probability of life developing on a planet, the time required for such an event, and the efficiency with which life becomes seeded in a new environment. Using current estimates for the input quantities, we find that the transfer rates are enhanced in the birth cluster, but the resulting odds for success are too low for panspermia to be a likely occurrence. In contrast, the expected inventory of alien rocks in the solar system is predicted to be substantial (where the vast majority of such bodies are not biologically active and do not interact with Earth).

Keywords: Solar system, Dynamical evolution, Small solar system bodies, Kuiper belt, Oort cloud

1. INTRODUCTION

The origin of life poses one of the most substantial — and so far largely inaccessible — unresolved scientific questions. Although this topic has many different facets, an important issue in astrobiology is whether or not life can be transferred from one planetary system to another. This type of transfer is generally known as panspermia and has been studied extensively in previous work (e.g., Melosh 1988; Melosh 2003; Napier 2004; Wallis and Wickramasinghe 2004; Adams and Spergel 2005; Valtonen et al. 2009; Wesson 2010; Belbruno et al. 2012; Ginsburg et al. 2018; Lingam and Loeb 2018). The recent discovery of the unbound interstellar objects 'Oumuamua (Meech et al. 2017) and comet Borisov (Jewitt and Luu 2019) passing through our solar system emphasizes that one part of the process, astronomical objects traveling from one system to another, is not only readily realized, but can also be observationally constrained. The other requirements for the transfer of life, however, are expected to less common, and most previous estimates suggest that the likelihood of transfer is extremely low (see the above references). With a focus on the astronomical aspects of the problem, this paper revisits the question of panspermia. Although a great deal of previous work has been carried out, the present treatment is motivated by recent observational input, especially the detection of unbound interstellar objects, and by recent numerical studies of the capture dynamics. We find that the odds of successful transfer of life remain low, although significant uncertainties remain.

The transfer of life between planetary systems requires a number of astronomical and biological processes to take place. These steps are illustrated in the schematic diagram of Figure 1. First, life must arise on a suitably habitable planet in order to provide the seeds for other planetary systems. The habitable planet must then be bombarded via impacts (or experience some other cataclysmic event) in order to lift biologically active material off the planetary surface and into interstellar space. These projectiles then travel from one planetary system to another, and must be captured by the recipient system(s). After capture into a bound orbit, the biologically active body must eventually find its way onto the surface of a habitable planet within its new system. Finally, the successful transfer of life requires that

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life actually takes hold in its new environment. The first and last of these processes are biological in nature and their odds of occurrence are largely unknown. Of course, Earth provides one example of life both arising and taking hold, but an honest assessment of the odds remains out of reach. In contrast, the dynamics of transfer can be calculated, and the corresponding odds of success can be estimated. This present paper thus focuses on these astronomical aspects of the problem.

As outlined in greater detail below, it is important to make the distinction between different dynamical environments, namely within clusters and in the field. Most stars form within embedded clusters (Lada and Lada 2003; Porras et al. 2003), and our Sun is thought to be no exception (Hester et al. 2004; Portegies Zwart 2009; Adams 2010; Pfalzner 2013; Parker 2020). Compared to the field, such cluster environments are more conducive to the transfer of rocky bodies between planetary systems (Adams and Spergel 2005; Belbruno et al. 2012). More specifically, the stellar density within clusters is much higher than the field, by a factor of $\sim 1000$, and the relative speeds are lower, by a factor of $\sim 40$. Both of these properties enhance the capture of rocky bodies. Working in the opposite direction, however, solar-type stars typically spend more time in the field, by a factor of $\sim 100$. As outlined below, the advantages of the cluster environment outweigh the loss of integration time. Many of the earlier estimates for the low probability of rocky bodies seeding life in an alien solar system (e.g., Melosh 2003) correspond to current conditions in the field (in the solar neighborhood). The consideration of the solar birth cluster enhances the odds of transfer, but the odds remain low.

This paper is organized as follows. The first step is to consider the ejection of rocky bodies from a planetary system that contains life (Section 2). Important considerations include the total amount of material ejected, the distribution of ejection speeds, and the size distribution of the rocky bodies. After rocks are successfully ejected from a planet, they must be captured by another planetary system, and the cross sections are considered next (Section 3). Here we determine the cross section as a function of asymptotic speed, with a focus on parameters appropriate for our solar system (although the cross section has the same general form for other systems). We then estimate the corresponding capture rates. Once the rocks are captured, they must remain bound to the new planetary system and eventually find their way onto the surface of a habitable planet (Section 4). The results can be combined to construct estimates for the optical depth for rock capture, the number of successful panspermia events, and the standing population of alien bodies in the solar system (Section 5). The paper concludes (in Section 6) with a summary of results and a brief discussion of their implications.

2. EJECTION

The first astronomical process of interest involves the removal of rocks from the surface of a planet, and ultimately the ejection of the rocks from the planetary system. On this point, we first note that rocks are observed to be transported from one planet to another within our solar system. For example, many meteorites found on Earth are known to be of Martian origin (McSween 1985), and the dynamics of such transfer is well-studied (Dones et al. 1999; Mileikowsky et al. 2000; Gladman et al. 2005). Next we note that the depth of the potential well from the surface of Earth (the escape speed $v_e \sim 11$ km/s) is comparable to, though somewhat smaller than, the depth of the solar potential at $a = 1$ au (where the orbital speed $v_{\text{orb}} \sim 30$ km/s and escape speed $v_e \sim 42$ km/s). We thus expect that only a fraction of the rocky bodies that are removed from planetary surfaces will be successful in leaving their planetary systems, but such events should nonetheless take place.

Mass in Ejected Rocks. Regarding the total amount of mass that can be ejected, simulations of the late stages of planet formation (e.g., Quintana 2004) and considerations of disk substructures (Rice and Laughlin 2019) suggest that star/disk systems eject of order $\sim 1-10M_\oplus$ of material during their early formative stages. We can parameterize this contribution by writing the total ejected mass in rocks in the form

$$M_R = f_R M_\oplus,$$

(1)

where we expect the dimensionless parameter $f_R$ to be of order unity (see also Melosh 2003; Dones et al. 1999; Adams and Spergel 2005).

Only a fraction of the mass $M_R$ will be ejected from the surface of a particular planet in the system, and only a fraction of that mass can possibly contain biologically active material. More specifically, we are interested in rocks that contain some type of life-bearing substance (spores, seeds, DNA) that can in principle start life on a suitable new planet. The ejected mass of biologically infused rock can thus be written in the form

$$M_B = f_B f_R M_\oplus,$$

(2)
where we expect $f_B \ll 1$. Although the value of $f_B$ is highly uncertain, we can make an order of magnitude estimate as follows. Suppose that we have a habitable planet with properties comparable to those of Earth. The mass of our biosphere is approximately $10^{-10} M_\oplus$ (e.g., Bar-On et al. 2018).\footnote{Note that this biomass landmass is dominated by land plants. In principle, seeds can be encased within rocks and transported through the panspermia mechanism, but experimental data is lacking. In addition, one should keep in mind that land plants have only existed for $\sim 10\%$ of Earth history.} On one hand, we expect that only a fraction of the total mass of the biosphere can be ejected; on the other hand, only a fraction of the mass contained in the rocky ejecta
is expected to contain biological material. As a result, an approximate upper limit is given by \( f_B \leq 10^{-10} \). As another estimate, previous authors find that \( \sim 15 \) biologically active rocks, with masses \( \sim 10^4 \) g, should be ejected from an Earth-like planet per year (Melosh 2003; Wallis and Wickramasinghe 2004). Over the age of the solar system, this mass loss rate corresponds to a total ejected mass of \( \sim 10^{-13} M_\oplus \) (so that \( f_B \sim f_B f_R \sim 10^{-13} \)). The ejection rate is likely to be higher at earlier stages of evolution, so that this estimate is probably a lower limit (although life has less time to develop at these earlier stages). These considerations thus indicate that the fraction of the ejected mass that is potentially biologically activated lies in the range

\[
10^{-13} \leq f_B \leq 10^{-10}.
\]

This estimate has considerable uncertainty, and the range is conservative. For example, if a planet develops life quickly and is subject to frequent impacts, then the ejected biomass could be a larger fraction of the total. In the extreme limit, the integrated biomass ejected over time could exceed the instantaneous mass of the biosphere (this ordering depends, in part, on the carbon turnover time – see Carvalhais et al. 2014). Alternately, a planet could have a much deeper biosphere than Earth, or more surface area covered by biomass, which would increase the efficacy of the process.

**Distribution of Ejection Speeds.** In order for biologically active rocks to be ejected from a planetary system, they must first leave the planetary surface. Since the escape speed from an Earth-like planet (~ 11 km/s) is somewhat smaller than the escape speed from the orbital location within the system (~ 42 km/s), rocks released from the planetary surface are likely to remain bound to the host star. Over subsequent orbits, however, such bodies will interact with other planets and can eventually be ejected from the planetary system. If rocks are ejected by close encounters in the outer regions of their solar systems, then the distribution of ejection speeds is expected to have the approximate form

\[
F(v) = \frac{4v/v_p}{(1 + v^2/v_p^2)^{3/2}},
\]

where the velocity scale is determined by the depth of the stellar potential well at the location of the planet (Moorhead and Adams 2005). More specifically, the velocity \( v_p \sim (GM_\odot/a_p)^{1/2} \), where \( a_p \) is the semi-major axis of the planetary orbit. Note that the planet that ejects the rocks from the planetary system (and defines \( v_p \)) is not necessarily the habitable planet of origin. In our solar system, for example, Jupiter and Saturn are responsible for most ejection events so that \( v_p \sim 10 \) km/s, although other planetary systems could have different architectures (see also Moorhead and Adams 2005; Adams and Spergel 2005).

Note that equation (4) characterizes the distribution of ejection speeds as the rocks leave their original planetary systems. As they travel through interstellar space, the rocks will eventually experience a series of distant encounters and will attain the velocity distribution of the larger dynamical system. Here we are interested in the birth clusters of planetary systems and the field. In the cluster environment, the stars (and eventually the rocky bodies) approach a Maxwellian velocity distribution with typical dispersion \( s \sim 1 \) km/s (Lada and Lada 2003). Since much of the distribution of equation (4) corresponds to higher speeds, only the low-speed tail of the original distribution will be retained within the cluster after the first crossing time. If we define \( u \equiv s/v_p \), then the fraction \( f_s \) of the distribution with speed \( v < s \) is given by

\[
f_s = \frac{2u^2 + u^4}{1 + 2u^2 + u^4} \approx 0.075,
\]

where we have used \( u = 1/5 \) to obtain the numerical value. The resulting reduced population of rocks can eventually reach a Maxwellian distribution, but will retain the distribution (4) in the short term. For comparison, in the field the stars have a Maxwellian distribution of speeds with typical dispersion \( s \sim 40 \) km/s (Binney and Tremaine 2008). However, observations indicate that the velocity dispersion increases with the age of the stellar population. As a result, the ejected rocks in the field eventually attain the same Maxwellian distribution as the star, but the required time scale is expected to be greater than \( \sim 1 \) Gyr (e.g., Haywood et al. 2013).

**Distribution of Rock Sizes and Masses.** The above discussion provides estimates for the total mass of ejected material from a habitable planet. To determine the probability of biological transfer, we need to specify the number of rocky bodies that could potentially carry biological material from one planetary system to another. The rocky ejecta will be produced with a distribution of rock sizes and masses. Since this size distribution is expected to be a steeply decreasing function of radius and hence mass (see below), the minimum mass necessary for a rock to safely transport biological material largely determines the total number of rocky bodies for a given total mass.
The first step is to thus specify the minimum rock mass/size necessary to transport biomass. A number of previous papers have estimated the minimum rock mass and find that $m_{\text{min}} \approx 10^4$ g (e.g., see Horneck 1993; Nicholson et al. 2000). With this minimum mass, the rock provides biological material with sufficient shielding from interstellar cosmic rays and other hazards (see also the discussion at the end of this section).

The mass distribution of the ejected rocks is expected to be nearly a power-law, which can be written in the form

$$\frac{dN}{dm} = A m^{-p},$$

where $A$ is a normalization constant and the power-law index $p = 1 - 2$. More specifically, for the case where the size/mass distribution is determined by collisional processes, one finds an index $p \approx 1.8$ (Dohnanyi 1969; O’Brien and Greenberg 1982; Napier 2001). For comparison, the observed distribution for objects striking the top of the Earth atmosphere indicates an index $p \approx 1.7$ (Schroeder 1991). For indices in the expected range $1 < p < 2$, most of the mass is contained in the (rare) largest objects, whereas most of the bodies by number are the smallest objects. We thus introduce an upper mass cutoff $m_2$ and a lower mass cutoff $m_1$. To a good approximation, the normalization condition implies

$$A = \frac{(2 - p) M_R}{m_2^{2-p}},$$

and the total number of rocky objects per star is given by

$$N_{R*} = \frac{(2 - p)}{(p-1)} \left( \frac{m_2}{m_1} \right)^{p-1} \frac{M_R}{m_2}.$$  \hspace{1cm} (8)

If we take $M_R$ to be the total mass (in all the rocks ejected from a given system), then $M_R \sim M_\oplus$ as discussed above. However, the remaining parameters can vary for a wide range. For example, Melosh (2003) uses the values $m_1 = 10^4$ g, $m_2 = 0.1 M_\oplus = 6 \times 10^{26}$ g, and $p = 5/3$, so that the total number of rocky bodies per star becomes $N_{R*} \approx 10^{16}$. For comparison, Napier (2001) uses the values $m_1 = 10^7$ g and $p = 11/6$, so that the number becomes $N_{R*} \approx 8 \times 10^{16}$. Since the fiducial number of rocks is given by $N_0 = M_R/m_1$, we define a dimensionless parameter $f_N$ such that

$$f_N \equiv \frac{(2 - p)}{(p-1)} \left( \frac{m_1}{m_2} \right)^{2-p},$$

so that $N_{R*} = f_N N_0$. The number of biologically active rocks produced per star is thus given by $N_{B*} = f_B f_N N_0$. Note that the number of rocks is sensitive to the value of the index $p$. Recent studies find a range of indices (Brown et al. 2002; Suggs et al. 2014; Ballouz et al. 2020) with values somewhat larger than $p = 1.7$. The steeper distributions imply larger numbers of small rocks (larger $f_N$).

**Minimum Rock Size for Survival.** As outlined above, we need to specify a lower cutoff to the mass distribution in order for the integrated number of bodies to converge. In addition, in order to survive transfer across interstellar space, biological material must be encased within rocky bodies with a minimum mass. Here we take these two mass scales to be coincident with a value of $m_1 = 10^4$ g. Notice that by using the minimum mass for survival as the lower cutoff, we are determining the number of rocky bodies large enough to carry biological material.\(^2\)

The value for the minimum mass $m_1 = 10^4$ g is advocated by Melosh (2003), although a number of alternatives have been put forth (see, e.g., Napier 2004). Experiments show that UV radiation can be lethal for spores and bacteria exposed to interstellar conditions (Horneck et al. 2001) and that a rocky casing of a few centimeters is required for protection. The mass scale used here ($10^4$ g) corresponds to a larger size scale (compared to a few cm) because of several additional considerations: First we note that the rocky ejecta and their biological cargo must survive the impact events that launch them from the surface of their original planet (Mastropa et al. 2001; Horneck et al. 2008), thus requiring somewhat larger rocks. In addition, after being captured by another planetary system, the rock must also survive the re-entry process onto the surface of its new planet, where this latter process is likely to be the limiting factor for survival (de la Torre et al. 2010).

\(^2\) We are thus neglecting the rocks that are too small to support life. Since most of the mass is contained in the largest objects, and most of the bodies by number reside in the smallest objects, this choice of lower mass cutoff does not affect the predicted number of biologically viable rocks for a given total mass.
3. CAPTURE CROSS SECTIONS

This section considers several mechanisms by which interstellar objects, including those containing biological material, can be delivered to our solar system (and other planetary systems). We begin by reviewing the process of gravitational capture. We then consider the case where interstellar objects collide directly with solar system bodies and conclude by considering capture by gaseous circumstellar disks.

Capture by Dynamical Interactions. The problem of gravitational capture of interstellar objects is now relatively well-understood (e.g., see the seminal paper by Heggie 1975; see also the more recent work of Hands and Dehnen 2020; Napier et al. 2021a; Lehmann et al. 2021). In order for capture to take place, the incoming object must experience the time-dependent gravitational potential induced by interactions with the giant planets and the Sun. The capture dynamics can be then broken into two regimes depending on the hyperbolic excess velocities of the incoming objects. In the low-speed regime \((v_\infty < 1 \text{ km/s})\), the incoming bodies enter the sphere of influence of the Sun. In the high speed regime \((v_\infty > 1 \text{ km/s})\), capture is dominated by close encounters with the giant planets. In both regimes, the bodies exchange energy in a process that is essentially the inverse of the well-known gravitational slingshot effect. The orbital speed of the solar system body (either the Sun or a giant planet) determines the maximum energy exchange, so that high speed objects require interactions with the planets (which have higher orbital speeds). Both analytic approximations (Heggie 1975; Napier et al. 2021a) and numerical simulations (Hands and Dehnen 2020; Napier et al. 2021a) show that the capture cross section depends on the incoming asymptotic speed of the rock according to the relation

\[
\sigma(v_\infty) = \frac{\sigma_0}{(v_\infty/v_\sigma)^2 \left[1 + (v_\infty/v_\sigma)^2\right]^2},
\]

where the best fit parameters for our solar system are given by \(\sigma_0 \approx 232,000 \text{ au}^2\) and \(v_\sigma \approx 0.42 \text{ km/s}\). Equation (10) enables the calculation of a capture rate for any distribution of the incoming velocity \(v_\infty\), which we discuss in Section 5. Figure 2 shows the data for the capture cross section derived from 500 million numerical experiments (Napier et al. 2021a), as well as the best fit from Equation (10). The numerical results span \(\sim 11\) orders of magnitude in capture cross section and agree well with the analytic form over the entire range. Note that the cross section is a sensitive function of \(v_\infty\). For other solar systems, the capture cross section has the general form given by equation (10), but with different values for the parameters \(\sigma_0\) and \(v_\sigma\). These values can be estimated using the analytic forms for the cross sections (Heggie 1975; Napier et al. 2021a; Dehnen and Hands 2021).

These data show that in the low-speed regime \(\sigma(v_\infty) \propto v_\infty^{-2}\), while in the high-speed regime, \(\sigma(v_\infty) \propto v_\infty^{-6}\). This velocity dependence implies that for objects with high \(v_\infty\), the capture cross section quickly becomes exceedingly small. At \(v_\infty = 15 \text{ km/s}\), for example, \(\sigma(v_\infty)\) is comparable to the geometric cross section of the Sun, and at \(v_\infty = 40 \text{ km/s}\), \(\sigma(v_\infty)\) is comparable to the geometric cross section of Jupiter. It is significant that there is a maximum value of \(v_\infty\) that an incoming body can have and still be captured by our solar system where \(v_{\text{max}} \approx 40 \text{ km/s}\). This speed limit is set by Jupiter’s orbital speed (for a derivation, see Napier et al. 2021a). In principle, non-gravitational effects such as atmospheric drag could allow faster bodies to be captured, e.g., if they execute orbits that skim a planetary atmosphere. However, such events are expected to be exceedingly rare (even compared to direct collision events considered below), so that the capture cross section for \(v_\infty \gtrsim 40 \text{ km/s}\) is effectively zero.

Capture by Direct Collision. Another mechanism for capture occurs through direct collisions with solar system bodies. As shown above, the dynamical capture cross section for objects with asymptotic speed \(v_\infty \gtrsim 15 \text{ km/s}\) (35 km/s) is smaller than the cross sectional area of the Sun (Jupiter). Furthermore, Jupiter (which is by far the most effective planet at capturing interstellar rocks) can only capture objects with \(v_\infty \lesssim 40 \text{ km/s}\). For cases where the velocity distributions of the incoming bodies have large dispersion, such in the field, direct collisions with a solar system object — rather than capture, followed by eventual collision — can be a more effective way of accumulating life-bearing rocks. The cross section for directly landing on the surface of Earth is of particular interest. The following discussion thus focuses on collisions with Earth, but other solar system bodies (e.g., potentially habitable moons of the giant planets) can be treated in analogous fashion.

In contrast to gravitational capture, direct collisions allow for simple analytic approximations. The capture cross section is the geometric cross section of the body of interest with corrections for gravitational focusing. For the case of Earth, the gravitational focusing due to the Sun is a much larger effect than that due to Earth itself. We first consider
Figure 2. Capture cross section as a function of $v_{\infty}$. The black dots represent the data derived from the numerical simulations in Napier et al. 2021a. The solid blue line is the best fit of equation (10) to the numerical data. The dotted blue line is an extrapolation of the solid blue line from 15 km/s to 40 km/s. The horizontal yellow and orange lines represent the geometric cross sections of the Sun and Jupiter, respectively.

the cross section for an incoming rock to reach a sphere of radius $r_0 = 1$ au centered on the Sun, i.e.,

$$
\sigma_1 = \pi r_0^2 \left(1 + \frac{2GM_\odot}{r_0 v_{\infty}^2}\right),
$$

(11)

where $v_{\infty}$ is the asymptotic speed. Of course, the cross sectional area of Earth is only a fraction $R_\oplus^2/4r_0^2$ of the cross sectional area of the 1 au sphere. Note that we are assuming an isotropic distribution of incoming bodies and a circular orbit. In addition, the Earth will introduce its own gravitational focusing factor, denoted here as $f_{g\oplus}$. With the inclusion of these two effects, the cross section for direct capture by Earth can be written in the form

$$
\sigma = \frac{\pi}{4} R_\oplus^2 \left(1 + \frac{2GM_\odot}{r_0 v_{\infty}^2}\right) f_{g\oplus},
$$

(12)

where the final focusing factor $f_{g\oplus}$ is expected to be of order unity. After the rock enters into the sphere of influence of Earth, it will have a speed $v \sim v_{\text{orb}} \sim 30$ km/s, which plays the role of the asymptotic speed for this second gravitational focusing factor. As result, we find that $f_{g\oplus} \sim 1 + (v_\oplus/v_{\text{orb}})^2 \sim 1.13$, where the escape speed from Earth $v_\oplus \sim 11$ km/s (see the Appendix for a more detailed calculation of Earth’s gravitational focusing factor).

Capture by Circumstellar Disks. Another possible channel for the capture of rocky bodies is provided by circumstellar disks (Napier 2007; Brasser et al. 2007; Grishin et al. 2019; Napier et al. 2021a), which are present during the earliest phases of evolution. The lifetime of gaseous disks follows a nearly exponential distribution of the form

$$
F(t) = \frac{1}{\tau} \exp[-t/\tau],
$$

(13)

where the time scale $\tau \sim 5$ Myr (Hernández et al. 2007). As a result, this mechanism for capture operates only for early times – when the solar system is still within its birth cluster. If life is to be transferred through this channel,
then it must arise relatively early (on time scales of a few Myr). Although timing issues are important for the possible transfer of life, circumstellar disks can efficiently capture rocks, as outlined below.

A rock passing through a gaseous disk will experience a drag force that can be written in the form

$$F_D = A_{\text{eff}} \rho g v^2,$$

where the effective area of the rock is related to the geometric cross section according to

$$A_{\text{eff}} = \frac{C_D}{2} \pi R^2,$$

where $R$ is the rock radius and $C_D$ is the drag coefficient (Landau and Lifshitz 1959). In order for a rock of mass $m_R$ to be captured, it must come to rest within the nebula, where this criterion can be written in the form

$$\frac{2A_{\text{eff}}}{m_R} \Sigma > \log \left[ 1 + \frac{v_{\infty}^2 r}{2GM_*} \right],$$

where $v_{\infty}$ is the asymptotic speed, and where the rock passes through the disk at radius $r$ from the central star (Napier et al. 2021a, Appendix B). Here $\Sigma$ is the surface density of the circumstellar disk (evaluated at the location penetrated by the incoming rock). This expression assumes that the rock passes vertically through the disk; corrections can be applied to take into other angles of the trajectory and also the relative velocity between the incoming rock and the gas due to orbital motion in the disk. Note that within the birth cluster, the asymptotic speed of incoming rocks $v_{\infty} \sim 1$ km/s is generally much smaller than the orbit speed at the locations of interest (where $v^2 \sim GM_*/r$), so that rocks will generally have incoming speeds comparable to the local orbit speed when they encounter the disk. For the sake of definiteness, we use the Minimum Mass Solar Nebula (Hayashi 1981) as a benchmark model, where the surface density has the form

$$\Sigma(r) = \Sigma_0 \left( \frac{r}{r_0} \right)^{-3/2},$$

where $\Sigma_0 = 3000$ g/cm$^2$ and $r_0 = 1$ au (Weidenschilling 1977). With this profile, we can determine the capture condition and write the result in terms of a cross section

$$\sigma \approx \pi r_0^2 \left[ \frac{4A_{\text{eff}}}{m_R} \frac{GM_*}{v_{\infty}^2 r_0} \right]^{4/5}.$$

Evaluating this expression for the minimum viable rock mass $m_R = m_1 = 10^4$ g and for $v_{\infty} = 1$ km/s (values appropriate for cluster conditions), we find $\sigma \approx 69,000$ au$^2$. This cross section corresponds to a radial scale $\ell = (\sigma/\pi)^{1/2} \sim 150$ au, which is comparable to the expected outer radii of circumstellar disks. As a result, rocks with the minimum mass of interest for panspermia can be captured over essentially the entire disk area (but only over a time span of 3 – 5 Myr while the disk retains its gaseous component).

4. SURVIVAL TIMES AND TRANSFER

In the previous section we considered the dynamical capture of interstellar objects by our solar system. Although the capture and survival of life bearing rocks must occur in order for life to be transferred between planetary systems, most rocks do not find their way onto the surface of a habitable planet. The vast majority of captured bodies are ejected and those that survive the longest spend most of their time in the outer regions of the solar system. As a result, only a fraction $f_{\text{surf}}$ of the captured objects will reach the surface of a habitable planet. This section reviews the dynamical lifetime of captured interstellar objects and assesses the chances for captured objects to reach the surface of Earth.

Most captured objects have lifetimes that are much shorter than the age of the solar system. This behavior follows from the initial orbits of the captured rocky bodies, which typically have semi-major axes $a \sim 1000$ au and periastra $q \sim 10$ au (Napier et al. 2021a). With these orbital elements, captured objects tend to cross the orbits of the giant planets (but not that of Earth). The continuing interactions with giant planets, which have escape speeds larger than their orbital speeds, can often lead to ejection. In a recent set of numerical simulations (Napier et al. 2021b), the orbits of newly captured objects were integrated over the age of the solar system in order to determine their lifetimes. The resulting fraction $F(t)$ of remaining bodies as a function of time since capture can be fit with a function of the form

$$F(t) = \frac{1}{1 + (t/\tau)^{8/5}},$$
Figure 3. Surviving fraction of captured objects as a function of time. The black dots represent the data derived from the numerical simulations in Napier et al. 2021b. The solid blue curve shows the best fit from equation (18) to the numerical data. Where the time scale $\tau = 0.84$ Myr. Figure 3 shows the numerically determined survival function along with the analytic approximation from equation (18). The captured objects survive for of order $\sim 1$ Myr, with their population steadily decreasing on longer time scales. Note that relatively few objects surface on time scales $\sim 1$ Gyr, so that the survival fraction is not well-determined over longer times. Nonetheless, a straightforward extrapolation of the numerical results suggest that only a fraction $\sim 10^{-6}$ (one in a million) of the captured bodies can survive over the age of the solar system.

The numerical simulations show that during their residence time in the solar system, captured bodies tend to have perihelia $q \gtrsim 10$ au. In order to intercept an Earth-like planet, however, the orbit must have $q \lesssim 1$ au (where this condition is necessary but not sufficient). Because of this mismatch in orbital elements, and because of the small geometrical cross section, the fraction $f_{\text{surf}}$ of captured bodies that impact the surface of a terrestrial planet is expected to be extremely small. The numerical simulations used to specify the survival function $F(t)$ in equation (18) provide a working estimate of this quantity. The simulations integrated the long-term behavior of $N_{\text{sh}} = 276,691$ captured objects, with most bodies being eventually ejected. About one third of the objects (specifically 107,812) have orbits with perihelion $q < 1$ au at some point while they remain bound. These orbits have high eccentricities so that the objects puncture the sphere of radius 1 au centered on the Sun as they make their closest approach (and thus have a chance to collide with Earth). Since the orbits are (nearly) isotropically distributed in space, the fraction of orbits that correspond to planetary collisions is proportional to $R_{\text{sph}}^2/(4r_0^2)$, where $r_0 = 1$ au and $R_{\text{sph}}$ is the radius of the sphere of influence of Earth. The radius $R_{\text{sph}} \approx r_0 (M_{\oplus}/M_{\odot})^{2/5} \sim 0.006$ au (Bate et al. 1971), so that less than $\sim 1$ of the aforementioned orbits can possibly intercept the planet. The number of collisions could be higher because the bodies make multiple orbits. In the limit where the orbits survive long enough to sample the full range of mean anomaly for
Earth, $\sim 300$ of the objects would collide (this would require the objects to live for $N \gg r_0/(2R_{\text{sp}}) \sim 333$ orbits, which is more than typical). As a rough approximation, we can use the survival half-life $\tau = 0.84$ Myr to specify the typical number of orbits ($\sim 25$) and find an optimistic estimate of $f_{\text{surf}} \sim 25/N_{\text{bh}} \sim 10^{-4}$.

In an independent estimate of the transfer fraction, Melosh (2003) performed a series of numerical simulations and found that a comparable fraction $f_{\text{surf}} \sim 10^{-4}$ of the captured objects reach the surface of Earth over the age of the solar system. Rocky bodies can also strike the surface of Jovian moons, which could represent additional habitable environments (e.g., Worth et al. 2013). The fraction of such impacts is about an order of magnitude smaller, $f_{\text{surf}} \sim 10^{-5}$. These results are thus comparable to those described above. For the sake of definiteness, we take $f_{\text{surf}} = 10^{-4}$ for the estimates of this paper (note that the results can easily be scaled for different assumptions).

After arriving on the surface of a potentially habitable planet, any given life-bearing rock will not necessarily be able to seed its new world. Many difficulties are possible, e.g., the lack of a suitable environment at the landing site, as well as the destructive effects of passing through the atmosphere and crashing onto the planetary surface. One expects many failed attempts. Unfortunately, the fraction $f_{\text{surf}}$ of biologically active rocks is smaller by a factor of $f$ well as the destructive effects of passing through the atmosphere and crashing onto the planetary surface. One expects many failed attempts. Unfortunately, the fraction $f_{\text{surf}}$ of biologically active rocks is smaller by a factor of $f$ many failed attempts. Unfortunately, the fraction $f_{\text{surf}}$ of biologically active rocks is smaller by a factor of $f$.

5. SYNTHESIS

For a given background environment (the birth cluster or the field), the solar system will accumulate rocks from interstellar capture at a rate given by

$$\frac{dN}{dt} = n_R(\langle \sigma v \rangle),$$

where $n_R$ is the number density of rocks and the angular brackets denote an average of the cross section over the velocity distribution. Note that the quantity $n_R$ corresponds to the total number density of rocks, and that the number density of biologically active rocks is smaller by a factor of $f < 1$. The accumulated number of rocks captured over a given time span is determined by the integral of the capture rate, i.e.,

$$N = \int [n_R(\langle \sigma v \rangle)] \, dt,$$

where the limits on the integral are implicit. In principle, all of the quantities in the integrand can be time dependent. To a good approximation, however, we can consider two distinct phases, i.e., the first $\sim 10 - 100$ Myr when the solar system resides in its birth cluster and the subsequent $\sim 4.5$ Gyr when the solar system resides in the field. For each of these two phases, we can write the number of captured rocks in the form

$$N_x \approx N_{R_\ast}(\langle \sigma v \rangle)_x \left[ \int n_x \, dt \right]_x \equiv N_{R_\ast} \tau_1,$$

where the final equality defines $\tau_1$ as the optical depth for capture per star. Here, the subscript $x$ denotes the phase (birth cluster or field) and the integral is taken over the appropriate span of time. The number of rocks per star $N_{R_\ast}$ is discussed in Section 2. The other two factors are specified below.

**Velocity-averaged Cross Sections.** Using the cross sections $\sigma(v)$ presented in Section 3, we can evaluate $\langle \sigma v \rangle_x$ for the regimes of interest. We start with the cross section from equation (10) for dynamical capture. For the velocity distribution of equation (4) appropriate for ejected objects (as expected in the birth cluster), we find the result

$$\langle \sigma v \rangle = \sigma_0 \frac{v_p^3}{3} K(\eta),$$

where the dimensionless function $K(\eta)$ is defined such that $\eta \equiv v_p/v_p$ and

$$K(\eta) \equiv \pi \frac{(1 + \eta)(1 + 3\eta) + 3\eta^3/4}{(1 + \eta)^4}.$$

Using parameter values appropriate for the birth cluster (and for $v_p \approx 10$ km/s), we find $\langle \sigma v \rangle_{bc} \approx 540$ au$^2$ km/s. Similarly, using a Maxwellian velocity distribution with dispersion $s$ (as expected in the field), we find

$$\langle \sigma v \rangle = \sigma_0 s \left( \frac{v_p}{s} \right)^2 \sqrt{\frac{2}{\pi}} J(\mu),$$

where $J(\mu)$ is discussed in Section 2. The other two factors are specified below.
where the dimensionless function $J(\mu)$ is defined such that $\mu \equiv v_1^2/(2s^2)$ and

$$J(\mu) \equiv \mu \left[1 - \mu e^\mu E_1(\mu)\right],$$

(25)

where $E_1$ is the exponential integral (see Napier et al. 2021a for a derivation). Using parameter values appropriate for the field ($s = 40\sqrt{2}$ km/s), we find $\langle \sigma v \rangle_{f_d} \approx 0.016$ au$^2$ km/s.

For the case of direct capture onto the Earth and the velocity distribution of the birth cluster, the velocity averaged cross section becomes

$$\langle \sigma v \rangle = \frac{\pi^2}{16} R_e^2 v_p \left[1 + 6 \frac{GM_{\odot}}{r_0 v_p^2}\right] f_{g\odot}.$$  

(26)

Using the same values as before ($v_p = 10$ km/s), we find $\langle \sigma v \rangle_{dir-bc} \approx 7 \times 10^{-7}$ au$^2$ km/s. For the velocity distribution of the field, with a Maxwellian form, the corresponding expression takes the form

$$\langle \sigma v \rangle = \frac{\sqrt{2\pi}}{4} R_e^2 s \left[2 + \frac{2GM_{\odot}}{r_0 s^2}\right] f_{g\odot}.$$  

(27)

The numerical value (for $s = 40\sqrt{2}$ km/s) becomes $\langle \sigma v \rangle_{dir-f_d} \approx 2 \times 10^{-7}$ au$^2$ km/s. Note that the (averaged) direct capture cross sections have roughly comparable values (within a factor of $\sim 3$) in both the birth cluster environment and in the field.

For the case of disk capture, we only need to consider the parameters for the birth cluster since the disk lifetime is shorter than the residence time in the cluster. We can write the disk-capture cross section from equation (17) in the form

$$\sigma(v) = \sigma_0 \left(\frac{v}{v_1}\right)^{-8/5},$$

(28)

where $\sigma_0 \approx 69,000$ au$^2$ and where we have defined $v_1 = 1$ km/s. The velocity averaged cross section thus takes the form

$$\langle \sigma v \rangle = 4\sigma_0 v_p \left(\frac{v_1}{v_p}\right)^{8/5} \int_0^\infty \frac{u^{2/5} du}{(1+u^2)^3} = \sigma_0 v_p \left(\frac{v_1}{v_p}\right)^{8/5} \frac{39\pi}{25(1+\sqrt{5})},$$

(29)

which can be evaluated to find $\langle \sigma v \rangle \approx 26,000$ au$^2$ km/s. The disk is thus much more efficient in capturing passing rocks than either dynamical or direct capture. On the other hand, the other two channels can take place over the entire age of the solar system, whereas the disk lifetime is only a few Myr ($\sim 1000$ times shorter).

**Integrated Number Densities.** The next quantity of interest is the stellar number density integrated over residence time. The stellar number density in the solar neighborhood is measured to be $n_* \approx 0.1$ pc$^{-3}$ (Binney and Tremaine 2008), and can be considered as constant over the age of the solar system (which corresponds to the integration time). For the field, we thus find $\int n_*=dt \approx 450$ pc$^{-3}$ Myr.

For the solar birth cluster, a number of studies have placed constraints on this integral, which is bounded from above by the requirement that the solar system is not overly disrupted during its residence time. Various considerations include the undisturbed nature of the planetary orbits, the observed edge of the Kuiper Belt, and the narrow spread of mutual inclination angles of solar system bodies (e.g., see Adams and Laughlin 2001; Portegies Zwart 2009; Li and Adams 2015; Pfalzner 2013; Parker 2020; Batygin et al. 2020; Moore et al. 2020; and the review of Adams 2010). Although the lack of disruption implies an upper bound on $\int n_*=dt$, many solar system properties can be explained if the Sun lived within its birth cluster for an extended span of time (typically, 10 – 100 Myr). For example, the observed elevated abundances of short-lived radioactive nuclei (such as $^{26}$Al) could be provided by a supernova explosion within the birth cluster (e.g., see Cameron et al. 1995). The requirement that the cluster provides such a supernova implies a lower bound on the integral $\int n_*=dt$ (Adams and Laughlin 2001). Although many uncertainties remain, a self-consistent picture of the early solar system — while it remains in its birth cluster — indicates that $\int n_*=dt \sim 10^4$ pc$^{-3}$ Myr.

**Capture Optical Depth.** Using the above considerations, we can evaluate the optical depth for rock capture. The optical depth for a given rock to be captured by the solar system is determined by the quantity $\tau_1 = \langle \sigma v \rangle \left[\int n_*=dt\right]$. These values, along with the aforementioned components, are listed in Table 1. The table also lists the total number of rocks $N_{cap} = N_{R_0} \tau_1$ that are predicted to be captured during the two phases of interest. To evaluate this quantity, we use $N_{R_0} = 10^{16}$ rocks per star and assume that only 10% of the ejected rocks remain in the birth cluster (see Section 2). Next, we provide an estimate for the number $N_{bio} = f_B N_{cap}$ of biologically active rocks that could be captured
by the solar system. The values listed in the table assume that the fraction $f_B = 3 \times 10^{-12}$, which corresponds to the geometric mean of the allowed range. The total number $N_{\text{pan}}$ of expected panspermia events is determined by the fraction of the captured rocks that cross Earth’s orbit and land on its surface, and by the fraction $f_{\text{seed}}$ of those events that lead to the successful propagation of life. As a result, $N_{\text{pan}} = f_{\text{seed}} f_{\text{surf}} N_{\text{bio}}$. For the entries in Table 1, we use the fraction $f_{\text{surf}} = 10^{-4}$ (see Section 4 and Melosh 2003), but leave the fraction $f_{\text{seed}}$ unspecified. Although we expect $f_{\text{seed}} \ll 1$, we have no means of estimating its value.

### Rock Transfer Estimates

| quantity | Birth Cluster | Field | Direct | Disk |
|----------|---------------|-------|--------|------|
| $\langle \sigma v \rangle$ | 540 | 0.016 | $3 \times 10^{-7}$ | 26,000 au$^2$ km/s |
| $f n_\star dt$ | $10^4$ | 450 | 1500 | 25 pc$^{-3}$ Myr |
| $\tau_1$ | $10^{-4}$ | $3 \times 10^{-10}$ | $10^{-14}$ | $10^{-5}$ |
| $N_{\text{cap}}$ | $10^{11}$ | $2 \times 10^6$ | 100 | $10^{10}$ |
| $N_{\text{bio}}$ | 0.3 | $5 \times 10^{-6}$ | $3 \times 10^{-10}$ | 0 |
| $N_{\text{pan}}$ | $3 \times 10^{-5} f_{\text{seed}}$ | $5 \times 10^{-10} f_{\text{seed}}$ | $3 \times 10^{-14} f_{\text{seed}}$ | 0 |

Table 1. Cross sections, optical depths, and expected numbers of events for rock capture in the solar birth cluster and in the field. The optical depth $\tau_1$ determines the probability of a given rock being captured by the solar system (note that $\tau_1$ is given by the product of the entries in the first two lines, when converted into the proper units). Here, $N_{\text{cap}}$ is the expected number of captured rocks and $N_{\text{bio}}$ is the expected number of biologically active rocks captured. Only a fraction of those rocks cross Earth’s orbit and have a chance to seed life. To estimate the expected number $N_{\text{pan}}$ of panspermia events (final row), we have taken this fraction to be $f_{\text{surf}} \sim 10^{-4}$. The number of panspermia events must also be multiplied by the unknown (but probably small) fraction $f_{\text{seed}}$, which specifies the likelihood for life to thrive in its new environment.

In Table 1 we also include estimates for the transfer of rocks onto the surface of Earth by direct capture. In this scenario, where interstellar rocks directly strike the Earth’s surface, the velocity averaged cross section $\langle \sigma v \rangle$ is almost the same for both the birth cluster and the field. In this context, the gravitational focusing factor (in the cluster environment) nearly compensates for the reduced speed. For this estimate we thus combine the integrated number density $\int n_\star dt$, including the reduction factor in the birth cluster because most of the ejected rocks are unbound. The net result is that the number of rocks captured by directly striking the surface of Earth is about $10^4$ times smaller than the total number of rocks captured by the entire solar system from the field. However, all of the rocks that strike the Earth in direct capture events reach the surface of a habitable planet, by definition, so the reduction factor $f_{\text{surf}}$ does not apply. As result, approximately the same number of panspermia events result from direct capture and from dynamical capture in the field (whereas the number of events from dynamical capture in the birth cluster is far greater).

For completeness, Table 1 also includes the expected capture events by the circumstellar disk. Since the disk lifetime is only $3 - 5$ Myr, these interactions take place in the birth cluster. This short time span results in the reduced effective value of the integral $\int n_\star dt$. In addition to the shorter integration time, the number density of rocks is smaller because ejection takes places over the entire cluster lifetime. Although a large number of rocks are captured by the disk ($\sim 10^{10}$, roughly comparable to the number from dynamical capture in the birth cluster), no biologically active rocks are expected due to the short lifetimes.

Putting all of the factors together, we can write the total number of expected panspermia events in the form

$$N_{\text{pan}} = \sum_x \left[ N_{R_x} f_{\text{seed}} f_{\text{surf}} f_B \langle \sigma v \rangle \int n_\star dt \right]_x,$$

where the sum is taken over the different channels for capture. Note that in principle all of the efficiency factors could vary with the capture mechanism. For the estimates given in Table 1, the sum of equation (30) is dominated by capture events in the birth cluster, and even this quantity ($\sim 10^{-5} f_{\text{seed}}$) is much smaller than unity. This number could be even smaller if life cannot arise during the time that the solar system spends in the cluster. In that case,
the number of events drops to $\sim 10^{-9} f_{\text{seed}}$, with comparable contributions from direct capture by Earth and from gravitational capture by the solar system followed by subsequent transfer to the planetary surface. Finally we note that the galaxy contains $\sim 10^{11}$ stars and that the fraction of stars harboring Earth-like planets $\eta_\oplus \approx 0.1$ (Petigura et al. 2013). As a result, the number of panspermia events for the entire galaxy is estimated to be $\sim 10^{f_{\text{seed}}}$. It is important to note that the input parameters required to evaluate equation (30) are uncertain. The number of rocks per star depends sensitively on the index $p$ of the power-law distribution of rock sizes (see equation [6]), so that $N_{R,\ast}$ can vary by several orders of magnitude. In addition, the value of the factor $f_{\text{seed}}$, which specifies the likelihood for life to survive and flourish, is rather poorly constrained. We also note that additional channels of transfer can be considered. For example, if life arises rapidly, then rocky bodies can be captured while the surface area of solid bodies was dominated by planetesimals instead of planets, so that the cross section for direct capture (via impact) would be larger. Moving away from the particular properties of our solar system, the transfer of terrestrial life to other planetary systems would be more likely if those systems had architectures with less of an impedance mismatch between capturing planets like Jupiter and Saturn and accretors like the Earth (Tremaine 1993; Bonsor and Wyatt 2012; Wyatt et al. 2017). In addition, a sizable fraction of stars reside in binary systems, which have larger capture cross sections than our solar system (compare the results of Adams and Spergel 2005 with those of Napier et al. 2021a). We also note that planetary systems can live in different galactic environments with larger stellar density (like the galactic bulge) and that the optical depth for capture is directly proportional to $\eta_\ast$.

The results found here indicate that the best chance of transferring life-bearing rocks occurs with the birth cluster. The main uncertainty for this scenario is the time required for life to arise on any planet within the cluster, since the cluster lifetime in only $\sim 100$ Myr. On one hand, one argument put forth in favor of panspermia is that life began too quickly on Earth to be the result of internal processes like ‘random chemical interactions’ (Wesson 2010). On the other hand, if life can arise rapidly on other planets in the birth cluster, the underlying necessity of panspermia is diminished. In any case, the time when life began on Earth remains highly uncertain, varying from just after the Moon-forming impact at $\sim 4.5$ Ga to $\sim 3.8$ Ga (Sleep 2018).

6. CONCLUSION

This paper presents an updated assessment for the probability of rock transfer between planetary systems, including the question of whether life can propagate through this mechanism. We find that the probability of transferring life from one planetary system to another is quite low. On the other hand, the chances of transferring rocks between systems is quite high. A more specific summary of our results is given below, followed by a discussion of uncertainties and possible future directions.

Summary of results. Successful panspermia events are predicted to be exceedingly rare. The number of potentially life-bearing rocks that are captured per solar system is found to be of order unity in the birth cluster and nearly a million times smaller in the field. In order for life to be successfully transferred from one planetary system to another, however, the biologically active rocks must also make their way onto the surface of the new habitable planet (e.g., Earth) and life must subsequently thrive. The first process is known be a low probability event, whereas the odds of the second are essentially unknown. In addition, in order for the enhanced estimates for the birth cluster to be applicable, life must arise on a relatively short time scale ($t \ll 100$ Myr — while the sun resides within the cluster). If life takes $\sim 1$ Gyr to arise (a common assumption in astrobiology; Lunine 2005; Scharf 2009), then the expected number of panspermia events is $N_{\text{pan}} \sim 10^{-10} f_{\text{seed}}$ where $f_{\text{seed}} \ll 1$.

Although the solar system has resided in the field for much longer than in its birth cluster, the cluster environment dominates the process of rock transfer. The lower relative speeds allow for much larger capture cross sections and the higher densities act to further increase the capture rates. These effects more than compensate for the reduced residence time in the birth cluster ($t \lesssim 100$ Myr) compared to the field ($t \sim 4.5$ Gyr).

Captured rocks have a well-defined distribution of (initial) orbital elements which continue to evolve afterwards, and generally lead to ejection from the system. The fraction of surviving bodies follows a well-defined function, which has the form $f(t) \sim t^{-8/5}$ at late times $t \gg 1$ Myr (see Figure 3, equation [18], and Napier et al. 2021b). This steeply declining survival function reduces the chances of captured objects striking the surface of Earth.

Combining the capture rates with survival rates, one can estimate the total mass in alien rocks that currently resides on bound orbits within the solar system. These results (see Napier et al. 2021b) indicate that the mass captured from the birth cluster and that remains today is given by $M_{R,\ast} \sim 10^{-9} M_\oplus$; for comparison, the standing population of rocks captured from the field has estimated mass $M_{RF} \sim 7 \times 10^{-14} M_\oplus$. For the size distribution of rocks used here
(Section 2), the corresponding numbers of captured rocks are approximately $N_{RC} \sim 10^7$ from the birth cluster and $N_{RF} \sim 70$ from the field.

Discussion. The estimates of this paper are subject to a number of uncertainties. Significantly, the astrophysical parts of the problem are now relatively well understood. We have good working estimates for the capture cross sections, the survival times for captured objects, and the distributions of velocities for ejected rocks. These quantities have been determined by both numerical simulations and by supporting analytic calculations. Additional astrophysical elements of the problem have been estimated, including the dynamical properties of the birth cluster, the collision rate of captured bodies on planetary surfaces, and the distribution of rock sizes. The most important remaining uncertainties are those derived from biology. In particular, we would like to know the time required for life to arise, how often habitable planets actually produce life forms, and the likelihood of life gaining a foothold after crash landing into a new environment. These latter quantities combine to determine the fraction of rocks $f_B$ that contain biological material and the fraction $f_{\text{seed}}$ of rocks that can seed a new planet after being delivered to its surface. The factors $(f_B, f_{\text{seed}})$ thus encapsulate the largest uncertainties regarding panspermia estimates.

One important bottleneck is that life must arise spontaneously at least once — otherwise the panspermia mechanism cannot operate. Current estimates suggest that the spontaneous development of life is rare (Lumine 2005; Scharf 2009) — otherwise panspermia would not be necessary. Since the transfer of life between planetary systems is also quite rare (see Table 1), the key question is which of these processes is more common (see Davies 2003 for an extended discussion of this issue).

Most discussions of panspermia focus on estimates for the probability that Earth was seeded by biological material from afar. Given that Earth is the one place in the galaxy where life is known to exist, however, it also makes sense to consider whether or not life from our solar system has propagated elsewhere. The results of this paper (see also references herein) can be used to make such estimates. However, the cross sections and survival times depend on the architecture of the planetary system capturing the rocks, and the results presented here are carried out for our solar system. Future work could thus explore how varying planetary configurations will affect the results. As one line of inquiry, binary star systems are expected to have enhanced capture cross sections (Li and Adams 2015), but also have somewhat reduced real estate for habitable planets (David et al. 2003).

Although the focus of this work is to consider astrophysical processes, specifically the ejection and dynamical capture of rocks through gravitational interactions, some authors have considered the directed propagation of life (see, e.g., Crick and Orgel 1973; O’Neill 1974; Jones 1976; Walters et al. 1980; Djošović et al. 2018; Lingam and Loeb 2018; and many others). The directed propagation of life across the galaxy is a far more efficient process than the dynamical processes considered here (see also Vukotić and Ćirković 2012; Djošović et al. 2019).

Although clusters provide a means of enhancing transfer of rocks between constituent solar systems, the dense environment also presents additional hazards. In particular, cluster environments have intense ultraviolet radiation fields and elevated levels of cosmic radiation. For example, the distribution of possible UV fluxes is wide (Fatuzzo and Adams 2008), but the median value is typically $\sim 3000$ times larger than the interstellar value (which is $\sim 1.6 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$). As result, the cluster environment can be more destructive to life forms than the field. On the other hand, the cluster environment also provides another opportunity for the transfer of life: If the cluster itself, or one of its constituent planetary systems, can capture life-bearing rocks from outside, then life can readily be transferred to other members of the cluster. In this context, the cluster acts as an amplification mechanism for the transfer of life.

The results of this paper show that while the transfer of rocks between planetary systems is common, the transfer of life is predicted to be rare. In addition to the scenario outlined here, however, other possible channels exist (Burchell 2004). For example, even if captured bodies do not cross Earth’s orbit and impact its surface, out-gassing can disseminate microbes into interplanetary space (Hoyle and Wickramasinghe 1999). This process could take place early in solar system history, when many of the rocks are captured and while the planets are still forming. In such a chaotic environment, biological material can be spread throughout the field of rocky debris (Narlikar et al. 2003). Provided that these seeds of life live long enough, they could be swept up by Earth, Mars, or perhaps even Europa as they trace through their orbits. Although standard lithopanspermia is highly inefficient, one should keep in mind that alternate scenarios could play a role in the propagation of life through the galaxy.

APPENDIX
A. GRAVITATIONAL FOCUSING BY THE EARTH

In Section 3 we used an estimate to compute Earth’s gravitational focusing factor, as the correction from using the full treatment is rather small. In this appendix we provide a full analytic treatment for the gravitational focusing factor as a function of the incoming body’s orbital parameters (see also Opik 1951; Shoemaker and Wolfe 1982).

Earth’s gravitational focusing gives it an effective radius of

\[ R_{\text{eff}} = R_\oplus \left(1 + \frac{v_{\text{esc}}^2}{v_{\infty}^2} \right)^{1/2}, \]  

where \( v_{\infty} \) represents the hyperbolic excess velocity of the incoming object as it enters into a hyperbolic orbit about Earth. In general, calculation of \( v_{\infty} \) depends on the incoming body’s semi-major axis (\( a \)), eccentricity (\( e \)), and inclination (\( i \)). All of these quantities are well-defined for both hyperbolic and elliptical orbits, so the following formalism should be generally applicable. We begin by considering the incoming body’s specific energy and angular momentum, defined by

\[ E = -\frac{GM_\odot}{2a} \quad \text{and} \quad J^2 = GM_\odot a(1 - e^2). \]  

It follows that the radial velocity of the incoming body with respect to the Sun is given by

\[ v_{r\odot}^2 = 2E - \frac{J^2}{r^2} + \frac{2GM_\odot}{r} = \frac{2GM_\odot}{r} - \frac{GM_\odot a}{r^2} (1 - e^2) - \frac{GM_\odot}{a}. \]  

The non-radial velocity component of the incoming orbit is determined by conservation of angular momentum so that

\[ v_{\Omega\odot}^2 = \frac{J^2}{r^2} = \frac{GM_\odot a}{r^2} (1 - e^2). \]  

We can then break this quantity into azimuthal and longitudinal components as follows:

\[ v_{\varphi\odot}^2 = v_{\Omega\odot}^2 \cos^2 i \quad \text{and} \quad v_{\vartheta\odot}^2 = v_{\Omega\odot}^2 \sin^2 i. \]  

We now make the assumption that Earth is moving on a circular orbit with \( i = 0 \). In this approximation, the incoming rock’s radial and longitudinal velocities are equivalent in the Earth and Sun frames. The velocity components can then be written in the Earth frame as

\[ v_{r\oplus}^2 = v_{r\odot}^2, \quad v_{\varphi\oplus}^2 = (v_{\varphi\odot} - v_{\varpi})^2, \quad v_{\vartheta\oplus}^2 = v_{\vartheta\odot}^2. \]  

Then the relative velocity of the encounter is given by

\[ v_{\infty\oplus}^2 = v_{r\oplus}^2 + v_{\varphi\oplus}^2 + v_{\vartheta\oplus}^2. \]  

If we work through some algebra and make the substitutions \( r = a_\oplus \) and \( v_{\oplus}^2 = GM_\odot / a_\oplus \), this expression can be written as

\[ v_{\infty\oplus}^2 = v_{\oplus}^2 \left[ 3 - \frac{1 - e^2}{\xi^2} - 2\xi \cos i \right], \]  

where we have defined \( \xi \equiv \sqrt{(a / a_\oplus)(1 - e^2)} \). We see that the velocity scale is set by \( v_{\oplus} \approx 30 \text{ km/s} \) This expression is minimized when the body is moving in the same direction as Earth, and maximized when moving toward Earth head-on. Including the gravitational focusing factor, Earth’s effective cross section becomes enhanced by the factor

\[ f_g = \left(1 + \frac{v_{\text{esc}}^2}{v_{\infty}^2} \right), \]  

where \( v_{\infty} \) is given by equation (A8).

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