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A Mechanism for Interstellar Panspermia

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ABSTRACT
Metre-sized boulders ejected from the Earth by large impacts are destroyed through collisions and erosion by impacting zodiacal cloud dust particles. The timescale for such disintegration in a dense zodiacal cloud may be $\lesssim 10^4$ yr. Once reduced to a critical size, the particles are rapidly ejected from the solar system by radiation pressure. The critical size for ejection is of order a micron, large enough to protect groups of micro-organisms within them from solar UV irradiation. Such life-bearing particles are ejected at a mean rate of $\sim 10^{20}$ per million years. During passages of the solar system through or close to dense molecular clouds, a significant proportion of the particles may be incorporated into protoplanetary systems and protected from cosmic rays within growing planetesimals. The specific number density of micro-organisms so deposited is highest in small, dense molecular clouds. On the assumption that this ejection mechanism is common in other planetary systems environmentally capable of supporting life, a 'chain reaction' may seed the disc of the Galaxy within a few billion years. In that case it is unlikely that life originated on Earth.

Key words: astrobiology - interplanetary medium - molecular clouds - comets: general - ISM: clouds

1 INTRODUCTION

In his presidential address of 1871 to the British Association, Lord Kelvin suggested that impacts between planetary bodies might scatter life-bearing meteoric stones through space and on to the surfaces of other worlds, thereby propagating life between the stars (Thomson 1871). The basic concept goes back at least to William Herschel, who suggested that interstellar bodies may spread or sustain life, by accreting on to the surfaces of stars like the Sun (see Schafer 1977). Interest in this hypothesis was revived following the (disputed) claim that microfossils are present in the meteorite ALH 84001 of probable Martian origin (McKay et al. 1996). Large land impacts may throw meteorite-sized fragments of rock from the inner planets into interplanetary space (Melosh 1988, Gladman et al. 1996), and a significant exchange of boulders between Earth, Mars and the Moon has occurred throughout geological history. Boulders more than 20 cm across, ejected from the topmost layers of an impact site, are probably never heated to more than 100 °C in their interiors during the few seconds' flight time from ground to space, while bacteria seem able to survive the accelerations involved (Mastrapa et al. 2001). Thus bacteria within such boulders will survive ejection into space. Over 4 Gyr there may have been $\sim$40 land impacts on Earth producing craters over 60 km in diameter, yielding in total about 40 billion such boulders (loc. cit.). In the 10 million years following an impact, there is a roughly constant delivery rate of meteorites between Earth and Mars. Conversely, about 15 Martian meteorites may currently be falling on the Earth each year (Gladman 1997). Lord Kelvin's conjecture thus seems to have been vindicated by recent work: viable micro-organisms may be exchanged between the planets of the inner solar system.

Transfer of micro-organisms between stellar systems by this mechanism is, however, a more formidable prospect. Melosh (2003) has followed the fate of boulders ejected from the Earth until they collide with a planet, fall into the Sun or are ejected from the solar system. He found that about 15 metre-sized boulders originating from the inner planets are ejected from the solar system every year. Their mean residence time within the solar system is about 50 Myr, although with a very wide dispersion. The mean ejection speed is 5 ± 3 km s^{-1}. With these figures, Melosh finds that only one meteorite ejected from a planet within our solar system is likely to have been captured into another stellar system in 1,000 Myr and that, having been so captured, there is only a probability $\sim 10^{-4}$ that it will land on a terrestrial planet in that system (if it has one) within another 4.5 Gyr. Furthermore, according to Mileikowsky et al. (2000), viable micro-organisms decline in numbers exponentially due to destruction by galactic cosmic rays. Characteristically, a population of 10^8 micro-organisms is reduced to $\sim$ 100 or less after a million years. Thus the boulders will in any case be sterile

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by the time they are ejected from the solar system, even before they have begun their interstellar voyage of several billion years' duration.

Thus two factors, (a) the extremely long residence and travel times of boulders in interplanetary and interstellar space, and (b) the extremely low probability that any ejected boulder will ever impact on another terrestrial planet, seem to ensure that 'lithopanspermia' as currently envisaged is a local mechanism. In the absence of other transfer mechanisms, the Earth and any other life-bearing planets in the Galaxy would seem to be biologically isolated from each other.

In the present paper, however, I show that these life-bearing boulders may be destroyed by erosion and fragmentation within a few thousand years, especially when there is a large, active comet in the inner planetary system to enhance the mass of the zodiacal cloud. Their disintegration proceeds until the boulder fragments become β-meteoroids (for which the repulsion due to sunlight exceeds the attraction due to gravity) and are expelled from the solar system within a few years or decades of their ejection from the surface of the Earth, before solar UV or cosmic radiation can significantly damage the organisms within them. The mass so ejected is an order of magnitude greater than that from the action of gravity alone. However what matters is not so much the mass expelled as the number of micro-organisms, essentially codes for replication, expelled: a single micro-organism in a suitable environment may, following Lord Kelvin, populate a planet. Thus the expulsion of $\sim 10^{14}$ particles/yr, each with the potential to populate a planet, is a far more significant event than the expulsion of the same mass in the form of a few boulders/yr. The long travel times to other star systems are obviated by the fact that, over its history, the solar system has passed through about half a dozen giant molecular clouds and close to a few dozen dark cloud complexes. During such passages the star factories within these nebulae are seeded with micro-organisms which have been protected from UV radiation and not yet destroyed by galactic cosmic rays. For reasonable assumptions about the frequency of Earth-like planetary systems, life may thus spread throughout the Galactic disc in less than the age of the Galaxy.

2 BOULDER EJECTION FROM THE EARTH

Boulders ejected from the Earth into heliocentric orbits are subject to mean motion and secular resonances, and long-term drift due to perturbations of the orbits by radiation pressure (the Yarkovsky effect: Bottke et al. 2000). Monte Carlo codes which neglect these effects yield median lifetimes of tens of millions of years for near-Earth asteroids before they strike a planet or fall into the Sun (Melosh 2003). Integrations with these codes reveal that the Earth and Mars are themselves incapable of hyperbolically ejecting boulders. Melosh (2003) finds that about 15% of boulders ejected from the Earth attain Jupiter-crossing orbits within 100 Myr, and are thereafter ejected quite rapidly. The inclusion of the above effects may change this figure by a factor of a few, but still an enormous timespan remains during which boulders would reside in the inner solar system, subject to solar flare irradiation, erosion and fragmentation, before they are expelled into interstellar space.

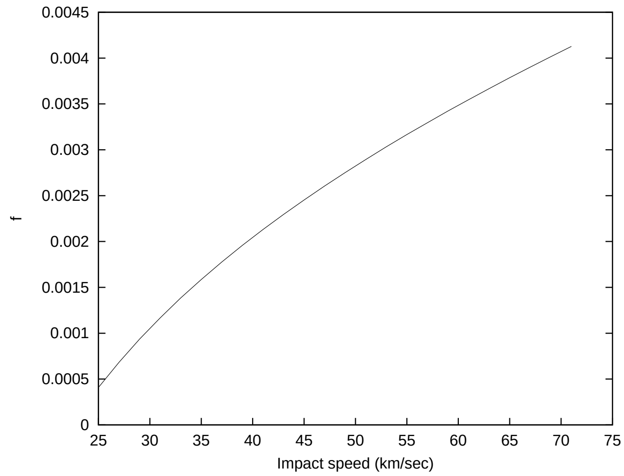

Figure 1. Mass m_e of ejecta thrown out from Earth (a fraction f of the impactor mass m) as a function of impact speed v_i.

According to Armstrong et al. (1989), the mass m_{ej} of material expelled by spalling of the target rocks on Earth, at speeds greater than escape velocity, v_e, is given as a fraction f of the projectile mass m by

$$f = \frac{m_{ej}}{m} = 0.75 \frac{P_m}{\rho c_L v_i} [(v_i/2v_e)^{5/3} - 1] \tag{1}$$

Here P_m represents the maximum pressure to which the debris (boulders) are subjected, ρ is their density and C_L is the speed of sound through the rock. v_i is the impact velocity of the projectile. Fig. 1 gives the survivable fraction as a function of impactor velocity, employing the rock data of Mileikowsky et al. (2000) (only material subject to shock pressures to less than 10^{10} dynes cm^{-2} is considered as otherwise shock heating would destroy organisms within the micro-pores of the rock). The equation has been derived under a number of conservative assumptions (loc. cit.). In particular it was assumed that ejecta must push their way through an unperturbed atmosphere: in reality, small fragments will be driven upwards through a cone evacuated by a large incoming bolide (Wallis & Wickramasinghe, pers. comm.). For material to escape at all from the Earth it is assumed that the impactor must strike the ground at more than twice the Earth's escape velocity.

Mean impact velocities of the various classes of near-Earth object have been computed by Jeffers et al. (2001). Their essential results are summarised in Table 1. It seems that over a 10 Myr period one may expect about 50 impacts of bodies (say) with masses in excess of 10^{16} g. The Halley-type comets peak strongly at $\sim$70 km s^{-1}. At these highest speeds, the contribution from dormant Halley-type comets is significant. Their existence is largely inferred rather than observed, however (Bailey & Emel'yanenko 1998) – strong selection effects operate against the discovery of dark objects with $\sim$200 yr orbital periods (Jewitt & Fernandez (2001) – but it is also possible that long-period and Halley-type comets disintegrate rather than become dormant (Levinson et al. 2002). The intermediate disintegration products could include many hazardous cometary meteoroids. The propor-

Table 1. Total impact probabilities and mean impact speeds $\bar{v}_i$ for various populations: near-Earth asteroids (NEA) >1 km diameter; short-period comets (SPC); Halley-type comets (HTC); and long-period comets (LPC). After Jeffers et al. (2001). The letter (d) refers to dormant populations which are hard to detect: their numbers are derived from considerations of population balance and are very uncertain.

impactor type	impacts per 10 Myr	$\bar{v}_i$ km/s
NEA (> 1 km)	29	22
SPC	1	20
SPC (d)	14	20
HTC	0	57
HTC (d)	3	57
LPC	3	54

tion of comets which end up as dormant bodies is at present an unresolved issue (Bailey 2002, Rickman et al. 2001). In general there are still many uncertainties in this area and the true impact rates of bolides in the various categories may be higher or lower than indicated by factors of at least two.

From Fig. 1 and the mean impact speeds of Table 1, we adopt a mean $f = m_e/m \sim 2\times10^{-3}$. Two thirds of impacts occur in the oceans and so an overall rate of one fast land impact per million years is expected. Over any given 10 Myr period, for a population distributed as $n(m) \propto m^{-\alpha}$, where the population index $\alpha \sim$1.7-2.0 down to a minimum mass ϵ, one typically finds a mean impactor mass in the range $\bar{m} \sim 2.0\text{-}3.5\epsilon$. For $\epsilon \sim 10^{16}$ g, the total mass of boulders ejected from the Earth at survivable temperatures is then $\bar{m}f \sim$400-700 million tons over a 10 Myr period. Of course the longer the interval considered the greater the probability of exceptionally large impact, and the interval 10 Myr has been chosen to represent, conservatively, the characteristic time which the solar system has spent in the environment of star-forming nebulae (Section 4). With impactor speeds of order 50 - 60 km s^{-1} rather than the 30 km s^{-1} adopted by Mileikowsky et al. (2000), hyperbolic ejection speeds up to $\sim$13 km s^{-1} may occur and so relatively few ejecta will be recaptured on subsequent passes of the Earth (Gladman et al. 1996).

3 FATE OF EJECTED BOULDERS

On leaving the Earth a boulder joins the zodiacal cloud and is subject to erosion by impacting dust and fragmentation by collisions with meteoroids. 'Dust' conventionally refers to particles with radii less than 0.1 mm (100 μm), 'meteoroids' to the larger bodies. About 95% of the zodiacal light is due to dust particles. This size also corresponds to a fairly sharp transition at 1 AU between radiation-dominated and collision-dominated dynamics (Grün et al. 1983): below 100 μm, the lifetimes of particles are limited by inspiralling due to the Poynting-Robertson effect; above it, they are limited by collisions. For a 1 mm meteoroid close to the orbit of the Earth (semi-major axis a=1 au, eccentricity e=0.1), the timescale for disruption against collisions is, in the present zodiacal cloud, τ_c=40,000 yr (Steel & Elford 1986). Erosion timescales τ_e are at least an order of magnitude longer.

The mass of the current zodiacal cloud, counting up to particles of 0.1 mm radius, is given by Leinert et al. (1983) as $\sim 10^{17}$ g, broadly in agreement with the dust impact rate measured with the *Long Duration Exposure Facility* (Love & Brownlee 1993). If the count is extended to include meteoroids up to 100 g, however, the mass of the zodiacal cloud has been variously estimated as 2.5×10^{19} g (Whipple 1967) and $3.0 \pm 1.0 \times 10^{20}$ g (Hughes 1996). However, over timescales of order 1 Myr, the zodiacal cloud is subject to strong, random surges in mass caused by the arrival of exceptionally large comets into short-period orbits followed by their disintegration (Napier 2001). Simulations allowing for both collisional disintegration and Poynting-Robertson drift indicate that the cloud may, following the entry of a Chiron-sized object into the inner planetary system, reach a mass two or three powers of ten higher than its current value for several millennia. When this happens the Poynting-Robertson lifetime is unchanged but the lifetimes against erosion and fragmentation are reduced by 2–3 orders of magnitude: the system becomes collision-dominated down to $\sim$10 μm. Over a 1 Myr period, therefore, there are likely to be several epochs when ejected boulders are subject to rapid destruction.

Consider a boulder of bulk density ρ_b and radius r immersed in zodiacal cloud particles whose density in space is ρ_z and which strike the boulder at V km s^{-1}. In time Δt the boulder loses a mass Δm, due to erosion, given by

$$\Delta m = -\pi r^2 \rho_z V \Gamma \, \Delta t \tag{2}$$

and its radius decreases by Δr obtained from

$$\Delta m = 4\pi \rho_b r^2 \Delta r$$

Here $\Gamma = m_e/m_z$ where m_e is the mass of boulder excavated by a colliding particle of mass m_z. Thus

$$\Delta r = -\frac{1}{4}(\rho_z/\rho_b) V \Gamma \Delta t \tag{3}$$

and so

$$r = r_0 - kt \tag{4}$$

The radius of the boulder thus decreases linearly until, in the absence of a catastrophic disruption, it would disappear in a time $\tau_e = 1/k$ given by

$$\tau_e = 4 r \rho_b / (V \Gamma \rho_z) \tag{5}$$

The excavation factor Γ – i.e. the mass excavated in units of the projectile mass – is found experimentally to vary as V^2 and has a value, for medium-strength rock with impact speed 10 km s^{-1}, $\Gamma \sim 5\times10^4$ (Grün et al. 1983). The erosion rate $\Gamma V \propto V^3$. Consider a metre-sized boulder with ρ_b=2.5 g cm^{-3} (mass 1.3 tons) injected into the current zodiacal cloud. Then in the absence of fragmentation, eqn (5) reveals that the rock would be destroyed by erosion within $\tau_e \sim$19000 yr if the cloud is taken to have mass 3×10^{20} g (Hughes 1996), or $\sim$230000 yr if we adopt the lower zodiacal cloud mass of Whipple. With a zodiacal cloud enhanced in mass by a disintegrating large comet, however, both number density and the mean encounter speed with an expelled boulder become significantly higher. The enhanced encounter speed comes from the higher mean eccentricity of particles derived from a short-period comet, before the Poynting-Robertson effect has had time to circularise their orbits. An enhancement by a factor 10 in cloud mass and 1.5 in particle velocity (Napier 2001, Fig. 5), reduces the erosion time to 560 yr and 6,800 yr respectively for boulders of this size.

When about half the mass of a metre-sized boulder has disappeared through erosion, it becomes vulnerable to fragmentation with cm-sized cometary meteoroids, and it joins the collisional regime of the zodiacal cloud as a whole. Napier & Dodd (1974) found that, in an environment where impinging particles have a power law distribution with population index α ~1.8, the fragmentation timescale τ_c for a basalt target is an order of magnitude shorter than the erosion one τ_e (Napier & Dodd 1974). It follows that the survival time of a boulder injected into an Earth-like orbit is very short, much less than 10^4 yr, during a period of enhanced giant-comet activity in the inner planetary system. A hierarchy of fragmentations reduces the boulder to dust whose ultimate fate (apart from planetary collisions which are a minor factor) is either infall to the Sun, or ejection from the solar system, both processes being radiation-driven.

Once the particles have become 'dust' ($< 100\,\mu m$ in radius) then ~50% of the mass excavated by collisions is immediately expelled as β-meteoroids, which are accelerated out of the solar system (Leinert et al 1983), although even before reaching this size, an increasing proportion of particles produced during erosive collisions may be expelled by radiation pressure.

Putting $\beta = P_R/g_\odot$ (P_R the solar radiation pressure on a grain and $g_\odot$ the gravitational acceleration), a silicate sphere of mass 10^{-10} g (4 μm diameter) has β ~0.1, increasing to β ~0.5 at 10^{-13} g or 0.4 μm diameter, before declining to β ~0.1 at 10^{-15} g (Ishimoto et al. 1993). Irregularly shaped grains in this size range may attain β values in excess of unity. In this size range the Poynting-Robertson timescale is ~1000 yr and probably comparable with or shorter than the timescale for collisions.

Unshielded micro-organisms will not survive exposure to solar ultraviolet radiation, but clusters of micro-organisms, imbedded in micropores of rock, may be adequately shielded: a layer of graphite ~0.024 μm thick has optical depth τ ~3 at ~2200 A, enough to protect the organisms within (Wickramasinghe 1967). Wickramasinghe & Wickramasinghe (pers. comm.) have pointed out that bacteria in clusters will, if exposed to ultraviolet light, develop a thin carbonised outer skin (~0.03 μm thick) adequate to shield interior organisms. Thus groups of micro-organisms within β-meteoroids may be self-shielded in their interiors from ultraviolet light.

In summary, during an episode of enhanced zodiacal cloud mass, by a factor of ten to a hundred over the present, the boulders ejected from Earth are destroyed in situ, becoming eroded or broken down to dust in a few thousand years. At 1 AU, the timescale τ_c for destruction by collisions is less than that for infall to the Sun τ_{PR} at all sizes down to about 10 μm, so that the dust particles remain in situ, at least half their mass then being expelled as β-meteoroids in the course of fragmenting collisions. The true proportion of mass so expelled is probably higher as losses occur during every eroding or fragmenting impact. It is likely that a large proportion of the expelled microbes are well protected from damaging ultraviolet radiation.

Moreno (1988) has suggested that sub-micron debris containing micro-organisms, and ejected from the Earth by impacts, may be driven to Mars by solar radiation pressure. We consider here the fate of small particles thrown into interstellar realms.

4 PASSAGE THROUGH A DENSE INTERSTELLAR CLOUD

A mean annual supply of 10 tons of life-bearing boulders, collisionally ground to β-meteoroids of (say) 1 μm radius, yields 10^{18} such particles/yr. For comparison the extremely common microbe *staphylococcus* has radius 0.125 μm, the T1 bacteriophage 0.03 μm (Secker et al. 1994). A gram of rich soil contains typically 10^9 micro-organisms, rock presumably at least one or two orders of magnitude less, depending on porosity, location and so on. Most of the lightly-shocked boulders ejected from Earth come from within a few metres of the surface due to interference and cancellation of shock waves near a free surface (Melosh 1988). We assume 10^8 micro-organisms per gram of ejecta, but clearly this figure will vary by orders of magnitude from one impact to another depending on accident of location and epoch.

The β-meteoroids ejected from the solar system will be concentrated in a number of expanding shells corresponding to discrete past impacts. The terminal velocities of the shells are given by

$$v_t = \sqrt{(}2\mu'/r) \tag{6}$$

where r ~1 AU is the distance at which the β-meteor was formed and μ'/r^2 is the net repulsive acceleration of the meteor due to the excess of solar radiation pressure over gravity. Thus for β-meteoroids with radiation force 10% in excess of the gravitational one, v_t=13 km s^{-1} and the shell has moved 1.9 pc from the solar system in 140,000 yr; for meteoroids with radiation force 40% over gravity, v_t=27 km s^{-1} and the shell has moved 1.9 pc from Earth in 70,000 yr. A meteoroid with solar repulsion four times greater than gravity will attain a terminal speed v_t ~85 km s^{-1} out of the solar system and travel 6 pc in this time. A 1 μm grain with a graphite coat 0.02 μm thick is an example (Wickramasinghe & Wickramasinghe, pers. comm.).

Exposed to Galactic cosmic rays, the viable microbe population declines exponentially, at a rate depending on the specific organism. From the examples given by Mileikowsky et al. (2000), half-lives of 50,000–100,000 yr seem characteristic. This kill rate includes the effect of irreparable damage to the DNA. Adopting a half-life of 75,000 yr, then in say 100,000 yr almost half the ejected organisms will still be alive, albeit dormant. For an ejection of n_0 microbes each year, the solar system is surrounded by an equilibrium 'biosphere' of $n_0 t_{1/2}$ ~8×10^{20} living micro-organisms, extending out to ~5 pc. The half-life adopted may, however, be highly conservative (Wickramasinghe, pers. comm.)

In the situation where the Sun is passing through a dense nebula, the distances travelled by the β-meteoroids allow them to penetrate small molecular clouds, or clumpy structure within giant molecular clouds, in timescales comfortably less than the half-lives for destruction of unshielded micro-organisms by galactic cosmic rays.

The sun has penetrated giant molecular clouds (mean mass $M{\sim}3$–$10{\times}10^5 M_\odot$, mean radius $R{\sim}20\,\mathrm{pc}$) about 5 times in the last 4 Gyr. At an encounter speed $V_\odot \sim 20\,\mathrm{km\,s^{-1}}$, the mean passage time through a GMC is $4/3(R/V_\odot) \sim 3\,\mathrm{Myr}$. Thus if the impact rate on Earth is unchanged from its current value the GMC is infected with terrestrial micro-organisms at a rate of $10^7\,\mathrm{g\,yr^{-1}}$, 10^8 micro-organisms $\mathrm{g^{-1}}$, for 3 Myr, yielding a deposition per passage of $3{\times}10^{21}$ micro-organisms.

A key feature of an encounter with a GMC is that the Oort cloud becomes gravitationally disturbed, generating a comet shower. Infall times of 2 - 3 Myr correspond to comets with semi-major axes in the range 25,000 - 33,000 AU so that the shower may peak while the Sun is still immersed in the GMC. Such encounters will take place when the Sun passes through the spiral arms of the Galaxy, where GMCs are concentrated. Detailed modelling of such a prolonged disturbance of the Oort cloud has not been carried out at the time of writing, but it seems inevitable that there will be at least an order of magnitude increase in the flux of long-period comets during the penetration. In that situation (see Table 1) terrestrial bombardment may become dominated by high-speed impactors, if Oort cloud comets are indeed significant contributors (directly or indirectly through replenishing the Halley comet reservoir).

In addition to the GMC penetrations, the Sun may pass close to a larger number of dark cloud complexes (DCCs) of smaller dimensions. Low-mass stars are formed in both types of cloud, but GMCs are the primary creation sites for stars of high mass (e.g. Mundy 1994). GMCs have a clumpy internal structure whose mass distribution can be represented as a power law with population index $\alpha = 1.6{\pm}0.2$ (Mundy 1994). The DCC population may likewise be so fitted: the mass spectrum of over 1500 clouds in the Perseus Arm has index 1.75 (Heyer & Terebey 1998). This fit extends down to nebulae with masses as low as $\sim 100\,M_\odot$ and suggests that both DCCs and GMCs may be part of the same population (Blitz & Williams 1998). The solar system passes within d pc of such nebulae at intervals Δt Myr given by

$$\Delta t \sim 800(M/5\times10^5)^{0.75}(d/20)^{-2} \qquad (7)$$

assuming the mass of molecular gas in the Galactic disc is unchanged over the lifetime of the solar system.

From (7) the solar system passes within 5 pc of a 5,000 $M_\odot$ nebula every 400 Myr or so, and a 1,000 $M_\odot$ nebula every $\sim$120 Myr. Biologically active material may therefore be deposited in passing star-forming nebulae at relatively frequent intervals in geological terms. The characteristic radii of nebulae in this mass range is one or two parsec.

Particles scattered into a dark cloud are preferentially absorbed into dense regions where the collision rate with nebular material is higher. Mantle accretion and grain growth occur in dense molecular cores (e.g. Pollack et al. 1994) and it is to be expected that the injected particles will take part in these processes. There is direct evidence that many comets have formed at temperatures which put them in the trans-Neptunian zone of the classical solar nebula, or even in a molecular cloud environment (Mumma 1996; see also the review by Napier & Clube 1997 for references). Large, fragile interplanetary dust particles of probable cometary origin have D/H isotope ratios approaching those of molecular clouds, indicating that molecular cloud material has been incorporated intact into comets (Messenger 2000). Thus micro-organisms may be incorporated directly into cold, growing cometary masses. Once so incorporated, they are protected from further destruction by Galactic cosmic rays. The growth of comets may take place on timescales as little as 1000 yr (Hills 1982, Napier & Humphries 1986).

Distributing $3{\times}10^{21}$ micro-organisms amongst 10^{39} g of molecular material in a GMC yields one micro-organism per 10^{16} g of nebular dust, assuming a dust-to-gas ratio of 3%. Consider the effect of this bio-material on a hypothetical planetary system identical to our own. At present 40,000 tons of dust fall on Earth annually. The smaller dust particles at least are braked gently by the current atmosphere and micro-organisms within them would survive flash heating during the fall (e.g. Hoyle & Wickramasinghe 2000, Coulson 2003). This flux has probably been constant over the past 3 Gyr, and if the current value is an ‘average’ then $\sim 1.2{\times}10^{20}$ g of cosmic material has fallen on Earth over that period, permitting $\sim$10000 dormant microbes to reach the ground, assuming the infalling material is relatively unprocessed material. However, the lunar cratering rate shows the mean impact rate to have been at least two or three powers of ten higher over the first 500 Myr of the record (Neukum & Ivanov 1994) or 2×10^{21}–2×10^{22} g This would imply the fall of some $2{\times}10^5$–$2{\times}10^6$ microbes on to the primordial Earth. The conditions would possibly be too harsh for life to take a hold, but as the cratering rate declined, there would be a transition to a time where incoming microbes could survive and replicate.

The mass M of molecular clouds ρ varies with cloud radius R as $M \propto R^2$ over at least eight decades of mass (Elmegreen & Falgarone 1996), whence small clouds are systematically more dense. As a result, for a dark cloud of mass 1000 $M_\odot$ passing through the biosphere and sweeping up micro-organisms, the resulting microbe concentration is readily found to be an order of magnitude higher than that in a GMC. Infall on to hypothetical early Earths forming within such a cloud is correspondingly higher. Since DCCs are the sites of low-mass stars and close encounters with them are an order of magnitude more frequent than with GMCs, it seems that these dark cloud complexes may be prime sites for the replication of life throughout the Galaxy.

5 DISCUSSION AND CONCLUSIONS

5.1 Earth to Galaxy

The mechanism described herein bridges the lithopanspermia of Lord Kelvin and the cometary panspermia of Hoyle & Wickramasinghe (2000), and indeed one may follow from the other. The largest uncertainty resides in the assumption that solar systems environmentally capable of supporting and disseminating life are common throughout the Galactic disk. However Europa and Mars have both been considered as possible sites for archaean or current life, and the existence of at least two other candidates for life in the solar system suggests that biofriendly planets may be common throughout the Galaxy. To populate 10^{10} suitable planets within the lifetime of the Galaxy would require about 33 generations with a doubling time of about 300 Myr, and, neglecting the contribution from DCCs, this would require inoculation of something like a dozen planetary systems during each GMC encounter. Since an OB association may typically contain 10^3–10^4 T Tauri stars, this requirement seems reasonable. Within the molecular ring of the Galaxy (3–8 kpc from the nucleus, peaking at $\sim$5.5 kpc), the number density of clouds is 5 or 6 times higher than the local density (Blitz & Williams 1998). In that case a microbe-losing star system would penetrate DCCs every few million years, and GMCs every $\sim$50 Myr, so providing an environment in which the reaction could propagate in no more than a few Galactic rotations.

5.2 Galaxy to Earth

On this hypothesis the Earth is part of a chain reaction whereby life has spread throughout the Galaxy, taking root and replicating wherever suitable environments occur: if the Galaxy were initially sterile, it could have been inoculated by transmission of life from Earth. However the fact that terrestrial life is part of this chain reaction does not mean that it initiated the reaction, and simple probability argues against it. Thus on the present hypothesis the origin of terrestrial life should be sought elsewhere, in the Galaxy or beyond.

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