EXCHANGE OF BIOMATERIAL BETWEEN PLANETARY SYSTEMS

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Abstract

It is now known that dynamical highways exist along which viable microorganisms may travel between the planets of the solar system. The extension of this concept to interstellar distances is explored here. Giant molecular clouds play a significant role in the process. They stimulate exoplanetary systems by disturbing their comet clouds and enhancing planetary impact rates. Biomaterial thrown out by impacts is injected directly into their stellar nurseries, with transfer times typically 0.1-0.5 million years. With reasonably conservative assumptions it is expected that, if life started at one locality in the Galaxy 5-10 Gyr ago, it would by now occupy ecological niches throughout the habitable zone. The chief uncertainty is the proportion of planetary systems capable of receiving life, nurturing it and re-ejecting it through impacts: a critical proportion of $\sim 10^{-3}$ to $\sim 10^{-4}$ such exoplanetary systems is necessary for the diffusion of life to go critical in the solar neighbourhood. This requirement is relaxed within $\sim$3-5 kpc of the Galactic centre.

Key words: astrobiology, comets, interplanetary dust, interstellar dust, panspermia.

1

1. INTRODUCTION

The idea that life may drift between the stars, taking root wherever it finds a suitable habitat, goes back to the 18th century, although precursors of the concept can be recognised in writings and myth extending back for over two millennia (Wainwright & Alshammari 2010). While the hypothesis may have a romantic appeal, it has not generally been seen as a serious proposition. One problem is that electromagnetic radiation and cosmic rays provide an effective barrier, sterilising life on such an interstellar journey (Mileikowsky et al. 2000). Another is that lithopanspermia – the transfer of life protected inside large boulders flung into space from an impact – seems to be a local phenomenon, confined to a single planetary system: boulders flung into interstellar space with their cargo of protected microorganisms are destined to wander forever, with virtually no chance of ever landing on a suitable exoplanet (Melosh 2003).

This scenario, however, takes no account of the molecular cloud system of the Galaxy. Massive nebulae, which are sites of star formation, are much larger targets than individual exoplanetary systems. Ordinary disc stars, such as the Sun, encounter them quite frequently on geological timescales. Giant molecular clouds are the most massive entities in the Galaxy (Solomon & Sanders 1980), and close encounters with them disturb the Oort cloud and may lead to episodes of cometary bombardment on Earth (Napier & Staniucha 1982; Wickramasinghe & Napier 2008). These close passages reduce the journey made by microorganisms into the interiors of the nebulae to a short-hop flight of perhaps 100,000 years' duration – a survivable time, especially in the reduced cosmic ray intensity of a molecular cloud. Since these nebulae are also prime sites for star formation in the Galaxy, the propensity is there for biomaterial to be injected directly into nascent planetary systems.

A further consideration is that erosion and fragmentation of boulders ejected from life-bearing planets, in the disturbed environment of a bombardment episode, may increase their information-carrying capacity by many orders of magnitude. A single fecund boulder may seed life should it end up on a suitable exoplanet; but if in the course of its journey erosion generates many particles containing microorganisms, the capacity for disseminating life is correspondingly increased. Erosion also allows radiation pressure to rapidly expel micron-sized particles reducing escape times from the planetary system by six or more orders of

magnitude (Napier 2004).

Since it would take only a few survivors to establish life on a receptive new world, we are dealing with the product of a very small number (survival fraction) and a very large one (multiplication factor). Should the product turn out to be favourable, we still have to ask how the diffusion timescale compares with the age of the Galactic disc, and this in turn depends on such factors as the metallicity evolution of the Galaxy, the frequency of suitable planetary systems and the importance of biohazards such as supernova explosions. To populate available niches throughout the habitable zone of the Galaxy within its lifetime, we require 0.01 - 0.1% of exoplanetary systems created in young star clusters to have a receptive planet and to be capable of ejecting microbiota cultured in that planet out of the system. While this requirement seems modest, more data on exoplanetary systems will be necessary to quantify this aspect of the problem.

2. ENCOUNTERS WITH MOLECULAR CLOUDS

Lithopanspermia, as usually discussed, starts with large impacts. There is good statistical evidence that these do not occur at random, but rather are part of bombardment episodes. For example the Chicxulub (180 km) and Boltysh (40 km) impact craters, associated with the Cretaceous-Tertiary extinctions, coincide in time to within 25,000 years (Jolley et al. 2010). This is not easily understood by anything other than the disintegration of a very large comet in the near-Earth environment. More generally, the significance of large impact clustering for panspermia is that they are probably indicative of cometary bombardment episodes (Napier 2006; Napier & Clube 1979). The prime source for comets appears to be the Oort cloud (Emel'yanenko et al. 2007; Biryukov 2007). This is a system of about 10^{11} comets extending out to 50,000 AU and only just gravitationally bound to the Sun. And because the Sun has such a tenuous gravitational hold, the Oort cloud is sensitive to external disturbances. A major source of such disturbances is the system of molecular clouds in the plane of the Galaxy, which have masses up to 5×10^5 that of the Sun, and which drastically perturb the Oort cloud during close encounters. These lead to episodes of bombardment of comets on the Earth, although other causes are also at work (such as occasional stellar penetrations of the inner Oort).
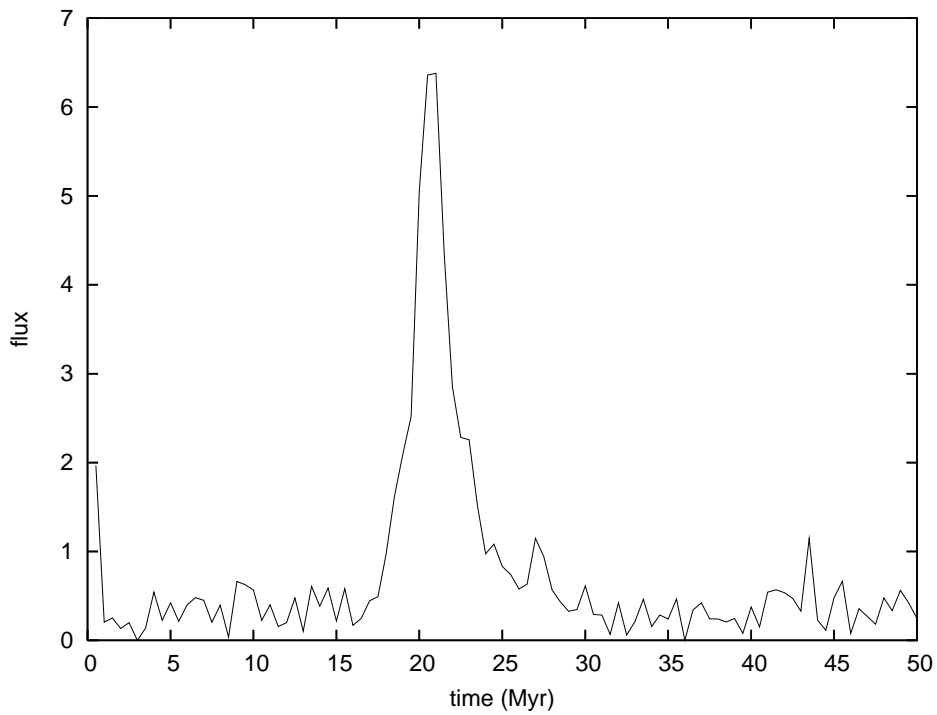
Figure 1: Flux of comets entering the planetary system from the Oort cloud due to a grazing encounter with a giant molecular cloud (Wickramasinghe & Napier 2008). Closest approach is at 20 million years, but the flux of long period comets into the planetary system increases significantly as the nebula approaches, and peaks just after closest approach.

M	R	t (5 pc)	t (20 pc)
500,000	20	3,900	500
100,000	10	2,600	200
50,000	6	1,800	140
5,000	2	650	40

Table 1: Mean interval (in Myr) between encounters with nebulae of various masses (in $M_\odot$). The corresponding mean radii R are shown in pc. Encounters within 5 pc and 20 pc of the centres of these nebulae are given. A mean encounter speed $20 \ \mathrm{km\,s}^{-1}$ is adopted. Note that the 5 pc time intervals for the larger masses are purely formal, since these encounters are actually penetrations of the nebulae.

Encounters with nebulae are quite frequent on geological timescales (Table 1). For the more massive nebulae, gravitational focusing is significant, reducing encounter times by a factor up to two (Napier 2004). The Earth has probably penetrated giant molecular clouds ∼10 times in its history, such passages taking typically two or three million years. There have probably been a comparable number of grazing encounters with nebulae of 5,000 $M_\odot$ or more, which have a comparable effect (although shorter in duration), and about thirty weaker encounters with such nebulae within 20 pc.

Figure 1 shows the outcome of a grazing encounter with a giant molecular cloud (Wickramasinghe & Napier 2008; see also Mazeeva 2004). There is an order of magnitude surge in the flux of long period comets into the planetary system. During the encounter there is a corresponding increase in the probability of terrestrial impacts, not only directly but also indirectly through a cascade of comets feeding into the Jupiter family system, since the Oort cloud appears to be a significant or prime source for the latter (Emel'yanenko et al. 2007; Biryukov 2007).

3. THE ZODIACAL CLOUD

The long-period comets, although relatively minor hazards themselves, feed into other populations such as the Halley-type and Jupiter family comets. A small proportion of these may be thrown into short-period, Earth-crossing orbits, when they become impact hazards. Comet breakup tends to be hierarchical, with secondary bodies and dormant meteoroids being formed en route to the disintegration into dust (Jenniskens 2008).

This dust constitutes a short-lived entity in the inner planetary system, the zodiacal cloud.

The zodiacal cloud can be seen by the naked eye in the right circumstances, and has been studied in the infrared, visually, and to some extent in situ by collection of dust particles on Earth and space. It is disc-shaped and extends from about 0.2 AU from the Sun to beyond 5 AU. There are different estimates for the relative contributions of comets and asteroids dust to this cloud. According to Nesvorný et al. (2010), 85–95% of the mid-infrared emission from this dust is generated by the breakup of Jupiter family comets, with small admixtures of asteroid dust and particles from long-period comets. Other estimates suggest an asteroid dust contribution up to about a third. The current mass of the zodiacal cloud is estimated at 1–2×10^{19} gm (Nesvorný et al. 2010), mainly in 100–200 μm particles, not very different from the 2.5×10^{19} gm estimate made by Whipple in 1967.

When material is ejected from Earth by large impacts, it is immediately immersed in the zodiacal cloud, and the effect of the cloud on the ejecta needs to be considered.

4. EXPULSION OF BIOMATERIAL FROM THE EARTH

4.1 Ejection of boulders

The ejection of rocks from the Earth through impact, the survival of microorganisms within them, and the exchange of life-bearing rocks between the inner planets have been studied through a mixture of theory and experiment (Wallis & Wickramasinghe 1995; Gladman et al. 2005; Melosh 2003; Mileikowsky et al. 2000; Reyes-Ruiz et al. 2011). Large impacts, of the sort associated with the Cretaceous-Tertiary extinctions, may result in the ejection of boulders from Earth, the proportion of material attaining escape velocity being sensitive to the velocity of the impactor (Melosh 1985). A few percent of the mass ejected during the formation of an impact crater is relatively unshocked, coming from a shallow layer within the crater rim where shockwaves tend to cancel each other out. The passage of this material through the atmosphere is swift, so that for boulders $\gtrsim 20$ cm in diameter internal temperatures remain at less than 100°C (Melosh 1989). For the launch conditions of a large impact, modern microorganisms lofted into space have survival fractions of $\sim 10^{-4}$–10^{-7} (Burchell et al. 2001; Horneck et al. 2008).
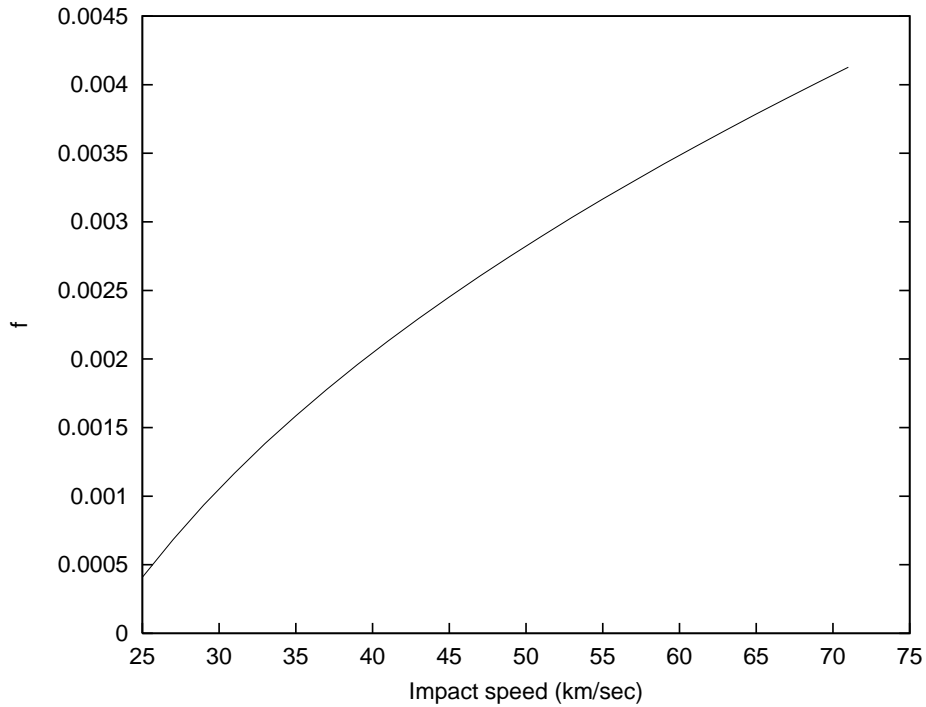
Figure 2: Mass of ejecta thrown out from Earth (expressed as a survivable fraction f of the impactor mass) as a function of impact speed.

At the highest impact speed considered by Reyes-Ruiz et al. (2011) – 33 $km\,s^{-1}$ – about one in 15 particles reached distances greater than 40 astronomical units within 30,000 years, the duration of the integration. Melosh (1983) estimates that about 15 life-bearing boulders from Earth eventually find their way into interstellar space, being ejected by the giant planets, their median residence time within the solar system being 50 million years (Melosh 2003). Wandering between the stars, there is a small probability ($\sim$3-10%) that some of these boulders will be captured into another planetary system and a further small probability that some of these captured boulders will land on an Earth-like planet. Putting numbers into these processes, it is likely that no fecund boulder from Earth has ever landed on the surface of an extrasolar planet by this means (Melosh 2003; Valtonen et al. 2009).

A number of somewhat conservative assumptions have gone into some of these studies:

7

First, the impact speeds in the 'ejection from Earth' simulations generally did not exceed 33 $\mathrm{km\,s}^{-1}$ (Reyes-Ruiz et al. 2011). This encompasses asteroid (22 $\mathrm{km\,s}^{-1}$) and Jupiter family comet impacts (20 $\mathrm{km\,s}^{-1}$), but not long-period or Halley-type comet impacts which, in the mean, impact at 56 $\mathrm{km\,s}^{-1}$, peaking at about 70 $\mathrm{km\,s}^{-1}$. The latter are considered to make a minor contribution to the impact rate of smaller bodies (about 15% of impactors over a kilometre across), but there are arguments to suggest that, as the impactor size increases, so also does the preponderance of Halley-type cometary impactors (Napier et al. 2004; Emel'yanenko & Bailey 1998). Fig. 2, based on Armstrong et al (2002), illustrates the mass fraction $f = m_e/m$ of material ejected from the Earth as a function of the collision speed v_i of the impacting body, where m is the mass of the impactor. It can be seen that cometary impactors yield a mass ejection on collision an order of magnitude higher than that expected from asteroids (Napier 2004). Further, their much higher impact speeds result in faster expulsion of boulders, which hastens their passage to Jupiter-crossing orbits and enhances the probability of their ejection from the solar system (Reyes-Ruiz et al. 2011).

Second, the assumption that viability stops at 100°C, as adopted in these studies, may also be challenged since there is experimental evidence that freeze-dried bacteria and spores are resistant to flash heating up to at least 350°C for 30 seconds (Hoyle et al. 1999).

Third, although only metre-sized boulders have been considered as the carriers for microorganisms, due to their ability to shield them from cosmic rays, Wallis & Wickramasinghe (2004) consider that cosmic ray protection may be provided by much smaller masses. They also point out that, in the case of a large impact, the bolide essentially blows a hole through the atmosphere and that debris down to millimetre sizes or less could be ejected. As discussed below, long-term protection from cosmic rays may be less necessary for the short transfer of material into passing nebulae.

Melosh (2003) used Monte Carlo integrations to follow the fate of bodies ejected from the surface of the Earth by a large impact. He found that about 15 unshocked metre-sized sized boulders are expelled from the solar system each year, the median residence time within the solar system being about 50 million years. Although it seems from these arguments that the rate of injection of biologically active material thrown into interstellar space may be much larger than that derived by Melosh, his figure is

adopted here as a benchmark.

4.2 Destruction of boulders

The microorganism count in modern soil is perhaps $\sim 10^7$–10^9 gm^{-1}. If say $m_b \sim 10^7$ g of life-bearing boulders leave the solar system each year in the form of metre-sized boulders, there are essentially ~ 10 units of information per annum being sent out from the planetary system. But if the boulders are fragmented or eroded, either within the planetary system or on entry into the molecular cloud or exoplanetary system, the same mass may carry the same biological information to many more potential sites, greatly enhancing the probability of its dissemination. It has to be seen whether the larger numbers of fragments is offset by their lesser shielding from cosmic rays.

Consider a system of bodies undergoing mutual fragmenting collisions. A state of equilibrium is reached, when the population has a power law with index $\alpha \sim 1.8$. Fragmentation occurs when the impacting body has a mass m greater than some threshold given by

$$m > \gamma' M \tag{1}$$

where M is the mass of the target body. Projectiles of smaller mass yield cratering rather than fragmentation, the ejected mass m_e being given by

$$m_e = \gamma M \tag{2}$$

Consider a rock of density ρ_b and initial radius r_0, struck by zodiacal cloud particles with speed V and space density ρ_z. Its initial radius r_0 declines linearly with time, and it is eroded away on a timescale

$$\tau = 4r_0\rho_b/(V\gamma\rho_z) \tag{3}$$

Laboratory simulation experiments and lunar microcrater studies (e.g. Fechtig et al. 1974) yield values for the mass excavation factor γ of a few hundred, for the μm to cm-sized projectiles likely to strike a boulder. This covers the great bulk of the mass of the zodiacal cloud dust and micrometeorites (Grün et al. 1985). Taking $\rho_b = 2$ g cm^{-3}, $\rho_z = 10^{-20}$ g cm^{-3}, $V = 20$ km s^{-1}, $\gamma = 200$, one finds that a 20 cm diameter boulder would be eroded away in about 0.65 Myr.

A boulder is, however, much more likely to be fragmented than completely eroded. For a mass of fragments distributed as

$$n(m) \propto m^{-\alpha} \tag{4}$$

the fraction of mass lost $\Delta M/M$ in erosive collisions before fragmentation takes place is

$$\frac{\Delta M}{M} \sim \gamma\gamma' \left(\frac{\alpha - 1}{\alpha - 2}\right) \tag{5}$$

(Napier & Dodd 1974).

For medium strength rock, an impact at 10 km s^{-1} has

$$\gamma' \sim 5 \times 10^4 \tag{6}$$

and so

$$\frac{\Delta M}{M} \sim 0.04 \tag{7}$$

and since $m \propto r^3$, the 20 cm boulder can expect to be fragmented in ≤ 9000 years. On disruption, the mass of the largest fragment is typically a third that of the initial body, and in consequence fragmentation cascades at an increasing pace. These rates are about an order of magnitude higher than those generally derived for the current interplanetary environment – for example Steel & Elford (1986) found that a 1 mm particle fragments in a few times 10^4 yr. This can be ascribed to the assumption above of collisional equilibrium: the zodiacal cloud we see is not in equilibrium; rather, it is a snapshot of a fluctuating system, with a recent large comet having supplied material. Without replenishment, much of it would be gone within a few 10^4 years due to mutual fragmentation and radiative drag.

Replenishment comes largely from comets deriving from the Jupiter family, and is likely to be erratic, being dominated by the arrival of rare, large bodies into the system on characteristic timescales 0.1 Myr. Fig. 3 illustrates this, and reveals that the mass of the zodiacal cloud is subject to strong, random surges caused by the arrival of exceptionally large comets entering short-period orbits. In the immediate wake of a giant comet dust input, the space density of zodiacal cloud particles in the terrestrial neighbourhood may be at least an order of magnitude higher. Since the particles are coming from an active comet and their orbits are not fully circularised, their mean eccentricities and hence asymptotic
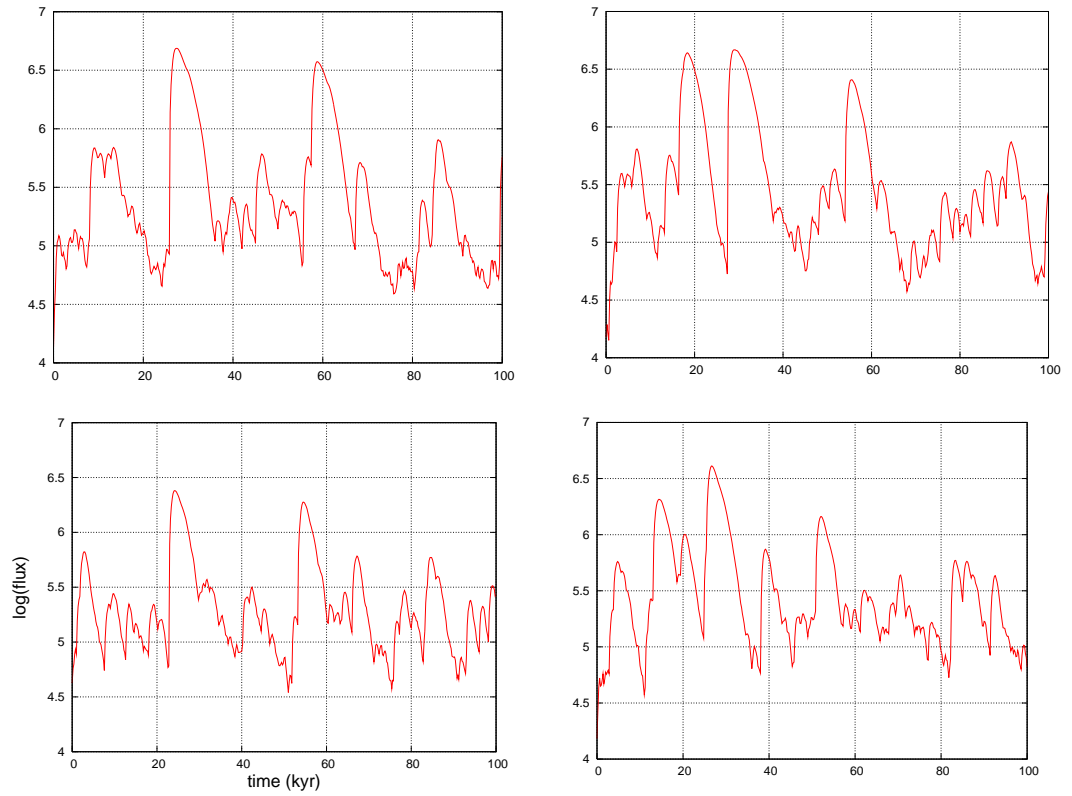
Figure 3: Illustrative histories showing the evolution of the zodiacal cloud flux on Earth for random arrival of comets into short-period orbits and their disintegration. Details of the model are given in Napier (2001). Order of magnitude mass fluctuations on timescales ∼0.1 Myr commonly occur (the vertical scale is logarithmic; flux in tons yr^{-1}). Boulders ejected from Earth during disturbed epochs are exposed to rapid fragmentation and erosion, generating μm-sized dust which is rapidly expelled.

11

encounter speeds V may be a factor of two greater (Napier 2001). The mass excavated from a boulder per impact is proportional to the impact energy, and so the erosion rate $1/\tau \propto V^3 \rho_z$. During such episodes the erosion and fragmentation timescales are thus reduced by at least two orders of magnitude. Small boulders orbiting 1 AU from the sun are then destroyed on centennial or millennial timescales, less than the residence and disintegration time of the large comet.

A boulder of 10 cm radius containing 10^7 microorganisms per gram could theoretically, if disrupted to dust a few μm across, increase its capacity to carry biological information by a factor up to 10^{11} or so over the lithopanspermia model. This factor will presumably be reduced, perhaps drastically, by the process of fragmentation and erosion, and also by clumping of bacteria, but it seems clear that even a modest amount of fragmentation will increase the information-bearing capacity of ejected boulders by many orders of magnitude, and any realistic assessment of interstellar panspermia must take account of this.

4.3 Expulsion of dust by radiation pressure

On collision, about half the mass of a 100 μm particle disintegrates into β-meteoroids, for which solar radiation pressure dominates over gravity, and the particles are rapidly expelled from the solar system (Wickramasinghe et al 2010; Wickramasinghe & Wickramasinghe 2003).

A bacterial clump of radius 1 μm, with a graphite coat of thickness 0.05 μm, ejected from the Earth and orbiting 1 AU from the sun, will become charred on its surface after prolonged exposure to solar ultraviolet light. The process is self-limiting, as reduced carbon is highly opaque to ultraviolet: a graphite sphere of radius 0.02 μm has a mass extinction coefficient of 5.75×10^5 cm^2 gm^{-1} at 2175 angstroms, and an optical depth of 3 is achieved for graphite thickness of only 0.024 μm. Thus genetic material in the interior of the dust particle would be well protected from solar ultraviolet light (Secker et al. 1994; Wickramasinghe et al. 2010). Such a 1 μm particle will have a ratio of radiation pressure to gravity of 1.5 and an asymptotic escape speed 30 km s^{-1}; it would reach 100 AU from the sun in about 15 years. The terminal speed $V_t = (2\alpha G M_\odot / r)^{0.5}$ where G is the gravitational constant and $\alpha = P/G - 1$, P/G the ratio of radiation pressure to gravity for the specific grain. A 40% excess at heliocentric distance r=1 AU yields $V_t = 27$ km s^{-1}, implying a travel time

of 2 parsecs in 70,000 years. A 10% excess yields $V_t = 13$ $\mathrm{km\,s^{-1}}$ and a travel time of 140,000 years for the same distance.

The exponential half-lives of unshielded microorganisms against galactic cosmic rays vary by some orders of magnitude. Half-lives of 50,000-100,000 years seem characteristic according to Mileikowsky et al (2000), although this may be highly conservative because no data are directly available that relate to microbes exposed to ultralow fluxes of ionising radiation for astronomical timescales (Wallis & Wickramasinghe 2004). For an annual ejection of n_0 microbes and a half-life $t_{1/2} = 75{,}000$ years, the solar system is then surrounded by a biosphere with an equilibrium population of $n_0 t_{1/2}$ living microorganisms, extending out to 5-10 pc, and conceivably out to 20 pc. These distances are well beyond the boundary of the solar system, ~ 0.7 pc, beyond which orbital motion is controlled by the Galaxy rather than the Sun (Rawal 1986). If we now adopt the 'benchmark' rate of 10 tons of boulders annually ejected from the solar system, having first been eroded to β-meteoroids, then for 10^8 microorganisms per gram we expect $n_0 \sim 10^{15}$ ejected annually yielding a population $\sim 8 \times 10^{20}$ in a biosphere surrounding the Earth. This number has to be multiplied by a factor say 10^{-1}-10^{-7} depending on the microorganism and the shock pressure to allow for the destruction of microorganisms during the shock of ejection from the ground into space (Horneck et al. 2008). Obviously, lacking experimental data on ancient microorganisms, these figures can only be a guide. Only very large terrestrial impacts have the capacity to eject large, lightly shocked fragments into space.

In consequence life-bearing boulders, either whole or in fragments, have probably been injected directly into starforming regions several times in the Earth's history, correlated with episodes of multiple bombardment on Earth (Kelley 2007, Napier 2006).

5. INJECTION OF BIOMATERIAL INTO A NEBULA

If we adopt 10^7 $\mathrm{gm\,yr^{-1}}$, 10^4 microorganisms $\mathrm{gm^{-1}}$ surviving ejection, deposition for 3 Myr into a giant molecular cloud, then an encounter with it deposits 3×10^{17} microorganisms from the solar system. The deposition will probably be some orders of magnitude higher since the adopted ejection rate is a long-term average, whereas the actual rate will spike during an impact correlating with the encounter.

A boulder entering a giant molecular cloud at 20 km s^{-1} will pass through it for a mean distance 27 pc, the encounter taking about 1.3 million years. If 1% of its mass is dust, the boulder will encounter $\sim$0.008 gm of dust along a square centimetre column. The mass loss through erosion of the forward hemisphere, assuming γ=500, is then about 4 gm per square centimetre column, which is enough to slow, trap and destroy pebble-sized ejecta, releasing their biomaterial into the cloud.

Molecular clouds are extremely clumpy, and the dense cores within them are shielded from cosmic rays (Skilling & Strong 1976; Cesarsky & Völk 1978). Barring the creation of a supernova in the course of star formation, the microorganisms will be subject to the same processes as other interstellar dust, and this will include incorporation into comets in the course of star and planet formation. There is evidence that relatively unprocessed molecular cloud material has been incorporated intact into comets, and some comets appear to have formed at temperatures appropriate to a molecular cloud (see Napier 2004 for references). Distributing 3×10^{17} microorganisms throughout the giant molecular cloud yields one organism per 3×10^{19} gm or so. This is adequate to transform large comets with liquid interiors into effective incubators, and to 'green' a planet subject to cometary bombardment including dust falls analogous to that on the Earth. Microorganisms may survive flash heating during the entry into the terrestrial atmosphere (Coulson 2004).

If there are say 10^6 habitable planets in the Galactic disc, then it would require 20 generations to saturate the system within the age of the Galaxy, with a doubling time $\sim$0.5 Gyr, about the interval between penetrations of molecular clouds at the solar circle. This would require one such planet to be 'greened' in a molecular cloud during each passage of a fertile planet. If there are 10^{10} suitable planetary systems, then 33 generations are required with a doubling time of about 300 million years, requiring 1.5 habitable planets within each giant molecular cloud at the distance of the solar circle. These requirements do not seem to be onerous, particularly as the number density of clouds within 3-5 kpc of the Galactic centre is about five times that of our locality. An OB association may contain 10^3-10^4 T Tauri stars, and the requirement is then that 0.01-0.1% of stars in process of formation have 'greenable' planets.

Encounters with small, dense molecular clouds are much more frequent (Table 1). These have little effect on the Oort cloud. However it is readily

shown that, for randomly placed impacts, there have been four or five occasions during which a large impact took place on Earth while it was passing close to such a nebula. Because these small clouds tend to be dense ($M \propto R^2$ for the molecular cloud system) the resulting concentration of deposited microorganisms turns out to be an order of magnitude higher than that in a giant molecular cloud. These small, dense cloud complexes are sites of low-mass star formation, and they would seem to at least compete with the giant molecular clouds as sites for the replication of life.

In any chain reaction, nearly all the action takes place in the last generation or two. Thus either panspermia has gone to completion with this process, or it has not gone at all.

6. THE 'BUG BUDGET' IN THE INTERSTELLAR MEDIUM

Stars are formed from the interstellar medium, and several processes operate to return material from stars back to the ISM. The cycle time is presently ∼2.5 Gyr and has been so for much of the ∼13 Gyr history of the Galactic disc (Zhukovska et al. 2008). Stardust condenses in the expanding shells of core collapse supernovae (e.g. Wesson et al. 2010a) and in the escaping atmospheres of asymptotic giant branch stars. Dust grains themselves are efficiently destroyed by thermal sputtering and shattering, primarily within supernova shocks (Grün & Landgraf 2001; Jones 2001); theoretical estimates of 0.4 Gyr and 0.6 Gyr respectively have been given for silicate and carbonaceous dust (Jones 2001). This would yield a much lower abundance of dust in the interstellar medium than is observed, and the bulk of the interstellar dust must therefore arise from a vigorous replenishing source other than stardust (e.g. Zhukovska et al. 2008). Taking the current mass of the galactic disc to be $10^{11} M_\odot$ of which 1% is in the form of dust, then the disc contains $M_g \sim 2 \times 10^{42}$ g of dust which, given a mean lifetime $L \sim$500 Myr of grains against supernova shocks, yields a required replenishment rate of 4×10^{33} g yr^{-1}, or $2M_\odot$ yr^{-1} for a steady-state.

This additional dust is generally assumed to be created in cold, dense molecular clouds, probably with stardust as nucleation sites for further growth. Growth timescales are of order 50 Myr in cold nebulae with a number density of hydrogen atoms $n_H \sim 10^3$ cm^{-3}, and vary inversely with n_H. This is in excess of the probable lifetimes of molecular clouds by

a factor a few and implies that dust mantles accrete through several excursions in and out of molecular clouds. Support for this accretion model is found in the gas phase depletion of the major dust-forming elements relative to solar abundances. Some elements are not significantly depleted, while others are depleted by factors up to 1000 (Jenkins 2004). These gas phase depletions are attributed to atoms freezing onto dust grains. They are correlated with the condensation temperature of the elements, the average density of the gas along a line of sight, and inversely correlated with the velocity of the gas relative to nearby undisturbed material. The latter is attributed to the effects of passing shocks, which tend to destroy the grains at the same time as they perturb the gas (loc. cit.). These correlations are consistent with the enhanced growth of dust grains in dense regions and their tendency to be destroyed by shockwaves. Charnley (1997) has described a theory whereby the organic molecules observed in the ISM may be built up on the mantles of grains in molecular clouds.

A radically different model for grain growth and composition has been proposed by Hoyle & Wickramasinghe (2000). They have pointed out that mixtures of hollow bacterial grains, biological aromatic molecules and nanobacteria provide excellent fits to numerous spectroscopic features found in astronomical sources, from UV to infrared (Wickramasinghe 2010a,b), with fewer adjustable parameters. The HW model calls for 25-30% of carbon in the interstellar medium to be in the form of bacteria-like grains, hence requiring something like

$$\dot{M}_{HW} \sim 10^{33} \text{ gm yr}^{-1} \tag{8}$$

of interstellar microorganisms to be injected into the interstellar medium. HW propose that microorganism numbers increase through repeated cycling between the interstellar medium and comets in exoplanetary systems. We ask whether the required bacterial population in interstellar space can be supplied from planetary impacts, and take the solar system as a representative source of injected microorganisms in the first instance.

Assume that the annual supply of unshocked material from the Earth into interstellar space is 10^7 gm (e.g. Mileikowsky et al. 2000). If there are $N_p \sim 10^{11}$ planetary systems in the disc, each ejecting $\dot{M}_p \sim 10^7$ g yr^{-1} of boulders and dust, then the rate of such material ejected from Earth-like planetary systems is

$$\dot{M}_g \sim \dot{M}_p N_p \sim 10^{18} \text{g yr}^{-1} \tag{9}$$

a factor $\sim 10^{15}$ less than required for replenishment (eqn. 8). Over the lifetime ~ 500 Myr of the Galactic dust, the total mass of planetary dust injected into the Galactic disc is 5×10^{26} g, about the mass of Mars. Only a small fraction $f_b \sim 10^{-4}$ say of this ejected dust will the biological in nature. Then the supply of microorganisms from planetary surfaces is deficient by a factor $10^{15}/f_b \sim 10^{19}$.

Giant comets are a potential source of biological amplification, since radiogenic heating may keep their interiors liquid for ~ 100 Myr (Wickramasinghe et al 2010). The star formation rate in the Galaxy is presently 3.5-5$M_\odot$ yr^{-1} (Smith et al. 1977; Sandage 1985). For the sun, the mass fraction of carbon in the photosphere is 2.9×10^{-3}, and if this is taken as typical then 0.015 $M_\odot$ yr^{-1} of carbon is sequestered annually inside stars. This may be compared with the requirement of generating $0.5 M_\odot$ yr^{-1} of microbes each year (eqn. 8) Galaxy-wide on the HW hypothesis. If a quarter of this material is carbon, then one requires that 0.125 $M_\odot$ of carbon is converted annually to micoorganisms in the course of planet formation, about 10 times as much as goes into the stars themselves. This biological material cannot be sequestered permanently inside comets, but must be returned to the interstellar medium for the HW hypothesis to hold. This would seem to require a quite different model of star and planet formation from that usually supposed; rather than straightforward Jeans collapse of gas, metals would have to be wrapped up in comets, with star formation proceeding inefficiently through their aggregation, and with most of the cometary bodies not being incorporated in nascent stars, but rather being destroyed and their microorganisms returned to the interstellar medium.

7. EXCHANGE OF BIOMATERIAL BETWEEN PLANETARY SYSTEMS

7.1 Direct capture

The capture of particles into the solar system, through binary encounters with Jupiter, has been discussed by a number of authors. The question arises whether interstellar dust so captured might add to the biological stock of the Earth. Using capture fractions derived analytically by Pineault & Duquet (1993), and assuming the mean number density of gas through which the Earth passes to be $n_H = 10$ cm^{-3}, with a 1% addition by mass of dust, one finds that about 10^4 tons yr^{-1} are captured into the solar system, mostly in Jupiter family orbits which will eventually feed in to the zodiacal cloud. For a residence time of say 5×10^4 yr, then 5×10^{14} gm of zodiacal cloud material has an interstellar provenance, that is about 10^{-5} of the total. Since the Earth intercepts $\sim$40,000$\pm$20,000 tons of dust each year (Love & Brownlee 1993), a ton or so of this material may have been directly captured from the interstellar environment. Essentially all of it will be dead given its mean residence time of $\sim$5 Gyr in the interstellar medium. If it is accepted that dormant microorganisms exist in comets and enter the Earth's stratosphere, any additional interstellar contribution of living micoorganisms is clearly negligible. If radiation pressure is taken into account, then the capture rate will be further reduced.

The Oort clouds of stars must intersect frequently, and the exchange of comets between stars, particularly binary stars, is a conceivable mechanism for interstellar panspermia. Pineault & Duquet (1993) give the example of a binary system with semimajor axis 10 AU and masses $(8.0, 1.0)M_\odot$. Passing through a field of comets with number density 10^{-3} AU^{-3} at 20 km s^{-1}, they find that the binary would capture about one comet every four years. For a duration of stellar encounter 10^4 yr and perhaps 4,000 such encounters for a 4 Gyr-old star, a population of perhaps 10^7 comets could have been so captured by the system over its lifetime. This again represents an extremely small contribution to an indigenous population of say 10^{11} comets.

The conclusion is that an incoming supply of living microorganisms to an isolated planetary system cannot contribute significantly to whatever biomaterial is already present. It should be noted, however, that even 'dead' microbes can be a source of genetic information, and could

contribute to the evolution of life on a planet. Wesson (2010b) has coined the term 'necropanspermia' for this concept, which was originally due to Hoyle & Wickramasinghe (1982; see also Wickramasinghe 2011).

7.2 Star clusters

Most stars, of course, do not form in isolation but rather in clusters. On the lithopanspermia model, transfer of life-bearing boulders becomes possible between stars within star clusters, because of their proximity and low relative velocities. Adams & Spergel (2005) have considered the spread of biological material from one planetary system to another in starforming clusters, based on the ejection and capture of life-bearing rocks down to 10 kg mass. They estimated capture cross-section of rocks ejected from a solar system into binary stars within the cluster and found that 0.001-1.6 'lithopanspermia events' were expected per cluster. Valtonen et al (2009) found that the Earth could have received $10^{2\pm2}$ boulders from other planets while inside its birth star cluster.

However it is likely that ejected rocks will be rapidly eroded in such environments, increasing the information-carrying capacity of a given rock by many orders of magnitude. On this basis it is to be expected that local panspermia will routinely occur in starforming clusters, given that life arrives (or is created) on one star system within the cluster. The subsequent dispersal of the cluster serves to spread exoplanetary 'nuclei', further assisting the diaspora of microorganisms. The chance occurrence of a supernova would be a hazard for this intracluster panspermia in the case of OB associations but not for the low-mass sites of star formation found in the smaller nebulae.

8. DISCUSSION AND CONCLUSIONS

How special is the Earth? Specifically, how many planetary systems have the capacity not only to nurture microorganisms, but also pass them on through impacts? Although the proportion required for a Galaxy-wide chain reaction seems reassuringly small ($\sim$0.01-0.1%), it will probably require another decade or more of planet-hunting before we can sufficiently narrow down this unknown.

The idea that life evolves in a closed terrestrial box has seemed insecure ever since the 70s, when it was realised that the Earth is a bombarded

planet and that some massive bombardment episodes in geological history can be associated with mass extinctions of life as well as the termination of geological ages (Urey 1973; Napier & Clube 1979; Alvarez et al. 1980). The extension of an 'open evolution' concept to the giving as well as taking of life by comets has been pioneered by Hoyle & Wickramasinghe from about that time, and the finding of mechanisms which may allow panspermia to take place over interstellar dimensions strengthens this concept.

If significant interstellar panspermia does take place, the range and number of candidate environments for life's origins is greatly extended, and the idea that life began on Earth – perhaps the last bastion of geocentricism – then becomes statistically improbable. One does not need to look far outside the Earth to encounter environments which overwhelm anything the Earth can offer in terms of biologically interesting mass, volume and range of conditions. Comets, and the meteoroids which derive from them, are rich with water and organic matter, and probably clays. Even within our solar system, it is likely that organic-rich liquid water, with a total mass of perhaps 10^5 times that of the world's oceans, has existed in the interiors of large comets for millions of years. If we multiply this by the probable number of Oort clouds existing around the stars of the Galaxy, then we have the potential for 10^{16} incubators within which microbial life may at least be amplified.

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