

To appear in *Monthly Notices of the Royal Astronomical Society*

# Interstellar transfer of planetary microbiota

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(Submitted May 2003, revised September 2003, accepted October 2003))

## ABSTRACT

Panspermia theories require the transport of micro-organisms in a viable form from one astronomical location to another. The evidence of material ejection from planetary surfaces, of dynamical orbit evolution and of potential survival on landing is setting a firm basis for interplanetary panspermia. Pathways for interstellar panspermia are less clear. We compare the direct route, whereby life-bearing planetary ejecta exit the solar system and risk radiation hazards *en route* to nearby stellar systems, and an indirect route whereby ejecta hitch a ride within the shielded environment of comets of the Edgeworth-Kuiper Belt that are subsequently expelled from the solar system. We identify solutions to the delivery problem. Delivery to fully-fledged planetary systems of either the direct ejecta or the ejecta borne by comets depends on dynamical capture and is of very low efficiency. However, delivery into a proto-planetary disc of an early solar-type nebula and into pre-stellar molecular clouds is effective, because the solid grains efficiently sputter the incoming material in hypervelocity collisions. The total mass of terrestrial fertile material delivered to nearby pre-stellar systems as the solar system moves through the galaxy is from kilogrammes up to a tonne. Subject to further study of bio-viability under irradiation and fragmenting collisions, a few kg of original grains and sputtered fragments could be sufficient to seed the planetary system with a wide range of solar system micro-organisms.

**Keywords:** Panspermia, comets, meteorites, Mars, planets, micro-organisms

## 1. INTRODUCTION

Panspermia in its various forms seeks to explore the problem of the propagation and dispersal of life in a cosmic context. Bypassing the fraught question of life's ultimate origin, the methodology of panspermia proceeds from the known properties of terrestrial life, in particular bacteria. Svante Arrhenius invoked the well-attested resistance of seeds and spores to extreme cold to argue for the long-term retention of viability under interstellar conditions. Furthermore he pointed out the relevance of radiation pressure from starlight in effectively dispersing particles of bacterial size. The Arrhenius model of panspermia was greatly enhanced and developed for over two decades by Fred Hoyle and one of the present authors (Hoyle and Wickramasinghe, 2000). The original criticisms of the Arrhenius version of panspermia were based on experiments carried out by Becquerel (1924) showing the loss of viability of bacteria exposed to ultraviolet radiation, but calculations show that a thin mantle of eg. graphite can provide sufficient shielding (Wickramasinghe, 1967; Wickramasinghe and Wickramasinghe, 2003). In recent years, cosmic rays causing damage over  $\geq 10^{4-6}$  yr timescales have been considered as the main limitation.

Panspermia has come into the scientific mainstream via the studies of meteorites from Mars. These have established that rocks can be ejected from planetary surfaces by colliding asteroids and comets, and moreover that these rocks can potentially harbour microorganisms and deliver them in a viable state to other planetary bodies. Lunar and martian meteorites provide evidence of actual material that has undergone this process, while the Chicxulub crater event 65 Myr ago provides evidence of the collisional ejection process. Our earlier study (Wallis & Wickramasinghe, 1995)

showed that ejecta from such a terrestrial event readily reach Mars and might bear microorganisms that quite probably survive the space radiation and landing events, though this had previously been thought exceedingly unlikely (Melosh 1988). Mileikowsky et al. (2000) have explored the transfer process in more detail. Their description of the ejection process is however flawed, in that it sees individual rocks of order a metre in size ejected through an atmosphere of density  $\sim 10^4 \text{ kg/m}^3$ , comparable to early martian or present terrestrial atmospheres. This process requires metre-sized rocks to have very high initial speeds in order to push aside several times their own mass of air.

While Melosh (1988) originally made a similar assumption, he did recognise that the sheer bulk of ejecta could far exceed the atmospheric mass. Thus rocks emerge with escape speeds ( $>v_{\text{esc}}=11 \text{ km/s}$  on Earth) primarily by being swept up with the high-speed vapour and particle plume produced in the collision, which blows a hole through the atmosphere (Melosh 1989). This means that rock fragments and debris down to mm sizes or smaller are also (and more readily) ejected at the same time, rather than being winnowed out as Mileikowsky et al. (2000) presumed. The detection of shocked crystalline quartz from the Chicxulub crater as far as  $10^4 \text{ km}$  away is evidence of debris riding with the vapour jet, because ejection at the 7-8km/s speed necessary to reach such distances would have melted the quartz (Alvarez et al. 1995). These shocked grains had been subject to pressures  $<40 \text{ Gpa}$  and their global distribution is consistent with Chicxulub's vapour plume or jet forming a vertical cone of  $25^\circ$  half-angle.

Till recent years, it had been thought that no life forms could remain viable over Myr timescales under cosmic radiation if in space or at the Earth's surface, or under radiation from terrestrial nuclides if at depths in the Earth's crust. The survival of bacteria is generally modelled on a simple physical picture as an inverse exponential function of accumulated radiation dose. When a cell is metabolising, its DNA repair mechanisms ensure the repair of strand breaks resulting from irradiation, but strand breaks can accumulate in spores and deep-frozen states. However there are counter-examples for survival of dormant microorganisms on the Earth to large doses of natural radioactivity. Microorganisms are known to have survived in a resting state on the Earth for timescales of  $\sim 0.5\text{-}100 \text{ Myr}$  (Cano & Borucki, 1995, Lambert et al, 1998) and possibly in a salt crystal for  $250 \text{ Myr}$  (Vreeland, et al, 2000). With average levels of natural radioactivity on the Earth in the range  $1\text{-}10 \text{ mGy/yr}$ , it is evident that microorganisms have survived doses of ionising radiation amounting to  $\sim 0.1\text{-}1 \text{ MGy}$ . A dose of  $100 \text{ mGy/yr}$  in interstellar space implies a timescale of  $\sim 1\text{-}10 \text{ Myr}$  for accumulating doses in this range. For an organism that halves its viable count under a dose  $\theta$ , the survival fraction at dose rate  $x$  after time  $T$  is  $(1/2)^{Tx/\theta}$ . Values  $T = 25 \text{ Myr}$  and  $x = 10 \text{ mGy/yr}$  with  $\theta = 5 \text{ kGy}$  appropriate to a hardy spore state imply a survival fraction  $f \approx 10^{-15}$ , so a starting amount of eg.  $1 \text{ mg}$  of bacteria ( $\sim 10^8$  in number) in the salt crystal or amber samples would have been entirely eliminated.

The radiation biophysics paradigm of exponential decline of surviving fraction with dose is put in question by the above terrestrial examples. Further arguments are included in the Appendix. It may be that a bacterium is able to put its DNA into a chemically saturated ultra-stable state (termed 'vitrified' - as a glassy medium), in which at low temperatures even free radicals are immobile. In the creation of spore states, it is known that small acid-soluble proteins saturate DNA bonds (Horneck et al. 2001b), but the conditions for forming vitrified states are largely unexplored at the present time. Freeze-drying over times  $\geq 1$  second is a well-proven technique for maintaining bacterial viability. Arid conditions or some other hostile terrestrial environments may similarly be good preparation for space hardness. So we doubt that the arguments given by Mileikowsky et al (2000) for decay of DNA due to loss of bases under hydrolysis or exposure are relevant to stable spore-states in interplanetary or interstellar environments . Until experiments are carried out on prepared spore states at low temperatures and near zero pressures, this issue cannot be tackled quantitatively. In this paper we focus on the physical delivery issue, though still with an eye to the radiation survival problem.

If solar radiation (energetic particles and X-rays) is limiting in the inner solar system, fast-track orbits can enable a fraction of ejecta to avoid it. While most terrestrial ejecta undergoing many planetary perturbations take  $10^4$ - $10^5$  yrs to reach Mars and pass onwards to Jupiter, a small fraction may be fast-tracked to Mars and onwards to Jupiter-crossing orbits within a few orbits or tens of orbits. Observe that it's the small ejecta from surface soils accelerated by the vapour plume that are more likely to attain ejection speeds for Mars-crossing orbits ( $v_{esc}+6\text{km/s}$  - see below) and get a good start on fast track orbits to Jupiter. Only a small fraction of the energetic solar flux [0.1% of particles and a similar fraction of X-rays] reach bacteria in the interiors of ejecta larger than several cm, so such shielding strongly increases the surviving fraction.

## 2. INTERPLANETARY PANSPERMIA

A limited version of panspermia that is becoming increasingly popular is known by the term 'interplanetary panspermia' and follows, perhaps unwittingly, Lord Kelvin's advocacy of impact ejection of material from planets. There is a growing body of evidence that planetary material is exchanged between the inner planets of the solar system. There are meteorites recovered on Earth that originated on the Moon (lunar meteorites) and others (SNC meteorites) that originated on Mars. We also know from studies of lunar craters that both the Earth and the Moon were subject to intense cometary and asteroid bombardment around 4Ga ago. And the same process continued at a much-reduced intensity at later epochs.

In a typical impact of a 10km sized comet at a speed of over 30km/s with Mars or Earth (which occurs on the average every 100 Ma at the present time) most of the material of the impactor and the immediate impact zone is vaporised. However, surface material from the ten times wider impact crater is ejected in the form of rocks and debris. Shock-caused spallation ejects near surface rocks at up to about half the impacter speed (Melosh 1989) and potentially ejects soils still faster (Alvarez et al. 1995). In any case, the rocks would throw up soils and loose overburden with relative ease. The vapour plume follows close behind, forming an expanding jet punching through to the upper atmosphere and taking the entrained soil and rock fragments into the mesosphere and out to space. Rocks and soil particles from the surface (few metres deep) are likely to harbour in their interiors viable microbes, microbial spores and eucaryotes including yeast cells (perhaps comprising specialist ecologies). The discovery of a Martian meteorite heated to  $\leq 40^\circ\text{C}$  supports the idea that spalled material can get sufficient start on the fireball vapour plume. Soils contain particles  $10\mu\text{m}$  upwards and only those carried out with the fastest vapour might escape heat sterilisation. Recent studies have followed Melosh (1988) in assuming sterilisation occurs at  $\sim 100^\circ\text{C}$ , but laboratory experiments have shown that freeze dried bacteria/spores are resistant to flash heating to at least  $350^\circ\text{C}$  for 30s (Al-Mufti et al, 1986).

The fraction of ejecta moving faster than the planetary escape speed (5km/s for Mars, 11.2km/s for Earth) escape into interplanetary orbit and are spread through space via successive gravitational perturbations, thus becoming available to impact other planetary bodies. Lifeforms that survived the trauma of the initial comet or asteroid impact face further hazards as the ejecta carrying them plunges through the atmosphere of a receiving planet. But they can survive a terrestrial-like landing within boulders of the size of a metre or more, or in ejecta smaller than  $\sim 100\mu\text{m}$ . For large boulders, the outer layers are heated and ablated, the remainder generally fractures, but the interiors of pieces that fall as meteorites remain cool.

In practice, fragile chemical structures have been found to survive the transit to Earth in meteorites and also in some Brownlee particles (Clemett et al, 1993). Thus the survival of microbes, spores and microscopic seeds in the interiors of suitable interplanetary ejecta is no longer in doubt. Of particular interest in this context is the Martian meteorite ALH84001. While it has a rock age of 3.6Gyr, it was ejected from Mars at a relatively recent epoch. It carries chemical and structural

signatures that could be indicative of early Martian life (McKay et al, 1996). For transfer in the opposite direction, landing on Mars of ejecta from Earth presents less of a problem, because gravity and orbital speeds are lower at Mars than at Earth orbit. However, the less dense atmosphere of Mars has lower braking power for boulder-sized debris (Melosh 1989). The satellites of Jupiter and the outer planets that are devoid of atmosphere suffer unbraked impacts, so survival is problematic - more favourable for the outermost icy satellites.

Over the last few years, it has become accepted that life could have started first on Mars and been transferred to Earth via an ALH84001-type missile up to 4 Gyr ago. This begs the question of how life got started on Mars. In our view, transfer of life between planets was frequent, with the impacts on Mars ejecting material to Earth every few Myr (Mars meteorites) and Earth sending material to Mars at least every 100 Ma, as evidenced by the Chicxulub impact (Wallis & Wickramasinghe 1995). Thus life is most likely to have developed in parallel, and the important question is whether it was seeded on both planets from outside.

Along with accumulating astronomical evidence supporting panspermia in one form or another, geological evidence has also been growing. The earliest evidence for terrestrial life has perhaps been pushed back beyond 3.83 Gyr, well into the epoch when the Earth was severely pummelled by comet and asteroid impacts (at a rate ~100 times the present). Whilst the Earth's early epoch of heavy bombardment would not have been conducive to prebiotic chemistry, it would nevertheless have offered a variety of environmental niches for microorganisms arriving from space to flourish, adapt and diversify.

### 3. ENERGY LIMITATIONS ON PLANETARY TRANSFER

It is well known from spaceprobe launches that interplanetary travel poses energy problems. To reach Venus in a single shot, an ejection of  $v_{esc} + 3\text{km/s}$  is needed, in the retrograde direction, and to reach Mars an ejection of  $v_{esc} + 6\text{km/s}$  prograde. Thus few ejecta from Earth reach these planets directly, but as their orbits are Earth-crossing, the ejecta suffer further perturbations that stochastically allow them to do so. When after many perturbations, the ejecta attain Venus or Mars crossing orbits in the ecliptic plane, they stand a chance of being swept up by these planets. Apart from the 50% reaccreted by Earth, successive orbit perturbations take the ejecta into the sun or into the outer solar system over a  $10^7\text{yr}$  timescale (Steel 1992, Gladman et al. 1996, Melosh 2003).

Spaceprobes are more efficient in using such gravitational 'sling-shots' from successive planetary encounters because the fly-by parameters are carefully chosen. Small fractions of the ejecta can similarly be quickly transferred. Thus Mars and comets might be reached via a single fly-by of Venus, or via a Venus swing-by followed by an Earth swing-by. Just the one return to an Earth swing-by can work for ejecta that had left the Earth at 1-3 km/s. Second encounters with Earth (radius R) have relatively high probability, with impact parameter d related to the distance of closest approach  $r_m$  at encounter speed V, by:

$$d^2 = r_m^2 + (v_{esc}^2/V^2) R r_m \quad (1)$$

with speed change

$$\Delta V = 2V (d^2 - r_m^2)/(d^2 + r_m^2) = 2V v_{esc}^2/(v_{esc}^2 + 2V^2 r_m/R) \quad (2)$$

The distance of closest approach,  $r_m$ , exceeds the Earth's radius R, and the maximum sling-shot increment in speed, from a grazing encounter with  $r_m = R$  is less than  $2V$ . If V is only 10 or 20% of  $v_{esc}$ , encounters with  $r_m = 2-3R$  are more probable than collisional encounters, and V could increase via several successive sling-shot encounters.

In this way, sling-shot transfers to Mars or Venus are possible, for ejecta that initially have velocities V that are too small. However, velocities need to be in the ecliptic plane if the ejecta are to encounter the planets. Consider what happens to orbits out of the ecliptic. These cross the Earth's orbit and the only planet encountered is the Earth. Thus they continue to be perturbed by it until reaching an orbit in the ecliptic plane. The alternative fate is a random walk out of the Earth's gravitational influence, with a low probability of being caught in planetary resonances. Monte-Carlo calculations of numerous orbits have been used to investigate this problem, with the general conclusion that interplanetary orbits in the inner solar system

- stay under the influence of one planet till handed on to the next (in sequence)
- terminate via collision with the planet or with the sun
- spend a time in the inner solar system  $10^7$  years
- once the aphelion reaches 5AU, larger perturbations by Jupiter take over and can be large enough to give orbits beyond the planetary region (into the cometary regions/Oort cloud) or escape entirely from the Solar System.

Calculations have also been made to estimate the fractions of ejecta from one planet which are re-accreted by itself or by another planet (Gladman et al. 1996, Melosh 2003). Re-accretion by Earth and Venus accounts for about 40%, a few % of Earth ejecta impact Mars while some 20% go to Jupiter and beyond. Of Mars's ejecta, the planet reaccretes some 30%, while Earth gets 25% and 25% are ejected to Jupiter and beyond. These proportions are used to derive the numbers in Fig. 1 (based on 20 t/yr from Earth - see next section). The timescales are  $\sim 10^6$  yr for Earth-Mars exchanges and  $\sim 10^7$  yr for Earth-Jupiter and beyond.

#### 4. FATE OF PLANETARY EJECTA IN THE OUTER SOLAR SYSTEM

We first estimate the rate of production of ejecta from Earth and Mars over the age of the planetary system. The amount of unsterilised material ejected to space in a 100Myr terrestrial cratering event the size of Chicxulub was estimated as  $3 \times 10^8 \text{ m}^3$  ( $\sim 0.1\%$  of the excavated material - Wallis & Wickramasinghe, 1995), which averages out as an ejecta rate of order 10 t/yr. We can integrate over the distribution of crater sizes, using the cumulative function  $N(D) \sim D^{-1.8}$  (for  $D > D_\#$  the minimum size for blow-out - Wallis & Wickramasinghe, 1995), and this gives twice as much. Let's note that the ejection process is erratic, with the largest impactors dominating the ejection rate, and that the 100Myr time interval is comparable to solar system residence times. In comparison, the current epoch flux of Martian material impacting Earth, taking the fraction of meteorites determined to be from Mars (0.1%) as representative, is some 30-40 t/yr. Melosh (2003) estimates 0.5t/yr Martian meteorites reaching Earth, corresponding to a total 2-3t/yr martian ejecta. Napier (2003) matches our estimate of 10 t/yr terrestrial ejecta from impacts of inferred asteroid and comet populations, but his total is probably overestimated since the average mass impactors is too small with craters  $< D_\#$ . ( $\sim 100\text{km}$ ). In this paper we shall retain our earlier estimate from Chicxulub plus a contribution from smaller craters  $> D_\#$  for the mass flux of unsterilised material from the Earth of 20t/yr.

Ejecta that attain orbits beyond Jupiter have one of three fates: escape from the solar system, impact on one of the outer planets, or sojourn for a long time just beyond the planets. It is this latter option, admitting the possibility of accretion by comets and other icy objects in the "Edgeworth-Kuiper belt", that we now discuss.

The 35-80AU region known as the Edgeworth-Kuiper belt has been identified in recent years as a reservoir of large icy bodies. This EK belt is thought to be the source of the short period comets (Holman & Wisdom 1993, Davis & Farinella 1997) and has been called the 'inner Oort cloud' (Bailey et al 1990), to distinguish it from the main Oort cloud which is the source of the near-

parabolic long-period comets. (The term Trans-Neptunian objects (TNOs) is a more modern name for this class of object.) The EK belt has a dynamical lifetime comparable to the age of the solar system and is estimated to contain half its original  $9 \times 10^9$  comets (of  $\geq 3$  km radius). The 35-45AU range of the belt is dynamically "active", being a source of TNOs coming under the gravitational influence of Neptune on the  $10^9$  yr timescale. For it to be the source of Jupiter-family comets, Weissman (1995) estimates  $6 \times 10^9$  dynamically "active" TNOs.

Ejecta under Mars' influence encounter Jupiter with several km/s (5-7km/s) relative speed and with one or two sling-shot doublings of V (see equation (2)) can attain solar system escape speeds (25km/s). However, more distant Jupiter encounters with  $r_m/R > v_{esc}^2/V^2$  have higher probabilities and allow Saturn perturbations to intervene and 'take over' the ejecta for a period. Saturn again can (a) induce large perturbations giving solar system escape speeds, or (b) hand back the ejecta to Jupiter, or (c) hand them on to Uranus. This process is repeated by Uranus and Neptune (at 30AU), with the latter sending the ejecta beyond 35 AU through the Edgeworth-Kuiper belt.

The planet-to-planet handing on process has been the subject of several studies, mainly in relation to the dynamical evolution of the TNOs, for purposes of estimating fractions placed in the Oort cloud or lost from the solar system. The corresponding dynamical processes for planetary ejecta, including their sojourn in the inner and outer Oort clouds and their escape from the solar system, can be inferred from the summary by Bailey et al. (1990) of early TNO studies. Levison and Duncan (1997) present more recent extensive computations of Neptune-encountering TNOs, showing that they relate to a class of the Jupiter-family comets.

The numerous distant planetary encounters have to be included in a realistic dynamical calculation. The net changes approximate to diffusion in orbit energy  $E = M_\odot G/a$  ( $a$  being the semi-major axis), with diffusion coefficient (an average over orbit inclinations) depending on perihelion  $q$ , relating to the nearest planet (see Fig. 8.3 of Bailey et al, 1990). The process is not simply diffusive in  $E$ , but includes an average energy increase (favouring solar system escape) which can outweigh radiation damping. The orbit calculations show that certain larger perturbations can directly place ejecta in the Oort cloud. Direct emplacement - defined as ejection into orbits with aphelia between 5000 and 100 000AU - is relatively more probable from Uranus and Neptune perturbations, whereas escape from the solar system is more likely from Saturn and Jupiter perturbations. Levison and Duncan (1997) cut off their calculations at too small values of aphelia ( $a > 1000$ AU) to judge this. Melosh (2003) found just 2% of Earth and Mars ejecta get as far as Saturn, though his calculations exclude planets beyond Saturn. Using the proportions given by Bailey et al. (1990), we estimate that of the planetary ejecta reaching the outer solar system, about half escape within a few Ma, some 20% attain Oort cloud orbits of 1 Myr period (where distant star and galaxy perturbations come into play), half this number spend time in the Edgeworth-Kuiper belt, 20% return to the inner solar system, and a few percent collide with the planets and their satellites.

While the majority of the trans-Jupiter ejecta leave the solar system, some 8kg/yr goes into the EK belt where collisions play a role. The Pioneer spacecraft detection of the solar system dust ring (Landgraf et al. 2002) implies collisional fragments are being generated at  $\sim 50$  t/s. The results of recent studies (Davis & Farinella 1997) can be used to infer probabilities of ejecta impact on TNOs and even mutual collisions between TNOs. Taking Weissman's (1995) figure of  $6 \times 10^9$  dynamically active TNOs of  $\sim 10$ km diameter, distributed around 34-45 AU and inclinations up to  $23^\circ$ , with a representative velocity difference between prograde orbits of 2km/s, the mean travel time of a piece of ejecta before impacting a TNO is  $\sim 2.5 \times 10^9$ yr. The ejecta passing through the main Oort cloud of  $10^{11-12}$  comets dispersed over a  $10^3$  times longer distance scale have a much lower frequency of impacts.

The EK belt is dynamically weakly unstable, with the timescale for Neptune or Uranus perturbations of  $10^9$ yr (Fernandez 1980; Duncan et al. 1995; Jewitt 1999), so on these estimates the

planetary ejecta that reach the belt have a 40% chance of colliding with the TNO complex and being buried either directly or indirectly. Burial depends on the physical structure of these comets. Taking them to be loose 'snowballs', collisions at 1-2km/s retain much of the ejecta intact at the bottom of a crater, while blowing off much snow. Subsequent impacts of the presumed abundant small EK debris would tend to bury the planetary ejecta, while there also is a chance of deeper burial via collision between two EK comets.

Taking the 8kg/yr to be the unsterilised Earth-origin flux into the EK belt (rather higher at earlier epochs) and the current  $6 \times 10^9$  EK comets to absorb 40-60% of this flux over their  $4.5 \times 10^9$  yr lifetime, we infer an average of 3kg per comet, much of it in the form of smaller debris up to cm sizes. Note in this context that in the early solar system, impact crater statistics show that comet and asteroid impact rates were far higher - about 100 times higher 4 Gyr ago than at present (Wallis & Wickramasinghe 1995). Maybe the life-bearing fraction was lower at the early epoch, but the ejecta from the early bombardment period clearly contributed an order of magnitude higher mass to rather higher numbers of TNOs.

We envisage that EK comets accumulate in their surface layers multiple samples of martian and terrestrial ecologies of microorganisms. These comets can store the samples in a deep frozen and radiation-protected environment for  $10^9$  yr timescales. The material from TNOs is potentially available to infect planetary objects in other stellar systems. The comets of the EK Belt suffer perturbations by Neptune and Saturn that can place them in the Oort cloud or eject them directly into interstellar travel (Fernández 1980, Fernández & Ip 1981, Duncan et al. 1995). Likewise, the Oort cloud comets are stochastically changed to interstellar ones due to close approaches of molecular clouds.

On the basis of the above discussion, we give the quantities shown in Fig. 2: fertile terrestrial material is ejected from the solar system by Jupiter (and Saturn) at the total rate  $Q = 4t/\text{yr}$ , in mm to m-sized fragments. This includes some 3kg ejected with each comet from the EK Belt, being its total collected since the comet's formation in the early solar system. Because collisions in the EK belt would have securely buried the fertile material, the cometary component commences its interstellar journey in a protected state.

## 5. INTERSTELLAR DELIVERY

We next consider the fate of life-bearing missives, ranging in size from soil fragments to a small bolide to an entire comet expelled from the solar system. The sun, located at a distance of  $\sim 8.5\text{kpc}$  from the galactic centre in the Orion spiral arm, moves in a Keplerian orbit about the nucleus at a speed of  $\sim 220\text{km/s}$ , and has a proper motion, at  $\sim 20\text{km/s}$  relative to the local interstellar environment. The average separation of sun-like stars (G-dwarf, main sequence) is  $\sim 2.5\text{pc}$ , while reaching the nearest planet-forming one at  $\sim 20\text{pc}$  takes 1 Myr travel time. Solar system ejecta and TNOs delivered to another planetary system at typically 15 to 20km/s generally fly straight through, so indirect delivery mechanisms need to be considered. From observations of comets, we know that some icy bodies eject particles into a coma when as far as 5AU distant from the sun, presumed to be due to the triggering of a chemical energy source or sublimation of highly volatile ices by the sun's radiation. But comets generally emit surface material as cometary dust and larger particles (say mm-sized) only within  $\sim 1\text{AU}$ . All such material emitted by a TNO traversing a solar type planetary system is on hyperbolic orbits and very little could be collected by the planets.

### 5.1 Dynamical Capture

Delivery to a fully formed planetary system requires passage close enough to a Jupiter-sized planet to undergo a capture perturbation. Melosh (2003) has considered this problem for isolated ejecta and the same dynamics applies to TNOs. Temporary Jupiter-captures into  $q \sim 5\text{AU}$  orbits have a

high probability of ultimate ejection out of the system (Melosh 2003), but note that EK comets may split and disintegrate (cf. comet Shoemaker-Levy-9) or eject grain comas, giving a chance of delivery at least to Jupiter-like satellites. For  $V_o=20\text{ km/s}$  ejecta, we use equations (1) and (2) to calculate

$$d^2/R^2 \equiv (V^2/\Delta v^2 - 1/4) (v_{esc}/V)^4 = 40 \quad \text{on setting } \Delta v = V_o, \text{ where } V = \sqrt{(V_o^2 + V_e^2)} \quad (3)$$

with  $V_e$  giving the escape speed to interstellar space from Jupiter's orbit (25 km/s). This gives the capture cross section of a Jupiter as  $1\times 10^{12} \text{ km}^2$ . Melosh calculates captures over a distribution of low encounter speeds,  $V_o \ll 5 \text{ km/s}$ , for nearly co-moving planetary systems, when a much larger zone of gravitational influence of a Jupiter-sized planet can be relevant, but this process would be less important than the ones we now discuss.

### **5.2 Delivery to the new system's TNOs**

Now consider a solar system analogue possessing a belt of icy TNOs like ours. At 20km/s, a piece of ejecta would bury itself in the base of a crater in the TNO. It is conceivable that bio material would still be viable if the target material is fragile like uncompactec ice crystals (cf. Burchell et al. (2001) experiments with speeds up to 7 km/s into rock). Horneck et al. (2001a) have found survival of 1 in  $10^4$  bacterial spores to the pressure and heat pulse - survival rates into porous ice would be higher. The cross section of  $4.5\times 10^9$  TNOs of typically 30km diameter amounts to  $2\times 10^{11} \text{ km}^2$ , which is similar to the impact cross section of Jupiter (including the gravitational focussing factor; a few times less than the capture cross-section above). Only a fraction (0.02 % of 1 per Myr) of TNOs deliver their solar system material to the inner planets, after passing through the giant comet phase (Bailey et al. 1989). So this process as a direct means of life-transfer on to planets seems somewhat restricted.

### **5.3 Delivery by sputtering**

Both condensing molecular clouds and a proto-planetary disc catch the interstellar missives not so much by gas drag, but by solid material sputtering, because the solids make up 1-3% of the mass of clouds and sputter many times their mass in 20km/s impacts. Hypervelocity grains and dust particles are highly efficient in sputtering ice and fragile uncompactec material, because of the low structural energy and the gases generated internally. Stern (1986) adopted an excavation factor  $6.6\times 10^4$  from ice at 20km/s. Koschny & Grün (2001) estimate two orders of magnitude more mass from impacts in ice than in rock, and Shrine et al. (2002) find  $\sim 20$  times more in impacts of Al-spheres into polycrystalline ice at up to 7 km/s. The latter experiments, combined with crater scaling formulae, lead to an excavation factor

$$E_f [\text{ice}] \sim 240 \rho_t^{-0.5} V^2, \quad (4)$$

for target density  $\rho_t$  in  $\text{g/cm}^3$  and impact  $V$  in  $\text{km/s}$ . Impacter and crater diameters,  $D$ ,  $d$ , are related by

$$\rho_i d^3 E_f \sim 0.2 \rho_t D^3 \quad (5)$$

taking the crater depth to be  $\sim 0.2 D$ .

Let us take  $E_f [\text{rock,ice}] \sim [5\times 10^3, 1\times 10^5] (V/20\text{ km/s})^2$ , corresponding to  $2.7\text{ g/cm}^3$  granite and crystalline ice. This may be a conservative assumption as the structural energy of porous cometary ices could be much lower than the crystalline ice of the experiments - the energy of impact goes in the first place into vapour, limited only by the energy needed to blow off the fragmented ice crystals. There is little experimental data, but the Burchell et al. (2002) tests of 50%-porous ice under impacts up to 7 km/s indicate 2-3 times lower  $E_f$  than the above formula. Impact experiments on porous and hydrated chondritic meteorites imply higher  $E_f$  than for granite

(Tomeoka et al., 2003) because of enhanced fracturing down to the sub- $\mu\text{m}$  scale, with collapse of pores and explosive production of  $\text{H}_2\text{O}$  vapour.

#### **5.4 Penetration into the general interstellar medium**

Lissauer & Griffith (1989) pointed out that a fraction of the galaxy (2-4%) is filled with gas clouds of  $\sim 20 \text{ H-atoms/cm}^3$ , and microdust (interstellar grains) with about 1% of this mass-density will also be present. Ejecta of mm-sizes passing through this low density cloud would suffer significant erosion. Lissauer & Griffith conservatively assumed a low erosion factor for basalt ( $E_f = 5V^2$ ); let's take instead  $E_f = 5000$  at  $V=20\text{km/s}$ , implying an erosion rate of  $\sim 50\mu\text{m}/\text{pc}$ . Up to cm-sizes are eroded away in passing through a 100pc cloud. Icy EKOs would lose an average 2.5cm of surface - as Alan Stern (1986) pointed out, grain-driven erosion is far more effective than gas accretion. Most of the eroded mass is in small fragments, less than a few times the impacting microdust particle mass, and moving a little faster than the 20km/s ejecta. Ultimately the eroding ejecta undergo catastrophic fragmentation into a few fragments some ten times the impactor size (Lissauer & Griffith 1989) and one or two of these fragments may be moving slowly relative to the local cloud. With microdust of sizes in the range  $0.1\text{-}0.2\mu\text{m}$ , the erosion products and probably even the final fragments would mostly be too small to contain intact  $1\mu\text{m}$  spores. However, interstellar grains, in order that they match the observed extinction data, must include a substantial mass fraction of larger particles with a distribution  $n(a)da \propto a^{-p} da$ ,  $p \approx 3\text{-}3.5$  (Wickramasinghe, 1967; Hoyle and Wickramasinghe, 1991). Thus a large mass contribution arises from sputtering by particles in the size range  $1\text{-}3\mu\text{m}$ , and the final fragments would be large enough to contain as well as shield bacterial spores.

#### **5.5 Capture by a proto-planetary disk**

The surface density of a proto-planetary disk is of order  $30 \text{ g/cm}^2$  (3% of a solar mass distributed in a 50AU radius disk). This is sufficient to erode and break up a 30km ice-ball comet if  $E_f \sim 10^5$  applies. The lower excavation factor in rock,  $E_f \sim 5 \times 10^3$ , implies that 500m-sized bolides are eroded away. Since the sputtered material can be a few times larger than the impacting mm-cm grains ( $\alpha$ -Lyr example of Lissauer and Griffith), it is likely to undergo catastrophic fragmentation on its next collision, producing slow-moving subfragments subject to gas friction ( $<1\text{km/s}$ ) and being captured by the embryonic planetary system. The cross section of the disk is  $\sim 10^{19} \text{ km}^2$ , so despite its short lifetime of only 2 Myr during which capture is possible, it catches  $10^{4\text{-}5}$  times as much fertile material as the EKOs.

#### **5.6 Capture by molecular clouds**

Life-bearing ejecta from the solar system encounter molecular clouds more frequently than stellar or planetary systems. The disk of the Galaxy in a region between  $\sim 3$  and  $8\text{kpc}$  (with a strong peak at  $5.5\text{kpc}$ ) from the nucleus is populated by  $\sim 3000$  Giant Molecular Clouds (GMC's) possessing an average radius of  $\sim 25\text{pc}$ , average mass  $\sim 10^6 M_\odot$ , giving a GMC spacing  $\sim 2.5 \text{ kpc}$ . The GMCs and subclouds within them (picture at lower right of Fig.2) are distributed in mass as  $dN \sim M^{-1.5} dM$  (from CO observations - Solomon et al 1989), so the numbers of  $10^4 M_\odot$  and  $10^2 M_\odot$  condensations within a single GMC  $\sim 10$  and  $100$  respectively. These numbers accord with the nearest GMC of the Orion complex at 500pc while the sub-giant ( $2 \times 10^4 M_\odot$ ) Taurus complex at 140pc is self-similar.

The dust to gas ratio is  $\sim 3\%$  (canonical interstellar value for dense clouds) and gas densities ( $\sim 10^4 \text{ H/cm}^3$  for Orion) are higher in smaller discrete clouds.  $M/R^2$  tends to be a constant for various cloud sizes, ie.  $\rho \sim R^{-1}$  (Solomon et al 1989). With sputtering power  $E_f \sim 10^5$ , an icy TNO traversing a cloud of mass  $M$  and radius  $R$  suffers erosion by

$$0.03 E_f M / R^2 \sim E_f \times 0.01 \text{g/cm}^2 \sim 1 \times 10^3 \text{ g/cm}^2 \quad (6)$$

for GMCs and their sub-clouds. This is 3000 times less effective than the proto-planetary disc and equates to 20 or 30m eroded from a porous icy surface. Smaller debris is largely sputtered into fragments, which mostly join the cloud. Note that the surface layer of the TNO, which has picked up fertile solar system material, is deposited within the first molecular cloud that is encountered, reached on the order of 25 Myr. This would be in the form of final erosion products that could deliver 1μm spores with protective ice coverings into the GMC.

### **5.7 Comet disintegration in HII regions**

Traversing a molecular cloud would not disperse an entire comet unless it passed through regions of high radiation density such as the HII regions of O and B stars of the Orion nebula, with suitable ambient radiation field. Then comets become active and outgas strongly as in the solar system around 1AU. Indeed, the presence of dust grains radiating at temperatures of ~ 300K, as in the Trapezium nebula, implies appropriate starlight energy density over an active starforming region of ~ 8 pc in radius (Hoyle and Wickramasinghe 1991), ie. about 10% of the target cross-section of a GMC such as Orion. Take for example Halley's comet at 1 AU when it emitted about 10t/s mainly H<sub>2</sub>O from its 400 km<sup>2</sup> surface. This amounts to ~80g/cm<sup>2</sup>yr and a lifetime of 2500yr, or 0.05pc depth of penetration into the HII region. Thus the comet discharges its solids and biomaterial at the margins of an HII region, making it available for inclusion within the adjacent star-forming regions.

## **6. Delivery rates**

Fertile material from a planetary system like our own can thus be delivered to the pre-planetary nebula of a neighbouring system in two forms - as individual mm to cm-sized ejecta, which suffer modestly from cosmic rays during the trip and from erosion/fragmentation on arrival; and secondly, as the sputtered surface layers of comets, which had been largely shielded during the trip but is roughly treated on arrival. The latter material is only 0.1% of the total on our estimates, but would be important for species that scarcely survive the galactic cosmic rays in cm-sized grains.

The solar system emission of  $Q = 4t/\text{yr}$  of initially fertile terrestrial material, including ~3kg/yr via EK comets is thus readily deliverable on the interstellar scale, though of course it is greatly diluted. It is also non-isotropically delivered, as the solar system's proper motion at ~ 20km/s is much faster than ejection speeds from the solar system (up to a few km/s). We therefore consider the probability of the solar system flying by a proto-planetary disc at distance  $D=1\text{pc}$  or a GMC at  $D=100\text{pc}$  and the amounts of material delivered to them. For the cross-section,  $A$ , of half the 50 AU radius disc (halved for average inclination) or the 25pc radius GMC, the integrated delivered amount on flyby for inverse square dilution is

$$AQ / 4DV = 5\text{kg} \text{ and } 1 \times 10^6 \text{ t resp., with the latter figure averaging 1 tonne per } M_\odot \quad (7)$$

These estimates are depicted in Figure 2.

One has to allow for inefficiency in the incorporation of the 1t per  $M_\odot$  into planetary systems (as well as the loss of viability in the fragmentation delivery process and in the UV exposure of fragments). A part goes into stars, a part is destroyed in regions around short-lived hot O and B stars, a part is ejected by radiation pressure. However, the GMC route would still appear more effective in ultimate seeding of new planets as viability would be little affected during the condensation phases. Any T-tauri phase of the new-born star with high stellar winds would affect all routes similarly - and spore material would find refuge on comets and outer planetary satellites. Moreover, the intervals between flybys at these distances ( $\pi v D^2$ )<sup>-1</sup>, where  $v$  is the space density of proto-planetary discs (~ $10^{-5}\text{pc}^{-3}$ ) or GMCs (~ $6 \times 10^{-8}\text{pc}^{-3}$ ), are 1.5 Gyr and 25 Myr resp. Thus we would infect a few nascent planetary systems at this 5kg level within the solar system lifetime, but

could more effectively deliver terrestrial material to proto-solar systems condensing from a GMC as long as viability is maintained through the GMC collapse and fragmentation (several  $10^8$  yr) timescale. Indeed, it is thought that the solar system has passed through several GMCs since life got started on the Earth - the above formula, modified to include gravitational focussing  $\{\pi v V D^2 (1 + MG/RV^2)\}^{-1}$ , gives an estimate of the solar system traversing a GMC every 220 Myr, taking  $\sim 2$  Myr to do so while delivering perhaps half the 4t/yr.

## 7. Summary and Conclusions

Although routes for interstellar transfers of terrestrial microbiota have been established, quantitative uncertainties still remain. We have relied on the early calculations of viable ('fecund') ejecta by Melosh (1988), but the sterilisation criterion was too strict, at  $<100^\circ\text{C}$  rather than  $<350^\circ\text{C}$ . Secondly, the calculations assumed that initial speeds of m-sized ejecta were high enough to individually push aside the atmospheric loading, rather than shoot out material with the jet-plume. The total mass excavated from the Chicxulub crater (transient diameter 110km) is of order  $10^{14}$  t, estimates of global fallout in the K/T boundary sediments world-wide are  $10^{11-12}$  t, so the 1988 estimate of  $10^9$  t viable ejecta was conservative. Napier (2003) uses the Melosh  $100^\circ\text{C}$  criterion and zero atmosphere to calculate the escaping fraction as  $\sim 3.5 \times 10^{-4}$  times the total excavated mass (valid above the minimum crater size  $D_\#$  for blow-out). With the more realistic  $350^\circ\text{C}$  limit, a viable fraction 0.1% of the Chicxulub crater could be ejected to space ( $\sim 10^{11}$  t), ie. 100 times the conservative early figure.

We have found solutions to the delivery problem - the problem that led Melosh (2003) to conclude erroneously that the chances of interstellar panspermia are "vanishingly small". We have higher ejection of material (averaging tonnes rather than kg per year) from the exceptionally large impacts, and we send out mm- to cm-sized ejecta as well as larger rocks. But the major difference in our model is the final stage delivery - not gravitational capture by fully-formed planetary systems, but hypervelocity fragmentation by solid grains of pre-stellar nebulae and proto-planetary discs. All ejecta, including boulders, are eroded and highly fragmented, whereby the viable fraction is reduced. Sputtered material is of similar size to the existing grains (mass,  $m_{\text{grain}}$ ) or as large as the granular structures within the impacting object. It continues at high speed until fragmenting in a further collision. The largest fragments - those most likely to preserve viable spores - are produced in the explosive collision of eroded remnants of about  $10^5 m_{\text{grain}}$  (Lissauer & Griffith 1989). A fraction of the fragmentation products (up to masses  $\sim 10^3 m_{\text{grain}}$ ) are moving slow enough relative to the nebula or disc to be gravitationally captured (eg.  $\sim 1$  km/s). Evidently, numbers of viable micron-sized spores captured via hypervelocity fragmentation is sensitive to the grain sizes  $m_{\text{grain}}$  (fewer by submicron grains) and proportional to the numbers rather than sizes of the pieces of ejecta. Delivery to the proto-planetary disc stage containing mm-sized grains (as  $\alpha$ -Lyr) is biologically far more effective than to the molecular cloud stages, though the available collection times are orders of magnitude larger for the latter. Judging which is more effective for seeding the new planetary system needs specific study.

We also conceive that some terrestrial ejecta can hitch a ride in the protected environment of an EK comet. There is a question as to whether spores can survive the  $10^{8-9}$  yr journey to the EK comet within mm-cm ejecta. If this were marginal, then one could consider a fraction launched from Mars on energetic Jupiter-crossing orbits and forwarded on their interstellar journeys within  $10^{2-3}$  yr. Terrestrial microorganisms could even successively colonise Mars and icy satellites of Jupiter and Saturn, using them as staging posts while awaiting impacts to send them on to the EK belt or out into interstellar space. But this strategy to substantially cut down the dose of energetic solar radiation means relatively slow transfer compared with direct forwarding. Delivery to a GMC would be eased for terrestrial ejecta emitted when the solar system is passing through it (Napier 2003 - occurs at  $\sim 220$  Myr intervals on our estimate, delivering  $\sim 10$  times more fertile material than

in the 100kpc flyby of Fig. 1). However, in this case the solar system dust cloud is strongly enhanced and itself fragments the ejecta. In the fragmented state, spores within  $\sim 10\mu\text{m}$  fragments are potentially more vulnerable to solar flare particles and X-rays, while isolated spores for which radiation pressure might approach or exceed solar gravity (Napier 2003) are more vulnerable to UV. So although fragmenting delivery when passing through a GMC is easier, the survivability problem might be more severe. The solar system is less likely to pass through smaller clouds. The solar system meets  $10^4 M_\odot$  clouds every 2200 Myr on the above dependencies (section 5b), not every 100 Myr as Napier (2003) estimates on the basis of a different set of assumptions. Our numbers for sizes and abundance of GMCs, applying to the mid-galactic disc, give about twice as many GMC encounters as Mumma et al. (1993) who discussed the erosion of Oort cloud comets by the same sputtering mechanism.

Another uncertainty lies in viability under galactic radiation. At the present time we lack experimental evidence and arguments to definitively resolve the survival issue for cryogenically stored bacteria and spores subject to exceedingly low fluxes of ionising radiation over astronomical timescales. The survival to solar CRs and X-rays in the inner solar system is amenable to experiment, but the results would not be crucial, and only throw light on the degree of shielding required (or the size limits of eventual fertile ejecta) and on the importance of fast-track orbits.

In a newly emerging planetary system, comets and cometesimals are expected to play a role, in accreting fertile material along with other condensable matter in the outer parts of the planet-forming disc. This biomaterial is then available for amplification. Radiogenic warming starts off biological activity, which itself adds to the warming (release of metabolic heat) and enables biotransformation of the comet interior (Hoyle and Wickramasinghe 1984). The amplified material is best suited for delivery to planets in the final accretion stages. Analogously, impacts in the EK belt with burial of terrestrial biomass might cause episodes of collisional warming sufficient to set off microbiological activity and enhance the mass of fertile biomaterial for onward transmission by orders of magnitude. The class of “red” TNOs may correspond to objects where such amplification has taken place (Hoyle and Wickramasinghe, 1998).

A kilogramme of spore-bearing material is plenty for seeding a new planetary system with life. With  $\sim 10^{12}$  microbes/kg, one could guess at  $10^6/\text{kg}$  in a highly-stable spore state. Only a fraction of the fertile material delivered to nascent planetary systems will of course reach the planetary surfaces in a viable form via ‘late bombardment’ comets and cometesimals. Cometessimals explode in the atmosphere (as did the 1908 Tunguska object) and spores may survive such a blast; but the normal process of cometary particulate release in the evaporating ices to join the interplanetary dust complex and of gentle accretion in upper atmospheres, is a better validated process for delivering cometary material to planets.

Pending resolution of the question of viability to galactic CRs, we see that the transference of evolved microbial life from the Earth to star and planet forming clouds in a GMC occurs on flyby at  $\leq 100\text{pc}$  about every 15 Myr. Once released into dense clouds, growth of organic mantles around the smallest particles and grain agglomeration into clumps would enhance protection against ultraviolet light as well as stellar flares and X-rays. A supernova outburst is thought to compress sub-clouds and trigger the formation of planetary systems, along with a complement of comets. The fresh radioactively-warmed comets may constitute a suitable environment for microorganisms to replicate and be amplified by orders of magnitude (Hoyle & Wickramasinghe 1984). Planetary perturbations start expelling comets to interstellar space in  $\sim 10$  Myr, although the expulsion of most comets would take place over longer timescales of a few 100Myr. For directions transverse to the 20km/s solar system motion, the comet expulsion speed ( $\sim 5\text{km/s}$  if ejected by a Jupiter (Melosh (2003))) is relevant. Thus on the average, comet-based life would spread through the galaxy at a rate of  $\sim 5\text{kpc/Gyr}$ , thus enveloping the entire galaxy in a few Gyr. If this happens for life from the Earth, a Copernican style argument implies that the process is unlikely to have begun in our solar

system, of order 10 Gyr after our Galaxy formed. Every planetary system would share a similar initial endowment of cometary life but offer a range of environments, in contrast to the little diversity in comet interiors. If it takes ~1 Gyr for significant evolutionary changes in the gene bank to occur on planets in response to the local environments, such changes have little time to become well mixed across the galaxy. Thus life on Earth and elsewhere would be the heterogeneous products of biological evolution on the grand galactic scale.

## ACKNOWLEDGEMENTS

We are grateful to Bill Napier for discussions and an early copy of his paper. We thank Phil Solomon for information on molecular clouds and Mark Burchell for information on hypervelocity collisions. Fred Hoyle was a co-author on an early version of this paper presented in abstract form at the SPIE Conference 3755 "Instruments, Methods, and Missions for Astrobiology II", San Diego, July 1999.

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## FIGURE CAPTIONS

### Fig.1

Tonnages of life-bearing rocks and soils ejected from Chicxulub-sized impacts on Earth partitioned in the solar system, with time scales as indicated. These tonnages are based on conservative estimates of ejected material and spore survivability in the process - the numbers could be 10 or 100 times higher (section 6) but don't include high inefficiencies in final delivery via hypervelocity fragmentation. Distances are not to scale - the active part of the Edgeworth-Kuiper belt of comets and giant TNOs at 35-50AU is relevant in the processes considered.

### Fig.2

Schematic depiction of the delivery of terrestrial ejecta from the solar system to a proto-planetary system and to a giant molecular cloud (GMC) as analysed in the text.

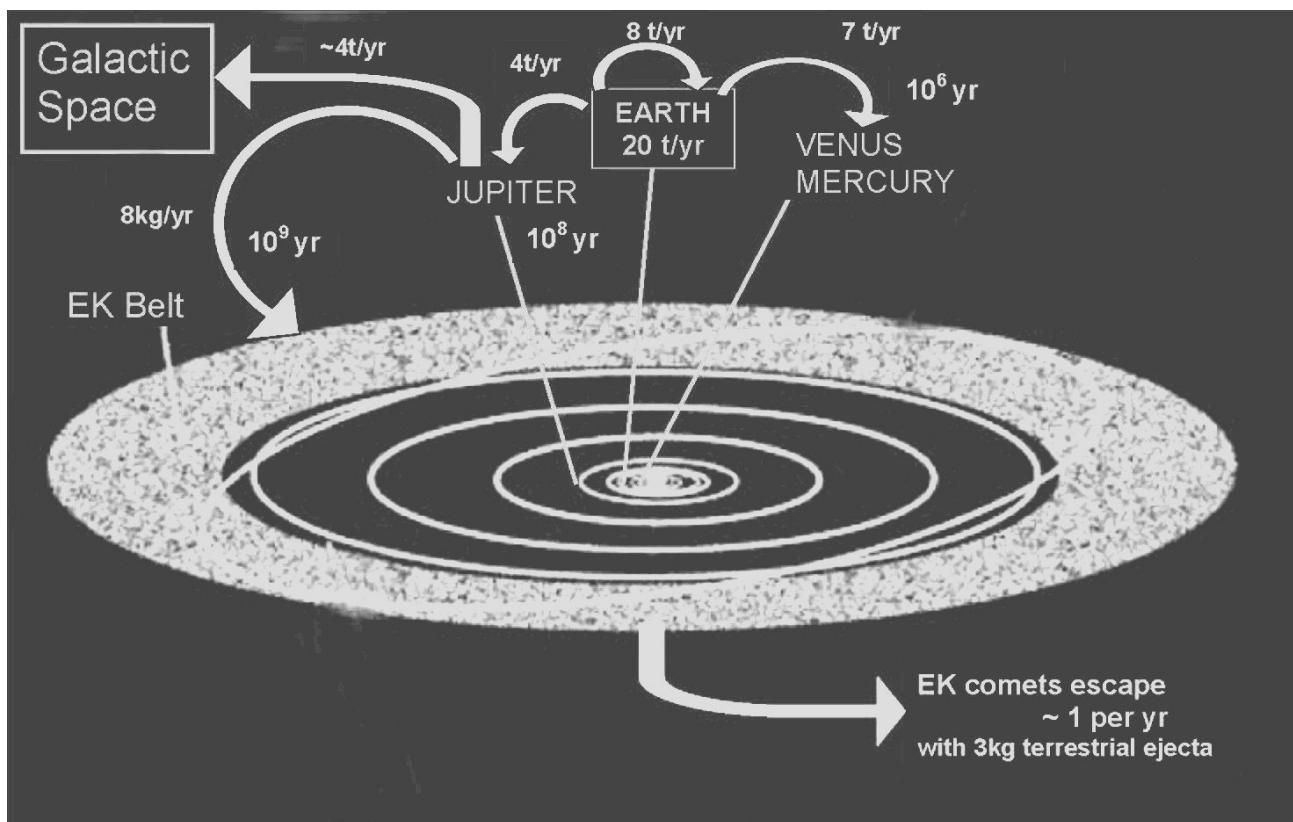


Fig. 1

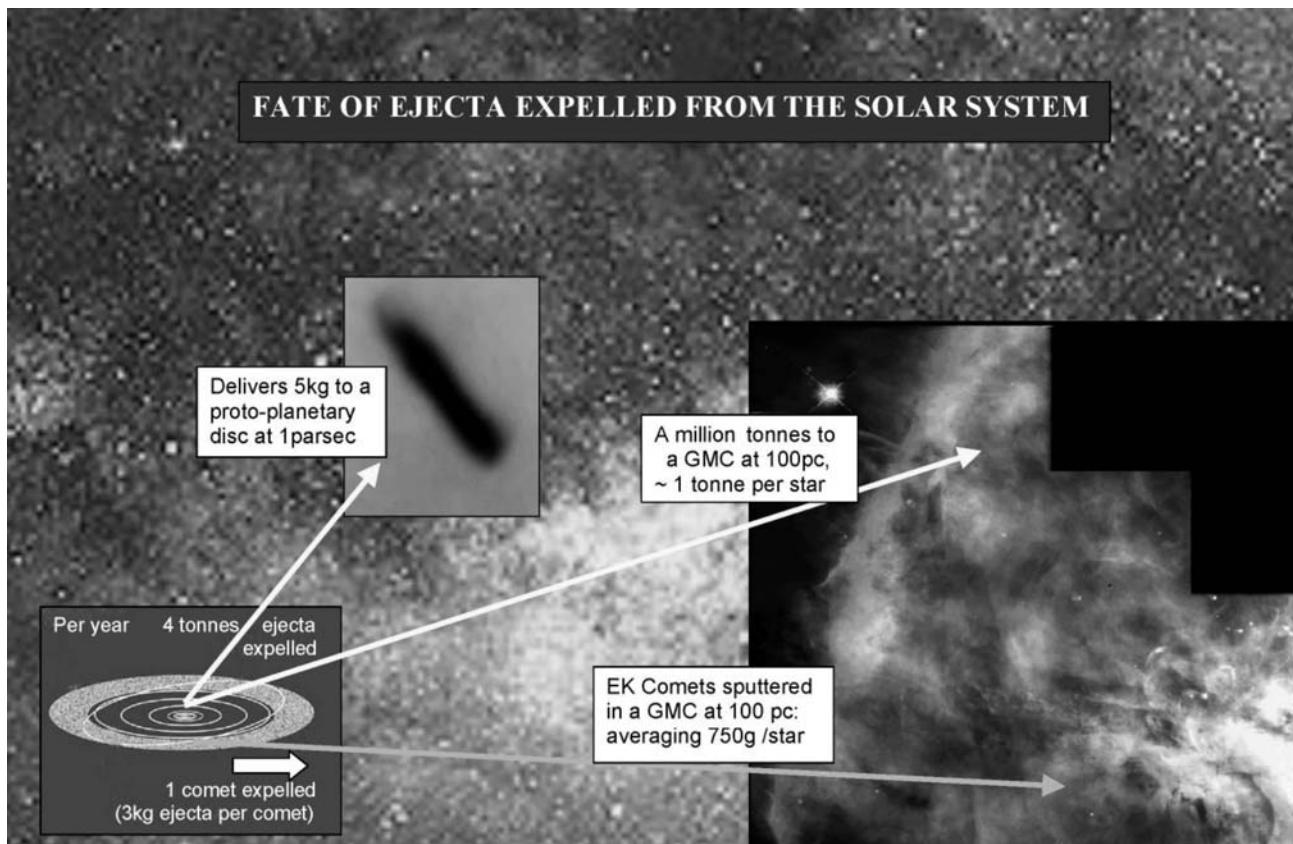


Fig. 2

## APPENDIX - SPACE-HARDINESS OF BACTERIA

Microbiological research of the past decade has shown that bacteria and other microorganisms are remarkably space-hardy, far hardier than had hitherto been thought. Heat-resistant microorganisms, thermophiles and hyperthermophiles, are present at temperatures above boiling point in oceanic thermal vents. Entire ecologies of microorganisms exist in the frozen wastes of the Antarctic ices, some inhabiting the interior regions of rocks in the Antarctic dry valleys. Microbes have also been discovered deep in fractures in granite, and a formidable total mass of microbes is thought to exist in the depths of the Earth's crust, as deep as 7km with total mass greater than the biomass at the surface (Gold, 1992). Such microorganisms are not photosynthetic, but make use of chemical energy sources. There are bacteria, which perform photosynthesis at exceedingly low light levels, as does a phototropic sulphur bacterium in the Black Sea (Overmann et al, 1992). There are bacteria (e.g. *Deinococcus radiodurans*) that thrive in the cores of nuclear reactors. Such bacteria perform the amazing feat of using an enzyme system to repair DNA damage, in cases where it is estimated that the DNA experienced upwards of 10,000 strand breaks. These bacteria survive upwards of 10 kGy of ionising radiation, whilst most species are damaged at much lower dose.

Experiments on bacterial spores (*B. subtilis*) show that within the solar system or within interstellar clouds, UV radiation is the main destructive agent. Survival is much greater at low temperatures (~10 K), low pressures and in the absence of water, which could be related to the creation of ultra-stable 'vitrified' states, whose vulnerability to UV is unexplored. UV protection is also afforded by thin carbonised coatings (~30nm - Wickramasinghe & Wickramasinghe 2003), by ice (>40nm - Warren 1984) or by condensates from molecular clouds (~100nm - Weber & Greenberg 1985). Survival rates are high in space exposure of spores mixed in soil analogues (Horneck et al. 2001b), though these authors argue that micron-sized soil particles attached to spores will not protect them. In the galaxy at large, molecular clouds both foster the growth of protective carbonaceous icy mantles and attenuate the ambient ultraviolet radiation field. Over long time scales, galactic cosmic rays and intrinsic radioactivity in rocks may kill off microorganisms within them - the calculation of Mileikowsky et al. (2000) gives  $4 \times 10^{-4}$  survival within 0.67-1m rocks after 1Myr. In interstellar transport, the shielding afforded within bodies larger than metre-size, including within comets, is near complete, while mm-cm sized bodies suffer less from cosmic ray secondaries.

Recent arguments for severe limitations of microbial viability (Mileikowski et al. 2000) are based on extrapolations of survival curves in experiments with bacterial spores flown in space. The survival of ~1% on the 6-year LDEF experiment disproves the exponential tail-off in the survival fraction at longer exposure times, presumably because a fraction of the spores achieve a highly resistant state. In other well-attested cases no exponential tail-off is found. For instance, even for an unresistant vegetative bacterium *Streptococcus Faecium*, a substantial viable fraction persisted after a radiation dose of 20 kGy (Christensen, 1964).

Radiation conditions in galactic space are thought to be dominated by cosmic rays (apart from UV light which affects only the submicron surface layer). Only the higher energy galactic cosmic rays (GCRs) penetrate into the heliosphere, so those below ~1GeV have to be modelled. The spectrum used by Cooper et al. (2001) has implausibly high energy density of ~10 eV/cm<sup>3</sup>; their calculations of radiation dose with depth could be scaled down by a factor 10. This gives, for example, a dose of 60 kGy/yr (6 Mrad/Myr) at a depth of 1 cm and five times this at a depth of 1mm. Clark (2001) argues that 50 kGy causes complete sterilisation, while Horneck et al (2001b) believe this is over-pessimistic and point to difficulty in extrapolating from high dose rates in the laboratory to low dose rates over Myr in space.

In the solar system, individual solar flares can produce extremely high fluxes of ionising radiation, but the average over a solar cycle at a distance of 1 AU from the sun is ~ 3 kGy/yr (double the  $2\pi$  flux of 1.0 GeV/cm<sup>2</sup>/yr from solar energetic particles deposited in the surface mm - Cooper et al.

2003). Considering ejecta to spend most of their 10Myr sojourn in the inner solar system between the orbits of Mars and Jupiter, say at  $\sim$  3AU, the relevant free space dose rate from  $\sim$ 10keV X-rays and  $\sim$ 10MeV protons is nearer 0.3kGy/yr] giving a damaging radiation dose (100 kGy) in 300yr. This is plenty of time for some terrestrial ejecta to reach Mars and the small fraction fast-tracked to Jupiter-crossing orbits would dominate the transfer of viable organisms because of the high survival fractions. Nevertheless, the question is still open whether significant fractions of the bulk of the ejecta taking  $10^{5-6}$  years to pass Jupiter survive, because radiation-hardiness may be much higher in spores subject to the cold, vacuum conditions of space than in the documented terrestrial examples. The radiation environment in the outer solar system, towards the heliosphere boundary (>100 or 150 AU), is thought to be dominated by "anomalous cosmic rays" accelerated in the terminating shock region. But on the models of Cooper et al. (2003), these 10-100MeV protons are 2-3% of the galactic CRs of similar energies, so would not be important for ejecta escaping from the solar system.