

# Panspermia today

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**Abstract:** Panspermia is the idea that life migrates naturally through space. Although an old idea, there has been much recent theoretical and experimental work developing the idea in recent years. In this review, this progress is considered and placed in context. Ideas concerning Panspermia now include mathematical treatments of the likelihood of transfer of life from Mars to Earth, the possibility of life transferring between the natural satellites of an outer planet such as Jupiter, and mathematical treatments and models of life migrating out of a Solar System. Not all predictions of the likelihood of successful Panspermia are positive, and some are contradictory. At present, Panspermia can neither be proved nor disproved. Nevertheless, Panspermia is an intellectual idea which holds strong attraction. However, at the heart of Panspermia is a still un-resolved mystery: in order to migrate, life has to start somewhere, and we still cannot tackle that moment of origin.

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## Introduction

Panspermia ('seeds everywhere') is an intellectual concept of widespread appeal. It is built on three key realizations: (i) life had an origin; (ii) the Earth is not the centre of the Universe; and (iii) planets such as the Earth are not isolated bodies, entire in themselves. Taken together this leads to the idea that life might be more widespread than just appearing on the Earth, and that if material can move between bodies in space, then maybe it can carry life with it. The history of the idea of Panspermia is discussed in articles such as Davies (1988).

Different societies will have their own history of the origin of the theory of Panspermia. What is interesting is that by the late 1800s, there was widespread interest in the industrial nations concerning the nature and origin of the Solar System, combined with a recognition of the Earth as a planet with a long history and a growing interest in the origin of life on Earth. It is the linking of these areas that leads to Panspermia. In the United Kingdom, Lord Kelvin's address to the British Society for the Advancement of Science in 1871 is often taken as a key crystallization of these separate ideas into one. He postulated that since meteorites came from space, perhaps they had brought life with them to the Earth. Part of the motive for such speculation was almost certainly unease with the idea of spontaneous generation of life. Indeed, it is not uncommon in education today to be earnestly told in one classroom that scientists have shown that spontaneous generation of life is impossible, and to be equally earnestly told in another classroom that Darwinian evolution shows that all life on Earth is descended from a common ancestor which just appeared.

In the early 1990s, the Swedish scientist Arrhenius wrote on this idea and coined the word Panspermia (Arrhenius 1908). In his book *Worlds in the Making* Arrhenius considered several emergent mysteries in science. He noted the occurrence of many volcanoes in chains and was sure it revealed something about the Earth's interior (which we now accept it does). He considered the idea that rocks could be hotter than their surroundings (but failed to make the link to what we now call nuclear physics). And he decided it was feasible that life could migrate through space. In doing so he gave this subject its name (Panspermia). As such he is often taken as the father of the field. As well as an intellectual organization of the topic, he attempted to consider the physical mechanisms necessary for such migration and the stresses that a life form would be subject to during transit. He suggested that Solar radiation pressure might drive spores across space (this is known as radiopanspermia).

The development of Panspermia as an idea then waxed and waned during the 20th century. As planetary science became an experimental discipline (backed up by astronomical observation and space exploration) the more fanciful ideas of a Solar System full of green, verdant planets, rich in life, died. However, there were advances which helped continue interest in the idea of life elsewhere. The Miller–Urey experiment (Miller 1953), which indicated that amino acids could be readily synthesized in the laboratory, undoubtedly stimulated the imagination. The realization that amino-acid synthesis was not, in itself, the big hurdle to life generation and the subsequent failures in generating life itself have had a negative impact.

One can, however, make a step forward. If amino-acid formation is taken as part of the chemistry that comes

before life, then the ease of its synthesis is significant. Further, there is direct evidence that it has occurred elsewhere. Meteorites are extra-terrestrial materials available here on Earth. Studies of the Murchison meteorite (which fell in 1968 and which was rapidly recovered before extensive terrestrial contamination could have occurred) have shown that it contained 74 identified amino acids, 55 of which have no known terrestrial counterpart (Cronin 1989). Thus pre-biotic chemistry certainly occurs elsewhere than just here on Earth, and the results have been delivered to this planet.

One can speculate in general on how much organic material has been delivered to the Earth from space (as distinct from being produced locally). It is possible that large quantities of such materials have been delivered. For example, as well as the occasional large impact from space, there is a continual input of dust to the Earth's atmosphere (Brownlee 1985) estimated to be a flux of some 40 million kg tons per year (Love & Brownlee 1993). Part of this flux will be organic material, some of which will survive capture (e.g. Anders 1989; Chyba *et al.* 1990; Chyba & Sagan 1992). It could thus reasonably be argued that Panspermia itself is merely the next step. However, it is still a big step.

### Interplanetary transfer (e.g. Mars–Earth)

An important step is to distinguish between meteorites and dust which arrive on Earth and that have never previously been incorporated into a larger planetary size body, and materials that come from other planets. Traditionally, meteorites were held to be materials that originated from small parents that had never formed planets, or from comet nuclei, etc. There are paths by which such bodies could have generated their own local conditions necessary for life (e.g. liquid water, etc.). Internal heating by short-lived radioisotopes could melt ice and help provide both energy and water. Some meteorites show signs of aqueous alteration of their mineral content indicating that something of this sort has indeed happened. One could argue that whilst such bodies are small, there are a large number of them in the Solar System, providing many potential sites for life to develop. And if the origin of life was a sub-surface event (deep in a hydrothermal system in rock, for example), then this should not be neglected. So as a source of life for Panspermia, such bodies should not be neglected. A collision in the asteroid belt could break apart such a body and the evolution of the orbits over time can deliver the fragments to the Earth.

Nevertheless, space is a harsh environment. Radiation hazards over time will sterilize small bodies (see Clark *et al.* (1999) for a discussion). The sources of energy in these bodies will die with time, reducing the time-scale on which life could have started. Also, the combined mass of all the minor bodies in the asteroid belt is less than that of a single rocky planet such as Mars. Finally, if we use a general principle, which may be labelled as that of familiarity, then the only example of a location where there is life is on a planet (Earth), so the best place to find life is planets. In which case,

establishing that materials transfer naturally between planetary surfaces is crucial.

There are several significant steps involved in establishing that rocks from another planet can be found on Earth. These include recognizing such rocks here on Earth, solving the mathematics for the orbital transfer to understand typical orbits and transfer times, and finally developing a mechanism to eject the rocks in the first place. Rather than present the results in order in which they occurred, they are presented here in the more logical order of ejection, transfer and recognition.

The energy per unit mass required to achieve the escape velocity from a planetary body is such that a local energy source is basically insufficient for any macroscopic body. Of course, a local concentration of energy can be provided under the right conditions (e.g. a rocket), but this is ignored here. However, an external input of energy does exist, namely impacts from space. Impacts are common phenomena (on Solar System time scales) as evidenced by the craters on the surfaces of the Moon, Mars, etc. Even small bodies such as asteroids and comet nuclei show craters on their surfaces. Spacecraft and solar panels retrieved from Earth orbit also show impact craters from small dust-sized impactors. These impact events are at high speeds. For example, Hughes and Williams (2000) calculate that bodies from interplanetary space will impact the Earth at speeds of typically 20–25 km s<sup>-1</sup>. As one proceeds outward in the Solar System these speeds start to fall, e.g. impacts on Pluto will be at typically 0.5–3 km s<sup>-1</sup> (Dell'Oro *et al.* 2001). It should, however, be remembered that the impact speed is the result of a combination of the relative speeds of the appropriate bodies in their heliocentric orbits (which as stated are lower the further out from the Sun), combined with a term due to the mutual gravitational attraction. In the case of a large planet like Jupiter this latter term can dominate. So the typical impact speed of an interplanetary body hitting Jupiter will exceed the typical impact speed on Earth (even though Jupiter lies further out from the Sun than Earth).

The results of impacts on solid surfaces at speeds in excess of a few km s<sup>-1</sup> are the craters we are familiar with. These are much larger in diameter and volume than the original impactor. The material removed from the crater can be ejected at high speed, in some cases at greater than the local escape velocity. This high-speed ejecta will consist of fragments of rock smaller than the original impactor, but are from the target. Thus interplanetary space will be seeded with rock that was originally from the planetary body. A mathematical treatment of this was developed by Melosh (1988), in which it was shown that the ejecta may only be lightly shocked in the process. This is important, as a high peak pressure pulse (during launch) can raise the internal temperature of the object and hence sterilize it. The launch method of Melosh (1988) holds out in the hope that this may not be the case.

Once ejected from a planet, the heliocentric orbit of a body can be calculated and extrapolated forward in time. Modelling of such orbits by, for example, Wetherill (1984)

showed that these orbits can eventually cause the body to collide with another planet (e.g. Mars–Earth transfer). These results have been confirmed by later more sophisticated modelling, which includes effects such as orbital resonances, etc. (e.g. Gladman *et al.* 1996; Gladman 1997). For Martian ejecta, the end fate and the timescale for the transfer can be found. Some material interacts with Jupiter, some of which is ejected into the outer Solar System after gravitational interactions with Jupiter, and some material ends up in the inner Solar System. Typically, of the order of 5–10% of Martian ejecta that achieves Martian escape velocity is predicted to impact the Earth within 100 Ma. The minimum timescale for the transfer is just seven months, with 20% (of the transferred material) arriving after just 1 Ma.

Finally, the rock arrives at the Earth and enters the atmosphere at high speed. Objects of centimetre size are expected to burn up during entry. However, slightly larger objects will penetrate the atmosphere, slowing down in the process, and arrive on the Earth's surface as meteorites. They will have developed a thin fusion crust of burnt material as a result of the heating during atmospheric entry, but the interior will still be cold. Larger objects can arrive and plunge into the atmosphere at high speed, shedding mass in fragments as they descend, or even exploding in the air showering the ground with material. The largest of objects (a few tens to hundreds of metres or above) arriving from interplanetary space will not slow down during atmospheric entry, but will impact the surface leaving a crater. Most of a larger object will be vaporized in the high-speed impact and this is thus not usually considered a good a route for successful transfer of material. Nevertheless, the smaller objects do transfer intact, minimally processed material from planetary surface to planetary surface on relatively short timescales.

The final step in this so far theoretical discussion lies in the work of those such as Bogard and Johnson (1983). There had been earlier speculation that some meteorites here on Earth were Martian in origin, but it was Bogard and Johnson (1983) who are often held as firmly establishing this link. They based their conclusion on overall relative gas abundance, and an analysis of the isotopes ratios of the argon and xenon gas trapped in an example meteorite. The identification with a Martian origin was made based upon the similarity of the results of this analysis and the Martian atmosphere as reported by the Viking landers. Currently there are some 20–30 meteorites widely accepted as Martian in origin, and they only represent a small fraction of the Martian rocks that must have arrived here on Earth in the past.

The famous ALH84001 with its putative nanofossils (McKay *et al.* 1996) is one of the Martian meteorites. The debate concerning the possible biological origin of some of the structures inside the meteorite continues. In the Panspermia context, however, fossils are not the goal: the transfer of extant life is. So, if a Martian meteorite containing a life form that colonizes rocks (e.g. an equivalent of a cyanobacteria that can be found in terrestrial rocks) were ejected into space, could it have arrived here still alive? In this context it should be noted that Clark *et al.* (1999) predicted

that a rock 10 cm in diameter would be sterilized in interplanetary space after 10 million years. Indeed, Clark (2001) points out that of the then-known Martian meteorites, given their size and transfer times (estimated from exposure to radiation in space), all will have received a sterilizing radiation dose during their transit to the Earth.

There are clearly routes for material to transfer naturally between planets such as Mars and Earth. Unlike the currently known Martian meteorites, some of the transfers will involve relatively short timescales, and the rocks can be large enough to harbour spores, microbes, etc. Their arrival at the Earth can be violent, but may not sterilize the rocks. To actually survive in a new environment, the life form still has to be released and then find an environment in which it can grow.

As well as just the transfer of ejecta, Panspermia requires that it should carry life. This has also been modelled and expressions derived for the probability that biologically active material can be successfully transferred from body to body (e.g. Mars to Earth). This is known as lithopanspermia. Several approaches exist. Clark (2001) broke the problem down into a series of separate steps, each having its own probability. The product of these individual probabilities gives the overall probability of successful transfer. Mileikowsky *et al.* (2001a,b) adopted a slightly more elaborate approach. They developed a series of equations, which again consider the various steps, but link them such that some steps are sums or integral terms, the various contributions to which depend on the assumptions in the previous steps (e.g. size of ejecta, etc.). Many assumptions still have to be made to turn the equations into exact predictive tools. As pointed out in Burchell *et al.* (2003), some of the terms in these calculations can be reasonably assumed or calculated by laboratory experiment; however, others (e.g. amount of micro-organism per gram of Martian soil) remain simple guesses until actually measured *in situ* on Mars. Thus the single definitive calculated probability for successful transfer of life from Mars to Earth is not achievable. However, both approaches do provide powerful tools for study of the problem.

### Jovian satellites

The Earth–Mars system is not the only place in the Solar System where natural transfer may occur. An analogue system is, for example, Jupiter and natural transfer of material may occur between its satellites. In this respect, it should be noted that whilst Jupiter is outside the normal definition of a habitable zone around a star, there are Jovian niche environments where life may occur, such as in subsurface oceans on ice covered satellites, e.g. Europa (Chyba and Phillips 2002). This idea of Jovian Panspermia was developed, for example, by Burchell *et al.* (2003). The same logic applies as in the Mars–Earth system. A giant impact on the surface of Europa would eject ice into a Jovian orbit. It can then subsequently collide with another satellite in the Jovian system. As well as advancing this hypothesis, in Burchell *et al.* (2003) it was shown that if bacteria are frozen in a block of

ice, the ejecta from a high-speed impact can indeed carry viable bacteria that can be captured and then cultured. So, if life exists in a sub-surface European ocean, it could possibly be spread to the other satellites in the Jovian system.

Equally, one can wonder if a body carrying a life form could have impacted Europa and delivered life to it in the first place. Recently, Burchell *et al.* (2004a) have shown that projectiles laden with bacteria or spores can be fired into ice blocks, and if the ice in the bottom of the resulting crater is sampled, viable bacteria and spores (originally from the projectile) can be found and cultured. Thus surviving high-speed delivery to an icy body is not an insurmountable obstacle to the transfer of life to Europa.

One thing that is not often fully appreciated is that Jovian satellites are not isolated from the rest of the Solar System. The Ulysses spacecraft found strong streams of dust particles emerging from Jupiter (Grün *et al.* 1993). These were confirmed by the dust detectors on the Galileo spacecraft (Grün *et al.* 1996). Modelling (Zook *et al.* 1996) showed that these had to be travelling at speeds of greater than  $200 \text{ km s}^{-1}$  (with sizes of order of 5–10 nm). The particles may originate from the volcanic plumes seen on Io, for example. They are charged by Solar photoelectric emission, and then accelerated in Jupiter's magnetosphere. Whilst, such small grains are unlikely to be carrying viable life forms, they may be carrying organic material outward from Jupiter. At such speeds they can leave the Solar System and as such may be seeding interstellar space with organic material from our Solar System (Hamilton 2004). This could also be happening around other planets with large magnetospheres (e.g. Saturn). In turn, it is known that interstellar dust penetrates our Solar System. This was first detected by the Ulysses spacecraft, which found grains of  $0.4 \mu\text{m}$  size (Grün *et al.* 1993, 1994), and interstellar dust was later found entering the Earth's atmosphere (Taylor *et al.* 1996). Whilst not Panspermia, this is an intriguing possibility that challenges the concept of the Solar System as an isolated region.

### Extra-Solar migration

As well as the emission of dust into interstellar space, there is also ejecta from planets that can escape the Solar System. The ejection mechanism (see above), which removes rocky material from the Martian surface, may not only send it to Earth, but some of the material will head into the outer Solar System. Modelling of the orbital evolution of Martian ejecta (e.g. Gladman *et al.* 1996; Gladman 1997) shows that some 15% undergoes interactions with Jupiter's gravitational field, and this can then head outwards through the Solar System. The effects of gravitational resonance mean that the timescales for this are shorter than previously thought. Melosh (2003), for example, pointed out that this material can then populate interstellar space.

The probability of such material traversing interstellar space and colliding with a planet in another Solar System can be modelled. Melosh (2003) does this and predicts that that

only one rock per 1000 Ma is likely to be ejected from our Solar System and captured by another. During periods of more intense bombardment of the planets, such as during the early history of our Solar System, this will increase (but of course there will have been less time for life to have evolved on a planet so soon after the formation of the Solar System). However, there is then a problem. Entering another Solar System is not sufficient for Panspermia; the rock would have to impact another planet. When this was factored in by Melosh, he found that only one in 10 000 captured rocks would do so. The chances of transfer from the surface of a planet in our Solar System to the surface of a planet in another Solar System are thus negligible. In addition, Melosh noted that the timescales for the processes he modelled are of order of 1000 Ma. The exposure to radiation in space for such a period has a high probability of sterilizing all but the largest rocky bodies. Nor is it clear how a life form could survive even in a frozen spore state (i.e. extreme low metabolic activity) for such a period. It was thus concluded in Melosh (2003) that interstellar Panspermia is not feasible.

Other researchers are less sure. For example, Napier (2004) noted that once ejected from a planet, rocks are subject to collisional erosion by interplanetary and interstellar dust. This produces small micrometre-sized dust grains of the parent rocks. These can now be readily accelerated out of the Solar System by Solar radiation pressure. This thus combines lithopanspermia with radiopanspermia (e.g. Parson 1996). Although a small grain offers little shielding against radiation damage from cosmic rays etc., the high speed reduces the ejection and transfer times in interstellar space compared with a larger gravitationally ejected rock. Once in interstellar space the dust can be captured in dense molecular clouds, star-forming regions, etc. This dust can then be incorporated into comets, rain down on a planet around another star and so on. Indeed, our Solar System could be the recipient of such material as well as a source.

Wallis and Wickramasinghe (2004) similarly tried to find an alternative Solar System ejection mechanism, which avoids the conclusions of Melosh (2003). They began by proposing (like Melosh (2003)) that the rocky material heads outward through the Solar System after its gravitational interaction with Jupiter, and noted that allowing gravitational interactions, not just with Jupiter but also Saturn, Uranus etc., in the modelling speeds up the outward transfer of material. They then suggested that once beyond the planets the rocky material might impact a comet or an icy body in the Edgeworth–Kuiper Belt (the region 35–80 astronomical units from the Sun). In this case, possibly life-bearing rock can accumulate in the interiors of these bodies. The result of Burchell *et al.* (2004a), which showed that life-bearing projectiles could be fired into ice with the life surviving, is relevant here. Also relevant are the works of Koschny *et al.* (2002) and Burchell *et al.* (2002), which showed that for impacts into porous ice at  $1\text{--}7 \text{ km s}^{-1}$ , a substantial fraction of the projectile survives relatively intact (or at least as macroscopic fragments).

Once the rock is embedded in the icy body, its putative biological content is now shielded from radiation by a larger mass than before. The icy bodies can then be ejected into interstellar space by perturbations from Saturn and Neptune or from extra-Solar influences. Once ejected, Wallis and Wickramasinghe suggested other delivery mechanisms to other planetary systems than the direct hit mechanism of Melosh (2003). They suggested that after capture an icy body might distribute material as a comet on a passage through the inner region of another Solar System, or sputtering of the surface of the icy body may occur as it passes through dense molecular clouds or protoplanetary disks etc. (where the results of Burchell *et al.* (2003) suggested ejected material can contain viable biological material) and the resulting dust grains are then captured somehow onto a planet. There are many uncertainties and assumptions in the model of Wallis and Wickramasinghe, but they concluded that, under favourable conditions, life might spread across a galaxy at the rate of  $5 \text{ kpc Ga}^{-1}$ .

### Impact experiments

As well as developing new hypotheses, research on Panspermia has moved into the experimental stage. Various aspects of the hazard to organisms of Panspermia are increasingly studied either in the laboratory or on space missions.

One aspect for successful Panspermia is the survival of organisms in space itself during their transfer to a new home. The low pressures and radiation doses associated with space (and a temperature that varies with distance from the Sun and degree of illumination) all seem hostile to life (see Horneck *et al.* 2002). Several experiments have been carried out exposing biological material to the environment of space, e.g. Horneck *et al.* (2001a). If spores are mixed with a thin covering of soil, survival is found for short-duration exposures in Low Earth Orbit lasting months. Thus for a minimum duration transfer from Mars to Earth (e.g. of the order of seven months), placing the spores in a mixture of rock and soil would shield biological material and deliver it in a viable state to the Earth.

A common feature of the various hypotheses discussed above, is that for successful Panspermia, the material involved can expect to be subject to shock impacts. In some cases this is the mechanism that launches it into space, in others it is the fate of the material on arrival at a new body. The impact speeds involved are measured in units of many kilometres per second. At such speeds, the resultant shock waves exceed the speed of compression waves in the materials (which result during an impact). This means that the normal deformation mechanisms that carry energy away from an impact site cannot operate. The result is a transient pulse of extreme high pressure (many GPa) and density. During the release from the shocked state there is a rise in temperature. The result can be melting or even vaporization of some of the material involved. Surrounding material in the target

then flows (the pressures exceed material strengths) to form a crater.

It is not surprising that for large bodies impacting solid surfaces the resulting impact event is held to be so violent that almost all of the projectile is consumed with less than 2% being recoverable at the impact site. This surviving fraction is not only small, but usually consists of melted and heavily processed fragments scattered in the floor of the crater or just beneath. Survival of any biological material is thus, at first glance, doubtful.

However, using flying plate techniques, Horneck *et al.* (2001b) demonstrated that spores can survive peak shock pressures at 32 GPa. They used *Bacillus subtilis* spores and found survival rates of  $10^{-4}$ – $10^{-6}$ . Burchell *et al.* (2001, 2004a) have gone further than this. They doped projectiles with loads of spores or bacteria and fired them in a two-stage light gas gun at speeds of up to  $5 \text{ km s}^{-1}$ . Impacts were onto targets such as agar plates (a very moist target) and ice. Again survival was found. This was for *Rhodococcus erythropolis* bacteria and *bacillus subtilis* cells and spores. Peak shock pressures varied from 1 to 70 GPa, and the survival rate typically fell from  $10^{-4}$  to  $10^{-7}$ . This demonstrates that survival rates are small but finite over the range of peak pressures expected during planetary impacts.

Small grains have a different fate on arrival at a planet with an atmosphere. They are decelerated and slowed in the atmosphere. The heating mechanisms and degree of resultant heating for grains entering an atmosphere have been estimated by, for example, Coulson (2002) and Coulson *et al.* (2003). The predicted values of elevated temperature are not as extreme in the grain interiors as might be imagined. This supports the proposals of those such as Anders (1989), Chyba *et al.* (1990) and Chyba and Sagan (1992) who suggested that a large inventory of organic material may have been brought intact to the early Earth as dust from space.

As well as this, biological material would have to survive at low temperatures for extended durations. Two areas of research are relevant here. The preservation of spores in cryo-environments for extended periods has been reported by, amongst others, Soina *et al.* (1995), and for even longer periods it has been claimed that viable cells can be extracted after preservation in salt crystals for 250 Ma (Vreeland *et al.* 2000), although in this latter case there is still some discussion about contamination, as it appears that the samples show relatively few genetic differences to similar organisms today.

### Cometary Panspermia

The most commonly discussed form of Panspermia is often that from comets. Organic material that may have been delivered from comets (or asteroids) has long been postulated (e.g. Oro 1961; Chyba *et al.* 1990). Hoyle was a leading supporter of this model of cometary delivery of material and indeed went further (see, e.g., Hoyle 1998). The idea was that comets harbour biologically active material, and during

passages through the inner Solar System dust grains are lifted off a comet's surface and can drift into planetary atmospheres. This is well known, with the meteor streams regularly seen in the sky here on Earth at certain times of the year. If the cometary dust stream is fresh and contains biological material it could be an example of Panspermia. However, no direct evidence for any biological material in a comet or in cometary dust has ever been found.

Cosmic dust has been collected from the atmosphere by aeroplanes (e.g. Brownlee 1985), and showed no biological content. Recently, dust was captured at 40 km by balloon flight and biologically active materials were obtained (Wickramasinghe *et al.* 2003). However, the nature and identity of this material is still under discussion and is subject to debate.

A direct visit to a comet would clearly be of great interest. Halley's comet's fly-bys in 1986 studied the freshly emitted dust by mass spectroscopy. The dust particles impacted the spacecraft mass spectrometer at some  $68 \text{ km s}^{-1}$ . The dust particles vaporized in the impact and mass spectra were obtained from the ionized material. Spectra indicating the presence of organic materials were obtained (Kissel *et al.* 1986a,b). However, no assignment of a specific biological nature was made.

In January 2004, the Stardust spacecraft (Brownlee *et al.* 2003) flew past comet P/Wild-2 at a speed of  $6.1 \text{ km s}^{-1}$ . Again a dust mass spectrometer was on-board (Kissel *et al.* 2003) and again produced spectra indicative of an organic origin but with no indication of the presence of amino acids (Kissel *et al.* 2004). Of more interest, however, is that the spacecraft was carrying a tray of aerogel. This is a low-density material (up to  $20 \text{ kg m}^{-3}$ ) designed to capture dust grains fairly intact. It is estimated that some  $(2800 \pm 500)$  grains greater than  $15 \mu\text{m}$  in size were captured (Tuzzolino *et al.* 2004). When the spacecraft returns the aerogel to Earth in January 2006 these grains will be available for study. It has been shown that organic grains can be successfully captured in aerogel with minimal processing (Burchell *et al.* 2004b). However, it has not been demonstrated whether grains carrying biologically active material survive capture in aerogel at  $6.1 \text{ km s}^{-1}$  with the material in a viable form. Nevertheless, the grains will have been collected within minutes of emission from the comet and then returned to Earth in a closed metal container. Their study will be fascinating.

For the future, the European Space Agency's spacecraft Rosetta has been successfully launched (January 2004) to visit comet 67P/Churyumov-Gerasimenko. It will rendezvous with the comet in 2014 and land a small probe on the surface. Although the instruments are physical or geochemical in nature, they will be the first *in-situ* measurements on the surface of a comet. These missions (Stardust, Rosetta) only represent visits to a very small fraction of the cometary bodies in the Solar System, but their results will mean that comets will no longer be the mysterious bodies of the past and will start to constrain ideas such as cometary Panspermia.

## Oceanic impacts

Relatively ignored in studies of impacts on planets (and by extension of Panspermia) are impacts on oceans. Recently, as craters that have formed in oceanic environments here on Earth are increasingly being identified, more attention has focused on this field (e.g. Dypvik *et al.* 2003). The mechanics that result from an impact into an ocean are very different to those on land. Previous studies (Gault 1978; Gault & Sonett 1982) indicate that more of the projectile survives. This, in turn, implies lower shock pressures and temperatures during the impact. Also, the water can readily penetrate cracked rock, releasing any biological material it carries. Thus in terms of survival an impact into an ocean may be more favourable than an impact onto land. Also, given that the Earth is typically covered with two-thirds water, this suggests that if the Earth was populated by Panspermia involving rocks arriving from space, then an oceanic first home may be more plausible than a land-based first home.

## Planetary contamination/sample return

Directed Panspermia is the idea that an intelligent guiding hand has deliberately engaged in spreading life through space (see, e.g., Crick & Orgel 1973). Since we have no evidence of life elsewhere, let alone intelligent life, this may seem an extreme idea. Nevertheless, we ourselves are in effect potentially engaged in directed Panspermia. Every spacecraft sent into space is carrying microbial life, spores, etc. To prevent accidental contamination of other biospheres, there are accepted guidelines on how to limit what is called planetary contamination (see, e.g., DeVincenzi *et al.* 1984). This includes the sterilization of space vehicles intended to land on another planet or body deemed potentially a viable habitat for terrestrial organisms. A lesser sterilization regime is required for vehicles that pass close to or orbit such bodies (in case they accidentally collide with/hit that body). Such a sterilization regime cannot reduce the bio-load to zero micro-organisms, instead it aims to reduce it to a level compatible with the minimal risk of contamination. So, spacecraft have almost certainly carried terrestrial organisms to Mars, for example. The hope is that there has been no release of these organisms and concomitant contamination of the landing sites. Indeed, in this context it is worth noting that to avoid potential accidental contamination of the Jovian moon Europa, the NASA Galileo spacecraft was deliberately directed to fly into Jupiter at the end of its mission touring the Jovian system.

The reciprocal issue is that of sample return. The Apollo missions brought materials back from the Moon (as to a much lesser extent did unmanned Russian missions at the same time). These (and the astronauts) were initially carefully kept in quarantine facilities designed to reduce the risk of contamination of the Earth, even though the surface of the Moon is not usually considered a suitable biosphere for micro-organisms viable on the Earth. The issue of which

planetary satellites and minor bodies may pose hazards of sources of returned material has been considered by, amongst others, Orgel *et al.* (1998). They concluded that the risk depended on the particular body under consideration.

Sample return is no longer limited to the Moon. In September 2004, the NASA Genesis space mission returned samples of the Solar Wind collected in space to Earth. Although this represents no particular hazard beyond that similar to spacecraft retrieved from Earth orbit for many years now, it does usher in a new era of deliberate sample return missions. The NASA Stardust space mission will return its comet samples to Earth in January 2006, and in 2005 the Japanese Hayabusa mission will collect samples from the asteroid Itokawa (1998SF36) for return to Earth in 2007 (Fujiwara *et al.* 2004). It could reasonably be argued that since asteroids and comets are held to be unlikely places for biological organisms to develop (Orgel *et al.* 1998) and that asteroidal and cometary dust regularly arrives in the Earth's atmosphere anyway, there is no need for concern. However, unlike natural occurrences, space missions represent a deliberate action and potential consequences (however remote) therefore require considered thought. Sample return missions from asteroids and comets will bring extra-terrestrial material to the Earth, which will require thought about contamination and storage issues (however minor the risk). The major contamination issue will, however, lie in a future Mars sample return mission. This will require great thought and planning before it occurs.

## Conclusions

In the last few decades the natural movement of material from planetary surface to planetary surface has been demonstrated. The mechanisms for ejection of material from the Solar System have been explored, and the mechanism for dust is clearly established as significant. The widespread distribution of organic and pre-biological materials has also been demonstrated, and in experiments in the laboratory and space key steps are being established as regards the survivability of biological material under the various stresses involved in the various hypotheses concerning Panspermia. New hypotheses and variants of old ones keep emerging. For example, Wells *et al.* (2004) suggested that when a giant impact occurs on a planet (e.g. a potentially planetary sterilizing impact such as that hypothesized as occurring occasionally during the early history of Earth), some of the material ejected into space might carry biological material that could later re-enter the planet's atmosphere. This can then re-seed the planet with life, i.e. a form of self-Panspermia.

However, as a field of study, Panspermia suffers from the weakness that it is consequent on the existence of life elsewhere other than Earth. Since this has never been demonstrated, Panspermia is somewhat lessened. Nor does Panspermia address the issue of the origin of life itself. It just shuffles the origin to another place and time. Nevertheless, Panspermia is an intellectually attractive concept that has

developed greatly in the last few decades and will undoubtedly continue to do so.

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