SURVIVABILITY OF BACTERIA EJECTED FROM ICY SURFACES AFTER HYPERVELOCITY IMPACT

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Abstract. Both the Saturnian and Jovian systems contain satellites with icy surfaces. If life exists
on any of these icy bodies (in putative subsurface oceans for example) then the possibility exists for
transfer of life from icy body to icy body. This is an application of the idea of Panspermia, wherein
life migrates naturally through space. A possible mechanism would be that life, here taken as bacteria,
could become frozen in the icy surface of one body. If a high-speed impact occurred on that surface,
ejecta containing the bacteria could be thrown into space. It could then migrate around the local
region of space until it arrived at a second icy body in another high-speed impact. In this paper we
consider some of the necessary steps for such a process to occur, concentrating on the ejection of ice
bearing bacteria in the initial impact, and on what happens when bacteria laden projectiles hit an icy
surface. Laboratory experiments using high-speed impacts with a light gas gun show that obtaining
icy ejecta with viable bacterial loads is straightforward. In addition to demonstrating the viability
of the bacteria carried on the ejecta, we have also measured the angular and size distribution of the
ejecta produced in hypervelocity impacts on ice. We have however been unsuccessful at transferring
viable bacteria to icy surfaces from bacteria laden projectiles impacting at hypervelocities.

Keywords: ejecta, hypervelocity, ice, impact, life, Panspermia

1. Introduction

That life may originate in one place and then naturally migrate through space is
an attractive idea. Expounded at various times by Lord Kelvin and Arrhenius for
example (see Davies, 1988, for a summary), it reflected a growing awareness that
planetary bodies were not isolated systems complete in themselves. This is cer-
tainly true as regards the influx of meteoritic material to the Earth. The formation
of planets via accretion of precursor planetesimals and the subsequent heavy bom-
bardment of the early planets is well accepted. Slightly less well understood is the
role played in the early evolution of planets such as the Earth by comets or micro-
meteorites delivering volatiles and organic compounds (e.g. Chyba *et al.*, 1990). It
is debatable as to what is the dominant mechanism for providing the organic mater-
ial on the early Earth, endogenous production (e.g. see Miller, 1998) or exogenous
delivery from comets (e.g. see Chyba and Sagan, 1992) or micrometeorites (e.g.

see Maurette, 1998). Although endogenous production is currently favoured, the debate is complicated by the need to predict the endogenous production rate (when the atmosphere and conditions of the early Earth are still somewhat uncertain). This then has to be compared to not only the estimated rate of delivery from external sources but also the fraction of the delivered material which survived intact (which is somewhat uncertain). Work is still continuing to understand the survival of such materials in the impact process involved in their delivery, i.e. a high speed impact event at many km s^{-1}. This delivery was concentrated in the early life of the Solar System, (e.g. the period of intense bombardment on the Earth ended some 3.8–3.9 billion years ago). But there is still a continual stream of material delivered to the planets today, consisting of individual meteorites, regular showers (from dust trails of comets), influx of micrometeorites and so on.

Panspermia is an extension of this idea that planets are not isolated. If the origin of life was elsewhere then perhaps life spread through space and found a new home. This ignores the question of the origin of life itself and glosses over the difficulty of surviving in space. Also, surviving the arrival at a new home planet in a violent impact event seems problematic at first glance. In recent years this idea has been given added impetus by the recognition of Lunar and Martian meteorites here on Earth. Thus not only material already free floating in space, but also material originally part of other large Solar System bodies (e.g. planets such as Mars) can travel naturally to Earth.

The mechanism for this transfer of planetary material is probably via an initial impact event on the large parent body. Melosh (1988) elucidated a mechanism whereby the primary impact generates shock waves, which accelerate material off the surrounding surface at speeds sufficient to achieve escape velocity. This mechanism can result in the ejected material being only relatively lightly shocked. Thus the heating associated with the passage of shock waves through a material can be minimal. Since the ejection through the atmosphere is brief (order of seconds) heating of the ejected material by atmospheric drag is also minimal. The conclusion is that lightly shocked material, subject to only modest temperature increases, can be expelled into interplanetary space. Weiss *et al*. (2000) claim that one of the Martian meteorites (ALH84001) suffered at best an increase of its internal temperature of some 40 °C during the cycle of ejection from Mars and transfer to the Earth's surface. This is important as it reduces the chance of heat killing any bacteria in the interior of the rock.

For such ejected material, the mechanics of transfer to another body, via a heliocentric orbit, has been modelled by several authors (e.g. Gladman *et al*., 1996; Gladman, 1997). Such transfer typically requires some 10,000–100 million years. However, given extremely favourable conditions it could take as little as a year (although this is unlikely, 10^{-7} probability). The environment of interplanetary space is a harsh one. Intense radiation, low temperatures and high vacuum all characterise this environment and all are inimical to life. Quantifying these hazards has been an ongoing task for many years. Recent papers, e.g. Clark (2001) and Mileikowsky *et*

al. (2000a, b), try to identify these hazards and produce probabilities for survival for each individual hazard, which can be multiplied together to form an overall survival rate for bacteria subject to such a journey. Clark (2001) predicts that all the Martian meteorites found to date would most likely have been completely sterilised by radiation during their sojourn in interplanetary space. By contrast, recent work by Horneck *et al.* (2001a), has shown that small rocky ejecta of only a few cm diameter provides sufficient shielding for survival of bacteria in space for limited periods. This result was obtained in space, with the shielding mainly effective against solar UV radiation and not cosmic ray radiation. Ice is not as effective a shield against solar UV as is rock, but if thicker layers of ice were used or 'dirty' ice (ice mixed with silicates) similar shielding can be obtained. A problem still remains in extrapolating the relatively short exposure times in space (10 to 15 days in Horneck *et al.*, 2001a) to the many thousands of years typical of transfer times for material between planets. However it must always be remembered that a minimum Mars-Earth transfer time is only of order 7 months.

One area in which studies of Panspermia are weak, is in the ejection and arrival phase. Both involve impacts, but most discussions of the plausibility of survival of life in such impacts are theoretical not practical. There are practical difficulties in achieving in the laboratory the high speeds required to reproduce such impacts. For example, if the planetary escape velocity is used to give a minimum impact speed for an impact from interplanetary space, then at least 11.1 km s^{-1} and 5.0 km s^{-1} are required to reproduce impacts on the Earth and Mars respectively. The mean impact speeds on both planets will be greater than this. Unfortunately, normal methods of accelerating macroscopic projectiles in the laboratory achieve maximum speeds of 1, maybe 1.5 km s^{-1} at best. Several means exist to get around this. It can be argued that for impact work the issue is not so much the speed, as the deceleration and shock pressure on impact. The survivability of bacterial spores at high accelerations has been tested in centrifuges (e.g. Mastrapa *et al.*, 2000, who achieved accelerations equivalent to 4.27×10^6 m s^{-2}) where spores were found to survive loading to high accelerations (10% survive this acceleration for 70 hr). However, the timescales for these accelerations are much shorter in reality than in the experiments. Similarly, Horneck *et al.*, (2001b) tested spore survivability when subject to shocks of up to 32 GPa, with positive results (survival rates of up to 1 in 10^4). To set this in context, it is estimated that the Martian meteorites recovered on Earth have endured accelerations of around 3×10^6 m s^{-2} and been shocked to between 20 to 45 GPa during ejection from Mars.

Recently another approach has been developed testing this survivability in impacts, namely using impacts at several km s^{-1} in a two stage light gas gun. Such guns were developed (Crozier and Hume, 1957) to exceed the 1 km s^{-1} barrier of normal guns. Not only do they exceed speeds of 1 km s^{-1}, more importantly they obtain speeds in the hypervelocity regime. Crudely stated this is where the impact speed exceeds the speed of the resultant compression waves in the target and projectile during a collision (typically a few km s^{-1}) resulting in extreme

densities and pressures in the materials involved. However, these guns have difficulty exceeding more than typically 8 km s^{-1} in practice. Thus although they can exceed the Martian escape velocity they do not achieve the speeds typical of impacts on Earth from space. A final drawback is that the projectiles used are small in size, maximum a few mm or cm, unlike meteorites or large planetary impactors. Nevertheless, the speeds achieved are close to those required for a full simulation of a planetary impact, and are in the hypervelocity regime. Therefore they offer an opportunity to test survivability of bacteria in near appropriate conditions.

Tests of the survivability of bacteria in hypervelocity impacts on various materials such as rock, metal and glass at 5 km s^{-1} are reported by Burchell *et al.* (2000, 2001a). Bacteria were loaded into projectiles and fired at the various targets, testing the resulting impact crater surfaces for successful transfer of viable bacteria. None of these tests produced a positive result. Intriguingly they also collected the ejecta from the craters in rock targets in these impacts and found they could recover viable transferred bacteria from the ejecta. However, they were not able to identify the mechanism by which this occurred.

More recently, Burchell *et al.* (2001b) reported on hypervelocity impacts (again approx. 5 km s^{-1}) of bacteria laden projectiles into agar (a gel) plates of nutrient growth media. They report successful transfer of viable bacteria to the target in the impact (with a survival rate of 1 in 10^7). Using the nutrient media as the target removes the need to transfer from the target surface to a growth medium in the analysis, thus simplifying the process and decreasing the risk of an error (contamination or accidental loss). The target was a soft, gel-like material which may aid successful capture, although it should be remembered that the impact occurred at high speed, and thus a high strain rate.

There is thus a body of evidence that bacteria can survive the conditions of an initial launch into space and subsequent impact on another surface that are required for rocky Panspermia. Indeed, one of the accidental consequences of the use of a gun to accelerate the bacteria laden projectiles in these studies, is that, when fired the bacteria are subject to a short intense period of acceleration similar to or in excess of that experienced during launch from a planetary surface. Thus any successful transfer of viable bacteria not only implies survival in impact, but also survival in the launch phase of rocky Panspermia.

Terrestrial planets may not be the only places in the Solar System where life could survive. Some of the outer planets have systems of satellites that have evoked great interest from an astrobiology viewpoint. The inferred presence of subsurface oceans on some of the icy satellites of Jupiter and Saturn (e.g. Europa, see Chyba and Phillips, 2002) would provide perhaps the most essential ingredient of life, that is liquid water. In addition, the complex chemistry that appears present in the atmosphere of Titan reminds us that although remote from the Sun, these regions are not inert but represent active chemistry laboratories. From a distance, and without the benefit of more detailed knowledge, one can thus speculate: Perhaps life exists on some of these icy satellites. If it does, perhaps there is a local icy

satellite Panspermia between the icy satellites of a parent planet equivalent to the rocky Panspermia between terrestrial planets.

2. Icy Satellite Panspermia

This icy satellite Panspermia would in most respects be similar to rocky Panspermia. Note that it does not refer to the initial seeding of biogenic material (or even life itself) from comets. Rather, like rocky Panspermia, it assumes life is initially present, trapped at the bottom of a local gravitational potential. Then via a suitable mechanism (again assumed to be an impact), some material is ejected from that gravitational well, travels through space and falls into another gravitational well. For Panspermia to occur, the transferred material would have to carry life and successfully seed the new body. The icy aspect of this is that both the original and new bodies are assumed to be icy. Similarly one can equally imagine a partially icy Panspermia process where one body is icy and the other rocky.

Since the natural satellites of Jupiter (or Saturn) can be small, the escape velocities required for this process are correspondingly lower than those for the terrestrial planets. Note that a much higher velocity is required to escape from the parent planet (Jupiter in particular) so ejected material is less likely to reach interplanetary space. By contrast however, if the body which caused the original impact (leading to the material being ejected) came from outside the Jovian (or Saturnian) system its impact speed will be high due to the gravitational attraction and proximity of the planet.

To properly characterise the probability of icy Panspermia there is a need to identify and assess all the elements involved in the transfer, in the same way as has been done for rocky Panspermia. Using the nomenclature of Clark (2001) the relevant equation is:

$$P_{AB} = P_{biz} \times P_{ee} \times P_{sl} \times P_{ss} \times P_{se} \times P_{si} \times P_{rel} \times P_{st} \times P_{sp} \times P_{efg} \times P_{sc} \,, \tag{1}$$

where

P_{AB}	=	the overall probability of successful transfer from A to B;
P_{biz}	=	the probability that the original impact hit a zone of biological activity;
P_{ee}	=	the probability of ejection of material into an escape trajectory;
P_{sl}	=	the probability that an organism in the ejecta survived launch;
P_{ss}	=	the probability of survival in space;

P_{se} = the probability of surviving entry into a target atmosphere;

P_{si} = the probability of surviving the impact on the target;

P_{rel} = the probability of release;

P_{st} = the probability the new environment is non toxic;

P_{sp} = the probability of surviving the attention of predators in the new biosphere;

P_{efg} = the probability of finding an environment favourable to growth;

P_{sc} = the probability of successfully competing with indigenous life in the new environment.

These terms can be divided into three categories, (i) those which are presently unknowable (P_{sp}, P_{sc}, P_{biz}) (ii) those which can be assumed or approximated by reasoned argument (P_{rel}, P_{st}, P_{efg}) and (iii) those which can be calculated from physical simulations (P_{ss}, P_{ee}, P_{sl}, P_{se}, P_{si}). It may at first appearance be odd to have a category labelled unknowable. For example, one might imagine experiments where 'tagged' bacteria are released in an environment and the area tested at later dates to assess the values of P_{sp} and P_{sc}. However, for the case of the icy Panspermia proposed here, we neither know the nature of the original organism, nor what organisms may, or may not, be present in the new environment. Therefore it is difficult to assign meaningful values to these quantities. Similarly, since there is no evidence for life in the Jovian or Saturnian systems P_{biz} might well be considered to be 0. This would of course render the whole discussion nugatory. So, it is simply considered to be unknown, but possibly finite.

The magnitudes of the quantities in the second category are somewhat arguable. For P_{rel} the issue is that the bacteria will be trapped in an icy body ejected from the primary surface. Even after arrival a mechanism is required to release the bacteria from the ice, and to do so in an area conducive to growth (P_{efg}). The main issue is that of arriving on an icy surface when the potentially biologically viable region is a sub-surface ocean below the ice. Ice however, is not a permanent, unchanging surface. Impacts may open up gaps in the ice which then seal over. There appears to be evidence for disruption of the ice on Europa and for re-surfacing in areas (as indicated by the lack of a heavily cratered surface, see Chyba and Phillips (2002) or O'Brien *et al*. (2002) for recent discussions). The question therefore is if transport occurs from the surface to the interior and on what timescale? Indeed, the impact may be large enough to disrupt the icy surface and directly contaminate the interior.

The factor P_{st} depends on the target body. Some common features will be the surface environment, which will involve low temperatures, radiation hazard, dust bombardment etc. It should be noted however, that the life form does not have to grow and be in a high metabolic state in this environment, just survive until it reaches the sub-surface water. To an extent P_{st} is just a variant of P_{ss}, unless the ice at the new body differs significantly from that at the old one. Note that one cannot argue that P_{st} is automatically equal to unity, by virtue of survival of the bacteria in

the ice on the original body. This is because the impact which caused the original ejection of material, may have released material excavated from below the surface.

This leaves the last category, which contains $\mathbf{P_{ss}}$, $\mathbf{P_{ee}}$, $\mathbf{P_{sl}}$, $\mathbf{P_{se}}$, $\mathbf{P_{si}}$. For example, $\mathbf{P_{ss}}$ is a variant of the similar probability for lifeforms trapped in rocky bodies travelling in interplanetary space. Ice should be substituted for rock as the shielding medium, and Jovian (or Saturnian) space for interplanetary space. The timescales for exposure would need determining by Monte Carlo simulations. The effect of the ambient temperature and vacuum can be assessed as for transit in interplanetary space. The radiation sources will differ, but the logic to assign a dose value will be similar to that for small bodies in interplanetary space as considered by Clark *et al.* (1999). The Galileo spacecraft has obtained detailed data for the radiation environment around Jupiter, and the Cassini spacecraft will do the same for Saturn. The results of laboratory exposures to the predicted radiation fluxes can then be found and survival rates from real space exposure experiments included in the discussion (e.g. Horneck *et al.*, 2001a).

The atmospheric entry term ($\mathbf{P_{se}}$) would only apply to a satellite such as Titan, which has an appreciable atmosphere, and can be approximated in the same way as it is for the terrestrial planets allowing for the atmospheric density, height etc. The resulting pulse of heating that is applied would ablate the surface of the ice. For entry to Titan it is estimated (by English *et al.*, 1996) that for small ice particles the peak ablation rate (10^{-5} kg m^{-2} s^{-1}) occurs at a height of 700 km. However, it is known in terrestrial meteorites of more than a few cm size that the heating is of sufficiently short duration that the interior remains cold, therefore large icy bodies will not totally ablate in the atmosphere. For larger bodies still, complete disruption can occur if during atmospheric entry the change in pressure across the body exceeds the strength of the body (c.f. as occurred in the Tunguska impact in Siberia in 1908, see for a discussion Chyba *et al.* (1993) or Bronshten (1999)). In this case the impactor is not vaporised, it explodes delivering a large quantity of much smaller bodies onto the surface below. This would be a very efficient mechanism for delivering materials over a dispersed area. However, for almost all of the icy satellites there is no appreciable atmosphere, so the term $\mathbf{P_{se}}$ is simply and conveniently not applicable.

The three remaining terms need closer inspection and are the subject of the experimental work reported in this paper. The term $\mathbf{P_{ee}}$ concerns the probability of ejection into an escape orbit. There is therefore a need to be able to characterise ejecta from impacts on icy surfaces. Angular, size and velocity distributions of ejecta in impacts are thus required. Unfortunately the field of ejecta from ice is limited in terms of experimental results. Data does exist from low velocity impacts on ice (e.g. Kato *et al.* (1995) give ejecta size distributions, Arakawa *et al.* (1995) give velocity distributions) but little exists at hypervelocities. In particular, there seems little information on angle of ejection. There are a few references in papers to ice ejecta occurring at high angles (as measured from the target surface) e.g. Croft (1981) who says it peaks at 60–65°, but no data is shown. Recently, Koschny

and Grün (2001) have looked at impacts on ice-silicate targets (5 to 20% silicate) at 1 to 11 km s^{-1} with glass beads of 20 to 80 μm diameter. They found that ejecta were emitted preferentially at an angle of 69.5°. However, no data were given for impacts on pure water ice. Frisch (1992) reported on impacts of similar glass beads onto water ice at speeds of 2 to 10 km s^{-1}, but gave no details of the angular distribution of the ejecta beyond noting that it was concentrated at high angles of elevation. Accordingly in this paper we report measurement of the size and angular distribution of ejecta from the hypervelocity impact of a mm sized projectile onto pure ice.

The probability of survival of the life form during the launch phase ($\mathbf{P_{sl}}$) is considered by doping the target ice surface with bacteria and testing the ejecta from hypervelocity impact for recovery of viable bacteria. In this context, viability is defined as ability to show growth when cultured. Finally the term for survival (of the life form trapped in the ejecta) during the impact associated with arrival at the destination ($\mathbf{P_{si}}$), is tested by firing doped projectiles into sterile ice and looking for successful transfer of viable bacteria to the target.

3. Method

The work reported herein was carried out in the Hypervelocity Impact Laboratory and the BioSciences Laboratory of the University of Kent. The expertise in impact studies was from the former, the skill in microbiology from the latter. This is important as any investigation which crosses tradition subject boundaries, is probably best performed with experts from both fields.

The impact work was carried out using a two-stage light gas gun (Burchell *et al.*, 1999). Such guns operate by using the initial shot to drive a piston compressing a light gas (here hydrogen) to high pressures. This is released explosively by rupture of a thin metal disk, and its escape through the hole in this disk accelerates a sabot, which carries the projectile. This method permits accelerations to speeds above the usual limit for guns (typically around 1 km s^{-1}). The range of the gun was evacuated in use to a pressure of typically 0.5 mbar. This was to prevent deceleration of the projectile in flight. The sabot was discarded in flight and only the projectile proceeded to the target (see Burchell *et al.* (1999) for details). The velocity was measured for each shot by a combination of the projectile passing through laser light curtains and measuring the time of impacts of the sabot parts on a stop plate. The projectiles used varied from shot to shot and details are given with the shot details in Table I. They were either aluminium (al.) spheres of diameter 1 mm, or pieces of porous ceramic (typically 10 per shot, sieved to be between 90 and 212 microns across).

The targets in this work were cylindrical blocks of water ice. These were 24 cm in diameter and 20 cm deep. The face surface was arranged to be perpendicular to

TABLE I

Shot programme

Shot	Velocity (km s^{-1})	Target	Projectile type and size
1	5.45	Sterile ice	1 mm dia. al. sphere
2	5.02	Sterile ice	1 mm dia. al. sphere
3	5.24	Sterile ice	1 mm dia. al. sphere
4	5.25	Sterile ice	1 mm dia. al. sphere
5	5.36	Sterile ice	1 mm dia. al. sphere
6	7.04	Sterile ice	1 mm dia. al. sphere
7	5.00	Ice with surface layer of *Rhodococcus erythropolis*	1 mm dia. al. sphere
8	5.25	Sterile ice	1 mm dia. al. sphere
9	5.36	Ice with surface layer of *Rhodococcus erythropolis*	1 mm dia. al. sphere
10	5.24	Ice with sub-surface layer of *Rhodococcus erythropolis*	1 mm dia. al. sphere
11	4.75	Sterile ice	1 mm dia. al. sphere
12	4.90	Ice with sub-surface layer of *Rhodococcus erythropolis*	1 mm dia. al. sphere
13	5.10	Sterile ice	Clean ceramic pieces
14	5.00	Sterile ice	Doped ceramic pieces
15	5.00	Sterile ice	Clean ceramic pieces
16	5.00	Sterile ice	Doped ceramic pieces

the direction of flight of the projectile. During a shot they were placed in the target chamber of the gun which was cooled by a liquid nitrogen cold plate.

For the shots which used bacteria, the bacterium chosen was *Rhodococcus erythropolis*. This is a hardy, rod shaped bacterium of size approximately 1×2 microns. It has a strong cell wall structure which is held to help explain its resistance to stress. These bacteria have been found in extreme environments such as deep sea sediments down to 6 km depth (Colquhoun *et al.*, 1998; Heald *et al.*, 2001). There is much literature on this bacterium, and a good compendium is Goodfellow and Alderson (1998) and successive papers in the same issue of that journal. It grows red in colour so is easy to distinguish from general background on an exposed petri dish and is not generally present in a laboratory environment. The strain used was *R. erythropolis* DSM13002 (from the German culture collection). Although we have no specific information about its being found in for example glacial or polar ice, we have found in the laboratory that it can be frozen in ice and

thawed without significant deleterious effects. During its use in our work standard microbial handling procedures were followed, with staff wearing sterile gloves, masks and gowns. Surfaces were cleaned with alcohol. Metals surfaces were baked in an oven where possible. All storage containers were sterilised in an autoclave before use.

4. Ejecta Physical Properties

Two methods of observing the ejecta from an impact were used. The first was by passage through a thin foil. The foil was aluminium of thickness (4.9±0.1) microns. A strip of foil 10 cm across was placed over the target in the shape of a semi-circle, of radius 24 cm. A square hole, 3 by 3 cm, was cut in the foil over the centre of the target. This was to permit passage of the projectile onto the target. After an impact the outward travelling ejecta penetrated the foil leaving holes. At high speed, passage of a particle through such a thin foil leaves a hole similar in size to the particle. Gardner *et al.* (1997) suggest that ejecta of diameter 20 microns will penetrate the foil leaving a hole which yields the ejecta size to better than 20% (a value which rapidly reduces to a few % for larger sized ejecta). Ejecta smaller that this penetrate, but leave a hole which systematically overestimates the ejecta size, until there is a sudden failure to penetrate, predicted here to occur for sizes less than 13 microns.

After the shot (Shot 1 in Table I) the foil was imaged under a microscope. The central 1 cm wide strip of foil was imaged in this way and represents a narrow band whose surface was approximately perpendicular to the direction of motion of the ejecta. The images were scanned using pattern recognition software, which located each hole and measured its area. The radius of the equivalent circle for each hole was then found. The scanning system had a minimum resolution of 10 microns (lower than the penetration limit). This permits both a size distribution and an angular distribution of the ejecta to be obtained after an impact.

Since the thin strip of foil used, covered only a fraction of the 2π solid angle visible to ejecta emitted from the target, the flux measured each angle of elevation (θ) from the target surface (where $\theta = 0°$ represents the target surface and $\theta = 90°$ was the normal to the target surface) was only a fraction of the number ejected. The correction for this acceptance effect changed with angle of ejection. A θ dependent correction was therefore applied to the observed flux to obtain the emitted flux. This corrected flux is shown vs. angle of ejection in Figure 1. It can be seen that the data suggest a small amount of ejecta is emitted at all angles, with a concentrated inverted cone of ejecta emitted at a high angle.

The data in Figure 1 were fit by a function, which combined a linear background with a Gaussian curve for the peak at high angles. The result of the fit was:

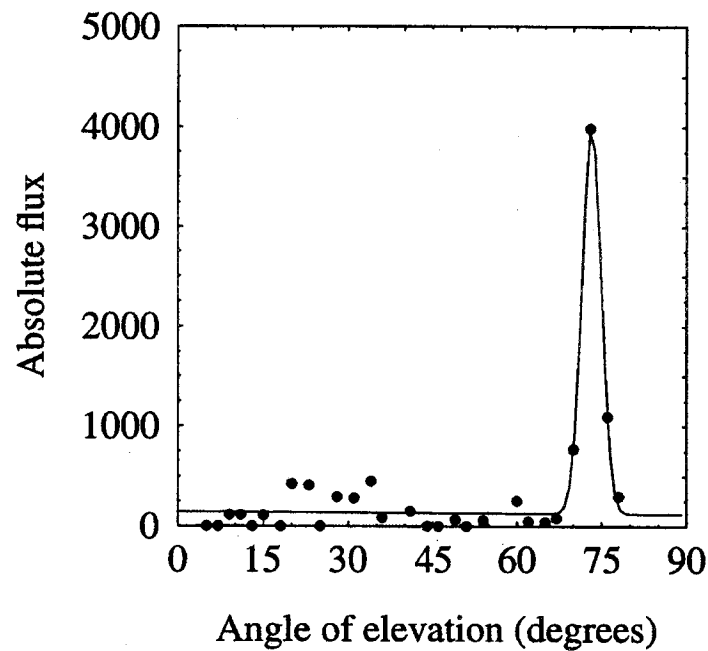$$y = 146.5 - 0.289x + 3885\exp[-0.174(x - 73.2)^2] \,, \tag{2}$$

Figure 1. Emitted flux of ejecta vs. angle of ejection.

with a regression coefficient for the fit of 96%. From the fit the peak position for the Gaussian and its width were found to be 73° and 3.4°, respectively. Standard works on impact ejecta, e.g. Melosh (1989) give 45° as the peak angle of ejection with no value for the width of the distribution about that value. However, this invariably applies to experiments on rock, not ice. Tests with rock targets (data not shown) in the same set up as here produced peak angles of ejection of 47–53°, compatible with the 45° expected for rock. Therefore the higher angle found here is not an instrumental bias.

As stated earlier there are references in the literature to a higher than expected angle of ejecta emission in hypervelocity impacts on ice. Croft (1981) refers to a peak ejection angle of 60–65° but gives no details and shows no data. Frisch (1992) refers to a dominant near vertical angle of ejection, and Koschny and Grün (2001) report a peak angle of 69.5° for ejecta from impacts on ice-silicate mixture targets. Data were also given for angle of ejection in Burchell *et al.* (1998), but for impacts on solid CO_2 (a different ice). They reported that there were virtually no ejecta below 40°, with a near constant flux vs. angle at higher angles. There is thus a consistent pattern emerging across a range of ice target materials that the cone of ejecta is concentrated at high angles around 70° from the target surface.

The size distribution of the ejecta was also obtained from the holes in the foil. The scanning software measured the area of each hole and this was then converted to the diameter of an equivalent circle. This is taken as the characteristic size of the
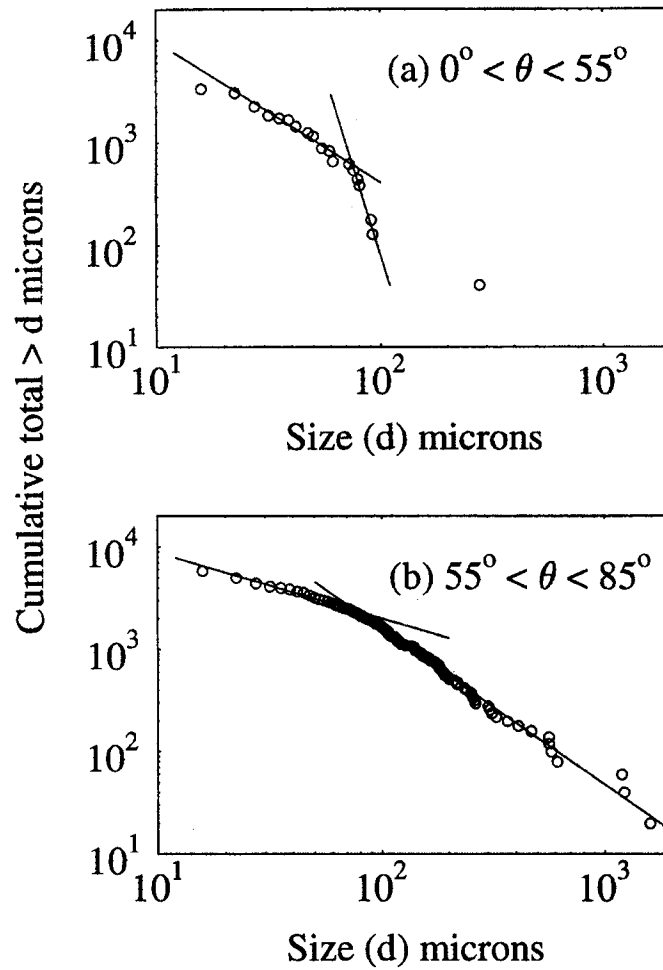
Figure 2. Ejecta cumulative size distributions. (a) Low angle (0 to 55°), (b) high angle (55 to 85°).

ejecta. The number of ejecta of each size at each elevation, has been scaled by the geometric correction factor described above. The data are shown in Figure 2 for the two separate regions of low angle (0–55°) and high angle ejecta (55–85°). The data are given as a cumulative size distribution, i.e. at any size the flux value gives the number of pieces of ejecta larger than that size. The data were fit separately above and below 75 microns, where a change in the slope of the cumulative distribution was observed at both low and high angles. The fits did not include the smallest piece of ejecta at each angle as this is where the hole size overestimates the particle size by greater than 20%. The data were fit by a function of the form:

$$N(\geq d) = \alpha d^{-\beta} , \tag{3}$$

TABLE II

Fits to ejecta cumulative size distributions

Angle of ejection	$20 < d < 75\mu$m	$d > 75\mu$m
$0 < \theta < 55°$	$N(d{\geq}x) = 2.26{\times}10^5 d^{-1.37}$,	$N(d{\geq}x) = 9.62{\times}10^{15}d^{-7.04}$,
	$r^2 = 96.9\%$	$r^2 = 98.0\%$
$55 < \theta < 85°$	$N(d{\geq}x) = 3.85{\times}10^4 d^{-0.64}$,	$N(d{\geq}x) = 1.75{\times}10^6 d^{-1.52}$,
	$r^2 = 97.9\%$	$r^2 = 98.1\%$

where $N(\geq d)$ is the number of pieces of ejecta greater than d microns in diameter. The fits to the cumulative size distributions are given in Table II.

As stated the ejecta size distributions exhibit a change of slope at 75 microns at both low and high angles. Above this size the slope increases. However the increase in slope is not equal in the two ranges of elevation. Nor for either size regime is the slope equal at the different elevations. Thus not only has the total flux changed with elevation, but also the size distribution of the ejecta has changed. This suggests a different mechanism is producing the ejecta at low and high angles of ejection.

When interpreting the size distributions caution should be used in the lower size regime as the relationship between hole size and ejecta size ceases to be as accurate in this region, and the size is overestimated.

The largest piece of ejecta at low angles corresponds to a diameter of 278 μm, approximately 28% of the diameter of the projectile, but note that due to the density difference between ice (ejecta) and aluminium (projectile) it is only 3.3% of the projectile mass. At high angles the largest fragment is equivalent to a diameter of 1,592 μm, approximately 160% of the diameter of the projectile, but only 19% of the projectile mass.

For hypervelocity impacts on water ice the only previous report on ejecta size distributions is that of Frisch (1992). However, he shows no data and just reports that the average value of the exponent (β in Equation (3)) of the size distribution was (1.75±0.26). He makes no differentiation between small and large ejecta. Values are however available for ejecta from lower speed impacts on ice (Kato *et al.*, 1995). They find that there is no single power law applicable to the cumulative size distribution. Two or three distinct regions are present in their data and the larger the fragment size the steeper the slope is. Burchell *et al.* (1998) reported on ejecta size distributions for hypervelocity impacts onto CO_2 ice. They also found that a single power law did not describe the data of different sizes. At different angles of ejection they found that two or three values of the exponent (β) were required as the size varied. They found that β had a smaller magnitude for smaller ejecta and was larger at larger sizes. For small ejecta at large angles of elevation they
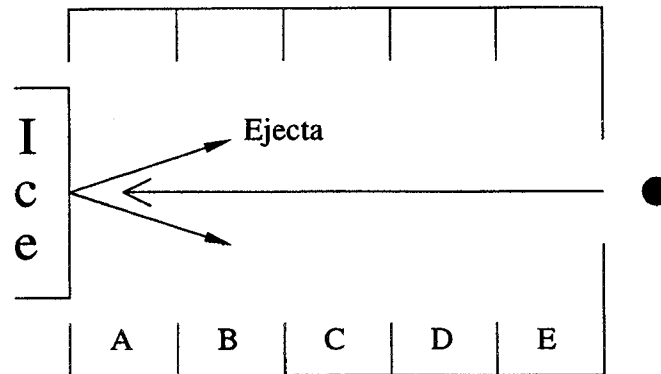
Figure 3. Ejecta capture system. Angular ranges are given in Table II.

found β was typically 0.5 to 1.0, whereas for larger ejecta at large angles it ranged from 1 to 2. Finally, Koschny and Grün (2001) measured the mass distribution of ejecta from ice-silicate mixture targets. Although the velocities were comparable to here (3–11 km s^{-1}) the projectile sizes were much smaller (20–80 μm diameter glass beads). Also, the data were averaged over all angles of ejection. A further complication was that much of the ejecta was of comparable size to the silicate grains used in their targets. However, the largest ejecta (order 100 μm) were found to obey a size distribution independent of silicate content of the target with a slope equivalent to $\beta = 1.6 \pm 0.3$. This is compatible with the results here indicating that the slope of the size distribution is independent of the nature of the ice.

One contribution to the ejecta that is missing from the current work is slow moving spall ejected parallel to the target surface. This does not intercept the foil. Thus in addition to the ejecta continuum independent of angle and the high angle ejecta cone, there is a third component of ejecta which goes unmeasured in the current set-up (and hence the measured ejecta does not equal crater volume). From the viewpoint of transfer of material off a surface this is not significant, as this third component, a very slow moving spall, will be unlikely to attain escape velocity.

The data obtained present for the first time detailed information on the size and angle of elevation of ejecta from hypervelocity impacts on pure water ice. Information on the velocity is however missing. For a full treatment of ejecta this is required, and has to be inferred from information from other sources (see Section 7 below).

5. Survival of Bacteria in the Ejecta

To capture the ejecta emitted from an impact event, an ejecta capture system was built. This consisted of a series of tins arranged as per Figure 3. Each tin served as a separate chamber in the ejecta capture system and covered the angular range

TABLE III

Angular range for each chamber in the ejecta capture system

Chamber	Angular range
A	0–25°
B	0–50° (or 25–50° if cell A is present)
C	50–65°
D	65–75°
E	75–85°

(as seen from the centre of the target) as given in Table III. After a shot the mass of ejecta captured in each tin was weighed. The data from the shots where this was done are shown in Figure 4. Note that in Figures 4a and b chamber A was not used. This was added for the next two shots (c and d) to differentiate the mass at low angles. With the exception of Figure 4d, they show a peak at high angles. The exception was caused in shot 5 by a single large piece of the ice target which fell off after the impact and was captured in chamber B. This method of measuring ejecta is measuring mass, and not number flux as with the foil system. That the peak flux of ejecta mass is also at high angle (as well as the number flux of Figure 1) is complementary information to the results on size distribution in Figure 2.

The reason for switching to a capture system was to preserve ejecta after impact for subsequent study. Thus after a shot the weighed ejecta was decanted into jars. Samples from each jar were then smeared on agar plates of nutrient growth media. For shots where bacteria were required to be present in the initial target, after the target was made from the sterile water, a highly concentrated suspension of *Rhodococcus erythropolis* (approximately 10^9–10^{10} cells per mL) was poured over the centre of the target surface and then frozen into place. This corresponded to a depth of doped ice of typically 0.5 cm. As described below, this method had to be modified after the initial shots and the final method of producing doped ice targets was different. The ice was at –18 °C and the targets were typically made 2 days before a shot. This strain of bacteria is routinely freeze dried and revived with no particular difficulty. Ice samples removed direct from a test target were melted and cultured with no apparent problems.

The projectile used in these shots was a 1 mm aluminium sphere. The first 5 shots (shots 2–6 in Table I) were all with clean ice targets, then a doped target was used (shot 7), a clean target (shot 8) and a doped target (shot 9). Between each shot the capture system was cleaned with alcohol and after each doped target shot it was also baked out. Tests after cleaning found no traces of bacteria left on the targets. The results of the shots initially appeared clean cut. In all the doped target shots
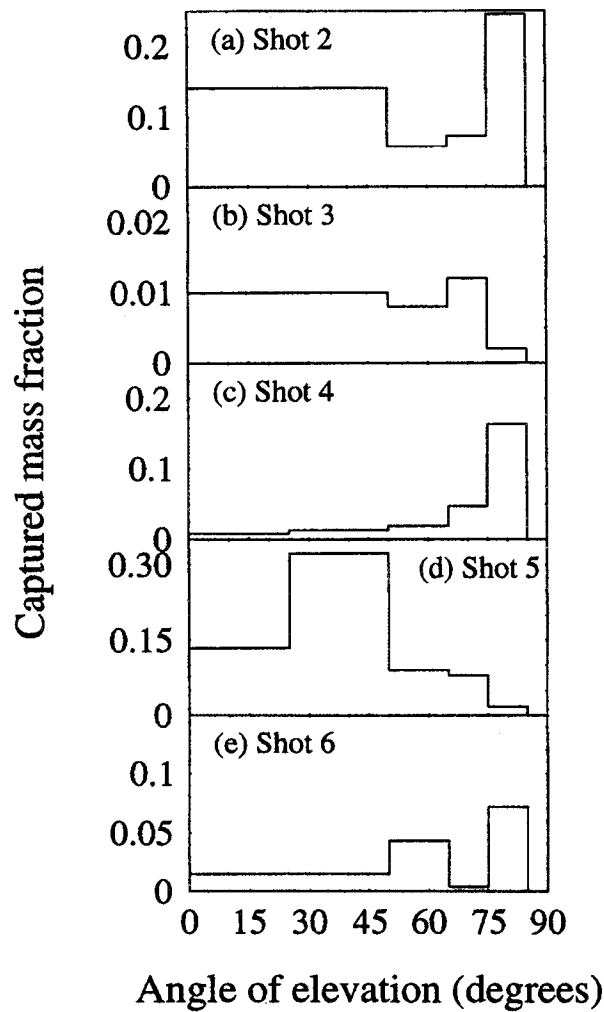
Figure 4. Captured ejecta mass vs. angle of ejection. For details of shots see Table I.

there was prolific *Rhodococcus erythropolis* growth as tested by colour, morphology and biochemical profile in the ejecta captured at every angle. Typically there were either between 50 and 200 separate colonies, or growth of so many colonies they had merged to cover large areas of the petri dishes used. By contrast there was no growth of *Rhodococcus erythropolis* in any of the ejecta from the clean target shots. Note that in most shots there was a trace of contamination on some plates (a yellow growth, easily distinguished from the *Rhodococcus erythropolis*).

The initial results thus suggested that the doped ice ejecta successfully carried viable bacteria. There was one exception to finding no *Rhodococcus erythropolis* growth after a control shot. In this case the doped target had been placed in the gun, the gun was pumped down to low pressure as normal, but was not fired. The target

chamber was raised to atmospheric pressure, opened and the target replaced with a sterile target and the ejecta capture system was left untouched in the gun. The gun was then prepared for firing and fired as normal. Afterwards when washed with sterile water the ejecta capture system was found to give growth of *Rhodococcus erythropolis* (although the cells were smaller and slightly paler in colour than from the shots with the doped targets). It was postulated that due to the low pressure in the target chamber during a shot, sublimation of the ice targets occurred and that this had carried material from the first doped target onto the ejecta capture chambers. Normally, this was not a problem as the capture system was washed with alcohol and sterilised between every shot. However, it raises the possibility that when doped targets were used the observations of *Rhodococcus erythropolis* may not have been associated with an impact.

Accordingly, tests were carried out to quantify this using a doped ice target. Both the doped target and the ejecta capture system, were placed in the gun and the gun sealed up and depressurised as if for firing. Then, after the same time duration as normal, the gun was opened up without a shot being fired. Afterwards the ejecta capture system was washed out with sterile water and the water used to provide samples for culturing as if it were melted ejecta. The results showed some growth of the *Rhodococcus erythropolis*, albeit at a very low level. The amount of the *Rhodococcus erythropolis* obtained in this fashion was typically (if present in a particular capture cell) at the level of 1–5% of that from when the gun was fired at doped targets. However, it was repeatable, suggesting that the sublimation was transferring viable bacteria from the target to the collection system. Whilst the amount of *Rhodococcus erythropolis* obtained in this fashion was significantly less than from real ejecta, it nevertheless potentially weakens the previous result. It should be noted that *Rhodococcus erythropolis* are routinely vacuum freeze dried and revived indicating that low pressures and temperatures are not particularly injurious to survival rates.

Accordingly a new layered ice target was developed. The original sterile ice target was made with a doped layer on top (10 mL of sterile water diluting a concentration of *Rhodococcus erythropolis*). Then another layer of sterile water, 5 mm deep, was added and frozen over the top of the doped layer. Sublimation at best only have removed 1–2 mm of ice from the targets in the previous measurements, so this should have sealed the doped layer below a sterile layer of ice at the moment of impact. The sublimation tests were repeated and this was found to have prevented the transfer of bacteria to the capture chambers.

With the new layered ice targets 3 new shots were carried out (shots 10–12 in Table I). Shots were again alternated, first a layered doped target, then a pure sterile target, then a layered doped target. The results for the two doped shots are given in Table IV. Again there was growth of *Rhodococcus erythropolis* from the ejecta from the doped target shots but not from the pure targets. Although, not all angles in every shot onto doped ice gave ejecta with viable bacteria, most angles did, and

TABLE IV

Results showing *Rhodococcus* content of ejecta as a function of ejection angle

Shot	Type of target	Capture cell			
		B	C	D	E
10	Doped, plus sterile surface layer.	Thin covering of *Rhodococcus erythropolis* colonies over the whole petri dish	Thin covering of *Rhodococcus erythropolis* colonies over the whole petri dish	Thin covering of *Rhodococcus erythropolis* colonies over the whole petri dish	No *Rhodococcus erythropolis* colonies[a]
12	Doped, plus sterile surface layer	5–10 *Rhodococcus erythropolis* colonies	Two *Rhodococcus erythropolis* colonies	5–10 *Rhodococcus erythropolis* colonies	One *Rhodococcus erythropolis* colony

[a] No solid ice ejecta was found in this chamber of the capture cell in this shot. The surface was washed down with sterile water and this was cultured.

when the set of shots is taken as a whole, viable transfer to the ejecta was observed at all angles.

Thus the original results are confirmed by the second, more reliable series of experiments and viable bacteria were found in icy ejecta from a hypervelocity impact event.

6. Survival of Bacteria in an Impact on an Ice target

To test this, sterile ice targets were placed in the gun. The projectiles used were different to before. Now they were porous ceramic, sieved to be between 100 and 212 microns, with about 10 pieces used per shot. They were washed in alcohol and baked out before use to ensure sterilisation. Clean projectiles were used with no further treatment. Doped projectiles were ones where, prior to shooting, the projectile had been placed in a highly concentrated solution of *Rhodococcus erythropolis*. This was the method used in Burchell *et al.* (2001) to obtain successful transfer of bacteria to a target (nutrient broth gel in a petri dish) in a hypervelocity impact. After each shot the target was examined, with samples of ice from the target crater being removed, melted and cultured on petri dishes of nutrient broth. The shots were performed in pairs, first a shot with clean projectiles, then a shot with doped projectiles. Four shots in total were carried out (shots 13–16 in Table I). In no shot was any growth of the *Rhodococcus erythropolis* observed from the cultured samples.

The results appear to indicate that no successful transfer occurred. This can be used to estimate a limit on the probability of successful transfer. If 10 pieces

of projectile per shot impact the target, and 5–10% of their mass is assumed to be composed of bacteria, then from two shots the number of bacteria fired was 1.4×10^7. The typical fraction of the ice target surface, around and including the crater, which was sampled was approximately 10%. This combined with the null result gives a limit on the probability of survival of order $<10^{-6}$.

7. Discussion

The experimental work above was carried out to permit estimates to be made of three factors in Equation (1), namely $\mathbf{P_{ee}}$, $\mathbf{P_{se}}$ and $\mathbf{P_{si}}$. Although information has been obtained, none of the three has been measured positively.

The first term, $\mathbf{P_{ee}}$, has been examined and much information obtained. The size and angular distributions of ejecta have been measured on the laboratory scale, but a measure of the velocity distribution is still required. This is essential to demonstrate if escape velocity will be reached. Early work on ejecta from rock has suggested that the majority (80% +) of ejecta is moving at less than 1% of the impact speed and that large ejecta moves more slowly than small ejecta.

In a recent attempt to model ejecta from hypervelocity in brittle materials, Rival and Mandeville (1999) considered the case of brittle targets such as rock or glass. They suggested that the mean angle of the cone ejecta was 60° to the target surface, and increased if the ratio of projectile/target densities was greater than one. This assertion is compatible to the observations here. Their model also suggests that the largest cone ejecta fragment found here should have radius 1.1 mm. This compares well with the value of 0.79 mm observed here. In their paper a model was included to predict the velocity of the ejecta as a function of its size. No experimental data was given to test this model. However, if we assume it is correct and applicable here, then, for the smallest ejecta which might carry bacteria (e.g. order 10 micron in size), the ejecta velocity is predicted to be only of order 100 m s^{-1}. This is disappointingly low compared to the escape velocity of the Earth (11 km s^{-1}), but is comparable to the local escape velocity of a small icy satellite of Saturn such as Mimas (175 m s^{-1}).

It should be stressed that this is a calculated ejection velocity, not a measured one. Further it is from a model which is for impacts on glass and not ice. Nevertheless, it does suggest if the impact in this experiment had occurred on an icy satellite such as Mimas, the factor $\mathbf{P_{ee}}$ might be one for small sizes of ejecta. It should be noted however that such small ejecta are not plausible for the success of icy Panspermia as they would offer little or no shielding to radiation and hence any bacteria content would be quickly sterilised. However, impacts by larger bodies would yield correspondingly larger ejecta at the highest speeds of ejection.

A related issue is if the small ejecta captured here carried viable bacteria. This was not tested. The experimental set-up made no distinction between ejecta size when testing for bacteria content. Nevertheless, given the results here that icy

ejecta did carry viable (i.e. culturable) bacteria, and that calculations indicate an ejection speed may have been achieved equivalent to escape velocity for a small icy satellite, then it does not look too implausible to assert that the product $\mathbf{P_{ee}} \times \mathbf{P_{sl}}$ may approach unity for a real impact on an icy satellite.

By contrast, less progress has been made on quantifying the term $\mathbf{P_{si}}$. The experiments that tested for survival in a hypervelocity impact found that the probability of survival was $<10^{-6}$. However, this limit is still above the value of 10^{-7} found by Burchell *et al.* (2001b) for survival in impacts on gel. Further work will test this result at the same level as for impacts on gel. In addition, impacts at oblique angles will be investigated to see if this affects survival (obliquity is known to affect the peak shock pressure involved in an impact, see for example Pierazzo and Melosh (2000) for a discussion).

8.   Conclusions

The concept of icy Panspermia has been considered in the framework of a probability calculation using the nomenclature of Clark (2001). It has been shown that some terms in such a calculation are still unknowable (e.g. is there life on any icy satellite? if life transferred to another habitat can it survive in this new home? etc.). It is argued that other terms in the calculation can be readily adapted from similar work on rocky Panspermia transposed to the vicinity of Jupiter or Saturn (calculation of survival rates in space etc). Laboratory results were presented to determine the possible values of some probabilities related to escape and capture by an icy surface of viable bacteria. It is shown that the escape of bacteria in ejecta after a hypervelocity impact is not implausible. However, no observation was made of successful capture onto a new icy surface via a hypervelocity impact. Future work will test spores and other strains of bacteria to generalise the results.

Finally, integral to this discussion is the idea that bacteria can be preserved in ice for long periods. This is not controversial. Here on Earth studies have shown (see for example Christner *et al.*, 2000) that viable bacteria can be recovered from glacial ice up to 20,000 yr old. Indeed, if we consider that at times the Earth has been subject to periods of intense glaciation, then terrestrial ejecta thrown into space after a giant impact could itself have been icy rather than rocky, and possibly carried viable terrestrial bacteria.

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