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Survival of seeds in hypervelocity impacts

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Abstract: Panspermia ('seeds everywhere') postulates that life naturally migrates through space. Laboratory studies of Panspermia often examine the survival of Earth's species under the conditions thought to occur during transfer through space. Much of this research has centred on bacteria, but here we consider seeds themselves. We simulated the extreme accelerations necessary for their hypothetical ejection from a planetary surface and the impacts associated with their arrival on another planet. Seeds of tobacco, alfalfa and cress were fired into water at speeds in the range 1–3 km s^{-1}, corresponding to impact shock pressures of circa 0.24–2.4 GPa. No seeds remained intact and able to germinate, even at the lowest speeds. Although fragmentation occurred, even at 3 km s^{-1} the size of some of the fragments was about 25% that of the seeds. Thus, whilst the seeds themselves did not survive extreme shocks, a substantial fraction of their mass did and might successfully deliver complex organic materials after impact. These results are discussed with respect to ancient Panspermia and the potential of contemporary impacts to eject living organisms into space.

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Key words: gas gun, hypervelocity, origin of life, panspermia, seeds, shock pressures.

Introduction

Panspermia has a long history. The idea that life might migrate naturally through space is an attractive one to many. However, since we do not currently know the details of the first appearance of life on Earth (or if there is indeed life elsewhere), the field remains speculative. In the 19th and early 20th centuries, the age of the Earth was still held to be relatively short, which prompted many to look for an exogenous origin for life. Today, some simply consider that the evolution of complex life would require timescales longer than the history of the Earth. Others note that life appeared on Earth shortly after it became a stable habitat and that life currently persists under conditions of extreme heat, cold, pressure, desiccation and radiation. Such arguments, and the observation that meteorites carry planetary materials via ejection caused by impact, have led some to seriously reconsider Panspermia. For examples of recent reviews, see Davies (1988), Parsons (1996), Wickramasinghe *et al.* (2003) and Burchell (2004).

Practical discussions of Panspermia tend to focus on two main aspects: the transport of life (including the mechanics and the associated hazards) and the survival of microorganisms in extreme environments. Building on reports of Martian meteorites found on Earth, Melosh (1988) proposed an ejection mechanism that uses impacts on Mars to launch ejecta off the Martian surface into escape trajectories, carrying life into space without sterilizing it. Mileikowsky *et al.* (2000) then considered all the steps in the journey of a rock from Mars to Earth (and *vice versa*), and at each stage estimated the possible survival of any microbial life in the sample. They concluded that it is not precluded that putative Martian life could reach Earth via such a route. Burchell *et al.* (2001) pointed out that the analysis of Mileikowsky *et al.* (2000) lacked knowledge of the survival of microorganisms in high-speed impacts, so they demonstrated in laboratory simulations that bacteria could indeed survive high-speed impacts (at 5 km s^{-1}), albeit with low survival rates. Similarly, Horneck *et al.* (2001a) showed survival of bacterial spores in extreme shocks (using a flying plate arrangement) at 35 GPa. Later, Burchell *et al.* (2004) showed that a range of late stage growth bacteria and their spores could survive impacts at speeds of 1–7 km s^{-1}, involving peak shock pressures of 1–78 GPa. Survival was at low rates, which fell strongly with increasing pressure in this range. More recently, Stöffler *et al.* (2007) found similar survival rates, using a range of microorganisms in flying plate experiments with peak shock pressures of 1–50 GPa.

A variety of microorganisms in active growth or spore state can thus survive the shocks associated with interplanetary transfer, albeit at low frequencies. Simpler organic structures (organic biomarkers) also withstand similar impacts (Bowden *et al.* 2008), albeit with slight thermal alteration due to heating. However, could more complex life forms survive high-speed impacts? And if not, to what degree would their biological content be inactivated?

It was proposed (Tepfer & Leach 2006) that plant seeds are suitable vehicles for Panspermia. In a habitable environment, they could germinate to form plants, and they contain a variety of molecules of biological interest (including DNA, RNA, lipids, proteins, amino acids), as well as mitochondria and plastids, which are themselves the descendents of early bacteria. Some seeds can also harbour contemporary microorganisms capable of living autonomously. Thus, if a seed, or fragment thereof, were to withstand transfer through space, it could deliver a source of biological material to a distant environment.

One attraction of seeds, rather than microorganisms, as vehicles for transport through space is the potential role of the seed coat in protecting the interior against UV radiation (e.g. Zalar *et al.* (2007); see Horneck *et al.* (2001b) and Nicholson *et al.* (2005) for examples of how microorganisms in space can be protected against UV radiation). However, UV radiation is not the only damaging radiation in space: see, for example, Clark *et al.* (1999) and Clark (2001). More penetrating radiations, such as galactic cosmic rays, are particularly deleterious. On long interplanetary transfers, the accumulated dose from such sources, even inside rocks, would be sufficient to kill any known terrestrial organisms including *Deinococcus radiodurans* (see the discussion in Clark *et al.* (1999)).

Plant seeds did not appear in the fossil record until the late Devonian period, i.e. about three billion years later than microorganisms. Nevertheless, they provide a useful model in the search for the attributes of life that would allow an organism to survive or partially survive transfer through space (Tepfer & Leach 2006). Seeds are also candidates for the contemporary transfer of life away from Earth following impact, i.e. through exospermia, or through intentional dispersal (directed Panspermia) (Crick & Orgel 1973; Tepfer & Leach 2006; Zalar *et al.* 2007). We thus wanted to simulate the effects of a contemporary impact on Earth, allowing us to determine whether seeds could survive the forces required for ejection into space and impact elsewhere. We therefore undertook high-speed seed acceleration and impact tests, using a two-stage light gas gun, with impact into water targets.

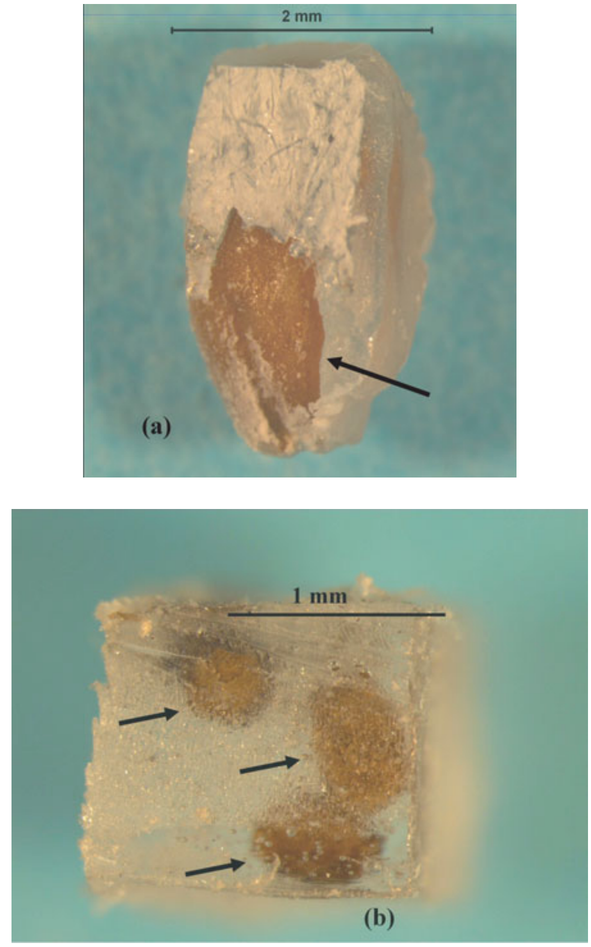

Fig. 1. Seeds placed in glue projectiles. In all cases the seeds are shown by arrows. (a) Cress seeds in superglue. (b) Tobacco seeds in Araldite.

Methods

Speeds associated with impacts in space are naturally in the range of km s^{-1}. To achieve such speeds in the laboratory a two-stage light gas gun was used. This gun (at the University of Kent; see Burchell *et al.* (1999)) can fire projectiles at 1–8 km s^{-1}. The speed is controlled pre-shot by varying the amount of gunpowder and the nature of the light gas used in the gun (the lower the mean molecular weight of the gas, the faster the speed). The projectile is fired in a plastic sabot that is discarded in flight, with only the projectile continuing to the target, which is placed in a vacuum chamber. The projectile's speed in flight is measured by its passage through two laser light curtains focused onto photodiodes, read out by a fast digital oscilloscope. The speed measurement is accurate to better than 1%.

Several seeds were embedded in a carrier, consisting of plastic moulded into cylinders (typically 3 mm long and 2 mm diameter) or cubes (1.2 mm a side), simulating seeds trapped in fractured rock. A carrier was used because initial tests showed that even at the lowest speed (1 km s^{-1}) naked seeds disintegrated into fine powder when fired. Secondly, according to the lithopanspermia hypothesis (e.g., Melosh 1988), interplanetary rocks (e.g., Martian) found on Earth could have been colonized by life before ejection from their home environment, and these rocks might have protected life during transfer through space. Thus, embedding seeds in a carrier was motivated both by necessity and by the possibility of lithopanspermia.

Three types of seeds were used in this work: tobacco (typical mean size 0.71 mm, germination time 4 days), cress (typical size 1.5 mm, germination time 1 day) and alfalfa (typical size 1.6 mm, germination time 1 day). The seeds were not necessarily spherical, so the mean size is averaged over minimum and maximum diameters and individual seed sizes showed scatter of typically ±25% around the mean values. These seeds were chosen as their size permitted ease of handling and their germination times meant tests for survival could be conducted on reasonable timescales after each shot. Examples of seeds in their plastic carrier are shown in Fig. 1. Originally, polymerized cyanoacrylate (superglue) was used

Table 1. *Shot programme*

Seeds	Speeds (km s^{-1})	Comments
Cress	1.0	1 shot
Alfalfa	1.0, 1.0, 1.0, 1.0, 2.8	5 shots
Tobacco	1.0, 1.0, 1.0, 1.0, 1.1, 2.8, 2.9	7 shots

as the carrier, set in a drinking straw, giving a long, cylindrical projectile. Later in the programme, cube moulds (made from clay) were used, filled with Araldite. In the final shots, the Araldite carrier was reinforced with iron filings (150–180 μm in length) with 10–100 filings per projectile. No adverse effect of the carrier material was observed (see results). Test germinations of untreated seeds were carried out successfully, as was germination of seeds removed from their glue carriers after setting of the glue, but without being fired in the gun (see the Results section). The seeds were removed by cutting with a scalpel, the same method as used post-shot. The latter tests were to establish that the embedding or extraction was not preventing survival.

Most of the shots (Table 1) were performed with tobacco seeds, because they were the most convenient to handle. In every case, the target was a bag of water, held with a flat front surface at an angle of 45° to the impact direction. The bags were composed of a thin-walled, water-rich plastic, and the target set-up was similar to that of Milner *et al.* (2006), who investigated impacts of organic-rich shale into water. Water was used as a target as the Earth has been predominately covered with water for most of its history. Rock or ice might be a better impact model for other planets in the Solar System, and they represent an extreme case for an impact. For a terrestrial type planet, an impact into an atmosphere might be more appropriate (see the Discussion section). The angle of 45° is the mean angle for an impact in space (see Pierazzo & Melosh 2000). After each shot, the water was collected and filtered through Whatman filter paper (grade 1), and the filtrate was analysed with stereo microscopy.

Shock pressures

The peak shock pressure in an impact can be estimated analytically or via numerical simulation (hydrocode). Here we attempted an analytical solution, using the planar impact approximation (PIA) method (see Melosh (1989) for a derivation). This approximation solves the Hugoniot equations in both projectile and target materials, assuming contact between two semi-infinite planar materials and a linear relation between particle and shock wave speed. It slightly over-estimates the peak shock pressure in the projectile, due to the lack of rarefaction waves from the real (finite) edges of the projectile. Also, the calculated pressure is a mean value; the real peak shock pressure falls over the length of the projectile. For well understood materials, the PIA method produces a shock pressure in good agreement with that predicted for the front half of the projectile in more detailed hydrodynamical simulations, but the PIA method over-predicts the pressure in the trailing half of the projectile by a factor of about three (see Crawford *et al.* (2008) for a discussion of this).

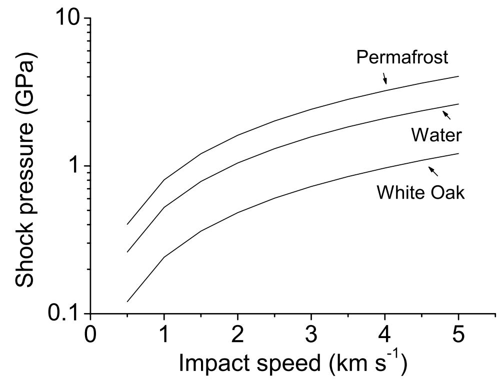

Fig. 2. Projectile shock pressures versus impact speed, calculated using the PIA (see text) and scaled by sinθ.

However, in the present case, the materials were not well characterized for high-speed impacts. In particular, the linear shock wave and particle wave speed relationship were not well known. This relationship can be written as

$$U = C + Su, \qquad (1)$$

where U is the shock wave speed and u is the particle speed. The constants C (dimensions of speed) and S (dimensionless) are found empirically by fits to data for the relevant materials. Separate relations exist for each material (projectile and target). However, the projectiles are not homogeneous materials, but rather mixtures of glue and seeds. Furthermore, whilst C and S are known for a wide range of materials, they are not available for either the glues used here or seeds in general. This makes estimation of the shock pressures difficult. As an approximation, we make use of C and S for a variety of materials. These include water (a low-density material as an analogue for the glue), soft wood – White Oak with a density of 750 kg m^{-3} (as analogue for the seeds) and water-saturated permafrost (as an analogue for one material held inside another). The C and S values for water (C = 1.48 km s^{-1} and S = 1.60) and permafrost (C = 2.51 km s^{-1} and S = 1.29) were taken from page 232 of Melosh (1989) and those for soft wood (C = 0.59 km s^{-1} and S = 1.37) from the shock wave database for condensed matter available at http://riodb.ibase.aist.go.jp/ChemTherm/index5.htm#o.

Based on the PIA and the above values for C and S, the shock pressures were calculated as a function of impact speed. One final step was then applied. The PIA assumes a normal incidence impact, but here impacts were at 45°. To adjust for this, Pierazzo & Melosh (2000) showed that in hydrodynamical simulations the peak pressure at normal incidence could be scaled to that at inclined incidence (θ) by multiplying by sinθ. This correction was applied and the shock pressures at θ = 45° are given in Fig. 2. These values are taken as indicative of the likely range within which the true shock pressures may lie. Thus, at 1 km s^{-1} we see a possible range of 0.24–0.81 GPa, whilst at 3 km s^{-1} this has risen to 0.73–2.42 GPa.

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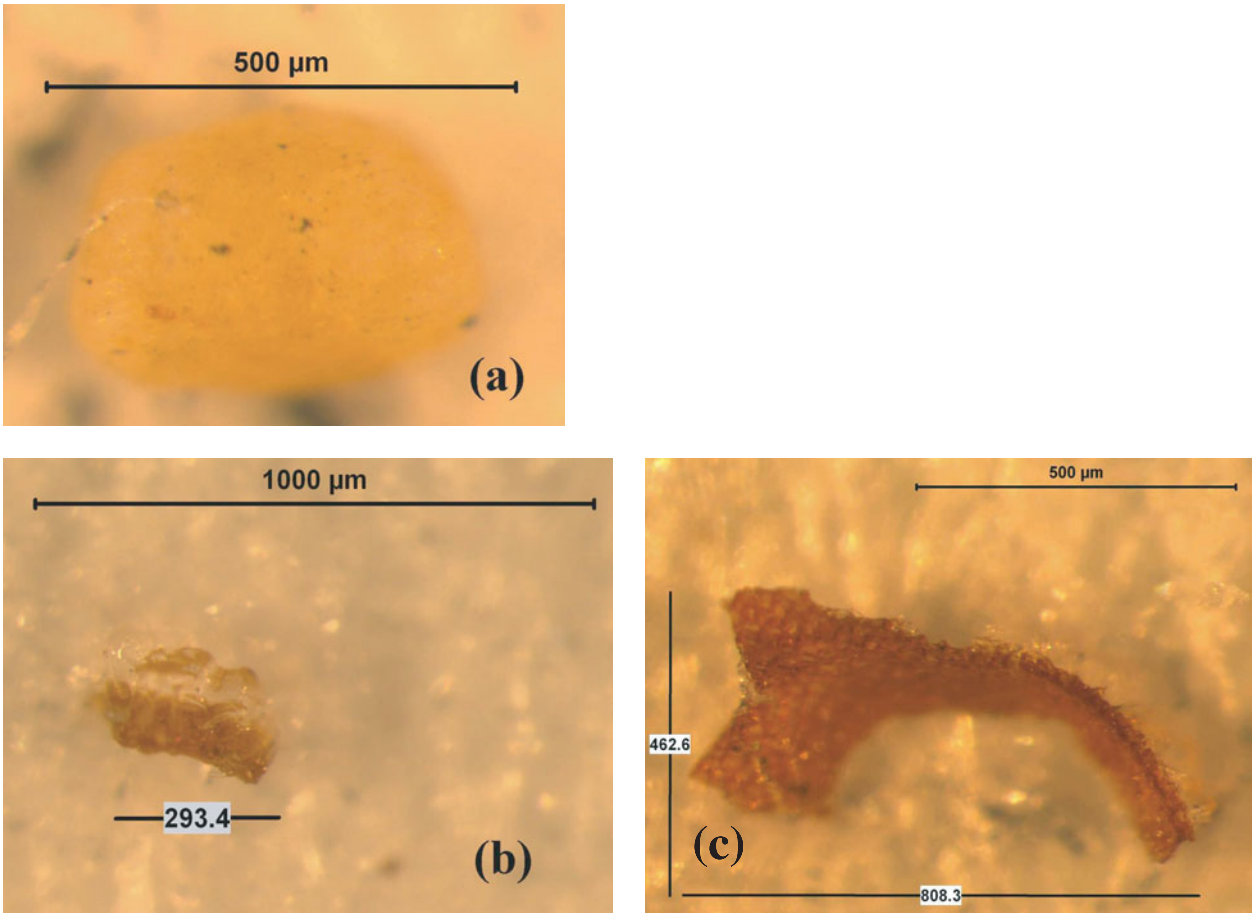

Fig. 3. Fragments of seeds extracted from the water target after impact at 1 km s^{-1}. (a) Tobacco. (b, c) Alfalfa.

The duration of the shock can be crudely estimated as the time it takes the projectile to travel its own length in flight. At 1 km s^{-1} a 1 mm length sets a timescale of 1 µs; projectiles of a few millimetre lengths and an inclined impact at 45° give a timescale of 10 µs. Thus 1–10 µs is a reasonable timescale for the impacts.

Results

Seeds fragmented in all tests; therefore, germination was not obtained. In the impacts at 1 km s^{-1}, several large fragments of the (glue) projectile were found in almost all the shots. These had what appeared to be intact seeds inside them. However, when extraction of the seeds was attempted, they were found to be in pieces. Similarly, in some of the shots at 1 km s^{-1}, large seed fragments were found on the filter paper with no glue adhering to them. None of these fragments consisted of an entire seed. Examples of recovered fragments are shown in Fig. 3 (1 km s^{-1}) and Fig. 4 (3 km s^{-1}).

Some of the fragments obtained after the shots were similar in appearance to those obtained by removing the coat from untreated seeds and cutting them up, others may have been seed coatings. This visual check indicated that they were indeed seed fragments. As already stated, attempts to germinate these fragments all failed. The longest dimension of each fragment was measured under the microscope, and the results are shown in Fig. 5(a). In Fig. 5(b) the same data are shown normalized to the mean of the seeds, indicating the degree of morphological integrity. In Fig. 5(b) some fragments have normalized sizes greater than 1, i.e. they appear larger than the original seeds. Since several seeds were used in each shot, it is not possible to normalize to the individual parent seed size and, as noted earlier, the individual seed sizes have a scatter of $\pm 25\%$ around the mean; there may also have been some flattening of fragments (e.g., seed coatings) during impact. At $\sim$1 km s^{-1}, a substantial fraction of the seed was intact, but in all cases the fragments seem to have had their coat removed. At $\sim$3 km s^{-1} the fragments were smaller and more numerous (as would be expected). Beyond noting that fragmentation had occurred, the degree of internal damage in each fragment was not assessed. Future work will examine the structure of these fragments and the state of the biological information contained in the plant DNA and RNA.

Discussion

As stated, the initial test shots showed that seeds fragmented during acceleration at speeds of 1 km s^{-1}. However, by mounting the seeds in a solid projectile it was possible to deliver them to the target at high speed. In the subsequent

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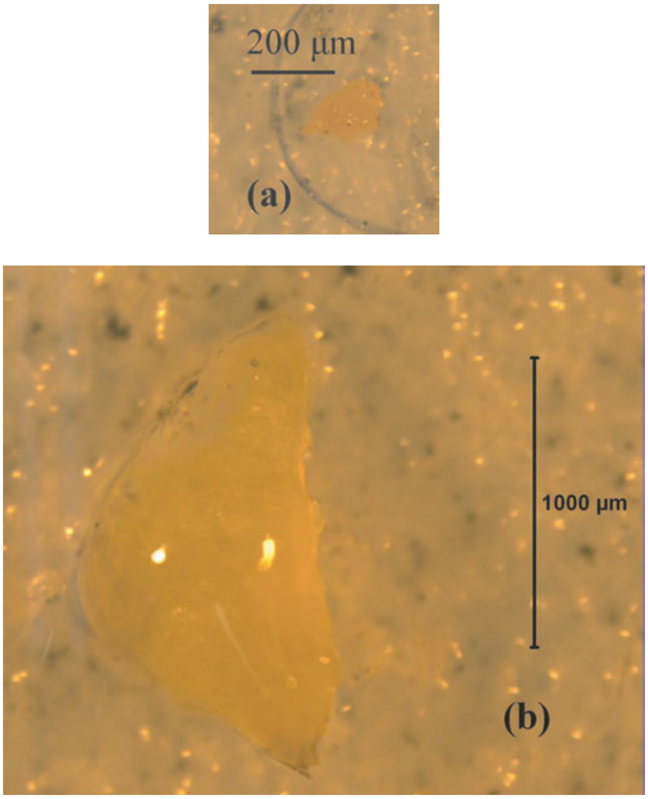

Fig. 4. Fragments of seeds extracted from the water target after impact at 3 km s^{-1}. (a) Tobacco. (b) Alfalfa.

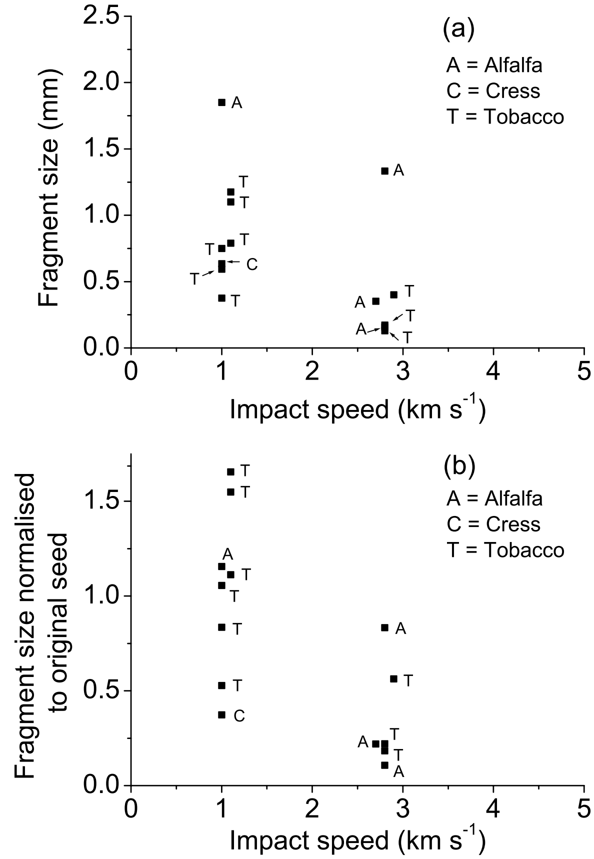

Fig. 5. (a) Size of largest surviving fragments vs. impact speed. (b) Fragment size normalised to original mean seed size (note: one of the data points for Alfalfa at 2.8 km s^{-1} has been displaced to an apparently slightly lower speed as it overlaid another data point).

impacts into water, the projectiles (including the seeds) suffered damage. At 1 km s^{-1}, parts of the projectiles sometimes survived intact, with no pattern related to the type of glue used to make the projectile. Independent of this, no undamaged seeds were recovered and germinated. Instead, large seed fragments, in some cases nearly the size of the original seed, but lacking the seed coat, were recovered. It is not clear if the seed coats were removed when the seed was freed from the carrier, but in some cases the seed itself had clearly broken into pieces ranging in size from 50 to 100% of the size of the original seed. This suggests that severe damage was occurring even at 1 km s^{-1} (and at the associated shock pressure, possibly in the range 0.2–0.8 GPa). As the impact speed increased to 3 km s^{-1} (with an associated shock pressure of 0.7–2.3 GPa), damage to the projectiles and the seeds became more severe, as seen by the smaller size of the recovered fragments which was typically 25–50% of the original size (although in one case a larger fragment was found).

The impact speeds and shock pressures used here are at the low end of those involved in most impacts from space; exact speeds depend on relative orbits. Planetary in-fall speeds can be taken as indicators: 11.2 km s^{-1} for Earth and 5.0 km s^{-1} for Mars. By contrast, the minimum speed for terrestrial impact ejecta that hit the Moon is only about 2.3 km s^{-1}. It has thus been proposed that the Moon is a good place to look for terrestrial fossils in meteorites (Armstrong *et al.* 2002; Crawford *et al.* 2008). However, as shown here, impacts into water at even these speeds will cause damage to seeds, and of course the Moon lacks an environment to support life. Ejecta can also return to Earth and re-seed the planet. Re-entry through an atmosphere has still to be simulated experimentally but some seeds are small enough to avoid excessive heating, even through Earth's current atmosphere (Tepfer & Leach 2006).

So-called 'icy satellite' Panspermia has also been proposed, in which ejecta from impacts on icy satellites in the Jovian or Saturnian systems might carry microorganisms between satellites (e.g., Burchell *et al.* (2003) who also demonstrated that ejecta from high-speed impacts on ice can carry viable bacteria). Such migration would be mostly restricted to satellites orbiting the same parent planet due to the high escape velocity of the large gas giant planets.

Although the soil seed bank contains as many as 12 000 seeds m^{-2} (Hözel & Otte 2003), and a contemporary impact could eject seeds, our results indicate that (for the seeds tested) sudden acceleration to escape velocity would probably cause unsupported seeds to disintegrate. Even embedding in a hard material may itself cause enough damage to preclude subsequent germination. Thus, whilst contemporary ejection from the Earth might involve accelerations too high to permit significant survival of the tested seeds, transfers of seed-like life forms between smaller entities, with lower escape velocities, might be more accommodating.

Similar experiments with bacteria (see the Introduction section) showed survival at low frequencies, but with sample sizes many orders of magnitude greater than those used here. With the seed sample sizes in the present report, no bacterial survival would have been detected in previous experiments. A definitive answer to the question of seed survival following a contemporary impact will require further experimentation, including testing seeds with hard, impervious coats, and using a variety of embedding materials, including elastic substances. Intentional dispersal of life through space, via directed Panspermia (Crick & Orgel 1973) using seeds (Zalar *et al*. 2007) might also profit from better understanding the constraints imposed by rapid acceleration.

Conclusions

Although impacts at 1 km s^{-1} fragmented cress, alfalfa and tobacco seeds embedded in plastic, the generated fragments were still a substantial fraction of the original seed. Damage increased at 3 km s^{-1}, suggesting that at speeds more typical of interplanetary transfers (5–10 km s^{-1} or more) much greater damage would occur, including melting. No seed fragment germinated after impact, but in all cases substantial fragments of complex organic material were delivered to the target in a recoverable fashion, suggesting that the survival of life after ejection and impact might be partial, which might not preclude delivery of functional components, such as subcellular structures or even endophytic organisms. A separate investigation will determine the degree of structural and biological damage to the material generated in these experiments and in particular DNA and RNA functionality.

The results here are the first in a line of planned experiments. For example, different methods will be used to extract materials from the after target after impact (e.g., centrifugal separation) along with a wider range of germination methods. A variety of more seed types (with harder coatings, different degrees of hydration etc.) will be used in later studies. Also, the experiments reported here are in some respects extreme, in that they suppose an impactor hits a water surface with no deceleration in a surrounding atmosphere. Capture at high speeds in ultra-low-density aerogels are one possible future route to test if a more gradual slowing from speeds of several km s^{-1} can aid survival of viable seeds.

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References

Armstrong, J.C., Wells, L.E. & Gonzales, G. (2002). Rummaging through Earth's attic for remains of ancient life. *Icarus* **160**, 183–196.

Bowden, S.A., Court, R.W., Milner, D., Baldwin, E.C., Lindgren, P., Crawford, I.A., Parnell, J. & Burchell, M.J. (2008). The thermal alteration by pyrolysis of the organic component of small projectiles of mudrock during capture at hypervelocity. *J. Anal. Appl. Pyrol.* **82**, 312–314.

Burchell, M.J. (2004). Panspermia today. *Int. J. Astrobiology* **3**, 73–80.

Burchell, M.J., Cole, M.J., McDonnell, J.A.M. & Zarnecki, J.C. (1999). Hypervelocity impact studies using the 2 MV Van de Graaff dust accelerator and two stage light gas gun of the University of Kent at Canterbury. *Meas. Sci. Technol.* **10**, 41–50.

Burchell, M.J., Galloway, J.A., Bunch, A.W. & Brandao, P. (2003). Survivability of bacteria ejected from icy surfaces after hypervelocity impact. *Orig. Life. Evol. Biosph.* **33**, 53–74.

Burchell, M.J., Mann, J.R. & Bunch, A.W. (2004). Survival of bacteria and spores under extreme pressures. *Mon. Not. R. Astron. Soc.* **352**, 1273–1278.

Burchell, M.J., Mann, J., Bunch, A.W. & Brandão, P.F.B. (2001). Survivability of bacteria in hypervelocity impact. *Icarus* **154**, 545–547.

Clark, B.C. (2001). Planetary exchange of bioactive material: probability factors and implications. *Orig. Life. Evol. Biosph.* **31**, 185–197.

Clark, B.C. *et al.* (1999). Survival of life on asteroids, comets and other small bodies. *Orig. Life. Evol. Biosph.* **29**, 521–545.

Crawford, I.A., Baldwin, E.C., Taylor, E.A., Bailey, J.A. & Tsembelis K. (2008). On the survivability and detectability of terrestrial meteorites on the moon. *Astrobiology* **8**, 242–252.

Crick, F.H.C. & Orgel, L.E. (1973). Directed panspermia. *Icarus* **19**, 341–346.

Davies, R.E. (1988). Panspermia: unlikely, unsupported, but just possible. *Acta Astronautica* **17**, 129–135.

Hölzel, N. & Otte, A. (2003). Restoration of a species-rich flood meadow by topsoil removal and diaspore transfer with plant material. *Appl. Vegetation Sci.* **6**, 131–140.

Horneck, G., Stöffler, D., Eschweiler, U. & Hornermann, U. (2001a). Bacterial spores survive simulated meteorite impact. *Icarus* **149**, 285–209.

Horneck, G. *et al.* (2001b). Protection of bacterial spores in space, a contribution to the discussion on panspermia. *Orig. Life. Evol. Biosph.* **31**, 527–547.

Melosh, H.J. (1988). The rocky road to Panspermia. *Nature* **332**, 687–688.

Melosh, H.J. (1989). *Impact Cratering: A Geological Process*. Oxford University Press, Oxford.

Mileikowsky, C. *et al.* (2000). Natural transfer of viable microbes in space: 1. From Mars to Earth and Earth to Mars. *Icarus* **145**, 391–427.

Milner, D.J., Burchell, M.J., Creighton, J.A. & Parnell, J. (2006). Oceanic hypervelocity impact events: a viable mechanism for successful panspermia? *Int. J. Astrobiology* **5**, 261–267.

Nicholson W.L., Schuerger A.C. & Setlow P. (2005). The solar UV environment and bacterial spore UV resistance: considerations for Earth-to-Mars transport by natural processes and human spaceflight. *Mutation Res.* **571**, 249–264.

Parsons, P. (1996). Dusting off panspermia. *Nature* **383**, 221–222.

Pierazzo, E. & Melosh, H.J. (2000). Understanding oblique impacts from experiments, observations and modelling. *Ann. Rev. Earth. Planet. Sci.* **28**, 141–167.

Stöffler, D. *et al.* (2007). Experimental evidence for the potential impact ejection of viable microorganisms from Mars and Mars-like planets. *Icarus* **186**, 585–588.

Tepfer, D. & Leach, S. (2006). Planet seeds as model vectors for the transfer of life through space. *Astrophys. Space. Sci.* **306**, 69–75.

Wickramasinghe, N.C. *et al.* (2003). Progress towards the vindication of Panspermia. *Astrophys. Space. Sci.* **282**, 403–413.

Zalar, A., Tepfer, D.A., Hoffmann, S.V., Kollmann, A. & Leach, S. (2007). Directed exospermia: II. VUV–UV spectroscopy of specialized UV screens, including plant flavonoids, suggests using metabolic engineering to improve survival in space. *Int. J. Astrobiology* **6**, 291–301.