Mon. Not. R. Astron. Soc. **352,** 1273–1278 (2004) doi:10.1111/j.1365-2966.2004.08015.x

Survival of bacteria and spores under extreme shock pressures

M. J. Burchell,[1]★ J. R. Mann[1] and A. W. Bunch[2]

[1]*Centre for Astrophysics and Planetary Sciences, University of Kent at Canterbury, Canterbury, Kent CT2 7NR*
[2]*School of BioSciences, University of Kent at Canterbury, Canterbury, Kent CT2 7NJ*

Accepted 2004 May 11. Received 2004 May 11; in original form 2004 February 6

ABSTRACT

Some rocky objects on Earth originated on other planets (e.g. Martian meteorites). Modelling of interplanetary transfer times (Mars–Earth) and calculations of the survival of cells and spores in the radiation environment of space show that this is not an insurmountable obstacle to the successful delivery of life from one planetary surface to another via these rocks. However, the initial launch into space and the subsequent arrival at a new planet involve short-duration extreme accelerations, and shock pressures in the 1–100 GPa range. Recently it has been shown that survival of such accelerations and at such shock pressures is possible. Here we show that in hypervelocity impacts (which involve extreme short-duration accelerations), as shock pressures vary from 1 to 78 GPa, the survival rate (N/N_0) for *Rhodococcus erythropolis* cells falls from 10^{-4} to 10^{-7}. Whilst survival rates are low at 78 GPa, they are still finite. For a different organism, *Bacillis subtilis*, the survival rate at 78 GPa was found to be of the order of 10^{-5}, i.e. significantly greater than for the *R. erythropolis*, indicating that survival rates may vary greatly with different organisms. By contrast, the variation between the survival rate in impacts on agar at 78 GPa for *B. subtilis* spores versus active *B. subtilis* was found only to be a factor of 2, well within the experimental uncertainties and not significant. Overall, whilst extreme shock pressures clearly have a deleterious effect on survival rates, it is shown that, even at extreme shock pressures of near to 100 GPa, there is still a finite and sufficient survival rate for this not to be an insurmountable obstacle to successful natural transfer of life through space.

Key words: astrobiology – comets: general – meteors, meteoroids – planets and satellites: general.

1 INTRODUCTION

The transfer of rocky material between planets such as Mars and Earth is now well established. Martian meteorites have been recovered on Earth (e.g. see McSween 1985), and models explaining both the ejection process from Mars (Melosh 1988) and the interplanetary transfer (e.g. Gladman et al. 1996; Gladman 1997) are well established. The ejection process is postulated to originate from a large crater-forming impact on a planetary surface throwing ejecta into space. Since here on Earth it has been shown that rocks to depths of several kilometres contain microbial life (Pedersen 2000), this has encouraged renewed speculation concerning whether ejected rocks can successfully transfer viable microbial life from one planet to another. Various authors have considered this afresh (e.g. Mileikowski et al. 2000) and conclude that in the main there are no longer any compelling reasons to discard the possibility. Previously, one of the main arguments against viable transfer concerned the effects of the space environment upon the organisms. Modelling of transfer times show that the shortest possible times are of the order of 6–7 months (the minimum-energy unpowered transfer time assuming optimal speed, trajectory and alignment of the respective planets) (Gladman et al. 1996). Also, periods of a million years result in transfer to the Earth of a sizeable fraction (10^{-2} to 10^{-1}) of material ejected from Mars as the result of a large impact event (Gladman 1997). Further, experiments and modelling of the effects of solar ultraviolet radiation and galactic cosmic rays show that, if organisms are inside rocky bodies, even metre-sized bodies provide sufficient shielding for survival to be plausible on such time-scales (e.g. see Clark et al. 1999; Clark 2001; Horneck et al. 2001b). Finally, whilst the temperatures and low pressures encountered in space may require microbial life to enter the spore state or a state of low metabolic activity, there is increasing evidence suggesting that microbial life can successfully survive such regimes [e.g. Soina et al. (1995) report on microbial survival after extended periods in permafrost conditions]. In addition, there is also some evidence (albeit controversial) that microbial life can survive over extremely long periods exceeding millions of years (Vreeland, Rosenzweig & Powers 2000). This leaves the survival of organisms during the initial launch off a planetary surface and during the impact on the new planet as the weakest links in the

★E-mail: M.J.Burchell@kent.ac.uk

chain for successful transfer of life between planets. (Note that the general process of microbial life migrating naturally through space is called panspermia, and the specific case of transfer from planet to planet is often called litho-panspermia.)

An interesting variant of this transfer between planets is when the ejected material passes outward from Mars into the outer Solar system beyond Jupiter. The work of Gladman (1997) explicitly recognizes this possibility. The ejecta can undergo orbital interactions with resonances, and, as a result, after 100 Myr, some 15 per cent of Martian ejecta are moved outward beyond Jupiter. The fate of such ejecta has recently been considered by, amongst others, Melosh (2003). Melosh finds that some 20 per cent of Martian ejecta pass outwards from the Solar system after interactions with Jupiter (and to a much lesser extent Saturn). It is not inconceivable that these ejecta will pass near another star. However, the chance that ejecta directly hit a terrestrial-like planet orbiting such a star is vanishingly small. Conveniently, the presence of a Jupiter-like planet in the new star system will allow the possibility that the ejecta could be captured into a bound orbit and thence collide with a terrestrial-like planet. However, Melosh (2003) calculates that, per 10^9 yr, only one rock ejected from a planet in our Solar system will be captured into a bound orbit in another solar system. Paradoxically, the fate of 94 per cent of such rocks is to be re-ejected into interstellar space as a result of a later orbital interaction with the Jupiter-sized planet, with a probability that it stays in the new system and strikes a terrestrial-like planet of only some 10^{-4}. Thus even without considering whether such rocks can carry viable microbial life for the time-scales required, Melosh (2003) discards both the idea that life from the Earth could seed planets in other solar systems, and also that life on Earth originated from outside our Solar system.

A different conclusion is reached by Wallis & Wickramasinghe (2004). They consider more elaborate mechanisms for the fate of ejecta from terrestrial planets. They suggest that when rocky ejecta reach the outer Solar system, some will collide with icy bodies in the Edgeworth–Kuiper (EK) belt at speeds of a few km s^{-1}. They estimate that each comet in the EK belt may contain up to 3 kg of rocky material from a terrestrial planet. Since the EK belt is dynamically unstable (suffering perturbations by Saturn, Neptune and Uranus), the comets and their contents can be ejected back into the inner Solar system (potentially reseeding the inner planets with life), or outwards into the main Oort cloud or interstellar space. This hypothesis serves not only to eject rocky terrestrial material into interstellar space, but also to provide it with a larger body to protect it against the deleterious effects of the environment. Subsequent delivery to a planet in another solar system is, however, still difficult. Wallis & Wickramasinghe (2004) acknowledge that the difficulties for direct capture by the new solar system as described by Melosh (2003) still apply. However, they envisage other delivery mechanisms. In their model they note that, whilst traversing a molecular cloud or protoplanetary disc, a body will be subject to hypervelocity impacts by small grains. These impacts will produce ejecta, effectively spraying the parent body into the local environment on size scales of micrometres to millimetres. Thus the material will be deposited into and incorporated into such clouds and discs. Similarly, they postulate that the elevated temperatures on the margins of H II regions can cause significant outgassing from an icy body, causing it to deposit its contents into the H II region and making it available for incorporation into nearby star-forming regions.

The details offered by Wallis & Wickramasinghe (2004) in support for their model are vague, as is the eventual fate of any microbial-bearing material carried into such regions on the icy bodies. Nevertheless, they claim that such material will spread at the rate of some 5 kpc Gyr^{-1}. As in earlier discussions, one crucial feature of this approach is the ability of microbial life to survive impacts (in this case, for example, the collision of a rocky piece of terrestrial planet ejecta with an icy body in the EK belt or in ejecta arising from the impact of a small projectile on an icy surface). In this context we note, for example, that Burchell et al. (2003) demonstrated that, if microbes are frozen into an ice target that is subject to a hypervelocity impact, then the resultant ejecta released from the site of the impact can carry viable cells, which can subsequently be grown in culture.

In parallel to Wallis & Wickramasinghe (2004), and again in contradiction to Melosh (2003), Napier (2004) has offered another possible mechanism for interstellar panspermia. The first step is still to launch material from a planetary surface as ejecta after an impact event. However, Napier postulates periods when the dust flux in the Solar system is elevated compared to currently, and this leads to enhanced collisional rates and hence increased sputtering of small-sized material off the rocky bodies whilst in space. If the subsequent debris is small enough, it will be driven out of the Solar system by radiation pressure. If this material can offer sufficient shielding against solar ultraviolet radiation and galactic cosmic rays, it could carry viable microorganisms into the outer Solar system. There it could either be ejected into interstellar space, or collide with comets and be incorporated into their structure. In such a scenario the Solar system effectively seeds the region of interstellar space around it with dust potentially containing microbial life. The eventual fate of such dust can be to be deposited in star-forming regions or comet-forming regions around another star. If such a star has a planetary system, some of the material will eventually migrate on to the surfaces of the planets. This proposal greatly shortens the time-scales required to eject material into interstellar space, as the driver for removal of material is radiation pressure on a small body (i.e. a continual outward force).

Whatever the final destination and the delivery mechanism, to achieve transfer of rocky material between planets, the initial step is the launch into space, and there will be subsequent collisions/impacts at hypervelocities typical of orbital motion inside a solar system. The favoured method for natural launch into space is via extreme acceleration of ejecta during a giant impact event (Melosh 1988). Note that it is not just the peak acceleration itself that is a hazard, but also the rate of change in acceleration or 'jerk' (which is related to the duration of that acceleration) has to be considered as well. For Martian ejection (escape velocity 5.03 km s^{-1}), the 'jerk' required, i.e. the acceleration divided by the duration, is estimated by Mastrapa et al. (2001) to be of the order of 6×10^9 m s^{-3} (i.e. acceleration of 3×10^{-6} m s^{-2} over time-scales of 0.5×10^{-3} s). Then, for example, upon arrival at the Earth, meteorites from Mars will have an impact speed of some 11–17 km s^{-1}. As well as the acceleration and its duration, such impacts are also characterized by the extreme pressure reached as a result of the shock waves involved as they propagate through the material. During impact on a planetary surface, the peak pressures are estimated to be in the range of 1–100 GPa, the exact value dependent on impact speed, the materials involved, etc.

Recently, it has been shown by Burchell et al. (2001) that a typical soil bacterium (*Rhodococcus erythropolis*) can successfully be accelerated to speeds of 5 km s^{-1} (Martian escape velocity) with a jerk of 6×10^{10} m s^{-3}. It thus seems that a successful launch from Mars of rocky material carrying viable microbial life is possible. The same authors (Burchell et al. 2001) also report that viable bacteria were subsequently recovered after an impact at 5 km s^{-1} into agar (10^{-7} survival rate). However, they made no estimate of the peak

pressures involved in the impacts. Independently, it has been shown by Horneck et al. (2001a), in a flying plate-type experiment, that viable spores (*Bacillus subtilis*) can survive peak shock pressures of 32 GPa (survival rate 10^{-6} to 10^{-4}). Taken together, these results seems to establish that microbial survival in a hypervelocity impact from space is not necessarily excluded.

It is important to investigate these results more fully given that the reported survival rates differ by up to three orders of magnitude. The whole critical pressure range of 1–100 GPa should be considered to see how survival evolves with shock pressure. Further, a direct comparison between spores and bacteria under the same conditions is required, and between the two types of cells used previously, *R. erythropolis* and *B. subtilis*. Also, given that the real events will also involve hypervelocity impacts (i.e. with short, sharp accelerations), this seems the appropriate method to use, and data for more than one target type are desirable to generalize the results further. In particular, given the proposals of Wallis & Wickramasinghe (2004) concerning icy bodies in the EK belt harvesting and storing rocky ejecta, studies of impacts into ice targets are appropriate.

Accordingly, results are presented here for survival rates using the same experimental methods as Burchell et al. (2001), namely use of a two-stage light gas gun to fire projectiles laden with microbial life. Here impact speeds are in the range 0.3–6 km s^{-1}. The experiments used late-stage batch cultures of *R. erythropolis* and *B. subtilis*, and spores of *B. subtilis*. Target materials were nutrient broth set in agar (a moist gel), as used previously by Burchell et al. (2001), and ice (a solid target). The peak shock pressures in the impacts are also estimated and the survival rates versus peak shock pressure are obtained.

2 METHOD

The microorganisms were infused into porous ceramic projectiles. These were loaded into a sabot, which was placed in the two-stage light gas gun (Burchell et al. 1999) and fired on to targets of nutrient agar or ice. The sabot was discarded in flight when the gun was fired, with just the projectile proceeding to the target. During a shot the projectile speed for larger projectiles (order 0.4–2 mm) was measured by passage of the projectile in flight through two laser light curtains of known separation. Each light curtain was focused on a photodiode, and the variation of the diode output provided timing information. As a result the speeds were found to better than 1 per cent. For smaller (0.1 mm sized) projectiles, a different system was used to find the speed. In this approach the four parts of the discarded sabot hit a series of plates of known separation along the gun. This removes the sabot parts from the line of flight. Two of the plates were equipped with impact sensors. These provided timing signals, which allowed the speed of the projectile to be estimated to approximately 4 per cent. The target chamber in the gun was maintained at a vacuum of approximately 1–2 mbar during a shot to prevent slowing of the projectiles in flight due to air resistance.

The agar plates used in the work consisted of glucose yeast extract nutrient broth, set in a semi-solid form using agar. The depth of the medium in a typical plate was 5 mm. The plates were prepared in sterile conditions and handled by staff following standard sterile procedures (e.g. wearing lab coats, gloves, face masks, hair nets, etc.). The plates were only exposed whilst in the target chamber of the gun.

The ice targets were made using distilled water. Before use, the water was boiled, then sterilized in an autoclave for 20 min at 121°C. The water was then rapidly cooled, and frozen in a sterile sealed container. This container was then placed in the gun's target chamber when a shot was required.

After a shot the agar plates were incubated at 25°C for up to 2 weeks. Post-shot, the ice targets were sampled across the impact crater and the ice samples placed on to similar nutrient agar plates as those used as targets and incubated. For every shot with microbial infused projectiles, a clean shot was also performed and the target plates (or ice samples) were similarly incubated. A clean shot is defined as one where the projectile was sterilized before use and not placed in suspensions of spores or active cells. After incubation, any resultant cultures were identified by visual analysis, regrowth on selective media (e.g. nitrile-rich agar for nitrile-degrading *R. erythropolis*), Gram staining and in some cases pyrolysis mass spectrometry. No shot with clean projectiles produced cultures that passed these tests. By contrast, several shots with microbial-loaded projectiles did produce positive results (see below). In addition, tests were carried out placing projectiles loaded with bacteria in the gun along with agar targets, and performing the full shot procedure except that the gun was not actually fired. The sabot was then removed from the gun by hand and the projectiles cultured. No problems with subsequent growth were observed, indicating that the handling was not particularly deleterious to the survival of the organisms. The target from the gun was also incubated with no sign of subsequent growth, indicating a lack of contamination. Similarly, agar targets were left exposed in the laboratory for periods of 30 min and then incubated. Again, no contaminant was obtained that could be confused with the organisms being handled in the shot programme.

When positive results occurred, a minimal estimate of the number of survival organisms was initially estimated by assuming one surviving cell per colony cultured. However, for *R. erythropolis* impacting at 5 km s^{-1} on agar targets, this was found to be incorrect. When an impact site was removed from the original agar plate and the agar dissolved and then smeared on a second plate, the single impact site produced 100 separate colonies. Similarly, a fluorescent stain (propidium iodide) sensitive to metabolic activity was injected into one of the agar plates at an impact site. When examined under a microscope, approximately 100 separate bodies could be identified. Thus when finding survival rates, the number of sites of growth in the agar plates was multiplied by 100 to give the survival rate. No correction was applied to the data for impacts on ice, as the ice target was sampled and the samples melted and spread over the agar plate, thus allowing a direct evaluation of the number of surviving cells by counting the resultant clusters of growth.

To obtain survival rates, the initial microbial load on a projectile was estimated by taking projectiles and immersing in sterile water, which was then progressively diluted and a fraction cultured. This method is probably accurate to a factor of 10. In addition, during the shot programme, different sized projectiles were used at times. When firing at ice targets, single projectiles of size 1.5–1.75 mm were used. With the thinner agar targets, smaller projectiles were used, with more than one per shot. Thus, as well as the load per projectile of given size, it was necessary to know what number of projectiles reached the target in a shot (in case of loss during firing or flight). Accordingly, to test how many small projectiles reach the target per shot, shots were carried out on to a thin (6 μm) foil. For shots with mid-sized projectiles (0.5 mm size), typically three projectiles per shot were used and all were found to reach the target in a typical shot. When smaller (0.1 mm sized) projectiles were used, it was found (from three shots on to foils) that typically 85 ± 9 reached the target. This, combined with the estimated load per projectile, permitted estimates of the number of organisms used per shot.

To vary the peak impact pressure, the shot speed was changed, with several shots carried out at each mean speed. The results are given in Table 1; the mean speed in each speed range is given along with the spread of speeds. This spread can be bigger than the measurement uncertainty on the speed of a single shot. The peak pressures were estimated in two ways. The first used the late-stage effective energy method (Mizutani, Takagi & Kawakami 1990). This assumes that late-stage energy (LE) is given by

$$\mathrm{LE} = P_0 V_\mathrm{p} = \tfrac{1}{2} m v \left(C_0 + \tfrac{1}{2} s v\right), \qquad (1)$$

where P_0 is the peak pressure, V_p is the projectile volume, M and v are the projectile mass and impact speed, and C_0 and s are material parameters from the normal linear shock wave speed equation of state. The coefficients C_0 and s are particular to the material involved. For the ceramic projectile material used, the coefficient values were not available, so those for a similar material (calcite) were used (Melosh 1989), giving 3.80 km s^{-1} and 1.42 respectively for C_0 and s. As it is a complicated medium not usually encountered in shock testing, no such values were found for agar. Accordingly, it was treated as water with values for C_0 and s of 1.48 km s^{-1} and 1.60 respectively (Melosh 1988).

In addition to this, a hydrocode simulation of each type of impact event was performed. This was using the AUTODYN hydrocode of Century Dynamics [see Hayhurst & Clegg (1997), for a general description of the code]. In the simulation, the ceramic was represented by a model for alumina developed by Lundberg, Westerling & Lundberg (1996). This used a linear equation of state, with Johnson–Holmquist strength and failure models. As the agar targets were a complicated system not normally used in impact simulations, they were represented by water as given in the standard tables in AUTODYN. The peak pressures estimated by AUTODYN for impacts on the agar plates were slightly less than those predicted by the late-stage energy method, with a difference of typically 10–20 per cent. The ice targets were represented in the hydrocode simulations in three ways. The first method was originally developed for impacts on glass (Taylor et al. 1999) and used a linear equation of state with Johnson–Holmquist strength and failure models. In this approach, the material-specific properties such as density, bulk modulus, etc., were simply changed from those for glass to those for ice. The second model was similarly originally developed for glass (Tsembelis 1998) but had a Tillotson equation of state and a Mohr–Coulomb strength model. Again, the only change made to the model was to replace parameters for properties of glass with those for ice. The third model used was that of McDonnell, Catling & Clegg (2001), which specifically attempted to model impact cratering in ice, again using a model originally developed for glass but subsequently adjusted by McDonnell et al. to reproduce observed craters in impacts on ice. Differences in the peak pressures predicted by the three different models were at most approximately 25 per cent, indicating good consistency between the models. At an impact speed of 4.9 km s^{-1} and ice target temperature of 250 K, the mean peak pressure from the three simulation models was found to be 49 ± 7 GPa. This compares to a value of 67 GPa predicted by using the late-stage effective energy approach. The two approaches to estimating peak energy are thus giving broadly similar results. For convenience, in the results given below, the peak pressures quoted are those given by the late-stage energy method.

3 RESULTS

A series of shots were carried out for projectiles doped with *Rhodococcus erythropolis* on to agar at mean speeds of (0.35 ± 0.03), (1.3 ± 0.2) and (5.4 ± 0.5) km s^{-1}. The results in terms of survival rates are given in Table 1 and plotted in Fig. 1. The survival rate falls with peak pressure and can be fitted by a power law (shown on Fig. 1), yielding

$$N/N_0 = (1.13 \pm 0.07) \times 10^{-3}\, x^{-(2.03 \pm 0.01)}, \qquad r = -1, \qquad (2)$$

where x represents peak pressure (GPa) and r is the regression coefficient of the fit.

Shots were also carried out at (4.9 ± 0.2) km s^{-1} for impacts of projectiles doped with *R. erythropolis* on to ice. Again survival was observed and the surviving fraction is given in Table 1.

The type of bacterium used was then changed to *Bacillis subtilis*. A set of shots was carried out at (5.4 ± 0.6) km s^{-1} using projectiles doped with late-stage growth cells of this type fired at agar plates. In addition, a set of shots using *B. subtilis* spores was also carried out at a mean speed of (5.4 ± 0.1) km s^{-1}, again impacting agar plates. In both cases survival was found as indicated by growth of identifiable colonies after culturing. The data (Table 1) appear to suggest that survival in impacts was slightly enhanced for the active cells compared to those in the spore state. This is a somewhat counter-intuitive result, as spores are usually considered as being hardier than active cells when stressed. However, as stated earlier, given the uncertainties in the method, the potential uncertainty in the survival fraction is of approximately 1–2 orders of magnitude. The two results for impacts of *B. subtilis* are well within one order of magnitude of each other, and should thus be considered similar.

The results for all the data for the different projectile–target combinations are shown on Fig. 2 (including the data from Fig. 1). A

Table 1. Results of impact experiments with *Rhodococcus erythropolis* and *Bacillis subtilis*.

Microbes	Target	Impact speed (km s^{-1})	Peak shock pressure (GPa)	Surviving fraction (N/N_0)
R. erythropolis	Agar	0.35 ± 0.03	3	1.5×10^{-4}
R. erythropolis	Agar	1.3 ± 0.2	12	7.6×10^{-6}
R. erythropolis	Agar	5.4 ± 0.5	78	8.8×10^{-8}
R. erythropolis	Ice	4.9 ± 0.2	67	3.8×10^{-6}
B. subtilis				
(active)	Agar	5.4 ± 0.6	78	3.9×10^{-5}
(spores)	Agar	5.4 ± 0.1	78	1.8×10^{-5}

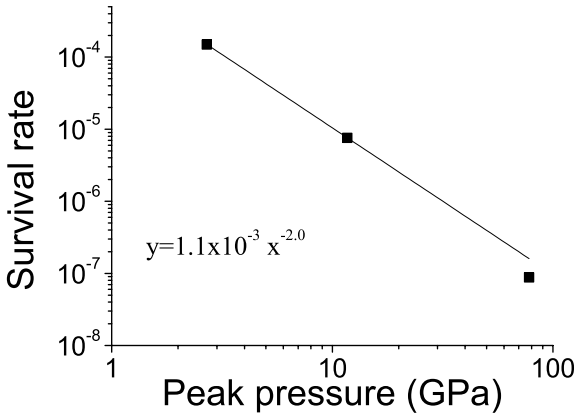

Figure 1. Survival rate for impacts of *Rhodococcus erythropolis* on agar targets.

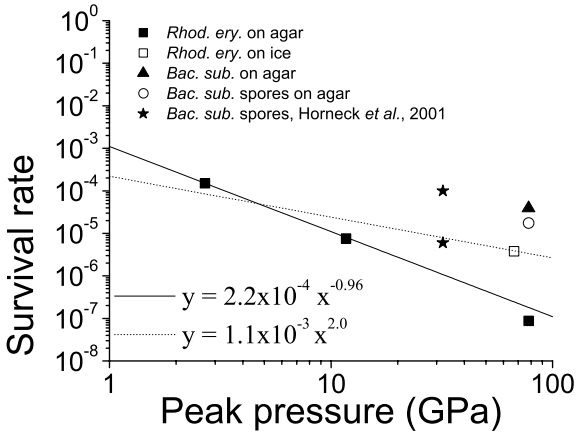

Figure 2. Survival rate for all experiments reported here and those from Horneck et al. (2001a). The fit to all data (except that of Horneck et al. 2001a) is shown as the dashed line. The fit to data from Fig. 1 is shown as the solid line.

fit to all the data obtained here is more problematic than before, because at high pressures the values of the survival fraction span several orders of magnitude with minimal changes in shock pressure. This means that the fit of a power law as to Fig. 1 would be dominated by the data at low shock pressures. A standard approach in such cases is to perform the fit to the data in log–log space, which makes more equal the contribution of each datum to the fit. Accordingly, carrying out a linear fit in log–log space and converting to the equivalent form in normal space gives

$$N/N_0 = (2.2) \times 10^{-4}\, x^{-0.96}, \qquad r = -0.53, \tag{3}$$

where x represents peak pressure (GPa) and r is the regression coefficient of the fit. The regression coefficient is low, and no uncertainties are given on the fit values, because given the procedure followed they can only be considered as being indicative of the general behaviour of the data. The fit result is shown as a dashed line on Fig. 2.

Also shown on Fig. 2 (star symbols) are the results from Horneck et al. (2001a). In their work, different runs of the flying plate experiment at one shock pressure produced survival rates for *B. subtilis* spores ranging from 6×10^{-6} to 10^{-4}. Hence the two values shown in Fig. 2 are the extreme values from their work. The range of values for survival of *B. subtilis* spores found by Horneck et al. are certainly very compatible with that found here at approximately twice the peak shock pressure, even though the method of delivering the shock was different (flying plate versus hypervelocity impact).

4 DISCUSSION

The results show that, although small, survival rates in hypervelocity impacts are finite. They appear to fall with increasing shock pressure, but even near 100 GPa they are still meaningful. Consider a Martian meteorite such as ALH84001: it has a mass of some 1.9 kg, a typical linear dimension of 10 cm and spent a lifetime in space of some 16 Myr. According to Clark (2001), whilst it is in space for 10 Myr, a rock of 10 cm radius (twice that of ALH84001) would, even at its centre, have received a radiation dose of order 65 Mrad, well above the limit for lethality for any organism known so far. This result is found for all currently known Martian meteorites. However, if the transit time were shorter (as it can be) or if the meteorite buried itself in a larger (icy) body in the EK belt as suggested by Wallis & Wickramasinghe (2004), then the dose would be lower. In such a case it is the survival rates found here under high shock pressures that become important for determining whether survival is possible.

For a single species *Bacillis subtilis* there is only a minimal difference between survival rates when subject to extreme shock pressures for spores as compared to active growth cells. By contrast, there was a significant difference for survival rates (at least two orders of magnitude) at equal shock pressure (78 GPa) for *Rhodococcus erythropolis* versus *B. subtilis*. Both are rod-shaped organisms of the order of 1–2 μm in length and both are, in different ways, considered hardy organisms. Here on Earth, *R. erythropolis*, for example, is known to exist in ocean-floor sediments under 5 km of water, indicating a good resistance to high static pressures. By contrast, *B. subtilis* is considered particularly resistant to heating and when stressed readily forms an endospore to aid survival. It is difficult to generalize based on just two observations, but the obvious conclusion is that resistance to heating may be a better indicator of survival against short-duration extreme pressures (which involve a degree of heating of the organism) than is good survival against high static pressures. In addition, for *R. erythropolis* survival rates at similar peak pressures (78 GPa) were found for impacts on two types of target material (agar and ice). For the impacts on ice, the survival rate was some 10 times greater than for impacts on agar. However, this is of similar magnitude to the experimental uncertainties in determining the survival rates. From this sample of two target types and the lack of a significantly clear difference in the results, it is hard to say if any property of the target other than the peak shock pressure generated has influenced the survival rate.

As well as transfer between planets, natural transfer between the satellites of a single planet may be possible. In the case of Jupiter, for example, there are a large number of small satellites surrounding the planet. Not all are atmosphereless rocks. Some are icy, and it has been surmised that there may be an ocean beneath the ice-covered surface of Europa for example. In this case, if some ejecta from one satellite reached Europa (or a body from interplanetary space hit Europa), the material could penetrate the ice surface and end up in the Europan ocean. In the present work it has been shown that microbial life can survive a hypervelocity impact with an icy surface; therefore, if life is ever found on Europa (e.g. as suggested by Chyba & Phillips 2002), it may not be native, but have arrived via an impact event. Chyba & Phillips (2002) had ruled out this possibility on the grounds that there was no significant atmosphere on Europa to slow small particles before they hit the icy surface. This, however, is now shown not to be critical. In addition, previously, Burchell et al. (2003) showed that, if frozen in an icy body, viable microbial life can be carried off the icy surface in the ejecta after a hypervelocity impact. Provided it is not sterilized in flight (e.g. by radiation), such ejecta could spread around the Jovian system and impact the other Jovian satellites with survival rates that depend on the shock pressures involved. Thus Europa could be seeding the other satellites of Jupiter with life.

Indeed, it is potentially possible for a body to reseed itself with life from space. It has been noted by Wells, Armstrong & Gonzalez (2003) that an impact on the early Earth would have ejected material into bound orbits as well as into interplanetary space. Some of this orbiting material would have eventually recollided with the Earth. Thus one of the putative planetary sterilizing giant impacts in the epoch of mass bombardment may have killed all life on Earth and rendered the planet uninhabitable for a time, but ejecta from the same impact may subsequently have reseeded the planet with microbial life. Again, the present work suggests that the severe shock pressures involved in such an event need not be sterilizing.

5 CONCLUSIONS

It is now apparent that the survival rates for microbial life experiencing short-duration peak shock pressures in the GPa regime is small but determinable. This has been demonstrated for two types of bacteria and also for both spores and late-stage growth cells. The impacts studied here involved speeds in the hypervelocity regime, and extreme accelerations and 'jerks' that exceed those estimated to be involved in launching material from or impacting a typical planetary surface (e.g. Mars to Earth). The survival rates have been parametrized throughout the critical 1–100 GPa range, and even at the highest shock pressures are in the range 10^{-7} to 10^{-5}. To set this in context, it is commonly given that on Earth a gram of soil contains some 10^9 microbes and in a rock this number may be less by a factor of 10 to 100. Transfer of even a small quantity of material (even a few grams) can thus potentially carry viable microorganisms. In addition, the pressure range examined here covers the shock pressures predicted for impacts on Earth from space [including reseeding of life on Earth by terrestrial ejecta after a giant impact (e.g. see Wells et al. 2003)] and also for migration of life between other Solar system bodies [e.g. inside the Jovian system of satellites (Burchell et al. 2003)] and for impacts of rocky ejecta into larger bodies such as icy members of the EK belt [which then help to preserve the microbial load by increased shielding, etc. (see Wallis & Wickramasinghe 2004)], which may subsequently exit the Solar system. There are thus a wide range of impact processes (with extreme shock pressures) relevant to the idea of panspermia where the survival rates can now be estimated with a reasonable degree of confidence.

ACKNOWLEDGMENTS

We acknowledge support from the Particle Physics and Astronomy Research Council (UK), the University of Kent and the University of Kent Alumni. We thank Mr M. Cole for firing of the light gas gun. We thank P. Brandão for assistance with preparing the samples. We thank W. Napier (referee) for useful comments on the manuscript.

REFERENCES

Burchell M. J., Cole M. J., McDonnell J. A. M., Zarnecki J. C., 1999, Meas. Sci. Technol., 10, 41
Burchell M. J., Mann J., Bunch A. W., Brandão P. F. B., 2001, Icarus, 154, 545
Burchell M. J., Galloway J. A., Bunch A. W., Brandão P. F. B., 2003, Origins Life Evol. Biosphere, 33, 53
Chyba C. F., Phillips C. B., 2002, Origins Life Evol. Biosphere, 32, 47
Clark B. C., 2001, Origins Life Evol. Biosphere, 31, 185
Clark B. C. et al., 1999, Origins Life Evol. Biosphere, 29, 521
Gladman B., 1997, Icarus 130, 228
Gladman B. J., Burns J. A., Duncan M., Lee P., Levison H. F., 1996, Sci, 274, 161
Hayhurst C. J., Clegg R. A., 1997, Int. J. Impact Eng., 20, 337
Horneck G., Stöffler D., Eschweiler U., Hornemann U., 2001a, Icarus, 149, 285
Horneck G., et al., 2001b, Origins Life Evol. Biosphere, 31, 527
Lundberg P., Westerling L., Lundberg B., 1996, Int. J. Impact Eng., 18, 403
McDonnell J. A. M., Catling D. J., Clegg R. A., 2001, Adv. Space Res., 28(10), 1551
McSween H. Y., 1985, Rev. Geophys., 23, 391
Mastrapa R. M. E., Glanzberg H., Head J. N., Melosh H. J., Nicholson W. L., 2001, Earth Planet. Sci. Lett., 189, 1
Melosh H. J., 1988, Nat, 332, 687
Melosh H. J., 1989, Impact Cratering: A Geologic Process, Oxford Univ. Press, Oxford
Melosh H. J., 2003, Astrobiology, 3, 207
Mileikowski C., et al., 2000, Icarus, 145, 391
Mizutani H., Takagi Y., Kawakami S., 1990, Icarus, 87, 307
Napier W. M., 2004, MNRAS, 348, 46
Pedersen K., 2000, FEMS Microbiol. Lett., 185, 9
Soina V. S., Vorobiova E. A., Zvyagintsev D. G., Gilichinsky D. A., 1995, Adv. Space Res., 15, 237
Taylor E. A., Tsembelis K., Hayhurst C. J., Kay L., Burchell M. J., 1999, Int. J. Impact Eng., 23, 859
Tsembelis K., 1998, PhD thesis, Univ. Kent
Vreeland D. H., Rosenzweig W. D., Powers D. W., 2000, Nat, 407, 897
Wallis M. K., Wickramasinghe N. C., 2004, MNRAS, 348, 52
Wells L. E., Armstrong J. C., Gonzalez G., 2003, Icarus, 162, 38

This paper has been typeset from a TEX/LATEX file prepared by the author.