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Hypervelocity Impact Experiments in the Laboratory Relating to Lunar Astrobiology

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Abstract The results of a set of laboratory impact experiments (speeds in the range 1–5 km s^{-1}) are reviewed. They are discussed in the context of terrestrial impact ejecta impacting the Moon and hence lunar astrobiology through using the Moon to learn about the history of life on Earth. A review of recent results indicates that survival of quite complex organic molecules can be expected in terrestrial meteorites impacting the lunar surface, but they may have undergone selective thermal processing both during ejection from the Earth and during lunar impact. Depending on the conditions of the lunar impact (speed, angle of impact etc.) the shock pressures generated can cause significant but not complete sterilisation of any microbial load on a meteorite (e.g. at a few GPa 1–0.1% of the microbial load can survive, but at 20 GPa this falls to typically 0.01–0.001%). For more sophisticated biological products such as seeds (trapped in rocks) the lunar impact speeds generate shock pressures that disrupt the seeds (experiments show this occurs at approximately 1 GPa or semi-equivalently 1 km s^{-1}). Overall, the delivery of terrestrial material of astrobiological interest to the Moon is supported by these experiments, although its long term survival on the Moon is a separate issue not discussed here.

Keywords Lunar · Impact · Astrobiology · Hypervelocity

1 Introduction

The presence of the Moon (a relatively large satellite) in close proximity to the Earth has long been held to be significant with regard to the study of astrobiology. A lot of the earlier

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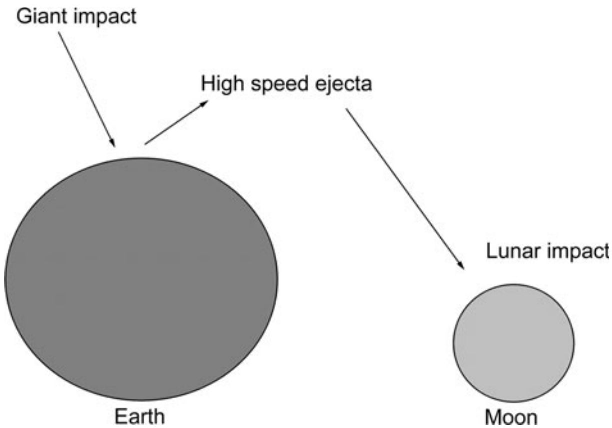

Fig. 1 Schematic diagram showing sequence of events giving rise to terrestrial meteorites on the Moon

work considers its astrobiological role to lie in encouraging or supporting an environment on the Earth itself which was conducive to the emergence or sustaining of life (e.g. Ward and Brownlee 2000). However, it has also been suggested that the Moon can play another role, that of a repository for the history of life on the Earth. This idea is based on the ejection of terrestrial meteorites into space after high speed giant impacts on the Earth (Fig. 1). Some of these will be intercepted by the Moon and could potentially be a source of information about the Earth's past (Armstrong et al. 2002; Gutiérrez 2002; see also the contribution by J. Armstrong elsewhere in this volume). The key point is that as an atmosphereless, more stable body than the Earth, materials gathered on the lunar surface have a longer potential retention time than those on the more active Earth.

Such a scheme relies on several key points, amongst these is that the terrestrial meteorite arrives and is captured with its contents relatively unaltered, and that any subsequent alteration is minor. The latter point is not trivial. Whilst geologically more stable over longer periods than the Earth, the lack of an appreciable lunar atmosphere means for example that even micrometre sized cosmic dust impacts the lunar surface, and over geological time this will significantly erode material exposed at the surface (e.g. Horz et al. 1991; Lucey et al. 2006). On the other hand, burial of terrestrial material preserved in ancient regoliths buried by later lava flows may provide a means of preserving it from meteoritic bombardment (e.g. Crawford 2006; Fagents et al. 2010). However, there still remains the issue of whether the terrestrial meteorites will survive their impact on the Moon in a state which contains a record of their origin which addresses the history of life on Earth in a meaningful way. Note that this is not Panspermia, i.e. the natural migration of life through space to a new habitat (see Burchell 2004 for a recent review of the subject) as it does not require any life to be active, it can already be a fossil, and neither does it require the life to remain in a viable state on the Moon. All that is required is for a fossil, or some other remnant of life or biological process, to be trapped within a terrestrial meteorite and to survive impact with the lunar surface.

One way to explore the possibility of a record of terrestrial life being found on the Moon is via simulation. Two types of simulation are possible, computational and experimental. In a high speed impact, a material experiences quite severe shock pressures, typically many GPa. For terrestrial rocks impacting the Moon, the typical impact speed will be of order a few km s^{-1} (for example see J. Armstrong, this volume). The resulting shock pressures have been modelled by, amongst others, Crawford et al. (2008) who find that the resulting shocks reach 10 s of GPa, but that these peak values are limited to the leading region of the impactor. The mean value in the leading half of an impacting cube was found by Crawford et al. (2008) to be ~20 GPa for vertical impacts on the Moon at 5 km s^{-1}. However, the mean peak shock pressure in the trailing half of cube shaped impactors in these simulations was lower at only ~10 GPa. These are worst case figures, most impacts of terrestrial meteorites on the Moon will be at slower speeds and non-normal incidence, and hence lower shock pressures. Whilst these are still severe regimes for a material, and fracturing and fragmentation will occur, they are insufficient to lead to significant melting of the impactor. Thus, whilst it may be broken apart and twisted etc., the impactor constituent fabric can reasonably be expected to survive. Searching for terrestrial meteorites on the Moon is thus not a priori a pointless exercise.

However, as a result of the shock pressures and accompanying high shock temperatures, the fabric of any such impactor may still undergo some heat induced alteration. Any organic compounds present may be particularly susceptible to damage. It is thus not a priori clear if, even if found, such terrestrial meteorites will be capable of providing information about the Earth's biological history. It is this question which we discuss in more detail here by considering laboratory impact experiments.

2 Laboratory Impact Simulations

The method used in the experiments considered here to reproduce high speed impacts, is via use of a two stage light gas gun. The gun used was at the University of Kent (Burchell et al. 1999) and can achieve speeds in excess of 8 km s^{-1}, however in the work here lower speeds were used as they are more relevant to the lunar impacts being considered (see below).

General details of the method are as follows: The desired speed was selected pre-shot by varying the amount of gun powder, the type of light gas used etc. (see Burchell et al. 1999, for details of how this is achieved with the Kent gun). The speed of the projectile was measured in flight in each shot, to typically better than 1%. The projectiles were mm sized and launched in discardable sabots. The targets were in a vacuum chamber (0.1–0.5 mbar typically) and were removed after each shot to be examined. After each shot fragments or traces of the projectiles were removed from the target (typically by sieving of granular targets by hand or by passing the water from water targets through filter paper) and then subject to a range of standard chemical analysis techniques including Raman spectroscopy, UV–VIS spectroscopy and GC–MS spectroscopy, in order of increasing sensitivity to the presence of trace amounts of materials. In some cases material was cultured on agar broths (these were the shot programmes that involved bacteria, see Burchell et al. 2004 for details of how samples were cultured after impact). Peak shock pressures were calculated using the Planar Impact Approximation—PIA (see Melosh 1989 for a discussion of the method) and a linear shock wave speed relation. In Parnell et al. (2010) the peak shock pressures found from the PIA were compared to those calculated using hydrocode simulations and found to be compatible with those generated in material close to the impact surface. However, as pointed out by other authors (e.g. Crawford et al. 2008; Armstrong, this volume), these peak values are not uniform throughout finite-sized projectiles and the trailing half of such an impactor will experience significantly lower shock pressures.

In recent years a whole series of impact experiments have been conducted at the University of Kent relevant to lunar astrobiology. Each has been reported separately, and the results are reviewed together here for the first time. The main details of the experiments are listed in Table 1. The speeds are typically 1–5 km s^{-1}. This covers the regime likely to

Table 1 Details of the shot programmes

Programme	Projectile type and size (mm)	Target type	Impact Speed (km s^{-1})	Impact angle from the surface (degrees)	Estimated Peak Shock Pressure (GPA)	Reference
1	Stainless steel spheres, of dia. 2 mm	Siltstone	5.39	90	~90	Parnell et al. (2010)
2	Stainless steel spheres, 1 and 1.5 mm dia.	Ice doped with complex organic compounds	4.9	90	~29[a]	Bowden et al. (2009)
3	Stainless steel spheres, 1 mm dia.	Ice containing frozen microbes	5	90	~30[a]	Burchell et al. (2003)
4	Siltstone spheres 1.25 and 2.67 mm.	Water	~5	90	~27[b]	Milner et al. (2006)
5	Siltstone cubes, 1.5 mm each side	Sand, water	2, 5 respectively	90	~6, ~27 respectively[b]	Bowden et al. (2008)
6	Siltstone cubes, 1.5 mm each side	Sand, water	2, 5	45	~4, ~15	Parnell et al. (2010)
7	Porous ceramic infused with microbes	Agar plates	5	90	~75[c]	Burchell et al. (2001)
8	Porous ceramic infused with microbes	Agar plates, ice	1–5.4	90	3–78	Burchell et al. (2004)
9	Seeds (tobacco, alfalfa, cress) mounted in 1.5 mm epoxy resin cubes	Water	1–3	45	0.24–2.4	Jerling et al. (2008)
10	Seeds (Arabidopsis, mint) mounted in 1.5 mm epoxy resin cubes	Water	1–3	30, 60, 90	0.5–1	LeVoci et al. (2009)

[a] Originally not reported, so the given value was calculated using the planar impact approximation with c and S values in the linear wave speed equation of 1.58 and 3.8 km s^{-1} and 1.56 and 1.28 km s^{-1} for stainless steel and water ice, respectively

[b] Originally not reported so the given values are taken from that for similar impacts reported in Parnell et al. (2010)

[c] Originally not reported so the given value is taken from that for similar impacts reported in Burchell et al. (2004)

be encompass most terrestrial meteorite impacts on the Moon: Armstrong et al. (2002), estimated 5 km s^{-1} as the maximum likely speed, and Crawford et al. (2008) pointed to 2.3 km s^{-1} as a suitable lower limit given the minimum lunar in-fall speed for an object coming direct from the Earth. In addition, the impact angle for terrestrial meteorites striking the Moon will not generally be vertical. Normally in space it is taken that a random distribution of impact directions results in a mean impact angle of 45° on the target surface (see Pierazzo and Melosh 2000 for a discussion). However, in the case here this is complicated by the presence of the Earth as the point of origin leading to a wide range of possible angles, including a component at shallow angles of incidence relative to the lunar surface (see contribution by J. Armstrong elsewhere in this volume). One of the major effects of this range of angles of incidence is to change the peak shock pressures in an impact at a given speed. So in Table 1, at a given speed it is the vertical impacts which set the maximum peak shock pressure at that speed.

In these simulations, the target and projectile material have been varied. The projectiles covered a range of materials. In some cases it was the projectile material itself that was the sample of interest, in other cases it was simply a carrier or just used to provide a high speed impact on a given target. Siltstone was used in several experiments. This was an organic rich stone, a mixture of silt, quartz and organic matter (1.4%) arising from deposition in a lake environment (see Parnell et al. 2010 for a fuller description). This has been well characterised previously and is rich in organic biomarkers. In other cases, porous projectiles were infused with solutions of microbes (*Rhodococcus erythropolis* and *Bacillus subtilis* were used) and looking for survival of these after impacts has obvious astrobiological significance. Finally, "artificial rocks" were made for Programmes 9 and 10; these were cubes of epoxy resin in which seeds were embedded.

The targets were equally varied. In some cases water was used. This is not to suggest that oceans or lakes were ever present on the Moon, but was for ease of extraction from the target of the surviving projectile material after a shot. The resulting shock pressures are given in Table 1 and are comparable to those relevant to the lunar impacts. Other programmes used sand, siltstone, ice and even agar broth as the target media. Again it was the impact generated peak shock pressure that is the critical parameter of interest. In Shot Programme 2 the target was ice doped with organic biomarkers—these were complex compounds (anthracene, stearic acid and β,β-carotene) with differing degrees of complexity and different thermal degradation temperatures, for example. And in Shot Programme 3 the ice target was doped with microbes (*Rhodococcus erythropolis*).

3 Discussion

As stated, each of the individual programmes in Table 1 has already been reported. Here we link the outcomes of the individual programmes together and discuss them in terms of their implications for lunar astrobiology.

3.1 Launch into Space

A mechanism is required in order for the terrestrial meteorites to be launched into space. It was proposed by Melosh (1988) that giant impacts on a planetary body could result in a relatively low shock pressure launch of impact ejecta into interplanetary space. As discussed by Mastrapa et al. (2001) for example, it is not just the peak shock pressure during launch that is critical, but also the "jerk", i.e., the acceleration divided by the time duration. These ideas were originally developed with regard to explaining Martian meteorites but apply equally well to the Earth, albeit with slightly different conditions (i.e. the typical infall speeds and also the escape velocities will differ). On Earth, typically giant impactors from space arrive at a mean speed of some 20 km s^{-1}, and the escape velocity is 11.1 km s^{-1}.

Programmes 1, 2 and 3 (listed in Table 1) test some of the conditions necessary for the successful launch of astrobiologically interesting material from the Earth to the Moon. The impact speeds are ~5 km s^{-1}; slower than for the Earth but sufficient to establish typical behaviour (note gas guns cannot achieve the necessary 20 km s^{-1} for giant terrestrial impacts). In each of these programmes impact ejecta was collected and analysed. The results were positive. Programme 1 (Parnell et al. 2010) tested if ejecta could still contain fossilised biomarkers. The results were clearly positive, although some alteration occurred of some biomarkers, indicating a degree of processing is likely during launch. Programme 2 (Bowden et al. 2009) also produced positive results: some of the compounds were found in the ejecta after impact, and again there was evidence of processing during launch. In this case the highest angle ejecta were most processed (with the most labile compound, β,β-carotene, only found in the lowest angles of ejection). Finally, Programme 3 (Burchell et al. 2003) yielded some of the most startling results; even the highest angle ejecta contained cultivable micro-organisms.

Taken as a whole, the results indicate that there is no a priori reason to suppose a whole range of biologically relevant materials cannot be launched at high speed in impact ejecta. There is however processing during this launch process—with higher angle ejecta (and hence probably the higher speed ejecta) undergoing the most processing. As indicated, perhaps the most startling result was that cultivable microbes could survive launch on impact ejecta fragments. This result has been confirmed by Fajardo-Cavazos et al. (2009), who reported on ejecta from impacts on rocks at 5 km s^{-1}. In their experiments the rock target surface had been painted with a solution of bacteria. They collected high angle ejecta after impact and also found survival—confirming that high speed impact ejecta can indeed carry viable micro-organisms.

3.2 Alteration in Space

Although not part of the Kent programme of work, there is a wide range of literature on survival of astrobiologically interesting materials in space. Many experiments have been flown in Low Earth Orbit (such as on the exterior of space stations such as the International Space Station or in purpose built modules flown on satellites with short flights lasing several weeks). It has been shown for example that bacteria and spores require a minimal covering to survive (Horneck et al. 2001a), and that there is 100% survival of lichens exposed in space, even after several weeks direct exposure (Sancho et al. 2007). And unlike transfers between planets, the transfer times for terrestrial meteorites to the Moon can be short. So transfer through space can reasonably be taken as possible for the astrobiologically interesting content of terrestrial meteorites.

3.3 Lunar Impact

In Table 1, Programmes 4–10 explore different aspects of survival of materials undergoing high speed impacts and thus experiencing peak shock pressures relevant to the discussion here. In Programme 4 (Milner et al. 2006), the effects of impacts with peak pressures of ~27 GPa (i.e. at the high end of those suggested as relevant by Crawford et al. 2008) on siltstone projectiles were examined. The mm sized projectiles broke apart during the impacts and the largest fragments had about 20% of the original projectile diameter. When examined under a SEM, the fragments were cracked with fractures a few micrometers across and tens of micrometres long. The analysis of the organic content was limited to Raman spectroscopy, but this showed the presence in the recovered fragments of both the broad carbon D and G bands and narrow carbonate bands.

In Programme 5 (Bowden et al. 2008), similar experiments to Programme 4 were carried out, with a more detailed investigation of the organic contents of the fragments recovered after the impacts using GC–MS. Several bio-markers were found to have survived the impact process, but by looking at their ratios (a standard test of thermal maturity) compared to those in original control samples, it was shown that a pyrolytic (thermal) signature was present after the impacts. Thus any potential terrestrial meteorites found on the Moon, can similarly be expected to have undergone some impact induced thermal processing.

Having established that some impact induced alteration was occurring, a much more detailed round of impact experiments using siltstone projectiles was carried out (Programme 6; Parnell et al. 2010). Here impact experiments using siltstone confirmed the previous results and quantified them for a wide range of biomarkers showing survival (and processing) of n-alkynes, hopanes, preganes, steranes, anthracene, phenanthrene and methylanthrene. Study of thermally sensitive ratios again indicates elevated temperatures during impact. The results also indicated that as well as loss of some compounds by thermal degradation, in some cases new synthesis of organic molecules was also taking place.

Programmes 7 and 8 are relevant to understanding what would happen to any microbial load on a terrestrial rock impacting the Moon. The peak shock pressures in these experiments significantly exceed those involved in the lunar impacts. Yet survival of cultivable microbes occurs, albeit at a level that decreases as shock pressure increases (see Burchell et al. 2004, where the survival rate falls off exponentially as shock pressure increases from a few GPa upwards). This is confirmed by the results of Horneck et al. (2001b) who reported on survival of microbes in flyer plate experiments at 38 GPa, and later by Horneck et al. (2008) who repeated the earlier flyer plate experiments under varying conditions yielding a range of shock pressures. Just like Burchell et al. (2004), Horneck et al. found an exponential decrease in survival as shock pressure increased. The reason for this is discussed in Burchell (2007), where a model was proposed that for shock pressures below a few GPa there is only moderate lethality as shock pressure increases, but that above a threshold at a few GPa survival falls off rapidly as cell walls start to rupture (falling from say 10^{-2} at the threshold to 10^{-6} at 60 or 70 GPa). Burchell (2007) proposed that this threshold depends on both the particular micro-organism and whether it is in an active growth or spore state etc., and can lie between 5 and 10 GPa (this idealised survival curve is shown in Fig. 2). This is of particular interest for lunar astrobiology as discussed here, as the threshold of a few GPa is just below the peak shock pressures involved in the lunar impacts. So for example, survival rates relevant to lunar impacts would be typically 1–0.1% at a few GPa, falling to 0.01–0.001% at 20 GPa; these rates should be considered in light of the typical 10^9 organisms per g of soil on Earth.

These results for survival of microbial life at GPa shock pressures were a surprise. There was work in the food technology sector (e.g. Loske et al. 1999; Zuckerman et al. 2002; Abe et al. 2007; Alvarez et al. 2008; also see Hazell et al. 2010 for a recent review) that seemed to show that shocks in the range 10 s to 100 s MPa gave complete sterilisation. However, Hazell et al. point out that the non-impact methods used in such work to

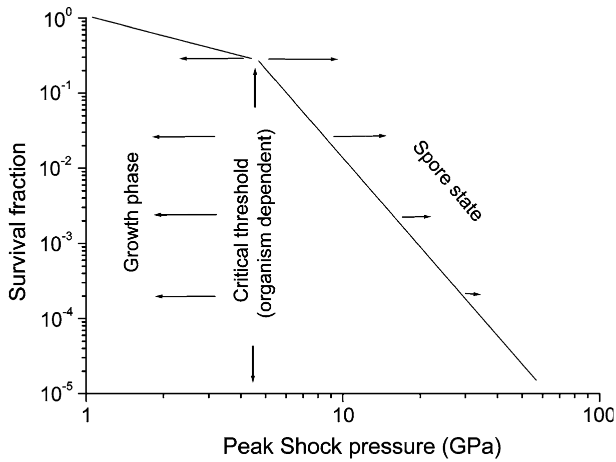

Fig. 2 Hypothesized survival curve vs. shock pressure for micro-organisms. The critical threshold is organism dependent. However, even for a particular organism the threshold depends on its growth state (active vs. spore state for example). (Adapted from Fig. 4 in Burchell 2007)

generate shocks often involved multiple shocks, generation of accompanying UV emission, cavitation etc. Accordingly Hazell et al. (2010) carried out flyer plate experiments with shock pressures of ~1 GPa, designing their experiments so that they could introduce cavitation (not normally featured in such work). They found little effect without cavitation, but that survival started to be reduced in yeast when cavitation was introduced. The suggestion they make is that the decrease in survival at relatively low shock pressures in other work may well be related to other aspects of the method used to generate the shock pressures.

Programmes 9 and 10, test the impact survival of more sophisticated biological constructs - seeds. The seeds were embedded in epoxy blocks and fired in the light gas gun. An analogy would be with seeds trapped in crevices in rocks on Earth which are then launched into space. In programme 9, at the lowest pressures (0.24 GPa) seeds were recovered seemingly intact, but did not germinate. At higher pressures the seeds increasingly fragmented. Interestingly, in Programme 10, two Mint seeds were recovered intact from impacts at 1 GPa and one of them germinated (but then failed to grow fully). This is at the lower end of the peak shock pressure in lunar impacts of terrestrial meteorites. Thus survival of intact cultivatable seeds in such meteorites is unlikely, but significant fragments of the original seeds should survive.

Taken together these results indicate that an impact of a terrestrial meteorite on the Moon does not necessarily destroy all the astrobiologically significant content. However, alteration may well take place either as a result of a thermal history during the impact, or, for from damage due to the mechanical shock itself.

4 Conclusion

The combined set of experiments described here provide a consistent set of results addressing some of the issues relating to study of terrestrial meteorites potentially stored on the Moon. Launch into space does not necessarily remove the astrobiological signature, but it may process it in a way that biases which materials survive. Admittedly this has been shown for a limited set of conditions, but the principle is established. Indeed, one could argue that simply successfully firing the relevant materials in a light gas gun shows that it is possible to accelerate them to high speed with a severe shock. The subsequent impact on the lunar surface involves peak shock pressures which are in the range studied. Again, survival of some materials was found, albeit it with evidence of thermal alteration. Thus, whilst lunar meteorites may (at least initially after impact) contain a history of their origin, this may have been biased or altered by the capture process. As might be expected, the more complex the materials being studied (organic molecules to microbes to plant seeds) the more prone the material was to damage. However, for the lowest imaginable shock pressures involved in lunar impacts it is not ruled out that substantial fragments of seeds (or even intact seeds) might survive.

There are still some gaps in the programme of work. One is to fire projectiles doped with the same suite of complex organic compounds used in Programme 2 (anthracene, stearic acid and β,β-carotene) at targets to see if these compounds survive impact. A second area is that in some programmes (e.g. 5 and 6) there was evidence that organic biomarkers in the siltstone projectiles were being altered during impact. This does not necessarily imply destruction and Parnell et al. (2010) comment that some further synthesis seems to be taking place. This should be investigated further. Indeed, there is need for a whole separate programme to look at synthesis of complex organic compounds during impact. Some work has already been done elsewhere on such synthesis, for example Nna-Mvondo et al. (2008) have shown (using a pulsed laser to simulate impacts) that organic synthesis occurs in ice targets doped with simple compounds. Similar work should also be carried out using impacts in light gas guns.

Finally, we note that the results presented here do not consider the subsequent history of a terrestrial meteorite on the lunar surface, or indeed how these might be found. The latter aspect has been considered in other work (e.g. Gutiérrez 2002; Crawford et al. 2008; Armstrong, this volume). What this work has done is demonstrate clearly that organic material trapped within terrestrial meteorites is very likely to survive impact with the lunar surface, and thus could become an important objective for future lunar exploration activities.

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