PLANETARY INTERCHANGE OF BIOACTIVE MATERIAL: PROBABILITY FACTORS AND IMPLICATIONS

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Abstract. It is now well-accepted that both lunar and martian materials are represented in the meteorite collections. Early suggestions that viable organisms might survive natural transport between planets have not yet been thoroughly examined. The concept of Planetary Interchange of Bioactive Material (PIBM) is potentially relevant to the conditions under which life originated. PIBM has been also invoked to infer that the potential danger to Earth from martian materials is non-existent, an inference with, however, many pitfalls. Numerous impediments to efficient transfer of viable organisms exist. In this work, the lethality of space radiation during long transients and the biasing of launched objects toward materials unlikely to host abundant organisms are examined and shown to reduce the likelihood of successful transfer by orders of magnitude. It is also shown that martian meteorites studied to date assuredly have been subjected to sterilizing levels of ionizing radiation in space. PIBM considerations apply to both the solar system locale(s) of the origin of life and to the applicability of planetary protection protocols to preserve the biospheres of planetary bodies, including our own.

Keywords: astrobiology, impacts, interplanetary, Mars, martian meteorites, panspermia, radiation, survival, transport

1. Introduction

Successful transfer of viable organisms between terrestrial planets within our solar system has been recognized as possible, in principle (Horneck and Bueckner, 1985; Clark, 1985; Melosh, 1988). The prospect that life originates in the cosmos and is then imported to Earth and the other planets was widely speculated in the 19th century, a concept that was highly championed and termed ‘panspermia’ in 1908 by Svante Arrhenius. To counteract various objections, including the argument that microbes would be inactivated by the space environment before they could make a chance encounter with Earth, it has been suggested that panspermia has been ‘directed’ by other intelligent organisms by purposely sending protected packages of special microbes on interstellar flights (e.g., Crick, 1981). Appealing to a cosmic origin beyond our reach, such theories have been often considered inconsequential since they do not illuminate the origin of life in any useful way and furthermore refer to events that do not seem susceptible to investigation.

With the increasing indications of the likelihood of an early environment conducive to life on Mars, there is renewed interest in the transport scenario. It has

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even been suggested (Gladman *et al.*, 1996) that planetary protection protocols to prevent inadvertent biotic transfers by exploration spacecraft may be unwarranted because of natural transfer events. However, many barriers render difficult the successful transfer of biologically-active material. In this article, the overall scenario is considered and certain particularly important aspects are examined in some detail.

Transport of viable organisms in the two directions, Mars-to-Earth and vice-versa, are quantitatively different in likelihood because of the heliocentric geometries, sizes of planets, and other factors. This non-equivalence of the probabilities of transport in the two directions, in space and time, influences both the ‘origins’ and ‘protection’ issues. Quantitatively-based constraints on the extent to which PIBM may have played a significant role in transporting viable organisms between Venus–Earth–Mars, both in the early history and the current epoch, are needed to rationally evaluate the likelihood of its importance in the history of life in our solar system.

2. Stochastic Nature of the Problem

For a successful transfer to occur, there are a number of barriers which must be overcome (Clark, 1985). Briefly, an impacting body of sufficient size and velocity (as well as proper entry angle) must excavate a planetary body at a location where living organisms are present. Material containing the organisms must be ejected into space with kinetic energy which exceeds the escape velocity for that body. The organism must survive the launch insults, and then must survive the additional insults in space during travel to the body to which it is ultimately transported. It must survive entry through any atmosphere, as well as the transient thermal and pressure environments during impact onto the solid or liquid surface. Once landed, the organism must be released, assuming it is occluded within the meteoroid, and survive the various challenges of the environment, such as toxic chemistry and possible biological predators and competitors.

An outline of this formulation is as follows:

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

where $\mathbf{P_{AB}}$ is the probability of a successful transplant to planet B of viable organisms due to any given hypervelocity impact onto planet A, as product of the following probabilities:

$\mathbf{P_{biz}}$ = probability that the impactor is into a biologically inhabited zone;

$\mathbf{P_{ee}}$ = probability of ejection onto an escape trajectory;

$\mathbf{P_{sl}}$ = probability that an organism survives the launch (impact temperature, pressure; ejection erosion);

$\mathbf{P_{ss}}$ = probability of survival in space (radiation, desiccation, thermal inactivation);
$\mathbf{P_{se}}$ = probability of surviving entry through the target atmosphere;
$\mathbf{P_{si}}$ = probability of surviving impact onto the target surface;
$\mathbf{P_{rel}}$ = probability of release (for entombed organisms);
$\mathbf{P_{st}}$ = probability that the environment is non-toxic (appropriate pH, Eh, osmolarity);
$\mathbf{P_{sp}}$ = probability of surviving predators in the target biosphere;
$\mathbf{P_{efg}}$ = probability of reaching an environment favorable to growth;
$\mathbf{P_{sc}}$ = probability of successfully competing with indigenous organisms in the environment.

Various probability levels can be assigned to these eleven factors, several of which are one or more orders-of-magnitude less than 1.0. The low joint probability of a successful transfer must be balanced against the large number of impacts which have occurred on every planet since their formation and transition to some state, however short-lived, providing a suitable abode for living organisms.

3. The Physical Evidence: The Martian Meteorites

Among the 20 000 or so rocks recognized as meteorites, more than a dozen martian meteorites have been identified. All are highly competent, well-crystallized igneous rocks, with evidence of some depth of origin (several meters) for most (McSween, 1994). Some contain minor veining, including chemical precipitates. From those for which radiometric ages have been determined, it appears that there may be three separate families of contemporary meteorites from Mars, presumably due to three separate impacts onto Mars. The space transfer times of these three groups are 2.6, 12 and 15 Myr (e.g., see Warren, 1994 or Gladman, 1997), based upon cosmic ray exposure measurements. An exception is the shergottite EETA 79001 which exhibits an exposure age of only 0.6 Myr, possibly due to breakup in space (compared to other shergottites which exhibit the 2.6 Myr exposure age).

The physical sizes of these transported objects is important for assessing the survivability of embedded organisms because of radiation shielding considerations and impact dynamics. In Figures 1 and 2, I plot the cumulative size distributions of these few samples of martian meteoroids, on two types of scales. In Figure 1, in consonance with the approach of Golombek and Rapp (1997) which fit rock sizes at the Viking landing sites on Mars to cumulative size distribution curves expressed as exponentials with respect to diameter, the martian meteorite data is suitably fit by the parameters of $s = 7.8$ and $L = 14$, given the equation:

$$N(> D) = L * \exp(-s * D), \tag{2}$$

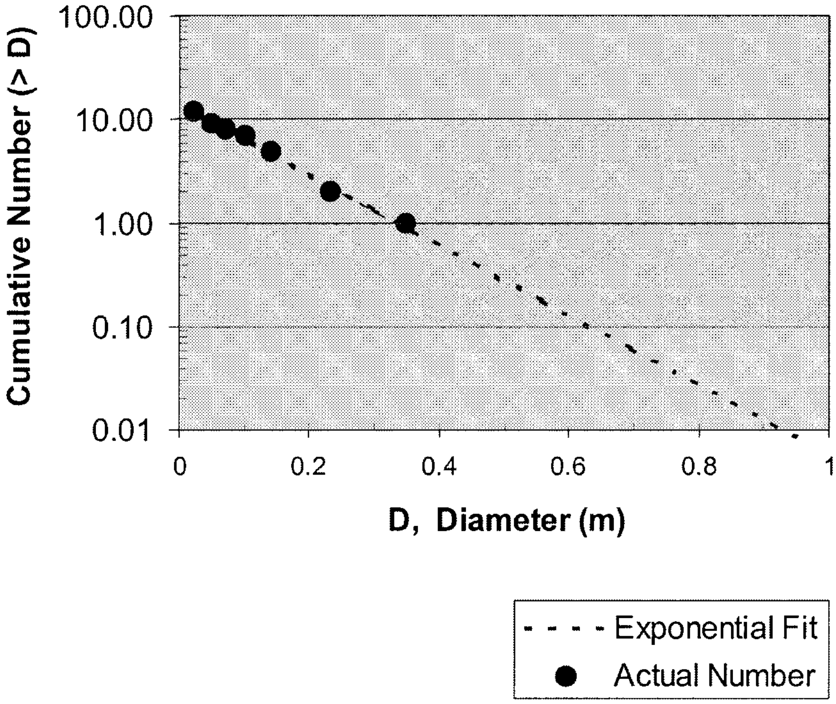


Figure 1. Cumulative size distribution (log-lin) of known martian meteorites.

where D is idealized rock diameter (derived from measured rock mass and density = 3 g cm^{-3}), $N(> D)$ is the number of rocks greater than that diameter (cumulative size distribution), and s and L are fit parameters. Rock distributions at the Viking sites have s values ranging from 7.5 to 12, with lower values (relatively more large rocks) at site-2 than at site-1. Exponential fits are a more accurate formulation for martian surface rock size distributions, and also for rock distributions which result from a variety of terrestrial fragmentation processes, than the power-law distributions (Golombek and Rapp, 1997).

However, because size distributions for many meteorite groupings have been shown to follow power-laws with mass, I have also plotted these same data on a log-log mass basis, which should produce straight lines for those portions which follow power law scaling. In Figure 2 it is seen that the available data describe a cumulative distribution which can be approximately fit by power laws over two regions.

At the higher end of the mass spectrum the power exponent is –0.6, the same value found by Huss (1990) for the pairing-corrected mass distribution of Antarctic meteorites in the Allan Hills main ice field. As pointed out by Huss, fragmentation during entry can result in skewing the distributions toward exponents as extreme as –1.20, whereas the distribution thought to apply to the infalling objects, prior to interaction with the atmosphere, is with exponent –0.83, close to that found in

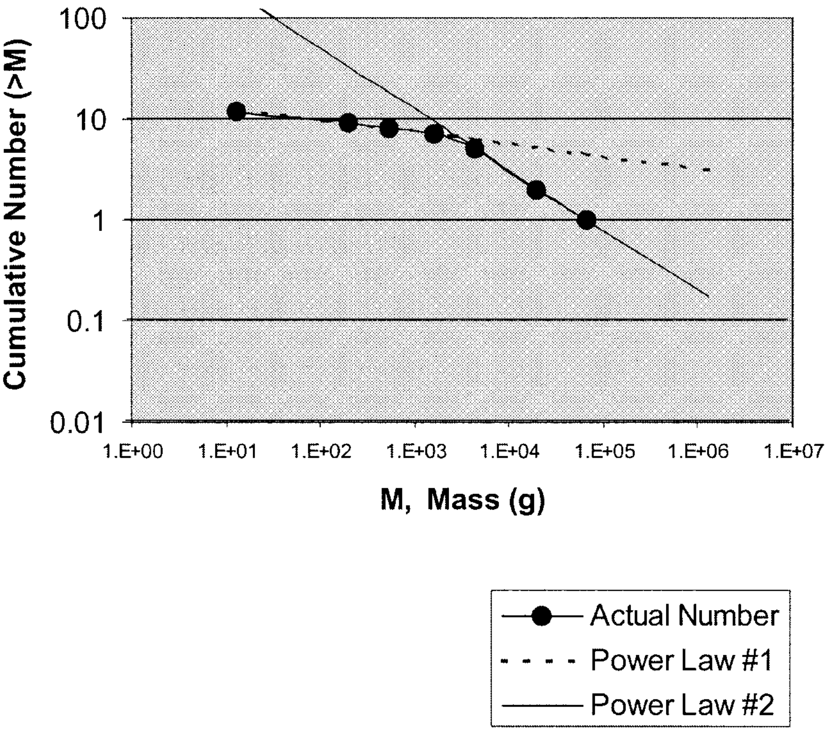


Figure 2. Cumulative size distribution (log-log) of known martian meteorites.

an exhaustive study of meteorites recovered from Roosevelt Country, NM (Huss, 1990).

Size distributions can also be affected by mechanisms such as ablation losses during entry, breakup during atmospheric passage, weathering after landing, and selection effects having to do with the poor efficiency of recovery. The latter two factors could, in principle depress the distribution curve at low masses, as suggested by Huss (1990).

These two models for the size distribution of martian meteorites result in quite different predictions of the likelihood of large objects impacting Earth. Since larger meteorites are more suitable havens for surviving interplanetary insults (see below), this consideration is highly relevant. For example, based upon the dozen meteorite examples so far, one might ask what is the probability that the next Mars meteorite discovered (or seen to fall to Earth) will be boulder-sized, at 2 m diameter or larger? The answer is 2×10^{-6} if the exponential curve fit with diameter holds (Figure 1), while it is still low but a significantly greater probability (4×10^{-4}), if the power-law-with-mass model (Figure 2) is more representative of the true distribution. These wide variations in models of the various factors are symptomatic of the general problem of attempting to theoretically determine an overall $\mathbf{P}_{\mathbf{AB}}$.

4. Nature of the Ejection Process

It has been a puzzle how geological objects can escape Mars with the relatively benign alterations that have been observed in martian meteorites, since hypervelocity impact by a large object generally pulverizes or melts target materials (O'Keefe and Ahrens, 1986). Two theoretical approaches in particular have sought to explain this observation.

For oblique impacts, more of the incident energy can be transferred into kinetic energy of target material, with lower shock pressures and temperatures, leading to the concept of ejection primarily by less common impacts within a few degrees of the local horizontal (Nyquist, 1983; Swift and Clark, 1983; O'Keefe and Ahrens, 1986). Vapor-jet entrainment might aid such ejections. Material which reaches the high velocities needed to escape the gravitational binding by Mars (>5 km s^{-1}) or Earth (>10.5 km s^{-1}) will nonetheless undergo significant shock heating, as well as strong drag deceleration and heating as it passes through the atmosphere to reach space. Small objects have a low mass per cross-sectional area and thus will be slowed more, requiring far higher initial velocities. The martian atmosphere, with a current minimum zenith thickness of about 16 g cm^{-2}, would severely retard or stop any stone smaller than a few cm in minimum diameter. Sand-sized and smaller particles would be stopped unless they were given velocities far in excess of escape velocity, or were not subject to atmospheric drag (either by escaping through a theoretical transient 'hole' in the atmosphere created by the incoming projectile (Melosh, 1989), or by escaping during a time in Mars' extreme obliquity variations where the atmosphere was frozen out to a low residual atmospheric pressure).

A different mechanism for imparting high velocity without large shocks has been proposed by Melosh (1989), whereby spallation of surface or near-surface material occurs due to interference of primary and reflected shock waves at a free surface.

In both circumstances, high-stress materials are needed in order to survive the forces of ejection and resistance of passage through the atmosphere.

As has been pointed out by Jones (1989), 'It is possible that only hard, dry rocks (such as young volcanics) are capable of being ejected as coherent fragments from a planetary body as large as Mars'.

In the view of Warren (1994) '. . . most old rocks on Mars have been weakened by a two-stage process of brecciation followed by pervasive weathering [physical and/or chemical] to the point where they seldom survive the stresses of spallation off the planet'.

For the spallation model especially, only coherent, high sound-speed targets like relatively unweathered basalt may be ejectable, which could explain the general preponderance of younger, less modified lithic samples in the meteorite collection in spite of the fact that the majority of the martian surface is abundantly cratered, implying ancient crystallization ages (Warren, 1994).

In particular, soils, water, mud and poorly consolidated sediments would (1) not spall, (2) be fragmented into dispersed fines by impacts, and (3) become strongly inhibited from escape by atmospheric drag.

The numerics of the impact ejection process at Mars have been studied by Gladman *et al*. (1996), who estimate that once every one million years or so a large impactor creates another 10 km diameter or larger crater on Mars, lofting some 10 million or so objects on interplanetary trajectories. Ejection efficiencies are based upon inferences from the number of known martian meteorites.

5. The Target Surfaces

Planetary surfaces consist of bedrock, rocks, fine particulates, sedimentary deposits, and various other potentially habitable environments (protected soils, rock weathering rinds, hydrothermal zones, fumeroles, deep aquifers, ices, etc.). Based upon materials properties, the survival biases of sampling from typical surfaces as well as specialized locales can, in principle, be evaluated.

6. Habitats and Ejection (P_{ee})

From known occurrences of microorganism ecologies on Earth, all of the following sites may be candidate habitats:

1. Surface Soils.
2. Duricrust layers.
3. Endolithic sites.
   a. Near-surface, below coatings or first-layer grains.
   b. Deep inside fissures, veins.
4. Paleolakes, Ancient Oceans, Water-rich Sediments.
5. Hydrothermal Oases.
6. Deep Underground Aquifers.

Potential habitats 1 and 2 are widespread on Mars, based upon observations by Viking and Pathfinder missions. The duricrust is a weakly-cemented variant of the soil, often with apparently higher salt content. Both are, in the contemporaneous environment, apparently highly desiccated. The endolithic micro-communities of organisms found in terrestrial deserts, including certain areas of dry valleys in Antarctica, take advantage of light-transmitting mineral grains to permit photosynthetic organisms to flourish at sufficient depth in certain coarse-grained rocks to moderate extreme environmental temperature fluctuations and to provide a partial barrier to water vapor loss (Friedmann, 1982). Because martian rocks seem to be relatively mafic, and quartz has not yet been identified, the availability of transparent grains is in question. Hence, habitat 3a is uncertain with respect to Mars. Site

3b is the location, however, of putative microorganism fossils reported by McKay *et al.* (1996). Such veins must have, of course, access to fluid water, presumably laden with dissolved ions and other nutrients, including a chemical energy couple to power metabolic activity.

Lakes, whether small or large (oceans), were undoubtedly restricted in time, although there could be, in principle, an ice covered body of trapped water, overlain with eolian deposits of dust, and maintained above the normal low temperature of the martian soils (typically, –55 °C at depths below a few cm) by a geothermal anomaly. Likewise, active hydrothermal springs are a promising abode for life, as evidenced by many examples on Earth. However, in this epoch of an apparently less-active Mars, residual hidden lakes and hydrothermal systems must be small in comparison with the martian surface – for example, an active area of size 10 by 10 km nonetheless is only 10^{-6} of the total area of the planet. Having a favorable impact precisely into such a relatively small target area is of commensurate low probability.

The most likely current-day abode of life, in the opinions of many investigators, is in some deep subsurface liquid-water zone, a martian acquifer system. In order to reach the 273 K isotherm corresponding to reasonable assumed heat flows for Mars, such an acquifer would need to be the order of 1 to 3 km below the contemporaneous surface (Clifford, 1993). Although subsurface structure could theoretically allow such an acquifer to breach the surface, such surface expressions would be small in areal extent, and in any event have not yet been detected. Habitat 6 may therefore be deeply buried in the case of Mars and launching such material would be quite difficult. First, the impactor would have to be very large to reach to such depths, and such impactors are relatively rare. Second, since it is not located near the planetary surface, neither the oblique impact nor the spall mechanisms of launching would directly apply. Third, the materials associated with aquifers are not well-consolidated, consisting of liquid water, porous horizons of presumably low strength, and possibly of chalky deposits of chemical precipitates.

In conclusion, only habitats 3a and 3b seem to be launchable with a significant probability. Virtually all other habitats considered here are poorly amenable to the hypothesized launch mechanisms and accordingly have extremely low values for $\mathbf{P_{ee}}$ (Equation (1)).

7. Nature of the Transfer Process

Once lofted into deep space, free of being bound into orbit around Mars, the ejected objects undergo multiple perturbations due to close gravitational encounters with various planets, potentially including Jupiter, Earth, Venus and Mars itself. Gladman *et al.* (1996) have determined through Monte Carlo trajectory analysis that although many of these objects escape the Earth-Mars region through perturbations by Jupiter or grazing the sun, many others eventually find themselves in

Earth-crossing orbits and are captured by impact with our planet. The vast majority, some 99.9% of the Monte Carlo trajectories which reach Earth, are slow transfers of between 10 000 and 100 million years. During this time, of course, these objects and any putative biological hitchhikers are subject to the environmental factors of deep space – variable temperatures, extreme desiccation (ultrahigh vacuum), and a variety of sources of ionizing radiation. However, for approximately 0.1% of objects, it is predicted that the transit times are less than 10 000 yr.

In addition, it has been estimated that some 10^{-7} of the objects might actually reach Earth in one year or even less (Gladman and Burns, 1996; Gladman, 1997). These extremely fast transfers are the same as the trip times for optimal minimum energy (Hohmann) transfers from Earth to Mars that are achieved only by the precise pointing and velocity adjustments of spacecraft missions between these two planets. Inspection of spacecraft error budgets (B. Sutter, private communication) to avoid a ‘miss’ lead to the conclusion that for any one launch on any one day, the probability of an impact in less than one year is probably considerably less than this, by several orders of magnitude. Utilization of Monte Carlo methods to predict probabilities at the level of 10^{-6} are difficult and also susceptible to subtle inadequacies of any overall model. In any event, it is clear that fast transfers are of low probability in the individual case, even though they might have occurred many times during geologic history *if* the yield of dispersed objects at escape velocities is sufficiently high enough.

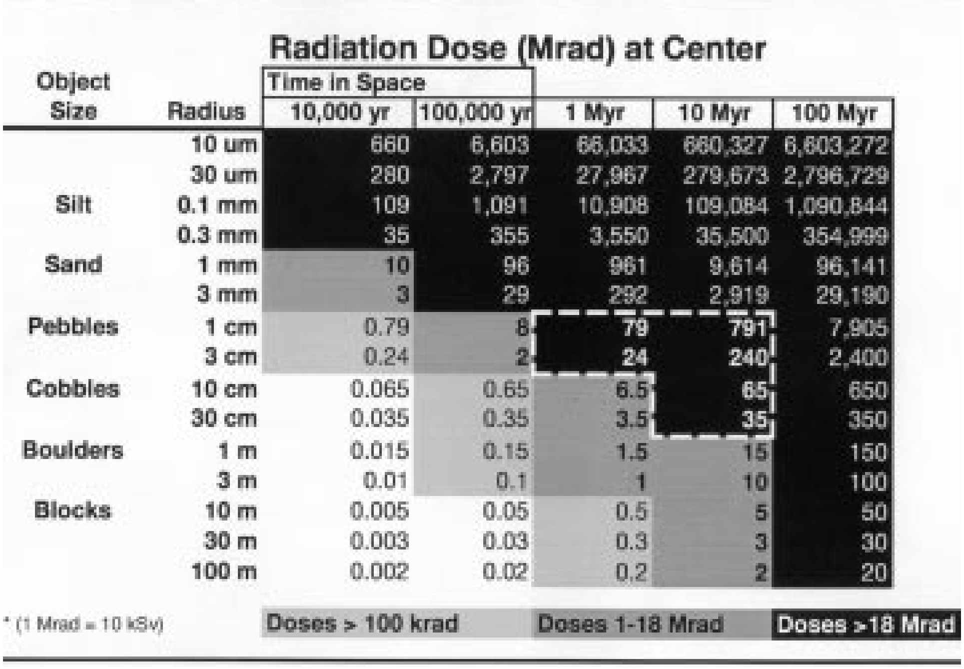
8. Surviving Irradiation During Interplanetary Transfer (P_{ss})

For those objects within which a viable organism has survived launch into space, the exposures to ionizing radiation include: solar ultraviolet irradiation, solar particle events (SPE), and galactic cosmic rays (GCR). Solar UV produces lethal effects in hours to days, but only to very shallow depths (micrometers to millimeters) in geological materials. SPE and GCR consist of energetic charged particles (ions), with GCR penetrating deeper but producing lower doses in the first tens of cm of depth. Transfer times can be long compared to space radiation survival times, even at meter depths.

Objects in deep space are subject to many deleterious environmental events which increase with time. Vacuum exposure is immediate, but bulk desiccation, being diffusion limited, takes time; irradiation is also cumulative, but episodic; impact events are stochastic. For the preponderance of objects which transfer slowly, at issue is whether they remain intact or are likely to suffer breakup by asteroidal impact during the voyage. Gladman (1997) argues against this on the grounds of cosmic ray exposure history and the results of the calculations on trajectories showing little time spent in the asteroidal belt. If large objects do breakup during passage to Earth, their interiors which could become refuges from radiation and desiccation would become more exposed to these insults.

TABLE I

Doses at center of geological object



Radiation Dose (Mrad) at Center

Object Size	Radius	Time in Space				
		10,000 yr	100,000 yr	1 Myr	10 Myr	100 Myr
Silt	10 um	660	6,603	66,033	660,327	6,603,272
	30 um	280	2,797	27,967	279,673	2,796,729
	0.1 mm	109	1,091	10,908	109,084	1,090,844
	0.3 mm	35	355	3,550	35,500	354,999
Sand	1 mm	10	96	961	9,614	96,141
	3 mm	3	29	292	2,919	29,190
Pebbles	1 cm	0.79	8	79	791	7,905
	3 cm	0.24	2	24	240	2,400
Cobbles	10 cm	0.065	0.65	6.5	65	650
	30 cm	0.035	0.35	3.5	35	350
Boulders	1 m	0.015	0.15	1.5	15	150
	3 m	0.01	0.1	1	10	100
Blocks	10 m	0.005	0.05	0.5	5	50
	30 m	0.003	0.03	0.3	3	30
	100 m	0.002	0.02	0.2	2	20

* (1 Mrad = 10 kSv)

Doses > 100 krad | Doses 1-18 Mrad | Doses >18 Mrad

An analogous problem, the survival of organisms on asteroids and other airless bodies in deep space, has been recently examined (Clark *et al*., 1999). Among the biocidal mechanisms present – desiccation, vacuum degradation, thermal inactivation and exposure to ionizing irradiation – the latter appears to be the most certain and the most serious. Radiation dose-rates beneath geological materials in space have been constructed to predict doses received over time (Clark *et al*., 1999). From these data, a table indicating survival regimes for the size-time relationships of various rock bodies in space has been constructed, using a typical rock density of 3 g cm^{-3}. The dose levels tabulated in Table I are calculated for the *minimum* doses, at maximum depth in an object. Nearer the surface, doses can be much higher, as can be readily seen by inspection of the rapid increase in dosages for smaller objects. Shading of the table is provided to scope out the range of *probable* sterilization (any dose above 0.1 Mrad for the large majority of terrestrial organisms) and *assured* sterilization at 18 Mrad for the most radiation-resistant microorganisms known (e.g., see discussion in Clark *et al*., 1999).

The martian meteorites for which published data are available at the time of this writing have sizes and space residence times which place them within the dashed boundary of Table I, which is deep inside the lethality regime. It is apparent that all three groups of recovered martian meteorites can be presumed to have received strongly sterilizing doses of ionizing radiation prior to their arrival at Earth. Also seen from this table is that centimeter and smaller-sized objects are sterilized in less than 10 000 yr, and a boulder-sized object is required to protect biotically active material for transit times longer than 1 Myr. Yet, as discussed above, boulder-sized objects are far less numerous than smaller ones, based upon observed steep size distributions of meteorites and rock populations, as well as theoretical arguments for ejection mechanisms.

9. Surviving Entry and Landing (P_{se} and P_{si})

Objects from deep space which enter Earth's atmosphere do so at a hypervelocity greater than the minimum of 10.5 km s^{-1}, due to the gravitational acceleration of Earth. For martian material, the velocity range is mostly encompassed between 11 and 17 km s^{-1}, resulting in ablation during atmospheric entry of 10–20% of the outer radius of typical hand-specimen sized meteorites (Gladman, 1997). For endolithic organisms residing near the surfaces of rocks, as they do in the dry valleys of Antarctica and several other deserts, the melting and ablation generally would be lethal except perhaps for rare occurrences of pre-melting spalls which provide gentler rides to the surface. Grazing entry might be the most favorable, as it would be for particulates (Flynn, 1989), because of the lower peak heating during slowing down. Habitat 3a would be typically destroyed by Earth entry. On the other hand, for many-cm sized rocks, the interiors can remain cold because of the protection by the ablation mechanism carrying away heat. Mineralized veins inside meteorites have been shown to avoid strong heating, even though their surface intersections may become sealed in the process. If microorganisms were located in veins or cracks within rocks, this sealing by the melted rind would effectively entomb them, until they could become released by weathering or other mechanism. During the atmospheric passage, many meteorites break up into smaller fragments due to the shock loading. These breakups presumably occur along weaknesses, such as are afforded by cracks and veins. Hence, even the 3b type of habitat might become exposed to heating in many, but certainly not all cases.

Larger bodies do not experience as much decrease in velocity during atmospheric passage and therefore will impact the ground or ocean at hypervelocities, causing nearly instantaneous bulk fragmentation, heating and melting, and hence are to a large extent, if not totally, self-sterilizing.

10. Relevance to Planetary Protection Issues

Even if a putative martian life form did successfully immigrate to Earth in some previous epoch, it may or may not have successfully interacted with the terra-biosphere. From the body of evidence of the paleontological record, some millions of species extinctions have occurred, the causes for the vast majority of which are currently unknown, and will probably remain so for some time. Abundant examples at all levels of organization of life are, however, well known for the havoc that introducing new biological competition (‘biological invasions’) and/or parasitization can create. PIBM, while perhaps re-assuring, is far too low in probability of having been successful during Recent or especially historic times to be pivotal in arguments for or against the precautions recommended for returning samples of Mars to Earth (NAS, 1997). Even if PIBM was early-on successful for a pre-historic Earth with no humans or a relatively small population of humans, the situation was fundamentally different from today’s large, interactive and highly-leveraged economic civilizations. The probabilistic model, though yet incomplete and with many uncertainties, already argues against any conclusion that martian contamination of Earth’s biosphere occurs pervasively. Furthermore, it cannot be argued that any putative successful biological transfer has been without consequences.

Even if life once did arise on Mars, but became extinct or sequestered, we should proceed carefully to also minimize the possibility of introduction of terrestrial organisms which might survive. There are multiple reasons for this, including (1) the potential for interfering with or confusing the biochemical evidence that could signal a discovery of previous or indigenous life on Mars; (2) the danger of inadvertently colonizing some favorable niche on the planet.

11. Relevance to Origin of Life Issues

The influence of PIBM is not accurately calculable at present. Most geological occurrences favorable to biotic activity may be unlaunchable – soils, weak sediments, liquid water, and all wet materials, including components of hydrothermally-active zones. Particulates, the most numerous of putative transport media, face the greatest hurdles due to non-launchability, poor attenuation of ionizing radiations, and whole-particle heating to high temperatures during entry.

Although the overall probability of successful transplant surely is extremely low per impact, the thousand-fold or higher bombardment rates when the early solar system cleared itself of interplanetary accretional remnants and impact debris, renders PIBM significantly more likely during the era of the first appearance of life on Earth. Mega impact events also occurred during this epoch. Having a more biologically underdeveloped, naïve or even pristinely sterile environment in which to ‘set up shop’ may have made successful inoculations yet more likely.

It is even possible that life arose first on Mars, which then ‘seeded’ Earth through the mechanism of PIBM. Much lower energies for escape are needed for the smaller planet, and Mars was also potentially subjected to higher fluxes of impactors due to its closer proximity to the asteroids. Finally, the interplanetary transfer is asymmetric and the diffusion of orbits favors successful Mars-to-Earth transfer rather than its inverse (Gladman, 1997). Unlike cosmic panspermia, this hypothesis seems subject to the potential for obtaining new evidence in the relatively near term.

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