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Impact resistance of bacteria entrapped in small meteorites

par

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Abstract.—ROTEN C.-A. H., GALLUSSER A., BORRUAT G. D., UDRY S. D., KARAMATA D., 1998. Impact resistance of bacteria entrapped in small meteorites. *Bull. Soc. vaud. Sc. nat.* 86.1: 1-17.

The lunar and Martian origins of some Antarctica meteorites demonstrate clearly the existence of regular exchanges of crust fragments between telluric planets of the solar system. Moreover, putative biological traces found in ejecta from the red planet led to the hypothesis that life was present in rocks of its surface. The distribution of life on at least two bodies of the solar system could easily be explained by transfers of biological know-how: either i) by simple organisms moved by radiation pressure once present in the uppermost level of the atmosphere or ii) by exchange of crust fragments containing entrapped life forms, ejected after a primary hypervelocity impact in solar orbit, and subsequently captured by an other planet. The final steps of the latter kind of interplanetary transfer are analysed with respect to small meteoroids. The comparison between observation of flight and impact parameters of small falling stones and classical microbiological ballistic experiments done between 300 to 600 meters per second lead us to propose for the first time that various kinds of bacteria entrapped in small impactors are able to withstand i) the heat produced by the Earth's aerobraking, reducing preatmospheric velocity (usually between 10 and 70 kilometers per second) to that of free fall (125 to 250 meters per second), and ii) the subsequent non-explosive impact. The importance of these biological properties for the origin and the early development of life in the solar system is discussed in this article.

Keywords: interplanetary transfer, Mars, Earth, meteorite, impact, ballistics, bacteria, lithopanspermia, panspermia.

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Résumé.—ROTEN C.-A. H., GALLUSSER A., BORRUAT G. D., UDRY S. D., KARAMATA D., 1998. Résistance aux impacts des bactéries emprisonnées dans de petites météorites. *Bull. Soc. vaud. Sc. nat.* 86.1: 1-17.

Les origines lunaires et martiennes de certaines météorites de l'Antarctique démontrent clairement l'existence d'échanges de fragments de croûte entre planètes telluriques du système solaire. En outre, les traces biologiques hypothétiques découvertes dans un des *ejecta* de la planète rouge suggèrent que la vie fut présente dans les roches de sa surface. La présence de la vie sur au moins deux corps du système solaire pourrait aisément s'expliquer par des transferts de savoir-faire biologique: soit 1) par des organismes simples mobilisés par pression de radiation une fois présents dans les plus hautes couches de l'atmosphère ou soit 2) par un échange de fragments de surface contenant de la vie, mis en orbite solaire suite à un impact primaire à haute vitesse, puis capturés par une autre planète. Les étapes finales de la deuxième sorte de transfert interplanétaire sont analysées en se focalisant sur les petites météoroïdes. La comparaison entre les observations des paramètres de vol et d'impact de petits impacteurs et les expériences microbiologiques classiques de balistique effectuées à des vitesses de 300 à 600 mètres par seconde permettent d'avancer la proposition inédite suivante: différentes sortes de bactéries cachées à l'intérieur de petits impacteurs sont capables de supporter 1) la chaleur produite par l'aérofreinage terrestre, réduisant la vitesse préatmosphérique (habituellement entre 10 et 70 kilomètres par seconde) à celle d'une chute libre (125 à 250 mètres par seconde) et 2) l'impact non-explosif subséquent. L'importance de ces propriétés biologiques sur l'origine et les premiers développements de la vie dans le système solaire est discutée dans cet article.

Mots-clés: transfert interplanétaire, Mars, Terre, météorite, impact, balistique, bactérie, lithopanspermie, panspermie.

An abstract of data presented in this contribution, as well as the observations of BLANC *et al.* (1997), will be presented to the Mars Society Founding Convention, August 13-16th, 1998, University of Colorado, Boulder, Co (ROTEN *et al.* 1998), and published in the proceedings of the meeting as a special issue of the Journal of the British Interplanetary Society.

1. INTRODUCTION

1.1. *Collecting meteorites in Antarctica*

The continent of Antarctica is one of the best places to collect meteorites, *i. e.* fragments of an impactor that survived transit through the Earth's atmosphere. First fallen into firn, these rocks are carried by South Pole glaciers toward the edges of the continent. If the ice flow meets an obstruction known as nunatak, ablation by strong polar winds or evaporation of ice occurs and meteorites collected by blue ice are concentrated (MCSWEEN 1987, p. 23-28). Thus, in these particular regions, trained people are now harvesting a tremendous amount of meteorites. This strategy was first used in 1969 when a Japanese field party found nine meteorites in the Yamato Mountain (HEIDE and WLOTZKA 1995, p. 71). Compared to the 3000 meteorites collected randomly and stored in museums, South Pole snowmobile excursions discovered 15'000 fallen rocks preserved in very clean conditions (DARS 1995, p. 7-10).

1.2. Meteorites from the Moon and Mars

If most of the meteorites fallen on Earth are now recognized as originating from asteroids (WAGNER 1991, p. 412), the so-called telluric planets are believed to be the source of two dozens of them: half originating from the Moon, and the other half from Mars. Due to striking similarities in composition and mineralogy to lunar highlands, ALH A81005 was the first impacting object recognized as coming from the Moon (MCSWEEN 1987, p. 120-123; EUGSTER 1989; CARION 1993, p. 96-97; HEIDE and WLOTZKA 1995, p. 185-186; GLADMAN *et al.* 1996) and the Antarctica field trip providing this additional lunar sample was facetiously called «the Apollo 18 mission» (MCSWEEN 1987, p. 137). Known historically as SNC meteorites according to three observed falls (Shergotty, India, 1865; Nakhla, Egypt, 1911; Chassigny, France, 1815), a dozen of them are supposed to come from Mars after mineralogy analysis and comparison of gasses entrapped in these meteorites with the composition of atmosphere of telluric planets (HEIDE and WLOTZKA 1995, p. 185-186; CARION 1993, p. 92-96; GLADMAN *et al.* 1996).

1.3. Life on Mars ?

Possible relics of biogenic activities were described recently in the Martian ALH 84001 found in Antarctica, allowing some scientists to suppose that life flourished on Mars in the past (MACKAY *et al.* 1996; BORTZ 1997). Even if this proposal is still debated (BRADLEY *et al.* 1997; MCKAY *et al.* 1997), the following question has now risen publicly: is the putative life of the red planet historically connected to that of the Earth ?

1.4. Natural transfer of life between planets

An answer to this question may reside in the possibility of natural life transfer between planets. The Greek astronomer Anaxagoras of Clazomenae in Asia Minor (ca 500 - ca 428 BC) was the first to consider panspermia in its original form, *i. e.* widespread distribution of life in the universe. He proposed that life-giving particles having the form of invisible germs are present everywhere and able to produce life from non-living matter (GLASSTONE 1968, p. 155-156). Later, two different ways of space travel were proposed (PARSONS 1996). Lithopanspermia, proposing that life was brought to Earth by meteorites carrying germs of life, was first discussed by the physiologist and physicist Hermann von Helmholtz and, one year later, by the Nobel Prize laureate, William Thomson, later known as Lord Kelvin (VON HELMHOLTZ 1874; THOMSON 1871; GLASSTONE 1968, p. 155-156; CROWE 1986, p. 400-406). Radiopanspermia was first developed by Svante Arrhenius, another Nobel Prize laureate (ARRHENIUS 1903, 1906, 1907; GLASSTONE 1968, p. 155-156; CRAWFORD 1996, p. 162-165; CROWE 1986, p. 400-406). The theory argues that unicellular organisms from the uppermost level of the atmosphere (GREGORY 1961, p. 135) can escape planetary gravitation through the action of electric forces and travel to other stars moved by radiation pressure. Due to the difficulty of explaining how bacteria are brought out of the atmosphere and to the very low number of cells able to precisely target an extrasolar

planet, HOYLE and WICKRAMASINGHE (1981a) recently modified this theory proposing that comets and molecular clouds are microbiological fermenters for these seeds of life.

The subject of this article is to focus on lithopanspermia and to analyse the following proposal: if putative life relics are able to travel from Mars to Earth, are bacteria entrapped in Martian ejecta able to survive a natural transfer between Mars and the Earth or, more precisely, able to support the stress of the terrestrial atmospheric braking and of the final shock?

2. THEORETICAL DEVELOPMENT

2.1. *Space mechanics*

Earth is orbiting the Sun at about 30 kilometers per second. In the solar system, the typical velocity of object crossing the Earth's orbit is about 40 kilometers per second. Thus, if the future impactor is orbiting the Sun in the same sense of rotation like almost all bodies of the solar system, *i. e.* having a prograde orbit, the Earth's velocity has to be subtracted from the faster one of the object. If the future impactor is rotating in the opposite sense *i. e.* a retrograde orbit, then velocities of both objects have to be added and a preatmospheric velocity up to 70 kilometers per second could be reached by the falling rock. Confirmation that regular future impactors have preferentially prograde orbits is obtained by the observed range of fireballs speeds usually falling between 10 and 30 kilometers per second (MCSWEEN 1987, p. 14).

2.2. *Physics of the fall*

2.2.1. *Hypervelocity impacts*

On the atmosphereless Moon all meteorites having a radius ranging from microns to kilometers create explosive craters due to an hypervelocity impact. The solid matter splashes like a fluid, and a crater much larger than the impactor is excavated. This mechanism explains why almost all Moon craters are round, their shape being independent of the impact angle (MARK 1987, p. 104-109).

Within the group of the so-called telluric planets, the presence of atmosphere is a distinctive feature, characteristic of Venus, Earth, and Mars. On these planets, hypervelocity impacts are produced by large impactors only. It was estimated that on Earth an object having an initial velocity of 20 kilometers per second creates a crater with a 10 times larger radius and a 1000 times bigger volume than those of the impactor (WASSON 1985, p. 11-16). The projectile is almost vaporized at the time of the impact. For smaller impactors weighting more than several tons, the fall velocity is affected by the atmospheric transit, but the impact velocity still represents a significant part of the preatmospheric velocity (HEIDE and WLOTZKA 1995, p. 31-32). Their drag coefficients, set by the fall angle, the size, the shape, and the density, are important enough to slow down the future impacting object. For example, a vertically entering iron meteorite weighting 3600 tons, having a radius of

4.8 m and a drag coefficient of 0.5, would have an impact velocity of 92% of the initial one (BUCHWALD 1975). With such a residual hypersonic velocity, the final impact is still explosive.

2.2.2. *Free fall impacts*

The second class of meteorites on Earth is represented by future impactors weighting no more than a few tons which are almost stopped by the atmosphere. This kind of meteorite hits the Earth's surface at a very low terminal speed of a free fall at which deceleration by drag is almost balanced by gravity (HEIDE and WLOTZKA 1995, p. 31). Several observations showed that masses from 1 to 100 kg were falling vertically with speeds of 125 to 250 meters per second just before the impact (BUCHWALD 1975, p. 25-32; WASSON 1985, p. 5-11; BIBRING and LANGEVIN 1986; MCSWEEN, 1987, p. 13-17). These low velocity impacts are non explosive. For instance, in 1869, 1 kg masses were recovered from a large shower on a frozen lake in Hessle (near Uppsala, Sweden) on New Year's Day. They were unable to penetrate the 2.5 to 5 cm thick ice layer (BUCHWALD 1975, p. 30).

Small meteoroids are subjected to important stresses during the deceleration from many times supersonic velocities to subsonic speeds. A friable object will immediately disintegrate. A tougher rock could be broken along preexisting cracks and would fall as a meteorite shower. A large part of the friction energy is used to warm air, and only a small part of it heats the falling rock. At the initial high velocities, the surface material melts and drops are lost in the air. Soon afterwards, during the free fall, the surface cools and a fusion crust appears before the impact. Easily recognizable on a polished surface, thermal effects are usually several millimeters deep in the poorly conducting stone or few centimeters in iron-rich material (WASSON 1985, p. 5-11). Due to the insulation of surrounding material and to the slow process of heat conduction, the meteorite interior remains cool even if the surface was melting (WAGNER 1991, p. 404-407; WASSON 1985, p. 5-11).

2.2.3. *Falling objects producing no impact*

Objects less than a few centimeters wide produce no impact. The complete rock is disintegrated by aerobreaking unless the object is smaller than a grain of sand. The surface of the latter type of minute particles radiates away the heat generated during the atmospheric entry (WAGNER 1991, p. 404-407).

2.3. *Mechanism generating stony planetary transfers*

Analyses of Martian impactors demonstrate that they must have been accelerated to the red planet escape velocity of 5 kilometers per second by an explosion following an hypervelocity impact (O'KEEFE and AHRENS 1986; VICKERY 1986; VICKERY and MELOSH 1987). Once in space, these meteoroids are orbiting the Sun, and, like those having originated from asteroids, could impact other bodies of the solar system. The same mechanism is proposed for lunar impactors which need a speed of only 2.4 kilometers per second to escape the Moon gravity (HEIDE and WLOTZKA 1995, p. 185-186; GLADMAN *et al.* 1996).

2.4. Comparison with the ballistic model

From the literature dealing with objects falling at terminal subsonic speeds, we can deduce that ballistic experiments are a good way to test impact resistance of bacteria. Recently reviewed (THADEPALLI and MANDAL 1991, p. 44-45; SELLIER and KNEUBUEHL 1994, p. 184-187) early experiments were conducted at the very end of the 19th century for medical purposes.

2.4.1. Lagarde's experiment

Knowing that the bullet temperature measured by von Beck ranges from 70 to 110 °C no more than 10 seconds after the firing, the U.S. military surgeon Lagarde addressed the following question: can bacteria spread on a firearm bullet infect a gunshot wound? Confirming clinical evidence, his rigorous inquiry showed that cartridges are sterile at the end of the manufacturing process. They were heavily loaded with bacteria once out of their original packages.

He tested the ability of bacteria to survive a bullet impact. Twelve sterilized metallic cartridges of a .38 Colt's revolver were mixed with floor sweepings and fired at 4 meters onto a sterilized iron target. After each round, the recovered projectile was transferred with sterilized forceps to melted agar broth and spread in Petri plates. Numerous colonies appeared two days later revealing that bacteria were able to survive the impacts. Next, working in the same conditions, he spread *Bacillus anthracis* on the bullet next to the powder or on the conical end. He chose this uncommon bacteria to identify easily a possible cross-contamination. As shown earlier, spores or vegetative forms of *B. anthracis* were able to stand the impact. Later, using a Springfield rifle, he demonstrated that *B. anthracis* spores survive this stronger impact. Finally, at the John Hopkins Hospital, he confirmed all previous results using rabbits as animal models (LAGARDE 1892).

Easily identifiable biologically, the use of the dangerous anthrax agent bacterium *B. anthracis* requires considerable precaution. Moreover, during the preparation of vegetative cells of *Bacilli*, it is not possible to avoid the presence of a few dormant spores, unable to metabolize, due to lack of free water in the cytoplasm, and very resistant to mechanical stress, heat and chemical aggression. Thus unaware of the possible presence of spores in vegetative cell preparations, Lagarde could have overestimated the resistance of vegetative bacteria to bullet impact.

2.4.2. Messner's experiment

As mentioned in the thesis of the physician Nadeschda PUSTOSCHKIN (1895) presented to the Bern University, Messner too performed experiments on three purified bacterial strains (MESSNER 1892). He selected the Gram-positive bacterium *Staphylococcus pyogenes* presently named *Staphylococcus aureus* (BAIRD-PARKER 1974), the Gram-negative *Prodigiosus* designated later as *Serratia rubidaea* (ATCC 1998), and an unidentified bacillus of green pus which could have been a *Pseudomonas*. Gram-negative bacteria have a thin peptidoglycan cell wall between the cytoplasmic and the outer membranes while vegetative cells of Gram-positive bacteria have only the

cytoplasmic membrane usually surrounded by a thick peptidoglycan cell wall. This comparison probably explains why members of the latter type of prokaryotes are more resistant to dehydration and mechanical stresses than those of the former type.

Using a 7 or 11 mm military rifle¹, Messner fired bullets at a gelatin containing cylindrical box at a distance of 125 or 250 meters. Control experiments were done by firing sterilized bullets through gelatin. With the exception of certain moulds or air bacteria, different from those listed here above, no growth was observed in control experiments. Spreading any of the three selected strains over the bullet and shooting with a preheated barrel, or spreading organisms in a piece of cloth surrounding the gelatin target at which the shot was fired, always led to growth on gelatin. In these experiments, non-sporogenic bacteria only were used, demonstrating for the first time that vegetative bacteria could withstand the firing of a bullet.

2.4.3. Pustoschkin's experiment

In 1895, four different types of bacteria were systematically tried in a bacteriological lab (PUSTOSCHKIN 1895): *Bacillus ruber* presently named *Serratia plymuthica* (ATCC 1998), *Bacillus coli* designated later as *Escherichia coli* (ØRSKOV 1974), *Bacillus subtilis* and *Streptococcus pyogenes*. The former two are Gram-negative bacteria while the latter two are Gram-positives (Table 1). Among organisms chosen by Pustoschkin, the non-pathogenic soil bacteria *B. subtilis* is the only one able to encyst itself in a spore, like *B. anthracis*. According to pigment production, cell shape (all are rod-shaped bacteria except the spherical or ovoid *Streptococcus pyogenes*), and the ability to sporulate, each of these four species can be easily identified.

The firing was performed at a distance of 7 meters using the Swiss Infantry Rifle Schmidt-Rubin model M1889, originally named Infanterie-Repetier-Gewehr M1889, and manufactured between 1891 and 1897 by the Eidgenössische Waffenfabrik in Bern. The overall length of the weapon is 1.302 meter. The 3-groove right-hand twist barrel is 0.78 m long. The rimless cartridge (7,5 x 53,5 mm) has a round nose steel jacketed bullet weighing 213 grains or 13,8 g. With 2 g of smokeless powder loaded in the cartridge, the bullet has a muzzle velocity of 590 meters per second. The mechanism² of the

¹Tentatively, we deduced from his article (MESSNER 1892) that the following Mauser bolt action carbines and cartridges were used: the 1871/84 and 11.15 x 60 R Mauser, or the 1892 and 7 x 57 Mauser. Smokeless powder was used in the latter military rifle (BARNES 1989, p. 265 and 279). Lengths of these 4-groove right-hand twist barrel, muzzle velocities, and magazine sizes are 800/738 mm, 430/670 meters per second, and 8/5 rounds, respectively (WALTER 1993, p. 170 and 181).

²The operation of the Schmidt-Rubin action is simple, but what appears to be bolt handle is actually attached to an operating rod sliding in its own groove in the action body. This carries a lug which engages in a helical groove in the bolt carrier. When the rifle has been fired, pulling back on the bolt handle causes the lug to travel down the helical groove, thus rotating the bolt assembly to unlock the lugs which are actually on the bolt carrier and lock into recesses in the receiver behind the magazine. Further movement of the handle then draws the bolt straight back. The return stroke forces the bolt forward to chamber a round, after which continued movement of the handle drives the lug forward in the helical groove and rotates the bolt carrier to lock it. The ring protruding from the rear is a combined safety device and re-cocking handle (HOOG and WEEKS 1991, p. 123-124).

rifle is a straight-pull bolt action, with two lugs on the rear of the bolt sleeve locking into the receiver ahead of the trigger. Twelve rounds can be loaded in a detachable box magazine (PELLATON 1985, p. 61; HOOG and WEEKS 1991, p. 123-124; KNEUBUEHL 1994, p. 157).

During the early experiments, the rifle was carefully sterilized and no contamination could be detected. Later, this apparently unnecessary precaution was abandoned. It was noticed that barrel disinfection was unnecessary if, prior to a previous firing, bacteria had not been spread on the bullet or in the barrel.

Reprocessed according to the recent nomenclature, Pustoschkin's results are presented in Table 1. Bacteria, spread in a piece of cloth, placed on the bullet or in the gun barrel, can survive the observed acceleration of around 100'000 g (KNEUBUEHL, personal communication 1998, fig. 1) as well as the impact of the fired bullet. In various shooting conditions, an average survival of 88% was observed for all examined bacteria; Gram-positives being more resistant (94%) than Gram-negative ones (82%). The difference between both type of bacteria was particularly noticeable when they were spread inside the barrel. The result is compatible with known structural differences, *i. e.* a thicker peptidoglycan cell wall, like that of Gram-positives, offers a better protection to shock than the thinner wall of Gram-negatives.

3. DISCUSSION

3.1. *Capability of bacteria to survive low-velocity impact*

Pustochkin's experiment confirms those of Lagarde and Messner. All seven different kinds of bacteria tested were able to bear a bullet firing. Lagarde showed that *B. anthracis* survives a hard impact, Messner and Pustoschkin demonstrated that a variety of bacteria can outlive a gentler collision. Recent experiments performed with a firearm (THORESBY and DARLOW 1967), a powerful airgun rifle capable of firing a pellet at 300 meters per second (BLANC *et al.* 1997), and a hypervelocity powder-gas gun ejecting a projectile at few kilometers per second (WHITFIELD *et al.* 1973) gave results in agreement with those previously reported.

Comparison of ballistic and astronomical data revealed for the first time that bacteria in small meteoroids are able to survive final atmospheric stages of planetary transfer, as briefly discussed by ZUBRIN and WAGNER (1996, p. 132-133). Moreover, following a tough primary shock, water, covering 71% of the Earth's surface (MURRAY 1887; COUPER 1983, p. 26), could gently brake the fall of stony meteoroids and thus be particularly suitable for this kind of interplanetary exchange of bacteria. Although presently liquid form of water can be found on the Earth's surface only, at much earlier times, rivers flowed towards a boreal ocean on Mars (KARGEL and STROM 1996), offering favourable conditions for interplanetary transfers from Earth to Mars.

Table 1.—Bacterial resistance to bullet impact:

This table shows the completely reprocessed data of PUSTOSCHKIN (1895) according the recent bacteriological nomenclature. Four bacterial species were selected for the experiment: 1) *Serratia plymuthica*, 2) *Escherichia coli*, 3) *Streptococcus pyogenes*, 4) *Bacillus subtilis*. The last column summarizes the figures for all examined bacteria 5). Experiments were done with a cold 6) or a hot barrel 7) preheated by firing twelve rounds in a row. Absolute figures 8) indicate the number of rounds shot in same conditions after which growth was observed on broth. If the survival 9) is not 100%, a figure in brackets indicates 10) the total number of cartridges fired under the same conditions.

Bacterial species	<i>S. pl.</i> 1)	<i>E. co.</i> 2)	<i>S. py.</i> 3)	<i>B. su.</i> 4)	Tot 5)
Description of the different experiments:					
1. Bacteria spread on a piece of cloth placed between the gun and the target:					
1.1. The barrel was cold. 6)	2 8) 100% 9)	1 100%	1 100%	1 100%	5 100%
1.2. The barrel was preheated. 7)	1 100%	1 100%	1 100%	1 100%	4 100%
2. Bacteria spread on the bullet:					
2.1. Bacteria on the body of the bullet.					
2.1.1. The barrel was cold.	1 100%	3 100%	1 100%	1 100%	6 100%
2.1.2. The barrel was preheated.	1 100%	1 100%	2 (3) 10) 67%	2 100%	6 (7) 86%
2.2. Bacteria on the conical bullet end.					
2.2.1. The barrel was preheated.	1 100%	1 100%	1 100%	1 100%	4 100%
3. Bacteria spread inside the barrel:					
3.1. The barrel was cold.	3 100%	2 (4) 50%	3 100%	2 100%	10 (12) 83%
3.2. The barrel was preheated.	0 (1) 0%	0 (2) 0%	1 100%	1 (2) 50%	2 (6) 33%
Total number of cases of bacterial growth observed for all shots done in various conditions.	9 (10) 90%	9 (13) 69%	10 (11) 91%	9 (10) 90%	37 (44) 84%
Average percentage of growth observed for all shots done in various conditions.	86%	79%	95%	93%	88%
For a bacterial type	Gram-negatives		Gram-positives		All types
Total number of cases of bacterial growth observed for all shots done in various conditions.	18 (23) 78%		19 (21) 90%		37 (44) 84%
Average percentage of growth observed for all shots done in various conditions	82%		94%		88%

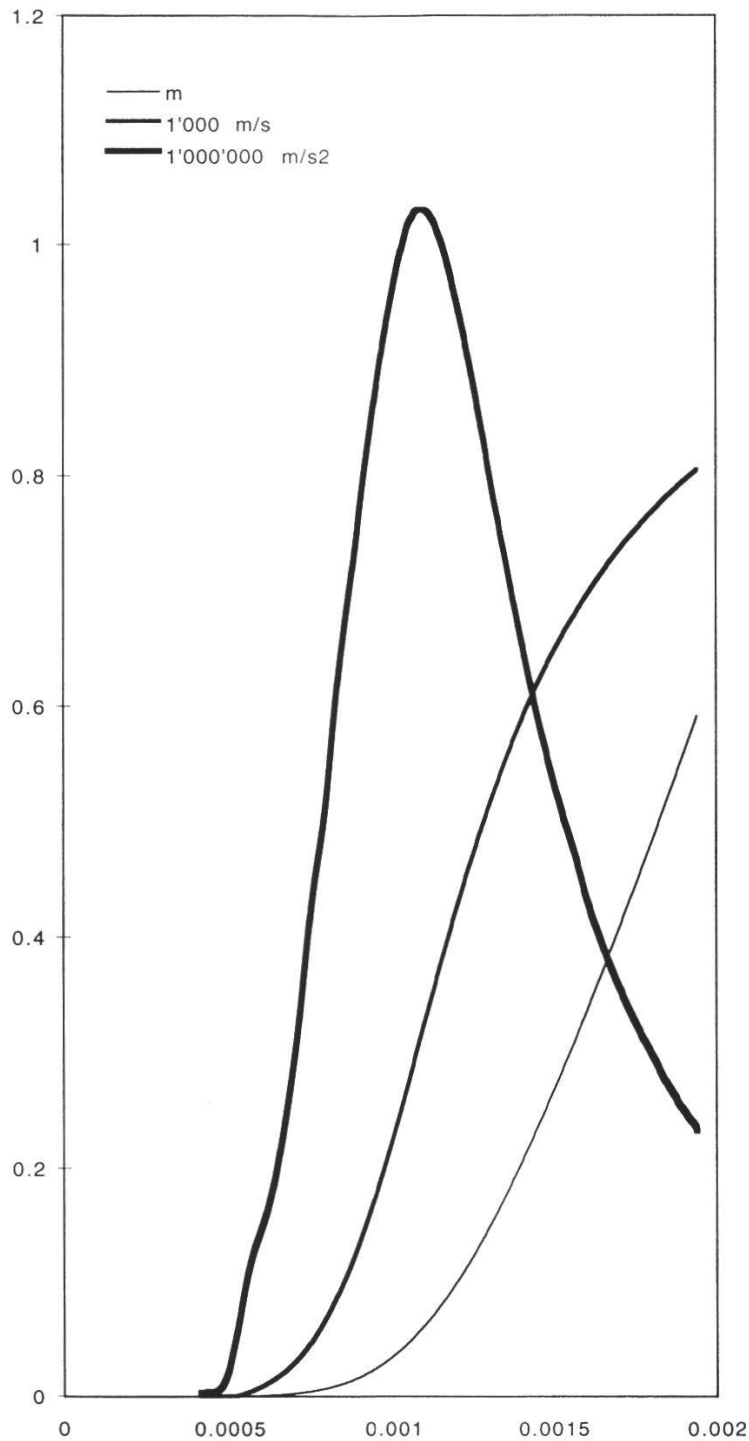


Figure 1.—Travel, velocity and acceleration of a bullet in a rifle as a function of time in seconds.

A pressure curve of a GP11 cartridge (7.5 mm, 3.5 g of smokeless powder, the weight and the shape of the bullet are those of Pustoschkin), kindly provided by B.P. Kneubuehl, was used to estimate the bullet acceleration in the barrel of a military rifle. The shape of the pressure curve, similar to the acceleration curve (STIEFEL 1988, fig. 7 to 14), allowed us to derive a relative velocity curve. From the muzzle velocity, *i. e.* 805 meters per second (KNEUBUEHL 1994), an absolute velocity curve can be deduced. The latter, in turn, allows to calculate the absolute travel and acceleration curves of the bullet in a barrel. The behavior characteristics of GP11 is very similar to that of the 7.62 mm Ball M80 (STIEFEL 1988, fig. 3).

3.2. Capability of bacteria to survive a planetary transfer by lithopanspermia

Analyses of lithopanspermia show that tough conditions exist during this kind of planetary transfer, although bacteria were apparently able to withstand them. Indeed, a putative life, entrapped in surface fragments, would have to endure a very strong acceleration, subsequent to a primary hypervelocity impact on a telluric planet. However, such an event is less severe than that of a bullet acceleration in a gun barrel, *i. e.* around 10'000 versus 100'000 g (VICKERY 1986; MILEIKOWSKY *et al.* submitted, fig. 1). If and when satellized, living organisms would be rapidly lyophilized in the space vacuum where no liquid water can remain in equilibrium on small bodies (PORTNER *et al.* 1961; MITCHELL and ELLIS 1972). Such a process is the method of choice of academic or private institutions to store live bacteria. As Martian rocks could wait millions of years before encountering an other planet, bacteria would have to be protected from solar and galactic radiations. Again, the interior of rocks would offer a good shelter against irradiation (WEBER and GREENBERG 1985; MILEIKOWSKY 1997; MILEIKOWSKY *et al.* submitted). Moreover, survival of *Bacillus sphaericus* spores during 25 to 40 million years in amber (CANO and BORUCKI 1995) in the absence of any free water in their cytoplasm supports the idea that dehydrated biochemicals could withstand such a long period. Possibly protected within the stone, some of them could withstand the heat entry and the final shock on Earth, as shown by ballistic experiments.

Such mechanism could allow transfer of biological material also in the opposite sense, *i. e.* from the Earth to Mars or to yet another planet. Life could have started on a solar system body other than Earth. Subsequently, when terrestrial conditions became appropriate for life, stone-borne interplanetary transfer would have permitted the colonisation of the blue planet.

3.3. Importance for the early terrestrial life to survive an Earth to Earth space travel

During the early history of the solar system, the flux of meteorites falling on Earth was so important that some hypervelocity impacts were able to vaporize all the oceans and to completely sterilize the terrestrial surface (MAHER and STEVENSON 1988; SLEEP *et al.* 1989; ZAHNLE and SLEEP 1996). However, bacteria present on Earth's ejecta could have survived in space. Later, upon falling back onto the Earth's surface, under more appropriate conditions, lyophilized bacteria could have recolonized the planet.

The ability to survive stone-borne interplanetary transfer as well as Earth to Earth space travel would severely limit the choice of organisms capable of participating in the early steps of life on the blue planet. This could explain why during the first half of the time during which there was life on Earth, only prokaryotes were present. Subsequently, the terrestrial biosphere was changed by bacterial metabolism, allowing a symbiotic association possibly yielding eukaryotic cells, *i. e.* cells with a nucleus, a mitochondrion, or in some cases a chloroplast (MARGULIS 1981, 1993; ROTEN and KARAMATA 1992).

3.4. *Looking for life on extrasolar planets*

Finally, in a few years time, exciting programs of the European Space Agency and the National Aeronautics and Space Administration (ANGEL and WOOLF 1996) should provide information on life signatures such as an oxygen atmosphere possibly present on extrasolar telluric planets, or on satellites (WILLIAMS *et al.* 1997) orbiting recently discovered extrasolar giant gaseous planets (MAYOR and QUELOZ 1995; MAYOR *et al.* 1997; BUTLER and MARCY 1997; CROSWELL 1997).

Presence of oxygen could be accounted for by life brought by lithopanspermia. Bacteria exported from other planetary systems and travelling in stones could have been present at the time of formation of a new planetary nebula together with heavy atoms constituting the telluric planets made during the last stages of stellar evolution. Life present in the building material could have colonized the new planets as soon as conditions allowing development of life were present on some of these bodies. Later, the atmosphere of some celestial bodies could have been transformed from a carbon dioxide atmosphere, in balance with the early geological conditions, to an oxygenic one, resembling the present day Earth's atmosphere. Such an atmosphere could allow the appearance of symbiotic prokaryotic associations similar to that encountered in the ancestor of eukaryotic cells and, later, the spreading of multicellular organisms.

3.5. *About the origin of life in the solar system*

This proposal explaining how life could be spread from one planetary system to another could also be relevant to the origin of life in the solar system. From an evolutionary point of view, there seems to be an apparent contradiction (fig. 2): the oldest fossils on Earth are traces of photosynthetic cyanobacteria (SCHOPF 1993) which are rather sophisticated prokaryotes according to biomolecular data (OLSEN *et al.* 1994).

To give an explanation to this puzzling observation, LAZCANO (1997) estimates that the average speed of evolution of the early terrestrial life was much faster than the present one.

Opposing Lazcano's hypothesis, we suggest that the origin of terrestrial life took place in a different planetary system, prior to Earth's accretion. Such a proposal, without implying a differentiated evolutionary speed, explains easily why relics of rather complex bacteria are found in the oldest fossils on Earth.

4. CONCLUSION

One way of assessing the possibility of life spreading throughout the solar system, as proposed here, is to examine if Martian putative life relics are biochemically similar to terrestrial metabolites. To circumvent the problem of terrestrial contamination that could have occurred in Antarctica meteorites during a long storage in ice (BADA *et al.* 1998), a conclusive answer would be brought by analyses of Martian samples collected by robotic or human missions designed nowadays.

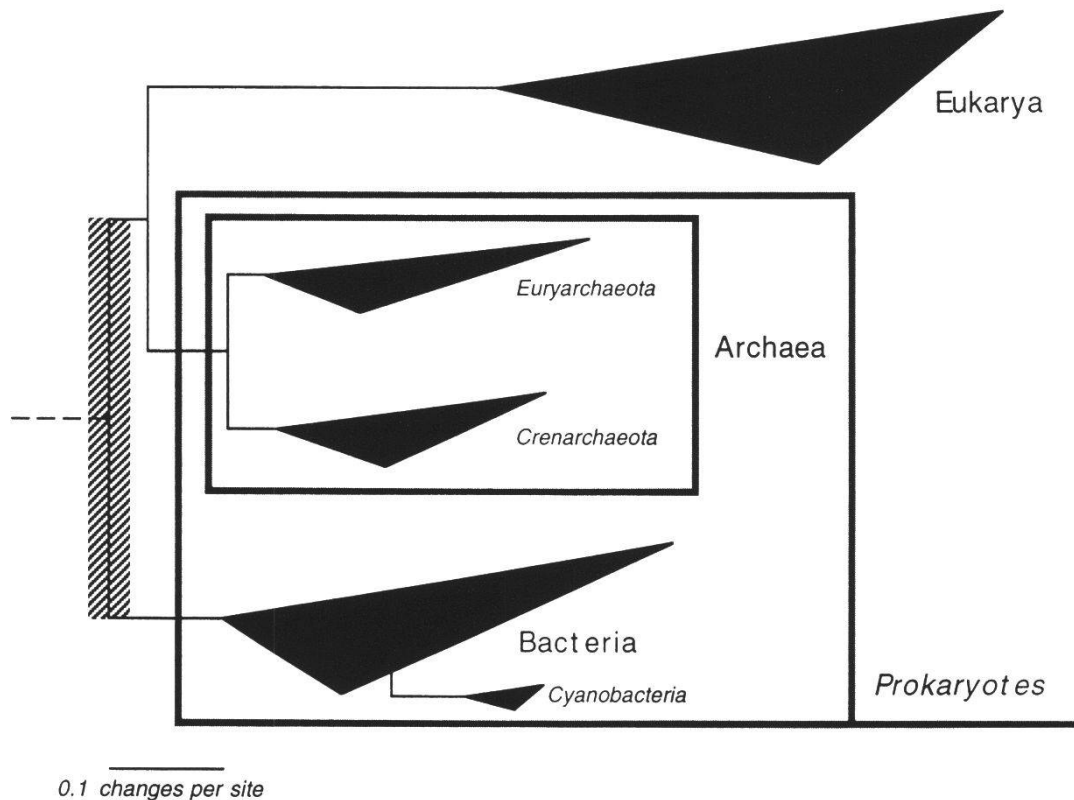


Figure 2.—A schematic summary of published data of a universal phylogenetic tree based on small subunit ribosome gene sequence (PACE *et al.* 1997). Horizontal distances are meaningful and the left scale bar corresponds to 0.1 change per nucleotide. A triangle corresponds to the number of changes for a specific taxon. Horizontal projection on the lower and upper left side of each triangle indicate the minimum and the maximum of change rates, respectively, from the last common ancestor of the phylum to present species.

The nucleotide change rate of cyanobacteria falls within the average of the Bacteria taxon. The distance between a universal ancestor and the last branch point common to cyanobacteria and other bacteria corresponds to two thirds of the total evolutionary distance. The final steps leading to the speciation of cyanobacteria corresponds to the remaining third.

Considering that life on Earth appeared soon after the solidification of the planet surface, *i. e.* 3.9-4 billion years ago, and knowing that the oldest bacterial and cyanobacterial fossils are 3.85 and 3.5 billion year old, respectively (MOJZSIS *et al.* 1996; SCHOPF 1993), it would appear that only about 400 million years were needed for the former evolutionary step, while 3.5 billion years were required to cover the last third of the evolutionary distance. For this to be true, the rate of mutagenesis during the earlier stage of evolution should have been at least 20 times faster than the present day one (LAZCANO 1997).

Therefore, it would appear that, with a constant present day mutation rate, the early evolution could not have possibly taken place on Earth, which was most likely contaminated by extrasolar material.

Analysis of the cyanobacterial example would suggest that the ancestor of the organisms which brought life to Earth would be as old as our galaxy *i.e.* 10 billion years. The resistance to stone-borne transfer, an important property allowing bacterial colonization of the early solar system, was possibly at the origin of intergalactic spreading of life, recently proposed by HOYLE and WICKRAMASINGHE (1981a, 1981b).

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