Natural Transfer of Viable Microbes in Space

1. From Mars to Earth and Earth to Mars

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The possibility and probability of natural transfer of viable microbes from Mars to Earth and Earth to Mars traveling in meteoroids during the first 0.5 Ga and the following 4 Ga are investigated, including:

—radiation protection against the galactic cosmic ray nuclei and the solar rays; dose rates as a function of the meteorite's radial column mass (radius × density), combined with dose rates generated by natural radioactivity within the meteorite; and survival curves for some bacterial species using NASA's HZETRN transport code

—other factors affecting microbe survival: vacuum; central meteorite temperatures at launch, orbiting, and arrival; pressure and acceleration at launch; spontaneous DNA decay; metal ion migration

—mean sizes and numbers of unshocked meteorites ejected and percentage falling on Earth, using current semiempirical results

—viable flight times for the microbe species *Bacillus subtilis* and *Deinococcus radiodurans* R1

—the approximate fraction of microbes (with properties like the two species studied) viably arriving on Earth out of those ejected from Mars during the period 4 Ga BP to the present time, and during the 700 Ma from 4.5 to 3.8 Ga. Similarly, from Earth to Mars.

The conclusion is that if microbes existed or exist on Mars, viable transfer to Earth is not only possible but also highly probable, due to microbes' impressive resistance to the dangers of space transfer and to the dense traffic of billions of martian meteorites which have fallen on Earth since the dawn of our planetary system. Earth-to-Mars transfer is also possible but at a much lower frequency.   © 2000 Academic Press

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1. BACKGROUND AND GOAL OF THE STUDY

The impact bombardment of planets and moons by comets and other small bodies was extremely intense during the first ~500 million years of our planetary system. It continues today but at a calmer rate. When an impactor hits the ground, a considerable amount of soil and rock is thrown up at high velocities, some fraction reaching escape velocity if the impactor is large and fast enough. These ejecta leave the planet and begin orbiting independently around the Sun, usually for time scales of a few hundred thousand or several million years until they either impact another celestial body or are expelled out of our planetary system forever.

Thirteen meteorites which are ejecta from Mars have been found so far on Earth. The most famous of them, ALH 84001, had traveled for 16 million years in space before falling to Earth. Sensationally, NASA experts have found in ALH 84001 a number of small carbonate nodules with rims containing material and structures which they interpret as possible fossils of martian bacteria (not all scientists agree with this view, however; a vivid discussion is going on). Of the other 12 meteorites, one had taken 0.6 million years in space, 3 had used 2.7 million years, 3 had spent 3.5 million years, and 4 had taken 11.7 million years. The accuracy of these figures is ±20%. The weights of the recovered martian meteorites (in kg) are: 18, 10, 8, 4, 4, 2, 0.8, 0.5, 0.16, 0.018, 0.013, and 0.012. It was generally unexpected that some of the meteorites would show little evidence of shock in the ejection process (Nakhla, ~10 kg; Chassigny, 4 kg; and ALH 84001, 2 kg). In these cases both temperature and pressure would have been low enough to allow survival of many bacterial species. A hypothesis explaining this production of unshocked ejecta (Melosh 1984) will be applied below.

During recent decades important discoveries have been made regarding a wealth of microorganisms, almost 10,000 new species, living deep underground or at the bottom of the terrestrial oceans (Fredrickson and Onstatt 1996). They are independent of light, some do not need oxygen, and some do not need organic material for food as they can live on a source of bound hydrogen, carbon dioxide, and metals. Some of them live thousands of meters below the surface in the pore space within granite. Some are thermophiles, withstanding and growing at high temperatures, over 100°C, and thriving as deep as their heat resistance allows. Some are even called extremophiles. Such microorganisms might well be representative of very early types in the history of the Earth.

It is a favored hypothesis among scientists today that similar underground bacterial populations might have existed on Mars at a time when the planet had much more water than today, or even may still exist. If so, martian ejecta could contain bacterial endolithic communities. Traveling through space, they would be confronted with the complex interplay of various adverse environmental factors, such as high vacuum, intense radiation, and temperature extremes. Whereas this harsh environment sets a definite barrier for most microorganisms known, some have developed survival strategies, by transforming into a dry state, the so-called anhydrobiosis (Crowe and Clegg 1978), or by producing spores, the dormant state of certain bacteria. In bacterial endospores of, e.g., the family of *Bacillaceae*, the inner spore section contains the cytoplasm and DNA in an anhydrous form, surrounded by a thick multilayered protective envelope. In this dormant stage, the *Bacillaceae* can resist adverse conditions over extended periods of time (Henis 1987). Concomitantly with their resistance to the adverse effects of drying, microorganisms in anhydrobiosis or spore stage are resistant to the effects of freezing to very low temperatures, elevated temperatures for brief periods, and the effects of ionizing radiation (Crowe and Crowe 1992). These characteristics make spores and anhydrobiotic bacteria especially prepared for coping with the extreme conditions of space (Horneck 1993).

The first of the two goals of this study—covered in the present Part 1—is to investigate whether microorganisms inside meteoroidal ejecta traveling from one planet to another in our planetary system, e.g., from Mars to Earth, could be sufficiently protected against lethal ionizing radiation for a sufficient number of years, avoid being exposed to temperatures >60–100°C during takeoff, orbiting, and landing, and furthermore survive DNA decay in such a way that they could arrive in a viable state and begin to multiply. If that happened while the Earth was still "virgin," the arriving bacteria might survive with only prebiotic material for food.

The second goal, the investigation of the possibility, probability, and credibility of transfer of viable microbes in large meteorites or comets from a planet in one planetary system to a planet in another planetary system, will be covered in the forthcoming Part 2 of this study.

The different sections of this first part of our interdisciplinary study have been presented in an easy-to-follow sequence. We begin with the launch and landing processes (Section 2). Section 3 demonstrates that an intense flux of martian meteorites has been arriving on Earth since the formation of our planetary system and that a sizeable proportion of them are unshocked. The flux of Earth–Mars meteorites is also studied here. Readers unfamiliar with mathematical formulae may obtain the relevant information by turning directly to the tables. Section 4 contains the findings of investigations which, to the best of our knowledge, have not been quantitatively undertaken before: the probability of microbe survival against the biologically effective radiation dose generated by the two sources of ionizing radiation: external from space and internal from the meteorite material itself. Other

risks to the microbes are examined in Section 5: those related to temperature (migrating metal ions and temperature during orbiting) and the threat from oxygen, hydrolysis, other chemicals, temperature, and vacuum. Conclusions as to the probability of and conditions for the viable transfer of microbes from Mars to Earth and Earth to Mars are put forward in Section 6.

2. THE LAUNCH AND LANDING PROCESSES

2.1. The Frequency of Impacts on Mars

The similarities in the lengths of time certain martian meteorites spent in space (2 spent ~0.9 million years, 3 required ~2.7 million years, 3 took ~3.5 million years, and 4 took ~11.7 million years) have been interpreted as indicating that the 12 currently dated meteorites come from only six impacts (Eugster *et al.* 1997). The average time between impacts would thus be a few million years or less. The mass of the impactors may not have been very large, on the order of half a billion tons (Table Ib).

Impacts creating 30-km-diameter or larger craters on Mars currently occur every 10 million years. This rate was obtained by a comparison with craters on the Moon. Such impacts would eject meter-sized rocks with velocities greater than the escape velocity, 5 km/s. One-meter boulders would not provide any shielding against GCR, but 10-m boulders would, as shown below (Section 4). Impacts creating 100-km-diameter craters would eject 10-m-sized boulders (Melosh 1984) and occur every 55 million years on average. Table Ia shows impact rates on Mars and ejecta sizes for ejecta leaving the surface at temperatures $<100°C$.

2.2. Temperature, Pressure, and Acceleration

Both the launch and the landing of ejecta meteorites occur during very energetic processes. It is easy to understand that a high fraction of these meteorites get *heated* to temperatures which microbes cannot survive, either at start or at landing. However, we have direct evidence that a significant fraction of ejecta avoid being heated above $100°C$, as exemplified by the fact that no less than 3 of the 13 martian meteorites are unshocked or very

slightly shocked, as mentioned above. An explanation of this important phenomenon was proposed by H. J. Melosh in 1984. The surface layer of the target where interference of a direct shock wave and a reflected shock wave takes place is called the spall zone. The wave which is reflected off the surface changes phase angle by $180°$. The superposition of the reflected shock wave on the direct shock wave reduces, by interference, the intensity of the resulting shock considerably. When the angles to the surface plane are small, the two waves almost cancel each other. Typical thickness of the spall zone is about half the impactor diameter or less.

The total time duration of the pressure pulse, $t_{tot} =$ rise time + decay time, is quite short and given by $L/2U + L/C_T$, where L is the impactor diameter, U is the vertical velocity component of the impactor, and C_T is the speed of sound in the target. For $L = 1$ km, $U = 15$ km/s, and C_T in pure rock $= 6$ km/s, $t_{tot} = 0.2$ s. The fact that matter in the spall zone does not get shocked will not reduce its ejecta velocity, because the acceleration is proportional to the *gradient* of the pressure, which is very large near the surface.

On the way up through a 1- to 5-Bar atmosphere—as during the first 0.5 Ga on Mars and Earth—additional heating occurs, which must not raise the ejecta temperature above $100°C$ for microbial survivability. A preliminary computerized simulation (Mileikowsky *et al.* 1999) has indicated that an ejecta diameter of >0.2 m is required to avoid the ejecta being heated to $100°C$ all through.

During landing, a body from interplanetary space that encounters a planet with an atmosphere like Earth is subject to the risk of overheating, as is well known. For example, the space shuttle must have a heat shield in front of it. A meteorite has its own heat shield in the form of its outermost layer. The fall through the atmosphere is so fast (taking only a few tens of seconds) that the heat does not have time to penetrate to the interior. It is well known that meteorites over a certain size are cool inside although the surface has been melted to glass. Large boulders often do not reach the ground in one piece. They easily break but the pieces may still be large enough to be cool inside upon reaching the ground. It is quite probable that a considerable number of

TABLE Ia
Impacts on Mars, Their Rates and Ejecta of <100°C

Impactor diameter, L (km)	Transient crater diameter, D_t (km)	Aprrox. increase of (%)	Final crater diameter, D (km)	Current cumulative rate, $N(\geq D)/10^9$ years	Cratering rate per size interval during 4×10^9 years	Mean fragment size $\bar{l}$ (m)	Max. fragment size $\sim 4\bar{l}$	Mass ejected from Mars at <100°C (kg)
100	470	50	700	5.2×10^{-1}		30	120	8.3×10^{14}
					11.6			
30	180	40	250	3.4		9	36	2.2×10^{13}
					12.4			
20	135	30	175	6.5		6	24	6.6×60^{12}

Note. Impactor diameter, 20–100 km; impactor velocity, 15 km/s.

TABLE Ib

Impacts on Mars: Their Rates, Ejecta of <100°C, and Number of Ejecta Arriving on Earth

Impactor diameter, L (km)	Transient crater diameter, D_t (km)	Approx. increase of diameter (%)	Final crater diameter, D (km)	Current cumulative cratering rate, $N(\geq D)$/Ga	Cratering rate per size interval during 4 Ga	Mean ejecta fragment size, $\bar{l}$ (m)	For meteorites with radius $=\bar{l}/2$					For meteorites with radius $=\bar{l}$				
							Shielding column density (g/cm²)	Survivable transfer time till $N/N_0 = 10^{-6}$ (Ma)		Nos. of		Shielding column density (g/cm²)	Survivable transfer time till $N/N_0 = 10^{-6}$ (Ma)		Nos. of	
								$D.$ radiodurans	$B.$ subtilis, wild	Fragments ejected from Mars at <100°C during 4 Ga	Ejecta meteorites at <100°C arriving on Earth within 8 Ma from launch during 4 Ga		$D.$ radiodurans	$B.$ subtilis, wild	Fragments ejected from Mars at <100°C during 4 Ga	Ejecta meteorites at <100°C arriving on Earth within 8 Ma from launch during 4 Ga
20	135	30	175	6.52	4.32	6.0	900	400	140	8.8×10^7	4.4×10^6	1800				
18	124	30	161	7.60	5.28	5.4	810	190	65	1.0×10^8	5.2×10^6	1620				
16	113	30	147	8.92	7.12	4.8	720	90	32	1.4×10^8	7.2×10^6	1440				
14	102	30	133	10.7	11.20	4.2	630	43	15	2.2×10^8	1.1×10^7	1260				
12	90	30	117	13.5	7.20	3.6	540	20	7	1.5×10^8	7.2×10^6	1080				
11	84	30	109	15.3	9.20	3.3	500	15	5	1.8×10^8	8.8×10^6	1000				
10	78	30	101	17.6	9.60	3.0	450	10	3.3	2.0×10^8	9.6×10^6	900	400	140	8.0×10^6	4.0×10^5
9	72	30	94	20.0	13.6	2.7	400	6.5	2.3	2.8×10^8	1.4×10^7	800	190	65	1.1×10^7	5.5×10^5
8	66	30	86	23.4	20.8	2.4	360	5.0	1.8	4.0×10^8	2.0×10^7	720	90	32	1.6×10^7	8.0×10^5
7	59	30	77	28.6	25.2	2.1	315	3.8	1.3	4.8×10^8	2.4×10^7	630	43	15	2.0×10^7	1.0×10^6
6	53	30	69	34.9	—	1.8	270	2.8	0.9	8.0×10^8	4.0×10^7	540	20	7	3.2×10^7	1.6×10^6
5	46	0	46	72.3	120	1.5	225	2.0	0.7	2.4×10^9	1.1×10^8	450	10	3.3	9.2×10^7	4.6×10^6
4	38	0	38	102	216	1.2	180	1.5	0.5	4.3×10^9	2.1×10^8	360	5	1.8	1.7×10^8	8.5×10^6
3	30	0	30	156	468	0.9	135	1.2	0.4	9.4×10^9	4.6×10^8	270	2.8	0.9	3.8×10^8	1.9×10^7
2	22	0	22	273	1724	0.6	90	1.0	0.3	3.4×10^{10}	1.7×10^9	120	1.2	0.4	1.4×10^9	7.0×10^7
1	13	0	13	704	4740	0.3	45	1.0	0.3	9.5×10^{10}	4.8×10^9	90	1.1	0.3	3.8×10^9	1.9×10^8
0.5	7.5	0	7.5	1890		0.15	22.5	1.0	0.3			45	1.0	0.3		

Note. Impact diameter, 0.5–20 km; impactor velocity, 15 km/s.

TABLE Ic
Volume of Mass ($T < 100°C$, $\rho = 3$ g/cm^3) Ejected from Mars during the Last 4 Ga
by Impactors of Diameter 0.5 km $\leq L \leq$ 20 km (See Table Ib)

Category	L_{imp} (km)	N_{imp} (during 4 Ga)		Average volume of mass$_{ej}$ ($T < 100°C$) per impact (cm^3), 2.8×10^{11} cm^3 ×	Volume of mass$_{ej}$ ($T < 100°C$) during 4 Ga (cm^3), 2.8×10^{11} cm^3 ×
4	20–15	13	0.18%	5.2×10^3	68×10^3
3	15–10	31	0.42%	1.9×10^3	58×10^3
2	10–5	100	1.4%	0.4×10^3	40×10^3
1	5–0.5	7270	98.0%	0.0054×10^3	40×10^3
	Σ 20–0.5	$\Sigma = 7418$	100%	—	$\Sigma = 206 \times 10^3 \times 2.8 \times 10^{11}$ cm^3

microbes in the interior of a meteorite can survive in the temperatures both at launch and at landing. However, small meteorites get uniformly hot and could even evaporate completely before reaching the ground. Extremely small meteorites, again, with diameters not exceeding one or a few micrometers, are not heated above 100°C because they are gently aero-braked by the upper atmosphere, while radiating heat, so that they are less heated in the thick lower atmosphere.

At ejection, the *pressure* caused by the shock wave is zero at the surface and increases with depth. For the survival of microorganisms, pressures up to about 1 Gigapascal (10 kilobar) are acceptable. This condition is fulfilled relatively near the surface. Experiments have shown that a certain fraction of spores of *Bacillus subtilis* (10^{-4}) survived even higher pressures up to 42.5 Gpa of a simulated meteorite impact (Horneck and Brack 1992). Of the surviving bacteria in ejecta just reaching the surface of ground, a significant fraction survives the landing shock (Roten *et al.* 1998) (experiments with rifle bullets). As to *acceleration*, bacteria are routinely subject to acceleration in laboratory centrifuges to 15,000g and much higher (where 1$g =$ Earth acceleration $= 9.8$ m/s^2), for purposes of sedimentation, different tests, etc., without being damaged. As the accelerations at launch of ejecta are $\sim$10,000g, the bacteria can withstand them with sufficient margins. According to a private communication from P. Setlow (1998), "In my experience, dormant spores of *B. subtilis* survive centrifugation at gravitational fields up to at least 15,000g with no significant ($<25\%$) loss in viability."

In ultracentrifuges, however, times of the order of tens of seconds are needed to reach the number of revolutions per second which produce such acceleration values. The rise time of 30 ms imparted to ejecta meteoroids by impacting asteroids or comets—a thousand times faster onset—thus causes much more stress on the microbes than the ultracentrifuges. To check survivabilities of *B. subtilis* (wild type) and *Deinococcus radiodurans* at high accelerations, up to 33,000g, and rise times of the order of 1 ms, shots were performed in an acceleration test facility (Mileikowsky *et al.* 1998). In each of three shots the projectile contained 10 lid-covered cavities, each cavity charged with approximately one million microbes inside different materials. Survival after the shots varied from a few percent to 100%. Not

surprisingly, the spores had the best survival rate. The results showed that a large number of each type of microbe survived each one of the three shots.

3. MARS–EARTH AND EARTH–MARS TRANSFER: METEOROID FLUX AND SIZE

3.1. Long-Time Shielded Transfers and Their Delivery Capacity: Mars to Earth

The present rate of formation of impact craters of diameter greater than D, N (dia $\geq D$), on Earth and the Moon is

$$N(\text{dia} \geq D)(\text{km}^2 - \text{years})^{-1} = 1.8 \times 10^{-15} \left(\frac{D(\text{km})}{22.6(\text{km})} \right)^{-1.8}.$$

Assuming a similar cratering rate on Mars, then for the entire planet over a period of 10^9 years,

$$N(\text{dia} \geq D)(10^9 \text{ years})^{-1} = 260 \times \left(\frac{D(\text{km})}{22.6(\text{km})} \right)^{-1.8}.$$

The transient crater diameter is found using scaling relations, assuming density 3 g/cm^3 for the projectile and for the target, the Mars surface acceleration of gravity, 3.72 m s^{-2}, and an impact velocity of 15 km s^{-1}, to be

$$D_{\text{transient}} = D_t(\text{m}) = 8.83 \times m_{\text{imp}}^{0.26}(\text{kg}) = 60 \times L^{0.78}(\text{m}),$$

where L(m) is the diameter of the projectile in meters. Thus, D_t(km) $= 13.0 \times L^{0.78}$(km) for impacts on Mars at 15 km s^{-1}. The observed crater diameter is somewhat larger depending on several factors: the transient diameter, the angle of repose of the local regolith, the depth of the crater, and the amount of material that falls back into the crater from the edge. Estimates are given in Tables Ia, Ib, and II.

Mass ejected with temperature restriction. For the temperature rise at ejection to be $\leq$100°C, the maximum pressure, P_{max}, must be less than 1 Gpa. The mass ejected from Mars at

Impactor diameter, L (km)	Transient crater diameter, D_t (km)	Increase to final crater diameter (%)	Final crater diameter, D (km)	Current cumulative cratering rate on land, $N(\geq D)/\mathrm{Ga}$	Cratering rate per size interval during 4 Ga	Mean ejecta fragment size, $\bar{l}$ (m)	For meteoroids with radius $= \bar{l}/2$			Nos. of		For meteoroids with radius $= \bar{l}$			Nos. of	
							Shielding column density (g/cm^2)	Survivable transfer time till $N/N_0 = 10^{-6}$ (Ma)		Fragments ejected from Earth at <100°C during 4 Ga	Ejecta meteorites at <100°C arriving on Mars within 8 Ma from launch during 4 Ga	Shielding column density (g/cm^2)	Survivable transfer time till $N/N_0 = 10^{-6}$ (Ma)		Fragments ejected from Earth at <100°C during 4 Ga	Ejecta meteorites at <100°C arriving on Mars within 8 Ma from launch during 4 Ga
								D. radiodurans	*B. subtilis,* wild				*D. radiodurans*	*B. subtilis,* wild		
20	145															
18	133															
16	122	60	195	5.6	4.4	1.1	165	1.4	0.5	2.5×10^9	$\sim 2.5 \times 10^6$	330	3.3	1.2	1.0×10^8	1.0×10^5
14	110	60	176	6.7	6.8	1.0	150	1.3		3.9×10^9						
12	97	60	155	8.4	4.4	0.84	126	1.2		2.5×10^9						
11	91	60	145	9.5	6.0	0.77	115	1.2		3.5×10^9					1.4×10^8	
10	84	60	134	11.0	5.6	0.7	105	1.1	0.35	3.2×10^9		210	1.8	0.65		
9	78	60	125	12.4	9.2											
8	71	60	114	14.7	12.8											
7	64	60	102	17.9	—											
6	57	30	74	32.0	36					2.1×10^{10}	$\sim 2.1 \times 10^7$				8.4×10^8	8.4×10^5
5	49	30	64	41	68	0.35	52	1.0	0.32	3.9×10^{10}		105	1.1	0.35	1.6×10^9	1.6×10^6
4	41	30	53	58	108											
3	33	30	43	85	628											
2	24	0	24	242	1590					9.2×10^{11}	9.2×10^8				3.7×10^{10}	3.7×10^7
1	14	0	14	640		0.07	10	1.3	0.37			21	1.1	0.33		

Note. Impact diameter, 0.5–20 km, impactor velocity, 30 km/s.

<100°C, m_{ej}, expressed in terms of the mass of the impactor, m_{imp}, is (Melosh 1985)

$$m_{ej} = 1.2 \frac{P_{max}}{\rho \times C_T \times V_{imp}} \left[1 - \left(\frac{2V_{ej}}{V_{imp}} \right)^{\frac{1}{3}} \right] \times m_{imp},$$

where C_T is the velocity of sound in target rock $\sim 6 \times 10^3$ m s^{-1}. This gives

$$m_{ej}(kg) = 5.3 \times 10^{-4} \times m_{imp}(kg)$$
$$= 5.3 \times 10^{-4} \times \left[\frac{\pi}{6} L^3(m) \cdot \rho(kg\,m^{-3}) \right] kg$$
$$= 0.83 \times L^3(m) = 8.3 \times 10^8 \times L^3(km)\,kg.$$

Note that we have chosen an impact velocity, 15 km/s, that is substantially larger than the minimum impact velocity on the martian surface. It is also somewhat larger than the mean impact velocity of 13.6 km/s (Bottke *et al.* 1994). Roughly 30% of all impacts on Mars are at speeds faster than 15 km/s. We choose this high velocity because slower impacts do not eject large quantities of debris from the planet. According to the equation above, the impact speed must exceed 10 km/s for any material to be ejected at all.

Average size and number of fragments. According to semi-empirical spall theory (Grady and Kipp 1980, Melosh 1984), the average size of fragments ejected, $\bar{l}$ is

$$\bar{l} = \frac{T}{\rho \times V_{ej}^{2/3} \times V_{imp}^{4/3}} \times L,$$

where T is the tension at fracture in Pa (Pascal), V_{ej} is the speed of ejecta $\sim 5.2 \times 10^3$ m s^{-1} on Mars, V_{imp} is the speed of impactor in m s^{-1}, with $T = 0.1 \times 10^9$ Pa (typical for basalt and other igneous rocks) and $V_{imp} = 15 \times 10^3$ m s^{-1}.

$$\bar{l} = 3 \times 10^{-4} L.$$

The average number of unsterilized fragments per impact, n, is determined from the total mass ejected and the average fragment mass as

$$n = \frac{m_{ej}}{m_{frag}} = \frac{5.3 \times 10^{-4} \times m_{imp}}{\frac{\pi}{6}(\bar{l})^3 \times \rho} = \frac{5.3 \times 10^{-4} \times \frac{\pi}{6} L^3 \times \rho}{\frac{\pi}{6}[3 \times 10^{-4}L]^3 \times \rho}$$
$$= 2 \times 10^7.$$

Note that n is independent of L. These estimates must be regarded as somewhat approximate, since they are based on rough averages of physical properties such as tensile strength and ejection velocity, but they should give at least a good order-of-magnitude indication.

Fraction of fragments with size $\bar{l}$. The distribution of fragment sizes is given by (Grady and Kipp 1980, Melosh *et al.* 1992)

$$F(\geq l) = \left(1 - \frac{l}{l_{max}} \right)^{m_w} \left\{ 1 + m_w \cdot \frac{l}{l_{max}} + \frac{m_w(m_w + 1)}{2} \left(\frac{l}{l_{max}} \right)^2 \right.$$
$$\left. + \frac{m_w(m_w + 1)(m_w + 2)}{6} \left(\frac{l}{l_{max}} \right)^3 \right\},$$

where m_W is Weibulls constant, which for basalt rock on Earth is 9.5. Using that value here gives: $F(\geq 2\bar{l}) = 4 \times 10^{-2}$. The maximum fragment size is $l_{max} = \frac{m_w + 3}{2} \bar{l}$.

Table Ib is based on the above calculations for several sizes of impactors. It gives the mean sizes of the fragments and their numbers as well as the numbers of fragments of sizes $2\bar{l}$. Also shown is the shielding mass in g/cm^2 from the surface to the center of the fragments.

3.2. Long-Time Shielded Transfers and Their Delivery Capacity: Earth to Mars

The expressions for Mars–Earth transfers can be scaled for Earth–Mars transfers according to the following:

$$D_t(E)(km) = D_t(M) \times \left[\left(\frac{V_{imp}(M)}{V_{imp}(E)} \right)^2 \times \frac{9.8\,m\,s^{-2}}{3.72\,m\,s^{-2}} \right]^{-0.22}.$$

Thus, with $V_{imp}(M) = 15$ km s^{-1} and $V_{imp}(E) = 30$ km s^{-1},

$$D_t(E)(km) = 14 \cdot L^{0.78}(km).$$

Again, the assumed impact velocity is higher than the mean impact velocity of 17.6 km/s for asteroids (Bottke *et al.* 1994), although it is lower than the mean impact velocity of comets (60 km/s). Only unusually fast asteroids can eject material from Earth. We assume that about one-third of Earth impactors fulfil this condition.

The final crater diameter on Earth D is obtained from

$$
\begin{array}{llll}
D \approx D_t(km) & \text{for} & D_t < 3\ km \\
D \approx 1.3 D_t(km) & \text{for} & 60 > D_t > 3\ km \\
D \approx 1.6 D_t(km) & \text{for} & 120 > D_t > 60\ km.
\end{array}
$$

Mass ejected with temperature restriction, $\leq 100°C$. Using the expression in Section 3.1,

$$\left(\frac{M_{ej}}{M_{imp}} \right)(Earth)$$

$$= \left(\frac{M_{ej}}{M_{imp}} \right)(Mars) \times \left(\frac{V_{imp}(M)}{V_{imp}(E)} \right) \cdot \frac{\left[1 - \left(\frac{2V_{ej}}{V_{imp}} \right)^{\frac{1}{3}} \right](E)}{\left[1 - \left(\frac{2V_{ej}}{V_{imp}} \right)^{\frac{1}{3}} \right](M)}$$

$$= \left(\frac{M_{ej}}{M_{imp}}\right)(\text{Mars}) \times \frac{15}{30} \times \frac{0.098}{0.1149}$$

$$= \left(\frac{M_{ej}}{M_{imp}}\right)(\text{Mars}) \times 0.427 = 2.3 \times 10^4.$$

Thus, $(\frac{M_{ej}}{M_{imp}})(\text{Earth})(\leq 100°C) = 8.3 \times 0.43 \times 10^8 \times L^3(\text{km}) = 3.6 \times 10^8 \times L^3(\text{km})$ per impact.

Average size and number of fragments. The average size of fragments for Earth are found by scaling relations:

$$\bar{l}(\text{Earth}) = \bar{l}(\text{Mars}) \times \frac{V_{ej}(M)^{\frac{2}{3}}}{V_{ej}(E)^{\frac{2}{3}}} \times \frac{V_{imp}(M)^{\frac{4}{3}}}{V_{imp}(E)^{\frac{4}{3}}}$$

$$= \bar{l}(\text{Mars}) \times \left(\frac{5.2}{11}\right)^{\frac{2}{3}} \times \left(\frac{15}{30}\right)^{\frac{4}{3}}$$

$$= \bar{l}(\text{Mars}) \times 0.607 \times 0.397.$$

Thus,

$$\bar{l}(\text{Earth}) = \bar{l}(\text{Mars}) \times 0.24 = 7 \times 10^{-5} \cdot L.$$

The average number of fragments per impact is

$$\bar{n} = \frac{m_{ej}}{m_{frag}} = \frac{2.3 \times 10^{-4} \cdot \left(\frac{\pi}{6}\rho L^3\right)}{\left(\frac{\pi}{6}\bar{\rho}\bar{l}^3\right)} = 2.3 \times 10^{-4}\left(\frac{L}{\bar{l}}\right)^3$$

$$= 2.3 \times 10^{-4}\left(\frac{1}{7 \times 10^{-5}}\right)^3.$$

Thus $\bar{n} = 6 \times 10^8$ fragments per impact, many of which may not escape the atmosphere.

Number of craters of diameter greater than D on land. The empirical number of new craters per 10^9 years of diameter greater than D on Earth is obtained by introducing Earth's land area in the first formula under subsection 3.1:

$$N(\text{dia} \geq D)(10^9 \text{ years})^{-1} = 270 \times \left[\frac{D(\text{km})}{22.6(\text{km})}\right]^{-1.8}.$$

The factor 270 is very similar to the corresponding factor for Mars (260) because Earth's land surface is almost the same as that of Mars. For Earth to Mars, see Table II.

3.3. Transfer Time Scales

Because the conditions during the interplanetary transfer are hostile to bacteria, it is crucial to understand both how many of the potential host meteoroids arrive on another planet and how long the journey took. Viable transfer is most likely if the highest possible fraction of the impact ejecta arrive rapidly at their destination. In particular, we will be most interested in the meteoroids that make the transfer in less than 1 million years and aim for an accuracy only to a factor of 2 (the other uncertainties

in the problem being much larger than those inherent in the transfer dynamics).

The answers to these questions are now amenable to solution via direct numerical integration of particles leaving the parent planet at speeds just above the planetary escape velocity. Gladman *et al.* (1996) discussed the general case of transfers to Earth from the other terrestrial planets. The specific case of meteoroid transfers from Mars to Earth was the subject of Gladman (1997), wherein it was shown that the delivery to Earth occurred at roughly a constant rate after launch, with the subsequent arrival of ~3–5% of the impact ejecta in ~10 Ma. Subsequently, the simulations reported in that work were reanalyzed to better determine the fraction of the ejecta reaching Earth on time scales shorter than 1 Ma, because an improvement in the statistics was required. In the reanalysis, every 5000 years the impact probability of the ensemble of surviving particles with Earth was computed using the algorithm of Farinella and Davis (1992), which is based on that of Wetherill (1967). The cumulative number of impacts, expressed as a percentage of all the launched particles that struck Earth, as a function of time is reported in Fig. 1, for several different velocities after escape from Mars. The agreement with the impacts directly detected within the integration code over 20 Ma (not shown) is very good, with a relative error of less than 30%.

The values of v_∞ reported in Fig. 1 are the speeds of the initial ejecta after leaving Mars. The numerical integrations began with a set of particles distributed on the surface of a sphere 100 martian radii from the planet, moving directly away at the given v_∞. The launch speed v_{ej} was larger but has mostly been used up escaping from the gravity well of Mars, according to the relation

$$v_\infty = \sqrt{v_{ej}^2 - v_{esc}^2},$$

where $v_\infty = 5.03$ km/s is the escape velocity of Mars. Because this was done in a spherically symmetric fashion whereas ejecta in a single impact leave from a single hemisphere, the delivery rates below need to be considered as averaged over many launch events; since we are discussing the entire set of martian impacts
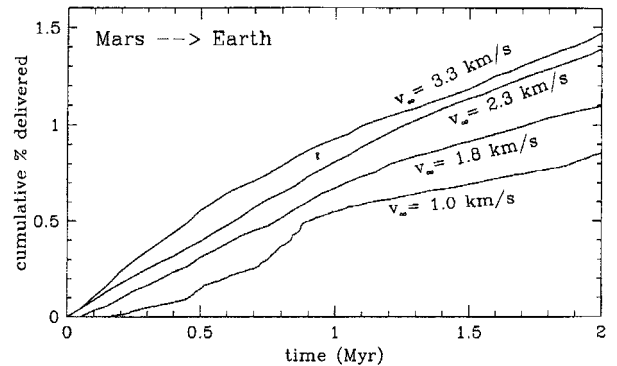
FIG. 1. Cumulative number of impacts, expressed as a percentage of all the launched particles, that struck the Earth, as a function of time for several different velocities after escape from Mars.

over Ga time scales, rather than single impact events, this approximation is valid.

It can be seen that the cumulative fraction of arriving particles climbs almost linearly, implying a nearly constant delivery rate. The more complex shape of the $v_\infty = 1.0$ km/s curve occurs because at this speed none of the martian ejecta initially lies on orbits which cross that of Earth, and it requires a few hundred thousand years before many are pushed into Earth-crossing orbits (Gladman 1997). However, because this corresponds to particles that are ejected at 5.13 km/s (only 100 m/s faster than the escape velocity), only a tiny fraction of the ejecta will be in this state, and thus the other three curves are much more typical. The cumulative delivery fraction of martian ejecta to Earth f_{M2E} can be reasonably approximated by

$$f_{E2M}(T) = 0.6\% \times T \quad (T < 10\,\text{Ma}),$$

to within a factor of 2, where T is measured in Ma. After about 10 Ma this constant delivery rate begins to decline, since destruction of the meteoroids by Sun-grazing dynamics and collisions become important (Gladman 1997).

A similar reanalysis of the simulations of Gladman *et al.* (1995) leads to Fig. 2. In this case the initial conditions are test particles which escaped to heliocentric orbit after being ejected from the Moon at the given v_{ej} (the lunar escape velocity is 2.38 km/s). These initial conditions also satisfactorily represent terrestrial impact ejecta leaving our planet just above Earth's escape velocity. Again, a roughly constant (but much lower) delivery rate to Mars results, which is approximately

$$f_{E2M}(T) = 0.016\% \times T \quad (T < 10\,\text{Ma}),$$

to a factor of 2, and losing validity at about 10 Ma for the same reasons as above.

Having the transfer efficiency from Earth to Mars, we can attempt to derive a second estimate of the launch rate based directly on the observed fraction of martian meteorites. Based on the observed fraction of the Antarctic sample, one can esti-

mate an incoming average flux of ~ 15 martian meteorites per year (Gladman 1997). Since impacts generate a roughly constant flux of ejecta to the Earth over ~ 10 Ma, this implies an averaged launch rate of ~ 300 meteoroids per year. Since it appears that over the last ~ 10 Ma we have only sampled 3 ± 1 impact events (Eugster *et al.* 1997), this implies of order 100 meteoroids/year from each event over the last 10 Ma, and thus we arrive at an estimated 10^9 fragments launched per impact, to be compared with the figure of 2 times 10^7 derived earlier from scaling theory. This suggests that about 1 in 50 fragments is launched at $P_{max} \leq 1$ Gpa. Since we expect (and observe) fragments shocked up to pressures of 50 GPa (e.g., ALH84001), this appears to constitute agreement of theory and observation (within <one order of magnitude) sufficient for our conclusions, particularly as the scaling theory value is on the conservative side.

Let us adopt an intermediate figure of $N_L = 10^8$ meteoroids launched per impact. Then the cumulative number that have arrived on Earth as a function of time (in an average sense) is

$$N(T) = N_L \times f_{M2E}(T) = 6 \times 10^5 T \quad (T < 10\,\text{Ma}),$$

implying that many martian meteoroids make the journey in less than a century, and a few potentially make it in less than a decade (Gladman and Burns 1996). The uncertainties present in these calculations yield these numbers uncertain by an order of magnitude, but it is clear that if one is willing to wait a thousand years then tens to thousands of martian meteorites have landed on Earth, and this must have happened many times during the history of the Solar System. All that remains is to understand if bacteria can survive the rigors of this transfer.

4. THE PROBABILITY OF MICROBES' SURVIVAL AGAINST RADIATION

4.1. Radiation Resistance of Bacteria

The most radiation-resistant bacteria known to exist on Earth today are cocci of the genus *Deinococcus*. The most studied species among them is *D. radiodurans* R1 (cf. the review by B. E. B. Moseley (1983) and that by K. W. Minton (1994)). *D. radiodurans* R1 is nonsporulating, but can go into dormancy or anhydrobiosis under any of the following three environmental conditions: lack of food, lack of water moisture (desiccation), or too-low temperature, $<0°C$. This microbe is very common, it exists in the soil and underground practically everywhere. Another microbe of interest for the present subject is *Bacillus subtilis*. It sporulates, like all Bacilli, and as a spore it withstands desiccation and low temperature very well. It is ubiquitous and highly radiation-resistant, although not to the same extent as *D. radiodurans* R1. These two modern microbes have been used as examples in our study. (Since it cannot be excluded that even more radiation-resistant bacteria might have existed in the harsh environments on early Earth or on early Mars, e.g., ~ 4 Ga ago, we have also included in the study a hypothetical microbe even more radiation-resistant than *D. radiodurans* R1.)
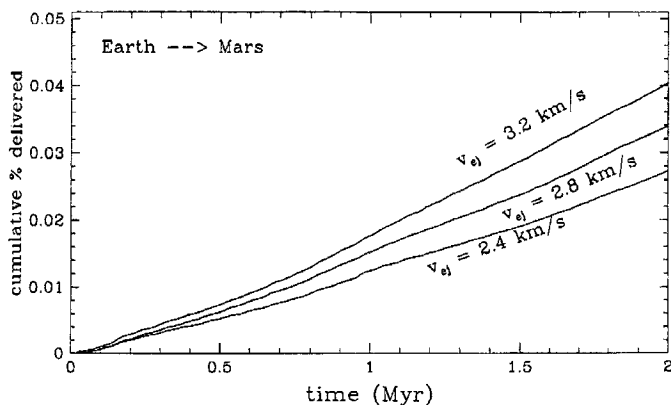

FIG. 2. Cumulative number of impacts, expressed as a percentage of all the launched particles, that struck Mars, as a function of time, for several different velocities after escape from Earth.

During dormancy at low temperature, metabolism, multiplication and repair of radiation damage to the DNA do not occur, or occur only at a negligible rate. When the microbe "wakes up" from dormancy the repair mechanism is started immediately by the repair enzymes, which in general resist radiation damage much longer than the DNA. Regarding the interesting question of how and why some microbe species can have such extraordinary radiation resistance the reader is referred to Moseley (1983).

4.2. Radiation from Space: Shielding Properties of Martian Regolith, Dose Rates, and Microbe Survival Curves

If not sufficiently shielded, microbes are lethally damaged by the following types of radiation in space:

- solar UV radiation, both non ionizing and ionizing
- diffuse X-rays
- galactic cosmic rays, GCR, both charged particles and gamma rays
- solar particles in interplanetary space.

A few micrometers of meteorite material are sufficient to give efficient protection against UV if the material is without cracks: less than 0.5 g/cm^2 is required against the diffuse X-rays, and about 30 g/cm^2 against the solar particles. However, because new particles are created in the shielding material by the GCR, the GCR-produced dose rates first increase with increasing shielding thickness to a maximum and decrease thereafter as more shielding is added, down to the same dose rate as is caused by the GCR without shielding, and then decrease further. For martian regolith the physical dose rate maximum is at 30 g/cm^2 and at 90 g/cm^2 the shield begins to reduce the physical dose rate below its value with no GCR-shielding at all (Table IIIa).

The probability of killing a microbe by ions is represented by an action cross section σ that is dependent on each ion charge and velocity as modeled in the track structure model (Katz *et al.* 1971, Cucinotta *et al.* 1995). The action cross section is multiplied by the particle fluence F to find the killing frequency, σF, and contributions from all ion species at a given shielding depth are summed. The biologically effective dose rates and the resulting killing frequencies σF per year do not coincide with physical dose rates although they have a similar behavior of first increasing to a maximum with increasing shielding thickness, before σF decreases down to the value of unshielded GCR exposure. However, the kill probabilities are different for different bacterial species and strains, because their sensitivity to radiation

TABLE IIIa
Shield Material Against the GCR: Martian Regolith

		Type of microbe							
		Bacillus subtilis (wild type)		*Bacillus subtilis* (pol-)		*Deinococcus radiodurans*		Hypothetical species	
Shield thickness (g/cm^2)	Physical dose rate (cGy/year)	Kill freq/ year σF ($\times 10^{-5}$)	Time till $N/N_0 = 10^{-6}$ (Ma)	Kill freq/ year σF ($\times 10^{-5}$)	Time till $N/N_0 = 10^{-6}$ (Ma)	Kill freq/ year σF ($\times 10^{-6}$)	Time till $N/N_0 = 10^{-6}$ (Ma)	Kill freq/ year σF ($\times 10^{-7}$)	Time till $N/N_0 = 10^{-6}$ (Ma)
0	19.4	2.1	0.66	5.2	0.27	4.9	2.8	3.3	42
1	22.2	3.9	0.36	9.7	0.14	11	1.3	8.5	16
2	22.6	3.9	0.36	9.7	0.14	10	1.4	8.4	16
3	22.8	3.8	0.36	9.6	0.14	10	1.4	8.3	17
5	23.1	3.8	0.36	9.6	0.14	10	1.4	8.3	17
10	23.8	3.8	0.36	9.8	0.14	11	1.3	8.8	16
20	24.6	3.8	0.36	9.9	0.14	11	1.3	8.9	16
30	24.9	4.4	0.32	11	0.13	13	1.1	11	13
40	24.6	4.5	0.31	11	0.13	14	1	12	12
50	23.9	4.5	0.31	12	0.12	14	1	13	11
75	21.3	4.4	0.32	11	0.13	14	1	13	11
100	18.3	4.0	0.35	10	0.14	13	1.1	12	12
125	15.3	3.6	0.39	9.2	0.15	12	1.2	11	13
150	12.7	3.2	0.43	8.1	0.17	11	1.3	9.8	14
175	10.5	2.8	0.5	7.0	0.2	9.2	1.5	8.7	16
200	8.7	2.4	0.58	6.1	0.23	8	1.7	7.6	18
250	5.9	1.8	0.77[a]	4.4	0.32[a]	5.9	2.4	5.6	25
300	4.0	1.3	1.1	3.1	0.45	4.3	3.2[a]	4.1	34
400	1.8	0.62	2.2	1.5	0.93	2.1	6.4	2	70[a]
500	0.8	0.29	4.8	0.7	2	0.98	14	0.94	150
600	0.3	0.13	10.7	0.31	4.5	0.44	32	0.42	330
700	0.13	0.05	26	0.13	11	0.19	73	0.18	770
800	0.06	0.02	60	0.06	25	0.08	175	0.08	1800

[a] Approximately where shielding becomes effective in prolonging the bacterias' lifetime.

can vary by several orders of magnitude. The result of this is that for every shielding material, there is a considerable thickness up to which the material does not shield at all: on the contrary, the dose rate and killing frequency are increased. Furthermore, that minimum thickness is somewhat different for different bacteria.

The calculation of survival curves. The atomic numbers of the nuclei in GCR which are of interest for this study are those from $Z = 1$ to $Z = 28$, i.e., from hydrogen to nickel. Nuclei with $Z > 28$ are rare and contribute very little to the dose rate. Each element's nuclei have their own energy spectrum and intensities in interplanetary space. They have been used in the calculations for energies up to 100 GeV/amu. Nuclei with energies above 100 GeV/amu are too rare to contribute significantly to the dose rate. The physical dose is the energy deposited in the cell. However, the total biologically effective dose imparted to the microbe depends also on the microbe's own properties and the composition of the radiation field at the dose point.

The survival curves—i.e., the fraction of surviving microbes N/N_0 out of an original population N_0 as a function of time t in space and of regolith shielding thickness—were calculated for this study according to $N/N_0 = e^{-\sigma F t}$, where σF is the killing frequency per year. The calculations are made with the HZETRN transport code using the track structure model of cell or microbe killing (Katz *et al.* 1971, Cucinotta *et al.* 1995a, 1996). The model was fit to the data of Baltschukat and Horneck (1991) for *B. subtilis* (wild type and pol$^-$) spores and of Moseley (1983) and Minton (1994) for *D. radiodurans* R1.

For the time being the code covers the dose rates and estimates of biological effects caused by the nuclei in the GCR, and not those of the primary GCR electrons and gammas. These latter contributions are an order of magnitude smaller than the GCR nuclei. The effects of fragmentation of the GCR ion of high charge and energy (HZE) are treated in detail, as are the secondary particle knockouts from the shield material constituents. The secondary pions and other mesons are not yet included in the codes and are known to contribute (mainly through the electromagnetic cascades resulting from the neutral pion decay) up to 30% of the total biological dose. These effects will be included in a later version of the HZETRN code and are more than compensated by use of the 1977 maximum GCR environment in place of the appropriate average over the solar cycle.

The calculations were made for a "worst case," the 1977 Solar Minimum GCR (maximum intensity), for four types of microbes, given in Table III with their gamma ray sensitivity for comparison. X-ray sensitivity of the microbes of the present study:

	D_0 (Gy)
Spores of *B. subtilis* (wild type strain)	222
Spores of *B. subtilis* (pol$^-$)	170
D. radiodurans R1	1000
Hypothetical, high radiation resistance	5000,

where D_0 is the dose of X-rays reducing survival to e^{-1}.

The martian regolith is used to represent the meteorite material in the present calculation as derived by Simonsen *at al.* (1990) from the data given by Smith and West (1983). The regolith density at the Viking 1 Lander site varied from 1 to 1.8 g/cm^3. A density of 3 g/cm^3 is more appropriate for martian meteorites and is assumed in the present calculation. The composition of the martian regolith (given as percentages by weight) is as follows: 44.7% SiO_2, 9.7% Al_2O_3, 18.2% Fe_2O_3, 8.3% MgO, 5.6% CaO, <0.3% K_2O, 0.9% TiO_2, 7.7% SO_3, 0.7% Cl (total 91.8%). For the purposes of the present calculation, minor elements are included with their nearest representative constituents (for example, Al is included as Mg and S as Si). This gives 58.2% SiO_2, 23.7% Fe_2O_3, 10.8% MgO, and 7.3% CaO.

One can see from Table IIIa that—considering the effects of the GCR and solar rays only—out of a population of 10^8 *D. radiodurans* R1 cells in the center of a regolith boulder with shield thickness 500 g/cm^2, 100 cells would survive the GCR after 14 million years in space, and the same proportion would still be alive after 32 million, 73 million, and 175 million years for shield thicknesses of 600, 700, and 800 g/cm^2, respectively. (This of course regards GCR-caused damage only.) Table IIIa shows the same type of survival curve for a similar population of 10^8 spores of *B. subtilis* (wild type strain). In this case, for a shield thickness of 500 g/cm^2, 100 spores would survive the GCR after 4.8 million years in space, and this survival time would increase to 11 million, 26 million, and 60 million years for shield thicknesses of 600, 700, and 800 g/cm^2, respectively (regarding GCR only).

One can see from Table IIIa that the kill frequency σF per year for *D. radiodurans* R1 has its maximum at about 50 g/cm^2 shielding and comes down to the same value as with no shielding at the shield thickness at about 280 g/cm^2, so the shield has to be at least 0.93 m thick before it begins to help. For *B. subtilis* (wild type) σF max. is also at 50 g/cm^2 but in this case it is at 220 g/cm^2 of shielding that σF is equal to σF at no shielding, so the shield helps from a thickness of 0.73 m and on. However, even at 50 g/cm^2, i.e., at a diameter of 0.33 m, the least favorable dimension of a meteorite from the point of view of GCR radiation, the time until $N/N_0 = 10^{-6}$ in interplanetary space is 1 million years for *D. radiodurans* R1 and 0.3 million years for *B. subtilis* (wild type) spores, as shown in Table IIIa.

If N_d is the desired minimum number of arriving viable individuals and with $N_d/N_0 > 1/N_0$, then the time τ (years) until N/N_0 is $= N_d/N_0$ is obtained from the expression

$$\tau(\text{years}) = \frac{\ln(N_0/N_d)}{\sigma F/\text{annum}}$$

For example, assume $N_0 = 10^8$, $N_d/N_0 = 10^{-6}$ as above. For *D. radiodurans* R1 shielded by 500 g/cm^2 martian regolith (diameter 3.3 m), $\sigma F/a = 9.8 \times 10^{-7}$ (see Table III). Then

$$\tau(\text{years}) = \frac{\ln \times 10^6}{9.8 \times 10^{-7}} = 14 \text{ million years.}$$

TABLE IIIb
Effects of GCR and Natural Radioactivity

Mass at $\rho=3.0$ g/cm^3 (kg)	Radius at $\rho=3.0$ g/cm^3 (cm)	Shield thickness (g/cm^2)	Physical dose rate, GCR (cGy/year)	*Bacillus subtilis* (wild type)				*Deinococcus radiodurans*			
				Kill freq/year σF ($\times10^{-5}$)	Time till $N/N_0=10^{-6}$ (Ma)			Kill freq/year σF ($\times10^{-6}$)	Time till $N/N_0=10^{-6}$ (Ma)		
					Natural radioactivity: 0	0.08 cGy/year[a]	5 cGy/year[a]		Natural radioactivity: 0	0.08 cGy/year[a]	5 cGy/year[a]
		0	19.4	2.1	0.66			4.9	2.8		
	0.33	1	22.2	3.9	0.36		0.27	11	1.3		0.94
		2	22.6	3.9	0.36			10	1.4		
	1.0	3	22.8	3.8	0.36			10	1.4		
		5	23.1	3.8	0.36			10	1.4		
0.340	3.0	9									
0.450	3.3	10	23.8	3.8	0.36		0.27	11	1.3		0.94
		20	24.6	3.8	0.36			11	1.3		
	10	30	24.9	4.4	0.32			13	1.1		
	13	40	24.6	4.5	0.31			14	1		
	16	50	23.9	4.5	0.31		0.24	14	1		0.78
	25	75	21.3	4.4	0.32			14	1		
340	30	90									
450	33	100	18.3	4.0	0.35		0.26	13	1.1		0.82
		125	15.3	3.6	0.39			12	1.2		
	50	150	12.7	3.2	0.43			11	1.3		
		175	10.5	2.8	0.5			9.2	1.5		
3,600	66	200	8.7	2.4	0.58		0.38	8	1.7		1.2
		250	5.9	1.8	0.77[b]			5.9	2.4		
12,600	100	300	4.0	1.3	1.1		0.54	4.3	3.2[b]		1.7
	133	400	1.8	0.62	2.2	2.2	0.74	2.1	6.4	6.4	2.4
	166	500	0.8	0.29	4.8	4.5	0.90	0.98	14	13	2.9
100,800	200	600	0.3	0.13	10.7	9.2	1.00	0.44	32	28	3.3
	233	700	0.13	0.05	26	20	1.06	0.19	73	55	3.5
237,000	266	800	0.06	0.02	60	35	1.09	0.08	175	99	3.5
		>800	~0	~0	69		1.11	~0	230		3.7

[a] 0.08 cGy/year corresponds to the highest natural radioactivity in any of the known martian meteorites. 5 cGy/a is the average dose-rate in granite on Earth.
[b] Approximately where shielding becomes effective in prolonging the bacterias' lifetime.

When studying probabilities of natural transfer between solar systems (our study, Part 2), very maximally long viable transfer times are essential. However, in studying natural transfer between Mars and Earth (this Part 1), the purpose was to arrive at the order of magnitude of viable arrivals after flight times shorter than 1 million years. In presenting the results (Tables VIIc–XI), flight times of up to 100,000 years and 330,000 years were chosen.

4.3. The Limitation of Microbe Lifetime as Caused by Natural Radioactivity

A bacterial population which is very efficiently shielded by the meteorite material could in principle be subject to a limitation of its lifespan by the natural radioactivity of the meteorite material itself. This natural radioactivity is mainly due to the three series starting with U^{238}, U^{235}, and Th^{232}, respectively, and to the K^{40}, with half-lives of 4.5×10^9 years 0.71×10^9 years, 14×10^9 years, and 1.3×10^9 years. Although the abundances of these elements on Mars are not known with precision, calculations can be made using (a) the measured concentrations in the known martian meteorites and (b) the normal cosmic abundances. The present mass fractions relative to Si of U^{238}, U^{235}, Th^{232}, and K^{40}, respectively, in cosmic abundance are 0.8×10^{-7}, 0.6×10^{-8}, 2.8×10^{-7}, and 5.6×10^{-7}.

From the Th and U decay chains the dominant energy deposition occurs via their α-particles, which have a range of only 20–30 μm. However, in the decay sequence are the gases radon and thoron which diffuse through the pores of the meteorite and deposit their solid daughter elements on the pore walls, from where they radiate the rest of the decay chain. In a relatively porous meteorite some of the radon and thoron may diffuse out into space. As to the β-decays it should be noted that two-thirds of the decay energy leaves the meteorite in the form of neutrinos without depositing any energy. The range of the β particles is up to $\approx$1 cm. Tables IVa and IVb show the physical dose rates and the doses generated in each of the martian meteorites by K^{40} and by the U^{238}, U^{235}, and Th^{232} series. The arithmetic mean value of the physical dose rates is 0.040 cGy/year with the highest value being twice the average (Shergotty) and the lowest being one-fifth of the average (ALH 84001). At present dose rates, and at the average value of 0.040 cGy/year, a martian meteorite receives an accumulated physical dose of 10 kGy after 25 Ma. This means that its effect is not significant relative to other risks for bacterial viability during space journeys.

Table IVb also shows the higher physical doses that would have been deposited in each of 10 of the martian meteorites had they been ejected shortly after the formation of the rock they are made from (and assuming the same times of flight to Earth as they actually had). Calculations based on cosmic abundances give a physical dose rate which is a low-level case.

The natural radioactivity in ejecta meteorites from Earth to Mars is given in Table V. It is clear that the high physical dose-rates are those in the granites (3–10 cGy/year), which are also the most common group. Sediments have dose rates which are lower (1–2.5 cGy/year), but still far above the average of the 12 known martian meteorites (0.04 cGy/year). The natural radioactivity of the very common granite rock group creates a physical dose of 5 kGy after only about 100,000 years, that of the sediments after a few hundred thousand years, and that of the basalts after about a million years. Overall the natural radioactivity in 99% of ejecta from Earth—although about two orders of magnitude more intense than that in the known ejecta from Mars—thus does not significantly limit their viable flight times relative to the limitations set by DNA decay. The combined effect of natural radioactivity and radiation from space is treated in Section 4.4 below.

TABLE IVa
The Naturally Radioactive Isotopes K^{40}, Th^{232}, U^{238}, and U^{235}, Their Concentration by Mass in the Known Martian Meteorites and Average Physical Dose Rates

	K^{40}	Th^{232}	U^{238}	U^{235}	Σ
Isotopic abundance	0.0119	100	99.28	0.71	
Decay constant, λ (year^{-1})	5.54×10^{-10}	0.495×10^{-10}	1.551×10^{-10}	9.85×10^{-10}	
Total decay energy, Ed_{tot} (MeV)	1.34	42.66	51.7	46.4	
Total energy retained after correction for neutrino energy loss, Ed_{ret} (MeV/decay)	0.69	40.4	47.5	44.4	
Physical dose/year in cGy/year $= c$ (ppm) $\times f$, where factor $f = 10^{-6} \times \frac{6.06 \times 10^{23} \times \lambda \times ED_{ret}(MeV) \times 10^6}{A \times 62.4 \times 10^{12}}$	$f = 0.093$	$f = 0.084$	$f = 0.300$	$f = 1.81$	
Present time					
Concentration c (ppm) for the average of known martian meteorites	0.085	0.14	0.059	4.1×10^{-4}	
Physical dose/a for average of known martian meteorites (cGy/year) $= c$ (ppm) $\times f$	0.008	0.012	0.018	0.0007	0.039
4 Ga B. P.					
Physical dose/year for average of known martian meteorites	$9.2 \times$ present $= 0.074$	$1.22 \times$ present $= 0.015$	$1.86 \times$ present $= 0.033$	$51.4 \times$ present $= 0.036$	0.16

Note. Number of years to reach 5 kGy of physical dose at present time: 12.5 Ma.

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TABLE IVb
The Natural Radioactivity of the Martian Meteorites

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| | Basic martian meteorite data[a] | | | Natural radioactivity in the martian meteorites | | | |
| | | | | At present time | | At the time of their rock formation, $t_{rf.}$ | |
	Mass (kg)	Measured age Average age (Ga)	Travel in space (Ma)	Actual physical dose rates from $K^{40} + Th + U$ (cGy/year (av.))	Actual physical dose from $K^{40} + Th + U$ (10 kGy)	Physical dose rate from $K^{40} + Th + U$ (cGy/year (av.))	Physical dose if travel at $\sim t_{rf.}$ Travel duration as col. 3 (10 kGy)
Nakhla	10?	0.8–1.4 1.1	10–12	0.046	0.46–0.55	0.062	0.62–0.74
Lafayette	0.8	0.8–1.3 1.1	6.5–11	0.023 + Th	0.15–0.25 + Th	0.036 + Th	0.23–0.40 + Th
Governador Valadores	0.158	1.32–1.36 1.34	8–9	0.041 + U	0.33–0.37 + U	0.073 + U	0.58–0.66 + U
Zagami	~18	0.18–0.26 0.22	2.8 ± 0.2	0.071	0.20 ± 0.015	0.079	0.22
Shergotty	5	0.16–0.25 0.21	2.8	0.082	0.23	0.085	0.24
Chassigny	~4	1.2–1.4 1.3	11	0.016	0.18	0.024	0.26
ALHA 77005	0.482	0.15–0.33 0.24	2.5–3.4	0.019	0.048–0.065	0.020	0.050–0.068
EETA 79001A	7.542	0.15–0.24 0.20	0.5–0.9	0.016	0.008–0.014	0.017	0.0085–0.0153
EETA 79001B	~0.400		0.5–0.9	0.030	0.015–0.026		
ALH 84001	1.931	3.6–4.5 4.1	14.5–18	0.0078	0.11–0.14	0.035	0.51–0.63
LEW 88516	0.013	—	3.0–4.1	0.020	0.061–0.089		
QUE 94201	0.012	0.33–1.3 0.82	2.4–2.6	0.012	0.029–0.031	0.015	0.036–0.039

[a] From Mars Meteorite Compendium 1996.

There is, however, one group of rocks which have very low natural abundance of radioactive elements. These are ultramafic rocks, such as peridotite and dunite, which are common in Earth's interior but very rare on the planet surface. Fragments of ultramafic rocks can be emplaced into the uppermost parts of Earth's crust by large-scale tectonic movements. Ultramafic rocks may have physical dose rates (10–25 μGy/year) that are even lower than the lowest rate among the known martian meteorites (80 μGy/year in ALH 84001). Even with a total abundance of only 1‰ of these rock types near Earth's surface, the 15-km impactors have probably delivered thousands of <100°C, 1-m-size ejecta of this type from Earth to Mars over the past 4 billion years, and even the more frequent 1-km impactors have probably delivered large numbers of smaller ones. During the "heavy bombardment" period the numbers of ejecta delivered were one to two orders of magnitude larger. The viable flight times of ejecta of this type are not limited by their very low natural radioactivity. However, the effects of cosmic and solar rays and, more so, of DNA decay limit the number of viable arrivals of such ejecta on Mars from 1‰ landing on Mars (given enough time as in Table II) to a fraction.

One should keep in mind that all the physical dose values in Tables IV and V are based on concentrations which are average values and which may vary considerably up and down (a factor of 3 in either direction as is quite common on Earth).

4.4 The Combined Effect of Radiation from Space and Natural Radioactivity

To estimate the contribution from alpha particles, action cross sections (Cucinotta 1995b) were used, generated by the track structure model for 5-MeV alpha, which can be considered conservative for energies of 4–8.8 MeV (the maximum is about 5 MeV). The action cross section changes slowly with alpha energy in this region. To be conservative it is assumed that total exposure due to natural radioactivity is from alphas. Fluence F for 1 cGy/year at LET of 32 keV/micrometer provides 1940 alphas per year. Then,

Microbe	σ (cm^2)	σF/year
Spores of *B. subtilis* (wild type strain)	1.29×10^{-9}	2.50×10^{-6}
Spores of *B. subtilis* (pol$^-$)	1.57×10^{-9}	3.05×10^{-6}
D. radiodurans R1	3.87×10^{-10}	7.51×10^{-7}
Hypothetical, high radiation resistance	1.41×10^{-10}	2.74×10^{-7}.

TABLE V

Physical Dose Rates from Natural Radioactivity in Ejecta Materials from Earth

Some typical rocks and terrestrial contexts	Dose rates caused by				
	K^{40} (cGy/year)	Th (cGy/year)	U (cGy/year)	Σ $K^{40} + Th + U$ (cGy/year)	Time till dose $= 5\,kGy$ (Ma)
Magmatic rocks					
77%					
G-1 granite	0.49	4.20	1.02	5.7	0.09
G-2 granite	0.41	2.02	0.6	3.0	0.17
GSR-1 granodiorite	0.50	8.74	0.6	9.8	0.05
22%					
BCR-1 basalt	0.16	0.50	0.51	1.2	0.42
W-1 diabase	0.058	0.20	0.18	0.44	1.1
BHVO-1 basalt	0.048	0.076	0.15	0.27	1.9
Av. basalt	0.093	0.23	0.27	0.59	0.85
<1%					
PCC-1 peridotite	0.1×10^{-3}	0.8×10^{-3}	1.5×10^{-3}	0.0024	210
DTS-1 dunite	0.1×10^{-3}	0.8×10^{-3}	1.8×10^{-3}	0.0021	240
Av. ultramafic	0.3×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	0.0010	500
Sediments					
72%					
Av. shale	0.30	1.01	1.11	2.4	0.21
15%					
Av. carbonates					
11%					
Av. sandstone	0.12	0.46	0.51	1.1	0.46
Av. upper continental crust	0.28	0.88	0.75	1.9	0.26
Archean (4.0–2.5 Ga) upper crust					
Present dose-rate					
Dose-rate 4.0 Ga BP	1.6	0.6	1.8	4.0	0.12
Archean mafic volcanic					
Present dose-rate					
Dose-rate 4.0 Ga BP	0.26	0.08	0.21	0.55	0.90
Primitive mantle					
Present dose-rate	0.0020	0.0054	0.0056	0.013	38
Dose-rate 4.0 Ga BP	0.018	0.0065	0.022	0.047	11

These numbers are added to σFs for GCR to estimate the time until $N/N_0 = 10^{-6}$ for combined GCR and natural radioactivity. Thus τ(years) $= \frac{\ln(N_0/N_d)}{\sigma F_{GCR}/\text{year} + \sigma F_A/\text{year}}$. Table IIIb shows that for *D. radiodurans* R1 and *B. subtilis* (wild type), an alpha dose rate of 0.1 cGy/years (as in the martian meteorite with the highest natural radioactivity) begins to decrease the time till $N/N_0 = 10^{-6}$ with increasing meteorite radius from ~1.3 m and up. At radius 2.7 m the decrease is ~40% and ~50% for *D. radiodurans* R1 and *B. subtilis* (wild type), respectively.

In the direction Earth–Mars the effect of natural radioactivity is usually much stronger than in the Mars–Earth direction because the dose rate of natural radioactivity in, e.g., granite is 5.0 cGy/year instead of 0.1 cGy/year. This means that the time until $N/N_0 = 10^{-6}$ is decreased by ~25% for ejecta of radii 3 to 30 cm, by ~50% for radius 1.0 m, by ~90% for radius 2.0 m, and by ~98% for ejecta of radius 2.7 m.

5. OTHER THREATS TO DNA AND ENZYMES

5.1. *Threats to DNA by Oxygen, Hydrolysis, Other Chemicals, Vacuum, and Temperature*

It has recently been shown by a German–Swedish–American group (Krings *et al.* 1997) that Neanderthal man (300,000 to 30,000 years ago) and modern man, although they coexisted for a long time, never interbred. This was proven by comparing their respective mitochondrial DNA. These experts state however that the same comparison can never be made for *Homo erectus*, who lived much earlier, because over that long period the fossils' DNA would have deteriorated by oxygen attack and hydrolysis, causing deamination, depurination, and depyrimidination. The *Jurassic Park* scenario is therefore not possible.

Could oxygen attack and hydrolysis similarly deteriorate the DNA of bacteria inside martian meteorites, shortening their

viable lifetime? That would seem to take a much longer time, the environment within the meteorite being completely different from that of fossils on Earth, and the prokaryotic microbes being completely different from the eukaryotic mammal cells. The fossils' environment on Earth is characterized by plenty of oxygen, abundant rainwater with a variety of ions in solution and temperatures above H_2O freezing point, except in permafrost. The environments inside the meteorites discussed here are largely the opposite for porous compartments open to the outside: no gaseous oxygen, no liquid water, high vacuum up to 10^{-14} Pa, temperature mostly below 0°C, and no migrating ions. DNA damage to metabolizing microbes depends to some extent on the pH-value, but this should not apply to spores and anhydrous *D. radiodurans* R1 because they do not metabolize in the dormant state (Setlow 1993). Also, such porous compartments which become isolated from the space vacuum by molten and vitrified ejecta layers during exit through the atmosphere (see Section 6) are subject to temperatures lower than in Earth soil.

Although some anhydrobiotes are very resistant to extreme dryness and even repeated freeze-drying/rehydration cycles (Fairhead *et al.*, 1994), some DNA decay seems to be caused in connection with the desiccating process itself. Exposure of spores of *B. subtilis* and cells of *D. radiodurans* to extended periods of vacuum (3×10^{-4} Pa) resulted in DNA strand breaks and crosslinking of DNA to proteins (Dose *et al.* 1991, Dose and Gill 1995). At low temperatures (e.g., 80 K) the rate constants for production of DNA strand breaks were reduced by approximately a factor of 2 compared to room temperature (Dose and Klein 1996). Unique tandem-base change mutations were observed in *B. subtilis* spores after forced dehydration of its DNA in vacuum of 10^{-5} Pa (Munakata *et al.* 1997). There is strong experimental evidence that such damage is repaired in *D. radiodurans* by the same DNA-repair mechanism that takes care of radiation damage (Mattimore and Battista 1996). Radiation-sensitive mutants of *D. radiodurans* R1 are more than one order of magnitude more sensitive to desiccation than the radiation-resistant wild-type strain. In comparison with another species, *Escherichia coli*, the superiority of *D. radiodurans* R1 in terms of desiccation resistance was even greater than could be explained by its superior DNA-repair system. It seems that *D. radiodurans* R1 possesses a unique defense mechanism against damage not only to its DNA but also to other biological molecules in the cell (perhaps the enzymes needed by the repair system?). In bacterial endospores, e.g., of *B. subtilis*, the DNA is extremely well-protected against damage resulting from treatments such as desiccation, temperature extremes, radiation, or oxidative stress. This protection is mainly due to the binding of a group of small acid-soluble proteins to the DNA, thereby changing the conformation of the DNA from B to A (Mohr *et al.* 1991) and altering its chemical and enzymatic reactivity (Fairhead *et al.* 1993). Furthermore, the low permeability of the spore wall, the cortex, and the low water content of the spore core play a major role in the high resistance of bacterial spores to environmental stressors. Nevertheless, damage to the DNA would accumulate during long-term exposure to the vacuum of space, because DNA repair is not active during anhydrobiosis. The survival will finally depend on the efficiency of the repair systems after rehydration and germination. It was shown that the high resistance to vacuum observed in repair-proficient strains of *B. subtilis* disappeared in strains that were deficient in DNA repair (Munakata *et al.* 1997).

A different threat to very long-term viability of DNA or microbes inside martian meteorites comes from damage by temperature, even at temperatures below 0°C. Spontaneous decay of biological macromolecules—e.g., proteins and DNA—decreases strongly with falling temperatures. At 0°C it is so low that it could not be measured until very recently. However, between 37 and 90°C, for example, decay rates have been measured, and the values can be put into a diagram as a function of $1/T$ (where T is the temperature in K) to form what is known as an Arrhenius plot; the sloping straight line formed by the points can then be extrapolated down to temperatures of and below 0°C. The form of the line is given by the expression $A_M \cdot e^{\frac{-\Delta E}{RT}}$, where A_M is a constant characteristic for each kind of molecule, ΔE is the activation energy, the energy required to cause decay (in cal mol^{-1}), R is the general gas constant (1.98 cal mol^{-1} K^{-1}), and T is the temperature in K. In solution, A_M can also depend on ions and chemicals in the environment.

Fundamental measurements for DNA by Lindahl *et al.* have provided values for A_M and ΔE for the main phenomena of deamination, depurination, and depyrimidination of bacterial DNA (Lindahl and Nyberg 1972, Lindahl and Andersson, 1972, Lindahl and Karlström 1973, Lindahl and Nyberg 1974, Lindahl 1993). The rate constants for depurination and depyrimidination of that experimental work which are applicable for the purposes of the present study are given in Table VIIa, as are several derived rate constants calculated for temperatures in the interval −20 to +30°C. The reason for including such relatively high temperatures above 0°C is that at solar luminosity $L_\odot$, a fraction of the meteorites are warmed—depending on their albedo and emissivity—during the relatively short time their orbit is near or crossing Earth's orbit.

TABLE VI
T_c (°K) Values and q Values

Astronomical units, semimajor axis	Eccentricity				
	0.0	0.2	0.4	0.6	0.8
1.6	220	221	225	233	250
	1.60	1.28	0.96	0.64	0.32
1.4	235	236	240	248	267
	1.40	1.12	0.84	0.56	0.28
1.2	254	255	260	269	289
	1.20	0.96	0.72	0.48	0.24
1.0	278	279	284	294	316
	1.00	0.80	0.60	0.40	0.20
0.8	311	313	318	329	353
	0.80	0.64	0.48	0.32	0.16

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TABLE VIIa

DNA Decay Processes by Hydrolysis and Their k Values $L = 1.0\, L_{\odot}$

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Range of values of $\frac{1-A}{\varepsilon}$ temp. T (°C)	Temp. T of meteoroid at 1 AU and at 1.5 AU (°C)	Depurination $k\,(\mathrm{s}^{-1})$	Depyrimidination thymine $k\,(\mathrm{s}^{-1})$	Depyrimidination cytosine $k\,(\mathrm{s}^{-1})^t$	$\Sigma k\,(\mathrm{s}^{-1})$	$\Sigma k\,(\mathrm{Ma}^{-1})$
	$+95^a$		2.3×10^{-8a}	1.8×10^{-8a}		
	$+70^a$	4×10^{-9a}				
	Temp. T of meteoroid in Earth-like orbit; distance to Sun 1 AU					
1.2	$+20$	1.59×10^{-12}	4.28×10^{-13}	3.32×10^{-13}	2.35×10^{-12}	74
1.15	$+15$	6.26×10^{-13}	1.69×10^{-13}	1.31×10^{-13}	0.93×10^{-12}	29
1.07	$+10$	2.40×10^{-13}	6.47×10^{-14}	5.02×10^{-14}	0.35×10^{-12}	11
1.0	$+5$	8.82×10^{-14}	2.38×10^{-14}	1.85×10^{-14}	1.31×10^{-13}	4.1
0.9	0	3.15×10^{-14}	8.5×10^{-15}	6.6×10^{-15}	0.47×10^{-13}	1.5
0.8	-10	3.55×10^{-15}	9.6×10^{-16}	7.5×10^{-16}	0.53×10^{-14}	0.17
0.7	-20	3.40×10^{-16}	9.2×10^{-17}	7.1×10^{-17}	0.50×10^{-15}	0.016
	Temp. T of meteoroid in Mars-like orbit; distance to Sun 1.5 AU					
1.2	-35	6.87×10^{-18}	1.85×10^{-18}	1.44×10^{-18}	1.02×10^{-17}	0.32×10^{-3}
1.0	-45	3.81×10^{-19}	1.03×10^{-19}	8.01×10^{-20}	0.56×10^{-18}	0.17×10^{-4}
0.85	-55	1.64×10^{-20}	0.44×10^{-20}	0.34×10^{-20}	0.24×10^{-19}	0.76×10^{-6}

Note. Regarding the applicability of the Arrhenius plot at temperatures below 0°C, see text in Subsection 5.4.

[a] Measurements. All other data are calculations by Arrhenius plots based on the measurements.

It should be noted that the experiments were made in solution, whereas in meteorites in the vacuum of space there is no liquid water. Thus the chemical attack on DNA, as pointed out above, must be far less effective in meteorites, making the rate constants in Table VIIa extremely conservative. These are nevertheless the values we will use.

5.2. Chemical Damage of Enzymes by Migrating Metal Ions and the Importance of Temperature

In liquid water, various metal ions (for example iron and copper) can inhibit enzyme activity. The enzymes in bacteria necessary for the repair of DNA damage are an order of magnitude or more resistant to DNA-damaging agents than DNA itself is. This is important because if during the long journey in space the repair enzymes lose their repair capability as a consequence of inhibition by migrating metal ions from the meteorite material, or from some other cause, then DNA damage cannot be repaired and only undamaged microbes stand a chance of surviving.

Ion migration can occur in water in the liquid state but not in ice or water vapor or in the absence of water. Microbes in meteorites ejected under dry conditions—for example in the dry season—should not run the risk of repair inhibition from metal ions. Neither should those in meteorites which orbit most of the time in cold regions and whose central temperatures stay below freezing point despite repeated visits to Earth's orbit.

5.3. Temperatures during Orbiting (see Table VIIb)

Since the DNA decay rate is strongly temperature dependent, it is important to estimate the temperatures experienced by bacteria inside meteoroids during the transfer between Mars and Earth. For this purpose, let us consider the thermal skin depth (S), which is the depth range over which the amplitude of a periodic (sinusoidal) temperature variation, induced by a periodic surface heating, decreases by a factor e. It is given by

$$S = \sqrt{\frac{KP}{\pi \rho C}},$$

where C is the heat capacity (~ 800 J kg^{-1} K^{-1}), K is the heat conductivity (~ 3 W m^{-1} K^{-1} for solid rock), P is the period of the heating cycle, and ρ is the density (~ 3000 kg m^{-3} for solid rock). If the meteoroid rotates with a period of a couple of hours ($\sim 10^4$ s), then $S \cong 5$–10 cm, and day–night temperature variations are effectively damped out at depths exceeding 0.5 m.

Thus, inside meteoroids of radii larger than 2 m, most of the volume stays at constant temperature as the meteoroid rotates. This temperature is set by the net average heat flux absorbed from solar radiation as a function of the varying heliocentric distance. As the meteoroid revolves in an eccentric orbit with a period of $\sim 5 \times 10^7$ s (about 1.5 years), the corresponding skin depth is $S \cong 4$–5 m, and only at depths of more than 10 m will the temperature stay more or less constant during the orbital revolution. For most of the volume to satisfy that condition, the radius of the meteoroid must be at least 50 m.

Let us consider two cases. The first case can be taken as representative of depths from a few decimeters to a few meters and thus the bulk of meteoroids whose radii are several meters. Here the temperature at heliocentric distance r (AU) is simply

given by

$$T_e(r) = \left\{ \frac{(1-A)F_\odot}{4\varepsilon\sigma r^2} \right\}^{\frac{1}{4}} \cong T_0 \times \left\{ \frac{1-A}{\varepsilon} \right\}^{\frac{1}{4}} \times r^{-\frac{1}{2}},$$

where $F_\odot = 1.36 \times 10^3$ W m^{-2} is the solar constant, A is the visual Bond albedo, ε is the surface emissivity, and $\sigma = 5.70 \times 10^{-8}$ W m^{-2} K^{-4} is Stefan–Boltzmann's constant. The default temperature at $r = 1$ AU for $\frac{1-A}{\varepsilon} = 1$ is $T_0 = 278$ K.

The second case holds at depths exceeding 10 m and is thus typical of meteoroids with radii of tens of meters or more. Here the temperature is an orbital average given by

$$T_c(a, e) = \left\{ \frac{(1-A)F_\odot}{4\varepsilon\sigma a^2 \sqrt{1-e^2}} \right\}^{\frac{1}{4}}$$

$$\cong T_0 \times \left\{ \frac{1-A}{\varepsilon} \right\}^{\frac{1}{4}} \times a^{-\frac{1}{2}}(1-e^2)^{-\frac{1}{8}},$$

where a is the semimajor axis of the meteoroid's orbit and e is the eccentricity.

The factor $\frac{1-A}{\varepsilon}$ may vary between individual meteoroids. We estimate, however, that values outside the range from 1/1.2 to 1.2 should be rare, so in particular we will use 1.0 as the normal case and 1.2 as a worst case, yielding the highest temperatures to be expected. Assuming a small (meter-sized) meteoroid, we have used both these cases to compute, as a function of a and e, the fraction of time spent within certain ranges of T_e.

Deep inside very big (10-m-sized) meteoroids, the constant temperature remains below the freezing point (273 K) during the whole flight time, as seen in Fig. 3, where one plots curves corresponding to $T_c = 273$ K in the (a, e) plane, also indicating the route of the above-mentioned standard transfer scenario.

We have calculated from the simulations that, for transfers that occur within <1 Ma, only 10–20% of the transit is spent in regions that in the present Solar System would produce temperatures in small meteoroids of $0 < T < 5°$C. Such orbits basically begin with pericenter at or near 1 AU and spend most of this period in that state. Thus we concentrate on cases where the transfer time is 5 or 10 times greater than the time τ spent at $>0°$C.

5.4. Survival Fractions against DNA-Decay Caused by Release of Bases Due to Hydrolysis

Hydrolysis leading to release of DNA bases normally occurs in solution. The process is strongly temperature-dependent. Its reaction rate constants, or k values, are given in Table VIIa, as measured at +90 to +70°C (Lindahl *et al.* 1972, 1973, 1974, 1993) and as calculated therefrom using Arrhenius plots from +20 to 0°C in solution and from 0 to −55°C in freeze.

The k values calculated from Arrhenius plots for 0 to −55°C in freeze, although very low, must still be regarded as an overly high estimate because hydrolysis should be much slower in ice—if functioning at all—than in liquid water solution. Although overconservative they will be used anyway, for lack of other figures.

The temperature of a meteoroid in interplanetary space depends on its distance from the Sun, the luminosity of the Sun, and the value on its surface of the entity $\frac{1-A}{\varepsilon}$, as shown in Table VII b. The bacteria inside the meteoroid obtain these temperatures, which define the strongly temperature-dependent release of DNA bases.

The low solar luminosity in the early planetary system—30% lower than today—gave very favorable conditions for transfer of bacteria between Mars and Earth, in both directions. Ejecta meteoroids leaving the wet, >0°C martian climate—at that time protected by an atmosphere—were chilled to −65°C if their $\frac{1-A}{\varepsilon}$ was = 1, and even lower temperatures if their $\frac{1-A}{\varepsilon}$ was <1. Beneficial in terms of limiting base release, still favorable after a varying number of orbits, they would find at 1 AU a temperature of −20°C.

After landing, they might again be in a wet, life-allowing climate, and in that case would start to repair radiation damage and DNA-decay damage. As energy source they would use available organic compounds, both produced on-site and delivered

TABLE VIIb
Temperature in Earth Orbit at Different Solar Luminosities and for Meteoroids Having Different Values of $\frac{1-A}{\varepsilon}$

Solar luminosity (L)	Insolation at 1 AU (kW m^{-2})	$\frac{1-A}{\varepsilon}$:	T_e (°C)						
			1.23	1.15	1.07	1.0	0.9	0.8	0.7
$0.7 \times L_\odot$	0.95		−5	−10	−14	−20	−25	−32	−41
$0.8 \times L_\odot$	1.09		+5	−1	−6	−10	−17	−24	−33
$0.9 \times L_\odot$	1.22		+12	+7	+3	−2	−9	−17	−25
$1.0 \times L_\odot$	1.36		+20	+15	+10	+5	−2	−10	−19

Note. $T_e = [278 \cdot (\frac{1-A}{\varepsilon})^{0.25} \cdot (\frac{L}{L_\odot})^{0.25} - 273]$°C, where $T_e =$ equilibrium temperature in a relatively small meteoroid at distance 1 AU from the Sun, $A =$ Bond albedo, $\varepsilon =$ emissivity (in infrared), $L =$ early solar luminosity, $L_\odot =$ present solar luminosity.

by comets. Of the many groups arriving, some could have multiplied successfully and achieved sustained survival on Earth, some species even on nonorganic energy sources, as mentioned in the introduction. This process would also operate in the opposite direction, from Earth to Mars.

As pointed out above, low values of the expression $\frac{1-A}{\varepsilon}$ would give meteoroids extra-low temperatures. This is of special importance at distances of ≤ 1 AU from the Sun to allow landing with minimum DNA base losses and maximum repairability. For example, meteoroids with $\frac{1-A}{\varepsilon} = 0.7$ would get a temperature $-40°C$ at 1 AU for the first 0.5 Ga of our planetary system and $-20°C$ today. At this $\frac{1-A}{\varepsilon}$, DNA decay should be negligible. Are such values realistic? The ejecta from both early Mars and early Earth, expelled through a thick atmosphere, were blackened by friction heat and other effects, increasing emissivity ε and thus reducing $\frac{1-A}{\varepsilon}$, but also reducing the Bond albedo and therefore to a certain degree counteracting the increased ε. Lower $\frac{1-A}{\varepsilon}$ are no doubt possible, but $\frac{1-A}{\varepsilon}$ values higher than 1.0 are not excluded either. (The percentage of deviation from the normal $\frac{1-A}{\varepsilon} = 1$ caused by blackening during passage through the planet's atmosphere has not been determined in this study, but it is clear that the normal value of $\frac{1-A}{\varepsilon} = 1$ is quite sufficient for our results and conclusions.)

Once the temperatures around 1 and 1.5 AU are known for the various planetary time periods, one can calculate the corresponding k values for DNA base release and the percentage of bases released as a function both of time spent near the planets and of total transfer time. These data are used in turn to calculate the number of repairable DNA molecules and thus the fraction of survivable bacteria.

In order to calculate survival times of microbes against DNA damage by hydrolysis, that is against base loss, we need some empirical information on two different relationships:

- What is the percentage of still repairable cells after base loss as a function of the percentage of lost bases due to hydrolysis?
- What is the rate of loss of bases in unfrozen H_2O as a function of temperature? In frozen H_2O, ice?

As to the first question, the repairable (surviving) fraction of bacteria decreases very rapidly with increasing number of lost bases, such that

—the release of 0.1% of the DNA bases allows survival of 10–30% of the bacteria,
—the release of 0.2% of the DNA bases allows survival of 0.3–1% of the bacteria,
—the release of 0.3% of the DNA bases allows survival of 0.001–0.1% of the bacteria.

This was shown in experiments on *Escherichia coli* B/r combined with some reasonable assumptions (Lawley and Brookes 1968). Those assumptions were later proven to be correct by experiments on *E. coli* (Karran *et al.* 1980), which convincingly strengthened the results of the Lawley paper.

For bacteria other than *E. coli*, we do not know of any experimental investigation regarding remaining survivability as a function of base release. However, there seems to be a common opinion among base release researchers that most bacterial species respond approximately similarly to base release, with only moderate variations. We will use the above-mentioned relationship obtained from *E. coli* regardless of bacteria or strain since species-specific repair capacity for this type of damage is not known in detail.

As to the second question, Chemical reaction rates decrease very rapidly with decreasing temperature. In solutions, the temperature dependence is usually quite well represented by the so-called Arrhenius plot. Because of the extremely low reaction rates around $0°C$ and below, which are not possible to measure, one normally falls back on extrapolation from warmer measurable temperatures by the well-proven temperature dependence expressed in the Arrhenius plots.

In Table VIIa, reaction rate constants, k_T, are given as extrapolated from the measured k_T values at warm temperatures down to $0°C$ and on down to $-20°C$ in unfrozen H_2O solutions. Note that much unfrozen water at temperatures well below $0°C$ exists on Earth. About 1% of the weight of the never-thawing permafrost deeper than 10 m under the land soil surface in the northern parts of the Siberian and canadaian land mass and Antarctica is unfrozen water at constant temperatures of $-10°C$ or lower. Researchers' numerous borings with sterilized equipment revealed—to their surprise—dormant microbe populations of about 10^7 individuals per gram permafrost, shown to be viable by careful incubation protected against contamination.

It is plausible that nonvacuated ejecta could also contain a percentage of unfrozen water—like the permafrost on Earth—for which normal Arrhenius plots in solution could be made, not only down to $0°C$, but down to -18 to $-20°C$, or further, in order to determine reaction rate constants at these temperatures. For the time being, as far as we know, these seems to be no measurement method precise enough to establish the possible unfrozen water content, if any, at temperatures far below $-20°C$.

During the first 500 Ma, when the Sun's luminosity is thought to have been about 30% lower than today, the equilibrium temperatures of ejecta in interplanetary space were -65 and $-20°C$ at distances from the Sun of 1.5 and 1 AU, respectively. For temperatures at and below $-20°C$ we have calculated the reaction rate constants for hydrolysis as if treating solution (caused by some freeze-point-lowering agent) and then regarding the resulting "virtual" rates as upper limits, arguing that hydrolysis by solid ice, if any at all, should occur at an even slower rate.

It should be understood that the above calculation procedure refers to *nonvacuated* pore volumes in ejecta. Volumes of pores could have been closed off tightly from the outer environment by the outer ejecta layers' melting during the passage through the atmosphere, and thereafter solidifying in cold space.

The time after which 0.1, 0.2, and 0.3% of the bases released at solar luminosity of $0.7L_\odot$ at temperature $-20°C$ at 1 AU is, respectively, 67,000, 134,000, and 200,000 years, as given in Table VIIc. From this we get the result that 10–30% of the bacteria are still repairable and viable if landing within 67,000 years, 0.3–1% within 134,000 years, and 0.001–0.1% within 200,000 years.

In *vacuated* ejecta volumes, on the other hand, DNA decay by vacuum-caused damage occurs much faster than damage by hydrolysis and radiation. In that case the latter are of little importance.

Whereas the survival fraction against radiation damage is time-dependent solely on the total time in space τ (independently of orbit shapes, position and temperatures), the survival fraction against DNA decay depends on both the total time in space τ—because the number of ejecta landing is linearly proportional to τ—and the time t thereof spent at such distances from the Sun that significant DNA base loss occurs. The time t is normally $\leq 20\%$ of τ. (The $\geq 80\%$ of τ without DNA decay make more ejecta landings possible.) The longer τ is, the more ejecta landings; the longer t is, the lower the survival fractions against DNA decay.

We have seen above that a release of 0.1% of the DNA bases allows repair of 10–30% of the DNA molecules. How long a time t can the bacteria spend in temperature $T°C$ before 0.1% of the DNA bases are released? This is when the fraction of not-yet-released bases is 99.9%. Thus,

$$e^{-\sum k_T \cdot t} = 0.999$$

from which

$$t = \frac{-\ln(0.999)^{-1}}{\sum k_T}\ \text{Ma} = \frac{0.0010}{\sum k_T}\ \text{Ma}.$$

For 0.2% bases released at the same temperature $T°C$,

$$t = \frac{-\ln(0.998)^{-1}}{\sum k_T}\ \text{Ma} = \frac{0.0020}{\sum k_T}\ \text{Ma}.$$

For 0.3% of the bases released, $t = \frac{0.0030}{\sum k_T}$ Ma.

In Table VIIc, the times t for release of 0.1, 0.2, and 0.3% of DNA bases are given for the temperature in meteoroids with $\frac{1-A}{\varepsilon} = 1$ at 1 AU and 0.7, 0.8, 0.9, and $1.0 \times L_\odot$, respectively. Two types of orbits are chosen as examples, those with $\tau = 5t$ and those with $\tau = 10t$. For each case the survival fraction against DNA decay caused by base release through hydrolysis was calculated. These survival fractions, multiplied by the survivals against all the other risks, give the total number of survivals.

The times t to release bases calculated above for size group 2 meteoroids are the same for meteoroid size groups 3–7. As each one of these groups supplies approximately the same number of survivals—because although size 3–7 meteoroids are fewer in number they are larger and provide better shielding—the total number of surviving bacteria in all the size groups combined is about six times the number in size group 2, i.e., about six

times the numbers in Table VIIc. (The above expression for the repairable fraction, f_{rep}, is conservative as it makes it fall more steeply—as a function of released bases—than is actually found by experiment. Further conservatism results from neglecting the additional repair probability which would have occurred if the calculation had not been limited to flight times covering the first 0.3% released bases only.)

Almost 4 Ga ago the conditions for transfer were changed as the heavy bombardment by comet and asteroid impacts became two orders of magnitude less intense (but still considerable and still continuing today). This diminished frequency of impacts resulted in a number of ejecta over the past 4 Ga that was 10 times smaller than the number of ejecta during the first 0.5 Ga of our planetary system's existence.

Conditions in space are of course different from those in the depths of ice on Earth. However, evidence for the survival of microbes against DNA decay over very long periods, up to 240,000 years has been provided (subject to 100% effective aseptic techniques) by experiments conducted by Russian scientists over several years at their Vostok station in central Antarctica. A fraction of the microflora found in the ice at a temperature of $-55°C$, were found to be *viable*: 6% in ice 100,000 years old at depth 1500 m, and 3% in ice 200,000 years old at depth 2750 m. (Abyzov *et al.* 1998). (Please note that the microflora in the Antarctic permafrost ground is far more numerous than in ice—cf. text above.)

5.5. Effect of the Vacuum of Space on Spore Survival

As already pointed out, the high resistance of bacterial endospores to desiccation is mainly due to a dehydrated core enclosed in a thick protective envelope, the cortex and the spore coat layers, and the saturation of their DNA with small, acid-soluble proteins whose binding greatly alters the chemical and enzymatic reactivity of the DNA (Setlow 1995). To study their responses to the vacuum of space, spores of *B. subtilis*, protected from solar radiation, were exposed in different experimental occasions for different durations, as follows:

Mission	Duration of vacuum exposure (days)	Survival fraction at end of exposure (%)	
Spacelab 1	10	70	(Horneck *et al.* 1994)
ERA, Eureca	327	25	(Horneck *et al.* 1995)
LDEF	2107	1.4 ± 0.8	(Horneck *et al.* 1994).

These data can be interpreted as suggesting a slow but progressive loss in survival of spores in space. It was also noted that other similar samples on board EURECA had much higher survival fractions than those in vacuum. Galactic cosmic rays and natural radioactivity can be excluded as causes because of the short duration of these missions, but—especially during the LDEF

TABLE VIIc

Mars to Earth Transfer in Meteoroids of Size Group 2 Showing Numbers of Arriving *D. radiodurans* R1, Surviving and Repairable, Depending on Solar Luminosity and on Time t in or Near Earth's Orbit, within Time τ after Launch (for Two Typical Orbit Examples)

	First three permille fractions of the DNA molecules' bases released by hydrolysis	The time t it takes to release p‰ of the bases at ejecta temperatures while in or near Earth's orbit[a], $t = \frac{\ln(1 - p \times 0.001)}{\sum k_T}$ (t (Ma))	One typical orbit example[b] ($\tau = 5t$)		Another typical orbit example[b] ($\tau = 10t$)	
			Nos. of arriving bacteria surviving (or repairable after) damages other than base release by hydrolysis within time τ	Nos. of arriving bacteria surviving (or repairable after) all damages including base release within time τ	Nos. of arriving bacteria surviving (or repairable after) damages other than base release by hydrolysis within time τ	Nos. of arriving bacteria surviving (or repairable after) all damages including base release within time τ
Solar luminosity $= 0.7$ times present $L_\odot$ during the first Ga. At 1 AU, temperature $= -20°C$. Hydrolysis reaction rate for DNA base release $= \Sigma k_{-20°} = 0.015$ Ma^{-1}. At 1.5 AU, temperature $= -65°C$	First permille fraction	0.067	$\bar{N}_0 \cdot 4.3 \times 10^{13}$	$\bar{N}_0 \cdot 4.3 \times 10^{12}$	$\bar{N}_0 \cdot 4.4 \times 10^{13}$	$\bar{N}_0 \cdot 4.4 \times 10^{12}$
	Second permille fraction	0.134	$\bar{N}_0 \cdot 8.0 \times 10^{11}$	$\bar{N}_0 \cdot 8.0 \times 10^{9}$	$\bar{N}_0 \cdot 1.4 \times 10^{10}$	$\bar{N}_0 \cdot 1.4 \times 10^{8}$
	Third permille fraction	0.200	$\bar{N}_0 \cdot 1.7 \times 10^{10}$	$\bar{N}_0 \cdot 1.7 \times 10^{7}$	$\bar{N}_0 \cdot 7.7 \times 10^{9}$	$\bar{N}_0 \cdot 7.7 \times 10^{6}$
Solar luminosity $= 0.8$ times present $L_\odot$. At 1 AU, temperature $= -10°C$. Hydrolysis reaction rate for DNA base release $= \Sigma k_{-10°} = 0.1666$ Ma^{-1}	First permille fraction	6.0×10^{-3}	$\bar{N}_0 \cdot 1.3 \times 10^{13}$	$\bar{N}_0 \cdot 1.3 \times 10^{12}$	$\bar{N}_0 \cdot 2.3 \times 10^{12}$	$\bar{N}_0 \cdot 2.3 \times 10^{11}$
	Second permille fraction	12.0×10^{-3}	$\bar{N}_0 \cdot 9.4 \times 10^{12}$	$\bar{N}_0 \cdot 9.4 \times 10^{10}$	$\bar{N}_0 \cdot 1.1 \times 10^{11}$	$\bar{N}_0 \cdot 7.7 \times 10^{9}$
	Third permille fraction	18.0×10^{-3}	$\bar{N}_0 \cdot 6.5 \times 10^{12}$	$\bar{N}_0 \cdot 6.5 \times 10^{9}$	$\bar{N}_0 \cdot 5.4 \times 10^{9}$	$\bar{N}_0 \cdot 5.8 \times 10^{6}$
Solar luminosity $= 0.9$ times present $L_\odot$. At 1 AU, temperature $= -2°C$. Hydrolysis reaction rate for DNA base release $= \Sigma k_{-2°} = 1$ Ma^{-1}	First permille fraction	1.0×10^{-3}	$\bar{N}_0 \cdot 2.6 \times 10^{12}$	$\bar{N}_0 \cdot 2.6 \times 10^{11}$	$\bar{N}_0 \cdot 5.0 \times 10^{12}$	$\bar{N}_0 \cdot 5.0 \times 10^{11}$
	Second permille fraction	2.0×10^{-3}	$\bar{N}_0 \cdot 2.4 \times 10^{12}$	$\bar{N}_0 \cdot 2.4 \times 10^{10}$	$\bar{N}_0 \cdot 4.4 \times 10^{12}$	$\bar{N}_0 \cdot 4.4 \times 10^{10}$
	Third permille fraction	3.0×10^{-3}	$\bar{N}_0 \cdot 2.3 \times 10^{12}$	$\bar{N}_0 \cdot 2.3 \times 10^{9}$	$\bar{N}_0 \cdot 3.9 \times 10^{12}$	$\bar{N}_0 \cdot 3.9 \times 10^{9}$
Solar luminosity $= 1.0$ $L_\odot$, recent and present value. At 1 AU, temperature $= +5°C$. Hydrolysis reaction rate for DNA base release $= \Sigma k_{+5°} = 4$ Ma^{-1}	First permille fraction	2.5×10^{-4}	$\bar{N}_0 \cdot 6.6 \times 10^{11}$	$\bar{N}_0 \cdot 6.6 \times 10^{10}$	$\bar{N}_0 \cdot 1.3 \times 10^{12}$	$\bar{N}_0 \cdot 1.3 \times 10^{11}$
	Second permille fraction	5.0×10^{-4}	$\bar{N}_0 \cdot 6.5 \times 10^{11}$	$\bar{N}_0 \cdot 6.5 \times 10^{9}$	$\bar{N}_0 \cdot 1.3 \times 10^{12}$	$\bar{N}_0 \cdot 1.3 \times 10^{10}$
	Third permille fraction	7.5×10^{-4}	$\bar{N}_0 \cdot 6.4 \times 10^{11}$	$\bar{N}_0 \cdot 6.4 \times 10^{8}$	$\bar{N}_0 \cdot 1.2 \times 10^{12}$	$\bar{N}_0 \cdot 1.2 \times 10^{9}$

[a] For detailed explanation of this column, see text in Subsection 5.4.

[b] Please note that the numbers for each orbit example are given as if all the arriving meteoroids were using that particular orbit type, In real cases, of course, the meteoroids have many different orbit types.

mission—some stray UV leaking in via the openings needed for vacuum might have contributed to some of the killings. It should be noted that 10 s of exposure to unfiltered extraterrestrial UV radiation was sufficient to kill 99% of the spores (Horneck and Brack 1992).

The strategies by which *B. subtilis* spores protect their integrity, including that of the DNA against vacuum damage, are not yet fully understood. The accumulation of nonreducing sugars such as trehalose or sucrose, which are used by other anhydrobiotes (Crowe and Crowe 1992), is not observed in spores. However, the addition of glucose to the spores substantially increased the survival rate of spores in vacuum (Horneck *et al.* 1994, 1995). These molecules help to prevent damage to the DNA, membranes, and proteins by replacing the water molecules during the desiccation process and thereby preserving the three-dimensional structure of the molecules anhydrobiotes (Crowe and Crowe 1992). Similar, but not yet identified, protective molecules may also exist in bacterial spores that may tend to stabilize the DNA double helix by taking over the place of the hydrate water which eventually leaves the spore during long-term exposure to vacuum. This may be a time-consuming procedure at room temperature and even more so at increasingly low temperatures.

The total process must be expected to be composed of several partial processes, each having its own time scale. Three partial processes are:

—the sublimation of ice—or evaporation of water—at onset of vacuum

—the release of the intermediary H_2O from inside the DNA "ball"

—the occupation by larger replacement molecules of abandoned former H_2O sites inside the DNA "ball."

The sublimation flux Z and H_2O molecules per m^2 and per s of a multilayer surface area of H_2O ice in vacuum is rather accurately given by

$$Z = \frac{1.2 \times 10^{12}\,\text{Pa} \times e^{\frac{-6000}{T}}}{\sqrt{2mkT}},$$

where m = the mass of the H_2O molecule, in kg, k = Boltzmann's constant, in J/K, and T = temperature, in K.

The formula shows that sublimation from multilayer surfaces is a very rapid phenomenon and quite temperature-dependent. The time scale is fractions of a second.

When it comes to actions inside the spore, and most importantly inside the DNA–H_2O macromolecular complex, many release-resisting forces come into play, such as adsorption, absorption, dry capillary forces, and quantum chemical interactions of various kinds. The time scale for overcoming the bonding forces which resist H_2O release from the intra-DNA configuration has, as far as we know, been neither measured nor calculated. Certainly, both calculation and measurement ought to be done.

If, after some time, the H_2O molecules have really abandoned their positions inside the DNA–H_2O macromolecular complex, there is a possibility that other molecules, larger than H_2O, will try to occupy these or adjacent sites. They would have to dig themselves in against the suction of the outside vacuum, but perhaps aided by quantum mechanical forces. We do not know how probable this is. Calculations and measurements will also be needed for this phase in order to get an idea of its time scale. These basic science tasks are time-consuming however and require adequate funding.

The experiments show that the time scale for vacuum-initiated damage to spore DNA is many, many orders of magnitude longer than the time scale for vacuum sublimation of multilayered crystal ice. It is difficult to see why these time scales would not be quite strongly temperature-sensitive, as most chemical reactions and processes are. Therefore, the low temperature of ejecta with $\frac{1-A}{\varepsilon} = 1$ to 0.7 during the first 0.5 Ga of our planetary system (-20 to $-40°$C at 1 AU and -80 to $-100°$C at 1.5 AU) should lead to much longer time scales than the one in the LDEF mission.

Inside an ejecta leaving its mother planet through an atmosphere of 1 Bar or more the conditions are in some ways very different from those in the above-mentioned experiments. The outermost layers of the meteoroid are heated to melting and partly to ablation, quickly solidifying again after the rapid passage out of the atmosphere into cold space. Thereby some domains in the meteoroid may have become very tightly isolated against both stray UV light and vacuum leakage, facilitating the further survival of those spores in the significant fraction that survives the other risks treated in this paper.

6. THE COMBINED EFFECT OF RADIATION FROM SPACE, NATURAL RADIOACTIVITY, DNA BASE RELEASE IN NONVACUATED EJECTA PORES AND VACUUM IN VACUATED PORES, AND RESULTING COMBINED SURVIVAL FRACTIONS

6.1. Which Cause of Damage—Radiation, DNA Base Release, or Vacuum—Dominates in Determining the Viable Flight Time?

This is a key question. The answer is that each of them can play the dominant role depending on circumstances. Important here are the effects of the melting of the outer layers of the ejecta during the passage up through the source planet's atmosphere (such as on early Mars and Earth), creating a tight shell which solidifies on leaving the atmosphere. As long as there are no cracks going all the way through the shell, the bacteria-containing pores inside are tightly isolated from the vacuum outside and the atmosphere does not leak out. Let us call this Case A (for atmosphere). On the other hand, if cracks appear that reach right through the shell, then the atmosphere in the pores around the cracks could leak out into space, and in those pores there would be vacuum, case V.

Case V: All pores containing bacteria vacuated, i.e., 100% Case V. H_2O ice sublimates into vapor, which disappears out into space. The viable flight times of these ejecta are determined by vacuum damage. Time scale: decades.

Case A + Case V: Consider as an example that each ejecta contains 10% Case A and 90% Case V. After a flight time of a number of decades, the bacteria in the vacuated (Case V) volume are dead, but those in the Case A volume will still be alive for a long time to come. That length of time will be determined either by DNA base release or by radiation. By which? Both DNA base release and radiation are strongly dependent, as killers of cells, on circumstances, but not on the same kind of circumstances. DNA base release depends strongly on temperature and only slightly on the bacterial species and strain. Radiation damage, on the other hand, depends strongly on bacterial species and strain and only slightly on temperature. As a result, the viable flight times of Deinococci and sporulating Bacilli are determined by base release, even at very low temperatures, while it is radiation damage that determines the viable flight time of the ordinary, rather radiation-sensitive bacterial species and strains, most of which—given equal conditions—have a similar response to hydrolysis. This is valid when Case A and Case V occur within the same ejecta.

6.2. Number of Ejecta and Number of Viable Bacteria Arriving on Target Planet, BEFORE Taking into Account the Effect of DNA Decay

Let us look at columns V and VI in Table VIIIa. The number of ejecta of size 2 having arrived on Earth up to 0.1 Ma after launch during the heavy bombardment was 3.3×10^8. The number of bacteria on those ejecta was $\bar{N}_0 \times 3.1 \times 10^{14}$, out of which, on landing on Earth after 0.1 Ma, some were alive undamaged, some were damaged but repairable upon landing, and some were irrevocably dead.

To demonstrate what happened during those first 0.1 Ma, let us divide the 0.1 Ma time into n portions of $\frac{0.1}{n}$ Ma each. If we take $n = 10$ for example, the number of bacteria on board during each portion of 0.01 Ma was thus $N_0 \times 3.1 \times 10^{13}$ alive, repairably damaged or dead. During the space trip of the first group landing after 0.01 Ma, the fraction of surviving bacteria against the Galactic Cosmic Rays is more than $e^{-12 \times 0.01} = 0.89$. In the second group, landing after 0.02 Ma, the fraction of survivals against the GCR is $> e^{-12 \times 0.02} = 0.79$, and so on. In the tenth group, $e^{-12 \times 0.10} = 0.30$.

Thus the number of bacteria arriving on Earth in meteroids of size group 2, having survived all risks and damages except those of DNA decay by base release through hydrolysis or by vacuum (those exceptions are made only to simplify the demonstration) becomes

$$N = \bar{N}_0 \times 3.1 \times 10^{13} \times 0.18 \times 5.49 = \bar{N}_0 \times 3.1 \times 10^{13}.$$

More generally expressed for size group 2 and accumulation time of landing up to 0.1 Ma,

$$N_{S2} = \bar{N}_0 \times 3.1 \times 10^{13} \times \frac{0.1}{n} \times f_1 \times f_2 \times f_4 \times f_6 \times \sum_{\nu=1}^{\nu=n} e^{-12 \times \frac{0.1}{n} \times \nu},$$

which becomes more accurate the higher n values we choose, i.e., integration. Using integration for some long flight times, $\tau \geq 0.1$ Ma, we get, for example,

τ (Ma)	N
0.1	$N_0 \times 3.1 \times 10^{13}$
0.2	$N_0 \times 4.04 \times 10^{13}$
0.5	$N_0 \times 4.43 \times 10^{13}$
1.0	$N_0 \times 4.44 \times 10^{13}$.

From these figures it can be seen that flight times which last longer than half a million years do not contribute very much percentage-wise more to the number of viable and repairable bacteria, but one should not forget that even the third decimal represents no less than $N_0 \times$ billions of such bacteria.

N_0—the average number of bacteria per gram on a planet, Mars or Earth, over a given period, the first 0.5 Ga or the last 4 Ga—is unknown for Mars (it could be high or zero) and for the early periods of Earth; today on Earth it is 50 million to a billion per gram of good soil but much less in, for example, rocks. $\bar{N}_0$ must have been high on Earth for a very long time. Extending the above considerations and calculations (for meteoroid size group 2) to meteoroid size groups 3 to 7 increases the number of viable bacteria which had the opportunity of arriving on Earth from Mars during the first 0.5 Ga—if there were any on Mars—by an order of magnitude. (This is before taking into account the effect of DNA decay and its repair, treated below).

Here a caveat about the intensity of the GCR in our planetary system for 4.5 to 4.0 Ga ago: To our knowledge, there is no indication that the *interstellar* galactic cosmic ray flux at that time differed strongly from the present one. However, our present Sun generates a dipole magnetic field which prevents a portion of the interstellar GCR—the lighter low-energy components—from entering our planetary system, thereby reducing dose rates by a factor of three. In young stars the magnetic fields are not well-ordered: they can be weaker or stronger or varying, and therefore their efficiency in reducing the GCR intensity is difficult to calculate. Some magnetic experts (e.g., M. H. Acuna, Goddard Space Flight Center, NASA, pers. commun.) believe that the magnetic field of our Sun was stronger in its youth. In our calculations we have used the present GCR intensities. (Even if we had applied a most extreme assumption—namely that the young Sun had no shielding magnetic field at all—this would have changed some figures somewhat but not the main conclusions of our study.) For more recent periods, studies of cosmic ray exposure in the planetary system over a Ga time scale, e.g., exposure of iron meteorites, have suggested that some mild variation has occurred on the level of a factor of 2, but not much more, during the last 1–2 Ga. In principle this could be caused

TABLE VIIIa

***D. radiodurans*: Number of Bacteria with Viable Arrivals from Mars to Earth during the First 0.5 Ga within 0.1 and 0.33 Ma after Launch**

Size group, s	Radius range (m)	Average mass of ejecta in radius range, $\bar{m}_s$ (g)	No. of Mars ejecta ($T \leq 100°C$) during 0.5 Ga from impactors with $L = 0.5-20$ km, $\bar{n}_s$	Accumulated No. of ejecta having arrived on Earth 0.1 and 0.33 Ma after launch during first 0.5 Ga, $n_s \times 0.007 \times \tau_{acc}$	Accumulated No. of bacteria having arrived on Earth 0.1 and 0.33 Ma after launch (alive + repairable + dead) during first 0.5 Ga, $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times \tau_{acc}$	$f_1 = f_{acc}$	$f_2 = f_{heat.atm}$	$f_3 = f_{GCR+SR}$	$f_4 = f_{nat.rad}$	$f_5 = f_{DNA.decay}$ at $\frac{1-A}{\varepsilon} = 1.0$ $f_5 = e^{-2.3 \cdot p}$ (if time t at 1 AU $= \tau_{acc}/5$)	$f_6 = f_{heat.atm}$	$f_1 \times f_2 \times f_3 \times f_4 \times f_5 \times f_6 = f_{tot}$	Accumulated No. of viable bacteria having arrived on Earth during first 0.5 Ga, 0.1 Ma, and 0.33 Ma after launch at $\frac{1-A}{\varepsilon} = 1.0$ $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times \tau_{acc} \times f_{tot} = N_v(\tau_{acc})$
1	0.00–0.03										0		0
2	0.03–0.67	0.95×10^6	4.7×10^{11}	0.1 Ma: 3.3×10^8 0.33 Ma: 1.1×10^9	0.1 Ma: $\bar{N}_0 \times 3.1 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 1.1 \times 10^{15}$	~ 0.5	≥ 0.6	0.1 Ma: 0.58 $\sigma F/$Ma = 12 0.33 Ma: 0.24	0.996 0.987	≥ 0.5 ($P = 0.3$) ≥ 0.1 ($P = 1.0$)	≥ 0.6	≥ 0.052 ≥ 0.0043	0.1 Ma: $\geq \bar{N}_0 \times 1.6 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 4.3 \times 10^{12}$
3	0.67–1.00	7.2×10^6	1.5×10^{10}	0.1 Ma: 1.1×10^7 0.33 Ma: 3.6×10^7	0.1 Ma: $\bar{N}_0 \times 7.9 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.6 \times 10^{14}$	~ 0.5	≥ 0.8	0.1 Ma: 0.75 $\sigma F/$Ma = 6 0.33 Ma: 0.24	0.996 0.987	≥ 0.5 ≥ 0.1	≥ 0.75	≥ 0.11 ≥ 0.013	0.1 Ma: $\geq \bar{N}_0 \times 8.7 \times 10^{12}$ 0.33 Ma: $\geq \bar{N}_0 \times 3.4 \times 10^{12}$
4	1.00–1.67	30×10^6	9.3×10^9	0.1 Ma: 6.5×10^6 0.33 Ma: 2.1×10^7	0.1 Ma: $\bar{N}_0 \times 2.0 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 6.6 \times 10^{14}$	~ 0.5	≥ 0.9	0.1 Ma: 0.88 $\sigma F/$Ma = 2.6 0.33 Ma: 0.67	0.996 0.94 0.94	≥ 0.5 ≥ 0.1	≥ 0.9	≥ 0.18 ≥ 0.027	0.1 Ma: $\geq \bar{N}_0 \times 3.6 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 1.8 \times 10^{13}$
5	1.67–2.00	75×10^6	1.4×10^9	0.1 Ma: 9.8×10^5 0.33 Ma: 3.2×10^6	0.1 Ma: $\bar{N}_0 \times 7.4 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.4 \times 10^{14}$	~ 0.5	≥ 0.9	0.1 Ma: 0.97 $\sigma F/$Ma = 0.7 0.33 Ma: 0.89	0.996 0.94	≥ 0.5 ≥ 0.1	≥ 0.9	≥ 0.20 ≥ 0.036	0.1 Ma: $\geq \bar{N}_0 \times 1.5 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 8.7 \times 10^{12}$
6	2.00–2.33	120×10^6	7.6×10^8	0.1 Ma: 5.3×10^5 0.33 Ma: 1.7×10^6	0.1 Ma: $\bar{N}_0 \times 6.4 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.1 \times 10^{14}$	~ 0.5	≥ 0.9	0.1 Ma: 0.98 $\sigma F/$Ma = 0.32 0.33 Ma: 0.95	0.996 0.94	≥ 0.5 ≥ 0.1	≥ 0.9	≥ 0.20 ≥ 0.038	0.1 Ma: $\geq \bar{N}_0 \times 1.3 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 8.1 \times 10^{12}$
7	2.33–2.67	187×10^6	4.9×10^8	0.1 Ma: 3.4×10^5 0.33 Ma: 1.1×10^6	0.1 Ma: $\bar{N}_0 \times 6.4 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.1 \times 10^{14}$	~ 0.5	≥ 0.9	0.1 Ma: 0.997 $\sigma F/$Ma = 0.06 0.33 Ma: 0.99	0.996 0.94	≥ 0.5 ≥ 0.1	≥ 0.9	≥ 0.20 ≥ 0.04	0.1 Ma: $\geq \bar{N}_0 \times 1.3 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 8.4 \times 10^{12}$
Σ				0.1 Ma: 3.3×10^8 0.33 Ma: 1.1×10^9	0.1 Ma: $\bar{N}_0 \times 7.9 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 2.6 \times 10^{15}$						$\frac{1.0}{7.9} = 0.13$ $\frac{5.1}{260} = 0.02$	0.1 Ma: $\geq \bar{N}_0 \times 1.0 \times 10^{14}$ 0.33 Ma: $\geq \bar{N}_0 \times 5.1 \times 10^{13}$
I	II	III	IV	V	VI							

Note. The unknown average number of *D. radiodurans*-like bacteria on Mars is assumed to be $\bar{N}_0$ per gram martian rock. Majority of ejecta pores assumed nonvacuated. $N_v(t_{acc})_s = \bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times \tau_{acc} \times f_{1s} \times f_{2s} \times f_{3s}(\tau_{acc}) \times f_{4s}(\tau_{acc}) \times f_{5s}(\tau_{acc}) \times f_{6s}$, where $f_{3s}(\tau_{acc}) = \frac{1}{(\sigma F)_s t_{acc}}[1 - e^{(\sigma F)_s \cdot t_{acc}}]$, and τ_{acc} = accumulation time.

by either a variation of the interstellar GCR or a variation of the solar dipole magnetic field shielding against some of the light low-energy components, or both. Under favorable conditions for analysis, the material may disclose the true cause. Nishizuma *et al.* (1980) discuss the possibility of a flux 1 Ga ago which was half the present flux. Voshage (1984) claims a rough constancy over the last 1–2 Ga, however, with an intensity in the past few Ma which is roughly 50% higher than that long-term average. Whatever their cause may be, such modest variations do not influence the conclusions of this Part 1 of our study.

6.3. Number of Ejecta and Number of Viable Bacteria Arriving on Target Planet, Taking into Account the Effect of DNA Decay through Base Release by Hydrolysis (in Nonvacuated Ejecta Pores)

Combining the effects of radiation from space, natural internal radioactivity and DNA decay by base release due to hydrolysis gives, for each size group s,

$$N/N_0 = e^{-[\sigma F_{GS}(RCD) + \sigma F_A(\text{dose-rate})]\tau} \times e^{\frac{-2.3 \cdot \sum k_T}{0.001} \cdot t},$$

where $\sigma F_{GS}(RCD)$ is the killing frequency per Ma by external radiation as a function of radial column density (RCD, in g/cm^2), $\sigma F_A(\text{dose-rate})$ is the killing frequency per Ma by natural radioactivity as a function of dose rate in cGy/year, $\sum k_T$ represents the sum, for a given temperature, of the reaction rates of the different kinds of DNA decay by base loss caused by hydrolysis, τ is the total flight time, t is the time spent near, in or crossing Earth's orbit, N_0 is the number of cells or spores ejecta material at launch, N is the number of live and repairable microbes remaining just before touching ground. For σF_{GS} we take the values in Table III, and for σF_A we use the expression in Section 4.4, which should be proportioned to the dose rate in cGy/year. (In the known martian meteorites 0.008–0.08 cGy/year (see Table IVb) and in for example granite on Earth 5 cGy/year (see Table V). As to DNA decay, we will use the values $\sum k_T$ given in Table VIIa.

6.4. The Accumulated Number of Viable Bacteria Having Arrived on Earth from Mars during the First 0.5 Ga at Accumulation Time τ_{acc} after Launch

The number of ejecta produced by all impacts by impactors of diameter $L = 0.5$–20 km has been calculated for each of seven size groups (Tables VIIIa and VIIIb).

Each size group, denominated s, with $s = 1, 2$, etc., up to 7, is defined in such a way that all ejecta within it have approximately the same $(\sigma F)_s$. This is necessary in order to take into account the effect of the size of the ejecta on survivability against GCR.

The ejecta from a given impact on Mars which arrive on Earth do not of course all land simultaneously but as a linear function of time (see Section 3.3). Consequently the number of ejecta landing on Earth from a single impact on Mars is a function of the accumulation time, τ_{acc}, from launch.

If the unknown average number of cells of a bacterial species per gram martian rock is denominated $\bar{N}_o$, and if all entities are as in Table VIIIa, then the expression for the accumulated number of viable cells having arrived on Earth during 0.5 Ga at time t_{acc} after launch becomes for each size group:

$$N_V(\tau_{acc})_s = \bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times t_{acc} \times f_{1S} \times f_{2S}$$
$$\times f_{3S}(\tau_{acc}) \times f_{4S}(t_{acc}) \times f_{5S}(\tau_{acc}) \times f_{6S},$$

where

$$f_{3S}(\tau_{acc}) = \frac{1}{(\sigma F)_s \tau_{acc}} \left[1 - e^{(\sigma F)_s \cdot \tau_{acc}}\right].$$

The sum then becomes $\sum_{s=1}^{s=7} N_V(\tau_{acc})_s$.

In vacuated pores, survival times are short because of damage by vacuum. Table IX gives the numbers of ejecta from Mars to Earth landing within very short accumulation times from launch—10, 1, and 0.1 ka—assuming approximately the same constant landing rate as for the longer accumulation times given in Fig. 1 by the straight line. One should of course keep in mind that the statistics for these short times are not as good as for the longer times.

The number of landings over a period of 0.5 Ga within 10, 1, and 0.1 ka of launch is then of the order of 30 million, 3 million, and 0.3 million, respectively. For the orbits, the relation τ/t (where $\tau =$ transfer time and $t =$ time in or in the vicinity of Earth's orbit) has a spectrum of values. If one assumes, as an example, $\tau/t = 10$, then the 300,000 ejecta landing within 100 years after launch have spent 10 years at $-20°$C and 90 years from $-20°$C down to $-65°$C. These seem to be favorable conditions for survival against the risk of intramolecular sublimation of ice in the DNA. A strong indication for this is the fact that *Bacillus subtilis* has experimentally been shown to survive 1-year-long exposure to the vacuum of space, protected from UV, at temperatures from 25 to 37°C, and 6-year-long exposure at temperatures from -9 to $+29°$C.

Table X shows the selected case of 6 years in space vacuum, chosen because of the existence of a measured value of the survival of *B. subtilis* wild after nearly 6 years of exposure to space vacuum during the LDEF mission. This survival value was 1.5% (Horneck *et al.* 1994). For Table X, the number of ejecta landings from Mars to Earth was obtained by extrapolating the straight line in Fig. 1 down to short travel times. The table shows that the number of ejecta landings within 6 years after launch during the first 0.5 Ga was approximately 20,000, and that the number of landing bacteria (*B. subtilis* and the like) surviving all the risks described in this article was roughly $\bar{N}_0 \cdot 2 \times 10^8$.

The value of the survival fraction of *B. subtilis* exposed 6 years to space vacuum during the LDEF mission was 1.5%, which included the effects of GCR + solar rays, natural radioactivity, DNA decay due to base loss by hydrolysis, DNA decay due to vacuum, and possibly some solar UV stray light leaking in through the openings for vacuum exposure. Using the

TABLE VIIIb

$B.$ $subtilis$ (Wild): Number of Bacteria with Viable Arrivals from Mars to Earth during the First 0.5 Ga within 0.1 and 0.33 Ma after Launch

Size group, s	Radius range (m)	Average mass of ejecta in radius range, $\bar{m}_s$ (g)	No. of Mars ejecta ($T \leq 100°C$) during 0.5 Ga from impactors with $L = 0.5$–20 km, n_s	Accumulated No. of ejecta having arrived on Earth 0.1 and 1.0 Ma after launch, $n_s \times 0.007 \times \tau_{acc}$	Accumulated No. of bacteria having arrived on Earth 0.1 and 1.0 Ma after launch (alive + repairable + dead), $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times \tau_{acc}$	Survival fractions, f_n							Accumulated No. of viable bacteria having arrived on Earth during first 0.5 Ga, 0.1 Ma and 1.0 Ma after launch, at $\frac{1-A}{\varepsilon} = 1.0$ $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.007 \times \tau_{acc} \times f_{tot} = N_v(\tau_{acc})_s$
						$f_1 = f_{acc}$	$f_2 = f_{heat.atm}$	$f_3 = f_{GCR+SR}$	$f_4 = f_{nat.rad}$	$f_5 = f_{DNA.decay}$ $\frac{1-A}{\varepsilon} = 1.0$	$f_6 = f_{heat.atm}$	$f_1 \times f_2 \times f_3 \times f_4 \times f_5 \times f_6 = f_{tot}$	
1	0.00–0.03										0		0
2	0.03–0.67	0.95×10^6	4.7×10^{11}	0.1 Ma: 3.3×10^8 0.33 Ma: 1.1×10^9	0.1 Ma: $\bar{N}_0 \times 3.1 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 1.0 \times 10^{15}$	~0.5	≥0.6	0.1 Ma: 0.26 $\sigma F/Ma = 38$ 0.33 Ma: 0.079	0.994 0.94	≥0.5 ≥0.1	≥0.6	≥0.023 ≥0.0014	0.1 Ma: $\geq \bar{N}_0 \times 7.3 \times 10^{12}$ 0.33 Ma: $\geq \bar{N}_0 \times 1.4 \times 10^{12}$
3	0.67–1.00	7.2×10^6	1.5×10^{10}	0.1 Ma: 1.1×10^7 0.33 Ma: 3.6×10^7	0.1 Ma: $\bar{N}_0 \times 7.9 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.6 \times 10^{14}$	~0.5	≥0.8	0.1 Ma: 0.46 $\sigma F/Ma = 18$ 0.33 Ma: 0.166	0.994 0.94	≥0.5 ≥0.1	≥0.75	≥0.069 ≥0.005	0.1 Ma: $\geq \bar{N}_0 \times 5.5 \times 10^{12}$ 0.33 Ma: $\geq \bar{N}_0 \times 1.3 \times 10^{12}$
4	1.00–1.67	30×10^6	9.3×10^9	0.1 Ma: 6.5×10^6 0.33 Ma: 2.1×10^7	0.1 Ma: $\bar{N}_0 \times 2.0 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 6.6 \times 10^{14}$	~0.5	≥0.9	0.1 Ma: 0.71 $\sigma F/Ma = 7.5$ 0.33 Ma: 0.13	0.994 0.94	≥0.5 ≥0.1	≥0.9	≥0.14 ≥0.04	0.1 Ma: $\geq \bar{N}_0 \times 2.8 \times 10^{12}$ 0.33 Ma: $\geq \bar{N}_0 \times 1.5 \times 10^{12}$
5	1.67–2.00	75×10^6	1.4×10^9	0.1 Ma: 9.8×10^5 0.33 Ma: 3.2×10^6	0.1 Ma: $\bar{N}_0 \times 7.4 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.4 \times 10^{14}$	~0.5	≥0.9	0.1 Ma: 0.90 $\sigma F/Ma = 2.0$ 0.33 Ma: 0.73	0.994 0.94	≥0.5 ≥0.1	≥0.9	≥0.18 ≥0.03	0.1 Ma: $\geq \bar{N}_0 \times 1.3 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 7.2 \times 10^{12}$
6	2.00–2.33	120×10^6	7.6×10^8	0.1 Ma: 5.3×10^5 0.33 Ma: 1.7×10^6	0.1 Ma: $\bar{N}_0 \times 6.4 \times 10^{13}$ 0.33 Ma: $\bar{N}_0 \times 2.1 \times 10^{14}$	~0.5	≥0.9	0.1 Ma: 0.96 $\sigma F/Ma = 0.9$ 0.33 Ma: 0.86	0.994 0.94	≥0.5 ≥0.1	≥0.9	≥0.19 ≥0.035	0.1 Ma: $\geq \bar{N}_0 \times 1.2 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 7.4 \times 10^{12}$
7	2.33–2.67	187×10^6	4.9×10^8	0.1 Ma: 3.4×10^5 0.33 Ma: 1.1×10^6	0.1 Ma: $\bar{N}_0 \times 6.4 \times 10^{12}$ 0.33 Ma: $\bar{N}_0 \times 2.1 \times 10^{14}$	~0.5	≥0.9	0.1 Ma: 0.98 $\sigma F/Ma = 0.35$ 0.33 Ma: 0.94	0.994 0.94	≥0.5 ≥0.1	≥0.9	≥0.2 ≥0.038	0.1 Ma: $\geq \bar{N}_0 \times 1.3 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 8.0 \times 10^{12}$
Σ				0.1 Ma: 3.3×10^8 0.33 Ma: 1.1×10^9	0.1 Ma: $\bar{N}_0 \times 7.9 \times 10^{14}$ 0.33 Ma: $\bar{N}_0 \times 2.6 \times 10^{15}$							$\frac{7.9}{79} = 0.10$ $\frac{2.7}{260} = 0.01$	0.1 Ma: $\geq \bar{N}_0 \times 7.9 \times 10^{13}$ 0.33 Ma: $\geq \bar{N}_0 \times 2.7 \times 10^{13}$
I	II	III	IV	V	VI								

Note. The unknown average number of $B.$ $subtilis$-like bacteria on Mars is assumed to be $\bar{N}_0$ per gram martian rock. Majority of ejecta pores assumed nonvacuated.

TABLE IX

Number of Ejecta from Mars Landing on Earth during the First 0.5 Ga—at Which Time L was 0.7 $L_\odot$—and the Numbers of Viable Bacteria per Arriving Ejecta

Time traveled from launch, τ_{accum} (ka)	t (years)	Ejecta size 2. Av. mass $= 1 \times 10^6$ g			Ejecta sizes $3+4$. Av. mass $= \sim 20 \times 10^6$ g			Ejecta sizes $5+6+7$. Av. mass $= \sim 130 \times 10^6$ g			All sizes
		No. of ejecta arrived within τ_{accum} from launch	Average time between ejecta landings (years)	No. of viable bacteria per arriving ejecta, N_{vs}	No. of ejecta arrived within τ_{accum} from launch	Average time between ejecta landings (years)	No. of viable bacteria per arriving ejecta, N_{vs}	No. of ejecta arrived within τ_{accum} from launch	Average time between ejecta landings (years)	No. of viable bacteria per arriving ejecta, N_{vs}	No. of viable bacteria arriving via all ejecta together, N_v
10	1000	33×10^6	15	$\bar{N}_0 \times 10^6 \times 0.17$ $= \bar{N}_0 \times 1.7 \times 10^5$	17.5×10^5	290	$\bar{N}_0 \times 2.0 \times 10^6 \times 0.28$ $= \bar{N}_0 \times 5.6 \times 10^6$	19×10^4	2,600	$\bar{N}_0 \times 130 \times 10^6 \times 0.40$ $= \bar{N}_0 \times 5.2 \times 10^7$	$\bar{N}_0 \times 2.5 \times 10^{13}$
1	100	33×10^6	150	$\bar{N}_0 \times 1.8 \times 10^5$	1.75×10^5	2,900	$\bar{N}_0 \times 5.6 \times 10^6$	1.9×10^4	26,000	$\bar{N}_0 \times 5.2 \times 10^7$	$\bar{N}_0 \times 2.6 \times 10^{12}$
0.1	10	0.33×10^6	1500	$\bar{N}_0 \times 1.8 \times 10^5$	0.18×10^5	29,000	$\bar{N}_0 \times 5.6 \times 10^6$	0.19×10^4	260,000	$\bar{N}_0 \times 5.2 \times 10^7$	$\bar{N}_0 \times 2.6 \times 10^{11}$

Note. Constant ejecta landing rate: 3300/year. Most porous ejecta volumes non-vacuated (Case A + V in the text). Short transfer times. The numbers N_{vs} are calculated for each size group s according to the expression $N_{vs} = \bar{N}_0 \times \bar{m}_s \times f_1 \times f_4 \times f_{2s} \times f_{6s} \times f_{3s}(\tau_{accum}) \times f_5(\tau_{accum})$, where the denominations $\bar{N}_0$ and $\bar{m}_s$ and survival fractions f_n are defined as in Tables VIIIa and VIIIb. The index $_s$ stands for the size groups. Those entities which are independent of S have no $_s$-index. The survival fraction f_5 includes DNA decay by release of bases through hydrolysis but not a potential effect of intramolecular sublimation of H_2O ice inside the cell's thick protection wall, in the DNA, in vacuum at temperatures -20 to $-65°C$.

TABLE X

Numbers of Ejecta (with T at Expulsion $\leq 100°C$) from Mars Landed on Earth during First 0.5 Ga within 6 Years from Launch, and Numbers of Surviving Bacteria (*B. subtilis* or *D. radiodurans* or Similar)

Size group, s	Radius range (m)	Average mass of ejecta in radius range, m_s (g)	No. of Mars ejecta ($T_{exp} \leq 100°C$) during 0.5 Ga from impactors with $L = 0.5$–20 km, n_s	Nos. of ejecta ($\leq 100°C$ at expulsion) landed on Earth within 6 years of launch during first 0.5 Ga, $n_s \times 0.007 \times 6 \times 10^{-6}$	Nos. of bacteria on board: undamaged + repairable + nonrepairable $\bar{N}_0 \times m_s \times n_s \times 0.007 \times 6 \times 10^{-6}$,	Total survival fraction, without vacuum effect, $f_{tot} = f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot f_5 \cdot f_6$	Nos. of surviving bacteria landing, without vacuum effect	Survival fraction against vacuum effect, f_{vac}	Nos. of surviving bacteria landing
2	0.03–0.67	0.95×10^6	4.7×10^{11}	2.0×10^4	$\bar{N}_0 \cdot 1.9 \times 10^{10}$	0.18	$\bar{N}_0 \cdot 3.4 \times 10^9$	0.015	$\bar{N}_0 \cdot 5.1 \times 10^7$
3	0.67–1.00	7.2×10^6	1.5×10^{10}	660	$\bar{N}_0 \cdot 4.8 \times 10^9$	0.30	$\bar{N}_0 \cdot 1.4 \times 10^9$	0.015	$\bar{N}_0 \cdot 2.1 \times 10^7$
4	1.00–1.67	30×10^6	9.3×10^9	390	$\bar{N}_0 \cdot 1.2 \times 10^{10}$	0.40	$\bar{N}_0 \cdot 4.8 \times 10^9$	0.015	$\bar{N}_0 \cdot 7.2 \times 10^7$
5	1.67–2.00	75×10^6	1.4×10^9	59	$\bar{N}_0 \cdot 4.4 \times 10^9$	0.40	$\bar{N}_0 \cdot 1.8 \times 10^9$	0.015	$\bar{N}_0 \cdot 2.7 \times 10^7$
6	2.00–2.33	120×10^6	7.6×10^8	32	$\bar{N}_0 \cdot 3.8 \times 10^9$	0.40	$\bar{N}_0 \cdot 1.5 \times 10^9$	0.015	$\bar{N}_0 \cdot 2.3 \times 10^7$
7	2.33–2.67	187×10^6	4.9×10^8	20	$\bar{N}_0 \cdot 3.7 \times 10^9$	0.40	$\bar{N}_0 \cdot 1.5 \times 10^9$	0.015	$\bar{N}_0 \cdot 2.3 \times 10^7$
Σ			5.0×10^{11}	2.1×10^4	$\bar{N}_0 \cdot 4.8 \times 10^{10}$		$\bar{N}_0 \cdot 1.4 \times 10^{10}$		$\bar{N}_0 \cdot 2.2 \times 10^8$

Note. All pores vacuated. Vacuum damage dominating, requiring very short flight times. For this table it has been assumed—as worst cases: that all ejecta spent 6 years in space, whereas in fact they arrive linearly in time, which, if taken into account, would increase survivals by a factor of 3; that the survival fraction used, 0.015, obtained by LDEF in space, was entirely due to vacuum and not to inleaking UV, whereas in fact the corresponding ground control gave a vacuum survival fraction of 0.05, which would increase survivals by a factor of 3; that impactor diameters were ≤ 20 km (cf. Table Ib), whereas in fact the impactors of diameters >20 km ejected a total mass from Mars which was more than twice the mass ejected by the impactors with diameters 0.5–20 km (cf. Table Ia); that if these three factors are taken into account, the numbers of surviving bacteria increase by a factor of 20. However, the assumption in this table that all pores are vacuated—which imposes the strongest restriction on survival—may not hold generally, because the skins of all ejecta melt during passage through thick atmosphere and thereafter solidify, thus creating in some number of ejecta tightly isolated volumes without vacuum. Even if only 1% of the pore volume was tight, a considerable number of surviving bacteria would arrive in those ejecta which landed more than 6 years after launch by the same impactors.

calculation of the first three of these effects are, for each one of them, higher than 0.999. Therefore the remaining effects were only that from vacuum on DNA and possibly that from inleaking UV stray light. No hazards from acceleration or heating by passage through atmosphere were in play. As part of LDEF, a parallel, similar, simultaneous exposure to high vacuum of the same duration, 6 years, was arranged on the ground. Here no UV could leak in. The survival fraction was found to be 5.5%, 3.5 times higher than in space vacuum. This corroborates the possibility that the results from LDEF space exposure were polluted by solar UV stray light. The number of survivors given at the bottom of the last column in Table X becomes then $\bar{N}_0 \cdot 8 \times 10^8$ if the value of the survival fraction against the vacuum effect on DNA from the ground measurement is more representative than the space value.

In natural transfer from Mars to Earth, with accumulation time of ejecta 6 years from launch, as in Table X, the survival fractions of GCR + SR, natural radioactivity, and DNA decay due to base loss are not different from those now calculated for the LDEF mission, i.e., each one larger than 0.999. However, the average survival fraction against the vacuum effect on DNA becomes larger than in the LDEF results because of the linear arrival of ejecta with time, of which those with travel time less than 6 years get a shorter exposure to vacuum and less DNA decay. On the other hand, the survival fractions against acceleration and direct contact passages through thick atmospheres must be accounted for in this case (Table X).

The calculation for Table X of the number of ejecta landings is based on the conservative restriction to impactor diameters ≤ 20 km (cf. Table Ib), whereas the impactors of diameters >20 km ejected a total mass from Mars which was more than twice the mass ejected by the impactors with diameters 0.5–20 km (cf. Table Ia).

Two further factors can be expected to lead to higher numbers of surviving bacteria after 6 years in space than those given in Table X:

—The 40 to 60°C lower meteoroid temperature during the first 0.5 Ga compared to the +20°C during the LDEF mission

—The assumption for Table X that all pores in the rock ejecta were quickly evacuated on leaving the atmosphere, although the unavoidable melting of the skin of the ejecta on their hypervelocity passage up through the atmosphere may tightly enclose some volumes of some of the ejecta, so that the vacuum threat is much delayed.

7. SOME LABORATORY EXPERIMENTS ON EARTH WHICH COULD FURTHER IMPROVE OUR KNOWLEDGE IN THIS FIELD

Examples of possible, relatively low-cost experiments relative to the issue of natural transfer of microbes between Mars and Earth are as follows:

- Statistically more accurate computer simulations of the number of martian ejecta arrivals on Earth within biologically interesting accumulation times (10 to 100 years).

- Measurement of the Bond albedo A and the emissivity ε of the material (under the burned surface) of the available martian meteorites, in order to get values of $\frac{1-A}{\varepsilon}$ and to know the temperature of meteoroids in Mars-like orbits, Earth-like orbits, and intermediary orbits.

- Measurement of DNA decay constants under dry conditions and in the frozen state. (Recent developments in methodology ( ) now make this possible.)

- More detailed computer simulations of velocity reduction and of temperature distribution in ejecta going up through atmospheres of 1–5 Bar.

- Measurement of the effect on DNA bonds of the expansion of liquid H_2O freezing to ice.

- Measurements checking possibly disturbing interaction when the repair mechanisms for DNA decay and those for radiation damage operate simultaneously.

- Experiments on the survivability of microbes inside small meteorite replica accelerated to realistic meteorite arrival speeds, crashing into various sterilized terrestrial surface types such as water, ice, sand, soil, and rock.

- Measurement of the time scale for the evacuation of vacuum-surrounded, somewhat porous meteorites under simulated laboratory conditions, and measuring, if possible, the steam pressure in the porous cavities

- Measurements on other bacilli and bacteria, including archeobacteria, of their survival fractions against radiation and DNA decay, particularly in vacuum, as a function of time.

Further to Earth-lab research, many valuable studies could be conducted by sending artificial "meteoroids" containing microbes into space.

Once some of the experiments listed above have been performed, a realistic test of viable entry through Earth's atmosphere would be of interest.

8. SUMMARY, DISCUSSION, AND CONCLUSIONS

8.1. Mars–Earth Transfers

The semiempirical calculations of the number of ejecta from Mars landing on Earth without having been subjected to temperatures higher than $100°C$ (Table Ib) and landing within 1 Ma from their launch produce a figure of some 1 billion over the past 4 billion years and a figure of some 10 billion or more during the preceding "heavy bombardment" period. The flight times of the 10 or more billion martian meteorites landing on Earth, however, ranged from 1 year up to about 20 million years. Of these numerous ejecta arrivals, only those landing within less than 1 Ma are important for viable transfer in *nonvacuated* ejecta pores. For *vacuated* ejecta pores, due to the dominance of DNA decay by vacuum, only flight times of less than a few hundred years are survivable.

About 98% of ejecta (see Melosh, Compendium) have radii between 2 and 80 cm (assuming $\rho = 3.0$ g/cm^3), and at these radiation shielding thicknesses the viable flight time for *D. radiodurans* R1, with respect to GCR and SR only, is just over 1 million years and for *B. subtilis* between 0.3 and 0.35 million years (Table III), which is approximately the same survival time given by DNA decay through base release when solar luminosity was 70% of present. Over the first 0.5 Ga more than 20,000 ejecta from Mars have landed on Earth within a decade from launch. In those ejecta, the total surviving number of bacteria such as *D. radiodurans* R1, *B. subtilis* (wild), and/or many other sporulating or anhydrously dormant species is billions $\times \bar{N}_0$, where $\bar{N}_0$ stands for the unknown number of live bacteria of the type in question per gram martian rock at launch, if there were any bacteria there. If not, $\bar{N}_0$ was zero.

At these relatively moderate viable flight times, the effect of natural radioactivity is negligible. The rate of temperature-induced DNA decay, however, depends on the temperature of the meteorite during its orbital path.

In *unvacuated* pores on the other hand, survival times are much longer, hundreds of thousands of years; they are determined by base release or radiation, whichever is the more damaging for the particular bacterial species.

The numbers of ejecta from Mars landing on Earth as calculated can be regarded as sufficiently accurate in this context and for the purpose of this study. The fact that these numbers are very high indeed is quite essential for the outcome. It keeps the door open for viable transfer under different conditions, even some less probable ones which would not be credible with infrequent ejecta traffic. Furthermore, high landing numbers give great diversity of source points and target points.

The relative occurrence of *nonvacuated* versus *vacuated* ejecta pores, within or among ejecta, is not and cannot be known, neither by experiment nor by calculation. However, all possible relative occurrences—even the most extreme ones, such as 100% nonvacuated or 100% vacuated pores—give quite large numbers of ejecta transfers, survivable by very large numbers of bacteria. Thus the main conclusion of the study is independent of the unknown relative occurrences. This certainly highlights the importance of the large numbers of landing ejecta.

Regarding the viable flight times to Earth of martian meteoroids, the following remarks can be made with respect to meteoroid size on the basis of the calculated data (Tables III, VIIIa and VIIIb):

Category 1: Small and medium-sized meteoroids (with radii from 2 to 80 cm and masses from 0.1 kg to ~6.5 tons (if $\rho \approx 3$ g/cm^3). These meteoroids provide no shielding against the galactic cosmic rays, on the contrary they increase the dose rates caused by unshielded GCR by the creation of more particles inside the meteoroids. However, they could still serve as vehicles for viable transfers from Mars to Earth lasting 1 million years for *D. radiodurans* R1 and 0.3 million years for *B. subtilis* (wild type) if DNA decay is not limiting. They are very numerous (Table Ib), billions during the last four billion years and one

to two orders of magnitude more during the preceding heavy bombardment period. They spend only a relatively short fraction of their time in the asteroid belt (Gladman 1997) so the effect of collisions there can be neglected. The effects of natural radioactivity are also negligible. At flight times of about 300,000 years, DNA decay by release of bases by hydrolysis and radiation damage give about equal survival fractions, as shown in Tables VIIIa and VIIIb for $\frac{1-A}{\varepsilon} = 1$. How this varies for those meteoroids in which $\frac{1-A}{\varepsilon}$ becomes 1.3 and 0.7, respectively, is shown in Table XI.

It should be noted that, whereas the survival fraction versus radiation is directly influenced by the ejecta's total flight time τ from launch to landing, the survival fraction versus DNA base release is mainly influenced by that time portion t during which the ejecta reach their highest temperature. In the main type of example here, $t = \tau/5$.

Category 2: Very large meteoroids, boulders (radii ≥ 2 m). The incidence of meteoroids of this category is about 2% of that of the "small and medium-sized" category above. Here the GCR-caused dose rate is considerably reduced in the center of the meteoroids, and this would allow for long viable flight times if not for the limiting effects of DNA decay. (Natural radioactivity of 0.08 cGy/year—as in the most radioactive martian meteorite—reduces viable flight times in a 2-m-radius meteoroid from 32 to 28 Ma for *D. radiodurans* R1, and from 10.7 to 9.2 Ma for *B. subtilis* (wild type), which is of interest only in Part 2 of our study.) Because of the slowness of temperature change in large bodies, the low central temperature of the boulder T_C prevailing during most of the orbiting time may not change much during the relatively short time of passage through Earth's orbit (see calculation in Section 5). In such cases DNA decay would reduce the viable flight time somewhat less than in Category 1 meteoroids. However, to be conservative, we have not made use of that effect.

Category 3: Large meteoroids (radius 0.8 to 2 m). These are characterized by a combination of the properties of category 1 "small to medium" and category 2 "very large" and are included in Tables VIIIa and VIIIb. The number of meteoroids in this category is less than 2% of that in category 1.

Which of these meteoroid categories has provided the greatest opportunities for viable transfer? A glance at Table Ic shows that the masses (and thus volumes) ejected from Mars at $T < 100°C$ are roughly equal for the four impactor categories studied, and all offer excellent potential for viable transfer. The very large meteroids (Category 2) offer the extra advantage of efficiently shielding against galactic cosmic rays inside the outer shell of thickness ~ 1 m, as well as a more constant low temperature which somewhat reduces DNA decay (although this latter effect, as just mentioned, has not been included in the calculation). However, the average interval, 3 Ma, between two impacts of such large impactors means that the 160 impacts occurring during the first 0.5 Ga cover 160×0.33 Ma $= 55$ Ma with the arriving ejecta $= 10\%$ of 0.5 Ga. This means that during 90% of the first 0.5 Ga there were no viable deliveries to Earth from Mars from such large meteoroites: their arrivals were concentrated inside a few short periods totaling ~ 55 Ma. These periods may or may not have coincided with conditions on Earth favorable for the proliferation of arriving life units. Impacts of small- and medium-sized meteorites (Category 1), on the other hand, occurred frequently over the first 0.5 Ga—70,000—at average intervals of ~ 7 ka.

8.2. Earth–Mars Transfers

The number of ejecta from Earth landing on Mars from 4.0 Ga to present time (Table II) was one to two orders of magnitude lower than the number of martian meteoroites landing on Earth during the same period of time, but nevertheless still very substantial, about a billion during the last four billion years. However, what fraction of the cells on board could survive?

The principal differences between Earth-to-Mars transfers and Mars-to-Earth transfers are the following:

—The escape velocity from Earth is 11 km/s, compared to 5 km/s from Mars.

—Of ejecta emitted from Earth, roughly 0.01% land on Mars, within about 1 Ma, whereas $\sim 0.5\%$ of martian ejecta land on Earth, a difference of a factor of 50.

—The natural radioactivity in meteorites ejected from Earth is usually much higher—by more than a factor of 10—than that in martian meteorites (Table V).

—The difference in atmospheric pressure that has existed most of the time: for almost 4 Ga Mars' surface-level atmospheric pressure has on average been less than the present 7 millibars (Toon *et al.* 1980). This is an advantage in terms of tranfer from Mars to Earth, with low resistance and heating for the outgoing ejecta and gradual braking during the fall through Earth's progressively denser atmosphere.

—Ejecta from Earth to Mars on the other hand do not enjoy such advantages. On their way out they immediately meet the resistance and heating of Earth's full atmospheric pressure, and on approaching Mars no significant atmosphere softens the hypervelocity landing. If there was surface water on Mars during the first 0.5 Ga, Mars should also have had a thick atmosphere, more or less like the one on Earth, with similar advantages and disadvantages.

8.3. Could Life Have Existed on Mars before It Existed on Earth and Been Transferred from Mars to Earth?

This question concerns the period before 3.8 Ga BP, possibly even before 3.6 Ga BP, whichever is the age of the oldest fossils known on Earth. An affirmative answer would require two main conditions:

—That conditions on early Mars, more than 3.6 Ga ago, were such that life could exist there

—that at that specific period microorganisms could be transferred from Mars to Earth without lethal damage.

TABLE XI

Sensitivity to Variation of $\frac{1-A}{\varepsilon}$. Numbers of Cells, Surviving or Repairable, Arriving on Earth from Mars in the Early Period 0–0.5 Ga, When Solar Luminosity was 70% of Today's $L_\odot$, as Depending on Meteoroids' $\frac{1-A}{\varepsilon}$ Values and Temperatures, for an Orbit Example and for the Microbe Species *D. radiodurans* and *B. subtilis* Majority of Porous Ejecta Volume Nonvacuated, Size group 2.

$\frac{1-A}{\varepsilon}$	T at 1 AU (°C)	Helio centric distance where $T=0$°C (AU)	$\sum k_T$ at 1 AU (Ma^{-1})	First 3‰ fractions released by hydrolysis	t = time spent in or near Earth's orbit releasing p‰ of the bases, $t=\frac{\ln(1-p\cdot0.001)}{\sum k_T}$ (Ma)	*Deinoeoccus radiodurans* RI			*Bacillus subtilis* (wild)			
						$\sigma F \times \tau =12\tau$ $= 12 \times 5t$	No. of surviving and repairable cells remaining after damage other than DNA decay (by base release through hydrolysis and by vacuum)	Surviving fraction against DNA base-loss by hydrolysis	No. of surviving and repairable cells remaining after damage including DNA decay by base release by hydrolysis but not vaccum effect	$\sigma F \times \tau = 38\tau$ $= 38 \times 5\tau$	No. of surviving and repairable cells remaining after damage other than DNA decay (by base release through hydrolysis and by vacuum)	Surviving fraction against DNA base-loss by hydrolysis	No. of surviving and repairable cells remaining after damage including DNA decay by base release by hydrolysis but not vaccum effect
Upper extreme													
1.3	−2	0.985	1	1st	0.001	0.06	$\bar N_0 \cdot 2.7 \times 10^{12}$	×0.1	$\bar N_0 \cdot 2.7 \times 10^{11}$	0.19	$\bar N_0 \cdot 2.5 \times 10^{12}$	×0.1	$\bar N_0 \cdot 2.5 \times 10^{11}$
				2nd	0.002	0.12	$\bar N_0 \cdot 5.2 \times 10^{12}$	×0.01	$\bar N_0 \cdot 5.2 \times 10^{10}$	0.38	$\bar N_0 \cdot 4.6 \times 10^{12}$	×0.01	$\bar N_0 \cdot 4.6 \times 10^{10}$
				3rd	0.003	0.18	$\bar N_0 \cdot 7.7 \times 10^{12}$	×0.001	$\bar N_0 \cdot 7.7 \times 10^{9}$	0.57	$\bar N_0 \cdot 6.4 \times 10^{12}$	×0.001	$\bar N_0 \cdot 6.4 \times 10^{9}$
Normal													
1.0	−20	0.859	0.015	1st	0.06666	4.00	$\bar N_0 \cdot 4.6 \times 10^{13}$	×0.1	$\bar N_0 \cdot 4.6 \times 10^{12}$	12.6	$\bar N_0 \cdot 1.5 \times 10^{13}$	×0.1	$\bar N_0 \cdot 1.5 \times 10^{12}$
				2nd	0.13332	8.00	$\bar N_0 \cdot 4.6 \times 10^{13}$	×0.01	$\bar N_0 \cdot 4.6 \times 10^{11}$	25.3	$\bar N_0 \cdot 1.5 \times 10^{13}$	×0.01	$\bar N_0 \cdot 1.5 \times 10^{11}$
				3rd	0.2000	12.00	$\bar N_0 \cdot 4.6 \times 10^{13}$	×0.001	$\bar N_0 \cdot 4.6 \times 10^{10}$	38.0	$\bar N_0 \cdot 1.5 \times 10^{13}$	×0.001	$\bar N_0 \cdot 1.5 \times 10^{10}$

Conditions on early Mars. There is evidence that about 3.8 Ga ago liquid water existed on Mars in the form of open rivers, lakes and oceans. Satellite observations show a number of riverbed-like formations. Some of the larger of these (1000 km long and very wide) seem to have been one-time and relatively short-lived events, caused for example by large comet or asteroid impacts or huge volcanic eruptions, and could have formed without a permanent thick atmosphere. The smaller ones on the other hand, called gullies, are thought to have been a long-lasting phenomenon requiring a thicker atmosphere. Further evidence of the former presence of liquid water is provided by the laminae, sediment deposits in the polar regions. Recently, it was reported that NASA's Mars orbiting surveyor had detected, around a huge basin, a contour at constant altitude, which could only be interpreted as the coastline of a large ocean on early Mars. The size: like Earth's Antarctic Ocean and the Mediterrianian together. (Head, private communication).

Most astronomers today agree that 3.8 Ga ago the luminosity of our Sun was 30% weaker than it is at the present time, and this of course affected the climates of both Mars and Earth. Furthermore, the planets' climates were—and are—to a large extent dependent on the nature of their greenhouse gases and the partial pressure exerted by these gases. Because Mars lies 1.5 times further from the Sun than Earth, its insolation per m^2 is only 44% of Earth's. This made it more difficult for an atmosphere of greenhouse gases to be produced and sustained that could create the surface temperature of 0°C or more without which surface liquid water could not be present.

The most effective greenhouse gases are either $CO_2 + H_2O$ vapor + a little SO_2, or methane +H_2O vapor + ammonia. However, because methane is photolytic (relatively rapidly destroyed by UV light), whereas CO_2 is relatively resistant to UV light, most planetologists now believe that Mars' early atmosphere was mainly CO_2. This also fits with the fact that Venus' atmosphere is CO_2 and that Earth's atmosphere contains much less methane than CO_2.

A theoretical study (Pollack *et al.* 1987) supported the idea that "Mars possessed a dense CO_2 atmosphere and a wet, warm climate early in its history. Calculations with a one-dimensional radiative–convective climate model indicate that CO_2 pressures between 1 and 5 bars would have been required to keep the surface temperature above the freezing point of water early in the planet's history. The higher value corresponds to globally and orbitally averaged conditions and a 30% reduction in solar luminosity; the lower value corresponds to conditions at the equator during perihelion at times of high orbital eccentricity and the same reduced solar luminosity. For the standard model, a surface pressure of 2.2 bars is needed to raise the surface temperature to the melting point of water ice."

On present-day Earth, most of the CO_2 not tied up in carbonate rocks is dissolved in the oceans and a much smaller amount is present in the atmosphere. On early Mars, on the contrary, most of the CO_2 not bound up in carbonate rocks was present in the atmosphere and acted as a greenhouse gas.

According to Pollack *et al.*, temperatures in excess of 273 K may have occurred over all or much of Mars during most or all seasons of the year for an extended period of time. (The key drive for the evolution from the hypothesized early, wet climate to today's cold, dry conditions "would have been the thermal evolution of the planet's interior".)

Although it was pointed out that a surface temperature above 0°C was unlikely on early Mars because of the probable presence of CO_2 condensed clouds in the early martian atmosphere (Kasting 1991), it was found at the California Institute of Technology (Yung *et al.* 1997) that a small amount of SO_2 in the martian atmosphere would have prevented the formation of such CO_2 clouds.

For our present study, we assume that on early Mars, more than 3.8 Ga ago, there was an atmosphere of 3 bars dominated by CO_2. Some Earth microbes living in such a level of permanent pressure would not be damaged.

Transfer from early Mars to Earth. Such a high CO_2 pressure, although favorable to sustaining any life that may have been present, could have had a negative impact on microbes' capacity to survive the transfer process from Mars to Earth. More specifically, two questions must be answered:

—what were the temperatures caused by the passage through this relatively thick atmosphere?
—what was the velocity reduction?

It should be noted that the same questions are relevant for ejecta leaving Earth.

Conditions on early Earth. According to recent ideas of planetary accretion, Earth and the other terrestrial planets were formed in 10–100 Ma and their interiors were hot due to large and frequent impacts. At the end of the main accretion period, the surface cooled and the steam atmosphere precipitated as rain, forming oceans. The atmosphere thereafter was probably mainly CO_2, CO, and N_2. According to J. Kasting (1993), "a primitive atmosphere containing 10 bars of CO_2 + CO along with approximately 1 bar of N_2 is possible during the first several hundred million years of Earth's history. Climate modelling indicates that the mean surface temperature of such an atmosphere would have been ~85°C."

This main accretion period was followed by the "heavy bombardment period," 4.5 Ga to 3.8 Ga. The frequency of impacts varied a lot over the period, but on average it was about two orders of magnitude more intense than it was from 3.8 Ga and on (as deducted from the study of thousands and thousands of impact craters on the moon).

Thus the opportunities for natural transfer of microbes during the heavy bombardment were $100 \times \frac{0.7}{3.8} = 20$ times greater than those during all times from 3.8 Ga to the present time calculated above in this paper. However, was the number of viable microbes that could be transferred also an order of magnitude greater?

This number could be influenced by the density of the atmosphere on the planet launching the ejecta. During that early

period, 4.5 Ga to 3.8 Ga, the probable CO_2 atmospheric pressure at the surface was 5 to 10 bar on Earth and 2 to 5 bar on Mars. The impact-caused unshocked or weakly shocked ejecta rising from the spall zones with temperatures not much below $100°C$ would be somewhat further heated by radiation from the hot gas plume created by the gazification of part of the impactor and part of the target material at impact and by friction with the mixed gas plume/original CO_2 atmosphere.

The partial volume of ejecta of different sizes where the temperature is less than $100°C$—the sum of spall-zone-caused temperatures and atmosphere-caused temperature rise—is being calculated, but the result of the calculation is not yet available. It is already clear, however, that in large ejecta of radius >1 m, the atmosphere-caused heating does not have enough time to penetrate further than a small relative distance from the skin before the ejecta leaves the atmosphere.

8.4. Dependence on Ejecta Size of Atmospheric Heating and Braking at Relatively Dense Pressure

In the same way that the surface shell of a meteorite entering the Earth's atmosphere glows with heat, ejecta launched from Earth at velocities equal to or greater than the escape velocity of 11 km/s will also be glowing hot at their surface. At equal initial speeds, the skin temperature of exiting ejecta will be higher than that of entering ejecta because they immediately encounter the resistance of full atmospheric pressure.

The same is true for ejecta leaving a thick CO_2 atmosphere on Mars. The lower martian escape velocity contributes to reducing heating, but on the other hand, heating is increased by the fact that, because of the lower gravity on the planet's surface, the mass of a martian atmosphere is 2.5 times that of an Earth atmosphere at equal surface pressure. The braking of ejecta entering a martian atmosphere is also influenced by these conditions.

In their capacity as vehicles for live cells, large ejecta are less affected by these conditions than smaller ones. Because of the hyperrapid exit through the atmosphere—taking only a few seconds—and because the heat created in the outer shell is conducted relatively slowly inward, a greater percentage of the volume of large-sized ejecta remains unheated or only slightly heated. Larger ejecta are also less slowed, because an ejecta's cross section increases as the square of its radius while its momentum is proportional to the cube of its radius.

As early as 1986 Ann Vickery made calculations on the influence of the impact-site gas dynamics on ejecta—particularly ejecta from the spall zone—as a function of ejection time and of radial launch position from the impact. She found that some ejecta were slower than the outward velocity of the gas, and therefore accelerated by the gas, and some were faster, and therefore decelerated, the tendency being to make ejecta velocities more equal.

However, independently of whether ejecta acceleration or retardation occurs, the ejecta skin is heated and the heat is conducted inward; the influence of this heating on the survival

fraction of any microbes inside varies according to ejecta size. Not yet having calculated what portion of ejecta of different sizes still has a temperature <$100°C$ after passage through the atmosphere, we have temporarily placed the fraction f 22—the survival fraction in ejecta of size 2 against heating when exiting up from the mother planet through the atmosphere and impactor gas—in the final column of Tables VIIa, VIIIb, XIIa, and XIIb, Earth to Mars. (This heating by passage through the atmosphere is additional to that caused by the launch mechanism in the spall zone, taken into account in our calculations as $\leq100°C$).

An extreme example of dense CO_2 atmosphere is offered by Venus: at its surface the pressure is 95 bar and the temperature is $470°C$. Such an environment is of course far too different from the conditions on early Mars for the results of the study of Venus to be directly applicable to Mars. However, certain findings could be indicative: for example that an impact can lead to reduction of the gas pressure above it. Ivanov *et al.* (1992) made a combined Russian–American study interpreting measurements by the Russian Venera probes and the American Magellan mission.

A simulation study has been started in Sweden for determining at which ejecta size the temperature remains below $100°C$ in $\geq50\%$ of the ejecta volume during exit passage through the mother planet's atmosphere. Preliminary results have been obtained, to be published soon (Mileikowsky *et al.*) which indicate that ejecta ≥20 cm across can fulfill that condition.

8.5. General

These figures must of course be taken for what they are: very approximate. Their significance is to demonstrate the orders of magnitude involved, as well as the relative trends when parameters change. Even if they were wrong by an order of magnitude or two—due to some erroneously conceived or overlooked or unknown factor—they would still demonstrate the frequent opportunities for transfers of subterranean microbes—where they may exist—via ejecta meteorites both from Mars to Earth and from Earth to Mars. The large numbers secure important diversity as to the environments of the microbes' departure points and even greater diversity in their numerous potential landing places.

If life existed on Mars very early, the question arises: did life as we know it appear independently on both Earth and Mars, or on one of these planets only, thereafter to be transferred to the other one? Here the two-way microbial traffic between the two planets gives an important argument. In considering this question we must remember that today all known living organisms use DNA as carrier of inherited information and employ the same genetic code for protein synthesis. This strongly indicates a single origin of present life forms.

Our study has shown a significant portion of those transfers to be viable transfers, not only for those microbe species which are most resistant to the dangers of prolonged existence in space, but also for many species of cells not quite as well equipped

TABLE XIIa
D. radiodurans: Number of Bacteria with Viable Arrivals from Earth to Mars during the First 0.5 Ga within 0.33 Ma after Launch

Size group, s	Radius range, m	Average mass of ejecta in radius range, $\bar{m}_s$ (g)	No. of Earth ejecta ($T \leq 100°C$) during 0.5 Ga from impactors with $L=0.5$–20 km, n_s	Accumulated No. of ejecta having arrived on Mars 0.33 Ma after launch, $n_s \times 0.00015 \times \tau_{acc}$	Accumulated No. of bacteria having arrived on Mars 0.33 Ma after launch (alive + repairable + dead), $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.00015 \times \tau_{acc}$	Survival fractions, f_n							Accumulated No. of viable bacteria having arrived on Mars during 0.5 Ga 0.33 Ma after launch at $\frac{1-A}{\varepsilon}=1.0$ $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.00015 \times \tau_{acc} \times f_{tot} = N_v(\tau_{acc})_s$
						$f_1 = f_{acc}$	$f_2 = f_{heat.atm}$	$f_3 = f_{GCR+SR}$	$f_4 = f_{nat.rad}$	$f_5 = f_{DNA.decay}$ at $\frac{1-A}{\varepsilon}=1.0$ 4 Ga BP	$f_6 = f_{heat.atm}$	$f_1 \times f_3 \times f_4 \times f_5 \times \times f_6$	
1	0.00–0.03												0
2	0.03–0.67	0.95×10^6	1.3×10^{12}	2.0×10^8	$\bar{N}_0 \times 1.9 \times 10^{14}$	~0.5	≥ 0.6	$\sigma F/\text{Ma} = 12$ 0.25	0.987	≥ 0.1	≥ 0.6	≥ 0.0043	$\geq \bar{N}_0 \times 8.2 \times 10^{11}$
3	0.67–1.00	7.2×10^6	3.0×10^{10}	4.5×10^6	$\bar{N}_0 \times 3.2 \times 10^{13}$	~0.5	≥ 0.8	$\sigma F/\text{Ma} = 6$ 0.43	0.987	≥ 0.1	≥ 0.75	≥ 0.013	$\geq \bar{N}_0 \times 4.2 \times 10^{11}$
4	1.00–1.67	30×10^6	6.5×10^9	9.8×10^5	$\bar{N}_0 \times 2.9 \times 10^{12}$	~0.5	≥ 0.9	$\sigma F/\text{Ma} = 2.6$ 0.67	0.987	≥ 0.1	≥ 0.9	≥ 0.027	$\geq \bar{N}_0 \times 7.8 \times 10^{10}$
5	1.67–2.00	75×10^6	6.0×10^7	9.0×10^3	$\bar{N}_0 \times 6.8 \times 10^{11}$	~0.5	≥ 0.9	$\sigma F/\text{Ma} = 0.7$ 0.89	0.987	≥ 0.1	≥ 0.9	≥ 0.036	$\geq \bar{N}_0 \times 2.4 \times 10^{10}$
6	2.00–2.33	120×10^6	1.7×10^6	2.6×10^2	$\bar{N}_0 \times 3.1 \times 10^{10}$	~0.5	≥ 0.9	$\sigma F/\text{Ma} = 0.32$ 0.95	0.987	≥ 0.1	≥ 0.9	≥ 0.038	$\geq \bar{N}_0 \times 1.2 \times 10^9$
7	2.33–2.67	187×10^6	4.6×10^3	Negligible	Negligible								Negligible
Σ					$\bar{N}_0 \times 2.3 \times 10^{14}$							$\frac{1.3}{230} = 0.006$	$\geq \bar{N}_0 \times 1.3 \times 10^{12}$

Note. The unknown average number of *D. radiodurans*-like bacteria on Earth is assumed to be $\bar{N}_0$ per gram rock. Majority of ejecta pores assumed nonvacuated. $N_v(t_{acc})_s = \bar{N}_0 \times \bar{m}_s \times n_s \times 0.00015 \times \tau_{acc} \times f_{1s} \times f_{2s} \times f_{3s}(\tau_{acc}) \times f_{4s}(\tau_{acc}) \times f_{5s}(\tau_{acc}) \times f_{6s}$, where $f_{3s}(\tau_{acc}) = \frac{1}{(\sigma F)_s t_{acc}}[1 - e^{(\sigma F)_s \cdot t_{acc}}]$, and $\tau_{acc} = $ accumulation time.

TABLE XIIb

$B.$ $subtilis$ (Wild): Number of Bacteria with Viable Arrivals from Earth to Mars during the First 0.5 Ga within 0.33 Ma after Launch

Size group, s	Radius range (m)	Average mass of ejecta in radius range, $\bar{m}_s$ (g)	No. of Earth ejecta ($T=100°C$) during 0.5 Ga from impactors with $L=0.5$–20 km, n_s	Accumulated No. of ejecta having arrived on Mars 0.33 Ma after launch, $n_s \times 0.00015 \times \tau_{acc}$	Accumulated No. of bacteria having arrived on Mars 0.33 Ma after launch (alive + repairable + dead), $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.00015 \times \tau_{acc}$	$f_1 = f_{acc}$	$f_2 = f_{heat.atm}$	$f_3 = f_{GCR+SR}$	$f_4 = f_{nat.rad}$	$f_5 = f_{DNA.decay}$ at $\frac{1-A}{\varepsilon}=1.0$	$f_6 = f_{heat.atm}$	$f_1 \times f_3 \times f_4 \times f_5 \times f_6$	Accumulated No. of viable bacteria having arrived on Mars during 0.5 Ga 0.33 Ma after launch at $\frac{1-A}{\varepsilon}=1.0$, $\bar{N}_0 \times \bar{m}_s \times n_s \times 0.00015 \times \tau_{acc} \times f_{tot} = N_v(\tau_{acc})_s$
1	0.00–0.03										0		0
2	0.03–0.67	0.95×10^6	1.3×10^{12}	2.0×10^8	$\bar{N}_0 \times 1.9 \times 10^{14}$	~0.5	≥0.6	$\sigma F/\text{Ma}=38$ 0.0086	0.987	≥0.1	≥0.6	≥0.0014	$\geq \bar{N}_0 \times 2.7 \times 10^{11}$
3	0.67–1.00	7.2×10^6	3.0×10^{10}	4.5×10^6	$\bar{N}_0 \times 3.2 \times 10^{13}$	~0.5	≥0.8	$\sigma F/\text{Ma}=18$ 0.17	0.987	≥0.1	≥0.75	≥ 0.005	$\geq \bar{N}_0 \times 1.6 \times 10^{11}$
4	1.00–1.67	30×10^6	6.5×10^9	9.8×10^5	$\bar{N}_0 \times 2.9 \times 10^{12}$	~0.5	≥0.9	$\sigma F/\text{Ma}=7.5$ 0.37	0.987	≥0.1	≥0.9	≥0.015	$\geq \bar{N}_0 \times 4.4 \times 10^{11}$
5	1.67–2.00	75×10^6	6.0×10^7	9.0×10^3	$\bar{N}_0 \times 6.8 \times 10^{11}$	~0.5	≥0.9	$\sigma F/\text{Ma}=2.0$ 0.73	0.987	≥0.1	≥0.9	≥0.029	$\geq \bar{N}_0 \times 2.0 \times 10^{10}$
6	2.00–2.33	120×10^6	1.7×10^6	2.6×10^2	$\bar{N}_0 \times 3.1 \times 10^{10}$	~0.5	≥0.9	$\sigma F/\text{Ma}=0.9$ 0.75	0.987	≥0.1	≥0.9	≥0.030	$\geq \bar{N}_0 \times 9.3 \times 10^8$
7	2.33–2.67	187×10^6	4.6×10^3	Negligible	Negligible								Negligible
Σ					$\bar{N}_0 \times 2.3 \times 10^{14}$							$\frac{8.9}{2300}=0.004$	$\geq \bar{N}_0 \times 8.9 \times 10^{11}$

Note. The unknown average number of $B.$ $subtilis$-like bacteria on Earth is assumed to be $\bar{N}_0$ per gram rock. Majority of ejecta pores assumed nonvacuated.

for natural space transfer. That follows, for example, from the numerous martian ejecta landed on Earth even after a relatively short travel time after launch. A short travel time greatly reduces the risks of radiation damage and DNA decay by base release, leaving the remaining critical risk to be DNA decay by vacuum in those ejecta pores which are vacuated. On the way up through the atmosphere, ejecta surfaces change profoundly, first melting and then solidifying or vitrifying upon exiting into space. These changes could protect against vacuation. In such nonvacuated volumes the bacterial lifetimes are determined either by DNA base loss or by radiation, whichever is the faster at the actual temperatures. The relative occurrence of nonvacuated versus vacuated volumes is not and cannot be known. However, all possible relative occurrences give large numbers of ejecta transfers, survivable by very large numbers of bacteria. Thus the main conclusion of the study is unaffected by the relative occurrence of vacuated versus nonvacuated volumes.

The main conclusion is that if procaryote microbes existed or exist on Mars, viable transfer to Earth must be considered not only possible but highly probable.

After viable arrival, their fate of course depends on their actual immediate environment. For successful multiplication thereafter the new environment must of course be favorable. "A sower went out to sow. And as he sowed, some seed fell on rocky ground. . . But when the sun rose the young corn was scorched. . . and it withered away. And some of the seed fell on good soil where it bore fruit, yielding a hundredfold" (Matthew, 13). (To estimate what fraction of the viable arrivals occur in environments favourable enough for multiplication and sustained life is beyond the scope of this study.)

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