Impact seeding and re-seeding in the inner Solar System

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Abstract

Assuming that asteroidal and cometary impacts onto Earth can liberate material containing viable micro-organisms, we study the subsequent distribution of the escaping impact ejecta throughout the inner Solar System on time scales of 30,000 years. We calculate the delivery rates of this terrestrial material to Mars and Venus, as well as back to Earth. Transport to great heliocentric distances may occur in just a few years because the Earth's relatively high escape speed means that, with only slight fractional increases above this speed, the departure speed is significant. Thus material is efficiently and quickly dispersed throughout the Solar System.

Compared to the work of Wells *et al.*(2003), our study carries out longer integrations, considers the fate of all the ejected mass (not just the slowly moving material), and tabulates impact rates onto Venus and Mars in addition to Earth itself. Expressed as a fraction of the ejected particles, roughly 0.1% and 0.001% of the ejecta particles reach Venus and Mars (respectively) in 30,000 years, making the biological seeding of those planets viable if the target planet supported a receptive environment at the time. In terms of possibly safeguarding terrestrial life by allowing its survival in space while our planet cools after a major killing thermal pulse, we show via our longer 30,000-year integrations that efficient return to Earth continues for this duration. A thorough analysis of the situation at various launch speeds indicates that roughly 1% of the launched mass returns to Earth after a major impact regardless of the impactor speed; although a larger mass is ejected following impacts at higher speeds, a smaller fraction of these ejecta are returned.

All in all, we are optimistic that bacterial life could have been safeguarded from any purported impact-induced extinction by temporary refuge in space.

1 Introduction

The reality of the modern-day impact hazard has now infiltrated the consciousness of the general public, with many citizens now aware that an asteroidal or cometary impact could produce major damage on a human scale during the next century (see, for example, Chapman 2004). Via telescopic census, planetary astronomers have established that the current near-Earth object population implies that kilometer-scale celestial bodies in Earth-crossing orbits (whose impacts would have global effects) strike our planet every few hundred thousand to a million years. The notorious K/T event linked to the extinction of the dinosaurs exemplifies the even rarer and larger impacts that occur on roughly 100-Myr intervals. However, even these ‘mass-extinction events’ pale by comparison to the largest impacts that must have occurred early in Earth’s history, during the so-called stage of late heavy bombardment, or LHB (see Hartmann *et al.* 2000 and Ryder *et al.* 2000 for elaboration of the definition of this term in the literature). During this era in the first 700 million years of terrestrial history (that is, ∼4.5-3.8 Gyr ago) the Earth was likely struck repeatedly by impactors so large that they delivered enough energy to vaporize the oceans and to emplace a rock-vapor atmosphere that could sterilize the Earth’s entire biosphere (Sleep *et al.* 1989). Clearly this might inhibit the development of life on Earth. The ‘impact frustration’ of life (Maher and Stevenson 1988) is the hypothesis that life might have arisen repeatedly only to be extinguished by the next giant impact.

The path-setting paper of Sleep and Zahnle (1998) discusses scenarios whereby early life may have avoided annihilation during this period. After a giant impact, conditions on Earth may have been lethal to the entire biosphere (including down to sub-surface depths of many kilometers) for of order 3000 years. For various reasons, Mars may have been a safer cradle for protecting the early development of life (Sleep and Zahnle 1998) against impact frustration. Early Mars may have indeed been habitable, as mounting evidence (e. g., Squyres *et al* 2004) of this planet having long-lived bodies of water seems to suggest. Thus, since dynamical transfer between Mars and Earth is efficient (Gladman 1997) and since microbial life is likely to survive in impact-ejected rocks voyaging through space for periods of at least tens of thousands of years (Mileikowsky *et al.* 2000, Nicholson *et al.* 2000), early life would be continously exchanged between the two planets in a process of 'natural panspermia' throughout the era of heavy bombardment. It may thus be no coincidence that the first signs of life on Earth appear just after the LHB ended (see Wells *et al.* 2003 and Ryder 2003 for a list of relevant literature).

On the other hand, if early Mars was not hospitable, was terrestrial life stymied until the heavy bombardment was over? Perhaps not. Sleep and Zahnle (1998) suggested the speculative hypothesis that space itself could serve as a temporary refuge. That is, given that bacteria-laden rocks may serve as temporary lifeboats for survival, pieces of impact ejecta launched by the giant impact would rain back down onto Earth after our planet cooled and would thereby re-seed the biosphere with life. This is the 'space refugium' hypothesis.

A short digression into the impact-induced launch of material is required for context.

The presence of lunar and martian meteorites on Earth (see Warren 1994, for an early review) proves beyond doubt that not only can intact rocks be transferred between the surfaces of planetary bodies in the inner Solar System, but that this process can happen with remarkably little shock being experienced by the transported fragments. Of the hypotheses in the literature, the shock-wave interference model of impact spallation (Melosh 1984, 1985) seems to fit best the available constraints related to the meteorites' shock levels, the shallow-depth provenance of the lunar samples, the relatively larger masses and the greater source-crater pairing of the martian meteorites (Warren 1994; Gladman *et al.* 1995; Gladman 1996, 1997; Head *et al.* 2002). In this model a thin near-surface layer, out to a few impactor radii around the contact point, is lofted up at faster than the planetary escape speed and with low peak-shock pressures. Once in interplanetary space this material can in principle be transferred to another terrestrial planet; studies of the time scales and efficiencies involved agree with the numbers and cosmic-ray exposure ages of the meteorites (Gladman *et al.* 1996). In its initial presentation, the Melosh (1984) theory gave that the maximum launch speed of the spalled ejecta is half the approach speed of the impactor. Accordingly (but see below), this requires impactors to strike the Earth with speeds of at least twice its escape speed of v_{esc}=11.18 km/s, or 22.36 km/s, in order to launch material that escapes the planet's gravitational well.

The space refugium (Sleep and Zahnle 1998) thus hypothesizes that the largest impacts launch so much material into space that viable returns of microbe-populated rocks occur after the ~3000-year lethal period they estimated the Earth would endure. However, as

Wells *et al.* (2003) explain, this 'impact re-seeding' process has a potential Achilles heel: large asteroidal impactors moving at less than 22.4 km/s might deliver lethal amounts of energy while launching no ejecta into space. Through a study of the dynamical re-delivery of this material to Earth and estimates of the survivability of bacteria against various hostile processes, Wells *et al.* (2003) conclude that, of the ejecta launched just barely above Earth's escape speed, sufficient material can return in a window 3000-5000 years after the impact to re-seed the Earth.

Because we believe that longer stays in space will not kill any ejecta-borne micro-organisms and because ejecta moving at higher launch speeds also make up a significant fraction of the returnning ejecta, we have extended the existing body of work. In this paper we examine in greater detail the impact re-seeding of the Earth over time scales of 30,000 years – an order of magnitude in time longer than the lethal stage but still short enough that viable returns are plausible. We study this process over the entire range of launch speeds, and also examine transport to Mars and Venus.

2 Launch via impact spallation

In the spallation theory of Melosh (1985; with the small error corrected by Armstrong *et al.* 2002 incorporated), the mass of spalled ejecta moving faster than a launch speed v_l can be expressed as:

$$\frac{M_e(v \geq v_l)}{m} = \frac{0.75 P_{max}}{\rho c_L U} \left[\left(\frac{U}{2v_l} \right)^{5/3} - 1 \right], \tag{1}$$

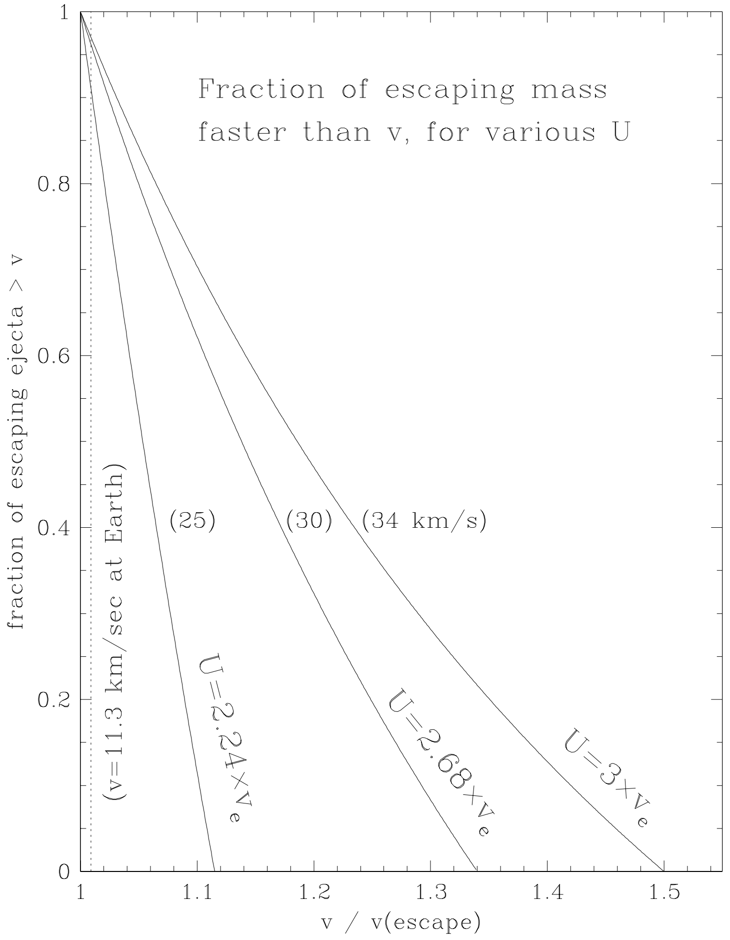

Figure 1: The speed distribution of spall-ejected material for various impactor speeds under the Melosh (1985) model, as corrected by Armstrong *et al.*(2002). For a planet having a given escape speed v_{esc}, speed distribution curves are shown for three different impactor speeds U, expressed as multiples of v_{esc}. For reference, the numbers in parentheses higher up each line show the values of U for escape from Earth. The ordinate gives the fraction of all *escaping* mass that is faster than the given speed, which thus is identically 1 at v=v_{escape} and drops to zero at $U/2$ according to the first-order spall theory. The vertical dotted line indicates an ejection speed at Earth's surface of 11.32 km/s, corresponding to $v_\infty \simeq 1.8$ km/s, the value taken by Wells *et al.*(2003); for each of the three impactor speeds shown, less than 10% of the escaping ejecta leave below such slow speeds.

where P_{max} is the maximum pressure experienced by the ejecta, ρ is the target density, c_L is the sound speed in the target material, U is the impactor's speed and m its mass. Note that $U > 2v_l$ in this formuation, as discussed above. In particular, setting v_l=v_{esc}, one gets the total mass M of escaped ejecta (which is a function of P_{max}, ρ, c_L, and U). One can thus calculate the *fractional mass* F of escaping ejecta with ejection speeds larger than some given v_l, relative to the total ejected mass M_e. This turns out to be most transparent if one scales all speeds to the escape speed (*i.e.*, $U \equiv \alpha v_{esc}$ and $v_l \equiv \beta v_{esc}$), for then the fractional mass ejected between v_{esc} and βv_{esc} is:

$$F(v_{esc} < v < \beta v_{esc}) = \frac{1 - \beta^{-5/3}}{1 - (\alpha/2)^{-5/3}} \ . \tag{2}$$

According to Melosh's (1985) formulation, impact ejecta never move faster than $U/2$, so escape of any material at all can only occur if $\alpha > 2$, and hence for the escaping fraction $1 < \beta < \alpha/2$. In this formulation we are computing the fraction of the total ejected mass, so all parameters related to the ejection physics cancel. Eq. 2 states that for fixed α (hence impactor speed U), the fraction F begins at zero for $\beta = 1$ and increases to 1 at $\beta = \alpha/2$, as expected. This expression allows us to plot in Fig. 1 the fraction of the total escaping mass leaving *faster* than a given launch speed v_l (which is thus $1 - F$). We see that launch speeds are distributed from the escape speed up to $U/2$ as expected.

The speed distribution of U for Earth-impacting objects depends on the source of the impactors. For Earth-crossing asteroids (which appear to dominate the speed distribution today) roughly half of the impacts occur at speeds below 22 km/s while for long-period and Halley-type comets the average impact speeds are factors of several higher (Jeffers *et al.* 2001). The mix between cometary and asteroidal impactors in the Earth-impacting distribution is not clear (Gladman *et al.* 2000), either today or in the distant past when the mix may have been more dominated by a cometary component. What is clear is that many impactors are moving sufficiency fast to expel impact ejecta off Earth's surface at speeds above Earth's escape speed.

Wells *et al.*(2003) examined cases with launch speeds from $v_\infty = 0.0 - 1.8$ km/s, where v_∞ (the speed 'at infinity' after escaping the planet's gravitational well) is related to the speed v_l from the surface by the simple relation

$$v_\infty^2 = v_l^2 - v_{esc}^2 \ , \tag{3}$$

and thus, for Earth's case, v_∞=1.8 km/s corresponds to $v_l = 11.32$ km/s. Fig. 1 indicates this ejection speed as a vertical dotted line; the ejecta spalled in the restricted range of v_l=11.18–11.32 km/s forms only a tiny fraction of the spalled ejecta (a few percent). While it is true that this material is the most likely to return to Earth, one can only determine whether or not this slowly-ejected portion of the ejecta dominates the *total* returned mass by calculating the yield of returning material for various launch speeds, weighted by the total mass launched into each ejection-speed interval. This is the purpose of our subsequent numerical studies.

3 Numerical simulations

We performed a suite of numerical integrations for 30,000 years to study the dispersal of terrestrial ejecta throughout the Solar System on this time scale. In order to be able to apply our results to differing launch conditions (that is, speed distributions), we chose to integrate several groups of ejected particles, each cluster having a different value of v_∞. To choose these initial conditions, we need to understand the range of v_∞ values which are reasonable.

3.1 Launch speeds

Among the terrestrial planets the Earth has the largest escape speed compared to its orbital velocity (more than one-third), making it by far the most effective of these bodies at disturbing the orbits of passing objects (*cf.* Gladman *et al.* 1996). In addition, because Earth's v_{esc} is large, small increases of launch speed above v_{esc} lead to relatively large v_∞ (see Eq. 3). For example, at $v_l = 13.0$ km/s, a speed only mildly above Earth's escape speed, the resulting $v_\infty = 6.6$ km/s is 22% of the 30 km/s orbital speed of the Earth; this percentage is to be compared to the ($\sqrt{2}$-1) (or 41%) increase in circular orbital speed that would yield an unbound orbit if the particle were projected towards the apex of Earth's motion. Because the velocity at infinity adds vectorially to the Earth's heliocentric orbital velocity vector (*cf.* Gladman *et al.* 1995), Fig. 2 shows that even launch at 12.25 km/s (only 10% above the escape speed), corresponding to $v_\infty = 5$ km/s, may produce some ejecta with perihelia as low as 0.5 AU or as high as 2.1 AU. Such particles thus cross the orbits of Venus, Earth, and Mars with encounter speeds that are large fractions of the escape speeds of those planets. Going even further, objects sent from Earth's surface with $v_l > 16.7$ km/s (*i.e.*, only 50% larger than Earth's escape speed, such as could be generated by impacts with $U > 33.4$ km/s in the basic spall theory) may escape the Solar System entirely if launched towards the Earth's apex of motion. Hence launch speeds just modestly above Earth's escape speed may produce heliocentric orbits that are extremely eccentric. The combination of these two aspects means that the early histories of Earth ejecta (which therefore often immediately intersect other planetary orbits) lie in a different regime than the superficially similar cases of lunar, martian, or mercurian meteorites (Gladman *et al.* 1996).

In view of these findings, for the short simulations of this investigation, we chose to consider launch speeds (listed in Table 1) that go from v_∞=1–12 km/s at 1 km/s intervals. Each simulation began with a radially expanding shell of impact ejecta at Earth's surface with the appropriate v_l so as to lead to these v_∞'s. No real impact would generate such an artificial velocity field; instead we view this distribution as representing the long-term average over impact locations on the Earth's surface, and to be testing the importance of the initial launch speed on the early history of planetary ejecta. In reality, any single impact expels particles at a continuum of speeds out along only some fraction of the possible directions.

```
 v(ej)   v(inf)  e_max   a_max   Q_max      e_min   a_min   Q_min
-----------------------------------------------------------------
 11.20   0.67    0.045   1.05    1.09       0.044   0.96    0.92
 11.30   1.64    0.112   1.13    1.25       0.106   0.90    0.81
 11.40   2.23    0.154   1.18    1.36       0.143   0.87    0.75
 11.50   2.69    0.188   1.23    1.46       0.172   0.85    0.71
-------------------------------------------- Venus Crossing -----
 11.60   3.09    0.217   1.28    1.55       0.196   0.84    0.67
----------------- Mars Crossing ---------------------------------
 11.70   3.45    0.243   1.32    1.64       0.217   0.82    0.64
 11.80   3.77    0.267   1.37    1.73       0.236   0.81    0.62
 11.90   4.08    0.290   1.41    1.82       0.253   0.80    0.60
 12.00   4.36    0.312   1.45    1.91       0.270   0.79    0.58
 12.10   4.63    0.332   1.50    2.00       0.285   0.78    0.56
 12.20   4.88    0.352   1.54    2.09       0.299   0.77    0.54
 12.40   5.36    0.390   1.64    2.28       0.326   0.75    0.51
 12.60   5.81    0.425   1.74    2.48       0.350   0.74    0.48
 12.80   6.23    0.459   1.85    2.69       0.372   0.73    0.46
 13.00   6.63    0.491   1.97    2.93       0.393   0.72    0.44
 13.20   7.02    0.523   2.09    3.19       0.413   0.71    0.42
 13.40   7.39    0.553   2.24    3.48       0.432   0.70    0.40
 13.50   7.57    0.568   2.32    3.63       0.441   0.69    0.39
-------------------------------------------- Mercury Crossing ---
 13.60   7.74    0.583   2.40    3.79       0.450   0.69    0.38
 13.80   8.09    0.612   2.58    4.16       0.467   0.68    0.36
 14.00   8.43    0.641   2.78    4.57       0.483   0.67    0.35
 14.20   8.75    0.669   3.02    5.04       0.498   0.67    0.33
----------------- Jupiter Crossing ------------------------------
 14.30   8.92    0.683   3.15    5.30       0.506   0.66    0.33
 14.40   9.08    0.697   3.30    5.59       0.514   0.66    0.32
 14.60   9.39    0.724   3.62    6.25       0.528   0.65    0.31
 14.80   9.70    0.751   4.02    7.03       0.542   0.65    0.30
 15.00  10.00    0.778   4.50    8.00       0.556   0.64    0.29
 15.20  10.30    0.804   5.11    9.22       0.569   0.64    0.27
-----------------  Saturn Crossing  -----------------------------
 15.30  10.44    0.818   5.48    9.96       0.575   0.63    0.27
 15.40  10.59    0.831   5.91   10.81       0.581   0.63    0.26
 15.60  10.88    0.857   6.98   12.97       0.594   0.63    0.25
 15.80  11.16    0.883   8.53   16.07       0.606   0.62    0.25
 15.90  11.31    0.896   9.59   18.18       0.612   0.62    0.24
-----------------  Uranus Crossing  -----------------------------
 16.00  11.45    0.909  10.94   20.89       0.617   0.62    0.24
 16.10  11.59    0.921  12.74   24.47       0.623   0.62    0.23
 16.20  11.72    0.934  15.22   29.44       0.629   0.61    0.23
-----------------  Neptune Crossing  ----------------------------
 16.30  11.86    0.947  18.91   36.81       0.634   0.61    0.22
 16.40  12.00    0.960  24.92   48.84       0.640   0.61    0.22
 16.60  12.27    0.985  68.20  135.40       0.651   0.61    0.21
 16.70  12.41    0.998 508.60 1016.20       0.656   0.60    0.21
---------------- Hyperbolic ejection from Solar System ----------
 16.80  12.54    1.011 -93.38 -187.76       0.661   0.60    0.20
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Figure 2: The relationship between the launch speed at Earth's surface and the v_∞ after escaping Earth's gravitational field. From that value of v_∞, we calculate maximum and minimum perihelia of the resulting heliocentric orbits. If the ejecta depart fast enough, some may have paths that immediately cross the orbits of other planets (indicated in the table). For example, surface ejection speeds of only 11.7 km/s (just 5% larger than Earth's escape speed) will allow some ejecta launched in the direction of Earth's motion to reach Mars with no further influences. Even Jupiter-crossing requires ejection speeds, if properly directed, to be merely 28% larger than escape speed.

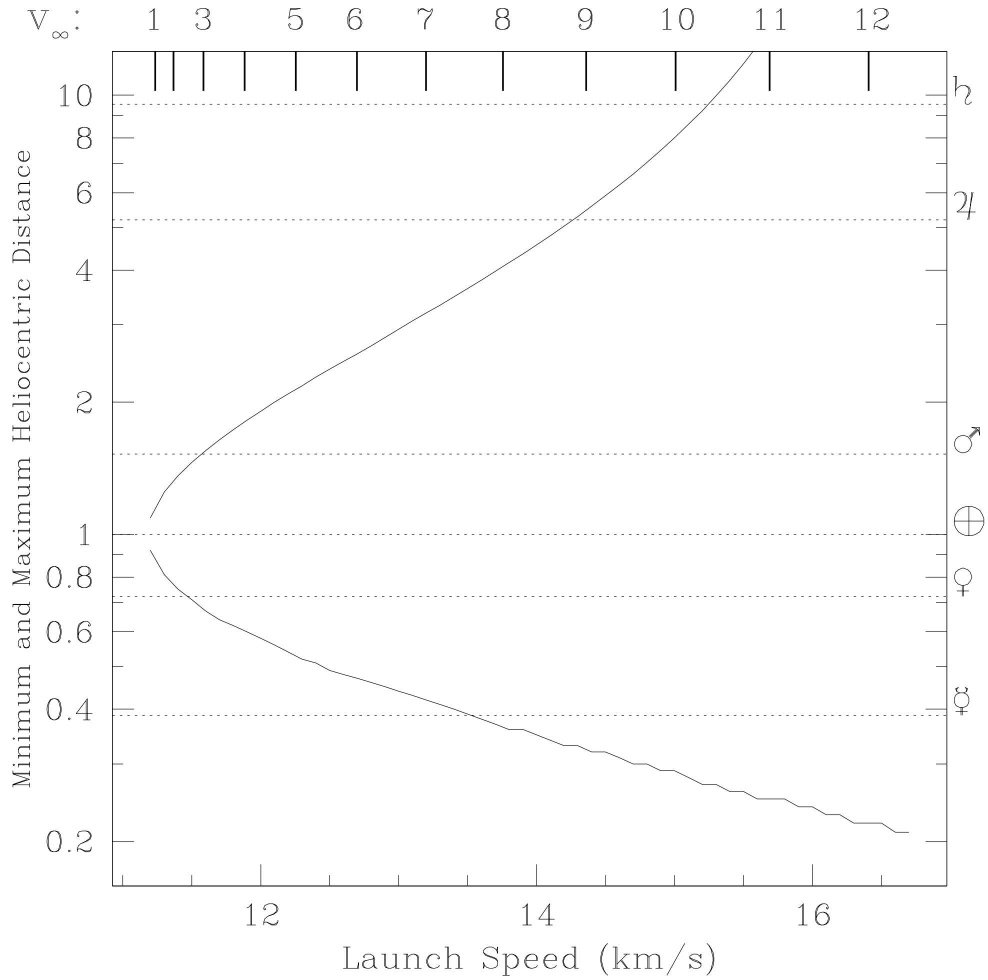

Figure 3: A graphical representation of some of the data presented in Fig. 2. As a function of both launch speed v_l (bottom) and v_∞ (top, km/s) this plot shows the maximum possible aphelion distance (if the ejected fragment is launched in the direction of Earth's motion and thus at perihelion) or the minimum possible perihelion distance (if ejected in the direction opposite to Earth's motion). The horizontal lines mark the semi-major axes of Mercury, Venus, Earth, Mars, Jupiter, and Saturn (moving outward from the Sun). As an example, at $v_\infty = 9$ km/s $\simeq v_l = 14.3$ km/s a particle ejected toward's Earth apex of motion would be on an orbit with perihelion at 1 AU and aphelion just outside Jupiter's orbit, while one ejected opposite to Earth's motion would have aphelion at 1 AU and perihelion interior to the orbit of Mercury. Note the strong compression of the v_∞ axis just above Earth's escape speed of 11.2 km/s.

4 Numerical method

Our choice of numerical method was guided by a desire to accurately integrate a large number of gravitational close encounters with the planets over a short time scale. In addition, we wanted to confirm our belief that the presence of Earth's Moon did not influence the statistical results; if it had, we would have needed to use a more computationally expensive numerical method. Our tests involved five different 30-kyr test integrations for the v_∞=2 km/s case, with 987 test particles per simulation, to examine the return of those particles to Earth. The first trio of test simulations had identical initial conditions but used three different integrators: swift-rmvs3 (Levison and Duncan 1994), Symba (Duncan *et al.* 1998), and a version of Symba adapted to test-particle integrations called Skeel. The fourth and fifth test simulations both used the Symba integrator, but added the Moon. In the fourth simulation, the Moon was on in its current orbit with semi-major axis of $\simeq$60 Earth-radii. In the fifth test the Moon was placed on an $e \simeq 0.05$ orbit with a 30 Earth-radii semimajor axis; to within a factor of $\sim$ 50% this is the expected lunar distance during the late heavy bombardment (see, for example, Burns 1986). We found negligible differences among the five simulations in the time distribution and quantity of terrestrial re-impacts; only Poisson fluctuations on a mean return efficiency of $\sim$36 of 987 particles were seen, and there was no evidence that the Moon's presence influenced the terrestrial re-impact rate. Thus, for what follows we adopted the Skeel integrator, which is best adapted to this problem with large numbers of close encounters and in which close

v_∞ (km/s)	1	2	3	4	5	6	7	8	9	10	11	12
v_{ej} (km/s)	11.22	11.36	11.6	11.9	12.2	12.7	13.2	13.7	14.4	15.0	15.7	16.4
Impacts												
N Earth	270	107	32	24	18	13	5	9	3	9	4	5
% Earth	9.0	3.6	1.1	0.8	0.6	0.4	0.2	0.3	0.1	0.3	0.2	0.2
N Venus	3	4	6	4	9	4	1	1	3	4	4	0
% Venus	0.1	0.1	0.2	0.1	0.3	0.1	.03	.03	0.1	0.1	0.1	0
N Mars	No direct martian impacts observed											
ppM Mars	2	4	11	18	18	15	13	12	9	7	6	2

Table 1: A list of our 30-kyr simulations of terrestrial impact ejecta. In each simulation, we integrated 3000 test particles that started at the given value of v_∞. The percentages for Earth and Venus are based on directly-observed impacts in the numerical integrations and thus uncertainties can be approximated as Poisson using the number of impacts. In the case of Mars we give an *estimate* of the impact rate based on a collision probability algorithm applied to the particle orbital histories; these fractions are quoted as the number of impacts expected from one million launched particles (ppM).

passages to the Sun are absent.

Each of our main integrations considered 3000 test particles. Our ‘base’ time step (which is decreased during planetary close encounters) was a very conservative 12 hours. Particles were removed from an integration if they struck a planet, went inside 0.1 AU from the Sun, or reached distances greater than 30 AU from the Sun. Table 1 lists results from these simulations over the first 30 kyr. No direct impacts were observed for Mars in our 3000-particle numerical intgrations, in agreement with expectations from a simple cross-section calculation, so we have computed an estimate of the transfer efficiency using a collisional probability code applied to the orbital histories recorded in our numerical integrations; such an Öpik collision-probability calculation typically under-estimates the real collision rate by 30–200% (Dones *et al.* 1999), consistent with what we will find below in the case of transfer to Venus. Peak martian transfer efficiencies in 30 kyr are $\sim 1.8 \times 10^{-5}$ with a corresponding expectation of 0.05 impacts in the v_∞=4 and 5 km/s simulations; the lack of directly observed impacts is thus not surprising and agrees with those previously published when converted to a common escape speed (Mileikowsky *et al.* 2000).

5 Return to Earth

Fig. 4 shows the cumulative percentage of ejected particles re-impacting Earth over our 30-kyr simulations. Because of the importance of gravitational focusing for the low-speed particles reaching heliocentric orbit, the return percentage for the lowest speed ejecta is much higher on this time scale; the effectiveness of this focussing drops quickly as time passes and the encounter speeds with the Earth diffuse to higher values via repeated gravitational scatterings (see Gladman *et al.* 1995 for a discussion in the similar case of lunar impact eject being accreted by the Earth). In the impact refugia scenario, Earth's surface is expected to remain lethal to returning ejecta for several thousand years (Sleep *et al.* 1989); the hatched portion of the graph shows that a fraction of the returning ejecta for each launch speed is thus returned to a hostile environment to perish despite their valiant effort at self-preservation. Wells *et al.* (2003) took the 3000–5000 year interval as optimal for the return of ejecta; in our simulations the fractions of returned ejecta arriving in this period are ∼0.6% and ∼0.2% for the v_∞=1 and 2 km/s cases; these are about a factor of three lower than found by Wells *et al.* (2003). We believe our results to be more

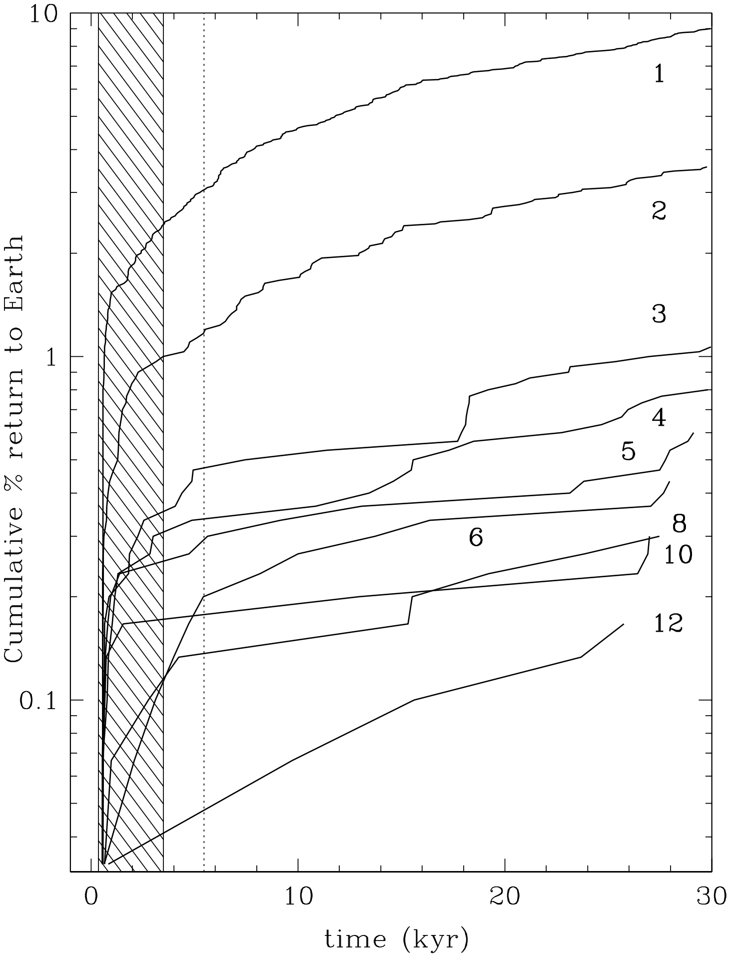

Figure 4: The 'raw' percentage of returns to Earth for ejected particles escaping with the labelled value of v_∞. In particular, these runs have not been weighted by the expected amount of mass present in that speed bin. The first 3000 years have been hashed to indicate this as being the period during which ejecta returning to Earth would still encounter a lethal environment after a major impact.

reliable given the factor of 3–4 greater number of impacts recorded in our studies in this 3–5 kyr time window.

Viable return to Earth on the longer time scales from 5–30 kyr is likely feasible. Of the problems faced by bacteria in the panspermia process (like acceleration, vacuum, shock, *etc.*), exposure to cosmic rays in the ejecta fragment in space is a minor killing factor. Wells *et al.* (2003) show that, unless the sensitivity of ancient micro-organisms to radioactivity is 2 to 3 orders of magnitude higher than that of modern bacteria, then radioactivity is one of the least important factors for survivability, and survival for ten times longer is likely. Therefore, we have chosen to include the entire 3–30 kyr interval as the period for viable returns. As Fig. 4 shows, only about one-tenth to one-third (at most) of the returns that do occur in <30 kyr happen during the 3000-year lethal period, so to an accuracy of about 30% we will herefater take the total return to Earth to be that which arrives in 30 kyr without deducting the small fraction that arrives during the 3000-year uninhabitable phase.

To compute the total returned mass, Fig. 4 needs to be weighted by the *mass ejected* in a given speed bin. That is, although 1 or 2 km/s ejection speeds give high return fractions to Earth, they form a minority of the ejected mass (unless the impactor speed is just barely above twice the planetary escape speed). Equation 1 allows the calculation of the total amount of mass ejected above the escape speed as a function of several parameters, but for a given impact these factors all cancel out when calculating the mass returned in any speed bin as a fraction of the total ejected mass. In particular, the fraction of

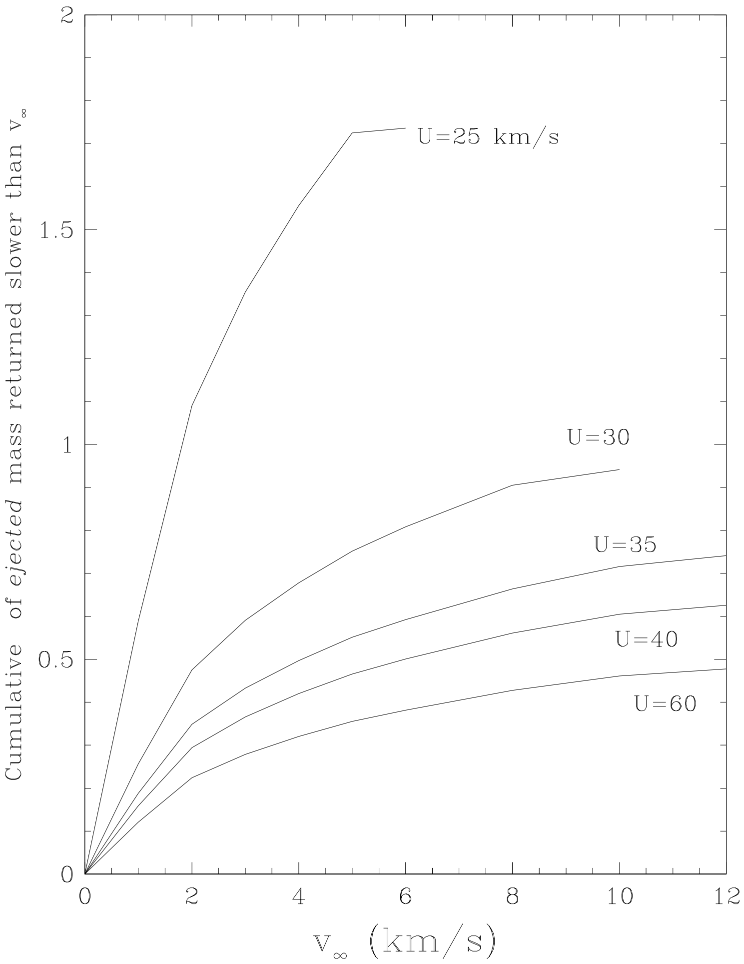

Figure 5: For each impactor speed U, this plot shows the cumulative percentage mass return to Earth in 30 kyr from launches slower than a given v_∞, *expressed as a fraction of the launched mass from that impactor*. The fraction of the mass in a given speed bin has been determined from Eq. 1. The curves for the lower impact speeds terminate because such impacts do not launch material faster than $U/2$. Note that these curves have *not* been weighted by the total amount of mass ejected by the impactors.

returned mass in each v_∞ bin depends on the impactor speed U because this changes the distribution of ejection speeds. Fig. 5 shows this fractional mass return for a variety of impactor speeds U; note that we have gone from a logarithmic scale to a linear one due to the much-decreased importance of the low-speed ejecta. Typical return fractions are $\sim$1% of the initially ejected mass. As a specific example, a $U = 30$ km/s impactor will have roughly one percent of the mass it ejects from the Earth return to our planet in 30,000 years, of which about half of this material was ejected at slower than $v_\infty = 2$ km/s. In fact, the material ejected with $v_\infty < 2$ km/s makes up about half of the returning mass *independent* of the impactor's speed; there is such a small launch speed (and hence acceleration) difference between these different v_∞ values in the case of the Earth that there seems little reason to restrict to the lowest speeds. Inclusion of the higher-speed ejecta increases the returned-mass fraction by about a factor of two, however.

The alert reader will have noted that the ejected mass is an increasing function of the impactor speed U (Eq. 1). Up until now we have concerned ourselves just with fractional return percentages from a given impact, either by number of ejected objects which return to Earth or by the fraction of the ejected mass. Fig. 6 shows the relative amount of mass returned to Earth (in 30 kyr) *relative* to the amount returned by a $U = 30$ km/s impactor (chosen as a reference). Note that this has been integrated over the entire speed spectrum of the launched ejecta appropriate to that impactor and integrated in time. Weighting Fig. 5 by the relative amount of ejected mass removes almost all dependence on impactor speed; the potentially surprising result is thus that all impacts yield (to within a factor of

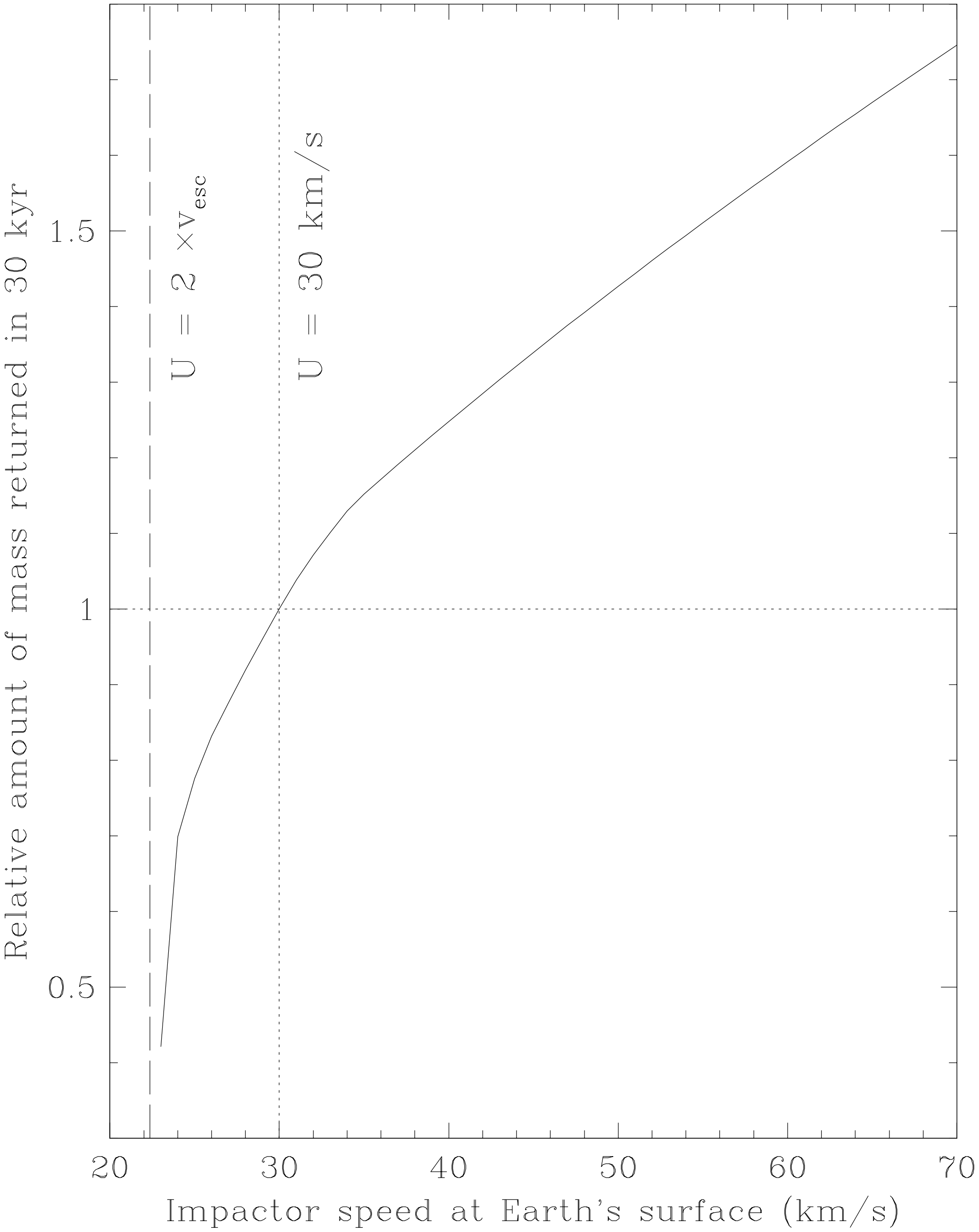

Figure 6: Returned mass to Earth in 30 kyr relative to the amount of mass returned by a $U = 30$ km/s impactor with the same mass. The result has been integrated with respect to the speed distribution launched (Fig. 1) for that impact speed, weighted by the relative return fraction at each launch speed, and integrated over time.

two) the *same* amount of returned mass to Earth, for given impactor mass m. Although higher-speed impacts launch their ejecta at generally higher velocities from Earth, the additional mass they launch (when integrated over the launch speed spectrum) more than compensates for the lower return probability per launched fragment. Therefore they return more mass (for fixed m) than the slower impactors.

For the purposes of Figs. 5 and 6 we have not eliminated the ejecta arriving in the first 3 kyr from consideration; inspection of Fig. 4 shows that this soonest-arriving material forms ∼15–35% of the material that returns in the first 30 kyr, so this is a small correction given the uncertainties of the total duration of the Earth's sterile period and the time over which viable ejecta can survive. We have thus chosen not to subtract this correction; it does not alter the conclusion that within a factor of two *all* impactors return nearly the same amount of mass to Earth in our 30-kyr window. Thus, the focus that Wells *et al.* (2003) placed on the lowest-speed ejecta is probably unnecessarily pessimistic, but our more careful calculations only imply a roughly factor of two increase in the total returned mass, which will certainly not modify the conclusion that viable returns to Earth of microbe-laden rocks are likely. Perhaps more important is the realization that, for a given impactor mass, even high-speed impactors (especially cometary objects) are still very efficient creators of 'space refugia' (Sleep and Zahnle 1998). We conclude that all Earth impactors with $U > 22.4$ km/s are roughly equivalent for the refugia problem in the sense that they all return of order 1% of the ejected mass back to Earth in 30 kyr.

5.1 Refugia in the case of complete sterilization

Wells *et al.* (2003) extend the discussion by Sleep and Zahnle (1998) on the potential of complete sterilization of Earth's biosphere by an impactor massive enough to deliver sufficient kinetic energy to vaporize Earth's oceans, but striking slowly enough that no ejecta are launched at faster than Earth's escape speed. Such a sterilizing impactor does not itself launch the rocks containing life's saviors into space. However, we feel it likely that during the period of heavy bombardment near-Earth space was continuously populated by viable ejecta due to the frequent occurence of smaller, non-sterilizing impacts which nonetheless launch viable fragments. Choosing an arbitrary impactor size of 1-km diameter, the current impact rate at this size is roughly one every 600,000 yrs (*e. g.*, Stuart and Binzel 2004) and appears to have been at least 100 times higher (Hartmann *et al.* 2000). This would imply <6-kyr intervals for 1-km impactors, each expected to launch of order 1 billion viable rocks with mean sizes of order a decimeter (Mileikowsky *et al.* 2000). Impactors of this scale would thus be continuously seeding near-Earth space, although at this decimeter-scale for the ejecta the Earth's atmosphere may present a considerable obstacle (Gladman *et al.* 1996). For 10-km impactors (which in the case of the K/T event produced globally-distributed ejecta) the interval would be 1-Myr during the LHB, or perhaps even 10^4 years if the LHB flux was 10,000 times greater than at present. As long as a fast ($U > 22.4$ km/s) impactor has struck the Earth during the window in which viable returns can occur, then a large slow impactor would not be able to snuff out terrestrial life. Even if it did, however, another possibility is the seeding of early Mars or Venus with life in order to later return it to Earth, as we now discuss.

5.2 Seeding Mars and Venus

Our integrations can be used to estimate the delivery rate to Mars and Venus over the 30-kyr time scale that we have investigated. This time scale was chosen based on the nominal 3000-year cooling time of Earth's biosphere after a major impact; viable delivery of terrestrial bacteria to Mars or Venus over such short time scale seems highly probable (see, *e. g.* Mileikowsky *et al.* 2000).

As previously discussed, it is relatively easy for Earth ejecta to be planet-crossing immediately after launch; for example, if ejected along the direction of Earth's motion they will have large aphelia (*cf.* Fig. 3). This results in it being relatively trivial for a large fraction of the ejecta escaping from Earth to cross the orbit of Venus or Mars and immediately begin delivering material to the atmospheres of those targets. Fig. 7 shows the orbital distribution just after the beginning of our simulations. In reality, almost any impact which launches ejecta from Earth will have some of that ejecta on orbits crossing those of other planets immediately, allowing fast (in principle, as quickly as a year) transfers.

Table 1 and Fig. 8 show that on time scales of 30 kyr roughly 0.1% of the ejected material arrives at Venus. For perspective, this would correspond to one million rocks from a billion-fragment launch. In the context of the impact-refugia problem, early Venus

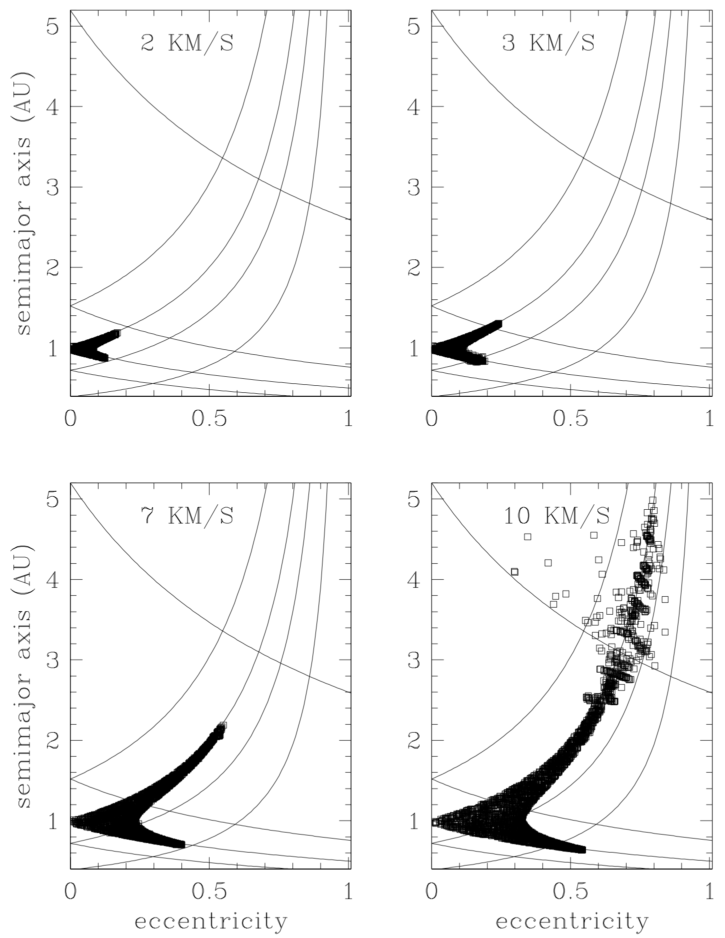

Figure 7: The heliocentric orbital distribution of the particles ejected from four of our numerical simulations after 100 years of simulated time. The web of lines shows perihelion or aphelion distance at the semimajor axis of one of the planets. For v_∞=2 km/s only the orbit of the Earth is crossed. At v_∞=3 km/s the orbits of both Venus and Mars are crossed by our expanding sphere of impact ejecta. In reality only part of the orbital parameter space covered here will be populated, depending on which hemisphere of Earth is struck in the impact; our simulations represent the situation averaged over all impact locations on Earth. In the 10 km/s simulation one can easily see the gravitational influence of Jupiter, which has in 100 yrs already considerably modified the heliocentric orbital distribution of the ejecta.

could therefore serve as a very easily-attained refuge for early life if it was more Earth-like than now and in particular if it had surface water (Donahue *et al.* 1997). If early Venus was indeed habitable, then we believe that viable microbial transfer from Earth to Venus is trivial because: (1) it seems relatively easy for bacteria to survive through the short transfer time; (2) our calculations show that the delivery fraction is a very high 0.003% per kyr; (3) entry speeds into the venusian atmophere will be low (around 11-13 km/s); (4) the density of the venusian atmosphere makes aerobraking possible and thus intact fragment delivery easier; and (5) the large cross-section of Venus and proximity to Earth make return to Earth (Gladman 1996) similarly easy.

Martian delivery of terrene ejecta is about two orders of magnitude less efficient than delivery to Venus due to the smaller martian cross-sectional area and gravitational focusing. The calculated yield of $\sim$0.001% in 30 kyr agrees with previous estimates (Mileikowsky *et al.* 2000); the very steep rise from $v_\infty = 1$ to 4 km/s in Fig. 8 is caused by the fact that little or no ejecta initially cross Mars's orbit at these low launch speeds (Fig. 7). As stated earlier, our martian estimates are probably underestimated by a factor of 2 or 3 since they are not based on directly observed impacts and the impact-probability algorithm underestimates collisions in this regime. We estimate a delivery rate of order 30 Earth-ejected meteorites per year to Mars after a major sterilizing impact. The efficiency is high enough that early Mars could serve as a useful refuge; the return of biotic material from Mars to Earth is a very efficient process (Mileikowsky *et al.* 2000) and the martian biosphere may be even more resistant to impact frustration than Earth's (Sleep

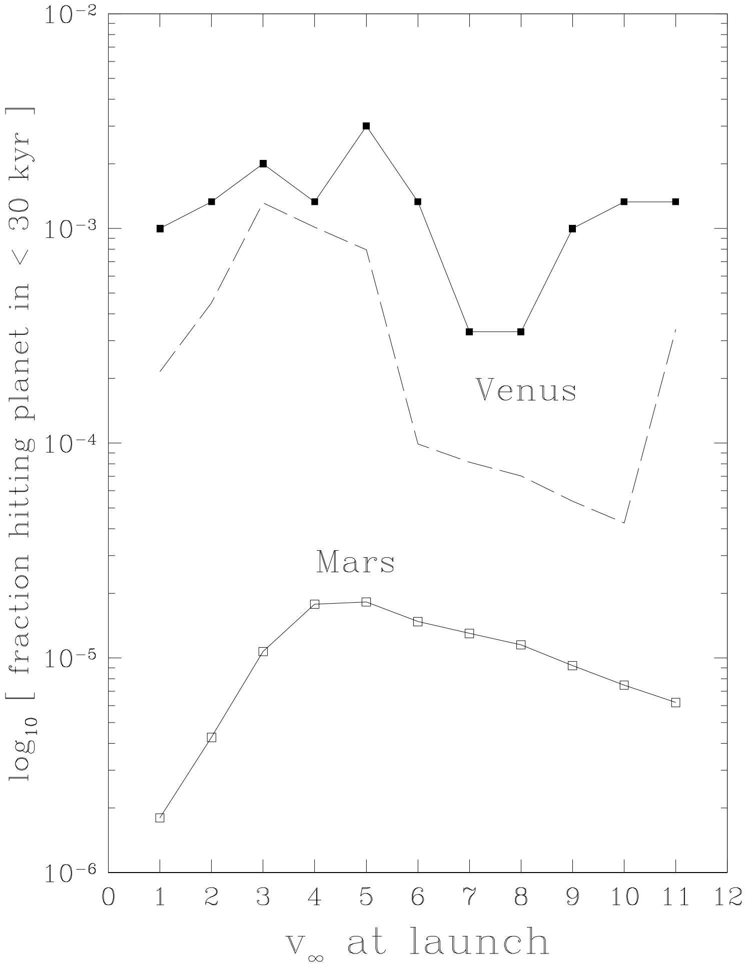

Figure 8: Fraction of ejected particles impacting Venus or Mars as functions of the v_∞ speed of launch away from Earth. Statistical errors on the Venus results are about a factor of two; for comparison the dashed curve below the Venus results shows the impact rate estimated by the Öpik method (see text), which in this case underestimates the impact rate by a factor of 2–10. The martian impact rate was estimated only by the Öpik method (since not enough particles were integrated to see a direct impact) and in reality is probably a factor of at least 2 higher than the estimates on this plot.

and Zahnle 1998).

6 Conclusions

Our simulations have shown that $\sim$0.1% of the material ejected from Earth will return in less than 30,000 years, a horizon which seems reasonable for microbial survival in space. We find that this return fraction is essentially independent of impactor speed (varying less than a factor of two for impactors striking at 22 to 60 km/s). Although we thus feel that the 'space refugium' hypothesis is even more viable than previous work had suggested, we also show that viable delivery to Mars and Venus (should either of these bodies have been habitable by terrestrial life in the first few hundred million years after planetary formation) is extremely efficient. Either of these planets could have harbored life if Earth's conditions were inhospitable (or, even more provocatively, could have served as the original cradle of life and held onto it long enough until Earth became a viable destination).

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