EXCHANGE OF METEORITES (AND LIFE?) BETWEEN STELLAR SYSTEMS

H. J. Melosh
Lunar and Planetary Laboratory
University of Arizona, Tucson AZ 85721
Tel. (520) 621-2806
FAX (520)621-4933
jmelosh@lpl.arizona.edu.

Running Title: Interstellar Panspermia

Keywords: Panspermia, origin of life, interstellar meteorites

ASTROBIOLOGY
Submitted to the Proceedings of the Rubey Symposium, May 2002
Revised, August 2002

Text Pages: 17
Figures: 4
Tables: 1

Abstract:

It is now generally accepted that meteorite-size fragments of rock can be ejected from planetary bodies. Numerical studies of the orbital evolution of such planetary ejecta are consistent with the observed cosmic ray exposure times and infall rates of these meteorites. All of these numerical studies agree that a substantial fraction (up to 1/3) of the ejecta from any planet in our solar system is eventually thrown out of the solar system during encounters with the giant planets Jupiter and Saturn. In this paper I examine the probability that such interstellar meteorites might be captured into a distant solar system and fall onto a terrestrial planet in that system within a given interval of time. The overall conclusion is that it is very unlikely that even a single meteorite originating on a terrestrial planet in our solar system has fallen onto a terrestrial planet in another stellar , over the entire period of our solar system's existence. Although viable microorganisms may be readily exchanged between planets in our solar system through the interplanetary transfer of meteoritic material, it seems that the origin of life on Earth must be sought within the confines of the solar system, not abroad in the galaxy.

"it is unlikely that a single meteorite of extrasolar origin has ever reached the surface of the Earth" Carl Sagan, 1972 (cited in Crick and Orgel, 1973)

Introduction:

It is now generally accepted that meteorite-size fragments of rock can be ejected from planetary bodies (McSween, 1985). There are currently some 20 meteorites in our collections that were probably ejected from the planet Mars during the past 15 million years and a comparable number that originated on the Moon. Numerical studies of the orbital evolution of such planetary ejecta are consistent with the observed cosmic ray exposure times and fall frequency of these meteorites (Gladman et al., 1996). Recent refinements in understanding the ejection mechanisms have resolved most of the outstanding puzzles that stem from the number and cosmic ray exposure ages of these planetary fragments (Head et al., submitted).

Almost as soon as the Martian origin of the SNC meteorite clan was recognized, it was suggested that living organisms, if they ever existed on Mars, might be able to travel from Mars to Earth, or vice-versa, in a dormant state (Melosh, 1988). This concept, which has recently acquired the name "lithopanspermia" because of its emphasis on the role of rocks in protecting dormant microorganisms from the full rigors of space, has become widely accepted by the Astrobiology community. Theoretical analyses suggest that the exchange of viable microorganisms between the planets of our solar system is overwhelmingly likely (Mileikowsky et al., 2000). Some authors even argue that Mars might be a more suitable place for life to have originated than the Earth (Kirschvink, 2002) and seek the ultimate origin of life abroad in the solar system.

The term “Panspermia” (from the Greek words for “seeds everywhere”) was originally coined by Svante Arrhenius (1908) who sought the origin of life on earth among the stars. The basic idea was proposed somewhat earlier by Lord Kelvin (Thomson, 1894). Modern studies suggest that naked microbes are too susceptible to UV radiation to survive more than minutes of direct exposure in space (Horneck, 1993). Encasement in rock fragments reduces this problem, but there is still a serious issue about how long viable DNA can survive even in spore form. Many studies show that dormant microorganisms can remain viable for periods of thousands of years (Seaward et al., 1976); however, claims for survival for periods exceeding ten million years (Cano and Borucki, 1995, Vreeland et al., 2000) are still regarded as highly controversial. Nevertheless, a small fraction of rocks ejected from Mars arrive on Earth within a few years (Gladman and Burns, 1996), and so impact ejecta remains a potential vector for the exchange of life between planets in our solar system.

One of the factors driving the modern interest in panspermia, especially between stellar systems, is the apparently very early appearance of life on the Earth. Carbon isotope shifts in rocks older than 3.8 Gyr suggest fractionation by living organisms (Mojzsis et al., 1996), although doubt is now expressed about the sedimentary origin of these rocks (Fedo and Whitehouse, 2002). Structures preserved in chert nodules led Schopf (1993) to infer the existence of apparently modern cyanobacteria as early as 3.465 Gyr. Although this evidence has recently been disputed (Brasier et al., 2002), biomarker studies show that cyanobacteria and eucaryotes were certainly alive by 2.7 Gyr (Brocks et al., 1999). Is this early appearance of life on Earth too early? No one really knows how quickly life can arise from nonliving precursors. Although some experts estimate this time to be as short as 10 million years (Miller and Lazcano, 1996), biologists in general have not reached a consensus on this still-unsolved problem. If it should turn out that the time scale for life to arise is very long, then an appeal to interstellar panspermia might seem desirable.

In this paper I examine the possibility that microorganisms may be exchanged between different solar systems by the natural exchange of meteorites. I explicitly exclude more radical suggestions (Crick and Orgel, 1973) that such exchange might occur by "directed panspermia", since that possibility is not open to further rational analysis. My approach is based on the theoretical conclusion that, in addition to an exchange of meteorites between planets, some meteorites are thrown completely out of the solar system. Numerical integrations of the orbits of material ejected from a planet demonstrate that a substantial fraction (up to 1/3) of the ejecta is eventually thrown out of the solar system during encounters with the giant planets Jupiter and Saturn. I will examine the probability that such interstellar meteorites might be captured into a distant solar system and subsequently fall onto a terrestrial planet in that system within a given interval of time. The final outcome of these considerations is that it is overwhelmingly unlikely that organisms have been exchanged between stellar systems by this mechanism. This conclusion is in good agreement with the results of an earlier study with the same goal (Mileikowsky et al., submitted).

Launch into interstellar space:

Planetary meteorites are currently believed to be ejected from their planets of origin by large impacts through the process of spallation (Melosh, 1985). Once ejected from a parent planet, such meteorites make many close passes to other planets or interact with orbital resonances created mainly by the giant planets. Because of these encounters the orbits of the ejecta alter with time and the ejected rocks may eventually end up falling onto another planet or leaving the solar system. In the present work I make use of the Arnold-Öpik Monte Carlo evolution scheme (Melosh and Tonks, 1994). This method explicitly ignores resonances and thus may lead to errors reaching perhaps a factor of two compared to the more exact symplectic integrator schemes (Dones et al., 1999). Nevertheless, this rapid method yields results sufficiently accurate for an order of magnitude estimate of the ejection frequency, while permitting many cases to be studied in the time that would allow the completion of only a few exact integrations. Figure 1 illustrates the fate of particles ejected from Earth and from Mars at a variety of initial velocities. The orbital evolution is computed according to the Arnold-Öpik Monte Carlo code, which is described in detail in Dones et al. (1999). The main inaccuracy of this code is the neglect of the "sundiver" (Farinella et al., 1994) resonance just outside the orbit of Mars, as well as the forest of secular and mean motion resonances in the inner solar system. Nevertheless, the predicted 30- 50 Myr lifetimes of Martian ejecta are close to those obtained from more exact orbital integrations (Gladman et al., 1996). It is clear that a large fraction of the ejecta from either Earth or Mars is eventually ejected from the solar system by Jupiter, with Saturn playing a smaller role.

A rough estimate suggests that about 500 kg of Martian rocks larger than 10 cm in diameter fall on Earth each year (Melosh, 1994). This is based on the number of Martian meteorites collected vs. the number of asteroidal meteorites in our collections times the estimated rate at which asteroidal meteorites fall on Earth each year. Another estimate puts the terrestrial flux of Martian meteorites at roughly 15 individual meteorites per year (Gladman, 1997). These estimates must be treated with caution, as the biggest objects dominate the spectrum of impactor masses, so this figure might be a considerable underestimate if integrated over the age of the solar system. Moreover, this ignores the much higher rates of impact that prevailed early in solar system history.

Our Monte Carlo simulations suggest that about as many Martian meteorites are ejected by Jupiter as fall on Earth each year (Melosh and Tonks, 1994), in agreement with the estimates of Gladman et al. (1996). We thus assume that about 15 rocks greater than 10 cm in diameter originating on the surface of a terrestrial planet leave the solar system each year. These meteorites exit the solar system with velocities in the vicinity of 5±3 km/sec. Both very slow and very fast ejection velocities are rare (see Figure 2), so I use a median ejection speed of 5 km/sec in the following discussion. Simulations in which the mass of Jupiter was either doubled or halved, or Saturn and Jupiter interchanged, gave results nearly identical to those in which Jupiter is in its conventional position. In addition, these computations show that the median time elapsing between ejection from a terrestrial planet and ejection from the solar system is about 50 Myr. Out of a sample of 5000 ejected particles the minimum time was 4 Myr. The only case in which the median ejection time became as short as a few million years is one in which Jupiter was placed at the orbit of Mars. It seems questionable whether such a solar system, with Earth at its present location and Jupiter at the orbit of Mars, would be stable for geologic intervals of time. Thus, the time scale for orbital evolution to expel planetary ejecta from the solar system is already near the limit of what dormant microorganisms might survive.

Probability of Reaching a Nearby Star:

Once planetary meteorites are launched into interstellar space, they coast outward at constant velocity. Although Jupiter does not eject the meteorites equally at all inclinations to the ecliptic, the number of encounters with distant stars is independent of the launch inclination if the target stars are distributed isotropically in space. Suppose that an annual "cohort" of N_0 ($\approx$ 15) rock fragments greater than 10 cm in diameter is ejected from the solar system each year. Then in a time interval of T years these meteorites will have traveled a distance of $s = v_e T$ from the sun, where v_e is the ejection velocity (5 km/sec = 5.1 parsecs/Myr). In this year they sweep out a new volume of $\Delta V = 4 \pi s^2 v_e (1 \text{ year})$ in which the mean number of stars is $\rho_s \Delta V$. The stellar density ρ_s is about 0.06 pc^{-3} in the Sun's neighborhood (Allen, 1955) (note that this does not distinguish stellar types—if we limited the density of target stars to, say G-type stars like the Sun, this density would have to be decreased by a factor of 10 to 20). Since the density of meteorites falls as $1/s^2$, the s^2 factor in ΔV cancels out. The number of impacts on extrasolar planets per year for this one-year cohort of meteorites is thus given approximately by $N_0 v_e \rho_s \sigma$, where σ is the cross section for a meteorite to strike a terrestrial planet in the stellar system.. This probability is independent of the distance s.

Note that, from the way cross section is defined, the rare cases when the Sun happens to be very close to a passing star receive their correct statistical weight in this formula. Integrating over T years, the mean number of impacts is T times this equation. In addition, during this T years there have been T annual cohorts of meteorites launched that have reached an average distance of $v_{e□}T/□2$ from the sun, so the total number of extrasolar impacts, N_{impact}, occurring within T years of launch is

$$N_{impact} = N_{0□}v_{e}□□_{s}□□□T^{2}/□2 \text{ impacts per T years.}$$

Inserting the rather optimistic numerical values for the factors given above, this amounts to

$$N_{impact} = 5.4□x□10^{-5}□ \text{ (AU}^{2}\text{)}□T^{2}\text{(Myr) impacts per T years.}$$

For the case of a direct impact of an interstellar meteorite on an extrasolar planet, the impact cross section □ would equal $\pi□R_{e}^{2}$, the projected area of a terrestrial planet in the target solar system, where R_e is the radius of the terrestrial planet. For a typical terrestrial planet of radius 6000 km, this cross section is only about 5 x 10^{-9} AU^2, and the number of impacts in even 10^9 years is only $3x10^{-7}$—a negligibly small chance of reaching the surface of such a planet.

The cross section □ for a direct impact on an extrasolar terrestrial planet is thus very small. However, two factors may raise this cross section substantially. The first is the gravitational focusing of incoming meteorites by the gravitational attraction of the target system. The spatial density of interstellar meteorites at a distance *r* from the target star is increased over the density far from the star by a focusing factor $v(r)/v$, where $v(r)$ is the meteorite's velocity at a distance r from the star and v is its velocity far from the star:

$$v(r)/v = \sqrt{1 + \frac{2GM_{star}}{r\,v^2}}$$

where G is Newton's gravitational constant and M_{star} is the mass of the star.

This increase in density near a gravitating object is a consequence of the Liouville theorem (Binney and Tremaine, 1987). This factor may reach a substantial size for rare, low-speed approaches. Although the magnitude of the velocity and spatial density of meteorites increases in the vicinity of the target star, Liouville's theorem also guarantees that the distribution of the directions of the velocities is isotropic in a non-rotating reference frame traveling with the star. This focusing factor makes the impact cross section a function of the approach velocity v. We shall see how to deal with this velocity dependence in the next section.

Another factor of even greater importance was suggested by Zheng and Valtonen (1999). These authors proposed that, instead of a direct impact on a terrestrial planet, it is much more likely that an approaching interstellar meteorite will be captured into a bound orbit by a hypothetical giant planet in the target system. Just as Jupiter is the main agent of ejection from our solar system, it may also serve as the main entry point for extrasolar meteorites. Once captured into the stellar system the meteorites have a much higher probability of eventually striking a terrestrial planet belonging to that system.

Following the usage in nuclear physics (Blatt and Weisskopf, 1952), the overall cross section for a particular event can be broken down into the probability of different intermediate steps. The impact cross section □ can thus be expressed as the product of two terms:

$$\square = \square_c \square P_{impact}$$

where $\square_c$ is the cross section for capture into the new solar system and P_{impact} is the probability that such a captured meteorite strikes a terrestrial planet. Our next task is to compute these separate terms to determine whether the capture process can make the process of interstellar transfer more probable.

Capture Cross Section:

I used a version of the Monte Carlo orbit evolution program to estimate the capture probability of interstellar meteorites as a function of the velocity of approach to the stellar system *v*. Instead of attempting a full orbital integration, the computation utilizes a pair of patched two-body approximations. First, assume that any meteorite that fails to enter the planet's sphere of influence will simply pass on through the system without being captured. The radius of a planet's gravitational sphere of influence is given by (Öpik, 1951):

$$R_{infuence} = a_{planet}\left(\frac{M_{planet}}{2M_{star}}\right)^{1/3}$$

Where a_{planet} is the semimajor axis of the planet's orbit, M_{planet} is its mass and M_{star} is the mass of the star.

This radius is nearly the same as the radius of the planet's Hill sphere, which could be used for the same purpose (I am following Öpik's lead in this choice). The capture cross section cannot be any larger than the projected area of the sphere of influence $\pi R_{influence}^2$. However, since this area can be many square astronomical units (AU^2) for a giant planet, it far exceeds the projected surface area of a terrestrial planet.

The computation of the capture cross section proceeds by following the orbits of interstellar meteorites that just enter the giant planet's sphere of influence. The number density of these meteorites is enhanced over the number density far from the star by the focusing factor $v(r)/v$ described above. Approach directions are chosen from a random deviate. The computer code randomly selects an impact parameter from a properly weighted random deviate. The hyperbolic orbit of the meteorite relative to the planet is then determined analytically by Keplerian dynamics. The relative velocity of the meteorite and planet is determined jointly by the approach velocity v to the stellar system, the acceleration of the meteorite as it falls into the star's gravitational field (its magnitude near the planet is $v(a_{planet})$), and the orbital velocity of the planet itself.

The velocity relative to the planet thus depends on the direction from which the meteorite approaches, which is why I average over all possible approach directions to get a mean capture cross section. Even when the meteorite approaches the star system very slowly, the velocity relative to the planet is comparable to the planet's orbital velocity around the star.

Occasionally, the meteorite actually strikes the planet and an impact is scored. When the meteorite leaves the planet's sphere of influence, its orbit relative to the star is again evaluated and it is determined whether the orbit is still hyperbolic, or whether the planet's attraction has been sufficient to bend the meteorite into a bound orbit about the star. Even in the most favorable cases, in which the stellar approach velocity is much smaller than the planet's orbital speed, at most half of the scattered meteorites are captured—it is basically a coin toss whether the meteorite is accelerated out of the system or decelerated into a bound orbit. The capture cross section is computed from the ratio of captures to the number of approaches as a function of the approach velocity v.

The principal results are shown in Figure 3, where the $1/v$ factor at low approach velocities is clearly seen on this log-log plot as a line of slope –1. The probability drops rapidly at approach velocities higher than about 1 km/sec, but even at this velocity the cross section approaches 1 AU^2 for most scenarios—far higher than that for direct impact on a terrestrial planet. In addition to case 1 for a solar system like our own, with Jupiter at 5 AU from the Sun, I varied the structure of the capturing system by doubling and halving the mass of Jupiter (cases 2 and 3). I also moved Jupiter out to the orbit of Saturn (case 4) and in to the orbit of Mars (case 5). Larger masses and greater distances from the Sun increased the capture cross section by factors of a few. In addition, I evaluated the capture cross section of Neptune (case 6). Although Neptune's mass is much smaller than Jupiter it is much farther from the Sun, so its mean capture cross section is about half that of Jupiter.

It is clear from Figure 3 that σ_c is a strong function of the velocity at which the meteorite approaches the stellar system. In this case, the cross section must be averaged over the distribution of the relative approach velocities. We assume that the peculiar motions of the stars relative to the Sun are represented by a Maxwell-Boltzmann distribution, such that the number of stars with one component of their velocity between v and $v + dv$ is given by $n(v)\,dv$, where

$$n(v) = \sqrt{\frac{2}{\pi}}\,\frac{e^{-v^2/2\Delta v^2}}{\Delta v}$$

In this equation Δv is the velocity dispersion, observed to be about ±20 km/sec in the solar neighborhood (Allen, 1955). Since Δv is typically much larger than v, the effective capture cross section σ_c can be closely approximated by averaging the capture cross section $\sigma_c(v)$ over the range of velocities of the field stars (Glasstone et al., 1941):

$$\bar{\sigma}_c = \frac{\int_0^\infty n(v)\,\sigma_c(v)\,dv}{\int_0^\infty n(v)\,dv}$$

Integrating the denominator, this simplifies to:

$$\bar{\sigma}_c = \int_0^\infty e^{-v^2/2\Delta v^2}\,\sigma_c(v)\,\frac{v\,dv}{\Delta v^2}$$

This integral can be evaluated from the numerically computed $\sigma_c(v)$ shown in Figure 3.

Table 1 summarizes the mean (velocity-averaged) cross sections for the six capture scenarios described above. Each run evaluated 10,000 encounters from random directions. The overall velocity-averaged cross sections are typically a few hundredths of a square AU. Using this average cross section in the equation for capture probabilities indicates that only one meteorite ejected from a planet belonging to our solar system is likely to have been captured by another stellar system in 1,000 Myr!

Impact on a Terrestrial Planet:

It is not enough that a potentially life-transporting meteorite should be captured into another solar system. It must also find its way onto the surface of a planet within a habitable zone. The capture simulation program indicates that the orbits of captured interstellar meteorites are very comet-like, with semimajor axes of typically several hundred AU (See Figure 4). Tracking the evolution of these orbits with the Öpik-Arnold orbital evolution code(Dones et al., 1999), some 94% of the captured meteorites are eventually re-ejected. The median time before ejection is about 60 Myr (the mean time is about 300 Myr: the distribution is strongly skewed), so most captured meteorites make about 100,000 perihelion passages before they are re-ejected.

For a wide range of assumptions about the location and size of a target terrestrial planet the probability P_{impact} that it strikes the planet sometime within 4.5 Gyr is only about 10^{-4}, as computed by the Arnold-Öpik Monte Carlo code. This code assumed the present structure of our solar system and includes the proper orbital motions of the terrestrial planets. I score a "hit" if the meteorite strikes any one of the four terrestrial planets. To generate adequate statistics nearly 100,000 orbits of captured meteorites were evaluated. This result agrees well with exact integrations of the orbits of long period comets: Jupiter is a highly effective defense against the impacts of objects from outside the solar system on the terrestrial planets (Levison and Duncan, 1997). This also agrees with the older estimate of Weissman (1982), that the probability of a long-period comet striking a terrestrial planet is about 2×10^{-9} per perihelion passage.

I also evaluated the probability of impact on a terrestrial-size moon of the giant planet. If the moon has the properties of Europa, the impact probability is even smaller, about 1.6 x 10^{-5}. This translates to only a very slim chance that life can be transported from one stellar system to another.

Discussion:

We have shown that over the course of post-heavy bombardment solar system history only one or two rocks from the surface of one of the terrestrial planets may have been temporarily captured into another stellar system. This figure would be increased early in solar system history when cratering rates were perhaps a factor of 1000 larger than at present and when the Sun may have been closer to other stars in its birth cluster. However, when the probability of one in 10,000 that the captured meteorite actually strikes a terrestrial planet is factored in, it seems unlikely that any rock ejected from a terrestrial planet in our solar system has ever reached a terrestrial planet in another solar system. This conclusion validates the quote from Carl Sagan which opened this paper. It is also in good agreement with the fact that no hyperbolic meteorites or comets have ever been observed. The spaces between the stars are immense and the probability of exchanging material with another stellar system is correspondingly tiny;

Even taking account of the fact that the structure of other solar systems is likely to be different from ours does not raise the exchange probability substantially. If our solar system lacked a Jupiter, impact rates on the terrestrial planets might be either lower or higher than they actually are (lower because without Jupiter the asteroid belt would not exist, so fewer impacts from asteroids would occur, and higher because Jupiter is not present to shield the inner solar system from long period comets). However, without Jupiter to eject rocks chipped off the terrestrial planets into interstellar space, there would be no source for interstellar meteorites. Similarly, without a giant planet, capture of interstellar meteorites into the stellar system would be very unlikely. And the probability of a direct hit on a terrestrial planet, without a giant planet intermediary, is many orders of magnitude smaller, as estimated in section 3.

When the long transit times from one star to another are added in, the prospect that life hopped from star to star by any natural agency becomes vanishingly small. The bottom line is that the origin of life on Earth must be sought within the confines of the solar system itself, not abroad in the galaxy.

Acknowledgement: This research was supported by NASA grant NAG5-11493 and the NASA Astrobiology program. The author thanks Bill Bottke for a thorough and helpful review.

References:

Allen (1955) Astrophysical Quantities. University of London,

Arrhenius, S. (1908) Worlds in the Making. Harper and Brothers, New York.

Binney, J. and S. Tremaine (1987) Galactic Dynamics. Princeton University Press, Princeton, N. J.

Blatt, J. M. and V. F. Weisskopf (1952) Theoretical Nuclear Physics. J. Wiley and Sons, New York.

Brasier, M. D., O. R. Green, A. P. Jephcoat, A. K. Kleppe, M. J. VanKranendonk, J. F. Lindsay, A. Steele and N. V. Grassineau (2002) Questioning the evidence for Earth's oldest fossils, *Nature* 416*,* 76-81.

Brocks, J. J., G. A. Logan, R. Buick and R. E. Summons (1999) Archean molecular fossils and the early rise of eucaryotes, *Nature* 285*,* 1033-1036.

Cano, R. J. and M. K. Borucki (1995) Revival and identification of bacterial spores in 25- to 40-million-year-old Dominican amber, *Science* 268*,* 1060-1064.

Crick, F. H. and L. E. Orgel (1973) Directed panspermia, *Icarus* 19*,* 341-346.

Dones, L., B. Gladman, H. J. Melosh, W. B. Tonks, H. F. Levison and M. Duncan (1999) Dynamical lifetimes and final fates of small bodies: Orbit integrations vs Öpik Calculations, *Icarus* 142*,* 509-524.

Farinella, P., C. Froeschlé, C. Froeschlé, R. Gonczi, G. Hahn, A. Morbidelli and G. B. Valsecchi (1994) Asteroids falling into the sun, *Nature* 371*,* 314-317.

Fedo, C. M. and M. J. Whitehouse (2002) Metasomatic origin of quartz-pyroxene rock, Akilia, Greenland, and implications for Earth's earliest life, *Science* 296*,* 1448-1452.

Gladman, B. (1997) Destination: Earth. Martian meteorite delivery, *Icarus* 130*,* 228-246.

Gladman, B. and J. A. Burns (1996) Martian meteorite transfer. Simulation, *Science* 274*,* 161-162.

Gladman, B. J., J. A. Burns, M. Duncan, P. Lee and H. F. Levison (1996) The exchange of impact ejecta between the terrestrial planets, *Science* 271*,* 1387-1392.

Glasstone, S., K. J. Laidler and H. Eyring (1941) The Theory of Rate Processes. McGraw-Hill, New York.

Head, J. N., H. J. Melosh and B. A. Ivanov (submitted) The small crater(s) origin of the Martian clan meteorites, *Science*

Horneck, G. (1993) Responses of Bacillus subtilis spores to space environment: Results from experiments in space, *Orig. Life Evol. Biosphere* 23*,* 37-52.

Kirschvink, J. L. (2002) Mars, panspermia, and the origin of life: Where did it all begin? (abstract), edited by Ed, presented at Impacts and the Origin, Evolution and Extinction of Life, UCLA, Earth and Space Sciences Dept. UCLA, 25.

Levison, H. F. and M. J. Duncan (1997) From the Kuiper belt to Jupiter-family comets: The spatial distribution o f ecliptic comets, *Icarus* 127, 13-32.

McSween, H. Y. (1985) SNC meteorites: Clues to Martian petrologic evolution?, *Rev. of Geophys.* 23, 391-416.

Melosh, H. J. (1985) Ejection of rock fragments from planetary bodies, *Geology* 13, 144-148.

Melosh, H. J. (1988) The rocky road to Panspermia, *Nature* 332, 687-688.

Melosh, H. J. (1994) Swapping rocks, *The Planetary Report* 14, 16-19.

Melosh, H. J. and W. B. Tonks (1994) Swapping rocks: Ejection and exchange of surface material among the terrestrial planets, *Meteoritics* 28, 398.

Mileikowsky, C., F. Cucinotta, J. W. Wilson, B. Gladman, G. Horneck, L. Lindgren, H. J. Melosh, H. Rickman, M. J. Valtonen and J. Q. Zheng (2000) Natural transfer of viable microbes in space, Part 1: From Mars to Earth and Earth to Mars, *Icarus* 145, 391-427.

Mileikowsky, C., F. Cucinotta, J. W. Wilson, B. Gladman, G. Horneck, L. Lindgren, H. J. Melosh, H. Rickman, M. J. Valtonen and J. Q. Zheng (submitted) Natural transfer of viable microbes in space, Part 2: From a planet in one solar system to a planet in another solar system, *Icarus*

Miller, S. L. and A. Lazcano (1996) From the primitive soup to cyanobacteria: It may have taken less than 10 million years. In Circumstellar Habitable Zones, edited by Ed. Travis House Publications, Menlo Park, CA, pp. 393-404.

Mojzsis, S. J., G. Arrhenius, K. D. McKeegan, T. M. Harrison, A. P. Nuttman and C. R. L. Friend (1996) Evidence for life on Earth before 3,800 million years ago, *Nature* 384, 55-59.

Öpik, E. J. (1951) Collision probabilities with the planets and the distribution of interplanetary matter, *Proc. Roy Irish Acad.* 54, 165-199.

Schopf, J. W. (1993) Microfossils of the Early Archean Apex Chert: New evidence of the antiquity of life, *Science* 260, 640-646.

Seaward, M. R. D., T. Cross and B. A. Unsworth (1976) Viable bacterial spores recovered from an archeological excavation, *Nature* 261, 407-408.

Thomson, W. (1894) Presidential address to the British Association, Edinburgh, 1871. In Popular Lectures and Addresses, vol. II, edited by Ed. MacMillan, London, pp. 132-205.

Vreeland, R. N., W. D. Rosenzweig and D. W. Powers (2000) Isolation of a 250 million-year-old halotolerant bacterium from a primary salt crystal, *Nature* 407, 897-900.

Weissman, P. R. (1982) Terrestrial impact rates for long and short-period comets. In Geological Implications of Impacts of Large Asteroids and Comets on the Earth, edited by Ed. Geol. Soc. Amer. Sp. Pap. 190, pp. 15-24.

Zheng, J. Q. and M. J. Valtonen (1999) On the probability that a comet that has escaped from the solar system will collide with the earth, *Mon. Not. R. Astron. Soc*. 304, 579-582.

Table 1:

Solar System Structure	Case #	Velocity-averaged capture cross section $\square_c$, AU^2
Jupiter in its normal place and mass	1	0.025
Jupiter in its normal place and 2X mass	2	0.051
Jupiter in its normal place and 1/2 mass	3	0.013
Jupiter at Saturn and normal mass	4	0.046
Jupiter at Mars and normal mass	5	0.007
Neptune in its normal place and mass	6	0.013

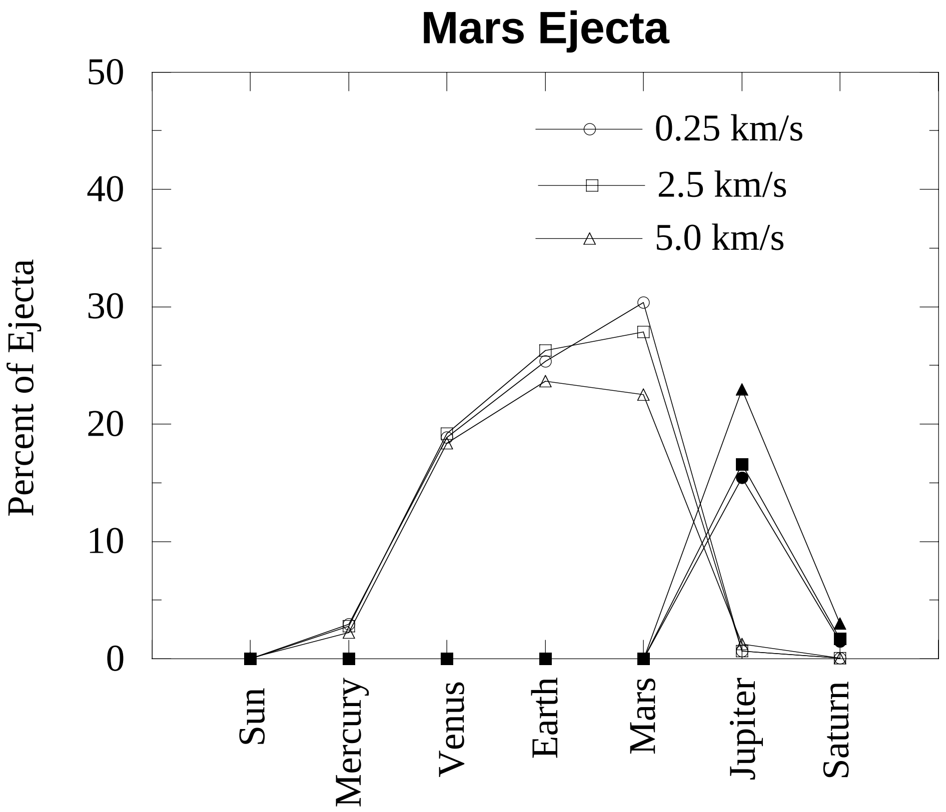
Figure Captions:

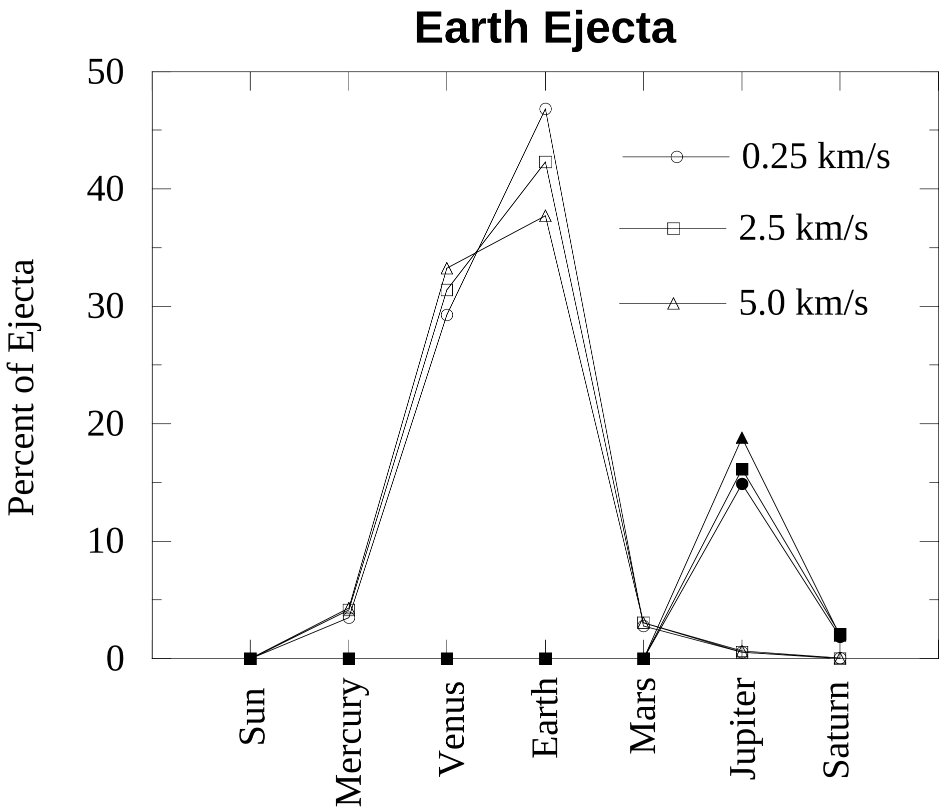
Figure 1: The fate of ejecta from the planets Earth and Mars. The three curves on each plot refer to different ejection velocities from their parent planet: 0.25, 2.5 and 5 km/sec. Open symbols indicate impacts, filled symbols ejection from the solar system. The only planets that can eject material from the solar system are Jupiter and Saturn.

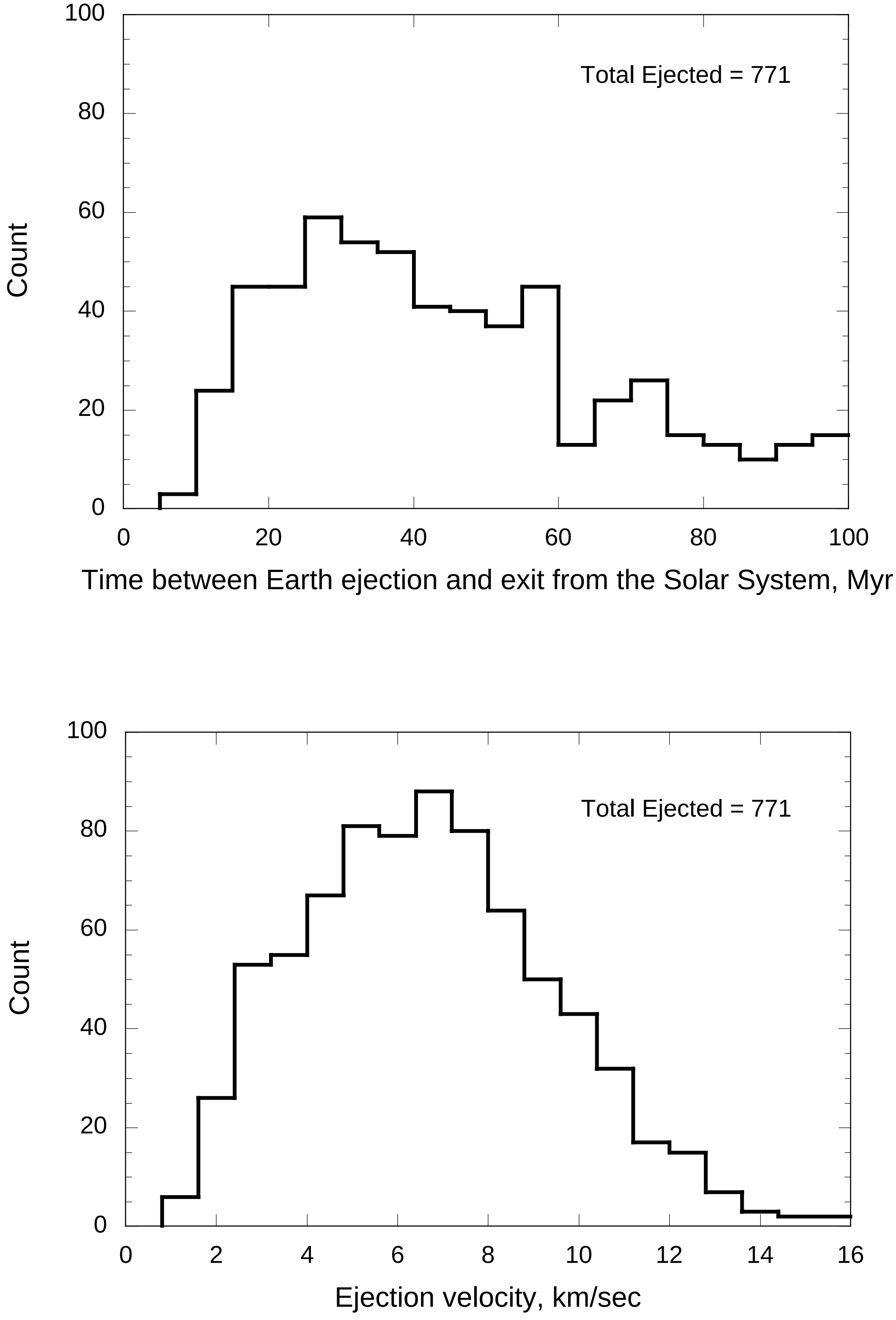
Figure 2: Velocities and times of ejection of Earth ejecta from the solar system by Jupiter. In this case the Earth ejection velocity was 2.5 km/sec. The median ejection velocity is about 5 km/sec relative to the Sun and the median time between departure from Earth and ejection from the solar system is about 48 Myr, although the distribution in time is very broad.

Figure 3: Cross section for capture from interstellar space into a bound orbit around a solar system containing a giant planet. The numbers refer to the six cases listed in Table 1. Note the enhancement of capture probability for very low encounter velocities. At velocities greater than a few km/sec the probability of capture becomes negligibly small.

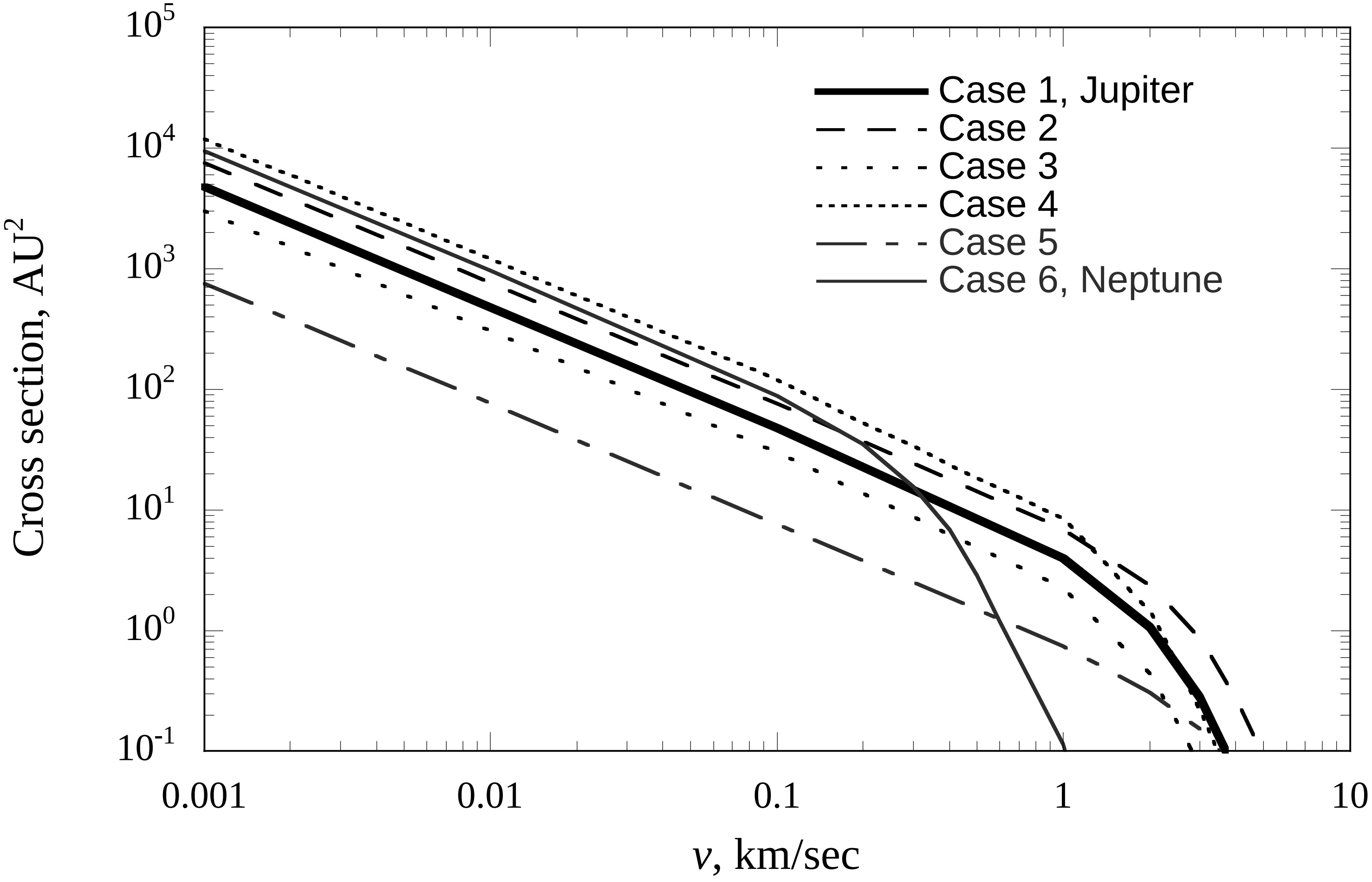
Figure 4: Semimajor axis of interstellar particles captured into the solar system by Jupiter. The peak of the distribution is at about 100 AU but there is a long tail toward larger semimajor axes. These orbits are very comet-like and the probability of any of these orbits crossing the orbits of terrestrial planets lying close to the star is less than 1 in 10,000.

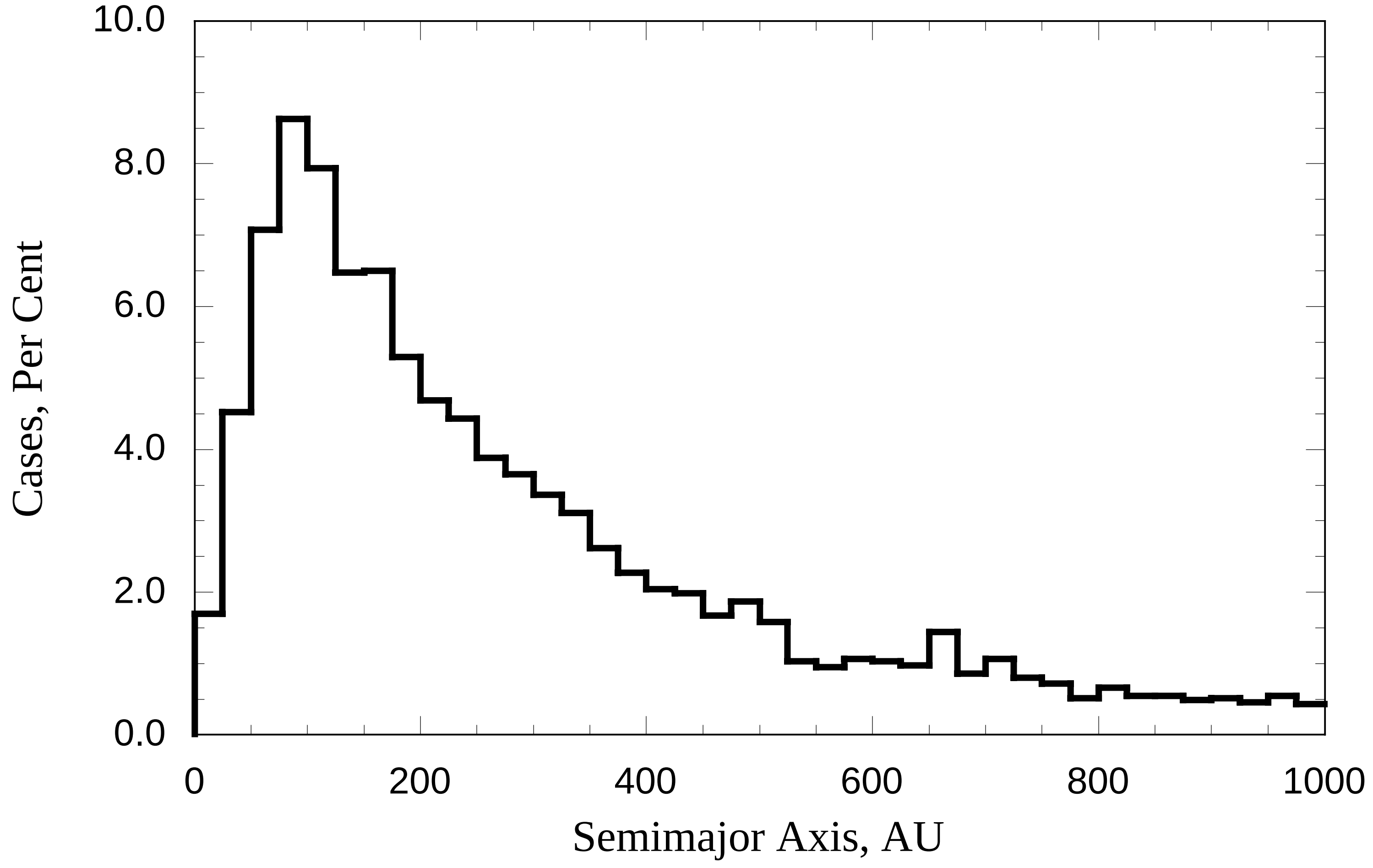

Mars Ejecta


Earth Ejecta



Jupiter Ejections from the Solar System
out of 5000 particles


10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Cross section, AU^2
0.001
0.01
0.1
1
10
v, km/sec
Case 1, Jupiter
Case 2
Case 3
Case 4
Case 5
Case 6, Neptune



Interstellar Meteorites Captured by Jupiter
v = 1 km/sec