models that assume stepwise mutation of the STRP imply that the variation of allele sizes increases linearly with time (48) [D. B. Goldstein, A. Ruiz Linares, L. L. Cavalli-Sforza, M. W. Feldman, *Genetics* **139**, 463 (1995)]. Thus, we can estimate *R* as the ratio of variances of allele sizes (in base pairs) for alleles less than 110 bp (22.5/0.75 = 30.0), giving a maximum age of 167,000 Y.B.P. Because we have considered only a single locus, the standard error on this variance-ratio estimate is high. However, the apparent lower boundary of 85 bp to the STRP allele size results in an underestimate of the time of origin of the Alu(−) chromosome in Africa, so again this estimate of *R* is conservative.

42. Despite a smaller effective population size of Alu(−) chromosomes (because of a lower frequency), the mean variance of STRP alleles on Alu(−) chromsomes among the 10 sub-Saharan African populations is still substantial [64% of the mean variance of STRP alleles on Alu(+) chromosomes], suggesting that while the origin of the Alu(−) chromosome is more recent than the origin of the Alu(+) chromosome, it is still quite ancient.
43. C. B. Stringer, in *The Origin and Evolution of Humans and Humanness*, D. T. Rasmussen Ed. (Jones and Bartlett, Boston, 1993), pp. 75–94.
44. M. Slatkin, *Mol. Biol. Evol* **12**, 473 (1995).
45. Both the STRP and the Alu deletion polymorphism are located in noncoding regions of the CD4 gene and are unlikely to have any functional significance. Except in the unlikely case of strong positive cis-acting epistasis of functional variants flanking exons 1 and 2 of the 90-bp Alu(−) chromosomes, selection cannot explain the maintenance of the linkage disequilibrium seen in non-African populations because there would be nothing to prevent formation of "non- 90 bp" Alu(−) chromosomes by recombination between the markers or mutation at the STRP. In addition, the very low frequency of the Alu(−) chromosomes in Asia, the Pacific islands, and the New World, as well as the very high frequency of 85-bp Alu(+) and 110-bp Alu(+) chromosomes in all non-African populations, argues against strong positive selection for the Alu(−) chromosome.
46. S. A. Tishkoff, W. C. Speed, J. R. Kidd, K. K. Kidd, *Am. J. Phys. Anthropol. Suppl.* **20**, 211 (1995); S. A. Tishkoff *et al.*, *Am. J. Hum. Genet.* **57S**, A42 (1995); K. K. Kidd *et al.*, *Alcoholism: Clinical and Experimental Research*, in press.
47. Very large and unlikely amounts of gene flow and drift acting in a similar manner in many geographically dispersed populations would be required for the 90-bp Alu(−) haplotype to have been recently introduced into preexisting *H. erectus* populations and achieve the frequencies seen today. The low frequency of the 90-bp Alu(−) chromosome in all Asian, Pacific island, and New World populations argues against high levels of gene flow from European or Middle Eastern populations into these regions before historical times.
48. M. Slatkin, *Genetics* **139**, 457 (1995).
49. We thank A. Deinard for providing nonhuman primate samples. For assistance with collecting African DNA samples, we thank H. Soodyall and G. Sirugo as well as R. Aman from the National Museums of Kenya. We thank M. Hawley for assistance with the HAPLO program. We also thank our many colleagues for helpful comments and criticisms in the course of this study, including J. Cheng, A. G. Clark, A. Di Rienzo, R. Dorit, R. Harding, L. B. Jorde, M. Slatkin, and an anonymous reviewer. Supported in part by the Medical Research Council of South Africa and by a grant to M.K. from Boehringer Ingelheim Fonds, NIH grant HG00348 to N.R., USPHS grants AA09379 and MH39239 to K.K.K., USNSF grant DBS9208917 to K.K.K. and SBR-9408934 to J.R.K., and a grant from the Alfred P. Sloan Foundation to K.K.K.

RESEARCH ARTICLE

The Exchange of Impact Ejecta Between Terrestrial Planets

Brett J. Gladman, Joseph A. Burns, Martin Duncan, Pascal Lee, Harold F. Levison

Orbital histories of ejecta from the terrestrial planets were numerically integrated to study their transfer to Earth. The properties of the lunar and martian meteorites are consistent with a recurrent ejection of small meteoroids as a result of impacts on their parent bodies. Long-range gravitational effects, especially secular resonances, strongly influence the orbits of many meteoroids, increasing their collision rates with other planets and the sun. These effects and collisional destruction in the asteroid belt result in shortened time scales and higher fluxes than previously believed, especially for martian meteorites. A small flux of mercurian ejecta appears possible; recovery of meteorites from the Earth and Venus is less likely.

The study of meteorites has illuminated the nature of extraterrestrial environments and astrophysical processes, particularly the conditions at the time of our solar system's formation. Most meteorites come from asteroids, but recently a number of objects from the moon and Mars have been recognized. These latter meteorites help to characterize the surfaces of these bodies, especially the martian meteorites, which are our only samples of that planet. To learn more about the parent bodies and the paths that the meteorites traveled before arriving on Earth, we must understand the orbital dynamics governing their transfer. In particular, what is the delivery efficiency, that is, the fraction of escaping ejecta that reach Earth, from different sources?

The SNC meteorites (*1*) have features that suggest they are derived from Mars (*2*) and are somehow delivered to Earth. Even though the petrology and young crystallization ages of the SNCs point to an origin on a large parent body with recent geologic activity, Mars was only recently accepted as their source because it was thought unlikely that rocks could survive being blasted off of a planet (*3*). Another argument against a martian origin was that if these objects were launched from Mars, surely there should be many more meteorites coming from the moon, which is closer and has a lower escape velocity; yet, as of 1982, there were six SNC falls but no lunar meteorites. Then the lunar meteorite ALHA81005 was recognized among Antarctic meteorites (*4*), and because of our familiarity with the returned Apollo and Luna samples, the origin of this meteorite was immediately accepted. With more Antarctic meteorites (*5*) being recovered, we currently have a dozen members of each class, although they comprise only 0.1% of all meteorites. The SNCs are now generally acknowledged to have originated on Mars, after further examination of their composition, especially the virtually perfect isotopic match between gases trapped within one of them and the martian atmosphere, as determined by the Viking landers (*6*). Thus, we use the term "martian meteorites" for the SNCs and ALH84001, the latter being distinct from the SNC classification (*7*).

We can learn about the dynamics of the inner solar system by comparing the measured transfer ages of such meteorites against orbital histories. Some of the ideas presented below are not new, but our dynamical simulations improve on previous work that, because of computational limitations of the time, used Monte Carlo calculations rather than full orbital integrations. In principle, some aspects of the cratering process itself can also be constrained (*8*).

A cosmic ray exposure (CRE) age (*9*) of a meteorite is the time during which the object was bombarded by energetic cosmic rays in space. During this exposure, measurable radioactive isotopes accumulate, allowing the duration of the exposure to be estimated (Table 1). Most lunar meteorites were delivered to the Earth in a far shorter time than any martian meteorite, and the martian meteorites have an average mass 38 times that of the lunar ones. The issue of pairing (*10*) is unlikely to affect these trends significantly.

B. J. Gladman and P. Lee are in the Department of Astronomy, Cornell University, Ithaca, NY 14853, USA. J. A. Burns is in the Departments of Astronomy and Theoretical and Applied Mechanics, Cornell University, Ithaca, NY 14853, USA. M. Duncan is in the Department of Physics, Queen's University, Kingston, ON K7L 3N6, Canada. H. F. Levison is with Geophysical, Astrophysical, and Planetary Sciences, Southwest Research Institute, 1050 Walnut Street, Suite 429, Boulder, CO 80302, USA.

The CRE studies reveal that most lunar meteorites have been launched from rather shallow depths (within several meters of the lunar surface), whereas all martian meteorites seem to have been shielded by at least several meters of rock before acquiring any CRE (*11*). Presumably this indicates that larger impact events were required to produce the martian meteoroids; because such impacts should be rarer, one must explain why roughly equal numbers of lunar and martian meteorites have been found. To address this question, we need to understand the efficiency of delivery of the meteoroids to the Earth once they have been launched from their parent bodies. With the advent of faster computers and improved numerical algorithms, we have been able to follow directly the motion of interplanetary particles over the necessary time scales.

Delivery from the moon. To escape the moon's gravitational field, the initial speeds v_l of launched ejecta must exceed the lunar escape velocity ($v_{esc} \approx 2.38$ km/s). For $2.38 < v_l < 3.5$ km/s, particles may not have enough energy after leaving the moon to immediately break free of the Earth's gravitational field and reach heliocentric orbit; instead, these may first pass through a phase of geocentric orbit. Following the paths of thousands of particles launched at numerous uniformly distributed locations on the lunar surface, we find that a large majority of the escaping ejecta eventually achieves heliocentric orbit (*12*). Of the material that does not, most hits the Earth within a few decades.

We then followed the particles that escape to heliocentric orbit with another numerical integrator (*13*), accounting for the gravitational effects of the planets from Mercury through Saturn, until the particles impact a terrestrial planet, cross Jupiter's orbit, or have their perihelia lowered to the sun's vicinity. Lunar meteoroids that escape to heliocentric orbit periodically re-approach the Earth and are scattered by its gravitational field to new orbits, with some striking the Earth after one or more scatterings. Depending on the launch speed from the moon, 25 to 50% of the heliocentric material impacts the Earth in the first million years (1 Myr), the percentage of returning material dropping monotonically as the initial ejection velocity rises from 2.4 to 3.2 km/s (Fig. 1). The steep initial decline in the population is almost entirely the result of collisions with the Earth; early in the simulation, Earth's gravitational cross section (*14*) is large because the meteoroids have low relative velocities, having barely escaped Earth's gravity well. As the evolution proceeds, particles that do not hit the Earth are scattered to higher relative velocities, and so the collision rate drops. Thus, of the particles that will hit the Earth within 10^7 years, more than two-thirds (including those that never escape geocentric orbit) do so in less than 50,000 years. After a few hundred thousand years, collisions occur with Earth and Venus at about equal frequency. The population's slower decline after 1 Myr is due to these collisions, as well as increasing fractions of particles that cross Jupiter's orbit or are driven into the sun. The swarm of lunar meteoroids in heliocentric orbit spreads with time throughout the inner solar system because of gravitational scatterings by the planets (Fig. 2). The initial diffusion along the $q = 1$ astronomical unit (AU) and $Q = 1$ AU lines (perihelion and aphelion, respectively) is driven by multiple close approaches with solely the Earth. After about 1 Myr, the particles no longer have any special affinity to Earth, having had encounters with more than one planet. We have observed the transfer of lunar meteorites to Mars in our simulations.

Our simulations yield an expected delivery spectrum (in time) of the lunar meteorites (Fig. 3) that can be compared to their 4π CRE ages (Table 1) (*9*). The 2.4-km/s simulation matches the data reasonably well. In the 3.2-km/s simulation, less than one-fifth of the hypothetical meteorites reach Earth in less than 20,000 years, whereas roughly half of the actual lunar meteorites do. Although the statistics are based on small numbers, this result suggests that the velocity spectrum of escaping fragments must be so steep that only a small fraction of the lunar meteoroids that escape the moon do so at speeds greater than 3 km/s. In view of the diverse geochemistry of the extant samples and their relatively young ages, it

Table 1. Properties of the lunar and martian meteorites (*9*). The SNCs with $t_\oplus$ given as fall or find have Earth residence times that are negligible compared to their 4π CRE ages. All of the numbered meteorites are from Antarctica. The last two meteorites of each class were only recently identified. This table updates table 1 in (*11*), correcting a typo on the mass of EET79001. The 0.2-Myr 4π age of Calcalong Creek is favored by Swindle *et al.* (*35*). The QUE93069 data are reported in (*36*). The 4π ages for QUE94281, ALH81005, and EET87521 are from a thermoluminescence study (*37*). Errors in the 4π ages are ≈20 to 30%.

Meteorite	Mass (kg)	4π age (Myr)	$t_\oplus$ (Myr)
		Lunar meteorites	
EET87521	0.031	<0.001	<0.06
ALH81005	0.031	0.01 ± 0.005	0.009
Y-791197	0.052	<0.019	0.06 ± 0.03
Y-793274	0.0087	<0.02	<0.02
MAC88104/5	0.724	~0.04	0.23 ± 0.02
QUE93069	0.021	<0.1 or 1.9	<0.07 or 0.18
Calcalong Creek	0.019	0.2 or 3 ± 1	<0.07
Asuka-881757	0.442	0.9 ± 0.1	<0.05
Y-793169	0.0061	1.1 ± 0.2	<0.05
Y-82192/86032	0.712	9 ± 2	~0.09
QUE94269	0.0032	Paired with QUE93069	
QUE94281	0.0234	0.001	?
		Martian meteorites	
EET79001	7.94	~0.7	0.011
ALH77005	0.48	~2.6	0.2
Zagami	18	~2.8	fall
Shergotty	4	~2.8	fall
LEW88516	0.013	~3.0	<0.1
Governador Valadares	0.16	~12	find
Chassigny	4	12.5 ± 1.7	fall
Nakhla	40	12.9 ± 1.7	fall
Lafayette	0.80	~14	find
ALH84001	1.93	~15	0.011
QUE94201	0.0120	?	?
Y-793605	0.018	?	?

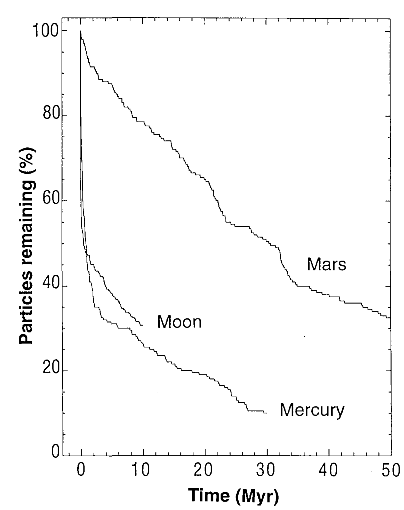

Fig. 1. The percentage of test particles remaining as a function of time for heliocentric simulations of ejecta from the moon, Mars, and Mercury. The initial ejection velocity for the lunar simulation was 2.4 km/s, whereas $v_\infty = 1$ km/s (*15*) cases are plotted for the Mercury and Mars simulations.

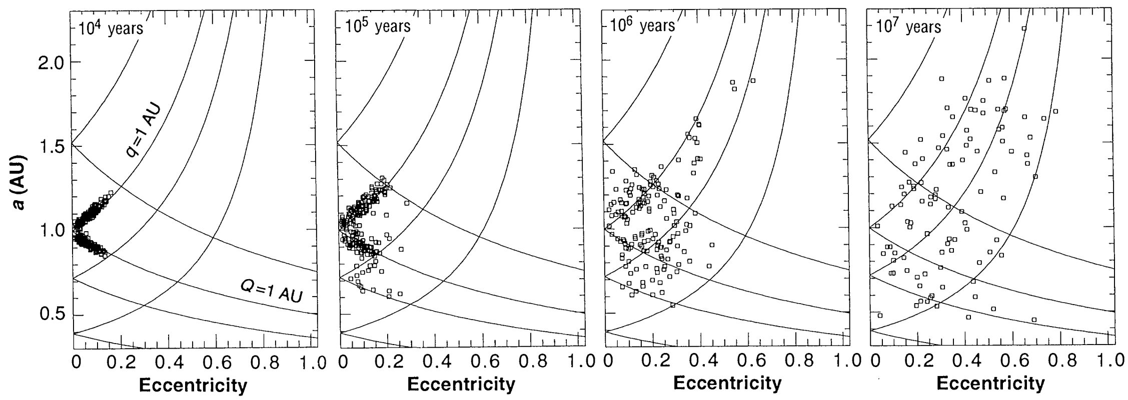

Fig. 2. Evolution of 324 particles escaping from the Earth-moon system after being launched from the moon with v_{ej} = 2.4 km/s. Each point gives the orbital semimajor axis (a) and eccentricity (e) of a surviving particle at the given time after launch. The web of curves indicate where the perihelion $q = a(1 - e)$ or aphelion $Q = a(1 + e)$ of a particle would coincide with the semimajor axis of one of the terrestrial planets. Particles to the right of both curves emanating from a planet's a have orbits that can cross that of the planet.

appears that many lunar meteorites are launched in frequent cratering events (at least as often as every 10^4 years). Because the number of lunar impactors drops off quickly with increasing impactor size and therefore energy, these common impacts must be small ones, resulting in craters with diameters of much less than 10 km (*11*). This frequent liberation of impact ejecta is not found for martian ejecta.

Delivery from Mars. The recovered martian meteorites have taken much longer to reach the Earth than the lunar ones (Table 1), simply because the orbits of most ejected martian meteoroids do not initially cross that of the Earth. However, because of the eccentric orbit of Mars, the v_∞ (*15*) of escaping particles need only be about 2.3 km/s (corresponding to an ejection speed of 5.5 km/s, merely 10% greater than the escape speed) for some ejecta to be on orbits that immediately cross Earth's. Thus, fast transfers are occasionally possible, and the short 4π CRE age of 0.7 Myr for EET79001 is not especially surprising. In fact, transfers as rapid as 16,000 years were observed in our simulations.

The ground-breaking work of Wetherill (*16*), who a decade ago addressed the delivery efficiency of martian meteorites using Monte Carlo simulations, presents, in hindsight, a puzzle given what we now know of the 4π CRE ages of these meteorites. Even though collisional destruction was included in those simulations, the majority of martian objects arrived at the Earth having taken longer in their journeys than the recovered meteorites with the greatest CRE age (15 Myr), unless the mean ejection velocities are very large (>6.4 km/s). Because the lunar results appear to indicate that proportionally little material is launched at speeds greater than 125% of the escape speed, we expect that most martian meteoroids should be launched at less than 6 km/s. Of course, it may be that the regolithic structure of the lunar surface is responsible for the sharp drop-off with velocity and that this result does not apply to Mars (*17*).

We simulated the gravitational evolution of 2100 particles escaping from Mars at various speeds. These simulations included the gravitational effects of Venus through Neptune. The initial conditions correspond to uniform cratering, and previous work (*16*) has shown that the delivery efficiency is insensitive to the orbital phase and current orbital elements of Mars. The depletion rate of the ejected particles (Fig. 1) is different from the lunar and mercurian cases because, even at this low ejection speed, re-collision with Mars is not a significant removal mechanism. Of the few Mars reimpacts that do occur, more than 90% take place in the first few million years; once the relative velocities increase above the escape velocity (*14*), collisions with Mars remove an insignificant fraction. For higher ejection speeds, typically less than 2% of the particles re-collide.

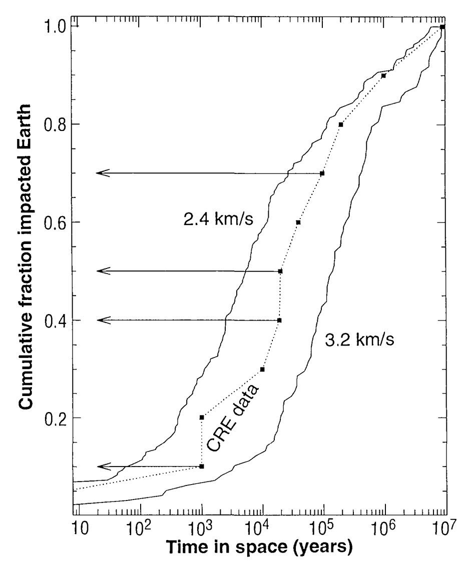

Fig. 3. Cumulative plot of the CRE age spectrum expected for the lunar meteorites. The curves show (as a function of time) the cumulative number of meteorites that have struck the Earth (as a fraction of those that do within 10 Myr). The solid curves show predictions from two simulations differing only in the launch velocity from the moon. The dotted line connects the data points from the lunar meteorites (*34*). Four of these meteorites have only upper limits (indicated by arrows) on their time in space.

The delivery efficiency of martian meteoroids to Earth for v_∞ = 1 km/s is 7.5%, with about one-third of these occurring in the first 10 Myr (Table 2). Raising the ejection velocity causes a small increase in the delivery efficiency (Table 3). Our yields are about an order of magnitude larger than those seen in Monte Carlo simulations (*16*). The discrepancy can be understood by examining Fig. 4, which shows how the orbits of the escaped ejecta evolve after launch. The particles remain in the vicinity of Mars (whose orbital semimajor axis is a = 1.5 AU) only for the first 0.1 Myr. By 1 Myr, several interesting phenomena have occurred: a few particles have diffused down the Q = 1.5 AU line, and some of these have had their orbits drastically modified by the Earth (having crossed the q = 1 AU line). The diffusion up the q = 1.5 AU line is halted by the presence of two nonlinear, second-order secular resonances near $a \simeq$ 1.6 to 1.7 AU (*18*). These resonances cause oscillations with periods of 10^5 years in the eccentricities of

Table 2. The fates of meteoroids after a v_∞ = 1 km/s launch from Mars and Mercury. The simulation for Mars included 900 particles and ran for 100 Myr; the simulation for Mercury included 200 particles over 30 Myr. No collisional effects were included. The position of Mercury was not tracked in the martian simulation, so collisions with it were not possible.

Meteoroid fate	Particles (% of total) from parent body	
	Mars	Mercury
Impact Mercury	N.A.	76
Impact Venus	7.5	6.5
Impact Earth	7.5	0.5
Impact Mars	9.0	0
Sun-grazing	38	4
Reach Jupiter	15	2
Survivors	23	11

particles in this region up to Earth-crossing values ($e \simeq 0.4$), thereby raising the efficiency of delivery for martian meteoroids. Because these resonances were not incorporated into earlier Monte Carlo simulations, it is not surprising that our results differ. Furthermore, delivery of particles to the $q = 1$ AU curve allows their semimajor axes to be raised to the inner edge of the asteroid belt ($a \simeq 2.1$ AU), where the powerful secular resonances ν_6, ν_5, and ν_{16} operate; these resonances are capable of driving the eccentricities of test particles to unity, at which point the particles strike the sun (*19*).

Sun-grazing is the dominant loss mechanism after 10 Myr. Within 100 Myr about 40% of the particles have been driven into the sun, more than twice the number removed from the system by crossing Jupiter's orbit. These two effects ultimately deplete the swarm and yield an almost linear decline in the number of surviving meteoroids (Fig. 1); this partly explains why no martian meteorites have 4π ages older than 15 Myr. The expected CRE age spectrum for our purely gravitational *N*-body simulation (Fig. 5) does not agree as well with the SNC data as in the lunar case; only a little more than half of the meteorites delivered in the simulation arrive within the 15-Myr upper bound of the recovered meteorites. This disagreement is not surprising because many orbits extend out to the asteroid belt ($Q > 2.1$ AU), and so the meteoroids are prone to catastrophic collisional disruption, with a half-life of 1 to 10 Myr (*20*). The mean time spent in the main belt as a function of transit time was computed from the simulations and convolved into the delivery spectrum (Fig. 5). With such a collisional model, the *N*-body simulation matches the CRE data quite well; however, the collisions lower the delivery efficiency for the $v_\infty = 1$ km/s case from 7.5 to 4.4%.

Thus, the age distribution of the martian meteorites is consistent with a model in which all fragments are launched at speeds modestly above the escape velocity as small bodies and are delivered independently to Earth. The simulated meteorites delivered in the first 15 Myr all have entry velocities into Earth's atmosphere in the range of 11 to 17 km/s, in agreement with the ablation data for the SNCs (*21*). However, our results do not explain the apparent clustering of the 4π CREs into at least three groups: 0.7 Myr (one object), 3 Myr (four objects), and 13 ± 2 Myr (five objects). Are these groups a result of source-crater pairing (*10*, *22*) or, alternatively, a result of separate collisional fragmentations of large meteoroids in space (*23*)? The martian meteorites share much closer petrologic affinities than the lunar meteorites (*7*): the 3-Myr group contains only shergottites, and three of the 13-Myr group are the only three nakhlites. In our view, these age clusters likely represent individual impact events into distinct source terrains (*23*).

A previously considered hypothesis (*24*)—that all the martian meteorites are derived from recent catastrophic fragmentations of large bodies that were launched 200 Myr ago and then stored in space—is rendered very unlikely because our simulations demonstrate that few parent bodies can dynamically survive for this time owing to the efficiency of meteoroid destruction by sun-grazing. This model would also have to explain why (i) there are no meteorites from the upper few meters of the parent meteoroids, (ii) no impacts more recent than 200 Myr have been sampled, and (iii) only shergottite parent meteoroids have been disrupted in the last 3 Myr, and none before. Our results show that the simpler model, which produces exclusively small meteoroids, explains all of the CRE evidence, although source-crater pairings and relative surface properties of the moon compared with Mars may be important. The issues of whether the groupings represent distinct impact events, why such groupings occur for Mars but not for the moon, and why there are equal numbers of lunar and martian meteorites (*16*) remain.

Delivery from Mercury, Venus, and Earth. Numerical simulations indicate that particles diffuse readily throughout the inner solar system, and so we now consider the likelihood that pieces of other terrestrial planets might also have come to Earth. It should be possible to liberate meteoroids from the surface of Mercury, as its escape velocity is lower than that of Mars (*14*). However, the dynamical transfer of this ejecta to Earth is substantially more difficult because Mercury lies deep within the sun's gravitational well. Ignoring resonance effects, a series of properly timed Mercury scatterings are needed for the meteoroids to be pushed across Venus's orbit and then to Earth. Monte Carlo calculations (*16*, *25*) have found the total delivery efficiency to

Table 3. Transfer efficiencies for Mars ejecta in the first 15 Myr after launch, as a function of the ejection speed v_{ej}, with no correction for collisional destruction. All simulations used 300 particles. Sun-grazing and Jupiter-crossing only begin to operate efficiently after 10 Myr and thus are under-represented here (compare with Table 2).

Ejection speed (km/s)		Efficiency (%) (in first 15 Myr)				
v_∞	Surface	Earth	Venus	Mars	Sun	Jupiter
1.0	5.13	3.1	1.5	9.5	9.0	3.0
1.8	5.34	4.0	2.7	2.7	8.0	6.0
2.3	5.53	7.7	4.7	0.7	9.0	5.0
2.7	5.71	5.3	4.0	1.7	9.3	5.0
3.3	6.02	6.3	3.7	2.0	13.3	6.7

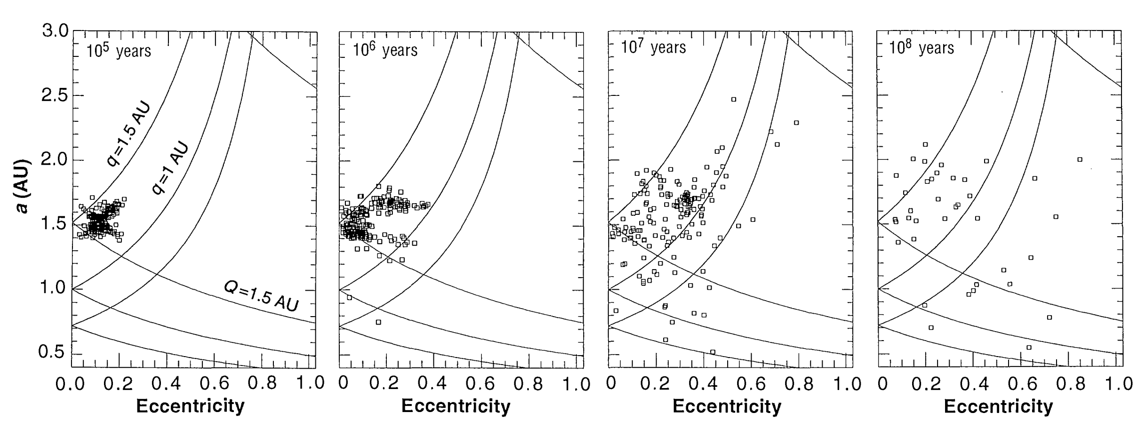

Fig. 4. Evolution of 200 particles launched from Mars with $v_\infty = 1$ km/s. See the caption to Fig. 2. The curve in the upper right of each panel marks aphelion at Jupiter (5.2 AU).

Earth to be on the order of 10^{-4} in 10^7 years.

We tracked 200 particles launched from Mercury in random directions having v_∞ = 1 km/s after escaping from the planet (*15*). The re-accretion rate is initially very high (Fig. 1), again because of the low relative velocity of the particles with respect to Mercury (*14*). The lunar and mercurian cases are similar because, compared to the planetary orbital speed, the initial random velocity is very small. For Mercury, about three-quarters of all of the launched particles were re-accreted during the 30-Myr simulation (Table 2).

Just one of the 200 particles was found to hit the Earth, after 23 Myr. This 0.5% delivery efficiency is 50 times higher than previously suggested (*16*) but is based on poor statistics; it is about an order of magnitude smaller than the efficiency for Mars. If we accept this efficiency and if the mercurian impactor flux is comparable to that of Mars (*26*), the existence of 12 martian meteorites should lead us to expect a few mercurian meteorites. However, a purely gravitational model may not be sufficient to accurately simulate the transfer of material from Mercury to Earth. Radiation forces in the inner solar system cause significant orbital evolution over tens of millions of years, times like that required for our single meteoroid to reach Earth. Orbital collapse as a result of Poynting-Robertson (P-R) drag at Mercury's heliocentric distance takes only 5 Myr (*27*) for a meteoroid 1 cm in radius with a density of 5 g/cm^3. On the other hand, the Yarkovsky effect, which dominates P-R effects for particles of this size with spin periods longer than 1 s (*27*), may induce some mercurian meteoroids to spiral outward to Earth (*28*). However, mercurian meteoroids may be catastrophically fragmented by dust-sized impactors, which, because of gravitational focusing, increase significantly as the sun is approached. Collisional lifetimes of 100-g bodies at Mercury's distance are estimated to be less than 10^5 years (*29*). Because of these complications, the likelihood of finding mercurian meteorites is difficult to quantify.

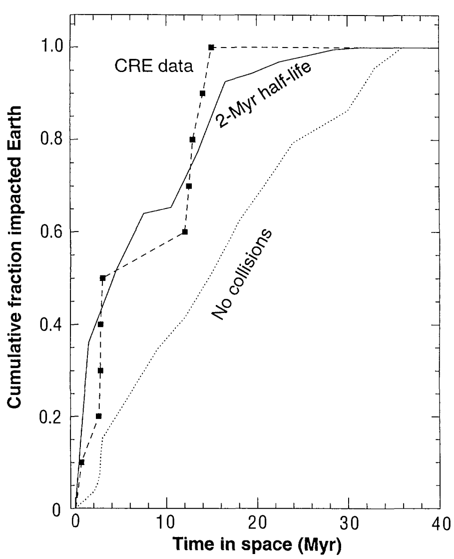

Fig. 5. Cumulative plot of the expected CRE age spectrum of the martian meteorites. The curves show (as a function of time) the cumulative number of meteorites that have struck the Earth (as a fraction of those that do within 40 Myr). The solid and dotted curves show predicted spectra, one incorporating catastrophic collisions (solid) and the other without (dotted). The dashed line connects the data points from the martian meteorites.

The identification of meteorites from the moon and Mars has allowed scientists to consider more seriously the possibility of finding meteorites from Venus or Earth (hereafter, venusian and terrene meteorites, respectively). The larger escape velocities of these planets will only be overcome by a tiny fraction of the ejecta, and then only in the larger and rarer impact events. The difficulty of successful ejections is heightened by the presence of the massive atmospheres of Earth and Venus, because such atmospheres effectively screen out all crater-producing impactors below a certain threshold size (*30*), and launched fragments have to plow back through the atmosphere (*31*). On the basis of our simulations, we expect that the re-accretion efficiency by the Earth of its own ejecta would be several times higher than Earth's accretion of venusian ejecta (*25*). Given the much more massive atmosphere of Venus, if venusian meteorites are possible, then certainly terrene meteorites should be much more abundant. Thus we restrict our attention to the latter.

It may be problematic to distinguish terrene meteorites from untraveled material. Presumably only falls, or finds with preserved fusion crusts, would be readily accepted as bona fide terrene meteorites; anomalous Earth rocks found on the Antarctic ice sheet are probably our best hope. Because only massive rare impacts are capable of launching such objects, the Earth likely has not recently experienced an event capable of ejecting Earth rocks at greater than the escape velocity. Thus, terrene meteorites should be comparitively rare in the relatively young (<1 Myr old) Antarctic ice sheet.

Earth impacts have ejected tektites (impact glasses), some of which may have been launched along suborbital trajectories arching above Earth's atmosphere before re-entry (*32*). With slightly higher speeds, other tektites might have escaped the Earth's gravitational field. Such objects would have a high probability (≈30 to 50%) of rapidly re-impacting the Earth. Isolated tektite finds (that is, not part of a strewn field) would be worth examining for evidence of a brief (≪1 Myr) CRE (*33*). A proviso in this picture is that tektites are not strictly analogous to the relatively lightly shocked lunar and martian meteorites.

The orbital histories of terrene meteoroids, if any exist, are also of interest in view of the enormous efforts expended to sterilize spacecraft to prevent the contamination of Mars by terrestrial organisms. This sterilization would make little sense if terrestrial microorganisms have already been carried to Mars aboard terrene meteorites (*31*).

REFERENCES AND NOTES

1. Named for the three large meteorite falls Shergotty, Nakhla, and Chassigny. H. Y. McSween Jr., *Meteorites and Their Parent Planets* (Cambridge Univ. Press, Cambridge, 1987).
2. D. D. Bogard, P. Johnson, L. E. Nyquist, *Lunar Planet. Sci.* **XV**, 68 (1984).
3. L. E. Nyquist, *J. Geophys. Res.* **88**, 785 (1983). The SNC meteorites record only very mild shock histories (<1 to 50 GPa), whereas escape from Mars was thought to require >100 GPa, which argued further against their being ejected in a cratering event. A. M. Vickery and H. J. Melosh, *Icarus* **56**, 299 (1983).
4. See D. D. Bogard and P. Johnson, *Geophys. Res. Lett.* **10**, 801 (1983) for references.
5. W. A. Cassidy and L. A. Rancitelli [*Am. Sci.* **70**, 156 (1982)] have reviewed Antarctic meteorites, and O. Eugster [*Science* **245**, 1197 (1989)] has focused on some early lunar Antarctic finds.
6. D. D. Bogard and P. Johnson, *Science* **221**, 651 (1983).
7. H. Y. McSween Jr., *Meteoritics* **29**, 757 (1994). The possibility of meteorites, like ALH84001, falling outside of the SNC categorization argues further for ceasing to use "SNCs" as a synonym for "martian meteorites." See also D. W. Mittlefehldt, *Meteoritics* **29**, 214 (1994).
8. High-speed, lightly shocked ejecta may be launched by shock wave interference [H. J. Melosh, *Icarus* **59**, 234 (1984)] or by vapor-plume entrainment [J. D. O'Keefe and T. J. Ahrens, *Science* **234**, 346 (1986)]. The cratering physics that launches ejecta at speeds above the escape velocity may differ greatly from the physics of the excavation flow that creates the impact crater.
9. Objects that are shielded by several meters of rock, or even by Earth's atmosphere, do not accumulate radioactivity, and the radioisotopes that are present begin to decay. Because of this, with enough measurements of a variety of isotopes, it is possible to calculate (i) the length of time that the object spent in the upper few meters of the parent body before launch (2π age), (ii) the depth at which it was buried, (iii) the duration of its transit to the Earth (4π age), and (iv) the terrestrial age or Earth residence time ($t_\oplus$) [R. C. Reedy, J. R. Arnold, D. Lal, *Science* **219**, 127 (1983)].
10. Paired meteorites are different pieces of the same meteoroid that fragmented during atmospheric entry or was broken apart by subsequent erosional processes. Such pairs should be counted as a single meteorite fall (for example, MAC88104/5 in Table 1). "Source-crater pairing" is also possible, in which two meteorites launched during a single cratering event may travel on independent paths to the Earth, spending different times in space and landing at different locations on the Earth. Nevertheless, CRE and petrologic data may link the two samples as being from the same source crater. It seems unlikely that any lunar meteorites are source-crater paired except for Asuka-881757 and Y-793169 (*11*). The case is less clear for the martian meteorites.
11. P. Warren, *Icarus* **111**, 338 (1994).
12. For details about the lunar simulations, see B. J. Gladman, J. A. Burns, M. Duncan, H. Levison, *ibid.* **118**, 302 (1995).
13. H. Levison and M. Duncan, *ibid.* **108**, 18 (1994). This integration method is based on the mixed-variable symplectic integrator developed by J. Wisdom and M. Holman [*Astron. J.* **102**, 1528 (1991)].

14. The gravitational cross section πb^2 (the area at ∞ through which passing particles will impact the body) for a body of radius R and escape speed v_{esc} is $\pi b^2 = \pi R^2[1 + (v_{esc}/v_\infty)^2]$, where v_∞ is the relative encounter speed at infinity. For Mercury, Venus, Earth, and Mars, v_{esc} = 4.2, 10.3, 11.2, and 5.0 km/s, respectively.
15. The relative planetocentric velocity at infinity, after being ejected at speed v_{ej} from a planet with escape speed v_{esc}, is approximately $v_\infty \simeq \sqrt{v_{ej}^2 - v_{esc}^2}$. This v_∞ is generally much less than the heliocentric orbital velocity of the planet and therefore produces a slightly eccentric and inclined orbit with respect to the planet's orbit.
16. G. W. Wetherill, *Meteoritics* **19**, 1 (1984).
17. A. M. Vickery [*Geophys. Res. Lett.* **14**, 726 (1987)] studied secondary crater fields around martian, lunar, and mercurian impact craters and found power-law decreases in the fragment size with increasing ejection speed.
18. The resonances are $2g = g_5 + g_6$ and $g - s = g_5 - s_6$, with the former the more dynamically effective of the two. Here g and s denote the precession rates of the perihelion and ascending node of the particle, and g_i and s_i are the ith fundamental secular eigenfrequencies of the solar system. The resonances are nonlinear because they involve more than one fundamental frequency, and second order because they do not appear in the expansion of the secular disturbing function until quadratic terms in the planetary masses are considered. See Ch. Froeschlé and A. Morbidelli, in *Asteroids, Comets, and Meteors, 1993*, A. Milani, M. Di Martino, A. Cellino, Eds. (Kluwer, Boston, 1994), pp. 189–204.
19. Sun-grazing is discussed for near-Earth asteroids by P. Farinella *et al.* [*Nature* **371**, 314 (1994)], for the short-period comets by M. E. Bailey, J. E. Chambers, and G. Hahn [*Astron. Astrophys.* **257**, 315 (1992)], and for the Jupiter-family comets by Levison and Duncan (*13*).
20. In rough agreement with the observed CRE ages of the ordinary chondrites (*1*). G. W. Wetherill [*Icarus* **76**, 1 (1988)] used a collisional half-life of $1.2r^{1/2}$ Myr for a meteoroid of radius r (in centimeters) when $Q > 2.1$ AU. Thus, a meteoroid with $r \simeq 3$ cm (pre-atmospheric mass, ~300 g) and aphelion in the main belt would have a collisional lifetime of 2 Myr. In our model, collisional fragments of martian meteoroids are not large enough to engender recoverable meteorites.
21. N. Bhandari *et al.*, *Geochim. Cosmochim. Acta* **50**, 1023 (1988).
22. D. D. Bogard, *Lunar Planet. Sci.* **XXVI**, 143 (1995). The cumulative spectrum (Fig. 5) is unchanged by source-crater pairings. If the interval between martian launches is 2 Myr, then the impactors are ≃1 km in diameter [W. F. Bottke, M. C. Nolan, R. Greenberg, R. A. Kolvoord, in *Hazards Due to Comets and Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1994), pp. 337–358].
23. Treiman and co-workers [A. H. Treiman, *J. Geophys. Res.* **100**, 5329 (1995); A. H. Treiman *et al.*, *Meteoritics* **29**, 581 (1994)] argue for one-stage exposures as small bodies but allow for source-crater pairing of the shergottites or nahklites-Chassigny. An additional constraint that must be satisfied is the puzzling prevalence of martian meteorites from young source terrains. This constraint has been used to argue in favor of large martian impact craters [see R. A. Kerr, *Science* **237**, 721 (1987)].
24. A. M. Vickery and H. J. Melosh, *Science* **237**, 738 (1987).
25. H. J. Melosh and W. B. Tonks, *Meteoritics* **28**, 398 (1993).
26. The current formation rate of craters with diameters larger than 10 km is a factor of 2 larger on Mercury than on Mars (although most of the crater-producing projectiles on Mercury are cometary) [G. W. Wetherill, *ibid.* **24**, 15 (1989)]. Mercury's smaller escape velocity should result in a larger meteoroid generation rate. A comparison based on the moon's supply (because the present cratering rate for Mercury is at least an order of magnitude larger than the moon's, but the delivery efficiency is 100 times smaller) also yields a few expected mercurian meteorites.
27. J. A. Burns, P. L. Lamy, S. Soter, *Icarus* **40**, 1 (1979).
28. S. G. Love and K. Keil [*Meteoritics* **30**, 1 (1995)] discuss the Yarkovsky effect and the problems of identifying mercurian meteorites.
29. E. Grün, H. A. Zook, H. Fechtig, R. H. Giese, *Icarus* **62**, 244 (1985).
30. The Earth's atmosphere prevents stony objects with diameters <50 m from reaching the ground and creating hypervelocity impact craters [C. Chyba, *Nature* **363**, 701 (1993)].
31. It is conceivable that ejecta could escape out through the atmospheric "tunnel" left by the impactor's entry [H. J. Melosh, *ibid.* **332**, 687 (1988)].
32. See C. Koeberl, *Annu. Rev. Earth Planet. Sci.* **14**, 323 (1986), and references therein.
33. Searches for radionuclides induced by cosmic rays in tektites have produced only upper limits on their time in space, varying from 900 to 90,000 years. Relevant papers are reviewed in J. A. O'Keefe, *Tektites and Their Origin* (Elsevier, New York, 1976), pp. 160–165. Because the tektites examined were from strewn fields, which implies that they never escaped to heliocentric orbit, these results do not necessarily constrain theories of objects that escape from the Earth.
34. Calcalong Creek and QUE93069 have large CRE age uncertainties because of incomplete analyses; we have used the lower ages given in Table 1 in analogy with the other lunar meteorites. Warren (*11*) argued that the remaining meteorites may be from seven different source craters. We accept the proposed source-crater pairing of Asuka-881757 and Y-793169 and go further to assert conventional pairing because the odds of having two lunar meteoroids from the same source crater arrive at the Earth at the same time after spending 1 Myr in space and landing close to each other is so small.
35. T. D. Swindle, M. K. Burkland, J. E. Grier, *Meteoritics* **30**, 584 (1995).
36. K. Nishiizumi, *Lunar Planet. Sci.* **XXVI**, 1051 (1995).
37. P. H. Benoit, D. Sears, S. Symes, *ibid.*, in press.

38. We thank H. J. Melosh, P. Farinella, P. Warren, and G. Wetherill for constructive input to this study, and three referees for valuable comments. This work was supported in part by National Aeronautics and Space Administration grant NAGW-310.

15 December 1995; accepted 7 February 1996