Mercurian impact ejecta: Meteorites and mantle

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Abstract—We have examined the fate of impact ejecta liberated from the surface of Mercury due to impacts by comets or asteroids, in order to study 1) meteorite transfer to Earth, and 2) reaccumulation of an expelled mantle in giant-impact scenarios seeking to explain Mercury’s large core. In the context of meteorite transfer during the last 30 Myr, we note that Mercury’s impact ejecta leave the planet’s surface much faster (on average) than other planets in the solar system because it is the only planet where impact speeds routinely range from 5 to 20 times the planet’s escape speed; this causes impact ejecta to leave its surface moving many times faster than needed to escape its gravitational pull. Thus, a large fraction of Mercurian ejecta may reach heliocentric orbit with speeds sufficiently high for Earth-crossing orbits to exist immediately after impact, resulting in larger fractions of the ejecta reaching Earth as meteorites. We calculate the delivery rate to Earth on a time scale of 30 Myr (typical of stony meteorites from the asteroid belt) and show that several percent of the high-speed ejecta reach Earth (a factor of 2–3 less than typical launches from Mars); this is one to two orders of magnitude more efficient than previous estimates. Similar quantities of material reach Venus.

These calculations also yield measurements of the re-accretion time scale of material ejected from Mercury in a putative giant impact (assuming gravity is dominant). For Mercurian ejecta escaping the gravitational reach of the planet with excess speeds equal to Mercury’s escape speed, about one third of ejecta reaccretes in as little as 2 Myr. Thus collisional stripping of a silicate proto-Mercurian mantle can only work effectively if the liberated mantle material remains in small enough particles that radiation forces can drag them into the Sun on time scale of a few million years, or Mercury would simply re-accrete the material.

INTRODUCTION

There are now several dozen lunar and Martian meteorites. While this represents only a tiny fraction of the worldwide meteorite inventory, these meteorites are especially interesting due to their coming from a highly evolved parent body. Study of the cosmic-ray exposure (CRE) histories of these meteorites show that they have spent 0.6–20 Myr in space for the case of Martian meteorites, with a more compressed 0–10 Myr range for the lunar meteorites (see the recent review by Eugster et al. 2006). The time scales turn out to be the natural dynamical transfer time scale, and numerical simulations of the orbital evolution of these meteorites (Gladman et al. 1996; Gladman 1997) are in excellent agreement with CRE data, supporting the hypothesis that such meteorites are fragments that are simply delivered to Earth after being launched during hypervelocity impacts on the Moon and Mars.

While the lack of meteorites from Venus is understandable due to the screening effect of the Venusian atmosphere, Mercury is an obvious candidate source for meteorites. The launch speed needed to escape the gravity well (4.2 km/s) is intermediate between that of the Moon (2.4 km/s) and Mars (5.0 km/s), so escape from the planet’s surface is obviously feasible. Once escaped from the surface of Mercury, conservation of energy requires that the meteoroid’s speed $v_\infty$ relative to Mercury after reaching “infinity” (in practice anything more than 100 planetary radii) is

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

where the ejection speed $v_{ej}$ from Mercury’s surface must of course be larger than the planetary escape speed $v_{esc}$. Because of this relation, ejection speeds must exceed roughly twice the escape speed before the velocity relative to Mercury (which is
then vectorially added to Mercury’s heliocentric velocity to produce the escaping particle’s heliocentric velocity) becomes comparable to the escape speed. This is rare in the lunar and Martian cases, and results in the escaped meteoroids having heliocentric orbits very similar to their parent planet.

After escape into heliocentric orbit, the Mercurian meteoroids orbit the Sun and will either impact a planet, impact the Sun, or perhaps be destroyed collisionally by other heliocentric projectiles. For Mercurian meteoroids with $v_{\infty} < 8$ km/s (meaning ejection speeds <9 km/s), the liberated particles are on orbits which only cross that of Mercury because Mercury’s large average orbital speed of 48 km/s (which the ejected particles inherit on average, modified vectorially by the value of $v_{\infty}$) is difficult to change. Thus, the resulting orbits are very “Mercury-like,” causing the most likely fate to be reaccretion onto the parent (Gladman et al. 1996). In this regime, Wetherill (1984) and later Love and Keil (1995) concluded on the basis of Monte Carlo orbital evolution calculations that only 1 in 10,000 of the escaping Mercurian meteorites reach Earth (about 100 times fewer than the Martian meteorites). Gladman et al. (1996) and Gladman (2003) performed full N-body calculations of the problem which took into account orbital resonant effects and found 0.1–0.5% of the Mercurian meteoroids would reach Earth for $v_{\infty} = 2–6$ km/s, and concluded that for these yields it might not be surprising that we have no Mercurian meteorites in the worldwide collection. (Note that we use the term “Mercurian meteorites” instead of “hermean meteorites,” due to the literature’s general preference for the former). In this paper, we argue that these low values for $v_{\infty}$ may be unrealistically underestimating the typical speeds and we re-calculate the transfer efficiencies for a variety of launch speeds.

**LAUNCH SPEEDS AT MERCURY**

The material ejected in a hypervelocity cratering event is divided into the subsonic “excavation flow” (material that will not escape the planet) and a high-velocity spalled component (see Melosh 1984). Estimates indicate that the mass of spalled material ranges from ~0.01–10% of the impactor mass (Melosh 1984; Head et al. 2002; Artemieva and Ivanov 2004). Although there is variation in the total amount of spalled mass depending on the launch physics, impactor speed and potentially angle, it is important to realize that our calculations below do not depend on the physics which produces the spalled ejecta. We calculate instead the fraction of material reaching various destinations as a function of the ejection speed.

Mercury is deep in the Sun’s gravity well, and thus not only is Mercury’s orbital speed high, but so are those of other objects that cross its orbit. In particular, asteroids and comets will cross the orbit of Mercury (and impact it) with speeds of many tens of km/s. Marchi et al. (2005) examined the impact speed distribution of Mercury-crossing asteroids (which are in rough steady state due to their continual escape from the main asteroid belt), and concluded that most asteroidal impacts occur with impact speeds from 20–70 km/s. While the fractional contribution of large (>100 m diameter) comets as Mercurian impactors is very unclear due to the potential for destruction as their perihelia are lowered down to ~0.4 AU, their larger semi-major axes (and often large inclinations) cause the cometary impact speeds to be even higher (with speeds up to and sometimes exceeding 80 km/s).

These high impact speeds place Mercury in a unique position for planets in the solar system, as it is the only planet which impactors strike at 5–20 times the planetary escape speed. In contrast, Earth is struck mostly at 15–30 km/s (1.5–3 times its escape speed) and 90% of the asteroids (the dominant impactor population) that strike Mars do so at speeds less than 4 times its escape speed (W. Bottke, personal communication). Since the maximum impact-ejecta launch speeds are a fraction of the impactor speed (up to about half for the theory of Melosh (1984), as an example) values of $v_{\infty} = 10–30$ km/s are quite feasible for Mercurian ejecta. This regime has not been quantified in earlier calculations.

**METHOD**

In order to calculate the dynamical fate of Mercurian ejecta, we have performed numerical integrations of the orbital evolution of large numbers of test particles escaping Mercury. For each simulation, test particles were randomly positioned moving radially away from Mercury with a single value of $v_{\infty}$. In reality a single impact will not eject particles in all directions and thus these initial conditions give results averaged over all impact locations on the planet. The speed distribution of the escaping ejecta will depend on the impact physics; an appropriately-weighted combination of our various single-speed integrations can be used to calculate the fraction of material delivered to a given target given one’s favored ejecta speed distribution. Our calculations are thus free of assumptions about the impact physics.

Using the same numerical integration method as in Gladman et al. (1996) we then tracked the ejecta’s heliocentric orbits taking into account the gravitational influence of the planets (Mercury through Neptune), and stopped the integration of a particular particle if it struck a planet, had its perihelion reach the surface of the Sun, or reached 60 AU from the Sun (with the latter fate never happening in these simulations). The integrations were carried out for 30 million years of simulated time. The dynamics were purely gravitational although we discuss non-gravitational effects below.

**Numerical Simulations**

We studied the cases of $v_{\infty} = 4, 9, 14, 20, \text{and } 25$ km/s by integrating 7000, 7000, 16,000, 18,000, and 18,000 test particles (respectively) for 30 Myr after their launch. The
variable number of particles was simply due to the available computer resources on the LeVerrier beowulf cluster at UBC at the time of the integration’s start. In each case, the number of launched particles is sufficiently large that the planetary impacts reported below are directly observed in the integrator, as opposed to estimating impact probability using the test-particle histories in conjunction with an Öpik collision probability estimate (see Dones et al. 1999). The simulations required roughly 30 CPU years of computational effort.

The basic orbital evolution of the particles is characterized by repeated gravitational encounters with the terrestrial planets, each of which modifies the meteoroid’s heliocentric orbit. Each planetary encounter could result (with low probability) in an impact instead of a flyby, which the integration algorithm then logs. The number of meteoroids in space will decline with time, and the region of orbital parameter space occupied by the meteoroids will expand as their orbits diffuse via gravitational slingshot effects with the planets into new regions of parameter space. For Mercurian ejecta this allows meteoroids to reach larger semi-major axes as they climb out of the Sun’s gravitational well due to fortuitous encounters with Mercury, Venus, and Earth (the opposite effect can also happen). The analysis presented here will focus on the distribution of impact times (after launch from Mercury) to Earth, Venus, and Mercury, expressed as a cumulative fraction (called the transfer efficiency) of the launched meteoroids reaching that target.

**CALCULATION RESULTS**

**Meteoroids Reaching Earth**

We begin our analysis by examining the fraction of Mercurian ejecta that reaches Earth (and thus may become meteorites). In the context of meteoroid delivery, we are interested in decimeter-sized and larger meteoroids because a smaller object is unlikely to produce a recoverable meteorite after passage through an atmosphere. Since the number of ejected fragments decreases rapidly with size (e.g., Head et al. 2002; Artemieva and Ivanov 2004) decimeter ejecta will greatly outnumber meter-scale objects. The typical preatmosphere size of Martian meteoroids fits this picture.

In Fig. 1, we first note that the results of the 4 km/s case are in agreement with the previous calculations of Gladman (2003), namely that about 0.1% of Mercurian meteoroids would reach Earth in the first 10 million years after launch. Because the CRE ages of stony meteorites (including Martian meteorites) are often factors of several longer than this, we have integrated three times longer (to 30 Myr) than the previous study and find an efficiency of 0.7% in 30 Myr for the 4 km/s case, again comparable to the 0.5% efficiency in 23 Myr estimated by Gladman et al. (1996). This reproducibility (despite using different initial conditions, different machines, and a slightly different version of the integration code) provides confidence in the calculations. The lack of Earth impacts near the start of the simulation is due to the fact that the 4 km/s case has no ejecta initially crossing the Earth’s orbit, or even that of Venus; gravitational scatterings by Mercury to reach Venus-crossing orbits then allow Venus scatterings to transfer some meteoroids to Earth-crossing orbits on time scales of 5 Myr.

Increasing $v_\infty$ to 9 km/s causes some of the ejecta to initially be on Venus-crossing orbits. This planet’s greater mass allows it to rapidly assist meteoroids to Earth-crossing orbits. The rate of Earth impacts is roughly constant, with a cumulative efficiency of about 0.8%/10 Myr.

Further increasing $v_\infty$ to 14 km/s enters the regime in which some ejected meteoroids (those that were “traveling forward” relative to Mercury once liberated) are in the Earth-crossing regime. Particles with aphelion distances slightly greater than 1 AU have high Earth-encounter probabilities per unit time (see Fig. 5 of Morbidelli and Gladman [1998]) and these objects have high probabilities of being accreted by Earth on 10 Myr intervals.

Once $v_\infty = 20–25$ km/s is reached, the Earth impact efficiency declines with further increases in launch speed. This is because many of the particles that are launched outwards are now deeply crossing Earth’s orbit, which lowers their per-orbit collision probability.
Although the Mercurian material accreted by Venus will likely be completely ablated in the Venusian atmosphere, we present the results in Fig. 2 for completeness. Here the two slowest cases have similar yields, with Venus absorbing 20\% of the material escaping Mercury in 30 Myr; in these cases many of the Venus-crossing meteoroid orbits only cross in a shallow sense while at aphelion, which is the highest collision probability per orbit state. The figure shows that for the 4 km/s case no escaped meteoroids cross the orbit of Venus initially; scattering by Mercury in ~1 Myr populates the Venus crossing state and results in the 4 and 9 km/s cases having similar Venusian yields after 3 Myr. By 14 km/s the largest semi-major axis orbit crosses Venus more deeply (lowering their collision probability per orbit), and they begin to enter the regime favorable for Earth impacts. This continues for larger speeds; for $v_\infty = 20$ and 25 km/s the transfer efficiency to Venus drops to 13\% and 8\% in 30 Myr, respectively. These large yields (factors of several above those to Earth) simply reflect that Venus has a non-negligible cross section and intersects a large fraction of the meteoroid swarm at any time.

Meteoroids Reaccreted by Mercury

Since all of the ejecta is initially Mercury crossing, it is not surprising that it is Mercury itself that accretes the largest fraction of its ejecta. The efficiency and the time scale over which this occurs are important to understand in the context of Mercury reaccreting its own mantle in a scenario in which the planet’s original outer layers were blown of in a giant collision.

For $v_\infty = v_{esc} = 4$ km/s the effect of gravitational focusing enhances the reaccretion rate until a combination of gravitational scattering to higher relative speeds and the preferential elimination of high collision-probability meteoroids via accretion slows the re-accretion rate (see Gladman et al. 1995 for a more complete discussion in the case of lunar ejecta). This results in fully half of the ejecta being reaccreted by Mercury in 30 Myr. Since a further 20\% has been accreted by Venus (Fig. 2), only about one third of the ejecta still survives in space after this time. It is likely that at least half of this remaining material would be swept up by Mercury in the following tens of Myr.

The gravitational focusing effect is much reduced in the 9 km/s case. For larger ejection speeds Mercury’s gravitational focusing becomes unimportant, with all the higher ejection speeds having roughly 25\% of the launched material returning to the planet. Taking into account the material absorbed by Venus and Earth, about two thirds of the Mercurian ejecta ejected with $v_\infty = 20$–25 km/s is still in space 30 Myr after launch. Given that the fraction of the launched material with $v_\infty > 20$ km/s is small, this remaining material represents a small amount of mass which will continue to be gradually accreted by the terrestrial planets over time scales of tens of millions of years. This possibility should be tempered by the realization that long-lived meteoroids will be prone to collisional disruption while in space due to the impacts of small debris in heliocentric orbit (Gladman 2003). With impact speeds of ~10 km/s (an appreciable fraction of the orbital speed because of the typically eccentric orbits) centimeter-scale projectiles can destroy decimeter-sized meteoroids. The spatial density of these projectiles inside 1 AU is poorly known, but such collisional activity should only decrease the number of long-duration transfers.

**DISCUSSION**

The transfer efficiency to Earth shown by these simulations (2–5\% in 30 Myr) is an order of magnitude larger than previous estimates, and is about half of the Martian delivery efficiency (cumulative Martian efficiencies are shown in Gladman 1997). However, we must first address the issue of whether radiation effects could invalidate the purely gravitational approach we have taken here.

**Poynting-Robertson Drag and Yarkovsky Drift**

Particles in the inner regions of the solar system are subjected to intense solar radiation; the role of the resulting non-gravitational forces may need to be considered when
evaluating the orbital evolution of the Mercurian ejecta. Although solar radiation is responsible for several forces, the motion of centimeter to decimeter-sized particles is predominantly affected by Poynting-Robertson drag (Robertson 1937). In the particle’s reference frame, the intercepted solar radiation is absorbed and re-emitted isotropically. In the solar frame of reference, however, more momentum is lost in the forward direction. This results in a velocity-dependent force which acts in the direction opposite to the particle’s velocity, decreasing the meteoroid’s heliocentric semi-major axis $a$. The time scale for the orbital evolution to bring a circular orbit with initial semi-major axis $a$ down to the Sun can be shown to be (see Wyatt and Whipple 1950):

$$T_{sprial} = \frac{7\text{Myr}}{Q_{pr}}\left(\frac{\rho}{1\text{g/cc}}\right)\left(\frac{r}{1\text{AU}}\right)^{1/2}\left(\frac{a}{1\text{AU}}\right)^{2/3}$$

(2)

where $\rho$, $r$, and $a$ are the meteoroid’s density, radius, and orbital semi-major axis respectively, and $Q_{pr} = 1$ is the Poynting-Robertson drag coefficient for this size range (Burns et al. 1979). When eccentricity becomes important numerical integration of the spiraling time scale from the PR-evolution equations has been presented in tabular form by Wyatt and Whipple (1950). Taking $e = 0.5$ and $a = 0.7$ AU for a typical outward-flung meteoroid with density of $3\text{ g/cc}$ and radius of $10\text{ cm}$ (the size we are interested in for reasons discussed above), the PR collapse time scale is ~70 Myr. Thus, except for the meteoroids with $a < 0.5$ AU (which are less likely to reach Earth-crossing orbits), PR drag should be relatively ineffective at dragging decimeter-scale Mercurian meteoroids down to the Sun; in addition, our simulations show that meteoroids which are on Earth and/or Venus-crossing orbits tend to be scattered by encounters with those planets to larger semi-major axes and perihelia on time scales of ~1 Myr, further weakening the PR effect.

A second non-gravitational perturbation is the Yarkovsky effect, in which the higher momentum carried away from the hotter afternoon region of the body causes a systematic acceleration (see Bottke et al. 2006 for a recent review). For decimeter-radius meteoroids, the so-called “diurnal” effect dominates and produces a maximum drift rate ~0.03 AU/Myr at 0.4 AU, scaling as $a^{-2}$ (Vokrouhlický 1999 and personal communication). This rate is not negligible (order unity change in semi-major axis over 15 Myr), but the drift could be outwards (for prograde rotators) or inwards (for retrograde rotators), and thus Yarkovsky could help meteoroid delivery to Earth by pushing about half of randomly oriented impactors out towards Venus crossing orbits. The drift rate will not be monotonic if collisions with small particles in solar orbit can reorient the spin axis. On average Yarkovsky may in fact be beneficial since reaching the Venus-crossing regime would be the rate-limiting step for low-speed ejecta, whereas the high-speed ejecta that is already on Earth-crossing orbits will again be prone to being scattered to larger semi-major axis and perihelia where Yarkovsky effects will be less important.

**Mercurian Meteorites on Earth**

This greater yield we calculate, enabled by the fast launches that likely occur from the Mercurian surface, reopens the possibility that Mercurian meteorites could be present in the worldwide collections. Love and Keil (1995) discussed the issue of what properties such meteorites would have and thus how we would recognize them as Mercurian (as opposed to asteroidal). The surface reflectance spectra provided by ground-based studies (e.g., Sprague et al. 2007) and soon to be provided by the Messenger spacecraft (see Boynton et al. 2007) will doubtless provide constraints on discussions of possible links of certain meteorite types to Mercury as a source body (examples: Palme 2002; Keuhner et al. 2006, 2007; Markowski et al. 2007).

Our modeling indicates that Mercurian meteorites reaching Earth would have preatmospheric radii of order 1 decimeter and 4-pi CRE ages (for the transfer itself, as opposed to a potentially longer near-surface 2-pi CRE residence age) of 5–30 Myr. This is similar to Martian meteorites with the interesting difference that the long CRE-age Martian meteorites are reduced by collisional destruction in the main belt (Gladman 1997) whereas Mercurian meteorites may be more limited by PR drag. Our calculations show that the atmospheric entry speeds of Mercurian meteoroids will be faster (15–30 km/s) than is common for Martian meteoroids, for which 10–15 km/s is typical; the Mercurian entry speeds are more in line with “normal” chondritic meteorites and thus the lower ablation concluded from cosmic-ray records and explained by low-speed arrivals (Gladman 1997) should be absent for Mercurian meteorites. Although it is very unlikely that a sufficient number of fireballs will ever be observed to confirm this, incoming Mercurian meteorites will exhibit a strong preference to fall in the morning rather than afternoon. Lastly, the common low masses of lunar meteorites will be rare in the Mercurian case since cm-scale Mercurian ejecta is rapidly depleted by PR drag.

**Mercury Reaccretion Efficiency and Dispersing the Proto-Mercurian Mantle**

Re-accretion by Mercury is of relatively little interest for the meteorite problem, but is of great importance for quantifying the hypothesis that the high bulk density of Mercury is due to the collisional stripping of the mantle from a proto-Mercurian planet by a giant collision (recently reviewed by Benz et al. 2007). In this scenario the lower-density mantle of an already differentiated proto-Mercury is ejected into space by the impact and then lost into the Sun via radiation effects.
Whether this convenient disposal of the stripped mantle will work depends critically on the conclusion regarding the size of the ejecta, for Equation 2 shows that the spiraling-in time scale increases linearly with the radius. Take the stripped mantle (Benz et al. 2007) to have a mass of 1.25 Mercury’s present mass and add the putative impactor of 0.35 Mercury’s mass (1/6 of the target). Taking the typical post-impact orbital inclination to be of order \( \left( \frac{v_\infty}{v_{\text{orb}}} \right)^2 \approx 2 \) degrees, this material will be spread out in a thin ring surrounding the Sun. Putting the ejected mass into 1 cm radius drops of density 2.5 g/cc and spreading them out over this ring, we calculate that their optical depth to the solar radiation is of order unity, and probably higher in the mid-plane. The ring is thus potentially capable of self-shielding the particles from the effects of PR drag, which will lengthen its PR decay time scale. Benz et al. (1998) point out that this ring of particles is likely collisional, and with encounter speeds of order \( v_\infty = 4 \text{ km/s} \) the collisions would disrupt these small particles rather than allowing accretion; the resulting smaller fragments will be even more prone to PR drag and further collisions. The collisional cascade will increase the surface area to mass ratio of the fragments and cause the optical depth perpendicular to the midplane to exceed unity, making the collision time scale drop to the orbital period. The ring will thus collisionally evolve much faster than PR drag can dispose of individual particles. Although there will be a phase in which the inner ring edge (which has passed optical depth unity) will shield the rest of the ring from solar radiation, this may not last once the ring becomes very thin due to the fact that the solar surface will subtend a degree, this material will be spread out in a thin ring surrounding the Sun. Putting the ejected mass into 1 cm radius drops of density 2.5 g/cc and spreading them out over this ring, we calculate that their optical depth to the solar radiation is of order unity, and probably higher in the mid-plane. The ring is thus potentially capable of self-shielding the particles from the effects of PR drag, which will lengthen its PR decay time scale. Benz et al. (1998) point out that this ring of particles is likely collisional, and with encounter speeds of order \( v_\infty = 4 \text{ km/s} \) the collisions would disrupt these small particles rather than allowing accretion; the resulting smaller fragments will be even more prone to PR drag and further collisions. The collisional cascade will increase the surface area to mass ratio of the fragments and cause the optical depth perpendicular to the midplane to exceed unity, making the collision time scale drop to the orbital period. The ring will thus collisionally evolve much faster than PR drag can dispose of individual particles. Although there will be a phase in which the inner ring edge (which has passed optical depth unity) will shield the rest of the ring from solar radiation, this may not last once the ring becomes very thin due to the fact that the solar surface will subtend a degree, this material will be spread out in a thin ring surrounding the Sun. Putting the ejected mass into 1 cm radius drops of density 2.5 g/cc and spreading them out over this ring, we calculate that their optical depth to the solar radiation is of order unity, and probably higher in the mid-plane. The ring is thus potentially capable of self-shielding the particles from the effects of PR drag, which will lengthen its PR decay time scale. Benz et al. (1998) point out that this ring of particles is likely collisional, and with encounter speeds of order \( v_\infty = 4 \text{ km/s} \) the collisions would disrupt these small particles rather than allowing accretion; the resulting smaller fragments will be even more prone to PR drag and further collisions. The collisional cascade will increase the surface area to mass ratio of the fragments and cause the optical depth perpendicular to the midplane to exceed unity, making the collision time scale drop to the orbital period. The ring will thus collisionally evolve much faster than PR drag can dispose of individual particles.
CONCLUSIONS

Given recent estimates of impact speeds on to Mercury, we have studied the fates of Mercurian impact ejecta for five launch speeds from 4–25 km/s, which are much higher than in previous studies. We have measured the delivery rates via numerical integration in the “gravity-only” regime and find that 40–70% of the ejecta is swept up by Mercury, Venus, and Earth within the first 30 Myr after launch. At low speeds Mercury reaccretion is dominant due to the gravitational focusing caused by that planet’s gravity, with 1/3 of the ejecta returning in 3 Myr and 1/2 within 30 Myr. For ejected meteoroids leaving Mercury with \( v_a \) speeds in excess of \( -9 \) km/s, 2–5% of the ejecta reaches Earth within 30 Myr (a time scale over which typical stony meteorites survive). This fraction is sufficiently high (comparable to Martian meteorite delivery) that Mercurian meteorites may be more plentiful than previously thought.

As discussed in Gladman (2003), centimeter- to decimeter-sized meteoroids must endure collisional erosion and may also have their orbits evolve due to radiation effects. A calculation of the mass flux of Mercurian meteoroids would have to account for these effects and use a detailed model of the rate and velocity distribution of Mercury impactors. Regardless of the estimated parameters for these processes, the calculations in this paper imply that the delivery rate may be a factor of 100 larger than previous transport calculations imply.

In the context of a mantle-stripping impact from Mercury, the calculations give the return rates for Mercurian ejecta to the planet and thus the time scale over which radiation forces must remove the material from Mercury-crossing orbit. The temporary heliocentric ring of ejecta may be sufficiently self-interacting that it would re-accumulate after collisionally damping to a thin ring and be swept up again by Mercury.

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