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The Depletion of the Putative Vulcanoid Population via the Yarkovsky Effect

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The geophysical history of Mercury is constrained by its crater record, its tectonics, and its magnetic field. Standard thermal models based on these constraints lead to inconsistent results unless Mercury was bombarded in its early history by an additional population of impactors. It has been suggested that the putative vulcanoid population, a belt of asteroid-like bodies residing on stable orbits inside the orbit of Mercury, may be the source of these impactors. Previous work has shown that collisions among vulcanoids are sufficient to deplete the stable vulcanoid zone of most multikilometer bodies within a billion years or so. In this paper, we examine whether the Yarkovsky effect, a thermal radiation force which forces asteroids to undergo semimajor axis drift as a function of their spin, orbit, and material properties, is strong enough to deplete the remaining material from the vulcanoid zone. Our results show that most kilometer-sized bodies escape into unstable orbits within a few billion years. We predict that the contemporary vulcanoid population, if it exists at all, may be limited to 300–900 bodies larger than 1 km in diameter.

Key Words: **asteroids; asteroids, dynamics; Mercury.**

1. INTRODUCTION

The vulcanoids are a hypothesized population of asteroids residing inside Mercury's orbit (e.g., Perrine 1902). Their existence is suggested by two theoretical scenarios for the formation of Mercury, each trying to explain the uncommon metal-rich composition of the planet. The first scenario assumes that condensed material from the solar nebula was aerodynamically sorted via gas drag before Mercury accreted. Iron-rich planetesimals, which preferentially avoided spiraling into the Sun relative to silicate-rich planetesimals, would then become Mercury's primary source of material (Weidenschilling 1978). A second scenario assumes that the vulcanoids are ejecta produced by a large planetesimal impact onto Mercury (Cameron *et al*. 1988, Benz *et al*. 1988, Wetherill 1988). Such a collision would presumably strip away much of Mercury's silicate mantle while leaving behind a higher density planet and a swarm of silicate-rich asteroids. In either scenario, the vulcanoids would retain a unique spectroscopic signature representative of their unusual history.

Any putative vulcanoids surviving today must reside in orbits that are dynamically stable over the lifetime of the Solar System. Numerical studies have shown that test bodies with mean e and $\sin i$ values $\approx$0.1 are stable if they adhere to $0.09 < a < 0.21$ AU orbits (Evans and Tabachnik 1999). The outer limit of the vulcanoid zone (VZ) stems from long-term changes to the eccentricities of Mercury and the vulcanoids themselves. The former causes Mercury's perihelion distance to vary between 0.29 and 0.35 AU on an $\approx$1-Myr timescale, while the latter causes bodies with $a > 0.25$ AU and $0.21 < a < 0.25$ AU to become Mercury-crossing within $\sim$1 and $\approx$100 Myr, respectively. Bodies along the inner boundary of the VZ are subject to eccentricity excitation via secular perturbations, radiative drag forces (i.e., Poynting–Robertson drag and Yarkovsky thermal drag), and thermal evaporation. These effects help eliminate vulcanoids over the age of the Solar System, though their efficiency at doing so depends on the unknown physical properties of the vulcanoids. These issues will be discussed in greater detail below.

Even though the VZ is dynamically stable today, it is plausible that all primordial vulcanoids were eliminated long ago by the same processes which produced the terrestrial planets. Numerical studies have shown that wandering protoplanets may have

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dynamically excited planetesimals in the VZ (via resonances and/or close encounters) during the late stages of planetary accretion (Chambers and Wetherill 1998, Agnor *et al*. 1999, Petit *et al*. 1999a,b). Gas drag may have also carried away material from the VZ; Weidenschilling (1978) has suggested that gas drag is capable of eliminating most $D < 10$ km planetesimals in the primordial solar nebula. Depletion via gas drag may be offset, however, by collisions among $D > 10$ km bodies or by the delivery of material to the VZ from $a > 0.2$ AU orbits. In addition, an empty VZ could have been restocked by collisional ejecta from a giant impact on Mercury. Hence, the concept of a present-day vulcanoid population cannot be dismissed without a thorough examination.

The existence of a substantial vulcanoid population at some early epoch has been invoked to help explain the chronology of events in Mercury's thermal history (Leake *et al*. 1987). Mercury, like the Moon and Mars, has ancient terrain that is heavily cratered. If Mercury's oldest craters are linked to the late heavy bombardment (LHB), which had its peak flux near 3.8 Gyr ago (Hartmann *et al*. 1981, 2000), constraints are placed on the geophysical evolution of Mercury (Strom *et al*. 1975, Solomon 1976, Melosh and McKinnon 1988) that may not be consistent with standard planetary interior models (Leake *et al*. 1987). These geophysical constraints are relaxed, however, if Mercury's surface was struck by a population of vulcanoids after the LHB. Such a prolonged surface bombardment would allow some of the craters on Mercury's ancient terrains to be younger than previously thought.

Several optical searches for vulcanoids have been attempted, but none so far have uncovered any objects (see review in Campins *et al*. 1996). These surveys are exceedingly challenging due to the VZ's proximity to the Sun. Advanced searches using the LASCO C3 coronagraph aboard SOHO constrain the largest prospective vulcanoid to a diameter $D < 20$–60 km (i.e., calculated using a limiting magnitude of $V = 8$, an albedo of 0.14, and a Mercury-like phase function; Durda *et al*. 2000). Future searches for vulcanoids will require even more innovative observational techniques (e.g., Stern *et al*. 2000).

Other constraints on the vulcanoid population are provided by collisional modeling. Any vulcanoids that escaped the primordial depletion mechanisms described previously should have undergone collision evolution over the past ∼4.5 Gyr. Numerical simulations show that test bodies residing in the VZ attain moderate eccentricity and inclination libration amplitudes from secular perturbations (Leake *et al*. 1987). These values, combined with short orbital periods intrinsic to bodies in the VZ, lead to high relative velocities and rapid comminution. Leake *et al*. (1987), using a numerical model which incorporated secular perturbation theory and a particle-in-the-box estimate for collision lifetimes, found that collisional grinding was a very efficient means of eliminating most kilometer-sized vulcanoids within the age of the Solar System. Their simulations also showed that increasing the mass of the initial population only resulted in more intense early comminution. Stern and Durda (2000), using a more sophisticated multizone collisional model, found that their starting populations typically "self-destructed" in less than 500 Myr, leaving behind (at most) a few hundred widely scattered kilometer-sized objects. The largest surviving object in their simulations had $D \sim 20$ km, consistent with the results of Leake *et al*. (1987) and with observational searches to date.

An optimistic reading of the collision model results suggests that a modest vulcanoid population may exist but is dominated by objects too small to be detected via observational surveys conducted to date. The relevant question then becomes whether these objects are capable of surviving loss mechanisms at work in the vulcanoid zone today. We address this question in the following sections.

2. RADIATIVE DRAG FORCES

Attrition among kilometer-sized objects in the VZ should be considerable even if mutual collisions could somehow be neglected. Poynting–Robertson (PR) drag, a radiation effect causing small bodies to spiral inward as they absorb energy and momentum from the Sun, is capable of eliminating $D < 0.2$ km vulcanoids spanning the VZ over the age of the Solar System (Wyatt and Whipple 1950). Since the VZ is near to the Sun, evaporations must also be considered an important effect. Estimates suggest that $D < 100$ km and $D < 2$ km bodies made entirely of iron will evaporate at 0.06 and 0.07 AU, respectively, over the age of the Solar System (Lebofsky 1975, Campins *et al*. 1996). As we move away from the Sun, however, evaporation becomes dramatically less effective. For example, at ∼0.08 AU, only $D < 0.1$ km bodies having some volatile content are susceptible to complete evaporation. Thus, while these two effects work together to remove $D \lesssim 0.1$ km bodies from the VZ, they leave the kilometer-sized bodies untouched.

The primary mechanism capable of modifying the orbits of kilometer-sized vulcanoids is the Yarkovsky nongravitational force, a radiation recoil effect causing objects to undergo semimajor axis drift according to their spin, orbit, and material properties (Rubincam 1995, 1998, Farinella *et al*. 1998, Vokrouhlický 1999). In the Yarkovsky effect, bodies orbiting the Sun absorb sunlight, heat up, and reradiate the thermal energy after a short delay produced by thermal inertia. This emission produces a force capable of modifying the object's semimajor axis. Previous work has shown that the Yarkovsky effect may play an important role in delivering meteoroids and asteroids to chaotic resonance zones in the main belt that bring them to Earth (Farinella *et al*. 1998, Bottke *et al*. 2000a). It may also explain the orbital diffusion seen among the small members of the Koronis asteroid family (e.g., 2953 Vysheslavia, Vokrouhlický *et al*. 1999) and tiny changes in the orbits of near-Earth asteroids (e.g., Vokrouhlický *et al*. 2000).

To quantify the dynamical effects of Yarkovsky thermal forces on vulcanoids, we tracked the long-term evolution of test bodies in the VZ using a code similar to that described in Farinella and Vokrouhlický (1999). Our objectives were to (i) estimate the fraction of vulcanoids that escape the VZ over time and (ii) determine the mean escape time and the flux of the escaping bodies. Both of these quantities depend on the size of the bodies and their physical characteristics. The test vulcanoids were given initial orbital parameters in the VZ ($a = 0.09$–0.21 AU, $e \simeq 0$, and $i \simeq 0$), isotropic spin axis orientations, and a range of surface thermal conductivities. Orbital motion was calculated using a simple analytic estimation of secular da/dt rates induced by Yarkovsky forces (Vokrouhlický 1999). This treatment is validated by the use of low e orbits, although more refined models might consider nonlinear effects in the heat diffusion problem. Other orbital changes (i.e., de/dt, di/di) via the Yarkovsky effect were found to be negligible. Objects drifting outside the boundaries of the VZ were removed from the simulation, since numerical integration results show that objects on the periphery of the VZ undergo scattering events or collisions with the Sun or Mercury in ~10–100 Myr (Leake *et al.* 1987, Evans and Tabachnik 1999). When desired, our code also includes the effect of collisions on test bodies in a statistical manner, as described further in the next section.

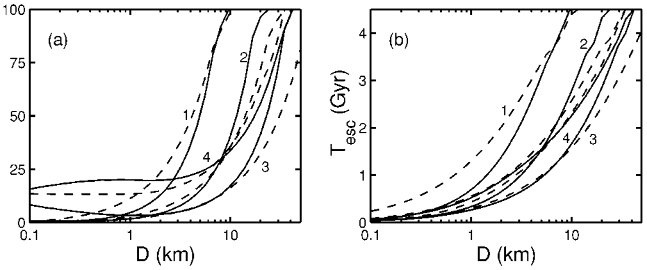

FIG. 1. (a) Percentage p of bodies remaining in the stable vulcanoid ring after 4.5 Gyr and (b) the average time $T_{\rm esc}$ (in Gyr) required to escape the stable ring vs size D (in km) of the objects. A collisionless population that was initially confined in the middle of the stable zone (i.e., at 0.15 AU) was assumed. Solid lines represent vulcanoids with a size-dependent rotation period of $(5/6)^2 \times D$ h, dashed lines those with a constant rotation period of 5 h. Objects with different surface thermal conductivity were considered: $K =$ (1) 0.02, (2) 0.2, (3) 2, and (4) 40 W m^{-1} K^{-1}.

3. RESULTS

Our model results show that common asteroid-type thermal conductivities (e.g., $K = 0.02$–2 W m^{-1} K^{-1}) lead to orbital motion in the VZ dominated by the diurnal variant of the Yarkovsky force (i.e., bodies can drift inward or outward, depending on their spin axis orientation). Only for very high conductive values, like those seen on metal-rich objects (e.g., 40 W m^{-1} K^{-1}), does the seasonal variant dominate (i.e., bodies drift inward toward the Sun, regardless of their spin axis orientation). This finding has important consequences for the evolution of the test bodies, as we will see below.

As a control, we first tested vulcanoids placed in the middle of the VZ ($a = 0.15$ AU) with diameters between 0.1 and 50 km. Mutual collisions between vulcanoids were not included for this set of runs. The surface thermal conductivities for these bodies were set to values appropriate for regoliths, porous rocks, compact rocks, and iron bodies (i.e., $K = 0.02$, 0.2, 2, 40 W m^{-1} K^{-1}, respectively; Farinella and Vokrouhlický 1999). Their spin periods were chosen to be (i) independent of asteroid diameter ($P \sim 5$ h) and (ii) to scale with diameter, such that small bodies spin much more rapidly than larger ones (i.e., $P = (5/6)^2 \times D$ h, with diameter in kilometers). Choice (i) is consistent with the median P values for small asteroids (Harris 1996), while choice (ii) corresponds to a function derived by measuring the spin rate of fragments measured in laboratory impact experiments (Farinella *et al.* 1998) and extrapolating these values to larger sizes.

Figure 1a shows the percentage of bodies remaining in the VZ for various values of K and D after 4.5 Gyr of evolution. The solid lines correspond to vulcanoids with a size-dependent rotation period, while the dashed lines are for bodies having a constant rotation period of 5 h. In general, we expect that regolith conductivity on the kilometer-sized vulcanoids to be ~0.02–0.2 W m^{-1} K^{-1}. These values are somewhat higher than the K values for lunar regolith (~0.002 W m^{-1} K^{-1}; Rubincam 1998) because the mean temperature in the VZ is considerably higher than that at 1 AU. Regardless, our results show that >80% of kilometer sized vulcanoids, regardless of composition, are eliminated within the age of the Solar System. Only a small fraction of kilometer-sized stony vulcanoids survived to the present day. The longest-lived bodies had high thermal conductivities (i.e., iron composition) and very slow drift rates. For reference, this depletion is roughly an order of magnitude higher than the corresponding threshold for PR drag.

Figure 1b displays the average escape time $T_{\rm esc}$ for those vulcanoids that reached the edge of the VZ within 4.5 Gyr. We found that typical kilometer-sized stony objects drifted from the center of the VZ to one of its borders in $T_{\rm esc} < 0.5$ Gyr, whereas same-sized iron objects lasted almost twice as long. In general, the longest-lived vulcanoids had spin axis orientations that minimized the cumulative forces of the diurnal and seasonal Yarkovsky variants.

For our next set of runs, collisions between our test vulcanoids and a "background" population were included via impact frequencies calculated using collision probability formulas (e.g., Bottke *et al.* 1994, Farinella *et al.* 1998). In general, nondisruptive collisions change the angular momentum of the target body, leaving its spin rate modified and its spin axis reoriented. This effect can potentially change both the object's drift speed and direction. To model this in a statistical manner, we have our test bodies undergo random spin axis reorientation events as a Poissonian process with a characteristic timescale of $15\sqrt{R}$ Myr (R is the body's radius in meters; Farinella and Vokrouhlický 1999). This ignores the possibility that tiny impacts occurring between the reorientation intervals cause the spin axis to undergo a slow random walk, but it is probably the best we can do until we understand more about the effects of high-speed subcatastrophic collisions. For this same reason, the target body's rotation rate is left constant for this simulation. Catastrophic

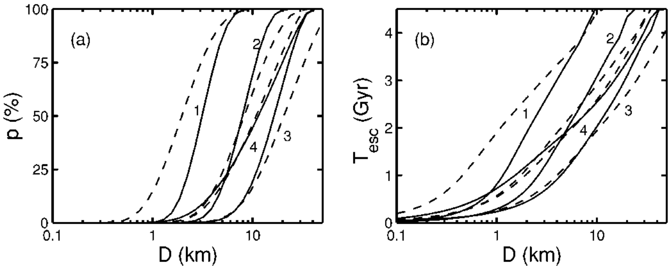

FIG. 2. The same as described in the legend to Fig. 1, but for an ensemble of vulcanoids with their spin axes being collisionally reoriented using a Poissonian process with a characteristic timescale of $15\sqrt{R}$ Myr.

collisions, though important, are not included, since they would require a sophisticated treatment of how the vulcanoid population's size distribution evolves over time (e.g., Stern and Durda 2000).

Figure 2a, like Fig. 1a, shows the percentage of vulcanoids that escape the stable zone over 4.5 Gyr. Here we see that no primordial $D < 1$ km objects with a size-dependent rotation period lasts to the present day. The escape time for these objects is also short; on average, no kilometer-sized objects lasted in the stability zone longer than 0.5 Gyr except for the lowest-conductivity bodies with $P = 5$ h (Fig. 2b). Overall, we found strong depletion (80–100%) for diameters smaller than 2 to 10 km in both simulations. Kilometer-sized and larger bodies typically escape on a timescale of a few gigayears, while smaller bodies escape even faster ($\leq$100 Myr timescale at $D \approx 0.1$ km).

For our remaining simulations, we filled the VZ uniformly with vulcanoids rather than starting them all in the center (Fig. 3, no collisions; Fig. 4, collisions with background population included). Thus, depending on their drift direction, objects close to the VZ border may escape immediately, or they may have to drive across the entire length of the VZ region. Since T_{esc} is calculated from the set of objects that escape within 4.5 Gyr, objects with slow da/dt rates converged to $T_{esc} = 2.25$ Gyr rather than 4.5 Gyr. Despite this difference, we found results comparable to those described above, except that the largest bodies in the sample (50 km) had a 5–25% chance of escaping the stable zone, depending on their spin axis orientation (i.e., Yarkovsky drift rate and direction) and their proximity to the VZ's periphery.

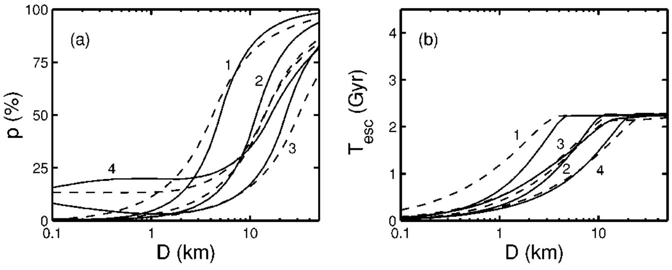

FIG. 3. The same as described in the legend to Fig. 1, but using an initially homogeneous (uniform) distribution of objects in the vulcanoid zone (VZ). There is little difference between these results and those in Fig. 1, apart from some greater leakage among large D objects that were started near the VZ boundaries. Note that T_{esc} values converge to 2.25 Gyr rather than 4.5 Gyr, since T_{esc} is calculated from only those objects that escape within 4.5 Gyr.

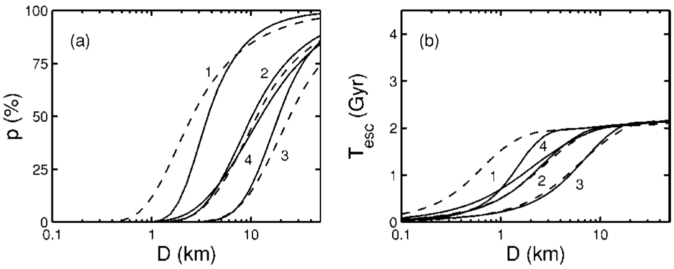

FIG. 4. The same as described in the legend to Fig. 2 (i.e., collisions included), but using an initially homogeneous (uniform) distribution of objects in the vulcanoid zone.

4. IMPLICATIONS

Based on our Yarkovsky simulations, the results of various collision models (Leake *et al*. 1987, Stern and Durda 2000), and estimates of other loss mechanisms, we believe that most/all of the vulcanoid population was obliterated or lost over the age of the Solar System. Collisions probably eliminated most larger ($D > 1$ km) vulcanoids, while Yarkovsky drift removed the small objects ($D < 1$ km). Thus, the sole remaining evidence supporting the existence of the vulcanoid population at any time is contained in Mercury's enigmatic crater record.

If we assume the vulcanoid population did exist at one time, we predict that kilometer-sized and larger vulcanoids, undergoing slow Yarkovsky drift, reached and impacted Mercury over a timescale of a few gigayears (provided that they were not previously eliminated by collisions). Hence, it is plausible that Yarkovsky drift forces helped extend the surface bombardment of Mercury's surface beyond the LHB. This possible augmented bombardment, lasting until comminution depleted the VZ of material, may account for inconsistencies between Mercury's crater history and the telltale scars of its geophysical evolution. Given how effective collisions are at obliterating the vulcanoid population, however, it is perhaps not surprising that this extra crater flux only lasted a billion years or so beyond the birth of Mercury.

Mercury's crater record can be used to derive constraints on the duration and importance of the putative vulcanoid bombardment. Strom and Neukum (1988) have shown that the shape of the crater size–frequency distribution ($D > 10$ km) on Mercury's intercrater and smooth plain units is the same as that of comparable geologic units on the Moon and Mars, although Mercury's crater distribution curve is laterally shifted from the other two curves. Strom and Neukum believe this result suggests that the same impactor population struck all three surfaces, presumably during the LHB, and that impact velocities on Mercury higher than those on the Moon explain the lateral shift. If their view is correct, the signature of the vulcanoid crater population on Mercury: (i) is nonexistent, (ii) has been obscured by craters produced by the LHB, or (iii) has a shape similar to that produced by the LHB, implying that Mercury's crater size distribution has been shifted by something other than velocity. We caution that factors like limited surface coverage, ambiguous data for $D \sim 10$ km craters, and the sensitive nature of extracting different impactor population signal(s) from the current crater data make interpretation of Mercury's crater record problematic. Proposed missions to Mercury, like NASA's MESSENGER and ESA's BepiColombo, will provide global coverage and enough high-resolution imaging to study this issue in greater detail.

If we assume that some remnant of the vulcanoid population still exists, we can, with some trepidation, set rough limits on its maximum size. We caution that such estimates are problematic, because no identifiable post-LHB crater signature has yet been found on Mercury (i.e., the youngest surface units on Mercury were formed during the tail end of the LHB; Strom 1979). To work around this problem, we look to the Moon to get some idea of how the impactor flux in the inner Solar System has changed over time. The cumulative crater density for $D > 10$ km craters on lunar surface units formed after the LHB (e.g., ~3.2 Gyr ago to today) is ~2–5 times smaller than comparable crater densities produced on the post-Orientale surfaces (e.g., ~3.8–3.2 Gyr) (Strom 1984). Since each crater population has a distinctive power-law slope index, and the post-Caloris crater population on Mercury is equivalent to the post-Orientale crater population in terms of slope index and density, we hypothesize that the nonvulcanoid component of the post-LHB impactor flux striking Mercury over the past 3.2 Gyr is comparable to that striking the Moon over the same time period. This means that the vulcanoid impactor population striking Mercury over the past 3.2 Gyr had to be small enough that the vulcanoid and nonvulcanoid impactor populations together were unable to change the power-law slope index of the post-Caloris craters. Hence, we postulate that the post-LHB vulcanoid impactor flux could only have been modestly larger than the post-LHB nonvulcanoid impactor flux. This statement also assumes that collisionally evolved asteroid populations (vulcanoid and nonvulcanoid) have similar power-law size indexes.

Mercury's nonvulcanoid impactor flux over the past 3.2 Gyr has probably been provided by Jupiter family comets (JFC), Halley family comets (HFC), and inner Solar System asteroids (ISA). The frequency of kilometer-sized ISA impacts into Mercury has been estimated to be 0.27 Myr^{-1} (Bottke *et al.* 2000b). The cometary collision rate is 2–10 times less frequent (Moses *et al.* 1999), although the collision velocities of HFCs (60 km s^{-1}) are somewhat larger than those of ISAs or JFCs (40 km s^{-1}). This means HFCs hit Mercury less frequently than other objects, but create larger craters. By assuming this impactor flux has been in steady state since the end of the LHB, we can estimate the escape rate of vulcanoids needed to create a comparable impactor flux on Mercury. Leake *et al.* (1987) estimate that the impact frequency between Mercury and test bodies residing just outside the VZ (between $a = 0.255$ and 0.28 AU) is 1.0–2.0 × 10^{-2} Myr^{-1}. For simplicity, we will assume that material escaping across the inner VZ boundary has a comparable impact frequency (i.e., their eccentricity is pumped up by resonances until they achieve Mercury-crossing orbits). Thus, to match the current impactor flux, the region $a = 0.255$–0.28 AU needs to have a steady-state population of roughly 10–30 $D > 1$ km vulcanoids. Since the dynamical lifetime of test bodies in this region is ~10 Myr (Evans and Tabachnik 1999), we can infer a VZ ejection rate of 1–3 $D > 1$ km bodies per million years. This value is somewhat conservative, since vulcanoids, striking Mercury at ~20 km s^{-1}, make craters smaller than those produced by the background population.

The vulcanoid population needed to sustain this "escape flux" can be calculated from

$$\text{Escape Flux} = \tau N_{\text{vul}}\ (D > 1\,\text{km}), \tag{1}$$

where $\tau \approx 1/T_{\text{esc}}$ and N_{vul} is the number of kilometer-sized vulcanoids. In this circumstance, the mean escape time for $D > 1$ km bodies can be determined from Fig. 2b. Using values of $K = 0.02, 0.2, 2,$ and 40 W m^{-1} K^{-1}, we estimate τ to be 0.0014, 0.0030, 0.0033, and 0.0014 kilometer-sized bodies per million years, respectively. The diurnal variant of the Yarkovsky effect dominates for $K = 0.02, 0.2, 2.0$ W m^{-1} K^{-1}, allowing objects to escape across both the inner and outer VZ boundaries. For $K = 40$ W m^{-1} K^{-1}, however, the seasonal variant dominates, such that material only escapes across the inner VZ boundary. Substituting these τ values and our estimated vulcanoid escape rate of 1–3 kilometer-sized bodies per million years into Eq. (1), we predict that the contemporary vulcanoid population was never larger than 300–2000 $D > 1$ km bodies. We speculate that $K = 0.02$–0.2 W m^{-1} K^{-1} values are more appropriate, since (i) the vulcanoid-origin models suggested in the Introduction favor the production of silicate-rich bodies and (ii) dust–particle impacts and/or thermal stresses would produce tiny surface defects and fractures in resident vulcanoids. Our favored K values would decrease the size of the vulcanoid population to 300–900 $D > 1$ km bodies. This value should be used with care, since it is unclear how many craters are really needed to modify the slope of the post-Caloris crater populations; it is possible that increasing the vulcanoid population by a factor of 2–4 would not be readily noticed. Better resolution images and more complete coverage of Mercury will be needed to resolve these issues.

5. FUTURE WORK

We believe that a detailed study of the feedback between collisional evolution and Yarkovsky depletion of the VZ would be an interesting extension of this work. Intuitively, a high depletion rate of small projectiles ($D \sim 10$–100 m) may prolong the lifetime of the larger vulcanoids. Their apparent absence, if eventually confirmed by observations, may further sharpen the understanding of the primordial condensation processes and mixing in the inner zone of the solar nebula.

ACKNOWLEDGMENTS

We dedicate this paper to the memory of our friend and co-author Paolo Farinella, who passed away on March 25, 2000. Paolo was an early and energetic advocate for the application of Yarkovsky forces to the evolution of small bodies in the Solar System. His imagination and intuition on the many interesting problems involving asteroids, comets, meteorites, and planetesimals will be sorely missed. The authors also thank Dan Durda and Don Davis for their careful and constructive reviews of this paper. Research funds for William Bottke were provided by grants from NASA's Planetary Geology and Geophysics program (NAG5-8950, NAGW-310). Travel support was provided by grants from NATO and NSF/CNRS.

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