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Meteorites from Phobos and Deimos at Earth?

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ABSTRACT

We examine the conditions under which material from the martian moons Phobos and Deimos could reach our planet in the form of meteorites. We find that the necessary ejection speeds from these moons (900 and 600 m/s for Phobos and Deimos respectively) are much smaller than from Mars' surface (5000 m/s). These speeds are below typical impact speeds for asteroids and comets (10–40 km/s) at Mars' orbit, and we conclude that delivery of meteorites from Phobos and Deimos to the Earth can occur.

1. Introduction

Meteorites are solid interplanetary material that survives its passage through the Earth's atmosphere and arrives at the ground. Most meteorites originate from minor bodies, but a few arrive from planetary bodies. The interchange of material between the Mars and Earth is now well-established, both from the point of view of the ejection of material from the martian surface (Head et al., 2002), as well as of the orbital dynamics of Mars-Earth transfer (Gladman et al., 1996). At this writing fifty meteorites from Mars are recognized among the world's meteorite collections (The Meteoritical Bulletin Database[1]). Here we examine one remaining open question in this field, and that is whether material might arrive at the Earth from the martian satellites.

This study is partly motivated by the claim that the Kaidun meteorite may have come from Phobos (Ivanov, 2004). This meteorite is largely made up of carbonaceous chondrite material, and spectral analysis suggests that the surface properties of Phobos and Deimos are bracketed by outer main-belt D and T type asteroids (Rivkin et al., 2002), the latter of which have been linked to carbonaceous chondrites (Bell et al., 1989). However, the Kaidun meteorite is unusual in that it contains a wide variety of fragments of other types (Ivanov, 2004). For a meteorite to be so varied, it would have to be formed in a region where impacts with a range of asteroidal materials can occur, and from which escape to Earth is dynamically possible. The martian moons certainly fit these requirements, though they are hardly unique in this respect as most main belt asteroids of any size do as well. We note that Phobos is thought to have compositional variations on scales of hundreds to thousands of meters (Murchie et al., 1991; Pieters et al., 2014; Basilevsky et al., 2014), consistent with a mixed composition. In any case, we do not argue here either for or against the origin of the Kaidun meteorite from a martian moon, but simply examine the dynamical processes by which such a transfer might take place.

That ejecta from Phobos can escape into interplanetary space was noted by Ramsley and Head (2013) but the conditions under which this occurs was not discussed in detail. That material released from the Voltaire impact on Deimos might escape Mars space was discussed by Nayak et al. (2016), though only as an aside to their study of mass transfer between the martian satellites. Our results differ slightly from theirs, probably due to a different criterion for escape, and this is discussed in Section 3.

The aim of this work is to determine if material ejected from either of the martian moons by impacts might escape to reach the Earth. In particular, we want to determine the ejection speeds required for this to occur, and compare them to typical impact speeds at Mars to determine whether the process is likely to occur. We do not examine the transfer process from Mars to Earth in detail, as this has been done by other authors (Gladman et al., 1996; Gladman, 1997) but simply assume that any material that leaves near-Mars space for interplanetary space could potentially reach the Earth. We will show that the speed distribution of ejecta from Mars and from its moons is similar upon leaving near-Mars space. As a result, the heliocentric orbits of ejecta from these sources is similar, and the dynamical transfer process from Mars to Earth should proceed in the same manner.

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[1] http://www.lpi.usra.edu/meteor/

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2. Methods

Particles ejected from Phobos and Deimos at different speeds are numerically simulated under the influence of Mars, the Sun and the other planets. One thousand particles are integrated for each ejection speed investigated. The RADAU integrator (Everhart, 1985) has used with a tolerance of 10^{-12}. In addition, the maximum time step allowed is 0.01 Earth days (14.4 min or $1/30^{th}$ of Phobos' 7.65 h orbital period). The J_2 component of the martian planetary potential is included. The mass of Mars is taken to be of 1/3098708 solar masses (Standish, 1998), Mars' pole to be at RA (J2000) = 317.68°, Dec (J2000) = +52.886° (Jacobson and Lainey, 2014), its equatorial radius to be 3396.2 km (Archinal et al., 2011) and $J_2 = 1.9605 \times 10^{-3}$ (Yoder, 1995).

Phobos' and Deimos' orbits are taken from Jacobson and Lainey (2014) for JD 2433282.5 (1 Jan 1950 TDT, their reference date). Particles are ejected spherically symmetrically from Phobos and Deimos at 10 positions spaced evenly around their orbits in time, to capture any effects related to the moons' orbital phase. In practice, impacts onto the moons are anisotropic and we expect more ejecta in the prograde direction due to higher impact speeds on the leading side (Colwell, 1993), but we are not attempting to model the amount of material released in detail. For comparison, we also eject particles from Mars' surface. Ten thousand particles are simulated at each ejection speed, with the material released outwards on a set of hemispheres located randomly on the martian surface. The effect of the martian atmosphere is neglected.

The effect of Mars location around its heliocentric orbit is known to be small, and impacts at aphelion are more likely since the planet spends more time there (Gladman, 1997). As a result, here we consider only ejection of material from Mars when it is near aphelion.[2]

The martian moons are included in the simulation, their masses are taken from Jacobson (2010), 1.08×10^{-15} solar masses for Phobos and 7.62×10^{-16} for Deimos. Gravitational perturbations by them are applied, and collisions with them are checked for, however they are treated as spheres of their mean radius for the purposes of collision detection. Collisions of ejecta with the moons are not seen in any of our simulations. Certainly the re-accumulation of ejecta by the moons would occur in practice, and may be an important process in the resurfacing of these moons (Ramsley and Head, 2013). However, given the small number of particles simulated, the small cross-sections of the moons and the short time scales considered, the effect of re-accumulation by the moons is negligible for our purposes.

Collisions with Mars are recorded and are a common outcome. The effects of radiation pressure and Poynting-Robertson drag are ignored here. These are important to the dynamics of small (cm-sized and below) particles, and any collision will certainly produce vast numbers of particles in this size range. However, for a meteorite to survive its high-speed entry into Earth's atmosphere, it must be of decimeter class or larger (Ceplecha et al., 1998), and radiation effects are negligible for these bodies, at least on the time scales examined here.

Simulations proceed for 10 martian years (18.8 Earth years, ~20000 Phobos periods or ~ 5000 Deimos periods). This was chosen because it represents more than 10^3 dynamical times for the ejecta, and because the bulk of the escaping ejecta in simulations escapes on much shorter time scales. As a test, a few simulations were run for longer (up to 100 Earth years) but only a very few additional particles escape over this longer time. The overall results are very similar and are not reported on here.

As a test of the method itself, we performed additional integrations of three of the simulations for Phobos where the results are the most mixed, and hence the simulations most sensitive to poor calculations. These three were the 800, 900 and 1000 m/s ejections, described in Section 3. These were rerun exactly the same initial conditions but with a maximum step size reduced by half to 0.005 days and with the integration tolerance reduced to 10^{-13} instead of 10^{-12}. The outcomes of the simulations were found to be identical in terms of numbers of particles reaching each end state, providing support for the reliability of the integration results.

The three end states of the ejecta considered here are either collision with Mars, escape from Mars (taken to occur when it leaves the Hill sphere, 1.08×10^6 km in radius), or survival on a circumplanetary orbit. Material from Phobos and Deimos that escapes Mars gravity well should evolve dynamically in much the same way as ejecta from Mars itself. This process has been extensively studied (Gladman et al., 1996), and is not duplicated here. The presence of escaping particles in our simulation will be taken as an indication that it is possible for material from the martian moons to reach Earth as meteorites.

3. Results

The results are summarized in Fig. 1. For impacts with Phobos, the lowest ejecta speed for which escape is seen is 900 m/s. This is much lower than the nominal escape speed from Phobos' orbital radius from Mars, 3 km/s, because its orbital speed of 2.1 km/s can contribute to the total for impacts on the leading surface. The process reaches 50% escape at roughly 2500 m/s. This inner moon is harder to escape from than Deimos (next) for two reasons. First, because it is deeper in the gravitational well of Mars; and second, because Mars' has a larger angular size, and so impacts with the planet are more likely from simple geometry.

Deimos requires only 600 m/s for the first escapes to occur, again from the moon's leading edge. This ejection speed is consistent with the difference between the local escape speed from Mars (1.9 km/s) and Deimos' orbital speed (1.3 km/s). Escape is easier from Deimos, beginning at speeds 30% less than from Phobos, and ejecta reaches 50% escape at speeds near 1500 m/s vs. 2500 m/s for the inner moon.

The onset of escape at a 600 m/s ejection speed from Deimos differs from the results obtained by Nayak et al. (2016) as presented in their Fig. 1, where escape can occur at speeds as low as 400 m/s. This discrepancy seems to arise from their choice of the sphere of influence as the boundary at which a particle is deemed to escape. The radius of Mars' sphere of influence or sphere of activity R_I (e.g. Roy, 1978)

$$R_I = \left(\frac{M_{Mars}}{M_{\odot}}\right)^{2/5} a_{Mars} \tag{1}$$

where M represents the masses of Mars and the Sun, and a is the semi-major axis of Mars, is 0.579 million km and smaller than the Hill sphere R_H (e.g. Murray and Dermott, 1999)

$$R_H = \left(\frac{m_{Mars}}{M_{\odot}}\right)^{1/3} a_{Mars} \tag{2}$$

at 1.08 million km, which is what we use. In our simulations, we find that particles with ejection speeds as low as 400 m/s can reach the sphere of influence, confirming (Nayak et al., 2016)'s results in this regard, however these particles do not escape from Mars' Hill sphere. We verify our choice of the Hill sphere as the appropriate boundary for escape by confirming that all of our particles which cross this surface move out into interplanetary space and do not immediately return to near-Mars space. We note that the boundary choice of Nayak et al. (2016) is unlikely to affect their results, though they are slightly underestimating the amount of material that remains within Mars gravity well.

From Mars' surface, the speeds needed for escape are given by the usual escape speed from the planet, 5.0 km/s. Below these speeds, re-impact with Mars is almost inevitable. However, at even at speeds of 4 km/s, we note that a small fraction (0.5%) of ejecta goes into orbit around Mars, though this contribution is almost imperceptible in Fig. 1. Our model of ejection from Mars' surface is not completely radial but

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[2] On 1 Jan 1950 TDT, Mars is near aphelion at a mean anomaly of 169.43°.

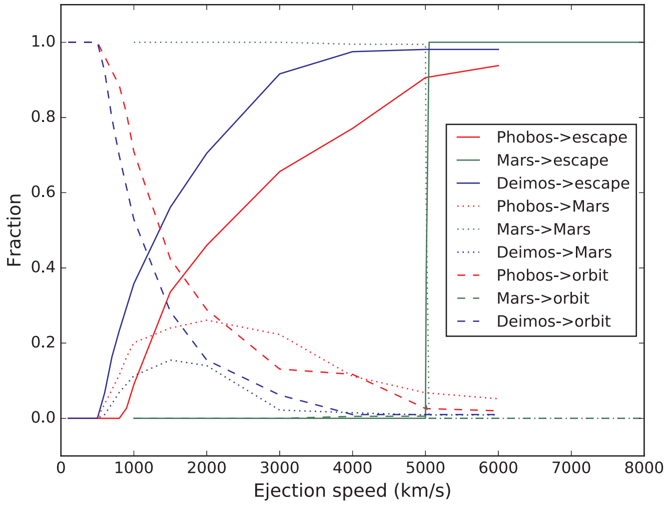

Fig. 1. End state fractions of particles versus ejection speed. Red is for Phobos, blue for Deimos and green is from Mars' surface. The solid lines ("escape") indicate the number of particles which escape Mars' Hill sphere, dotted lines ("Mars") are those that impact or return to Mars' surface, and the dashed lines ("orbit") indicate those particles that are still in orbit around the planet at the end of the simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

allows ejection angles from zero to ninety degrees from the local normal. As well, the addition of the J_2 term to the potential also allows the transfer of angular momentum to the orbits. As a result, particles ejected onto orbits near the escape speed from Mars do not necessarily fall back to the planet's surface but can remain in orbit. Thus the impact events which produce martian meteorites likely inject material into martian orbit as well, but this has not been investigated further here.

The speeds needed for escape from the martian moons are achievable in large impacts. Simulations of the large 9-km Stickney crater on Phobos by Asphaug and Melosh (1993) show peak particle velocities that can reach these speeds and higher, though only for a small fraction of the ejecta. It is unlikely, however, that Kaidun was ejected by the Stickney impact itself. Stickney is expected to have formed more than 2.6 Gyr ago (Schmedemann et al., 2015), though some have argued for a younger age 0.5 Gyr (Ramsley and Head, 2015). In either case, the lifetime of material on orbits crossing those of the terrestrial planets, only a few million years (Gladman et al., 1997), is much shorter than this large crater's age. The Kaidun meteorite was recovered as a freshly-found meteorite fall, and is unlikely to be as old as Stickney. Whether impacts onto from Phobos or Deimos have released material into interplanetary space in the last several million years is unclear, but we conclude that it is a possibility.

The escape trajectories of material from Phobos and Deimos are similar to that ejected from Mars. Fig. 2 shows heliocentric perihelion and aphelion distances for the material ejected at lowest escape speeds from their respective targets, as well as their inclinations and Tisserand parameters relative to Mars. Given that lower speeds are easier to generate than higher ones, we expect that the bulk of the material will be released just above the minimum threshold in most cases. The similar spreads for the different types of material in this figures justifies the assertion that their transfer to the Earth should occur by very similar means as well. Thus we expect that material from Phobos and Deimos can reach Earth by the same dynamical pathways as martian material.

An interesting feature of Fig. 2 is the smattering of a few points from Phobos and Deimos at higher/lower Q than is seen in the Mars results. It arises from particles which do not immediately escape, but which rather are injected into Mars orbit, followed by eventual diffusion into interplanetary space through the L_1 and L_2 points.

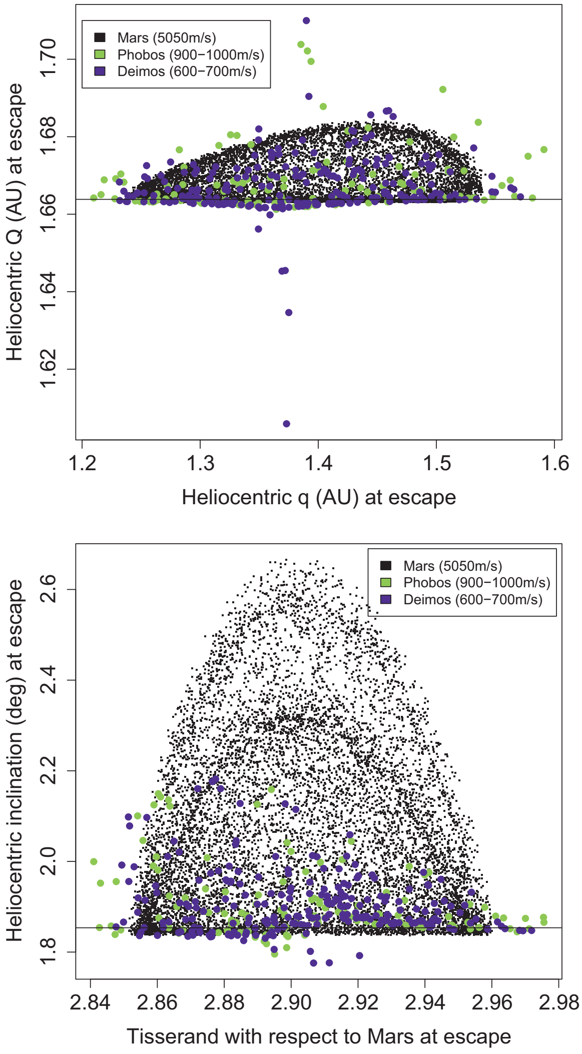

Fig. 2. Upper panel: Heliocentric perihelia q and aphelia Q of material escaping from Mars' Hill sphere at the lowest launch speeds for each target. The horizontal line indicates the Mars-Sun distance at the start of the simulation. Lower panel: Heliocentric inclination and Tisser and parameter of the same material. The horizontal line indicates the inclination of Mars orbit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4. Discussion

The ejection of material from Phobos or Deimos into interplanetary space, where it may be transferred to Earth, is seen at ejecta speeds below 1 km/s: 900 m/s for Phobos, 600 m/s for Deimos.

The typical asteroidal impact speed at Mars is estimated to be 10 km/s (Le Feuvre and Wieczorek, 2011; Galiazzo et al., 2013). Though these are likely the most common impactor, comets are also possible. Long-period comets impact at typical speeds of 40 km/s, and Jupiter-Family comets, 20 km/s (Christou et al., 2014). These high impact speeds imply that the ejection of material from the martian moons to escape speeds is possible.

The escape velocity from Mars is 5.0 km/s, and the existence of martian meteorites allows us to conclude that martian ejecta reaching at least such speeds is produced by impacts. However, we cannot so easily conclude that lower-speed ejecta is necessarily produced by similar impacts on Phobos or Deimos. The speed at which ejecta is released is strongly dependent on the target properties, and Head et al. (2002) for example have shown that ejecta speeds from damaged as opposed to solid surfaces is much reduced. The nature of the surfaces of Phobos and Deimos indicates that the conditions that apply on Mars are unlikely to be reproduced there.

Determining the relative efficiency of meteorite delivery from Mars and its satellites is difficult. Though arguably the speed distribution of impacts onto Mars and its moons, as well as the dynamical transfer from source to the Earth are similar, the difference in the ejecta production processes from each body complicates matters greatly. Mars has higher gravity, an atmosphere, a different composition, not to mention that ejection from the martian surface was shown by Head et al. (2002) to be enhanced by the presence of strong target material (bedrock) on the planetary surface, all conditions which are not applicable to the moons. Instead we ask a simpler question: what are the implications of ~ 1 Phobian meteorite in our meteorite collections vis-a-vis the ejection process, and are they reasonable? If we make the rough estimate that the bulk of the relevant ejecta is produced by the smallest impacts capable of doing so, the question becomes what is the smallest impactor onto Phobos/Deimos that will produce one decimeter sized fragment? Head et al. (2002) found that an impact by an asteroid as 3 km in diameter would produce $\sim 10^7$ decimeter size fragments with escape speeds high enough for them to become martian meteorites on Earth. Using the subscript P for Phobos, a simple dimensional estimate of the relative fraction of meteorites from Mars to those from Phobos is

$$\frac{N}{N_p} \sim \left(\frac{D}{D_p}\right)^{-\alpha-1} \frac{F}{F_p}\left(\frac{R}{R_P}\right)^2 \tag{3}$$

where N is the number of meteorites in our meteorite collections, D is the diameter of the smallest asteroid that can produce suitable fragments, F is the number of those fragments, and R is the radius of the body. The size distribution is parameterized as a power-law by α, which typically is used to describe the cumulative size distribution, though we are using the differential distribution here, hence the -1. The value of α is ≈ 1.95 for the near-Earth asteroid population (e.g. Stuart and Binzel, 2004) and we adopt this value for the Mars impactor population. If we solve Eq. (3) for D_P, the smallest impactor onto Phobos which can generate one decimeter fragment at a speed high enough to escape Mars' Hill sphere, we get

$$D_P \sim D\left[\left(\frac{N}{N_p}\right)^{-1} \frac{F}{F_p}\left(\frac{R}{R_P}\right)^2\right]^{1/(-\alpha-1)} \tag{4}$$

$$\sim \ 3000\text{m}\left[\left(\frac{50}{1}\right)^{-1} \frac{10^7}{1}\left(\frac{3387}{11}\right)^2\right]^{-0.34} \tag{5}$$

$$\sim \ 0.3\text{m} \tag{6}$$

where we have assumed a radius of 3387 km for Mars and 11 km for Phobos. We conclude that it is reasonable that our meteorite collections would contain 1 meteorite from Phobos if a 0.3 m impactor onto Phobos could release one decimeter particle at a speed greater than 800 m/s.

The amount of mass released doesn't present a problem, as a high-speed impactor might excavate a crater of whose volume exceeds its own by a substantial factor. The volume excavated is also likely to contain some larger pieces, and not just fines: the surfaces of the Moon, Eros and Itokawa have volume fractions of boulders which range from less than 1% to 25% (Michikami et al., 2008). But the question of whether the large fragments could attain high enough speeds is unclear, as the ejection of fragments of a decimeter sizes from asteroidal bodies is not well-studied. Most impact experiments into porous/unconsolidated targets tend to be done at centimeter impact sizes or below, and to show low ejection speeds ($\sim 1 - 10$ m/s) (O'Keefe and Ahrens, 1985; Ryan and Melosh, 1998; Housen and Holsapple, 2003; Michikami et al., 2007). The fastest ejecta is seen to reach higher speeds (e.g. a few hundred m/s for a 2300 m/s impact into basalt powder (Hartmann, 1985)) but larger fragments tend to have smaller speeds (Ryan and Melosh, 1998). There has been some simulation work done which has shown that ejecta speeds above 1000 m/s can be achieved for meter-sized ejecta during impacts by 8 m impactors into km-sized porous asteroids (Asphaug et al., 1998); this would imply that similar impacts on the martian moons might do the same. However, in contrast Housen and Holsapple (2003) found lower ejection velocities, and argued that the absence of compaction and the scale of the pore spaces in the Asphaug et al. (1998) simulations might account for their higher ejection velocities. So we can conclude that there may be Phobos/Deimos meteorites to Earth, with the primary unknown the distribution of ejecta speeds from impacts onto the martian moons.

5. Conclusions

The process of meteorite delivery from the martian moons to Earth is examined. Two factors which increase its efficiency relative to that of meteorites from the surface of Mars are the lowered ejection speeds needed, and the ability of smaller impactors to launch material. However, these are offset by the smaller cross-sections of the moons, and the primary unknown, which is the speed distribution for large ejecta fragments from this impacts. We conclude that it is not unreasonable that Phobos/Deimos meteorites might exist among the Earth's current meteorite collection, but more detailed analysis will have to await a better understanding of the cratering process on the moons themselves.

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