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Effects of mass transfer between Martian satellites on surface geology

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ABSTRACT

Impacts on planetary bodies can lead to both prompt secondary craters and projectiles that reimpact the target body or nearby companions after an extended period, producing so-called “sesquinary” craters. Here we examine sesquinary cratering on the moons of Mars. We model the impact that formed Voltaire, the largest crater on the surface of Deimos, and explore the orbital evolution of resulting high-velocity ejecta across 500 years using four-body physics and particle tracking.

The bulk of mass transfer to Phobos occurs in the first 10^2 years after impact, while reaccretion of ejecta to Deimos is predicted to continue out to a 10^4 year timescale (cf. Soter, S. [1971]. Studies of the Terrestrial Planets. Cornell University). Relative orbital geometry between Phobos and Deimos plays a significant role; depending on the relative true longitude, mass transfer between the moons can change by a factor of five. Of the ejecta with a velocity range capable of reaching Phobos, 25–42% by mass reaccretes to Deimos and 12–21% impacts Phobos. Ejecta mass transferred to Mars is <10%.

We find that the characteristic impact velocity of sesquinaries on Deimos is an order of magnitude smaller than those of background (heliocentric) hypervelocity impactors and will likely result in different crater morphologies. The time-averaged flux of Deimos material to Phobos can be as high as 11% of the background (heliocentric) direct-to-Phobos impactor flux. This relatively minor contribution suggests that spectrally red terrain on Phobos (Murchie, S., Erard, S. [1996]. Icarus 123, 63–86) is not caused by Deimos material. However the high-velocity ejecta mass reaccreted to Deimos from a Voltaire-sized impact is comparable to the expected background mass accumulated on Deimos between Voltaire-size events. Considering that the high-velocity ejecta contains only 0.5% of the total mass sent into orbit, sesquinary ejecta from a Voltaire-sized impact could feasibly resurface large parts of the Moon, erasing the previous geological record. Dating the surface of Deimos may be more challenging than previously suspected.

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1. Introduction

Several features about the surface geology on the moons of Mars remain poorly understood. The grooves on Phobos, which do not exist on Deimos, have received the most attention (Horstman and Melosh, 1989; Thomas, 1979; Weidenschilling, 1979), and theories for their formation continue to be proposed to this day (Asphaug et al., 2015b; Basilevsky et al., 2014; Hamelin, 2011; Murray et al., 2006; Wilson and Head, 2015; Nayak and Asphaug, 2015). However this is far from the only mystery. Though both moons are heavily cratered, with saturated surfaces and fine-grained regolith from impact debris accumulation (Lunine et al., 1982; Thomas, 1979), a large portion of ejecta produced on Deimos is retained in the form of crater fill of ~5 m depth, a phenomenon not noted on Phobos (Thomas and Veverka, 1980a). This difference is still unexplained (Lee, 2009). The surface of Deimos is also significantly smoother and brighter than Phobos, likely a result of crater fill (Thomas, 1993; Thomas et al., 1996; Veverka, 1978).

Phobos also exhibits two distinct spectral units, one of “redder” origin and one of “bluer” origin, possibly stemming from a compositional difference (Lee, 2009; Murchie and Erard, 1996). The bluer unit is associated with the Stickney crater and an origin from depth. The redder unit associated with the surface and small craters; it is spectrally similar to D-type asteroids, but also to Deimos (Murchie and Erard, 1996, 1993). It has been proposed that the red unit is a wide-spread shallow layer superimposed on a blue base

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(Murchie and Erard, 1996), for which there are four possible causes (Britt and Pieters, 1988; Murchie et al., 1991): (1) accretion of D-asteroid material onto blue Phobos material; (2) optical alteration of the bluer unit; (3) accretion of ejecta from Martian basin impacts and subsequent space weathering or (4) Phobos is an inherently heterogeneous rubble pile and the red/blue units are end-member compositions. One aim of our study is to investigate the possibility that the red veneer on top of the base blue unit may be ejecta accreted from Deimos rather than Mars.

Previous work has established that impact ejecta can reimpact the target body or nearby companions after an extended period, creating so-called "sesquinary" impact morphology. Examples of sesquinary studies in the literature include Earth's Moon (Gladman et al., 1995), Phobos (Nayak and Asphaug, 2015), Io (Alvarellos et al., 2008), Ganymede (Alvarellos et al., 2002), Europa (Zahnle et al., 2008) and Pluto (Bierhaus and Dones, 2014). For Mars, previous work suggests ejecta released at slightly greater than the satellite's escape velocity could remain in the system and subsequently reimpact at low relative velocities (Soter, 1972, 1971). Possible evidence for this was noted in analysis of Viking images (Veverka and Duxbury, 1977), however the efficiency of this process was previously unknown (Thomas, 1979). We report here on the distribution of impact velocities and geometries from inter-moon mass transfer trajectories, and present conclusions on the role and importance of sesquinary mass transfer between the Martian moons.

2. Methods

2.1. Impact model: generating 2-D velocity streamlines

Voltaire, the largest confirmed crater on Deimos, has a diameter of 3 km (Thomas and Veverka, 1980b; Thomas, 1979). By modeling the orbital evolution of ejecta from the Voltaire-forming impact, we aim to characterize an end-member case of mass transfer from Deimos to other Martian system bodies.

To model the streamlines ejected by the Voltaire impact, we use a simplified form of Maxwell's Z-model (Maxwell and Seifert, 1974; Maxwell, 1977; Roddy, 1977). Though limited by its neglect of interactions across streamlines, the Z-model reasonably approximates several experimentally observed features (Melosh, 1989; Richardson et al., 2007). The limitations of a Z-model implementation are discussed at length by (Barnhart and Nimmo, 2011). Our application is only concerned with ejecta streamlines that escape Deimos, and is unaffected by the details of cratering flow beneath the ground plane, surface material mixing during ejection or direct retention and emplacement of deposits. Therefore it provides a suitable level of insight into an outbound velocity distribution; approximations made by the Z-model are unlikely to alter our qualitative results.

We adopt the formulation of Barnhart and Nimmo (2011), who use $Z = 2.71$ for a Mars application. When tested against numerical computations, $Z = 2.7$ represents surface explosion cratering flow well (Melosh, 1989). All streamlines are ejected at a constant angle of 35.4° from the horizontal, set according to the relation (Maxwell, 1977):

$$\varepsilon_{ej} = \tan^{-1}(Z-2) \tag{1}$$

Outbound radial (v_r) and vertical (v_z) ejection velocities vary inversely with distance from the center of the crater r (Maxwell, 1977) as:

$$v_r = \alpha / r^Z \tag{2}$$

$$v_z = (Z-2)v_r \tag{3}$$

where g_D denotes the acceleration due to gravity for Deimos (0.003 m/s^2) and:

$$\alpha = \sqrt{\frac{g_D R_t^{2Z+1}}{4Z(Z-2)}} \tag{4}$$

Using a final crater radius $R_f = 1500$ m for Voltaire (Veverka, 1978), the transient crater radius is calculated as $R_t = 0.65\ R_f$ (Barnhart and Nimmo, 2011). For the analysis presented here the number of streamlines (n) has been chosen to yield a suitably dense streamline distribution with velocities greater than the Deimos escape velocity. Setting $R_{min} = 0$ and varying $R_{min} \leqslant r \leqslant R_t$, $n = 600$ streamlines evenly spaced in radius are generated within the Voltaire crater. Converting streamlines into axisymmetric coordinates (cf. Barnhart and Nimmo, 2011, Fig 1), we extract the radial and vertical coordinates as:

$$r = R_i \sin\theta(1-\cos\theta)^{\frac{1}{Z-2}} \tag{5}$$

$$z = R_i \cos\theta(1-\cos\theta)^{\frac{1}{Z-2}} \tag{6}$$

where θ is the angle from the vertical $\{\theta | \theta \in 0 : \pi/2\}$ and:

$$R_i = \frac{R_f - R_{min}}{n} \tag{7}$$

2.2. Creating 3-D velocity streamlines

The 2-D axisymmetrical distribution is now used to create an approximation to a 3-D excavation. The fate of the ejecta particle (reaccretion to Deimos, impact to Phobos, impact to Mars or escape) can vary greatly depending on the azimuth of the streamline. To rotate around the azimuthal direction, we define the Topocentric Horizon frame (Appendix A), adapted from the South-East-Zenith (SEZ) frame (Vallado, 2013). The azimuth of the ejection velocity vector β is measured from the north, clockwise as viewed from above the impact site. We select a 30° span as a compromise between computational efficiency and sampling a variety of azimuths across the possible solution space, such that $\beta | \beta \in (0 : \pi/6 : 2\pi)$ for a total of 11 possible azimuths. This yields a three-dimensional outbound velocity distribution tied to Voltaire. For use with the Mars gravity system integrator, these coordinates are then rotated into the Mars Centered Inertial (MCI) frame; details of coordinate transformations through the Deimos-Centered Deimos-Fixed (DCDF) and Deimos-Centered Inertial (DCI) frames are presented in Appendix A.

Finally, we are specifically interested in those streamlines that have sufficient velocity to reach the orbit of Phobos. Since both moons lie in the same orbital plane (Cazenave et al., 1980), the minimum velocity at Deimos to reach Phobos can be analytically calculated with the Hohmann transfer (Section 6.3, Curtis, 2013). Particles begin to cross the orbit of Phobos at velocities above 500 m/s, so we set the lower bound on velocities of interest at 400 m/s. From Deimos, the minimum velocity to escape the gravitational well of Mars is analytically approximated as (Eq. (2.80), Curtis, 2013):

$$v_{esc} = \sqrt{2\mu / r_{Deimos}} \tag{8}$$

where r_{Deimos} is the distance from Deimos to Mars and μ is the product of the gravitational constant and the mass of Mars. From (8), $v_{esc} = 1.91$ km/s; we set the upper bound on velocities of interest at 2 km/s. Therefore, we examine velocity streamlines in the range $\{v | v \in 400 : 2000\ \text{m/s}\}$. Nineteen of 600 streamlines fall within this range; rotated around 11 azimuthal positions, this creates a 209-streamline distribution. While we focus here on ejecta with sufficient velocity to reach Phobos (~400 m/s), we note that the majority of ejecta launched from Deimos at lesser velocities will ultimately re-impact Deimos.

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