
Natural impact craters preserved on the Moon and terrestrial planets have provided an opportunity to study the cratering process under a wide variety of conditions of formation and preservation. Because of their small size, Phobos and Deimos offer a potentially significant end point in the study of the effects of gravity, target strength, and curvature in the cratering process. In addition, they may provide important information on the surface history and present characteristics of other small solar system bodies such as asteroids. In this study both moons (Table 1) were taken to be spheres as opposed to the more accurate but correspondingly more complex triaxial ellipsoid approximations, and the gravitational effects of Mars on crater ejecta were ignored.

Several major parameters will be significant in causing differences in the cratering process and resulting landforms on Phobos and Deimos. The extremely small (and variable) radii of curvature (Fig. 1) will play an important role in shock wave and cavity geometry, and in the distance that ejecta will travel (Fig. 2). In addition, the exceedingly low gravitational accelerations imply that much ejecta from a single event should reach escape velocity and the remainder should be much more widespread over the target body (Fig. 3) than for a similar size impact on a larger planet. Gravitational modification of the transient cavity should be minimal, and strength scaling laws should govern final crater morphologies and geometries.

Cratering Process (Excavation Stage:) - A qualitative evaluation of ejecta ballistics on small bodies was obtained by extrapolating laboratory experimental results (where impact velocity is 1.57 km/sec, ~25% that calculated for Phobos and Deimos). Observed ejection velocities and angles were utilized in calculating ballistic ranges over spherical surfaces (Figs. 2,3). Ejecta which was transported approximately 1 m under terrestrial laboratory conditions would have traveled on the order of 1.4 km on Phobos and more than 3 km on Deimos. If larger scale events at higher impact velocities are considered, the low escape velocities (Table 1) would imply that a large majority of ejecta would be placed into escape trajectories. These paths are velocity-dependent only, as long as they do not intersect the surface of the target body on the way out. Since material nearest to the rim of the transient cavity is subjected to the lowest peak shock pressures and is transported the shortest distances, the largest fragments created during an impact event should come from the rim region and, at the same time, have low ejection velocities. Boulders and relatively large fragments should constitute a sizeable fraction of non-escaping ejecta on both bodies, assuming relatively coherent target material. (Modification Stage:) The sizes and masses of the two moons essentially rule out gravitationally driven modification of impact craters. Both lithostatic pressure and ejecta fallback effects (e.g., rim loading, cavity shallowing, etc.) should be virtually nonexistent in light of target strength and ejecta transport distances. For example, if an "average" lunar soil (ρ = 1.6 gm/cm³, cohesion = 0.006 bars) is taken as a model for Phobos' strength, cohesion effects alone would not be overcome until depths on the order of 50 m
CRATERING ON SMALL BODIES

Cintala, M. J. et al.

were attained. Obviously, a thin regolith overlying more cohesive material\textsuperscript{1,10}, a more realistic model, would increase this depth substantially. Any observed fresh crater morphologic variations, then, should be primarily considered in light of dynamic modifications which take place during the formational events themselves; formation times of various features would be governed by strength scaling laws\textsuperscript{9}. Long-term modifications would be dominated by non-gravitational processes (e.g., impact erosion, outgassing, etc.). Martian tidal effects, although small, should be relatively more significant than gravitational effects attributable to the moons themselves.

**Ejecta:** As the approximately hemispherical shock wave of a major (km scale) event is driven through the target, the rapid lateral falloff of the surface due to the small effective radius of curvature keeps the free surface closer to the impact point. This effect may enhance rapid lateral cavity growth in the upper part of the cavity. Material ejected early in the event should escape. As rarefaction waves begin to dominate event dynamics\textsuperscript{11}, ejection should take place at higher angles (measured from the horizontal), but escape velocity should still be exceeded by the vast majority of ejecta. Only late-stage ejecta (that subjected to the lowest shock levels and having the least velocity) would be emplaced on the surface. Although the scaling relationships for craters formed by low-velocity impact in a regolith in a low-g environment are uncertain, the most energetic of the returning ejecta should be able to form secondary craters. The lowest velocity fraction of this ejecta should consist of the largest fragments. Their extremely low emplacement velocities would not be conducive to large crater formation; rather, the fragments may land intact, or break up (but not be totally destroyed), upon impact. This phenomenon could explain the presence of abundant boulders on the surface of Deimos. Upper bounds on the minimum cohesive strength necessary for these fragments to survive emplacement (on the basis of stagnation pressure considerations for normal incidence at escape velocity) are \(
\approx 0.5 \text{ bars for Deimos and } \approx 1.7 \text{ bars for Phobos, well below average rock strengths.}
\)

Mechanisms have been postulated by which a considerable fraction of escaped ejecta is swept up by Phobos and Deimos after a number of orbits\textsuperscript{12}, creating relatively fine-grained regoliths\textsuperscript{1}. This would not be possible for asteroids, implying that a large portion of the surface material on these bodies would consist of blocky ejecta as opposed to fine-grained debris. This is consistent with spectral reflectance observations of asteroids\textsuperscript{13} which suggest immature surfaces with low glass content\textsuperscript{14,15}. Increasing gravity would tend to decrease the average particle size in the regolith and increase its apparent maturity by preventing the escape of more highly shocked, comminuted, and vitrified material.

References: \textsuperscript{1}J. Pollack et al. (1973) JGR, 4314; \textsuperscript{2}J. Veverka and T. Duxbury (1977) JGR, 4213; \textsuperscript{3}J. Veverka et al. (1977), BAAS, 517; \textsuperscript{4}D. Gault and J. Wedekind (1978) in Impact and Explosion Cratering, in press; \textsuperscript{5}V. Oberbeck and R. Morrison (1976) PLSC 7, 2983; \textsuperscript{6}E. Shoemaker (1962) in Physics and Astronomy of the Moon, Z. Kopal, ed. 538 pp.; \textsuperscript{7}V. Oberbeck (1975) RGSP, 337; \textsuperscript{8}W. Quaide et al. (1965) A.NYAS, 563; \textsuperscript{9}J. Mitchell et al. (1972) NASA SP-315,8-1; \textsuperscript{10}P. Thomas et al. (1977) BAAS, 517; \textsuperscript{11}D. Gault et al. (1968) in Shock Metamorphism of Natural Materials, 87; \textsuperscript{12}S. Soter (1972) Rep.CRSR 462, Cornell U.; \textsuperscript{13}T. McCord et al. (1970) Science, 1445; \textsuperscript{14}D. Matson et al. (1977), PLSC 8, 1001; \textsuperscript{15}R. Schaal
CRATERING ON SMALL BODIES

Cintala, M. J. et al.


Table 1.

<table>
<thead>
<tr>
<th></th>
<th>MAJOR AXIS 16 (KM)</th>
<th>VOLUME 1 (KM^3)</th>
<th>DENSITY 2 (G/CM^3)</th>
<th>AVERAGE RADIUS (KM)</th>
<th>FOR AVERAGE RADIUS</th>
<th>ESCAPE VELOCITY (M/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHOBOS</td>
<td>27 X 21 X 19</td>
<td>5748</td>
<td>2.2</td>
<td>11.1</td>
<td>0.68</td>
<td>12.3</td>
</tr>
<tr>
<td>DEIMOS</td>
<td>15 X 12 X 11</td>
<td>1054</td>
<td>2.2</td>
<td>6.3</td>
<td>0.39</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Fig. 1. Comparison of curvatures of various solid bodies. D represents the dropoff (in meters) of a sphere from a plane target at a point 15 (linear) km distant. At this scale, the dropoffs are of the same order as the line thickness. The parabolic profile below the lunar limb segment represents an idealized 10 km crater profile (neglecting rim topography). For impacts at similar velocity on Moon and Phobos a constant effective depth of burst would cause more extensive lateral excavation on Phobos. The observed crater would occur below the dashed chord in the figure.

Fig. 2. The effects of target curvature on ballistic ranges for a spherical Phobos model (Table 1) at various ejection angles. The calculated ranges over the sphere are normalized to the calculated range for a plane with Phobos' gravitational acceleration.

Fig. 3. Ejecta kinematic parameters for Phobos and Deimos extrapolated from an experimental crater. Ballistic ranges over spherical bodies are presented as functions of the observed velocity/angle relationships. At this scale, the terrestrial laboratory results would plot as a nearly straight line ranging from about 0.004 to 0.03 mm from the velocity axis.

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System