MARS IMPACT EJECTA IN THE REGOLITH OF PHOBOS: BULK CONCENTRATION AND DISTRIBUTION. K.R. Ramsley[1,2] and J.W. Head III[2], [1]School of Engineering, Brown University, Providence, RI USA. [2]Department of Geological Sciences, Brown University, Providence, RI, USA. Kenneth_Ramsley@brown.edu.

Introduction: The impact on Phobos of ejecta from primary craters on Mars [1] initiates an additional process where ejecta fragments from Phobos are inserted into orbits around Mars. Orbiting secondary ejecta re–impacts Phobos and produces tertiary and further generations of re–impacts. With each subsequent ejecta re–impact on Phobos new ejecta fragments are launched with typically lower velocities and a lower bulk proportion of Phobos ejecta is inserted into orbits of Mars. The process continues until re–impacting ejecta fragments no longer produce new ejecta that exceeds the local escape velocity from Phobos. [Fig. 1.]. While in orbit around Mars, ejecta fragments from Phobos are perturbed by gravitational and solar photon forces in a process that predominantly affects smaller fragments [2–3]. Also, in recent geological time the rapidly decaying orbit of Phobos substantially increases the intensity of Mars ejecta flux, and overwhelms the net effect of solar system primary impact flux on Mars that is generally decreasing. We analyze these processes to predict the bulk concentration and distribution of ejecta from Mars on Phobos. Is Phobos dominated by ejecta from impacts on Mars, is Mars ejecta rare on Phobos, and, is Mars ejecta heterogeneously emplaced and preserved?

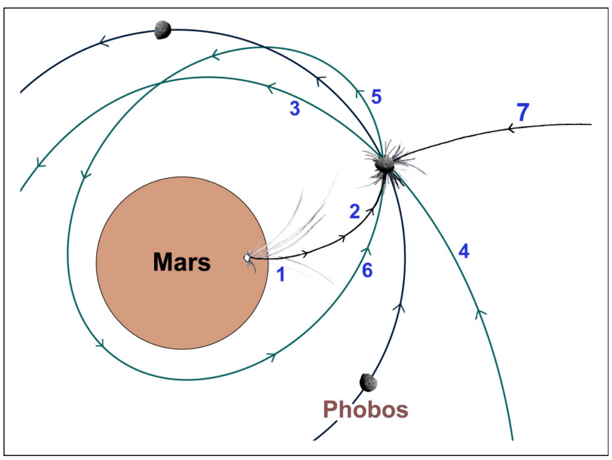

Fig. 1. The fate of impact ejecta from Mars is governed by typical steps outlined in this scenario: **1.** Primary impact on Mars. **2.** Primary Mars ejecta impacts the leading hemisphere of Phobos. **3.** High–velocity Phobos secondary ejecta is launched ahead of Phobos into higher energy orbits. **4.** Higher energy fragments overtake Phobos and re–impact with the opposite (trailing) hemisphere of Phobos. **5.** Slower velocity Phobos tertiary ejecta is then launched from the trailing hemisphere and falls behind Phobos. **6.** Phobos overtakes the slower velocity tertiary ejecta fragments which then re–impact with the opposite (leading) hemisphere of Phobos. The process continues until all fragments attain orbits that are similar to Phobos and no longer launch ejecta from Phobos at escape velocities. **7.** Impacts from primary solar system flux further redistribute regolith fragments on Phobos.

Methods and Key Parameters: We verify that Mars and Phobos are exposed to nearly the same solar system meteoroid (SSM) projectile flux and that nearly all of the secondary ejecta that is produced by impacts on Phobos returns to Phobos. From this, we define the proportional relationship of primary ejecta flux from Mars compared with flux from the solar system that reach Phobos. With this proportion constrained, we compute a bulk concentration of Mars ejecta in the regolith of Phobos using the observed concentration of SSM fragments in lunar regolith of 3% ±1.5% [4]. Although ejecta from the Earth's Moon returns to the Moon from ballistic trajectories and ejecta from Phobos returns to Phobos from orbits of Mars, both systems have similar escape velocity upper limits of ~2.5 km/s and should return the same proportion of ejecta.

Outbound ejecta: Primary ejecta that is launched from Mars at martian escape velocities crosses the orbit of Phobos, and is predicted to equal 3% ±2% of the primary SSM projectile mass that impacts Mars [5]. Including the radius of Mars and the stronger gravitational focus closer to Mars [6], the target area of Mars to primary impacts from SSM flux is ~3.6 x 10^7 greater than for Phobos. Outbound ejecta plumes that rise from Mars take the form of an expanding toroid generally in the shape of a cone. At the altitude of Phobos, outbound ejecta plumes are regionally localized. Consequently, Phobos, has a ~7% likelihood of intersecting an outbound ejecta plume. During an intersection with an outbound plume, Phobos sweeps at most ~1.7 x 10^{-5} of the total plume volume. In the present day, the full transit of Phobos through the plume would require more than one hour, whereas an outbound ejecta plume maintains a high density concentration of fragments at the altitude of Phobos for < ~30 minutes. Thus, in the present day, Phobos would sweep at most ~50% of the densest volume of an outbound plume [Fig. 2.].

Inbound ejecta arrives at Phobos in a rapidly thinning volumetric density that diminishes essentially to zero after ~1–2 months. Beyond this time, particles travel to altitudes that are perturbed by their proximity to the Hill radius of Mars and are lost to solar orbits [7]. Phobos passes through the inbound fragment plume during most of its orbital period, and on average it is exposed to inbound ejecta approximately equal to its exposure to outbound ejecta minus the proportion of fragments that escape from Mars to solar orbits.

The re–impact / re–ejection process: Primary ejecta from Mars typically impacts with Phobos with velocities of ~2–3 km/s [8]. When combined with the low gravity of Phobos [9] this results in surface escape velocities of ejecta from Phobos that range from ~4–10 m/s depending on the latitude, geographic elevation and local time of the launch site on Phobos [2–3]. Consequently, approximately 95–99% of ejecta from initial secondary impacts on Phobos from Mars are launched into temporary orbits of Mars [10–14]. Phobos ejecta typically remains trapped in orbits of Mars until it re–impacts with Phobos and is eventually deposited into the regolith of Phobos [15-16] [Fig. 1].

De–orbiting dust: Anisotropic martian gravity and solar photon forces combine to produce an increase in the orbital eccentricities of smaller Phobos ejecta particles. Ejecta fragments < ~300 µm are removed within several years; whereas fragments > ~300 µm tend to remain in orbit of Mars until they are deposited on Phobos, typically within several hundred to several thousand years. [15; 17–20].

The decaying orbit of Phobos: In the present day, Phobos is losing altitude at a rate of ~20 cm/year. The decay rate was not as rapid in the past since orbital decay increases with proximity to Mars. Nonetheless, this suggests that Phobos has orbited at an altitude > 4000 km above the present day altitude during all but the most recent ~500 Myrs [21–24].

Conclusions and Predictions: *The bulk concentration of ejecta fragments from Mars*: From our model we predict that SSM flux at Phobos in the present day is ~200X greater than the flux of primary impact ejecta from Mars. Where the bulk concentration of SSM fragments in the lunar regolith is ~3% [4], we predict a mean bulk concentration of Mars ejecta fragments in the regolith of Phobos of ~150 ppm (3% / 200X) and an uncertainty range of 15–700 ppm, which is comparable to the predictions of Chappaz et al., 2012 [25].

The fate of orbiting ejecta: The rapid de–orbiting of Phobos ejecta fragments that are < ~300 µm severely limits opportunities for re–impacts with Phobos. Compared with the lunar regolith this suggests a deficiency of dust fragments < ~300 µm in the regolith of Phobos.

The distribution of Mars ejecta on Phobos: Rather than falling proximal to impact sites on Phobos, Phobos ejecta that includes Mars ejecta fragments is typically launched into orbits around Mars and generally returns to Phobos on opposite hemispheres from the previous impact site [26]. This suggests that ejecta fragments from Mars are uniformly and globally dispersed across Phobos including surface regions of Phobos that are not directly exposed to the initial flight trajectories of primary impact ejecta from Mars. Also, primary SSM flux on Phobos continues to insert ejecta from Phobos into orbits of Mars which further redistributes Mars ejecta fragments.

The effect of the decaying orbit of Phobos: In lower orbits that are typical only of the most recent ~500 Myrs, Phobos is exposed to a substantially higher density of outbound primary ejecta plumes from Mars. At lower altitudes denser plumes produce a bulk concentration of Mars ejecta fragments closest to the surface of Phobos that is one to two orders of magnitude greater than older Mars ejecta at depth. Consequently, we predict that the computed ~150 ppm bulk concentration of Mars ejecta may be found preferentially closer to the top of the regolith of Phobos.

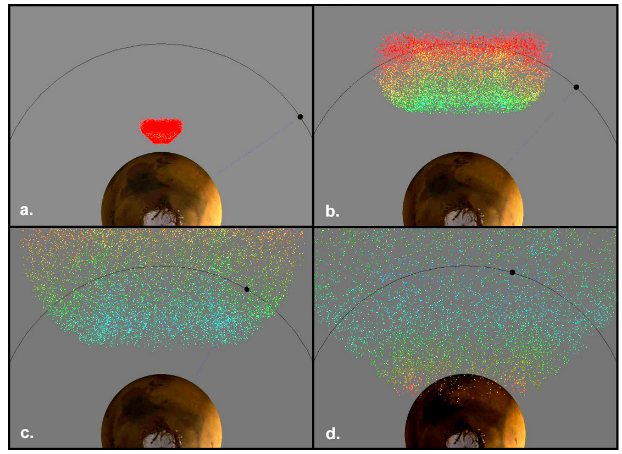

Fig. 2. Phobos is shown at a geometric scale that is 20X larger than actual. 10,000 test particles simulate a toroidal ejecta plume from Mars. Red particles represent the highest velocities relative to Mars. Blue particles represent the slowest velocities. Launch velocities shown are limited to ~4.0–5.2 km/s. The surface angle of ejection varies from ~30–45 degrees from the vertical, corresponding to ejection angles that may be characteristic of higher velocity spalled ejecta [27]. Progress of the outbound plume is shown from 6 to 56 minutes after the primary impact. At minute 56, particles are already beginning to disperse before Phobos has traveled through 1/2 of the outbound plume volume.

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