MATERIAL TRANSFER FROM THE SURFACE OF MARS TO PHOBOS AND DEIMOS L. Chappaz[1], H. J. Melosh[2], M. Vaquero[1], and K. C. Howell[3], [1]Ph.D. Student, Purdue University, School of Aeronautics and Astronautics, Armstrong Hall, 701 West Stadium Avenue, West Lafayette, Indiana 47907-2045, [2]Distinguished Professor of Earth and Atmospheric Science, Purdue University, College of Science, Civil Engineering Bldg, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051, [3]Hsu Lo Professor of Aeronautical and Astronautical Engineering, Purdue University, School of Aeronautics and Astronautics, Armstrong Hall, 701 West Stadium Avenue, West Lafayette, Indiana 47907-2045.

Introduction: The ill-fated Russian Phobos-Grunt spacecraft launched in November 2011, originally planned to return approximately 200 grams of surface material from Phobos to Earth in mid-August 2014. Although it is anticipated that this material is mainly from the body of Phobos, there is a possibility that a sample could also contain material ejected from the surface of Mars by large impacts.

We performed an analysis of this possibility using the best current knowledge of the different aspects of impact cratering on the surface of Mars and of the production of high-speed ejecta that might be able to reach Phobos or Deimos. Although many uncertainties exist, we conclude that, on average, a 200-gram surface sample from Phobos can be expected to contain on the order of 0.15 milligram of Mars surface material that had been ejected in the last 10 Myr. The sample may contain as much as 50 milligram of Mars' surface material ejected in the past 3.5 Gyr. The results for Deimos are similar to those for Phobos, except that the Mars surface mass expected in a Deimos sample is approximately 100 times smaller than that for Phobos.

One of the major uncertainties in the expected mass contamination derives from the stochastic nature of the impact process itself. Most of the mass ejected is derived from the largest impact events, of which there are only a small number. Whether ejecta from a given impact on Mars reaches Phobos depends on the location of Phobos in its orbit at the time of the impact. Not every large impact that ejects material from Mars will deposit material on Phobos. Nevertheless, the Martian meteorite record indicates that at least 4 large launch events have occurred within the last 10 Myr and it is likely that one or more of these events deposited ejecta on Phobos.

Approach: A numerical procedure is implemented to compute the probability of impact on Phobos (or Deimos) for ejecta particles originating from the surface of Mars at sites of potential Martian impact craters. The procedure is based upon numerical integration of the trajectories representing individual particles that are likely to be ejected as a result of an impact with the planetary surface. Then, the probability of impact is defined as the ratio of impacting trajectories over the total number of trajectories integrated, weighted by the distribution of trajectories over the space of intitial conditions.

To accomplish the numerical integration of these trajectories, a dynamical model is developed that incorporates force models for the significant bodies in the system, that is, Mars, one of its moons and the particle of interest. Mars is modeled as oblate and is the only significant gravity force in the environment. A gravity model incorporating spherical harmonics of second degree and order is developed to describe Mars' gravitational contribution. The moons and ejecta particle are assumed to be gravitationally insignificant and are modeled as massless. Also, the two moons are assumed to move in equatorial circular orbits. In addition, an ejecta curtain is generated by numerically integrating a collection of initial conditions lying on a cone of fixed angle, β, with a fixed initial velocity magnitude labeled 'ejection velocity'. [1]

The total probability of impact is computed based on the results of the numerical simulations. An array of initial conditions is introduced to propagate representative ejecta particles. Each path is assessed to determine if the particle enters a sphere of appropriate size that surrounds a specific moon. Then, for a given point on the grid, that is, for a given curtain of ejecta, the probability of impact is calculated as the ratio of impacting trajectories over the total number of trajectories, as illustrated in Figure 1. Ejecta curtains from anywhere on the Martian surface can be simulated and probabilities summed to assess the likelihood of impacts with Phobos from ejecta at all locations on Mars. The total pro bability curve is then defined as the total

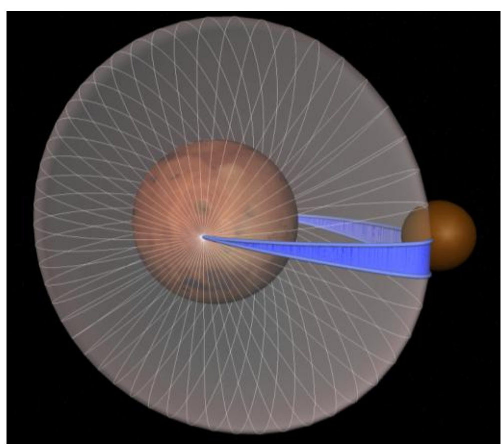

Fig. 1: Orbit path integration. The white lines represent the integrated array of initial conditions. The trajectories in blue intersect the target.

probability for a given angle of ejection as a function of the ejection velocity.

To support the numerical results presented in this investigation, an analytical approach was also developed. One method is based on the Öpik model. [2] This model provides equations that relate orbital parameters to the probability of collision between orbiting objects. In this investigation, the Öpik model is modified to consider the probability of collision between ejected mass particles from Mars with Phobos; Phobos is then the larger orbiting object.

Results: The numerical process is applied to Phobos and the probability of impact is on the order of 10^{-6}. The total probability curve, defined for three sample ejection angles, that is, 30, 45, and 60 degrees, appears in Figure 2. A similar analysis completed for Deimos yields a probability on the order of 10^{-8}. The Öpik model is employed and the results for the probability of collision support the numerical results. Thus, the probability of impact between particles ejected from Mars' surface and Deimos is reduced from 10^{-6} to 10^{-8}.

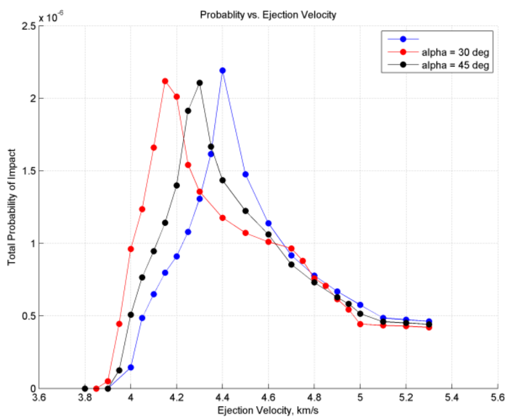

Fig.2: Total probability curve for Phobos with three sample ejection angles

The objective of these computations is to determine an approximation of the mass of material from impacts on Mars possibly delivered to Phobos over some period of time, i.e., 10 Myr in this investigation. To complete this task, empirical results from impact cratering physics are employed to compute an approximation of the mass of such material that may have reached Phobos and/or Deimos. Already available from this analysis is the total probability of impact on Phobos of ejecta originating from Mars as a function of the impact ejection velocity. Next, the mass ejected from Mars, representative of the Mars impacting process over the last 10 Myr [3], as a function of ejection velocity, is required to compute the probabilistic mass impacting Phobos at a given velocity. The probabilistic mass impacting Phobos at a given velocity is then directly obtained by multiplying the probability of impact and the mass ejected, both expressed as a function of the ejection velocity. Then, the net mass on Phobos is obtained by integrating the probabilistic mass over velocity of ejection for the last 10 Myr. Implementing this method for an ejection angle of 45 degrees, an integrated mass per unit of volume in Phobos soil and per year is computed, that is, $m_{imp\,vol\,yr} = 0.25\ \mu g / m^3 / yr$. Finally, for the Phobos-Grunt mission, the spacecraft was designed to collect a 200 g sample. From the results of this computation, the mass computed translates to 167 micrograms of possible material from Mars over the last 10 Myr. The same procedure is applied for the two other ejection angles considered in this study, that is, 30 and 60 degrees.

The size of the ejecta particles that impact Phobos is another parameter of interest. However, estimation of the size of a particle is the most uncertain parameter in the analysis. Semi-analytical approximations based on observations of secondary impacts on Mars, as well as the Moon, relate the size distribution of the largest ejecta particles to ejection velocity through an inverse power law. [4] Relationships of the form $d = a' v^{-\alpha'} D^{\gamma}$ are sought, where D is the diameter of the crater, v the ejection velocity, and γ, α', and a' are constant coefficients to be determined. This approach yields an estimate for the order of magnitude of the size of the largest ejecta particles as a function of the ejection velocity and factoring in the diameter of the observed crater. From these results, the upper limit on the size of the ejecta particles ranges from 15 to less than 45 meters for 3.8 km/s, down to particles of diameter 10 to 20 meters, for 5.3 km/s ejection velocity, where 3.8 to 5.3 km/s is the range of ejection velocities considered in this analysis. Although these sizes are relatively large, they agree well with the estimated sizes of the parent bodies that produced the Martian meteorites collected on Earth. Although this gives the largest expected eject fragment size, the most probable size is determined by the distribution of sizes of smaller fragments. It is likely that the overall secondary ejecta size distribution is a steep function of particle diameter. The very few established power laws for this distribution indicate that most of the mass is in a small fraction of ejecta. The mass distribution is thus dominated by the smallest particles, which have been rather arbitrarily assumed to be 10^{-6} m in our present analysis.

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