

SOLAR RADIATION PRESSURE AND TRANSIENT FLOWS ON ASTEROID SURFACES. D.J. Scheeres, *U. Michigan, Ann Arbor* (scheeres@umich.edu).

Introduction The motion of particles on the surfaces of asteroids are a strong function of the body's shape, gravity, spin state, and environment. Small particles will, in addition, be subject to non-gravitational accelerations. Any event on an asteroid that lofts material will expose these smaller particles to a strongly perturbed orbital environment where substantial migration across the surface may occur, and may even lead to escape from the body.

There is much previous research investigating the effect of these forces on regolith distributions on asteroids, reviewed in [1]. Recent observations have verified the existence of regolith down to very small grains. Specifically, the NEAR-Shoemaker mission at Eros discovered the presence of dust ponds apparently consisting of fine particles at isolated regions on its surface [2]. Similarly, recent observations of comet Wild 2 during the Stardust flyby indicates the presence of dust on the surface of that body [3]. Recent studies have attempted to explain the presence of the Eros dust ponds by introducing non-gravitational forces that preferentially act on small particles, the most prominent being electromagnetic levitation of dust fines and seismic shaking. Several recent studies discuss the possibility that these effects lead to the transport and pooling of particles on the surface of Eros, and hence on other asteroids as well [4].

In this abstract we discuss the effect of solar radiation pressure (SRP) on small regolith particles. SRP is an additional force that acts on asteroid regolith whose effect has not been considered as having an influence on the motion of small particles across asteroid surfaces. We show that the effect of SRP is easily large enough to play a major role in the migration of dust particles, whether or not electromagnetic levitation or seismic shaking is present. In general, the sunlight that reaches the particle at dusk and dawn will be the most effective in mobilizing it, as in these conditions SRP will provide the largest lateral force. Another important aspect is that SRP will not be a constant force, but will turn in the asteroid surface frame as the asteroid rotates, providing a time varying force that can lead to the transient flow of material on an asteroid surface. We find that these forces can be an important factor in controlling the distribution of the smallest particles on an asteroid, and is a factor that helps explain the "dust ponds" found on Eros. We apply our analysis to the asteroids Eros, target of the NASA's NEAR mission, and Itokawa, target of the Japanese Space Agency's Hayabusa Mission.

Basic Model We briefly review the basic model for the SRP acceleration that a particle would feel. A more detailed description of the force environment on the surface of an asteroid is reviewed in [1]. The acceleration that a particle will feel due to SRP can be approximated by

$$a_{SRP} = \frac{\mu_S \beta}{d^2} \quad (1)$$

and will be directed away from the sun. In this equation μ_S is the gravitational parameter of the sun ($\sim 1.33 \times 10^{11} \text{ km}^3/\text{s}^2$), d is the distance of the particle from the sun in km, and β equals:

$$\beta = \frac{(1 + \sigma)G_1}{B\mu_S} \quad (2)$$

where σ is the reflectance of the particle ($\ll 1$ for natural particles, usually), G_1 is a solar constant approximately equal to $1 \times 10^7 \text{ g km}^3/(\text{s}^2 \text{ cm}^2)$ and B is the mass to area ratio of the particle specified in g/cm^2 . We note that this is a simple model of reflectance, and that more detailed models should include the orientation of the surface, its temperature, and other parameters. To discuss bulk and qualitative effects, however, these additional details are not needed.

In this study we conservatively assume that $\sigma \sim 0$ and that the particles are spherical with total mass $M = 4\pi/3\rho r_o^3$ and total projected area πr_o^2 , where we measure the density ρ in g/cm^3 and the particle radius r_o in cm. We consider this to be conservative as the sphere is the most compact arrangement of matter possible, and it is expected that actual small regolith grains will have larger projected areas and hence smaller mass to area ratios. For a spherical particle, the mass to area ratio equals

$$B = \frac{4}{3}\rho r_o \quad (3)$$

Minimum size of regolith grains As the size of regolith particles shrink they naturally become subject to larger SRP accelerations. At a certain size the SRP accelerations can overwhelm gravitational accelerations and can directly remove particles from the surface of a body. The ideal size at which this occurs is when SRP acceleration is balanced by gravitational attraction, although in reality such "stripping" can occur at larger grain sizes, as will be discussed.

Equating SRP and gravitational accelerations we have $\mu_S \beta / d^2 = \mu / R^2$, where R is taken to be the mean radius of the asteroid and μ its gravitational parameter. Solving for the particle radius we find:

$$r_o = \frac{3}{4} \frac{G_1}{\mu \rho} \left(\frac{R}{d} \right)^2 \quad (4)$$

For the asteroid Eros, with $\mu \sim 4.5 \times 10^{-4} \text{ km}^3/\text{s}^2$, $R = 8.4 \text{ km}$ and $d = 1.13 \text{ AU}$, the mass to area ratio where this condition is satisfied equals $5.5 \times 10^{-5} \text{ g/cm}^2$. For a grain density of 2.5 g/cm^3 this corresponds to a particle grain radius of 0.2 micron . For the asteroid Itokawa, with $\mu \sim 5 \times 10^{-9} \text{ km}^3/\text{s}^2$, $R = 0.2 \text{ km}$ and $d = 0.953 \text{ AU}$, the mass to area ratio is $4 \times 10^{-3} \text{ g/cm}^2$ and the particle grain radius is 15 microns . These grain sizes can be construed as the minimum size-particle on the surfaces of these asteroids, as smaller grains

can be directly stripped from the surface whenever exposed to SRP.

Larger particles are also subject to being stripped from the body. This can occur in several different ways. First, grains on the surface of a rotating asteroid already have a relatively large speed with respect to the center of mass of the body, and hence will also have a relatively large centripetal acceleration that counteracts the gravitational attraction. Thus, the addition of an SRP acceleration lateral to the surface (such as may occur at the particle's dawn or dusk) can cause a larger grain to be easily mobilized and inject it into an orbit that can escape from the asteroid. Additionally, micro-meteoroid impacts and electro-magnetic levitation that acts on small particles can loft them into orbit with large enough energies to allow them to escape from the asteroid.

We have developed a quantitative expression that allows us to compute the grain size at which a particle can be stripped out of orbit from the asteroid if mobilized off of the surface. The following analysis is not a sufficient condition for a particle to be orbitally stripped, but is a necessary condition at the least. Following the analysis in [5] we compute the particle grain size at which it becomes energetically possible for a particle on the surface of a spinning asteroid to escape from the asteroid. The concept of energy used here is not Keplerian energy, but a modified form that accounts for the SRP acceleration acting on the particles. The resulting formula incorporates the gravitational attraction of the asteroid, the spin rate of the asteroid, and the solar radiation pressure. It is not a direct force balance, but rather computes the grain radius at which it becomes energetically possible for a grain lofted from the surface to escape. This number serves as a conservative upper-bound on grain sizes susceptible to escape from the surface. The mass to area ratio at which such orbital stripping becomes possible is

$$B = \frac{1}{\left[\sqrt{2 - \frac{\omega^2 R^3}{2\mu}} - 1 \right]^2} \frac{G_1}{\mu} \left(\frac{R}{d} \right)^2 \quad (5)$$

where ω is the rotation rate of the asteroid in rad/s. For Eros and its rotation period of 5.27 hours the mass to area ratio equals $4 \times 10^{-4} \text{ g/cm}^2$ and the corresponding particle radius equals 1 micron. For Itokawa, with its 12 hour rotation period, the mass to area ratio equals $1 \times 10^{-2} \text{ g/cm}^2$ and the corresponding particle radius equals 40 microns. If we account for the fact that larger particles can be lofted into low-energy orbits due to impacts, seismic shaking, and electro-magnetic levitation this threshold radius for orbital stripping can be increased substantially.

We expect particles of size smaller than the above limits to be depleted on the surfaces of asteroids, as the SRP effects can sweep them away from the body. This does not mean, however, that all such small particles will be removed. It is possible for many of these particles to be located in areas that do not receive direct sunlight, or that when they are illuminated the net SRP acceleration does not move them tangential to the surface of the asteroid. Thus, it is quite likely that there will be local regions on the asteroid surface where smaller particles will be trapped due to the combined effect of surface topology

and asteroid spin state. When the effects of small impacts are considered, these localized "ponds" of material should have a transient nature, as the smaller particles trapped there would be easily mobilized by an impact event on the asteroid, and could thus be transported away from the local sink and become subject to orbit stripping. The same event, however, would likely create and mobilize other small grains which could then migrate into these local sinks. Additionally, as the asteroid's spin state evolves due to planetary flybys and YORP effects, the locations of these regions could shift over time. We also note that dust grains larger than these sizes will still be subject to strong SRP "winds," yet may not be stripped out of orbit.

Transient flows When considering larger particles, we cannot immediately discount the effect of SRP on their surface motion. Indeed, particles of size 10 microns on Eros and over 100 microns on Itokawa are still subject to SRP accelerations that are a non-negligible fraction of the total gravitational acceleration. When mobilized by impacts or levitation, the motion of these particles is clearly modified as compared to particles subject to gravitational attraction alone. SRP also provides a time-periodic variation in the local slope of the individual particles that has daily and yearly components. While slope angles may only fluctuate by a few degrees per day, the long-term effect of such "shaking" should be to liberate grains towards lower energy conditions on the surface of the body.

The most drastic effects are expected at local sunrise and sunset for the particle, since exposed particles will experience a lateral SRP acceleration which can act perpendicular to local gravity and centripetal accelerations. Only the upper layer of regolith will be subject to this direct effect, in some sense similar to the effect of winds on sand dunes. An intriguing possibility is that similar "dune motion" may occur on the surface of an asteroid at these smallest scales, leading to transient surface topography at smaller scales.

We note that the grain radius normalized by the mean asteroid radius provides a relation of the form $r_o/R \propto 1/R^2$, where we note that $\mu \propto R^3$. Thus, the effect of these transient and stripping effects will fall drastically with asteroid size, not to mention asteroid distance from the sun. We do note, however, that for the asteroid Eros the grain sizes we consider are entirely consistent with the necessary grain sizes to give a blue color to the dust ponds over the surface of that body [3]. This is especially true when we realize that our SRP acceleration model is conservative, meaning that the effect should be enhanced for particles larger than our computed sizes. In fact, this implies that Eros could easily host a transient dust atmosphere where particles can be blown across the surface and occasionally be lofted into orbit, but not necessarily escape from the body. A detailed study of this effect for the asteroids Eros and Itokawa will be carried out in the future.

References: [1] Scheeres et al. 2002, *Asteroids III*, 527-544. [2] Robinson et al. 2001, *Nature* 413, 396-400. [3] Burrati et al. 2004, *Icarus* 167, 16-29. [4] Cheng et al. 2002, *MAPS* 37(8), 1095-1105; Mantz et al. 2004, *Icarus* 167, 197-210. [5] Scheeres and Marzari, 2002, *J. Astronautical Sci.* 50(1), 35-52.