THE RELEVANCE AND ROLE OF COHESIVE FORCES FOR SMALL ASTEROIDS.

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A comparison of physical forces in the small asteroid environment shows that cohesive attractions between regolith grains due to van der Waals forces are significant. An understanding of these forces as a function of particle size suggests a new model for the terminal evolution of rubble pile asteroids.

Introduction Visual imaging of the surfaces of asteroids Eros and Itokawa show that at size scales of meters to centimeters and less their surfaces are dominated by boulders and grains. The recognized forces that act on regolith grains on the surface of an asteroid are gravitational attraction, electrostatics and solar radiation pressure. It has also been speculated that, for these particle size scales, cohesive van der Waals' forces should be included in this list [2]. A survey of the relative effects of these forces in the asteroid environment makes it clear that cohesion should play a significant role for the evolution of small bodies.

Physics of the asteroid environment The asteroid environment can be defined in terms of the "ambient acceleration" on its surface, due to gravitational attraction and rotational accelerations. These effects generally act against each other and can reduce the ambient acceleration significantly – Fig. 1 shows the ambient accelerations across the surface of the primary of 1999 KW4, ranging from 0.01 to 30 μGs. For comparison, the ambient acceleration on Itokawa is less than 10 μG and on Eros is less than 1 milliG.

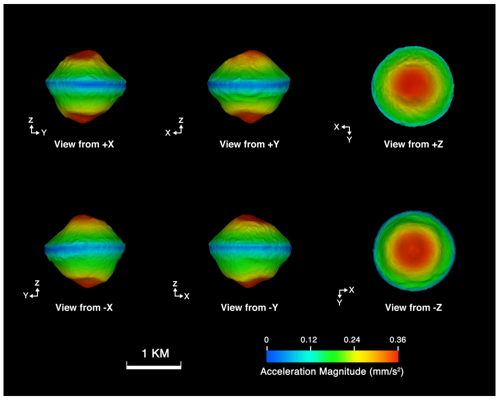

Figure 1: Accelerations across the surface of the 1999 KW4 Primary.

To characterize the relative effects of different forces on grains we compare a grain's weight with the force under consideration. For an ambient acceleration of g_A the ambient weight is defined as $W = mg_A$, where $m = \frac{4\pi}{3}\rho r^3$, ρ is the grain density (assumed to be 3.5 g/cm^3), and r is the grain radius. There are three main non-gravitational forces that are relevant for grains on asteroids: electrostatic, solar radiation pressure and van der Waals cohesion.

Electrostatic: Electrostatic forces arise due to the charge of a grain and the ambient electric field in which is lies. Assuming Gauss' Law for the distribution of charge across a grain (and asteroid surface) we find a functional form for this force as $F_{es} \sim C_{es} r^2$, where C_{es} is a characteristic constant and r is the particle radius. Due to photo-emission and solar wind currents alone the constant $C_{es} \sim 3 \times 10^{-9}$ kg/m/s^2 and is not significant. Researchers have argued that in the terminator regions of the moon [4] and, by extension, of asteroids [7] that supercharging phenomenon occurs that increases the electric field by many orders of magnitude, although the detailed physics of this are not understood. Applying published estimates of this effect we find that C_{es} may be as large as 0.1 [7] – a significant force, albeit one that only acts in isolated regions, under special conditions and for brief periods of time.

Solar radiation pressure: For grains larger than one micron the momentum of photons striking a surface can also supply a relevant force which can be modeled using geometrical optics [3]. The force scaling is $F_{srp} \sim C_{srp} r^2$ where $C_{srp} \sim 1.4 \times 10^{-5}$ kg/m/s^2 at 1 AU from the sun.

van der Waals Cohesion: The nature of cohesive forces between grains has been well studied in the past and an approximate form for the force between a grain of radius r and a larger body has been found to vary as $F_{vdw} \sim C_{vdw} r$ [10]. The appropriate force constant has been determined for Lunar regolith, which we take as an analog for asteroid regolith, and is $C_{vdw} \sim 3.6 \times 10^{-2}$ kg/s^2 [10].

Fig. 2 Top shows these forces compared with particle weights (at different Gs) as a function of particle size. Fig. 2 Bottom shows the radius at which these forces are equal to a particle's weight as a function of ambient acceleration. We note that cohesive forces are important for centimeter sized grains and smaller for Gs less than 1 milliG, and are important for even larger grains as G decreases further.

Cohesive granular mechanics and asteroids Based on these comparisons we note that terrestrial experiments with cohesive, dry powders with grain sizes of 10's to 100's of microns should recreate relevant scaled asteroid surface mechanics for grain sizes at the millimeter size and above, depending on the body in question. A survey of this literature shows a number of important effects that are consistent with asteroid observations.

Dilation and contraction: Dynamic or quasi-static flows of cohesive powders can cause significant dilation of material, increasing macro-porosity by up to 25% to values above 50% [1, 12]. This increase is relatively independent of whether the material flows rapidly or incrementally [9]. The process is also reversible, so that dilated material can loose its porosity gains if subjected to repeated tapping [14]. The observed ranges of macro-porosity for cohesive powders is consistent with estimated macro-porosities in small bodies.

Cohesive shear: The presence of cohesive forces directly alters the friction angle and shear strength of cohesive aggre-

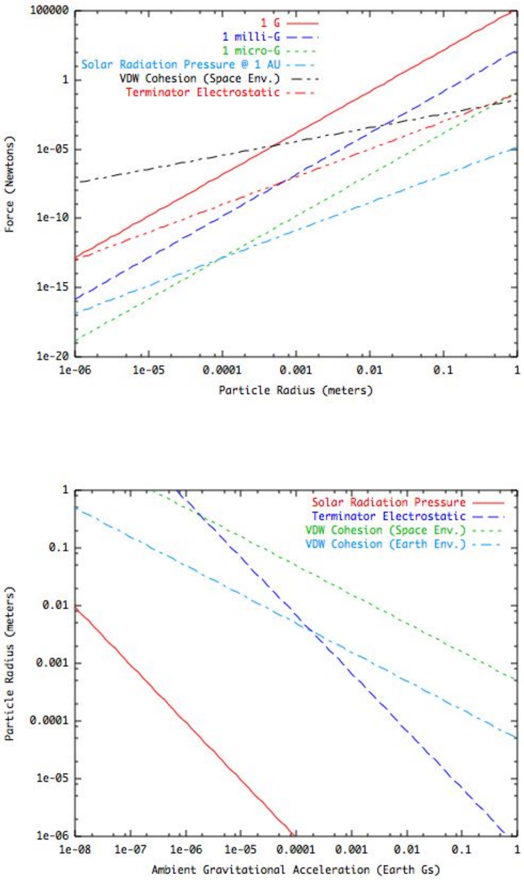

Figure 2: Top: Comparison of forces for particles of different radii (note, vdw forces in the space environment are significantly stronger [10]). Bottom: Radii of surface particles for weight equal to force as a function of ambient G.

gates. For Lunar regolith, the strength differential between day and night can be on the order of 0.5 kPa with a friction slope increase on the order of 20 degrees or more, and should be greater on asteroids. The addition of cohesive strength as the ambient weight becomes small allows larger bodies to assume structures usually only seen in fine powders on the Earth [9], including stress fractures and shear cliffs [2].

Flows of cohesive materials: Models of cohesive powders show that they flow by mobilizing a sub-strata that becomes separated from a surface layer and allows a conglomerate of cohesive material to flow as a rigid body down slopes. On Eros, we see evidence for such flows consistent with cm and smaller sized regolith [8]. Studies also indicate that cohesive powders tend to clump into larger agglomerates that can then more easily flow relative to each other due to their increased weight [12]. Such clumping may have occurred at the spatial resolutions which Itokawa and Eros were observed at and should be investigated.

A new model for the terminal evolution of asteroids to small, fast rotating populations The enhanced cohesion present in the asteroid environment can strengthen rubble pile asteroids against disruption. In particular, positive accelerations at the surface of a 100 meter asteroid are only 0.1 milli-Gs for a half-hour rotation period and 1 milliG for a six minute rotation period, while a 10 meter asteroid will have a 1 milliG acceleration for periods less than a minute. Cohesive forces can balance this positive acceleration for grain radii of $\sim$2 centimeters or less. This suggests a possible end state for rubble pile asteroids subject to YORP rotational acceleration consisting of centimeter-sized grains and smaller held together with cohesion. This is also consistent with published continuum models of asteroids [6].

In general, larger asteroids consist of distributions of boulders of all shapes and sizes, as seen at Itokawa [5]. When subject to YORP they spin faster and will preferentially shed their largest components [13]. Loss of these components can change the YORP torques and either reinforce the loss process or provide a hiatus when the body undergoes a spin down and spin up YORP cycle. Repetition of this process gradually removes the largest component boulders or conglomerates from the asteroid (sometimes forming temporary binary systems), while preferentially retaining the smaller, relatively more cohesive grains on the separated components. This produces a simple evolutionary model where asteroids shrink in size by progressively shedding their largest components until they consist of smaller collections of cohesively bound grains.

Such rapidly spinning bodies would be susceptible to fracture, however, as a micro-meteorite impact could break cohesive bonds between conglomerates within these bodies. Given our knowledge of the physics of cohesive powders, such a fracture would not cause the small body to uniformly disrupt but would cause it to fail along naturally occurring stress fractures within the powder [9]. After such a fracture the components would initially rotate at the same rate, but the large changes in mass distribution would cause the components to immediately enter a tumbling rotation state. We note that a number of small, rapidly rotating bodies have been found in tumbling rotation states [11] – consistent with this model. It could also change the YORP torques into a deceleration state for some bodies and lead to the observed slowly rotating, tumbling small asteroids.

Several other implications can be drawn from this simple model, and will be discussed at the conference.

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