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# Scaling forces to asteroid surfaces: The role of cohesion

D.J. Scheeres [a,*], C.M. Hartzell [a], P. Sánchez [a], M. Swift [b]

[a] Department of Aerospace Engineering Sciences, The University of Colorado, Boulder, CO 80309-0429, USA
[b] School of Physics and Astronomy, The University of Nottingham University Park, Nottingham NG7 2RD, United Kingdom

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ABSTRACT

The scaling of physical forces to the extremely low ambient gravitational acceleration regimes found on the surfaces of small asteroids is performed. Resulting from this, it is found that van der Waals cohesive forces between regolith grains on asteroid surfaces should be a dominant force and compete with particle weights and be greater, in general, than electrostatic and solar radiation pressure forces. Based on this scaling, we interpret previous experiments performed on cohesive powders in the terrestrial environment as being relevant for the understanding of processes on asteroid surfaces. The implications of these terrestrial experiments for interpreting observations of asteroid surfaces and macro-porosity are considered, and yield interpretations that differ from previously assumed processes for these environments. Based on this understanding, we propose a new model for the end state of small, rapidly rotating asteroids which allows them to be comprised of relatively fine regolith grains held together by van der Waals cohesive forces.

## 1. Introduction

The progression of asteroid research, especially that focused on the smaller bodies of the NEA and main belt populations, has expanded from understanding their orbits, spins and spectral classes to include more detailed mechanical studies of how these bodies evolve in response to forces and effects from their environment. Along these lines there has been general confirmation that small NEAs are rubble piles above the 150 m size scale, based both on spin rate statistics and on visual imagery from the Hayabusa mission to Itokawa. However, the nature of these bodies at even smaller sizes are not well understood, with imagery from the Hayabusa mission suggesting that the core constituents of a rubble pile asteroid consists of boulders on the order of tens of meters and less (Fujiwara et al., 2006) while spin rate statistics imply that objects on the order of 100 m or less can spin at rates much faster than seems feasible for a collection of self-gravitating boulders (Pravec and Harris, 2000). Extrapolations such as these are based on simple scaling of physics from the Earth environment to that of the asteroid environment, but perhaps this is a process which must be performed more carefully. In this paper we probe how the physics of interaction are expected to scale when one considers the forces between grains and boulders in the extremely low gravity environments found on asteroid surfaces and interiors. It is significant to point out that in previous research, Holsapple (2001, 2004, 2007, 2009) has shown analytically that even small amounts of strength or cohesion in a rubble pile can render rapidly spinning small bodies stable against disruption.

We note that asteroids are subject to a number of different physical effects which can shape their surfaces and sub-surfaces, including wide ranges in surface acceleration, small non-gravitational forces, and changing environments over time. Past studies have focused on a sub-set of physical forces, mainly gravity, rotation (inertial) accelerations, friction, and constitutive laws (Holsapple, 2001, 2004, 2007, 2009; Richardson et al., 2005; Scheeres et al., 2002; Scheeres, 2007; Sharma et al., 2009). Additional work has been performed on understanding the effect of solar radiation pressure (Burns et al., 1979) and electrostatic forces on asteroid surfaces (Lee, 1996; Colwell et al., 2005; Hughes et al., 2008), mostly motivated by dust levitation processes that have been identified on the lunar surface (Colwell et al., 2007).

The specific goal of this paper is to perform a survey of the known relevant forces that act on grains and particles, state their analytical form and relevant constants for the space environment, and consider how these forces scale relative to each other. Resulting from this analysis we find that van der Waals cohesive forces should be a significant effect for the mechanics and evolution of asteroid surfaces and interiors. Furthermore, we identify terrestrial analogs for performing scaled experimental studies of asteroid regolith and indicate how some past studies can be reinterpreted to shed light into phenomena that occur on the surfaces of asteroids, the smallest aggregate bodies in the Solar System.

Taken together, our analysis suggests a model for the evolution of small asteroids that is consistent with previous research on the physical evolution and strength of these bodies. In our proposed

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[*] Corresponding author.
*E-mail address:* scheeres@colorado.edu (D.J. Scheeres).

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model, rubble pile asteroids shed components and boulders over time due to the YORP effect, losing their largest components at the fast phase of each YORP cycle, eventually reducing themselves to piles of relatively small regolith. We find that for sizes less than 100 m it is possible for such a collection of bodies to be held together by cohesive forces at rotation periods much less than an hour. The implications of this work should also extend beyond asteroids, due to the fundamental physics and processes which we consider. Specific applications of this work may be relevant for planetary rings and accretion processes in proto-planetary disks, although we do not directly discuss such connections.

The structure of the paper is as follows. First, we review evidence for the granular structure of asteroids. Then we perform an inventory of relevant forces that are at play in the asteroid environment and discuss appropriate values for the constants and parameters that control these results. Following this, we perform direct comparisons between these forces and identify how their relative importance may scale with aggregate size and environment. Motivated by these results we perform a review of the experimental literature on cohesive powders and argue that these studies are of relevance for understanding fundamental physical processes that occur in asteroid regolith. Finally, we discuss relevant observations of asteroids and their environment and the implications of our studies for the interpretation of asteroid surfaces, porosity and the population of small, rapidly spinning members of the asteroid population.

## 2. Evidence for the granular structure of asteroids

Before we provide detailed descriptions of the relevant forces that act on particles and grains in the asteroid environment, we first review the evidence that has been drawn together recently which indicates that asteroids are dominated by granular structures.

### 2.1. Observations of asteroid populations

For small asteroids, there are a few elements of statistical data that indicate the granular structure of these bodies. First is the size and spin distributions that have been tabulated over the years, culminating in Pravec and Harris (2000) where sufficient observations are combined to clearly identify a relation between asteroid size and spin rate and providing population-wide evidence for asteroids being made of aggregates with weak cohesion between components, at best. The naive implication of this is that larger asteroids are composed of distinct bodies resting on each other and when these bodies reach sufficiently rapid rotation rates these components can enter orbit about each other and subsequently escape or form binaries (Scheeres, 2007). The smaller components that escape, or conversely the larger asteroids that are eventually "worn down" by these repeated processes, then comprise a population of smaller bodies which have been presumed to be monolithic bodies that can spin at elevated rates (although recent work has indicated that even small degrees of cohesion can stabilize these small bodies (Holsapple, 2007)). This has led to the development of the rubble pile model for asteroid morphologies with larger asteroids composed of aggregates of smaller bodies. These smaller components are then available to comprise the population of fast spinning asteroids and apparently range in size up to hundreds of meters.

The second evidence pointing to the granular structure of asteroids is the determination that they have high porosities in general. The evidence for this has again been accumulated over many years, and has especially accelerated since the discovery of binary asteroids which allow the total mass, and hence density, to be estimated once a volume is estimated. Porosity values have been correlated with asteroid spectral type (Britt et al., 2002), with typical porosities ranging from 30% for S-type asteroids up to 50% and higher for C-type asteroids. Given good knowledge of the porosity of meteorite samples (on the order of 10% in general) it is clear that asteroids must have significant macro-porosity in their mass distributions. Existence of macro-porosity is consistent with a rubble pile model of asteroids, where there are components that have higher grain density resting on each other in such a way that significant open voids are present, leading to the observed macro-porosity. This also motivates the application of granular mechanics theories to asteroids.

### 2.2. Observations of specific asteroids

Prior to the high resolution images of the surfaces of Eros and Itokawa, little was known about the small scale structure of asteroids. Eros shows fine-scale material with sizes much less than centimeters (Veverka et al., 2001) with localized areas of very fine dust (presumed to be of order 50 μm) (Robinson et al., 2001). Itokawa shows a surface with minimum particle sizes at the scale of millimeters to centimeters (Yano et al., 2006) with evidence of migration of the finest gravels into the potential lows of that body (Miyamoto et al., 2007). Following these missions our conception of asteroid surfaces has changed significantly. We now realize that the surfaces of small asteroids can be dominated by loose regolith and that flow occurs across the surfaces of these bodies, causing finer materials to pool in the local or global geopotential lows of the body.

In terms of geophysics, the important results from NEAR at Eros include the relatively high porosity (21–33%) (Wilkison et al., 2002) along with a homogenous gravity field, implying a uniform internal density (Miller et al., 2002; Konopliv et al., 2002). For this body, which is large among NEA's, this implies a lack of large-void macro-porosity within its structure and instead implies a more finely distributed porosity throughout that body. Observations of the surface of Eros have also enabled a deeper understanding of its constituents and internal structure. By correlating degraded impact craters to physical distance from a recent, large crater on the surface of Eros, Thomas and Robinson (2005) are able to show that seismic phenomena from impacts are important for this body and cause migration of regolith over limited regions. Support for this view also comes from simulations carried out by Richardson et al. (2004) which have attempted to determine a surface chronology for that body based on simple geophysics models. In addition, based on observations of lineaments across the surface of Eros, some authors have claimed that the body consists of a number of monolithic structures, perhaps fractured, resting on each other (Procktor et al., 2002; Buczkowski et al., 2008). Alternate views on interpreting surface lineaments have also been proposed, however, noting that they could arise from cohesion effects between surface particles (Asphaug, 2009a,b).

The porosity of Itokawa was measured to be on the order of 40%, and its surface and sub-surface seem to be clearly dominated by a wide range of aggregate sizes, ranging from boulders tens of meters across down to sub-centimeter sized components. The precision to which the asteroid was tracked precludes a detailed gravity field determination, as was done for Eros, thus we currently only have the total mass and shape of the body from which to infer mass distribution. There is some tangential evidence for a non-homogenous mass distribution within the body, however, consistent with a shift in the center of mass towards the gravel-rich region of Itokawa, indicating either an accumulation of material there or a lower porosity (Scheeres and Gaskell, 2008). Another clear feature of the Asteroid Itokawa is its bimodal distribution, allowing it to be interpreted as a contact binary structure. The bulk shape of Itokawa can be decomposed into two components, both