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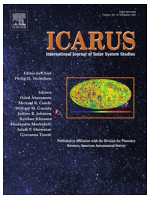

The spherical Brazil Nut Effect and its significance to asteroids

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ABSTRACT

Many asteroids are likely rubble-piles that are a collection of smaller objects held together by gravity and possibly cohesion. These asteroids are seismically shaken by impacts, which leads to excitation of their constituent particles. As a result it has been suggested that their surfaces and sub-surface interiors may be governed by a size sorting mechanism known as the Brazil Nut Effect. We study the behavior of a model asteroid that is a spherical, self-gravitating aggregate with a binary size-distribution of particles under the action of applied seismic shaking. We find that above a seismic threshold, larger particles rise to the surface when friction is present, in agreement with previous studies that focussed on cylindrical and rectangular box configurations. Unlike previous works we also find that size sorting takes place even with zero friction, though the presence of friction does aid the sorting process above the seismic threshold. Additionally we find that while strong size sorting can take place near the surface, the innermost regions remain unsorted under even the most vigorous shaking.

1. Introduction

Asteroids are small bodies that are remnants of the early planet formation process (Asphaug, 2009). Space missions have imaged certain asteroids and as a result have greatly helped the understanding of asteroid surface properties. However, due to the lack of seismic data, it has been difficult to definitively constrain the internal structure of asteroids. The understanding of their internal structures is important for planetary science, for future asteroid exploration and mining (Hatch and Wiegert, 2015), and for deterring potential Earth impact hazards (Shapiro et al., 2010).

Previous works have inferred that asteroids 150 m to 10 km in size are likely rubble-pile objects that are a collection of smaller objects held together by gravity and possibly cohesion (Michel et al., 2001; Pravec et al., 2002; Richardson et al., 2002; Sánchez and Scheeres, 2014). This characterization arises from several key observations:

1. Craters on their surfaces and the dynamical evolution of asteroids indicate that asteroids have undergone many impacts over their lifetimes that will have left disrupted, reaccumulated objects (Asphaug et al., 1998; Richardson et al., 2004).
2. Low bulk densities and high macroporosities of asteroids indicate the presence of large internal voids (Carry, 2012).
3. The limited spin rates of asteroids possibly point to loosely held aggregates (Scheeres et al., 2015).
4. Spacecraft images have shown that some asteroids have large boulders that seem to be protruding from their surfaces such as Eros (Asphaug et al., 2001) and Itokawa (Miyamoto et al., 2007; Tancredi et al., 2015).

As a rubble-pile asteroid is being seismically shaken by impacts, its constituent particles should undergo granular flow once frictional forces are overcome. Particularly, the Brazil Nut Effect where larger constituent objects rise to the top against gravity may occur on these rubble-pile asteroids (assuming the constituent objects are approximately the same density). Past work has shown that when a collection of particles of varying sizes is excited, over time larger particles will accumulate at the top given gravity is downward (Rosato et al., 1987). Some large boulders on asteroids could be the result of the Brazil Nut Effect, though this may not be the only mechanism for producing large surface boulders (e.g. Thomas et al., 2001).

The Brazil Nut Effect is a complex phenomenon, but it has been proposed to be mediated through two primary mechanisms:

1. Smaller particles may fill in and pass through spaces created by excitations while larger particles do not (Williams, 1976). If the direction of gravity is downward, this results in smaller particles migrating to the bottom while larger particles are ratcheted upwards.
2. Depending on boundary conditions, excitation of particles may set up granular convection that brings larger particles to the

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top but prevents them from moving downward (Knight et al., 1993).

The Brazil Nut Effect has been studied in a terrestrial context through computer simulations using hard spheres (i.e. simulated spheres do not deform when forces are applied to them) (Rosato et al., 1987), using soft spheres (i.e. simulated spheres deform when forces are applied to them) (Kohl and Schmiedeberg, 2014), and through experiments in cylindrical columns (Knight et al., 1993). Additionally, in the context of the low-gravity environments of asteroids, simulations have been done using a soft spheres method in rectangular and cylindrical box configurations (Matsumura et al., 2014; Tancredi et al., 2012) and parabolic flight experiments have been done in a cylindrical configuration to momentarily obtain equivalent low-gravity conditions of the Moon and Mars (Güttler et al., 2013).

Previous preliminary work in two-dimensions has suggested that size sorting can occur in self-gravitating aggregates (Sanchez et al., 2010); however, the Brazil Nut Effect has not been studied in a fully three-dimensional configuration. Here we have conducted simulations using a spherical, self-gravitating configuration of particles since that configuration is more representative of asteroids. In Section 2, we discuss the *N*-body gravity code we used (Section 2.1) and our initial conditions along with a short discussion of how we created the aggregate that was used for the simulations (Section 2.2). In Section 2.3 we describe the simulations that were conducted and the section concludes with a discussion of how we compare our simulations to asteroids (Section 2.4). In Section 3, we state our results while focussing on the central region of the aggregate (Section 3.1), the effect of friction (Section 3.2), and the time evolution of particle distributions (Section 3.3). In Section 4, we discuss our results considering asteroid surface processes (Section 4.1), the central region of our aggregate (Section 4.2), and the driving mechanism of the Brazil Nut Effect (Section 4.3). Finally, we summarize and discuss future work in Section 5.

2. Method

2.1. PKDGRAV

For our work we used PKDGRAV, a parallel *N*-body gravity tree code (Stadel, 2001) that has been adapted for particle collisions (Richardson et al., 2009; Richardson et al., 2000, 2011). Originally collisions in PKDGRAV were treated as idealized single-point-of-contact impacts between rigid spheres. We use a soft-sphere discrete element method (SSDEM) to model the collisions of particles. In SSDEM, particles are allowed to slightly overlap with one another. Particle contacts can last many time steps, with reaction forces dependent on the degree of overlap (a proxy for surface deformation) and contact history. The code uses a second-order leapfrog integrator to solve the equations of motion, with accelerations due to gravity and contact forces recomputed each step.

The spring/dash-pot model used in PKDGRAV's soft-sphere implementation is described fully in Schwartz et al. (2012) and is based on Cundall and Strack (1979). Two overlapping particles feel a Hooke's law type reaction force in the normal and tangential directions determined by spring constants (k_n and k_t). We chose a normal spring constant (k_n) that kept particle overlaps $<1\%$. The choice of a linear spring was made during the original implementation of the soft-sphere code. While a Hertzian spring contact may provide benefits in certain circumstances we find the linear spring to be adequate for the problem at hand, with the added advantage of simplicity. In particular, we note that experimentally the coefficient of restitution of meter-scale granite spheres has been found to have no dependence on impact speed for low-speed impacts (Durda et al., 2011), which is suggestive of a linear contact response. User-defined normal and tangential coefficients of restitution used in hard-sphere implementations, ϵ_n and ϵ_t, determine the plastic damping parameters (C_n and C_t), which are required to resolve a soft-sphere collision (see Eq. (15) in Schwartz et al., 2012). Frictional forces can also be imposed on the interaction by adjusting static, twisting, and rolling coefficients.

This SSDEM implementation has been validated through comparison with laboratory experiments (e.g., Schwartz et al., 2012 and Schwartz et al., 2013). In addition, Ballouz et al. (2015) used this SSDEM to model the collisions of rubble-pile asteroids made up of 40 m spheres, and showed that the outcomes of binary collisions were consistent with scaling laws for low- and high-speed collisions. Furthermore, Matsumura et al. (2014) studied the classical Brazil Nut Effect for centimeter-sized grains in a cylindrical container using this method.

2.2. Initial conditions

The initial spherical aggregate used in the following simulations was made by creating 500 particles of radius 40 m (colored yellow) and 500 particles of radius 80 m (colored red) that were randomly positioned inside a cubic space of 4 km per side. All particles had a density of 3 g/cm^3. Particles were then allowed to gravitationally collapse due to self-gravity with the coefficients of friction set to zero to form a mixed aggregate and left to settle for 75 simulation hours. The maximum free-fall time of the initial cubic distribution of particles (i.e. from the corners) is around 3 h.

The aggregate that was created in the process had a mass of 3.62×10^{12} kg, a bulk radius of about 800 m, and a bulk density of about 1.7 g/cm^3. The aggregate properties are representative of common asteroids. The escape speed of the aggregate was 75 cm/s. In order to properly resolve particle collisions, we use a normal spring constant of

$$k_n = m_p \left(\frac{v_{\max}}{x_{\max}} \right)^2 \qquad (1)$$

where m_p is the typical particle mass, $v_{\max}$ is the maximum expected particle speed, and $x_{\max}$ is the maximum expected fractional overlap, which we set to 1% of the typical particle radius. This chosen value of k_n allows all the kinetic energy of the particle collision to be stored in a single spring that compresses to $x_{\max}$. Furthermore, in order to ensure that a collision is properly resolved, we require that particle overlaps last at least 12 time steps for the smallest particles. The length of a single time step can be estimated by considering the oscillation half-period of a spring with normal spring constant k_n (see Eqs. (36)–(38) in Schwartz et al., 2012). Using the typical particle sizes, masses, and expected speeds we find that a spring constant of $k_n \sim 4.856 \times 10^9$ kg/s^2 and a time step of 8.523×10^{-2} s are required to properly resolve the collisions in our simulations. The tangential spring constant, k_t, is taken to be equal to $\frac{2}{7} \times k_n$. Tests with one half and one quarter of our chosen time step showed no deviation in behavior demonstrating that our chosen time step is adequate.

Since Matsumura et al. (2014) found that the Brazil Nut Effect is largely insensitive to the choice of the coefficients of restitution and since we wanted to focus on the magnitude of seismic shaking and the coefficients of friction, we set the normal coefficient of restitution to 0.2 and the tangential coefficient of restitution to 0.5 for all our simulations. We will further examine the effect of these damping coefficients on the Brazil Nut Effect in a future study.

In Fig. 1 we show the likelihood that radial distributions of larger (red) and smaller (yellow) particles were drawn from the same parent population as a function of settling time. A higprobability indicates that it is more likely that the two particle