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Rotational evolution of self-gravitating aggregates with cores of variable strength

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ABSTRACT

This paper presents a study, through the use of a Soft-Sphere Discrete Element method, of possible deformation and disruption patterns of spinning, self-gravitating spherical aggregates with cores of variable strengths. We present this study as a complement to our previous study about aggregates with strong cores that also provided some insight into the occurrence of surface shedding. It is observed that the inclusion of a weak core produces a very symmetric deformation pattern and even a shape that resembles that of asteroid 25143 Itokawa though this only happens for the weakest of the tested cores. At this level of shell strength, and in agreement with our previous studies, most aggregates fission off coherent pieces of the original bodies, which could potentially form binary systems. Additionally, we try to understand how strong, relative to the shell, the core has to be to prevent it from failing before the shell does.

1. Introduction

During the last two decades, the study of asteroids as self-gravitating granular systems has gained importance. Much of this interest and interdisciplinary approach to their study has been influenced by different space missions to asteroids and comets. In particular, the images and samples obtained by the JAXA mission Hayabusa to asteroid Itokawa (Fujiwara et al., 2006; Yano et al., 2006; Miyamoto et al., 2007) supported the idea that small asteroids are self-gravitating aggregates that are held together by not only gravitational, but also, cohesive and adhesive forces (Jewitt et al., 2013, 2014; Hirabayashi et al., 2014; Rozitis et al., 1950; Hirabayashi and Scheeres, 2015). Furthermore, these images showed surfaces that were far from homogeneous in structure and that, much more interestingly, presented size-segregated particles.

If the surface of asteroids present this heterogeneity, it seems only logical that their interiors could also be heterogeneous. Prompted by the discovery of active asteroids P/2013 R3 and P/2013 P5 (Jewitt et al., 2013, 2014), Hirabayashi et al. (2015) analyzed the disruption mechanism of self-gravitating aggregates with a strong core and a weak shell. This research concluded that this morphology produces surface shedding in a rotating self-gravitating aggregate with some degree of cohesive strength. Additionally, it has also been suggested by Tardivel et al. (2018) that the presence of a strong core, together with kinetic sieving in the surface of asteroids 2008 EV5 (Busch et al., 2011) and 2000 DP107 (Naidu et al., 2015), could have produced the cavity on their equators through rotational fission.

Of course, there is no reason to believe that a strong core is the only type of heterogeneity that could exist or that heterogeneities have a single origin. Heterogeneities could appear as a result of the inclusion of grains of different materials which would produce different material and bulk densities, different cohesive and adhesive forces and different packing fractions that would in turn have an effect on the overall strength of certain regions of the asteroid. Also, as the strength of the grains that form an asteroid are linked to the different crystallographic phases of the materials that form them, grains of different materials would produce grains with different morphologies; more or less angular edges or irregular shapes will have an effect in the geometric interlocking of particles which will in turn have an effect on the angle of friction of the system. Additionally, the strength of the grains themselves will likely determine their size distribution, regardless of the production method (impacts or pulverization due to thermal cycling). In this paper we first study the dynamics of cohesive, self-gravitating aggregates with a weak core where the source of the strength is the cohesive forces between the particles. With this objective in mind, we follow a very similar approach to Hirabayashi et al. (2015) and after that we choose two core sizes to observe, step by step, the effect of the variation of the strength of the core. We do

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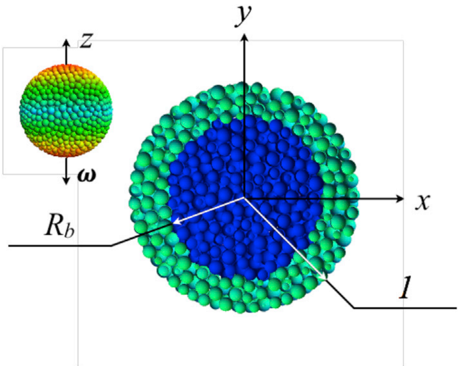

Fig. 1. Cross-sectional cut of an aggregate with the internal core ($R_b = 0.7$). The sphere is assumed to be spinning constantly along the z axis. The normalized radii of the sphere and the internal core are given as 1 and R_b, respectively. The sphere on the top left corner shows the initial configuration of the aggregates and it is rotated 90° with respect to the cross-sectional cut. The colours represent latitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

this so that a coherent picture, if still very basic, about the role of size and strength of interior heterogeneities can be understood.

This paper is organized as follows: first we will describe the physical model and the simulation method that is going to be used for this work. Then we will describe the geometry of the aggregates and how we varied it. After this, we will describe the initial deformation and disruption patterns of aggregates with a constant core strength, but variable core size. At this point we will focus on a couple of geometries to observe the effect of a variable core strength and constant core size. Finally we will relate our results to asteroids 1999 KW4 and 25143 Itokawa to then establish conclusions about their internal structure and superficial morphology and how they are related to each other.

2. Internal core model

Fig. 1 shows the model we are going to be using for this study. We suppose that our test body is spherical, that it is uniformly rotating around the z axis and that it is granular in nature so that it can be deformed or disrupted at high enough spin rates. The body itself is not homogeneous, but it has a concentric spherical core that is weaker than its outer shell. We assume that this difference is originated only due to different tensile strengths whereas all other characteristics (bulk density, porosity, angle of friction) are left unchanged. This structure guarantees that by the time the shell starts to fail, the core will not present any resistance; furthermore, it should prompt the failure of the shell at a lower spin rate than had the aggregate been homogeneous.

The bulk density, the total radius and the gravitational constant are denoted as ρ, R and G, respectively. We normalize lengths, body forces, spin rates and stress tensors by R, $\pi\rho G$, $\sqrt{\pi\rho G}$ and $\pi\rho^2 G R^2$, respectively. With this normalization, the sphere radius is denoted as 1 and the radius of the internal core is defined as R_b, so the thickness of the surface shell is given as $1 - R_b$.

3. Simulation method

The simulation program that is used for this research applies a Soft-Sphere Discrete Element Method (SSDEM) to simulate a self-gravitating granular aggregate (Cundall, 1971; Cundall and Hart, 1992; Sánchez and Scheeres, 2011). The particles, modeled as spheres that follow a predetermined size distribution, interact through a soft-repulsive potential when in contact. This method considers that two particles are in contact when they overlap. When this happens, normal and tangential contact forces are calculated (Herrmann and Luding, 1998). The former is modeled by a hertzian spring-dashpot system and is always repulsive, keeping the particles apart; the latter is modeled with a linear spring that satisfies the local Coulomb yield criterion. The normal elastic force is modeled as

$$\vec{\mathbf{f}}_e = k_n \xi^{3/2} \hat{\mathbf{n}}, \tag{1}$$

the damping force as:

$$\vec{\mathbf{f}}_d = -\gamma_n \dot{\xi} \hat{\mathbf{n}}, \tag{2}$$

and the cohesive force between the particles is calculated as

$$\vec{\mathbf{f}}_c = -2\pi \frac{r_1^2 r_2^2}{r_1^2 + r_2^2} \sigma_{yy} \hat{\mathbf{n}} \tag{3}$$

where r_1 and r_2 are the radii of the two particles in contact and σ_{yy} is the tensile strength of this contact, which is given by a cohesive matrix formed by the (non-simulated) interstitial regolith (Sánchez and Scheeres, 2014). Then, the total normal force is calculated as $\vec{\mathbf{f}}_n = \vec{\mathbf{f}}_e + \vec{\mathbf{f}}_c + \vec{\mathbf{f}}_d$. In these equations, k_n is the elastic constant, ξ is the overlap of the particles (in length units), γ_n is the damping constant (related to the dashpot), $\dot{\xi}$ is the rate of deformation and $\hat{\mathbf{n}}$ is the unit vector joining the centres of the colliding particles. This dashpot models the energy dissipation that occurs during a real collision.

The tangential component of the contact force models surface friction statically and dynamically. This is calculated by placing a linear spring attached to both particles at the contact point at the beginning of the collision (Herrmann and Luding, 1998; Silbert et al., 2001) and by producing a restoring frictional force $\vec{\mathbf{f}}_t$. The magnitude of the elongation of this tangential spring is truncated in order to satisfy the local Coulomb yield criterion $|\vec{\mathbf{f}}_t| \leq \mu |\vec{\mathbf{f}}_n|$.

Rolling friction (Ai et al., 2011; Sánchez and Scheeres, 2016) has also been implemented in order to mimic the behaviour of aggregates formed by non-spherical grains. Particles are subjected to a torque that opposes the relative rotation of any two particles in contact. This model "places" a winding spring of sorts that is extended when two contacting particles roll on one another along with a velocity dependent dashpot. Much like the tangential spring that models static friction between particles in our code, this spring also breaks and allows rotation when a certain limit has been reached. This torque, similar to surface-surface friction, is implemented as linearly dependent on the relative angular displacement of any two particles in contact and has a limiting value of:

$$M_r^m = \mu_r R_r |\vec{\mathbf{f}}_n| \tag{4}$$

where μ_r is the coefficient of rolling resistance and $R_r = r_1 r_2/(r_1 + r_2)$ is the rolling radius.

The viscous damping torque M_r^d is assumed to be dependent on the relative rolling angular velocity $\dot{\theta}_r$ between the two particles in contact and the damping constant C_r:

$$M^d_{r,t+\Delta t} = \begin{cases} -C_r \dot{\theta}_r & \text{if } \left|M^k_{r,t+\Delta t}\right| < M_r^m \\ -f C_r \dot{\theta}_r & \text{if } \left|M^k_{r,t+\Delta t}\right| = M_r^m \end{cases} \tag{5}$$

This last equation contains a term f, which determines whether the viscous damping torque is only active before the contact rolling torque is fully mobilised ($f = 0$) or if it is always present ($f = 1$). For simplicity we have chosen $f = 0$ for our simulations.

This implementation allows our simulations to reach angles of friction of up to $\approx 35^\circ$ as evaluated by the Druker-Prager yield criterion (Sánchez and Scheeres, 2012). This value for the angle of friction is typical of geological aggregates, though friction angles of $\sim 40^\circ$ are not rare. This implementation of rolling friction is similar to that of surface friction, but depends on the incremental relative rotation, as such we have effectively