EPSC Abstracts
Vol. 8, EPSC2013-889, 2013
European Planetary Science Congress 2013

Rotational Fission of Cohesive, Self-Gravitating Aggregates

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Abstract

We use a Soft-Sphere Discrete Element Method (SSDEM) code to study the evolution of self-gravitating granular aggregates that are spun to disruption. We use these aggregates as a proxy for the understanding of "rubble-pile" asteroids that are spun up under the influence of the YORP effect. In this work we have implemented a model for cohesion and also rolling friction. These two new features in our simulation code is found to only lead to the fission of initially ellipsoidal aggregates, with surface shedding not observed.

1. Introduction

It is well known that asteroids in the Solar System have a limiting spin period of $\sim 2.3h$ [1]. However, this limit disappears when asteroid size decreases below a few hundred meters. With these observations, it has been argued that these small bodies must simply be monoliths of coherent rock. However, other theories have indicated that these smaller bodies could still be "rubble-piles" if they had some cohesive strength between components, as gravity alone is not sufficient to keep them intact at these high rotational speeds.

In a recent paper Scheeres, *et al* [2] have shown that cohesive Van der Waals forces could suffice to strengthen the structure of small rubble-pile asteroids and enable them to achieve some of the high spin rates found in the fast rotator population. Aditionally, Sánchez and Scheeres [3, 4] found that the net cohesive strength due to Van der Waals forces in granular aggregates is mainly controlled by the size of the grains if the aggregate was considered as a cohesive matrix formed by fine dust in which larger rocks were embedded, much like cement. Then additional material parameters such as the Hamaker constant and porosity play an important role.

Here we report on the results of simulations carried out applying this cohesion model to self-gravitating granular aggregates with high angles of friction.

2. Method

The simulation code used for this research applies a Soft-Sphere Discrete Element Method [5, 6] to simulate interactions between the "grains" constituting the aggregate. Each particle is modeled as a perfect sphere whose radius follows a predetermined, but randomized, size distribution and which interact through a soft-repulsive potential when in contact. This method considers that two particles are in contact when they overlap. For each particle-particle contact, the code calculates normal and tangential contact forces [5]. Such a model produces aggregates with friction angles no larger than 25°. For our simulations however, we wish to simulate larger friction angles that result from the geometrical locking of non-spherical spherical particles. A way to achieve this is by adding rolling friction, which allows aggregates of spherical particles to behave as their non-spherical counterpart through the application of an external torque that depends on the relative angular dispalcement of two particles in contact[7]. We "place" 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 implementation allowed us to simulate cohesionless aggregates with angles of friction over 35°, as evaluated by the Druker-Prager yield criterion. The bulk density of the aggregates was then changed until a rotation period of $\sim 2.3h$ was attained. These cohesionless aggregates were used as a proxy for the larger NEOs in which theory shows that cohesive forces should not be of great importance.

3. Cohesive Strength Model

The adopted model for cohesive forces for these simulations is based in our own previous research [4]. There, we argue that the strength of rubble-pile asteroids originates in the Van der Waals forces present when any two grains are in contact. Though these forces are generally negligible, in a μG environment they are as important as gravity. Simulations have shown that the net cohesive force between two "boulders" depends mainly on the average size of the fine grains that form what we term is a "granular bridge" between them. This net force can be modeled as:

$$F_c = \left(2\pi \frac{R_1^2 R_2^2}{R_1^2 + R_2^2}\right) \frac{s_{yy}}{\bar{r}_p} \quad (1)$$

where the term between parenthesis is an average cross-sectional area of the contacting boulders, s_{yy} is a numerical constant that depends on material and geometrical parameters, and $\bar{r}_p$ is the average radius of the regolith particles.

4. Results

A series of experiments were run with the code, keeping the size, density and number of grains constant while increasing the cohesive strength of the matrix holding the grains in place. It can be shown, through a scaling analysis, that when the cohesive strength of the regolith is increased by a factor of f, (enforced by scaling the mean particle size by $1/f$) that the effective size of the asteroid being modeled will decrease by a factor of $1/\sqrt{f}$. To evaluate this we ran a series of 12 cases with increasing cohesive strength, effectively modeling rubble piles of size from 0.1 km up to 100 km. The spin rate at which fission occurs was calculated for each case and the results are shown in Fig. 1. Also shown in this figure is the theoretical spin limit for an asteroid with a matrix strength of 25 Pa [4] and the spin period versus size data from observations[8]. We note that the numerically simulated fission spin rates follow the theoretical constant strength curve once the appropriate scaling to the asteroid size is applied.

When the cohesion was incorporated into our model we note that the way in which our rubble piles changed. In previous simulations for cohesionless piles we found that sometimes episodes of surface shedding would occur, followed later by rotational fission. With cohesion incorporated, however, surface shedding no longer occurs in our simulations and failure only happens through the fission and breaking of the body. These simulations are the first step towards a more accurate model of small rubble pile asteroids and will enable us to probe the implications on cohesive forces for the global evolution of rubble pile asteroids.

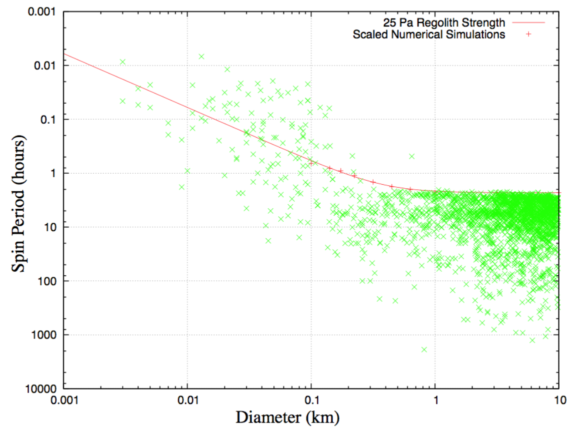

Figure 1: Spin rate versus size data, theoretical strength curve, and the simulation results.

Acknowledgements

Respectively, PS and DJS acknowledge support from NASA grants NNXlOAJ66G and NNX08AL51G (PG&G Program). Both also acknowledge support from NASA grant NNX10AG53G (NEOO Program).

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