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Numerical simulations of collisional disruption of rotating gravitational aggregates: Dependence on material properties

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ABSTRACT

Our knowledge of the strengths of small bodies in the Solar System is limited by our poor understanding of their internal structures, and this, in turn, clouds our understanding of the formation and evolution of these bodies. Observations of the rotational states of asteroids whose diameters are larger than a few hundreds of meters have revealed that they are dominated by gravity and that most are unlikely to be monoliths; however, there is a wide range of plausible internal structures. Numerical and analytical studies of shape and spin limits of gravitational aggregates and their collisional evolution show a strong dependence on shear strength. In order to study this effect, we carry out a systematic exploration of the dependence of collision outcomes on dissipation and friction parameters of the material components making up the bodies. We simulate the catastrophic disruption (leading to the largest remnant retaining 50% of the original mass) of km-size asteroids modeled as gravitational aggregates using `pkdgrav`, a cosmology *N*-body code adapted to collisional problems and recently enhanced with a new soft-sphere collision algorithm that includes more realistic contact forces. We find that for a range of three different materials, higher friction and dissipation values increase the catastrophic disruption threshold by about half a magnitude. Furthermore, we find that pre-impact rotation systematically increases mass loss on average, regardless of the target's internal configuration. Our results have important implications for the efficiency of planet formation via planetesimal growth, and also more generally to estimate the impact energy threshold for catastrophic disruption, as this generally has only been evaluated for non-spinning bodies without detailed consideration of material properties.

1. Introduction

Collisions dominate the formation and evolution of small Solar System bodies (SSSBs). In the early stages of the Solar System, planetesimals interacted with one another in a dynamically cold disk (see Levison et al., 2010). This allowed planet-size objects to form through collisional growth. Later, asteroid families formed through the catastrophic disruption of parent bodies. Outcomes of collisions between SSSBs are divided into two regimes: those dominated by material strength and those dominated by self-gravity (Holsapple, 1994). Since the dominant source of confining pressure for planetesimal-size SSSBs is self-gravity rather than material strength, they can be assumed to be gravitational aggregates (Richardson et al., 2002). Hence, the collisions can often be treated as impacts between rubble piles, the outcomes of which are dictated by collisional dissipation parameters and gravity (Leinhardt et al., 2000; Korycansky and Asphaug, 2009). Understanding the effects that contribute to changes in the mass (accretion or erosion) of gravitational aggregates is important for collisional evolution models of the early Solar System (e.g., Leinhardt and Richardson, 2005; Weidenschilling, 2011). The outcomes of impacts in these models are characterized by a catastrophic disruption threshold $Q_D^\star$ (e.g., Benz and Asphaug, 1999), which is the specific impact energy required to disperse permanently half the total mass of the system, such that the largest remnant retains the other half of the system mass.

The specific impact energy at which a body disrupts catastrophically is dependent on the “strengths” of the body's material. These are the tensile, compressive, and shear strengths. There is evidence that small asteroids with sizes above a few hundred meters are likely to be cohesionless, and, therefore, lacking tensile strength (Pravec et al., 2008). However, these bodies are not completely strengthless. While the dominant confining pressure is self-gravity, their granular nature gives them the capability to

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withstand considerable shear stress when under pressure. The shapes of the components physically impede their neighbors from flowing around them. The macroscopic effect is a pile of granular material with an angle of repose that is characteristic of that material. The angle of repose depends not only on the bulk shapes of the components, but also on the other material properties that dictate the frictional forces to which they are subject. A stack of perfectly smooth, frictionless cannonballs can be stable simply because of their rigid shapes (so long as the bottom plane is fixed). Friction is not required to maintain a non-zero angle of repose, however friction can increase this angle (Zhou et al., 2002; Richardson et al., 2012). The envelope of permissible equilibrium shapes of a granular body is typically parameterized by a Mohr–Coulomb angle of internal friction, ϕ. The angle ϕ varies from 0° to 90°, where a body with $\phi = 0^\circ$ is a fluid, and higher values represent materials that are able to resist higher shear stresses. Normal terrestrial granular materials have $\phi \sim 30$–40°. Very little is known about the internal structure of SSSBs, despite the increasing amount of observational data from ground- and space-based resources (e.g., Belton et al., 1994; Veverka et al., 2000). The most direct way to measure the strength of material is by physically breaking it. However, attempts to damage SSSBs (e.g., A'Hearn et al., 2005) are expensive and, therefore, limited in number.

In the past decade, advances in analytical and numerical studies have been made that attempt to correlate shape and spin states of SSSBs with their possible internal configurations. Holsapple (2001) determined lower limits for ϕ for various C-, S-, and M-type asteroids based on their shapes and spins. Walsh et al. (2008, 2012) and Holsapple (2010) studied the shape and spin changes of self-gravitating bodies in response to YORP-induced increases in their angular momentum. Walsh et al. (2012), using spherical particles, found that ϕ is also influenced by the size distribution of the particles that make up the body. These studies have provided the necessary groundwork to begin to understand the internal make-up and actual strength of SSSBs.

Korycansky and Asphaug (2009) studied binary collisions of rubble piles modeled as collections of polyhedral particles. Using a non-penetrating-rigid-body approach, they studied the mass loss outcomes for three different dissipation parameters and two different size distributions of particles (a monodisperse size distribution and a polydisperse power-law size distribution with a power-law index of -1). They found that both these factors affect the catastrophic disruption threshold, with $Q_D^\star$ increasing for higher dissipation and for a power-law size distribution of particles. For constant mass, a power law distribution of particles would have a larger internal surface area than a monodisperse distribution. The larger number of particle contacts would allow more collisional energy to be dissipated through friction and inelastic collisions. However, their study used a single power law index; therefore, it is uncertain whether this result is true for any power law distribution of particles. Furthermore, their work used a limited number of particles ($N \sim 10^3$) and modeled dissipation using arbitrary friction and restitution parameters, and they did not study the effect of rotation on collision outcome.

Ballouz et al. (2014) found that catastrophic disruption is sensitive to the initial pre-impact rotation of the target. Since rotational evolution depends on the internal structure of SSSBs, it is unclear whether rotationally enhanced collisional mass loss also depends on the material properties of a small body.

In this work, we study the dependence of catastrophic disruption outcomes on the material properties of both the target and the impactor, which are obtained from comparisons with laboratory experiments. Furthermore, we study whether this sensitivity could be dependent on the rotational properties of the colliding bodies. By doing so, we begin to map out the relation between the strength of a small body and collision outcomes. This will help inform planetesimal formation and evolution studies by providing physically realistic descriptions of the energies required for catastrophic disruption. This aids in delineating the transition from accretion to erosion in collision outcomes.

We solve numerically the outcomes of rubble-pile collisions using a combination of a soft-sphere discrete element method (SSDEM) collisional code (Schwartz et al., 2012) and a numerical gravity solver, `pkdgrav` (Richardson et al., 2000; Stadel, 2001), which is needed to model the reaccumulation stage accurately. The SSDEM code allows us, for the first time, to model multi-contact and multi-frictional forces accurately as well. We compare our results to the dissipation-dependent catastrophic disruption study by Korycansky and Asphaug (2009), and to the mass-ratio-dependent study by Leinhardt and Stewart (2009).

In Section 2 we explain the computational methods and outline the parameter space that we explore. In Section 3 we provide our results. In Section 4 we summarize and offer perspectives.

2. Methodology

We use `pkdgrav`, a parallel *N*-body gravity tree code (Stadel, 2001) adapted for particle collisions (Richardson et al., 2000, 2009, 2011). Originally collisions in `pkdgrav` were treated as idealized single-point-of-contact impacts between rigid spheres. A soft-sphere option was added recently (Schwartz et al., 2012); with this option, particle contacts can last many timesteps, with reaction forces dependent on the degree of overlap (a proxy for surface deformation) and contact history. This allows us to model multi-contact and frictional forces. 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). Briefly, a (spherical) particle overlapping with a neighbor feels a reaction force in the normal and tangential directions determined by spring constants (k_n, k_t), with optional damping and effects that impose static, rolling, and/or twisting friction. 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). The static, rolling, and twisting friction components are parameterized by dimensionless coefficients μ_s, μ_r, and μ_t, respectively. For cohesionless material, the angle of repose ϕ is determined by a combination of frictional and shape properties. Shape effects, arising from the sizes and geometries of the grains, can alone be important in determining the angle of repose, especially in material that exhibits nonexistent or weak friction and cohesion. Even for $\mu_s = 0$, rubble piles made of idealized spheres have a non-zero angle of repose, owing to cannonball stacking. Using spherical particles, Walsh et al. (2012) were able to correlate the internal structure (particle size distribution) of such rubble piles with a value of ϕ by simulating their spin and shape evolution and comparing the results to the analytical theory developed in Holsapple (2001).

The numerical approach has been validated through comparison with laboratory experiments; e.g., Schwartz et al. (2012) demonstrated that `pkdgrav` correctly reproduces experiments of granular flow through cylindrical hoppers, specifically the flow rate as a function of aperture size, Schwartz et al. (2013) demonstrated successful simulation of laboratory impact experiments into sintered glass beads using a cohesion model coupled with the soft-sphere code in `pkdgrav`, and Schwartz et al. (under review) applied the code to low-speed impacts into regolith in order to test asteroid sampling mechanism design.