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A General Catastrophic Disruption Law for Planet Formation

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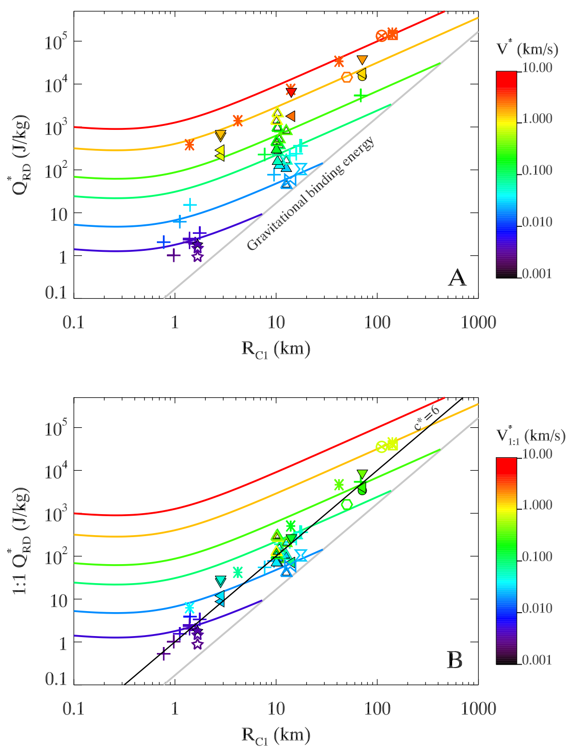

Figure 1: Catastrophic disruption data from this work and the literature: rubble piles (+, ★, ▲), ice (hexagon), and basalt (strong: ∗, ▼, ⊠, hourglass; weak: ◀; hydrodynamic: •; porous: ⊗, ⋈). A. Data adjusted for impact angle to equivalent normal impact. B. Data adjusted to equivalent equal mass (1:1) impact. The 1:1 data define the *principal disruption curve* (black line).

1. Introduction

Collisions are the central process in planet formation. Because of the diverse range of possible outcomes (cratering, merging, disruption, hit-and-run, and erosive hit-and-run events) and variations in the material properties of planetary bodies, no general set of equations exist to capture the basic physics of collisions. At present, collisions outcomes in planet formation simulations are applicable only to a specific subset of possible collision parameters (e.g., perfect merging or disruption of specific types of planetary bodies).

Based on new simulations and scaling laws, [1] and this paper present a complete analytic description of the dynamical outcome for any collision between gravity-dominated bodies (100's m planetesimals to planets). All collision outcomes are described in terms of the impact conditions and the catastrophic disruption criteria, Q^*_{RD}, the specific energy required to disperse half the total colliding mass [2]. This paper presents the general catastrophic disruption law and its implications for planet formation.

2. Results

We find that catastrophic disruption follows nearly pure momentum scaling, in contrast to the assumption of energy scaling currently used in planet formation and collisional evolution studies. As a result, Q^*_{RD} is strongly dependent on the impact velocity and projectile-to-target mass ratio in addition to the total mass and impact angle. Figs. 1 and 2 present catastrophic disruption data derived from simulations in this and previous work for a wide range of planetary bodies and using 3 different shock physics codes and a N-body code. Open symbols are oblique impacts; closed and line symbols are head-on.

To account for the impact angle, we derive the interacting mass fraction of the projectile; the total kinetic energy of the impact is based on the interacting mass rather than the total mass. The data corrected to an equivalent normal impact agree with a family of disruption criteria (colored lines in Figs. 1 & 2) defined by

$$Q^*_{RD} = (\rho_1 G)^{3\bar{\mu}/2} R_{C1}^{3\bar{\mu}} V^{*(2-3\bar{\mu})}, \qquad (1)$$

where R_{C1} is the radius of the combined mass at $\rho_1 \equiv 1$ g cm^{-3}, G is the gravitational constant, $\bar{\mu}$ is the coupling parameter [3], and V^* is the critical impact velocity to achieve catastrophic disruption. In pure energy scaling, $\bar{\mu}$=2/3 and there is no dependence on impact velocity. The data show a clear dependence on impact velocity, and $\bar{\mu}$ is fit to the data with values of 0.33 to 0.37, nearly pure momentum scaling.

We find that the mass ratio of the impact may be scaled to an equivalent normal equal mass impact by taking into account both (i) the difference in impact velocity from the mass ratio and (ii) the adjustment to Q^*_{RD} from the change in impact velocity. The scaled data fall on a single curve given by

$$Q^*_{RD,1:1} = c^* \frac{4}{5} \pi \rho_1 G R_{C1}^2, \qquad (2)$$

which we call the *principal disruption curve*. The single material parameter c^* represents the equal-mass disruption curve in units of the specific gravitational binding energy. For a diverse range of planetesimal compositions and internal structures, c^* has a value of 6 ± 2; whereas for strengthless planets, we find $c^* = 1.8 \pm 0.3$. Note that data for strong basalt targets at impact velocities of about 3 km/s and higher are not well described by a single value of c^*.

Only two material parameters (c^* and $\bar{\mu}$) and the definition of the interacting mass are needed to calculate the Q^*_{RD} for any collision scenario between gravity-dominated bodies. The disruption criteria and the universal law for the largest remnant [2] are used to bound the transitions between accretion, erosion, and hit-and-run regimes [1].

3. Conclusions

Previous studies of planet formation and collisional evolution of small body populations have applied a single value for Q^*_{RD} for a given size target. In fact, Q^*_{RD} is a strong function of velocity and mass ratio; hence, the impact energy required for disruption changes dramatically over the course of planet formation. In particular, the disruption criteria for collisions between comparable mass bodies are much lower than the fixed values explored in the planet formation literature. Our new self-consistent scaling laws will significantly improve the physics of collisions between gravity-dominated bodies in numerical simulations of planet formation and collisional evolution.

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References

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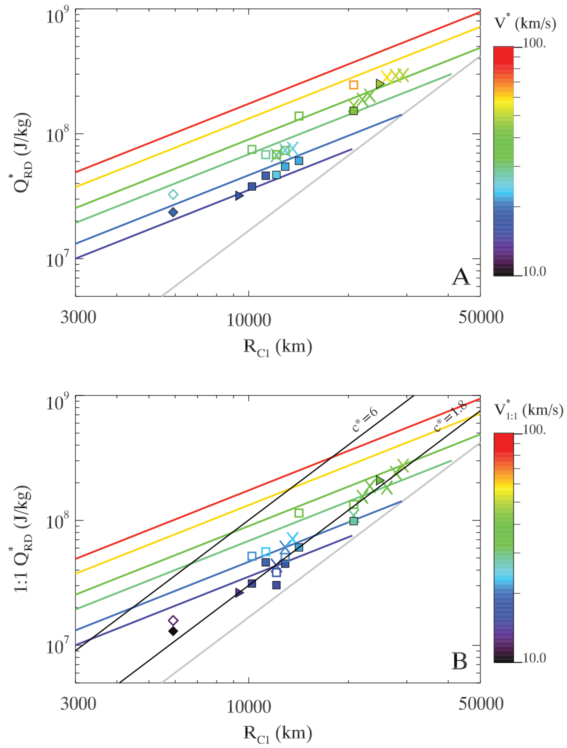

Figure 2: Catastrophic disruption data for planet-size bodies from the literature: pure rock (►), differentiated rock and iron (×, ♦), differentiated water and rock (■). A. Data adjusted for impact angle to equivalent normal impact. B. Data adjusted to equivalent equal mass (1:1) impact. The 1:1 data define the *principal disruption curve* (black line).