DISRUPTION IN GRAVITY-DOMINATED IMPACTS: SIMULATION RESULTS AND SCALING

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Introduction: Predicting the outcome of a collision between planetary bodies is crucial component of planetary accretion models. The basic question is whether a collision leads to net accretion or net erosion of the colliding system, as determined by the mass of the largest gravitationally bound fragment post-collision, M_{LB}. A related question is that of the criteria for *catastrophic disruption*, which may be defined as a collision that leads to half the total colliding mass escaping the system post collision. These criteria have been the subject of many studies, theoretical [1], numerical [2], and experimental [3], but the question is not yet settled, especially in the so-called gravity regime where experiments are restricted to cratering impacts and data on impacts leading to disruption must come from numerical simulations.

Here we report on a suite of hydrocode simulations of collisions between planetary bodies with radii from 100 to 1000 km, strictly in the gravity regime. The simulation data are used to derive a simple scaling law for the threshold of catastrophic disruption. Compared with previously suggested scaling laws ([4], [5]) we find in general a lower threshold for disruption. This finding has implications, for example, for collisional grinding in the asteroid belt [6] and Kuiper belt [7], and of course for early solar system accretion [8].

Method: We consider disruptive collisions between a *target* with radius $100\text{ km} \le R_T \le 1000\text{ km}$ and mass M_T, and a *projectile* with radius $r_p \le R_T$ and mass m_p, at impact velocity v and impact angle θ. In this size and velocity range the impacts are gravity dominated and elastic strength of both bodies is ignored. The composition of the colliding bodies (rock or ice) affects the outcome through the choice of equation of state and primarily through the target's average density. Both bodies are assumed to be undifferentiated and non-rotating, and are given initial density profiles that are close to hydrostatic equilibrium. We simulate the resulting impact with the SPH-based hydrocode SPHERAL [9] and determine M_{LB} by applying two iterative energy-based algorithms, one building a gravitationally bound mass starting with the lowest energy mass element and the other reducing the system to a gravitationally bound mass by removing unbound mass elements from the system. If $M_{\mathrm{LB}} > 0.5$ we rerun the simulation with v increased and if $M_{\mathrm{LB}} < 0.5$ we rerun with v decreased. Eventually we find v^* such that $0.49 \le M_{\mathrm{LB}}(v^*) \le 0.51$. In this way we find $v^*(R_T, M_T, r_p, m_p, \theta)$ for 5 target radii, 3 – 4 projectiles for each target, 3 impact angles per projectile, and for 3 composition options: ice, basalt, and mixed (ice targets and basalt impactors). More than 200 simulations are needed to produce v^* for ~50 impact scenarios covering, sparsely, the volume of interest in parameter space. We use these to derive a simple, energy-based scaling law.

Results: The conditions identifying a critically catastrophic impact involve six variables. To efficiently predict the outcome of a collision with given initial conditions we would like to reduce the available data to a relationship between fewer variables. The choice of derived variables is not obvious. For strength regime impacts and for cratering impacts in the gravity regime it is known that a coupling parameter $C = m_p v^\mu$ is a good measure of the impact under the assumption $m_p \ll M_T$ where μ is between 0.35 and 0.45 depending on material. This so-called point source limit cannot be assumed to hold in gravity-dominated impacts between similar sized bodies and we look for a measure that considers the projectile and target equally. Experimenting with several options, we found that the best measure of the impact is the kinetic energy of the system in the center-of-mass frame

$$K^* = \frac{1}{2}\frac{m_p M_T}{m_p + M_T} {v^*}^2$$

when this measure is compared with the gravitational binding energy of the system at the moment of impact:

$$U = \frac{3GM_T^2}{5R_T} + \frac{3Gm_p^2}{5r_p} + \frac{GM_T m_p}{R_T + r_p}.$$

In figure 1 we show the critical energy K^* obtained for all head-on ($\theta = 0$) impacts. We indicate $\gamma = m_P/M_T$ by color, the values of γ corresponding to projectile-to-target size ratios between 1 and 0.2. Filled symbols indicate basalt bodies and empty symbols indicate ice bodies. The black plus markers indicate an ice target and basalt impactor (where in some cases the impactor is more massive than the target). All data seem to fall near a straight line in log scale suggesting a power law. In fact the slope of the best-fit line is close to 1, suggesting an even simpler relation:

$$K^* = cU,$$

with all data falling inside $2.1 \le c \le 8.4$. Although a

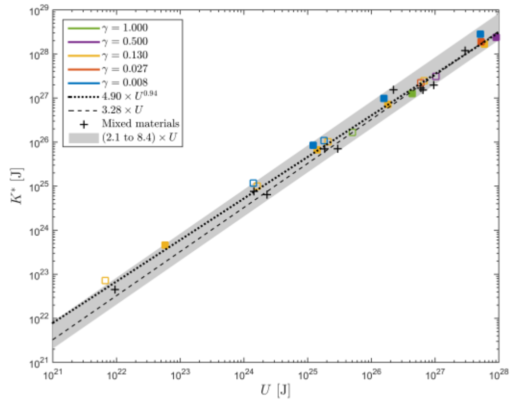


Figure 1. Kinetic energy (in center-of-mass frame) of critically catastrophic head-on collisions plotted against gravitational binding energy of the two-body system at the moment of impact. Filled symbols indicate basalt bodies, empty symbols indicate ice bodies. Plus markers indicate basalt impactor and ice target. Color indicates projectile-to-target mass ratio.

better fit power-law to these particular data may be obtained with a slightly shallower slope, the linear relation is more physically justified.

Figure 2a shows the critical energy K^* in oblique impacts normalized by the value of K^* for the corresponding head-on impact. In figure 2b the critical energy is shown after a zero-order correction for the fraction α of impact energy contained in the volume of the projectile that intersects the target during the collision. Following a procedure suggested in [5] we find that if $l = (R_T + r_p)(1 - \sin\theta)$ then

$$\alpha = \begin{cases} \dfrac{3r_p l^2 - l^3}{4r_p^3}, & l < 2r_p, \\ 1, & l \geq 2r_p \end{cases}$$

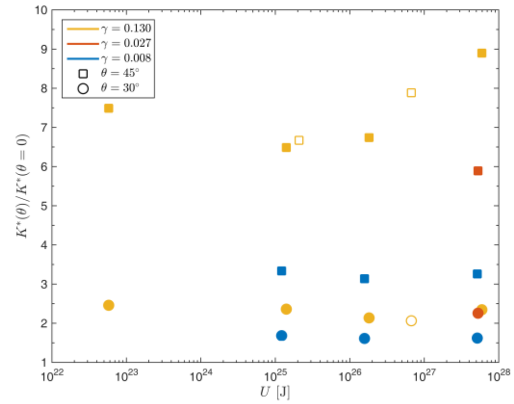
and the available kinetic energy is

$$K_\alpha = \frac{1}{2}\left(\frac{m_p M_T}{m_p + M_T}\right)\left(\frac{\alpha M_T + m_p}{m_p + M_T}\right)v^2.$$

The critical energy values after this correction is applied appear to require some constant factor of the corresponding energy in head-on impacts, about 2 times as much energy for $\theta = 30°$ and about 3 – 4 times for $\theta = 45°$.

The data plotted are from non-grazing impacts. Grazing impacts are common, and their outcome can be less simple, transitioning abruptly from merging to hit-and-run with increasing impact speed.

Summary: We suggest the following simple scaling for predicting the onset of catastrophic disruption in gravity-dominated collisions: the kinetic energy of impact in the center-of-mass frame must exceed a few times the gravitational binding energy of the system at the moment of impact, $K > K^* = cU$. For head-on impacts c is between about 2 and 8. For oblique impacts the geometrically corrected K_α must exceed about 2 times K^* for $30°$ impacts and 3 – 4 times K^* for $45°$ impacts. Future simulations will fill in the gaps in parameter space and hopefully discover a systematic increase in threshold energy with increasing impact angle. The scaling law suggested here generally leads to a lower threshold for disruption than previously published scaling laws [4], [5] except for very oblique impacts with $m_p \ll M_T$ where the predicted threshold may be higher.



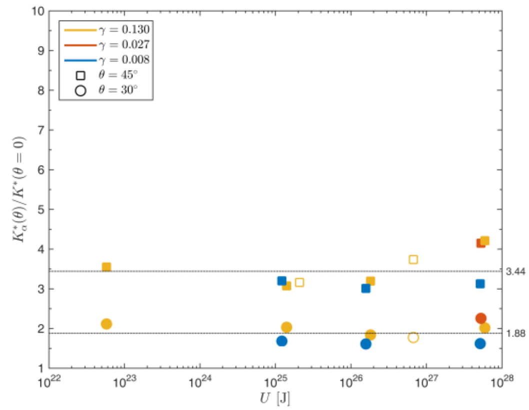


Figure 2. (a) Increase in kinetic energyrequired for disruption with increasing impact angle. **(b)** After applying a correction for the fraction of kinetic energy coupled to the target during collison.

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