Icarus 275 (2016) 85–96

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Impact disruption of gravity-dominated bodies: New simulation data and scaling

N. Movshovitz[a,*], F. Nimmo[a], D.G. Korycansky[a], E. Asphaug[b], J.M. Owen[c]

[a] Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA, USA
[b] School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA
[c] Lawrence Livermore National Laboratory, Livermore, CA, USA

ARTICLE INFO

Article history:
Received 2 October 2015
Revised 10 April 2016
Accepted 12 April 2016
Available online 20 April 2016

Keywords:
Collisional physics
Planetesimals
Planetary formation

ABSTRACT

We present results from a suite of 169 hydrocode simulations of collisions between planetary bodies with radii from 100 to 1000 km. The simulation data are used to derive a simple scaling law for the threshold for catastrophic disruption, defined as a collision that leads to half the total colliding mass escaping the system post impact. For a target radius $100 \leq R_T \leq 1000$km and a mass M_T and a projectile radius $r_p \leq R_T$ and mass m_p we find that a head-on impact with velocity magnitude v is catastrophic if the kinetic energy of the system in the center of mass frame, $K = 0.5 M_T m_p v^2/(M_T + m_p)$, exceeds a threshold value K^* that is a few times $U = (3/5)GM_T^2/R_T + (3/5)Gm_p^2/r_p + GM_T m_p/(R_T + r_p)$, the gravitational binding energy of the system at the moment of impact; G is the gravitational constant. In all head-on collision runs we find $K^* = (5.5 \pm 2.9)U$. Oblique impacts are catastrophic when the fraction of kinetic energy contained in the volume of the projectile intersecting the target during impact exceeds $\sim 2K^*$ for 30° impacts and $\sim 3.5K^*$ for 45° impacts. We compare predictions made with this scaling to those made with existing scaling laws in the literature extrapolated from numerical studies on smaller targets. We find significant divergence between predictions where in general our results suggest a lower threshold for disruption except for highly oblique impacts with $r_p \ll R_T$. This has implications for the efficiency of collisional grinding in the asteroid belt (Morbidelli et al., [2009] Icarus, 204, 558–573), Kuiper belt (Greenstreet et al., [2015] Icarus, 258, 267–288), and early Solar System accretion (Chambers [2013], Icarus, 224, 43–56).

1. Introduction

Collisions between planetary bodies have played a crucial role in the Solar System's formation and subsequent evolution. The dynamical outcome of planetary scale collisions has, for this reason, been the subject of much research including theoretical, experimental, and numerical studies. Guided by scaling theory (see the review by Holsapple, 1993) many previous studies have reported results from laboratory and computer experiments carried out on portions of the parameter space (an incomplete list includes (Benz and Asphaug, 1999; Durda et al., 2004; Jutzi et al., 2010; Leinhardt and Stewart, 2012; Marcus et al., 2010; Stewart and Leinhardt, 2009) as well as reviews by Holsapple et al. (2002) and Asphaug et al. (2002)). But the huge range in sizes and energies of interest makes a general description of collision outcomes difficult.

A complete characterization of the outcome of a collision is a complex task even with perfect knowledge of the governing physics. The size and velocity distribution of fragments, the amount of melt or vaporization, the pressure history of different parts of the colliding bodies are all of interest in different applications. A more restricted problem that is of prime importance in models of planetesimal growth is the distinction between broad classes of possible collision outcomes: merging, accretion, erosion, or disruption; the definition of these categories being based on the masses of the colliding bodies before and after collision. An even more modest question that is nevertheless of great interest, both in its own right and as a basis for more complete characterization of outcomes, is that of the criteria for *catastrophic disruption* (a precise definition of which is given below). Finding these for collisions involving bodies between 100 and 1000 km in radius is the focus of the present study.

We focus on the 100–1000 km size range for two reasons. First, many satellites of the outer planets have sizes in this range, and their origin and evolution were possibly heavily influenced by big impacts during the Late Heavy Bombardment (e.g. Movshovitz et al., 2015; Nimmo and Korycansky, 2012; Asphaug and Reufer, 2013; Charnoz et al., 2009; Sekine and Genda, 2012). Second,

* Corresponding author. Tel.: +18312398965.
E-mail address: nmovshov@ucsc.edu, nmovshov@gmail.com (N. Movshovitz).

http://dx.doi.org/10.1016/j.icarus.2016.04.018
0019-1035/

this size range seems to have been neglected by previous studies, which have simulated targets either smaller (e.g Benz and Asphaug, 1999; Leinhardt and Stewart, 2012) or much larger (e.g. Marcus et al., 2009; 2010) than the icy satellites. Therefore, applying previously obtained scaling laws (Benz and Asphaug, 1999; Leinhardt and Stewart, 2012) to mid-sized satellites requires extrapolating beyond the size and velocity range of the simulations used to derive them. The results of such extrapolation, we show below, can diverge from simulation data.

In the following we present in Section 2 results from a new suite of hydrocode simulations of collisions involving bodies in the 100–1000 km size range and with impact velocities between 1 and 50 km/s. In Section 3 we suggest a new scaling law that predicts the conditions for catastrophic disruption in this size range. We compare our results to previously obtained simulation data and scaling laws in Section 4 and summarize our conclusions in Section 5.

2. New simulation results

In this section we present results from a suite of hydrocode simulations aimed at finding the conditions for critically catastrophic collisions (defined below) between planetary bodies in the 100 to 1000 km size range. We give our results first in table form followed by our reduction and interpretation of the data in Section 3.

2.1. Definitions

In the size and velocity range of interest collisions are gravity dominated. By this we mean that shock-induced pressure at the impact site, and overburden pressure throughout most of the interior of both the colliding bodies are much greater than the elastic strength of the material the bodies are made of. This simplifying assumption allows us to treat the colliding bodies as fluid spheres in hydrostatic equilibrium (prior to impact of course) fully described by their mass, radius, and an equation of state. The compositional difference between different planetary bodies (e.g. mostly icy versus mostly rocky) affects the outcome mostly through the different bulk densities and the resulting gravitational fields. We also assume the colliding bodies are undifferentiated and non-rotating, and non-porous. Most simulations were performed with both colliding bodies of the same composition. We discuss the possible implications of these assumptions further in Section 5.2.

Note that the above simplifications, while surely unrealistic for many planetary bodies, are perhaps *least* problematic for bodies that are some hundreds of kilometers in size. In this respect the 100–1000 km size range is arguably the simplest to investigate numerically. A planetoid much smaller than 100 km in radius is likely to be heterogeneous and may be dominated by elastic stresses, while a satellite or small planet much larger than 1000 km in radius is likely to be differentiated.

With the above assumptions in mind consider a collision between a body of mass M_T and radius R_T and a second body of mass m_p and radius $r_p \leq R_T$. We refer to the larger body as the *target* and to the smaller as the *projectile*. The relative velocity between the centers of the spheres at the moment of impact has magnitude v. The angle between the relative velocity vector and the line joining the target and projectile centers at the moment of impact is θ. These six initial conditions plus a choice of equation of state (already implied by the assumption of hydrostatic equilibrium) then fully define the collision.

We wish to find initial conditions that lead to *critically catastrophic* collisions, defined as collisions where the largest remaining post-collision gravitationally bound mass, denoted $M_{\rm LB}$, is exactly half the initial mass. Here we run into the first of several ambiguities found in the literature, as "initial mass" may refer to either the target mass or the combined target and projectile mass. When $m_p \ll M_T$ it is of no consequence but when $m_p \approx M_T$ either choice can be defended. While considering only the target mass introduces an artificial asymmetry and degeneracy to the definitions, taking initial mass to mean combined system mass leads to the strange result that glancing or "hit-and-run" collision (where both bodies separate mostly intact) are considered catastrophic, as $m_p \approx M_T$ and therefore $M_{\rm LB} \approx M_T \approx (M_T + m_p)/2$. Following Asphaug (2010) and Leinhardt and Stewart (2012) we define a critically catastrophic collision as one that leaves $M_{\rm LB}$ equal to half the combined mass:

$$f_{\rm LB} = \frac{M_{\rm LB}}{M_T + m_p} = \frac{1}{2}, \tag{1}$$

but restrict our discussion to *non-grazing* collisions, with

$$\sin\theta \lesssim \frac{R_T}{R_T + r_p}. \tag{2}$$

The criterion in (2) is a purely geometrical constraint which corresponds to the impact angle at which the center of mass of the projectile is tangent to the target. Higher impact angles are more likely to result in the hit-and-run outcome. But it is a convenient reference rather than a strict definition. For example, an impact with $R_T = 2\,r_p$ and $\theta = 45^\circ$ qualifies (barely) as grazing by Eq. (2) but is well behaved, showing a smooth decrease in $M_{\rm LB}$ with impact speed. In principle, identifying a collision as hit-and-run requires that we look at the outcome rather than at the initial conditions, and this outcome depends on impact speed as well as geometry (e.g. Genda et al., 2012). In practice Eq. (2) is a useful way to avoid confusing a hit-and-run collision with catastrophic disruption.

2.2. The parameter space

As discussed above, six initial conditions plus an equation of state define a collision. But the assumptions of homogeneity and hydrostatic equilibrium mean that the masses and sizes of the colliding bodies are not independent. A convenient way to explore the parameter space then is to first select the equation of state used to represent the colliding bodies' composition, then choose a target radius in the range of interest followed by a projectile radius some fraction of the target's, then an impact angle. A series of hydrocode simulations is then run to find the impact velocity v that leads to $f_{\rm LB} = 0.5$, starting with an initial guess and adjusting the impact velocity up or down as needed. We use this approach to identify, from 169 simulations, 38 critical disruption conditions corresponding to two choices of composition (ice and rock) for 4 target radii, 3–4 projectiles per-target, and 2–3 impact angles per projectile.

Note that different choices are also possible; for example fixing the impact velocity and varying m_p (Benz and Asphaug, 1999) or fixing the ratio $\gamma = m_p/M_T$ and varying target and projectile size together. Each option offers some advantages but ultimately the values should cover the same region of parameter space. The main disadvantage of varying impact speed for a given projectile size is that for small targets and large projectiles disruption may happen at subsonic speed. Different physics might govern the coupling of energy to the target at supersonic and subsonic impacts and this may show as scatter in the critical disruption data.

2.3. Hydrocode simulations

We use the hydrocode Spheral (Owen, 2010; 2014; Owen et al., 1998), a Lagrangian SPH based shock physics code coupled with an oct-tree gravity algorithm. We run the code in fluid mode, disabling elastic strength and damage calculations. For an equation of