EPSC Abstracts
Vol. 6, EPSC-DPS2011-1525-1, 2011
EPSC-DPS Joint Meeting 2011

A Model for Collisional Regimes in Planet Formation

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1. Introduction

Collisions are the core component of planet formation. Using new high-resolution simulations of collisions between planetesimals for a wide range of projectile-to-target mass ratios, impact angles, and impact velocities, we have derived a complete analytic description of the dynamical outcome for any collision between gravity-dominated bodies (100 m planetesimals to planets). The range of impact parameters encountered during growth from planetesimals to planets span multiple collision outcome regimes: cratering, merging, disruption, hit-and-run, and erosive hit-and-run events. We have derived equations to demarcate the transition between collision regimes and to describe the size and velocity distributions of the post-collision bodies. The scaling laws include only four material parameters, which are tightly constrained by the available data. 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. The self-consistent scaling laws will significantly improve the physics of collisions between gravity-dominated bodies in numerical simulations of planet formation and collisional evolution.

This corpus of work, [1], has been split into two abstracts. In this abstract, we focus on the transitions between collisional regimes. In our companion abstract [2], we focus on describing a general catastrophic disruption law for planet formation.

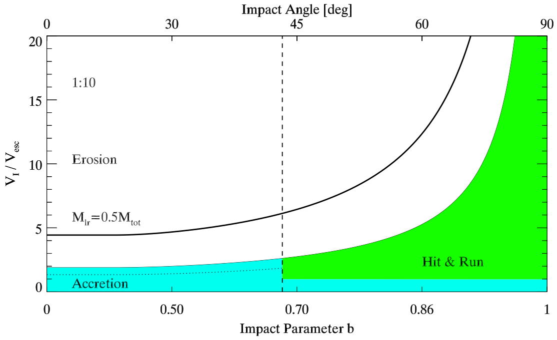

Figure 1: Collisional regimes for strengthless planets with mass ratio of 1:10. The y-axis is relative impact speed in units of mutual escape speed. The x-axis is impact parameter spaced by probability. The cyan region represents accretion or growth of the largest remnant, the green region shows hit-and-run, a regime in which the target's mass is unchanged. The thick solid line represents the catastrophic disruption. Above this line more than half of the total mass is permanently removed from the largest remnant; below this line less than half of the total mass is removed. The dotted line indicates where half of the projectile is accreted.

2. Collisional Regimes

Using our scaling laws, we derive an example collision regime map for an impact between strengthless planets with a mass ratio of 1:10 (Fig. 1). This example is particularly illustrative of the complexity of collisions during the final stage of planet formation, which is dominated by giant collisions between protoplanets. A mass ratio of 1:10 is common for the giant impact stage [3]. Giant impacts produce more diverse outcomes than typically modelled. Over the expected range of impact velocities during the end of planet formation (up to about 4 times the escape velocity), all major collision regimes are encountered. Note that the center of the probability distribution of impact angles, impact parameter $b = 0.7$, nearly coincides with the transition to hit-and-run collisions ($b > 0.66$) for a 1:10 mass ratio. Hence, about half of all impacts (less than $4V_{esc}$) fall in a regime that transitions from accretion to erosion and half of all impacts transition from accretion to a hit-and-run regime. Note that although the target body may remain effectively intact after a hit-and-run event, the escaping body (the original projectile) may undergo significant modification (e.g., devolatilization) [4].

For all mass ratios, we find that the onset of the hit-and-run regime coincides with a geometric definition from [4]. Above a critical impact parameter, b_{crit} (dashed vertical line Fig. 1), more than half of the projectile misses hitting the target. Below b_{crit} the collision transitions from net accretion onto the target (cyan region) to net erosion of the target (uncolored region). The transition between accretion and erosion is determined by the specific energy necessary to produce a largest remnant that is the mass of the original target, which is calculated from Q^*_{RD} and the universal law for the largest fragment (defined in [5]).

As the impact angle increases, the fraction of the projectile that directly impacts the target decreases. Previous work assumed that all of the kinetic energy of the projectile was deposited in the target. Here, we defined a geometrically determined interacting mass, which corresponds to the true kinetic energy involved in the collision. Hence, the transition between accretion and erosion increases slightly with impact parameter because of the decreasing interacting mass.

If the collision is grazing, $b > b_{crit}$, the impact transitions from perfect merging (cyan region) to a hit-and-run regime (green region). At higher impact velocities, the transition out of the hit-and-run regime to the disruption regime has a strong dependence on impact angle because of a combination of the interacting mass and the increasing impact velocity [2].

For smaller projectiles, the parameter space filled with hit-and-run collisions systematically decreases because of the corresponding increase in the value of b_{crit}. The catastrophic disruption threshold also increases with smaller projectiles because of the effects of both the mass ratio and impact velocity [2]. Conversely, if the projectile is closer in mass to the target, the hit-and-run regime becomes larger and the catastrophic disruption threshold drops significantly.

The analytic transitions between collision regimes agrees well with numerical simulations of km-scale planetesimals and planet-size bodies. Hence, the same set of equations may be used throughout the planet formation process.

In addition to defining the boundaries between collision regimes, we derive the velocity of the largest remnant with respect to the center of mass and the size and velocity distribution of smaller fragments.

3. Summary

A general description of collision outcomes that spans the growth from planetesimals to planets is required to build a self-consistent model for planet formation. In previous work, the description of collision outcomes drew upon a combination of laboratory experiments and limited numerical simulations of collisions between two planetary-scale bodies. Because of the lack of a general formulation for collision outcomes, the implementations of collision physics in planet formation simulations were restricted to specific subset of possible outcomes (e.g., perfect merging or high-velocity disruption). In fact, collision outcomes are quite diverse, and several distinct regimes are encountered over the course of planet formation: merging, disruption, super-catastrophic disruption, hit-and-run, and erosive hit-and-run events.

In this work, we present the first complete description of collision outcomes for gravity-dominated bodies. Using a combination of new and published collision simulations and new scaling laws, we derived analytic equations to demarcate the transitions between collision regimes and the size and velocity distribution of the post-collision bodies. These scaling laws are a significant improvement in the physics of collisions in simulations of planet formation and collisional evolution.

Acknowledgements

ZML is supported by an STFC Advanced Fellowship. STS is supported by NASA grant #NNX09AP27G. The numerical simulations required for this work were completed on the University of Cambridge Astrophysics Fluids facilities in the Department of Applied Mathematics and Theoretical Physics.

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