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Sequential Giant Impacts

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Abstract

Collisions between similar sized bodies often result in multiple remnants. We study two most common pathways of growth during 'late stage' accretion, which are graze and merge, and hit and run return where a hit and run is followed by a slower accretionary encounter, accounting for the presence of the Sun or a central planet. With initial N-body study we find that in case of an hit and run return the impact velocity is mostly determined for the prior impact while impact angle and direction are not. This has implications for the formation of our Moon if resulted from a hit and run collision, as the disk would be offset relative to the equator of the Earth.

1. Introduction

Collisions at near-escaping velocities between similar-sized planetary bodies (i.e. giant impacts) are seldom efficient when it comes to accretion. More often than not, a significant part of the smaller, the impactor, 'misses' the target, leading to the collision resulting in multiple remnants [1]. This part of the impactor becomes either a 'runner' stripped of its exterior materials, or fragments into a suite of genetically-correlated smaller planets. The relative velocity is decreased following the collision; when the bodies remain gravitationally bound, the result is successive collisions separated a day or so in the case of graze and merge collisions (GMC) [6]. When not, the result is hit and run collision (HRC) where the runner eventually returns in a time scale of thousands to millions of years [4], leading to a hit and run return collision (HRR).

2. Methods

Collisions are modelled with the SPH technique using a code suited for large scale collisions and that includes a strength model for solid friction [7, 3]. We model both kinds of accretions, and study the thermodynamic (P, T) evolution and spatial mixing of particles to ascertain the effectiveness of successive giant impacts, especially on isotopic equilibration and formation of large satellites. GMC can be studied using uninterrupted hydrocode simulations, provided the dynamics of the runner is advanced accurately enough to predict the angle and velocity of the return collision, upon which the final outcome depends sensitively. When graze and merge happens in orbit around a planet or close to a star, however, GMC can becomes HRC if the bodies range beyond the Hill sphere. In the case of HRC the escaping runner must be tracked for many orbits until its next encounter with the target; this can be a close encounter leading to escape of the runner, or a follow-on collision that we model by mapping the outcome of one hydrodynamical simulation into another. We map the target and runner emerging from one collision (ignoring lost collision products) into an N-body code, assuming a range of possible pre-impact orbits following [5]. This provides timing, velocity and geometry constraints for the return collision.

3. Results

In our initial N-body studies we find that the impact velocity of the return collision is mostly determined from the end conditions of the prior collision, with a greater dispersion in impact velocity as the time between collisions increases (Fig. 1). The presence of other planets in the system causes a further increase in the dispersion of impact velocities, but barely affects the delay between the collisions. On the other hand, the impact direction and angle are essentially unconstrained.

4. Discussion and outlook

Hit and run return and graze and merge are the most common mechanisms of late stage accretion; in either case the second impact must be modeled with some precision to understand the actual outcome. This results in sensitivity of the outcome to parameters such as impact velocity, impact angle and rotation state and composition, and also orbital dynamics of the collid-

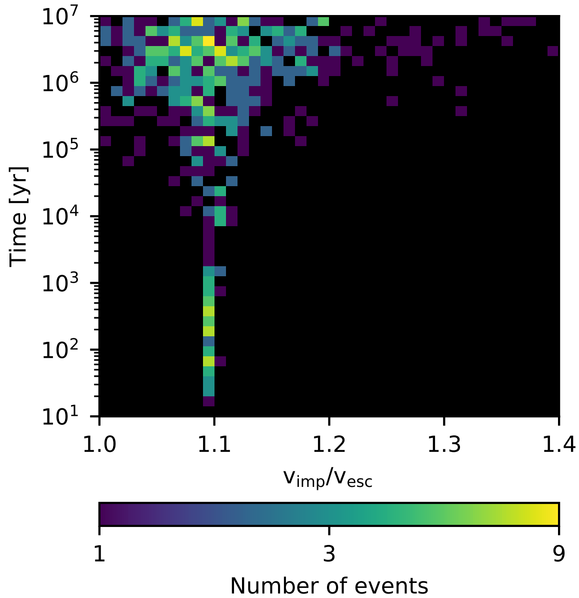

Figure 1: Correlation between the impact velocity versus delay between the successive collision for an hit and run return case. The characteristics of the prior collision are $m_{\mathrm{tar}} = 1\ \mathrm{M}_{\oplus}$, $m_{\mathrm{imp}}/m_{\mathrm{tar}} = 0.1$, $v_{\mathrm{imp}}/v_{\mathrm{esc}} = 1.2$ and $\theta = 50°$. It results in two remnants with a mass ratio $m_{\mathrm{slr}}/m_{\mathrm{lr}} = 0.078$ and a relative velocity such that the return collision would have $v_{\mathrm{imp}}/v_{\mathrm{esc}} = 1.099$ if the value was conserved.

ing bodies around the Sun, or around a central planet. Runners emerge at a reduced relative velocity, and are smaller than the projectiles that made them. The follow-on giant impact in HRR is therefore expected to strongly favor merger compared to the first giant impact. This means that a first return is more common than a subsequent return and so on. However, a simple merger is rare, that is not a graze and merge [2]. Lastly, since the specific geometry (though not the velocity) of the second encounter is random, we consider how HRR might establish an offset between the spin axis of the merged body and the disk material that is launched in the original collision. If Theia and proto-Earth accreted by HRR, then the protolunar disk spawned by the first collision would be offset relative to the equator of the Earth. We use this dynamical constraint to begin to identify scenarios for Moon formation as a sequential merger.

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