COLLISION CHAINS AMONG THE TERRESTRIAL PLANETS.

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Introduction. Giant impacts are seldom efficient when it comes to accretion. More often than not, when the smaller body – the impactor – is similar in size to the target (i.e. the late stage) its trajectory does not fully overlap the target, and part of it continues downrange in a hit and run collision (HRC) [1]. HRC reduces the relative velocity between colliding bodies, and because they remain on crossing orbits after the collision, they might collide again. This has sometimes been used to argue that HRC is irrelevant and that perfect merger by giant impact is a good approximation.

Depending on their post-collision trajectories, they may also intersect the orbits of other planets, or be perturbed by them, potentially colliding with these bodies. We call these sequences of giant impacts *collision chains*, and given the high probability of HRC to begin with, collision chains may well be the normal path to accretion. The remnants of HRC may also avoid further collisions for an extended period, perhaps becoming dynamically independent (see Fig. 1).

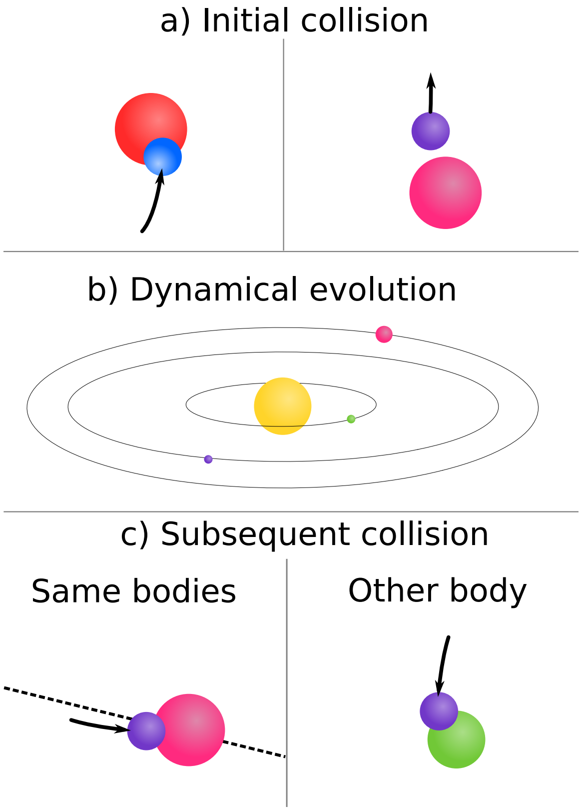

Figure 1: Sketch of the collision chain process. First, a hit and run collision results in the production of two largest remnants. The two bodies are initially on similar orbits, which can result in a second collision between the same, or after being affected by other objects, collide with another body.

Here we study the dynamical evolution of remnants of HRCs relevant to the accretion of the Earth and Venus, to determine subsequent collisional evolution.

Methods. We model collisions using Smoothed Particle Hydrodynamics (SPH). The mass of the target is fixed, $m_{\mathrm{tar}} = 0.9\,\mathrm{M}_\oplus$, while the impactor's mass is either $m_{\mathrm{imp}} = 0.2\,\mathrm{M}_\oplus$ or $0.5\,\mathrm{M}_\oplus$. We select impact velocities of $v_{\mathrm{coll}} = 1.1 - 1.2$ in accordance with outcomes from terrestrial planet formation models [2], and impact angles that produce giant impacts in the HRC regime.

At 24 h after initial contact, the hydrodynamical results from SPH are transferred into an N-body code, *Mercury* [3] for long-term dynamical evolution with the other solar system bodies (assuming current planetary configurations). The SPH results are cloned many times assuming different orientations of the same collision with respect to the Sun. For most of the cases we assume that the target – proto-Earth – has a circular orbit at 1 AU prior to the collision, while the orbit of the impactor is computed following [4]. We also ran a series where the target is initially at 0.723 AU to model a collision with proto-Venus.

For each study of post-HRC dynamical evolution, we flag the follow-on collision if one occurs, and determine the parameters of the second giant impact: the velocity, angle, and orientation.

Results. Higher-velocity collisions have a broader range of impact angles resulting in HRC (Fig. 3). Due to shock dissipation and momentum transfer during the first giant impact, the runner velocity is always slower than the impact. Runners that depart barely above the mutual escape velocity have the highest probability to collide again with the same target body (Fig. 2).

For HRCs at higher relative velocity, the runner is faster and tends to survive dynamically for longer periods before re-colliding; it can also collide with other nearby planets. In one case for initial collisions with the Earth, we obtained a higher probability of re-collisions with Venus than returns back to the Earth.

The velocity of the return collision, which occurs thousands to millions of years later, is correlated with and generally slower than the velocity of the initial giant impact. But the impact angle and orientation of the return collision are essentially unconstrained [5]. The slower return speed implies that return collisions have a greater tendency to be accreting.

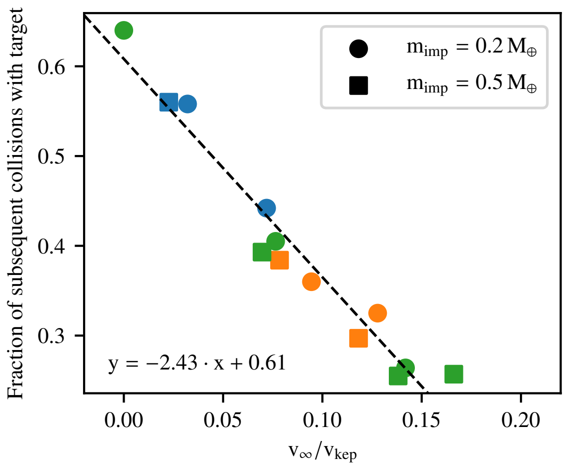

Figure 2: Fraction of dynamical evolution runs ending with a further collision between the runner and the target as a function of the relative velocity after the collision.

Collision chains are terminated in two ways. When the departing velocity is slower than the escape velocity, it is a “graze and merge collision” (GMC) and the projectile comes back in ten or twenty hours. Here the velocity, angle and orientation are closely correlated. When the collision is close to head-on, less than about 30° for collisions close to v_{esc}, no significant second remnant is formed and collisions are accretionary with few if any sizable remnants.

Venus. A runner from an HRC with proto-Venus is more likely to re-collide with Venus, than a runner from an HRC into Earth is to re-collide with the Earth. Higher eccentricity is required for a body with semi-major axis near 0.7 AU to reach 1 AU, than vice-versa; Venus is more of a closed system. But for a subset of runners returning to Venus following HRCs into Venus, the return impact is actually faster than the initial giant impact. This means there is a significant likelihood of further HRC (see Fig. 3). Even though the collision does not end the chain, it remains probable that Venus is the final destination of the chain. This is curious, because Venus does not have any natural satellite [6], yet we find that it should have suffered, due to all of these exchanges, from a similar or even greater number of disk-producing HRCs and GMCs than the Earth.

Earth. Overall we find that the probability of a direct return from an HRC into proto-Earth is far from certain. Only 2/3 come back directly even in the slowest cases, and around 1/3 of them come back overall (Fig. 2). A large fraction do not return after tens of millions of years, rendering the assumption of perfect accretion invalid.

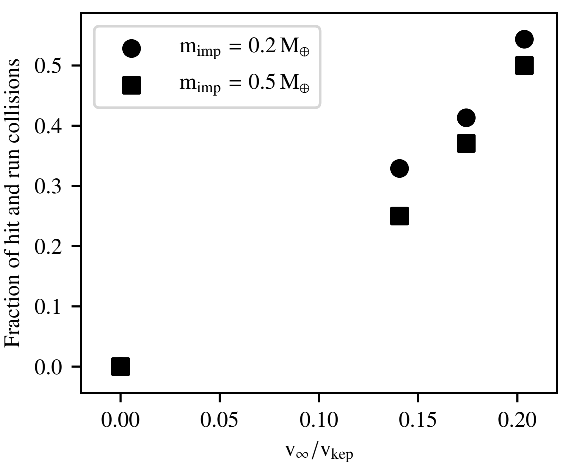

Figure 3: Fraction of collisions in the HRC regime as function of the impact velocity, assuming impact angles follow a distribution resulting from uniform distribution in space. The relative velocity is normalized by the Kelperian velocity at 1 AU.

We furthermore estimate that a fraction, about 5–10% of giant impacts into the Earth, can be the result of a chain involving one event with Venus in an intermediate step. The bottleneck is the low probability of a runner emerging from Venus to collide back with Earth. In this case the impact velocity on Earth remains similar to the departing velocity from Venus, so such an event is likely to be accretionary with the Earth, ending the collision chain. But the generally favored pathway for a multi-planet collision chain is to be directed inward, to start with proto-Earth and end with the runner impacting Venus.

Mercury and Mars. A small fraction of runners ($< 5\%$) from Venus or Earth are found to collide subsequently with Mercury or Mars. Conversely, these planets being less massive, their runners from giant impacts [7, 8] are also slower and can only have a limited interaction with distant terrestrial bodies. But so far we have only approximated the smaller masses of these planets by scaling the SPH results to smaller size and escape velocities; a full study will require explicit modelling of collisions involving bodies of this size.

References: [1] Asphaug E. et al. (2006) *Nat.*, 439:155–160. [2] Raymond S. N. et al. (2009) *Icarus*, 203:644–662. [3] Chambers J. E. (1999) *MNRAS*, 304:793–799. [4] Jackson A. P. et al. (2018) *MNRAS*, 474:2924–2936. [5] Emsenhuber A. and Asphaug E. (in rev.) *ApJ*. [6] Sheppard S. S. and Trujillo C. A. (2009) *Icarus*, 202:12–16. [7] Marinova M. M. et al. (2008) *Nat.*, 453:1216–1219. [8] Marinova M. M. et al. (2011) *Icarus*, 211:960–985.