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Collision chains among the terrestrial planets: Why Venus doesn't have a Moon?

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1. Introduction

Giant impacts are not very efficient at accretion. For nominal random stirring (e.g., [1]) most collisions result in two bodies, the slightly disrupted target and a badly damaged "runner" or projectile remnant that continues downrange at a lower relative velocity; it is expected to collide again with the target and eventually accrete. This has sometimes been used to argue that so-called hit and run collisions (HRCs) [2] are irrelevant, and that perfect merger by giant impact is a useful approximation. We have found [3] that accreting planets in late-stage scenarios often collide sequentially, and sometimes "planet hop", and that direct merger is unusual.

To first order, at nominal random velocities, merger happens about half the time and the rest are HRCs. This means that in rough numbers, half the time, it takes more than one collision to end up with net accretion. The result is for bodies to acquire a "collision chain" that records a sequence of attempted mergers, until finally the merger does occur, and the chain is dissolved intro the final target. (We encode the record of collisions in each chain, and construct a tree for each final target.)

We find there is a significant probability that a runner might avoid accretion altogether, at least for the 20 Ma duration we have studied so far. A dynamically independent "stranded runner" has been proposed for the origin of Mercury[3].

2. Methodology

We use a similar methodology as in previous work [3]. We begin by modelling a HRC using Smoothed Particle Hydrodynamics (SPH). Once the mechanical effects of the collision have equilibrated to a small pressure variation with time, we transfer the results into an N-body code to study the evolution of the runner and its destination.

For the evolution study, we assume the collision occurred at the present location of the Earth. The background planetary configuration of the present solar system, including the major planets out to Saturn, is included. For an initial collision, we perform 1000 realisation assuming different orientation.

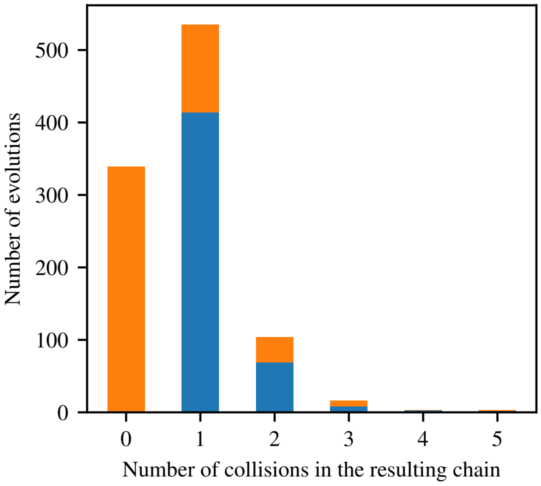

Figure 1: Histogram of the dynamical evolution scenarios for 20 Myr. The horizontal axis is amount of subsequent collisions the runner undergoes. The blue portion is for runner that have been accreted at that collision, and orange where it is still out there. Most are accreted by the next collision (blue, 1) and an almost equal number have not collided again yet with anything after 20 Myr (orange, 0).

The N-body code has been extended to allow for other outcomes than perfect mergers, using [4]. This allows us to obtain realistic situations even after a subsequent collision is detected during the dynamical evolution. Hence, we continue the dynamical evolution until the runner is accreted by one of the bodies.

3. Results

We plot the number of further collisions of the runner in Fig. 1, and the possible paths up to the second further collision in Fig. 2. One primary result is con-

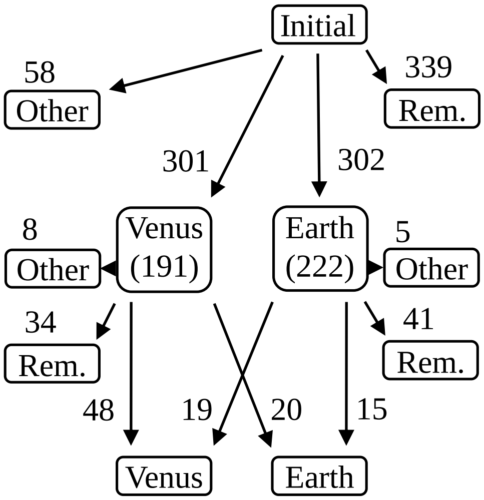

Figure 2: Graphical tree of the destination of the runner, up to the second further collision. "Rem." stands for runner than remain out there unaccreted. The number indicates the amount of cases that followed each path, from 1000 realisations. The numbers in parentheses denote the number of accretion collisions.

trary to expectation: after 20 Myr, the most probable outcome (34% of the cases) is for the runner to have experienced *no* subsequent collisions. Next most probable is for the runner to be accreted by either the Earth or Venus the next time it collides with them (41% of the cases). All the other possibilities account for about a quarter of the results. Most of the subsequent collisions are accretionary. Still, the fraction of HRCs is slightly higher for runner colliding with Venus than when they return to the Earth. However, the runner from collisions with Venus are more likely to collide back again: less runners remain unaccreted, and the probability of a third collisions with the Earth is less than half the one with Venus. Hence, Venus is not only a likely destination for runners emerging from HRCs with the Earth, but once it collides with Venus, there is only a small chance for the runner to bounce back to the Earth.

4. Discussion

About half of giant impacts are HRC, for a nominal size distribution and random stirring. This implies that collision chains may be the nominal path to accretion, as opposed to anything resembling a simple merger or graze-and-merge collision. A runner from a HRC can re-impact the same target, or move on to a different planet, and be accumulated in the next collision (these are plotted in blue in Fig. 1). Or a runner can have a second or even a third HRC and remain unaccreted (orange). The number of stranded runners after 20 Ma, represented by orange bars showing 1, 2 or even more HRCs, is not an insignificant percentage. The accreted runners, shown in blue, tend to have had one or more hit and run collisions before being finally accreted, either by the same or a different planet. The terrestrial planet that ultimately accretes a runner, is not necessarily the target of the first collision.

Merging giant impacts involve the coupling of a significant amount of angular momentum. In part because it conveys so much angular momentum, binary merger has been the favoured hypothesis for the formation of the Earth-Moon system. Venus is therefore a problem because of its extremely long rotation period, -270 days. Maybe Venus somehow slowed down from a fast rotation. Maybe it avoided giant impacts altogether. Maybe the giant impacts into Venus were mostly head-on, something that might explain the lack of a satellite. Maybe opposite giant impacts cancelled out.

We still don't know why Venus doesn't have a moon, but there are some important asymmetries that could provide a clue as to the differences, that may be systematic, about late stage accretion in the inner versus outer terrestrial planet forming system. For one thing, we note that Venus has a similar likelihood as the Earth to accrete a runner from the Earth. The converse is not true; the Earth accretes relatively few runners from Venus. Venus, in turn, re-accretes most of its own runners. In terms of giant impacts, then, Venus appears to be more of a closed system—greater accretion efficiency when considering cumulative events — whereas giant impacts into Earth are more of an open system, with overall lower accretion efficiency.

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