MOON FORMATION AT THE END OF A COLLISION CHAIN Erik Asphaug and Alexandre Emsenhuber
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Introduction. In the standard model of Moon formation, a Mars-sized planet collides with proto-Earth at a nominal impact angle $\theta_{\rm coll} \sim 45°$ and at $v_{\rm coll}$ close to $v_{\rm esc}$, i.e. $v_\infty \approx 0$. It is a graze and merge collision (GMC), the most common kind of pairwise planetary merger [1]. Powerful torques are generated when the cores and inner mantles merge. Silicates, derived mainly from the smaller planet by proportion of angular momentum about the new center of mass, go into orbit [2]. The Moon, thus composed mostly of Theia, would be isotopically distinct, but it is not. Another puzzle is how such a slow collision would come about, requiring a Mars-sized planet existing quite close to Earth [3] – a configuration that is not readily explained, and that has to go unstable in the end. These and various other problems [4] have led to a range of new ideas, as well as to large (though hardly exhaustive) datasets of simulations that put Moon formation in the context of pairwise late stage accretion.

Neural networks [5] and physical scaling [6] applied to sets of high resolution giant impact simulations are able to reliably map key parameters like $v_{\rm coll}$ and $\theta_{\rm coll}$ to the major outcomes required for modeling the growth of planets. In particular they can predict accretion efficiency and the transition to hit and run collisions, as a function of $v_{\rm coll}$, mass ratio, and $\theta_{\rm coll}$. For non-rotating planets, and for random velocities $v_{\rm coll} \sim 1.1$ to $1.4\, v_{\rm esc}$ now thought to represent the late stage, and for "oligarchic" mass ratios 0.01 to 1 $M_\oplus$, it is found that HRCs happen half the time during late stage accretion. A predictive model informed by pre-impact rotation would require a training dataset of $\sim 10^5$ simulations that does not yet exist. For now we reason that HRCs will be no less common when random pre-impact rotations are included.

The realities of accretion must be kept in mind when interpreting the results of N-body codes that evolve the growth of planets through the late stage. Most published studies assume that every giant impact is a perfect merger, regardless of velocity, except for catastrophic disruption that happens when $v_{\rm coll}$ is several times $v_{\rm esc}$. Masses and linear momenta are summed into one merged body ($N \to N-1$) and angular momentum is swept under the rug [7]. This "merge or die" approach fails to characterize a majority of events, those that are too fast to hang on, but hardly erosive, let alone disruptive.

HRCs are a general outcome of collisions. Mergers are always lossy. Accounting for these facts changes the character of planetary growth [8] in ways that have yet to be understood. It also provides an opportunity for new theories of Moon formation, where Theia is an unaccreted "runner" from a previous collision with proto-Earth that slowed it down. This can never happen in a perfect-merger study. The accreting planets would obtain an extra stage of mixing, helping to solve the lunar isotope problem. The end would be a slow collision, consistent with the standard model.

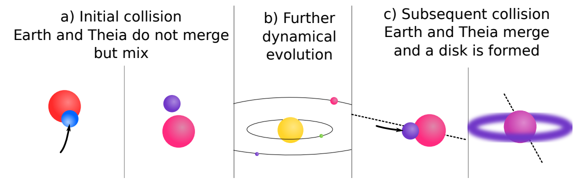

Figure 1: Summary of our model. (a) Two original planets mix somewhat in an HRC and the runner loses a fraction of its mantle. (b) Interlude for $\sim 10^{3-6}$ years where Theia is the runner. (c) Return collision is much slower, consistent with the standard model. The two impacts are randomly aligned so the disk has high inclination.

We have shown [9] that giant impact chains were common in the late stage. To turn this into a model for Moon formation, we work our way backwards from the standard model, which except for the isotopes works quite well, with $v_{\rm coll}$ close to $v_{\rm esc}$. The fact that it is at 45° is not unusual so we don't stipulate any angle as a requirement. But what kind of HRC produced Theia? Now there are too many parameters. The outcome of every HRC is different, with slower collisions producing mantle-stripped runners, and faster, steeper collisions producing chains of clumps that can vary from core-rich to oxide-rich [10]. To make headway we have conducted a pilot study (Figure 1) divided into three phases: (a) the giant impact that produced Theia, the runner; (b) the interlude where the pair orbited the Sun with the other planets; and (c) the return collision, a slow GMC.

Modeling. For (a) and (c) we use an SPH code derived from the first numerical studies of lunar formation [11] but with modern equations of state and evolving the entropy equation instead of energy. For the first collision we assume a non-rotating target $0.9 M_\oplus$ in circular orbit at 1 AU, of 30/70wt% iron/rock composition. Proto-Theia is $0.15 M_\oplus$, modeled with the same composition and entropy profile. We consider various HRCs with $v_{\rm coll} = 1.1$ or $1.2 v_{\rm esc}$ and impact angles $\theta_{\rm coll} = 43°$ to 55°. The runner, Theia, ends up about $0.1 M_\oplus$; for now we ignore that it loses a silicate fraction because the fraction depends on the HRC. The target neither gains nor loses much mass in the HRC, but it gets knocked from a stand-still to a rotation period ranging from $T \sim 8$ to 11 hours. No significant disk is produced. We also calculate the egress velocity of the runner relative to the target.

For (b) we transfer the target and runner from each HRC to an N-body code [12], cloning each outcome into 1000 random orientations to represent all possible collisions. We evolve the clones dynamically, including the major planets, until they have another collision with a planet, or for 20 Ma until most giant impact chains are finished. For runners returning to the target, the impact velocity has a computed probability shown in Figure 2. In almost all cases the return velocity is similar to the egress velocity. Later collisions have an increasing random component but are less probable.

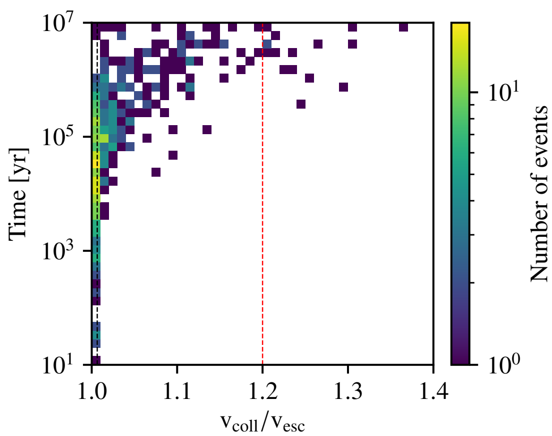

Figure 2: 2D histogram of v_{coll} for all returning runners, for an HRC at $v_{coll}/v_{esc} = 1.20$ (red dashed line) and $\theta_{coll} = 43.5°$. The egress velocity from the HRC is $1.01 v_{esc}$ (black dashed line). Vertical axis is interlude duration, in this case $\sim 10^{4-5}$ years for most returns. Logarithmic scale so most returns are the yellow pixels. Faster runners have longer interlude durations and often don't return [9], or they find another planet.

For (c) we give proto-Earth the same compositional and entropy profile as before, but more massive ($0.95 M_\oplus$) and spun to 8 or 12 hour period, based on (a). The projectile is Theia, which we keep of nominal mass $0.1 M_\oplus$ and composition (30/70wt% iron/rock) in all simulations. By ignoring mantle stripping in (a), which varies from (hit and) run to run, we over-estimate Theia's silicate contribution to the Moon. For the return velocity we set v_{coll} to 1.00 or 1.05 v_{esc}. We have assumed a nominal impact angle $\sim$ 45° throughout; another variable is the *offset angle* between the two collisions, ranging from prograde (0°) to retrograde (180°). This is random [9], and 90° (across a pole) is the most probable return.

The modeled return collisions, being variants of the standard model, end up with a lunar mass or more in orbit. The HRCs leave little orbiting material, so the Moon is the product of the GMC, but with a chemical and a dynamical imprint of the HRC. In terms of the lunar isotopes, it gives an improved solution by tens of percent, worth further study because SPH tends to underrepresent mixing. Dynamically, the disc ends up inclined because of the significant offset angle. For 90° the disc ends up at $i \approx 16°$ relative to Earth's equator. Inclination is strongly damped in the disc phase, and thereafter tidally once accumulation takes place, but if accumulation is rapid (e.g. around a surviving clump of Theia) this offers a potential explanation for the inclined lunar orbit, especially in combination with other processes.

Conclusions. Collision chains might be a common and even typical pathway in planet formation, whereby terrestrial planets slow down enough to merge. Concerning lunar formation, while it is premature to hone in on a favorite scenario, one region of the parameter space seems to work well: a proto-Theia of about $\frac{1}{6} M_\oplus$ that collides with proto-Earth at 1.1 to $1.2 v_{esc}$, producing a mantle-stripped Theia of one Mars-mass, that returns to accrete with the now-spinning Earth in an off-axis GMC thousands to millions of years later. More complicated chains are possible, each one making geochemical predictions.

References

[1] S. T. Stewart and Z. M. Leinhardt. Collisions between gravity-dominated bodies. ii. the diversity of impact outcomes during the end stage of planet formation. *Astrophys. J.*, 751(1):32, 2012.

[2] R. M. Canup. Simulations of a late lunar-forming impact. *Icarus*, 168(2):433–456, 2004.

[3] A. P. Jackson, T. S. J. Gabriel and E. Asphaug. Constraints on the pre-impact orbits of Solar system giant impactors. *MNRAS*, 474:2924–2936, 2018.

[4] E. Asphaug. Impact Origin of the Moon? *Annual Review of Earth and Planetary Sciences*, 42:551–578, 2014.

[5] S. Cambioni, et al. Realistic on-the-fly outcomes of planetary collisions: Machine learning applied to simulations of giant impacts. *Astrophys. J.*, 875(1):40, 2019.

[6] T. S. J. Gabriel, et al. Gravity-dominated collisions: Semi-empirical model for largest remnants with treatment for 'hit and run' and density stratification. *Astrophys. J.*, in press.

[7] C. B. Agnor, et al. On the character and consequences of large impacts in the late stage of terrestrial planet formation. *Icarus*, 142(1):219–237, 1999.

[8] A. Emsenhuber, et al. Realistic On-the-fly Outcomes of Planetary Collisions. II. Bringing Machine Learning to N-body simulations. *Astrophys. J.*, in press. arXiv:2001.00951

[9] A. Emsenhuber and E. Asphaug. Fate of the runner in hit-and-run collisions. *Astrophys. J.*, 875:95, 2019.

[10] E. Asphaug, et al. Hit-and-run planetary collisions. *Nature*, 439:155–160, 2006.

[11] W. Benz, et al. The origin of the moon and the single-impact hypothesis. I. *Icarus*, 66:515–535, 1986.

[12] J. E. Chambers. A hybrid symplectic integrator that permits close encounters between massive bodies. *MNRAS*, 304:793–799, 1999.