BEYOND PERFECT MERGING: THE EFFECT OF INEFFICIENT ACCRETION ON PLANETS' CORE-MASS-FRACTION.

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Introduction: Collisions between similar-sized bodies ("giant impacts") dominate the final stage of planet formation [1]. The energy involved in these events is high enough to substantially melt the remnants and create deep magma oceans [2]. This realization prompted a series of studies ([3] for a review) showing that the cores of the terrestrial planets have formed through a multi-step process, impact after impact. These studies assumed perfectly inelastic collisions ("perfect merging"), which implies that the whole impactor plunges into the target, where the impactor's Fe-rich reservoir equilibrates (totally or partially) with the target's mantle. In reality, a large fraction of collisions result in failed mergers known as hit-and-run collisions (e.g., [4, 5, 6, 7]). By combining recent advancements in machine learning of giant impacts [8, 9] with the planetary differentiation code by [10, 11], this work investigates the effect of inefficient accretion on the differentiation of terrestrial planets in the solar system.

Machine learning of planetary collisions: To overcome the bottleneck of perfect merging in planet formation studies, we use Machine Learning (ML) to realistically predict the outcome of giant impacts [8]. The ML algorithms are collision surrogate models, in the sense that they are trained on high-resolution hydrocode simulations of giant impacts. The surrogate models predict the collision outcome at a known level of accuracy with respect to the SPH simulations. Being fast predictors, the models have been implemented in a N-body routine called collresolve [9] to realistically model giant impacts "on-the-fly" in planet formation studies. To address the question of how inefficient accretion affects planet differentiation, it is useful to define distinct accretion efficiencies for the core and mantle (e.g., for the largest remnant's mass M_L, Figure 1):

$$\xi_L^c = \frac{(M_L^c - M_T^c)}{M_P^c} = \frac{Z_L}{Z_P}\xi_L + \frac{Z_L - Z_T}{Z_P}\frac{1}{\gamma} \qquad (a)$$

$$\xi_L^m = \frac{(M_L^m - M_T^m)}{M_P^m} = \frac{1 - Z_L}{1 - Z_P}\xi_L - \frac{Z_L - Z_T}{1 - Z_P}\frac{1}{\gamma} \qquad (b)$$

where γ is the ratio between the mass of the projectile M_P and the target M_T. The superscripts "c" and "m" refer to the planet's "mantle" and "core", respectively. $\xi_L = (M_L - M_T)/M_P$ is the target's accretion efficiency as introduced in [1] and computed by the ML algorithms presented in [8, 9]. The values Z_T and Z_P are the colliding bodies' core-mass-fractions, which evolve during accretion as computed by the planetary differentiation codes by [10, 11]. Equations analogous to (a, b) are derived for the second largest remnant too. Furthermore, $Z_L = Z_T + \Delta Z_L$, where ΔZ is provided by new ML functions trained on our SPH simulation dataset. We acknowledge that this is an approximation, as the colliding bodies in the dataset have core-mass-fractions equal to 30%. Current work includes expanding the training dataset by introducing variable core-mass-fractions for the input bodies to relax this assumption.

N-body simulations with fragmentation: We post-process the simulations of solar system terrestrial planet formation by giant impacts presented in [9], which repeated the investigation by [12] but using the more realistic treatment of collisions. The simulations evolve the orbits of Moon-to-Mars-size embryos under the influence of Jupiter and Saturn. Different initial mass distributions are also explored. A separate set of simulations with same initial conditions, but assuming perfect merging, is used as a fiducial set.

Metal-silicate equilibration: Magma ocean formation on the collision remnants promotes chemical equilibration between Fe-rich metal and silicate liquids at high pressure prior to the segregation of the former to the core. By modelling the chemical equilibrium between metal and silicate liquids for every giant impact event, we can track how the mantle and core composition evolve in N-body planet formation studies as planets accrete [3]. Following the approach by [10, 11] we assign a bulk composition to every initial embryo in the N-body simulations based on their original heliocentric distance. All the initial embryos are differentiated into an iron-rich core and silicate mantle (the same materials used in the SPH collision simulations to prescribe the equations of state). Al_2O_3, MgO, CaO, Na, FeO are present in the silicate phase, while Si, O, H are present in the iron-rich phase. The code models also the partitioning of other minor species (Ni, Co, Nb, Ta, V, Cr, Pt, Pd, Ru, Ir, W, Mo, S, C and H_2O) and the exsolution of droplets of immiscible FeS liquid from the silicate melt structure in a deep S-bearing magma ocean.

The parameters used to build the bulk composition of the starting embryos are those corresponding to the best-fit solution for Earth in [10]. However, since we do not model debris re-accretion yet, this study is not meant to provide any suggestion of how Earth formed.

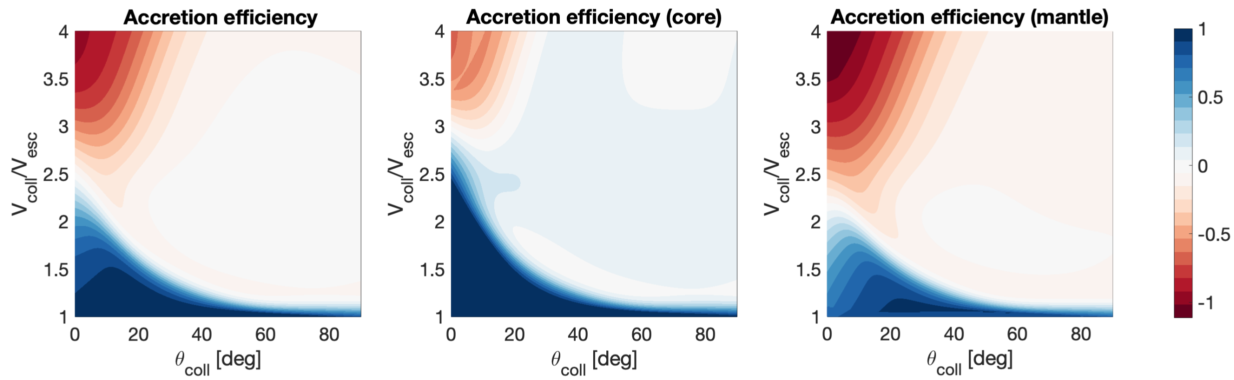

Figure 1. Target accretion efficiencies: $\xi_L = \xi_L^c Z_P + \xi_L^m(1 - Z_P)$ (left), ξ_L^c (a) (center) and ξ_L^m (b) (right) for Earth-size planet colliding with a body of $\gamma = 0.9$, as a function of impact angle θ_{coll} and impact velocity V/V_{esc}.

Preliminary results: Figure 1 shows a slice of the parameter space of the core and mantle accretion efficiencies for the largest remnant. In case of accretionary events, the projectile core plunges into the target's mantle but some debris is still produced. In case of hit-and-run events, the projectile escapes accretion, but the target may still accrete some projectile's mantle material. At low impact angle and impact velocity ~ 2.5 V_{esc}, the impact geometry still leads to core accretion, but the overall accretion efficiency is negative because the event disperses part of the target's mantle. Core erosion is also possible in case of catastrophic disruption.

In order to quantify the effect of inefficient accretion on the core-mass-fraction Z, we are interested in the deviation of the planets' Z-value with respect to the "perfect merging standard", which is built by smoothing the Z-values of the largest bodies in the N-body simulations with perfect merging as a function of heliocentric distance, for same initial conditions:

$$\delta Z = \frac{Z_{Inefficient\ accretion} - Z_{Perfect\ Merging}}{Z_{Perfect\ Merging}} \times 100$$

Figure 2 shows the δZ of the planets in the N-body simulations by [9] as a function of planets' mass. The data are color-coded in terms of h-number, which measures how many hit-and-run events a planet survived during accretion. In a hit-and-run event, the runner's h-number is increased by 1. In a merging event, the largest remnant's h-number is the mass average of the target's and projectile's h-numbers.

When inefficient accretion is realistically modelled in N-body simulations (although, so far, ignoring debris re-accretion), the planets' core-mass-fraction values may deviate significantly from the corresponding "perfect merging standard" values ($\delta Z = 0$, dashed horizontal line). As similar-size planets are expected to have comparable equilibration temperatures and pressures, differences in core-mass-fraction between bodies of the same size are likely due to differences in the accretion histories of the solar system analogs. These include bodies that have experienced hit-and-run events (h-number > 0) whose evolution cannot be modeled assuming perfect merging. Future work will investigate the effect of debris re-accretion on the final Z-values.

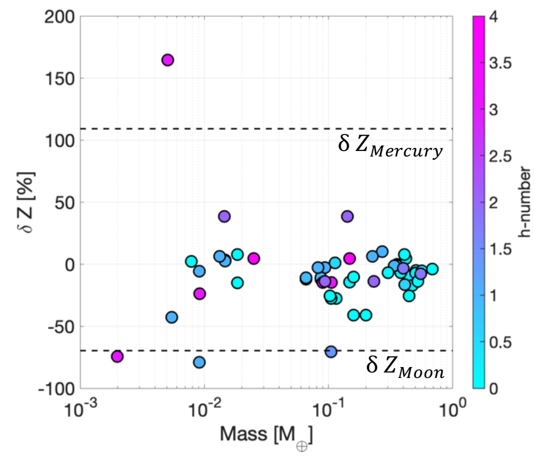

Figure 2. Core-mass-fraction in δ notation (see text) as a function of planets' mass. The dashed lines indicate where Mercury's and the Moon's Z would plot with respect to an Earth-like Z, which is roughly chondritic.

References: [1] Asphaug, E. (2010). ChEG, 70, 199-219, 2010. [2] Tonks, W. B., & Melosh, H. J. (1993). *JGR: Planets*, *98*(E3), 5319-5333. [3] Rubie, D. C., and S.A. Jacobson (2016). *Deep Earth,* 217:181-190. [4] Agnor, C., & Asphaug, E. (2004), *ApJL*, 613, L157. [5] Kokubo, E., & Genda, H. (2010), *ApJL*, 714, L21; [6] Stewart, S. T., & Leinhardt, Z. M. (2012), *ApJ*, 751, 32. [7] Burger, C et al. (2018), *Celest. Mech. Dyn. Astron.*, 130, 2. [8] Cambioni, S., et al (2019). *ApJ*, 875, 40. [9] Emsenhuber, A. et al., (2020) *arXiv preprint: 2001.00951*. [10] Rubie, D. C., et al. (2015). *Icarus* 248: 89-108. [11] Rubie, D. C. et al. (2016) *Science* 353.6304: 1141-1144. [12] Chambers (2001). *Icarus*, 152(2), 205-224.