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# Realistic modeling of water transport to terrestrial planets by combining long-term dynamics and collision physics

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## Abstract

The last stage of terrestrial planet formation probably comprises the growth of planetary embryos – along with remaining smaller bodies – into the final planets, marked by chaotic interactions between the relatively few remaining large bodies, including similar-sized (giant) collisions and radial mixing of material that originated at very different locations in the disk. Despite the increasing trend of treating individual collisions beyond the (over-)simplified perfect merging assumption, this has not yet been applied consistently to (N-body) simulations of water transport to terrestrial planets, and none of the collision-outcome models that emerged in recent years seems to be well-suited for this task [1].

To close this gap between current planet formation models and the actual fate of volatile material in collisions, we present a framework to consistently combine the dynamics of late-stage planet formation with transfer and loss of material in collisions. Our results show that overall water losses in single collisions can often be tens of percent, and in the common hit-and-run encounters the smaller body is frequently stripped of the majority of its pre-collision volatiles. This strongly suggests the necessity to track both large survivors of a hit-and-run collision (and their retained and transferred volatiles) through the further N-body evolution.

## 1. Methods

We use a hybrid approach to combine the dynamical long-term evolution, with fully three-dimensional hydrodynamical simulations of individual collisions. For modeling the N-body dynamics over 10s to 100s of Myrs we use the REBOUND[1] package [3], while collisions are simulated with our SPH code [4]. The latter allows for optional solid-body rheology including a damage model, multiple materials, along with self-gravity, and is implemented to utilize powerful GPU hardware to allow large particle numbers combined with still practical computing times.

[1]REBOUND can be downloaded freely at http://github.com/hannorein/rebound.

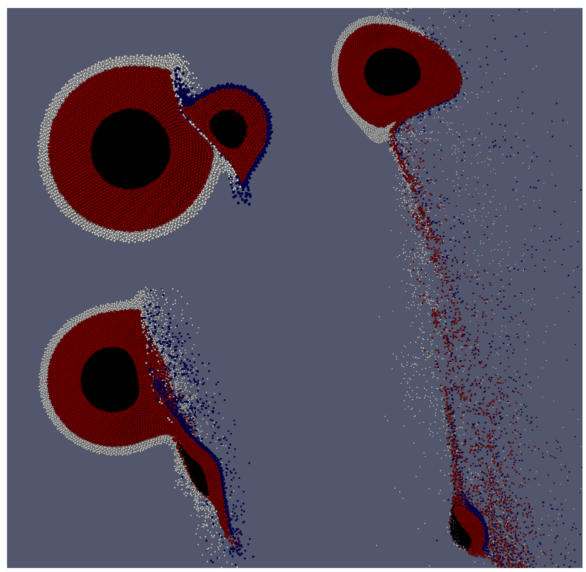

Figure 1: SPH collision snapshots (cut views), illustrating water transfer and loss in a typical hit-and-run encounter. The color-coding shows the bodies' composition, where the initial water inventories of projectile and target are highlighted in different colors (blue and white). The total colliding mass is $10^{23}$ kg, $\gamma = 1{:}9$, $v/v_{\mathrm{esc}} = 2.5$, and $\alpha = 45°$.

## 2. Results and conclusions

Collisions between similar-sized bodies exhibit a diverse range of possible outcomes between (partial) accretion, hit-and-run, and (partial) erosion. In previous work [2] we already showed that not only the impact velocity ($v/v_{\mathrm{esc}}$), impact angle ($\alpha$) and projectile-to-target mass ratio ($\gamma$), but also the total colliding mass are important for determining volatile losses. Fig. 2 summarizes the total amount of water loss (combined for all large fragments) for a suite of collision scenarios. Highly energetic encounters result in losses well above 50%, but already moderate collision parameters can lead to values in the tens-of-% range.

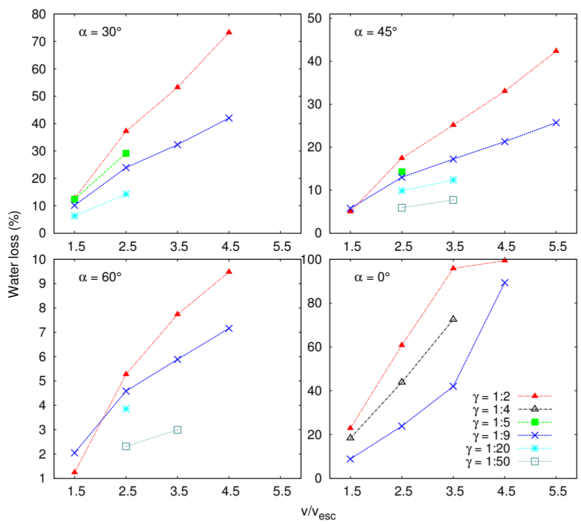


Figure 2: Overall water losses of projectile+target as a function of $v/v_{\mathrm{esc}}$, for a large variety of impact angles $\alpha$ and mass-ratios $\gamma$, from [1]. The strong dependency on each of these parameters is clearly visible.

Especially for relatively fast and non-central encounters, so-called hit-and-run, the individual post-collision water inventories become important, and great differences between the 2 large fragments can emerge, as illustrated in Fig. 3. While the most-massive body remains rather unaltered, it is often especially the smaller one of the colliding pair that is affected down to the core, and efficiently stripped of volatiles, as exemplified in Fig. 1. Therefore combining physically correct collision outcomes with N-body dynamics has to include the 2 large hit-and-run survivors separately, even if this results in a considerable computational slow-down since the number of bodies decreases naturally much slower with time (compared to having strictly only 1 survivor).

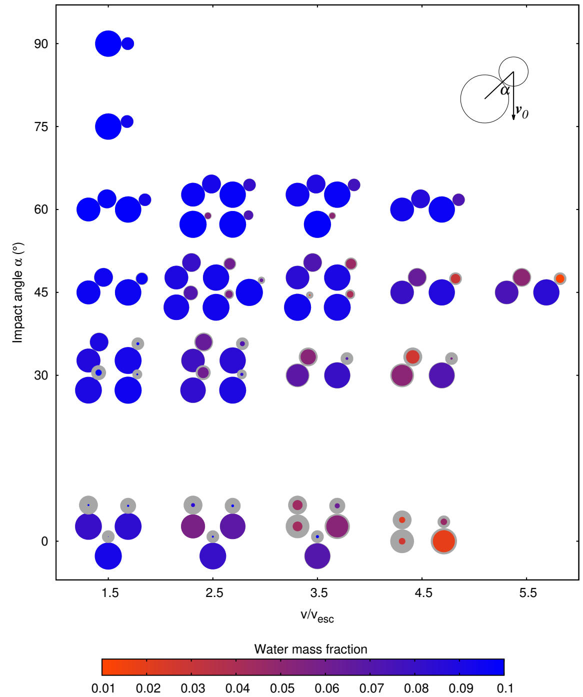


Figure 3: Results of similar-sized, giant collisions, including the distinction between the largest and 2nd-largest fragment, in a grid of $v/v_{\mathrm{esc}}$ and $\alpha$, and for different $\gamma$ (sizes of the light-grey pictograms) from [1]. All circle-sizes are $\propto$ mass$^{1/3}$, and the colored circles indicate post-collision mass. The pre-collision water-mass fractions are always 0.1 for both bodies.

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