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Water transport and water loss by collisions during planet formation

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Abstract

In this contribution, we present results of collision simulations pertaining to water loss covering body masses ranging from a small planetary embryo to the mass of Earth. We find that for most realistic combinations of object masses, collision velocities, and impact angles a considerable amount of water is lost, which may significantly change the water inventory of formed terrestrial planets. Also, there is indication that beyond the 'usual' parameters characterizing a collision (velocity expressed in units of the mutual escape velocity v_{esc} and impact angle), water loss depends on factors like absolute mass, the projectile-target mass ratio, and to a certain extent the water distribution inside the objects.

1. Introduction

It is well established that planet formation involved a long-term sequence of collisional events between protoplanetary bodies. Typically, dynamical evolution studies use n-body simulations to investigate this collisional growth, but simplify the collision model based on perfect inelastic merging and linear momentum conservation (e.g., [9, 11]) or the application of simple fragmentation models ([2]). However, depending on the involved masses, collision speeds, and the impact angle (e.g., [10]) the collision outcome is one of efficient accretion/perfect merging, partial accretion, hit-and-run, or erosion and disruption ([3]). The perfect merging assumption does not model the actual physics of collisions ([1, 3]).

While water transport in giant impacts has been investigated (e.g., [7, 15]), the fate of volatiles such as water in small to mid scale collisions – which dominate at least the early stages of planet formation – remains largely unstudied. Existing planet formation simulations overestimate the water content of terrestrial planets. [8] study planet formation in binary systems and estimate an artificial increase of their water contents by a factor of 5–10; [16] use the perfect merging assumption for planet formation in single star systems and estimate their water contents to be accurate only within a factor of two.

2. Method

We perform simulations with our parallel 3D smooth particle hydrodynamics (SPH) code as introduced in [13] and [17]. It implements solid state continuum mechanics extended by a model for simulating brittle failure (cf. [5, 6]) and includes self-gravity. We apply a tensorial correction along the lines of [18] to achieve first-order consistency.

The material model is based on the Tillotson equation of state ([19]). We use the same material parameters for rock (basalt) and water ice as stated in [17].

In the individual scenarios described below we resolve the objects into between 20k SPH particles for the parameter study of Ceres-sized colliding bodies and one million SPH particles for the collision of a small planetary embryo with an object of Earth mass.

3. Results and conclusion

We performed three suites of simulations in different mass regimes, totaling to some 60 scenarios: (a) Ceres mass objects with velocities and impact angles from a dynamical study in a solar system-like environment ([12]); (b) larger planetary embryo collisions from n-body simulations by [9]; (c) Ceres-sized projectiles hitting planet-size targets in binary star systems at higher speed from [4].

Figure 1 summarizes the water loss resulting from the three suites of scenarios for one particular impact angle $\alpha = 30^\circ$ (measured from the vertical, chosen because it occurs in all three scenario sets) and several collision velocities up to 6 v_{esc}. We define water loss as the ratio of the water-mass not gravitationally bound to the surviving object(s) and the total initial water. Please refer to [14] for a more comprehensive discussion of the simulation results.

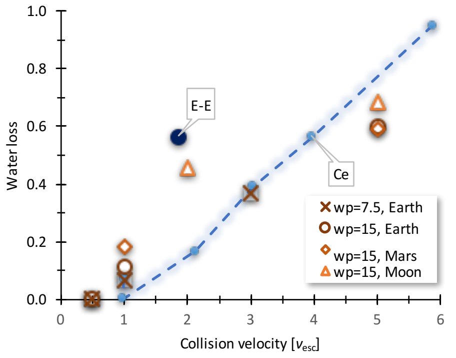

Figure 1: Water loss (y-axis) at a given impact angle (here, 30°). It not only depends on the collision velocity (x-axis), but also on absolute body mass (light blue: Ceres mass, dark blue labeled 'E-E': embryos of $0.5\,M_\mathrm{Mars}$ and $0.8\,M_\mathrm{Moon}$, brown: Ceres mass projectiles with different water content wp hit planet-sized targets as indicated).

Our results show that even for collisions at moderate speed water loss is not negligible – for embryos colliding at twice their mutual escape velocity as much as 10 %…60 % of their water content are lost *per collision*. Keeping in mind that (a) evaporation and sublimation further increase water loss and (b) a long series of collisions may happen until a planet is formed, it gets obvious that the assumption of perfect merging – in particular 100 % accretion of volatiles – whenever a collision occurs does not hold. Present n-body based planet formation simulations suggest terrestrial planet water abundances which are too high by up to a factor of 5–10 (cf. [8, 16]). Finding a way to combine realistic collision simulations and n-body studies will likely close this gap between reality and simulations.

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