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Water transfer and loss in hit-and-run collisions

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Abstract

This work focuses on transfer and loss of volatiles, like water, in hit-and-run collisions, where especially the smaller one of the colliding pair is often stripped of considerable amounts of its initial volatile content, but still survives the encounter more or less intact. We find water losses up to 75% in a single collision, depending on various parameters, especially velocity, impact angle and mass ratio, but also on the total colliding mass. The physical state, especially vaporization of volatiles, is found to be particularly important in collisions of ~ Mars-sized bodies, with high impact energies, but still potentially easy volatile escape.

1. Introduction

The formation of (terrestrial) planets is believed to end with a phase dominated by similar-sized collisions between planetary embryos, once the gas disk disappears and dynamical friction by planetesimals becomes inefficient. It is characterized by chaotic interactions and mixing of material originating from different locations in the disk (e.g., [7]) which shape the final characteristics and composition of planets. Volatile material like water(-ice) is particularly affected by transfer and loss processes, also because they are preferentially found in the outer layers of (partly) differentiated bodies. Studies of late-stage accretion by means of N-body simulations mostly treat collision outcomes only rudimentary, if at all, where perfect merging is still an often-used assumption. This falsifies results in general, and even more for volatile inventories (see e.g., [5, 2]). While impacts of small bodies on much larger ones are usually hit-or-miss events, a broad range of distinct outcomes is possible for collisions between similar-sized bodies ([6]). For head-on collisions they transition from accretion to erosion with increasing impact velocity, but for sufficiently oblique collisions an additional outcome regime emerges: hit-and-run. These encounters are characterized by 2 large surviving bodies, or even by a large one and a chain of smaller ones. Having more than one large survivor makes them difficult to track, but also interesting, and important to the fate of volatiles (and also to various other questions, like Mercury's large core). Recent results have shown that up to half of all giant collisions in an active planet formation environment are actually from the hit-and-run type (e.g., [4]), therefore understanding their characteristics is a necessity for a realistic treatment of volatile transport in the next generation of N-body simulations.

2. Method and scenarios

We perform collision simulations of self-gravitating, differentiated (iron core – basaltic mantle – water ice shell), embryo-sized bodies with our SPH code ([8]), which allows us to study the dynamical fate and also the physical state of volatile inventories during and after a hit-and-run collision. The parameter space is large, where the impact velocity $v/v_{\rm esc}$, impact angle α, mass ratio γ and also overall mass $M_{\rm tot}$ ([3]) are the most important ones. We ran a suite of simulations with typical impact velocities up to several times $v_{\rm esc}$, impact angles between $30°$ and $90°$, mass ratios ranging from 1:2 up to 1:50, and total masses between 10^{22} and 10^{25} kg. The majority of simulations comprise hydrodynamical objects, but we also compare them to results obtained with our solid-body material model to clarify the influence of material strength.

3. Results and conclusions

In general the impact energy is partitioned between the projectile and the target, thus the projectile is proportionally more affected the lower the mass ratio. Disrupting bodies via impacts (by smaller projectiles) has been found to be very difficult once they grow large enough (e.g., [1]), which we can confirm also for their volatile contents, albeit to a lesser degree. Focusing on the smaller of the two survivors in a hit-and-run collision provides a new perspective to that, since they outline a reasonable path towards stripping large bodies of volatiles or even disrupting them entirely, once they are hit by an even larger body. Our results confirm that neither of the two largest fragments ever increases its water mass fraction. The largest fragment (initially the target) barely looses mass and only little volatiles (cf. Fig. 1), except for low impact angles and high velocities, but the projectile is much more affected, with water losses up to 75% in a single collision. Since objects are expected to suffer a sequence of giant collisions in the late stages of planet formation this clearly indicates that the usual assumption of perfect merging is highly inaccurate, particularly w.r.t. volatile components.

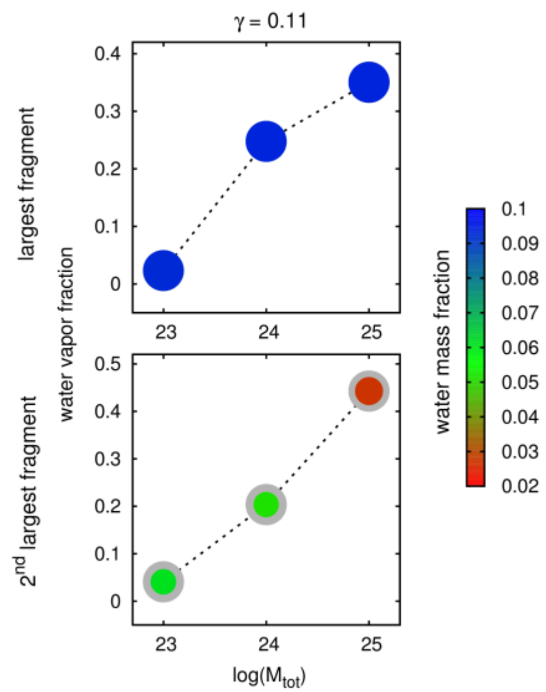

Figure 1: Water vapor fraction on the 2 largest post-collision fragments as a function of total colliding mass (kg), with all other parameters equal ($v/v_{\rm esc} = 2.5$, $\alpha = 45°$, $\gamma = 1{:}9$). The grey circles indicate pre-collision sizes of the projectile and the color-coding illustrates the water mass fraction (all states) after the collision, which is initially 0.1 for both bodies.

In order to better understand the mechanisms leading to stripping of volatile layers it is instructive to clarify which physical processes dominate under which collision conditions. This includes purely mechanical effects (like shears) as well as shock acceleration. We also track the physical state of water reservoirs, especially the amount of vaporized material (mainly due to shocks), where we estimate the ratio of vaporized to non-vaporized water after the collision for a broad range of masses – and thus collision energies. Figure 1 illustrates this for a subset of our scenarios. Overall we find water vapor fractions on the two large surviving fragments essentially spanning the whole possible range between 0 and 1. Especially our intermediate mass scenarios (∼ Mars-sized bodies) are interesting in this respect, because impact energies are already high enough for large scale vaporization, but the collision fragments are still small enough for potential escape of considerable amounts of water vapor.

For a relatively narrow range of parameters the target survives quite intact, but the projectile is ripped into a chain of small, but still planetesimal-sized (around 0.1% of $M_{\rm tot}$) fragments, mostly sharing the chemistry of their precursor body. We find that these chain elements tend to be increasingly dry, the more massive the colliding bodies or the more energetic the collision is, respectively. This trend is even enhanced when escape of vaporized material from these low-gravity bodies is included. Besides this compositional footprint this also implies that their significance for further water transport strongly decreases with $M_{\rm tot}$.

Acknowledgements

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