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The First Accurate and Quantitative Model of the Formation of Terrestrial Planets and Origin of Earth's Water

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Abstract

We have developed a comprehensive methodology to model the formation of terrestrial planets and origin of Earth's water. Using a combination of SPH and N-body codes, we model the collisions and growth of embryos to planetary bodies accurately. We simulate collisions directly, and for the first time, consider the loss of water due to the heat of the impact, mass-removal during collisions, and ice-sublimation during orbital evolution of bodies. Our results present a more accurate and quantifiable estimate of the water delivered to Earth and are informed directly from geological evidence of Earth evolution. Our methodology also tracks the transfer of water and volatiles from one body to another, self-consistently.

1. Introduction

It is widely accepted that collisions among solid bodies, ignited by their interactions with planetary embryos is key to the formation of terrestrial planets and transport of water and other volatiles to their accretion zones. Unfortunately, due to computational limitations, these collisions are often treated in a rudimentary way where impacts are considered to be perfectly inelastic and water is fully transferred from one object to the other. This perfect-merging assumption, while useful for the proof of the concept, portrays an unrealistic image of the formation and properties of the final planetary bodies that is unquantifiable and grossly overestimates the masses of these objects and the amount of their volatiles. It also entirely neglects collisional-loss of volatiles and draws an unrealistic connection between these properties and the chemical structure of the protoplanetary disk. Modern collision models have tried to overcome these difficulties by determining the outcome of collisions and the number of produced fragments by either using an impact catalog or a pre-set prescription. However, these models still do not treat the transport and transfer of water accurately. They consider no loss of water during the orbital evolution of an object and consider perfect transfer of volatiles from one body to the other after a collision.

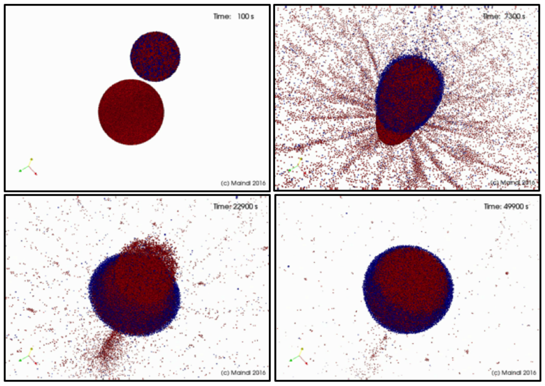

Figure 1: Snapshots of the SPH simulation of an impact between a 0.8 Moon-sized embryo with 10% water and a dry, 0.5 Mars-sized object (impact velocity = 6 km/s).

We have developed a new and comprehensive approach in simulating collisions and the growth of embryos to planetary bodies where we use a combination of SPH and N-body codes to model collisions as well as the transport/transfer of chemical compounds accurately. We simulate collisions directly (i.e., without using impact catalogues and fragmentation prescriptions), and for the first time, consider the loss of water due to the heat of the impact, mass-removal during collisions, and ice-sublimation during orbital evolution of bodies.

2. Description of our codes

We simulate terrestrial planet formation using a combined N-body+SPH code. Our N-body code has been developed to allow collisions to happen only when bodies are physically in contact with one another. At that stage, we model the collision using our full 3D SPH impact code [2,3].

Our SPH code includes material strength and self-gravity, and implements full elastoplastic continuum mechanics extended by a model for simulating brittle failure [4, 5]. It also includes a fragmentation prescription and accounts for evaporation during the impact as well as the re-accretion of scattered materials. Following [6], we apply a tensorial correction to achieve first-order consistency. The material model is based on the Tillotson equation of state [7]. As a result of this approach, i.e., SPH modeling of collisions within the N-body integration, our simulations are free of collisional artifacts and present more accurate values for the mass and volatile contents of the final planets.

3. Simulations and Results

To accurately model the formation of terrestrial planets and the delivery of water, we carried out a large number of traditional N-body simulations. Each simulation included a few hundred Moon- to Mars-sized planetary embryos and several thousand km-sized planetesimals. To avoid un-necessary computations, we limited SPH simulations to only collisions with the seed embryos that resulted in the formation of final planetary bodies. For each seed embryo, we simulated its collision with other embryos as well as planetesimals. The latter is necessary to account for the loss of water due to ice sublimation from impact craters. In each simulation, we determined the amount of ice exposed at the bottom and walls of the crater as well as those re-accreted on the surface of the embryo. We then calculated the amount of sublimated ice until that embryo collided with another embryo or the exposed ice was fully sublimated.

Each collision of a seed embryo with other protoplanetary bodies was simulated using our SPH code. We considered embryos to be rocky and used the parameters for rock (basalt) and water ice as stated in [3]. Porosity was included using the $P-\alpha$ model [8-11]. At the lowest resolution, each embryo was resolved to at least 500,000 SPH particles. We determined the water content of the resulting body by keeping track of each SPH particle, and continued this process for subsequent collisions until the last impact event when the final planetary body formed. During this process, mass of the final planet and its water content were accurately determined. Figure 1 shows a snapshot of a sample of our embryo-embryo SPH simulations.

We carried out 60 SPH simulations of collisions between embryos of Ceres size and larger. Results indicated that even for collisions at moderate velocities, the amount of water lost during the impact is non-negligible. For instance, for embryos colliding at twice their mutual escape velocity, 10% to 60% of their water is lost in a collision. Figure 2 shows this in more detail. Noting that in addition to collision, water is also lost due to evaporation and sublimation, and a seed embryo may be subject to a large number of collisions until a planetary body is formed, the above-mentioned water-loss percentages may be even larger.

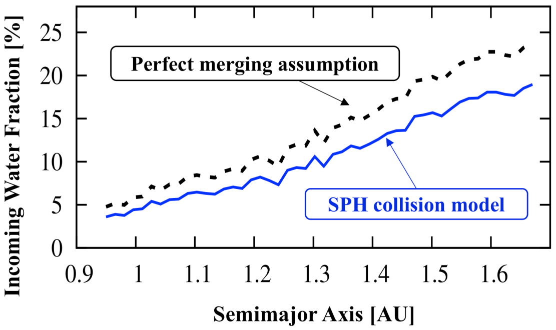

Figure 2: A comparison between the amount of water introduced to the terrestrial region in perfect merging and in our model.

4. Summary and Conclusions

Accurate simulations of collisions of protoplanetary bodies show that tradition-al N-body modeling of terrestrial planet formation overestimates the amount of the mass and water content of the final planets by over 60%. This implies that, as indicated by [1], i) small planets such as Mars can also form in these simulations when collisions are treated properly and ii) the distribution of water, volatiles, and chemical compounds cannot be post-formation and must be handled during a simulation, through proper treatment of collisions.

5. References

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