Hydrodynamic Simulations of Giant Impacts

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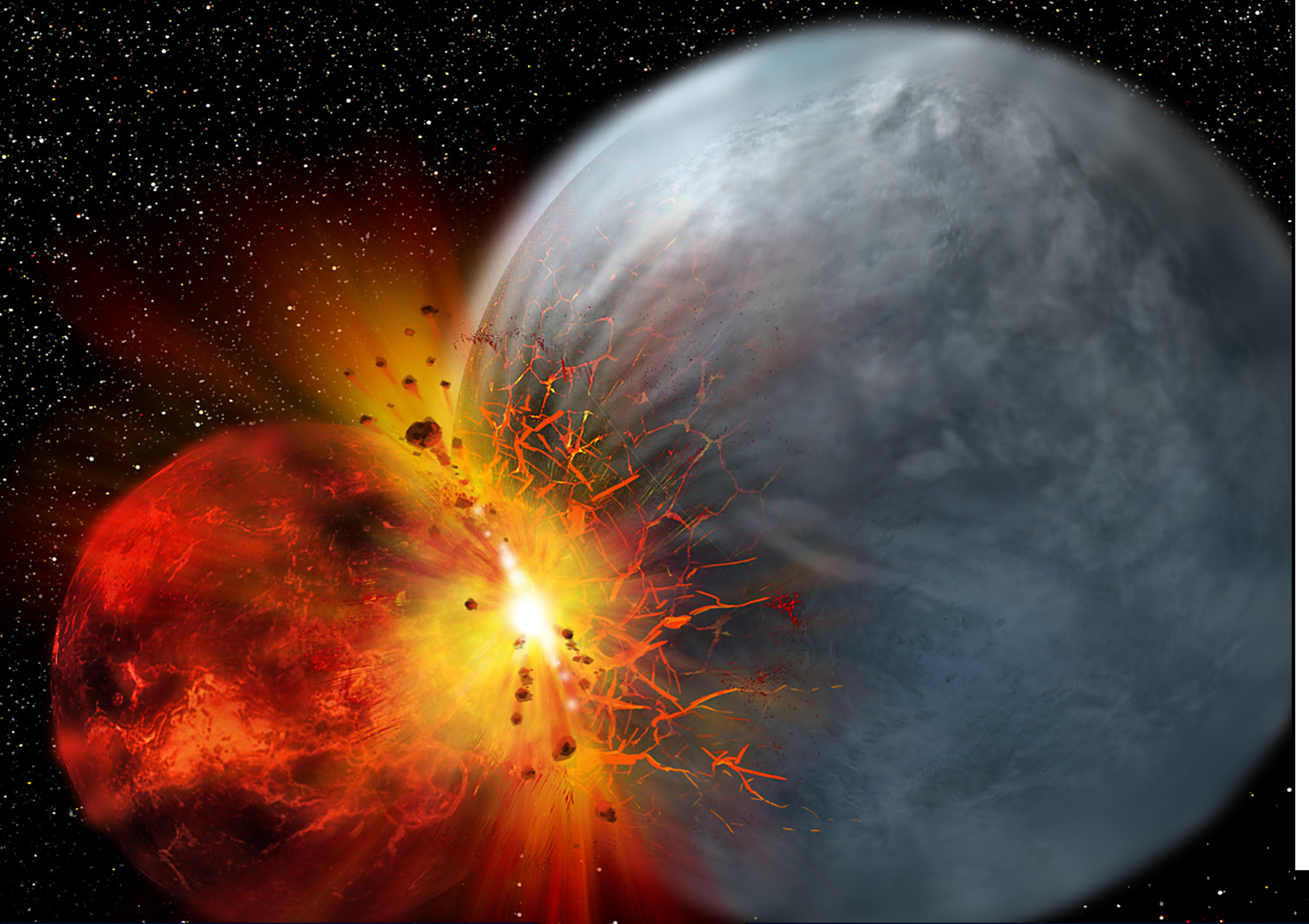


Introduction

Giant Impacts (GI) are large collisions between planetary embryos and form the last stage of terrestrial planet formation. They also provide a possible explanation for the origin of our moon. Since the mid 80s computer simulations played an increasingly important role in investigating such giant impacts (e.g. Benz 1986, Canup 2001) and are one of the main tools used today. Both bodies can be treated as fluids so numerical methods similar to those used for ideal gas physics in cosmology can be applied to the problem.

To study the basic numerical aspects of GI we modified GASOLINE, a massive parallel, multi-stepping Smoothed Particles Hydrodynamics code that has been extensively used in such cosmological simulations, to simulate condensed materials like granite or iron. Since it could handle hundreds of millions of particles for a ideal gas physics we were curious to see how well it performs for condensed materials. To keep the focus on the computational part of the problem we decided as a first step to model both bodies as isothermal granite spheres and switch to more realistic models once we got a good understanding of simulating "condensed" fluids.

As a first step we reproduced the main features of Benz pioneering work from 1986 (see lower left panel). Then we increased the number of particles to 48k and run several simulations for different impact angles and initial velocities. The best resolution we reached so far in our simulations was $1.2*10^6$ which drastically improves how the shock wave and the "arm" like structure of ejected material is resolved. How much material is ejected and how much it is bound depends on the initial conditions but also clearly on the resolution.

Currently we are investigating some numerical issues we encountered during our simulations and are implementing differentiated models, making one step closer to more realistic simulations.

A "Condensed" Fluid

Assumptions:

- Since for such large bodies gravity is dominating over material strength we could treat them as fluids.
- To focus on the numerical aspects of the problem we used granite spheres rather than differentiated bodies.
- For the relatively short time scales (several hours) we covered in our simulations radiative cooling of the material can be neglected.

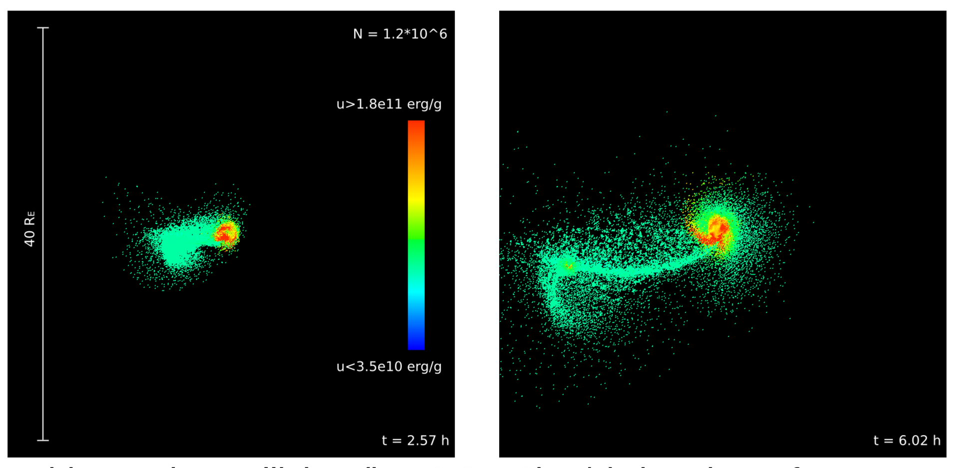
Smoothed Particles Hydrodynamics:

- We used Smoothed Particles Hydrodynamics (SPH) to solve the equations of motion of the fluids and coupled it to a particle based gravity solver.
- In SPH the fluid is sampled with particles that represent the fluid at discrete locations and move with the flow (Lagrangian technique). The physical quantities are then calculated by summing over neighboring particles.

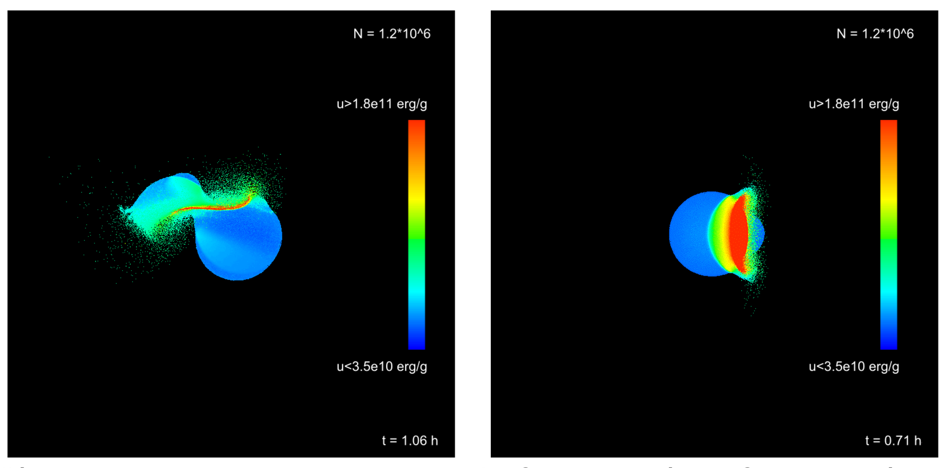
Advantages:

- SPH has excellent conservation properties (energy, momentum and angular momentum)
- It can be used to simulate very deformed geometries.
- We can track the origin of the material, which is important for matching our results with observations.

Examples of Giant Impacts

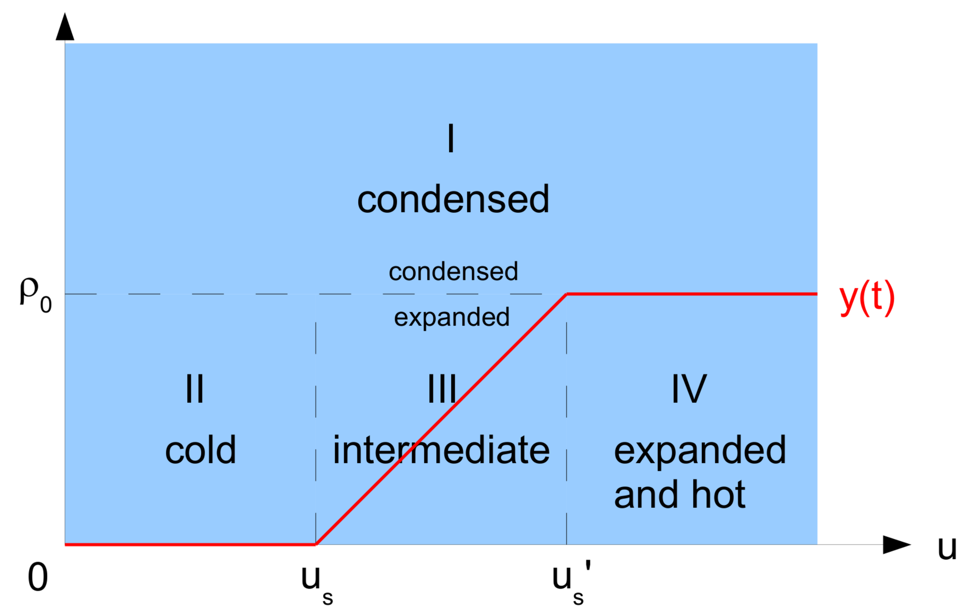


In this grazing collision (b = 0.8, 10km/s) the ejecta forms a compact, "arm" like structure mostly made of impactor material. Some remains bound and could form a future moon.



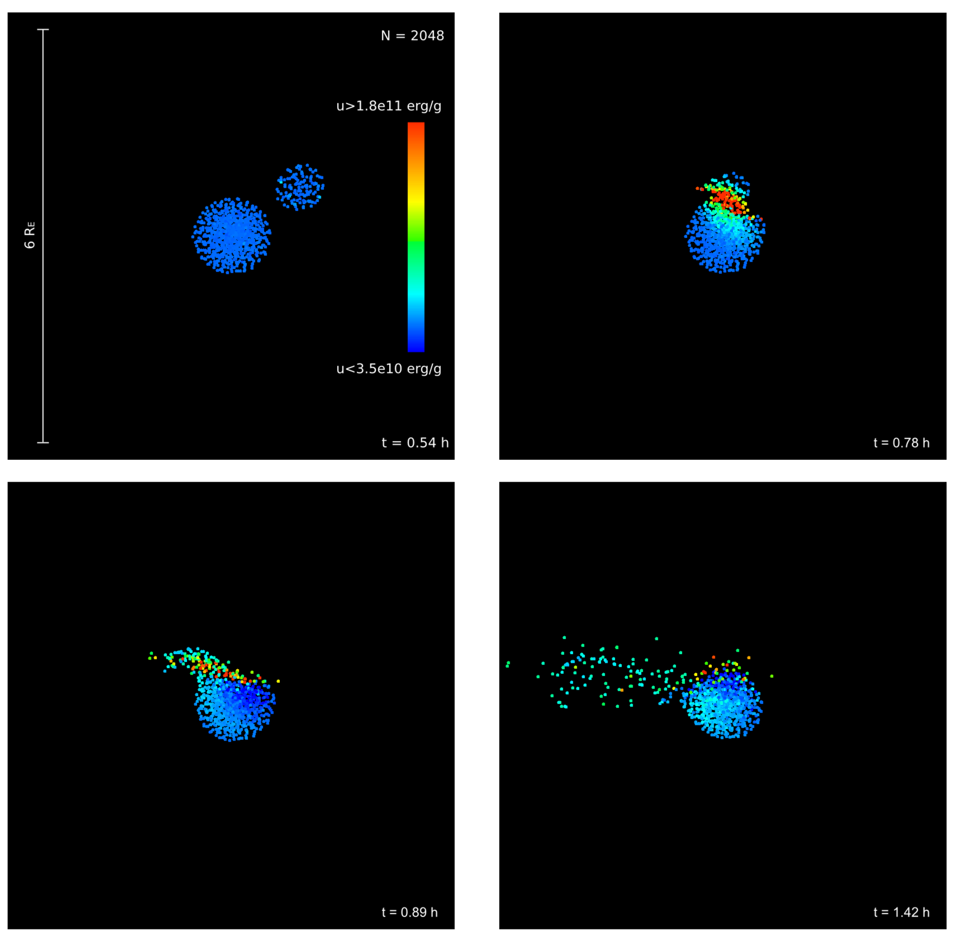
Shown are two extreme cases. Left we see how for a grazing impact (b = 0.9) the material at the impact site is evaporated and the part of the impactor that survived the direct collision is sliding by the target. Right is an example of a direct collision (b = 0) where the impactor is destroyed entirely by the impact.

Equation of state



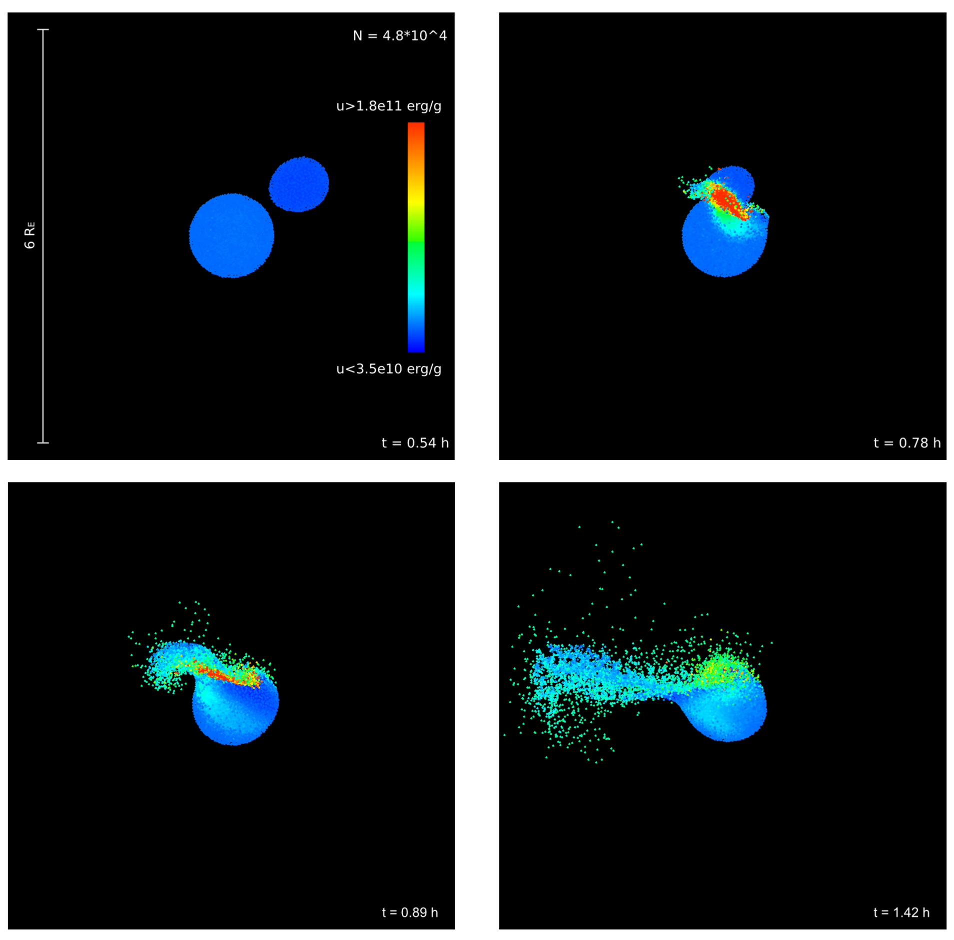
The *Tillotson equation of state* (EOS) is a generalization of the Mie-Gruneisen EOS for condensed materials to also describe vapor phases and was especially developed for hyper velocity impact calculations. It has been widely used in previous impact simulations because of its simplicity and ability to accurately capture shocks. Depending on the density and internal energy of the material the Tillotson EOS can be divided into four distinct regions (see picture) where is has a different analytic form. This not only makes it easier - compared to a tabulated EOS - to handle and implement it in a code but also helps to physically interpret the results of the simulations and setup initial conditions.

Low resolution



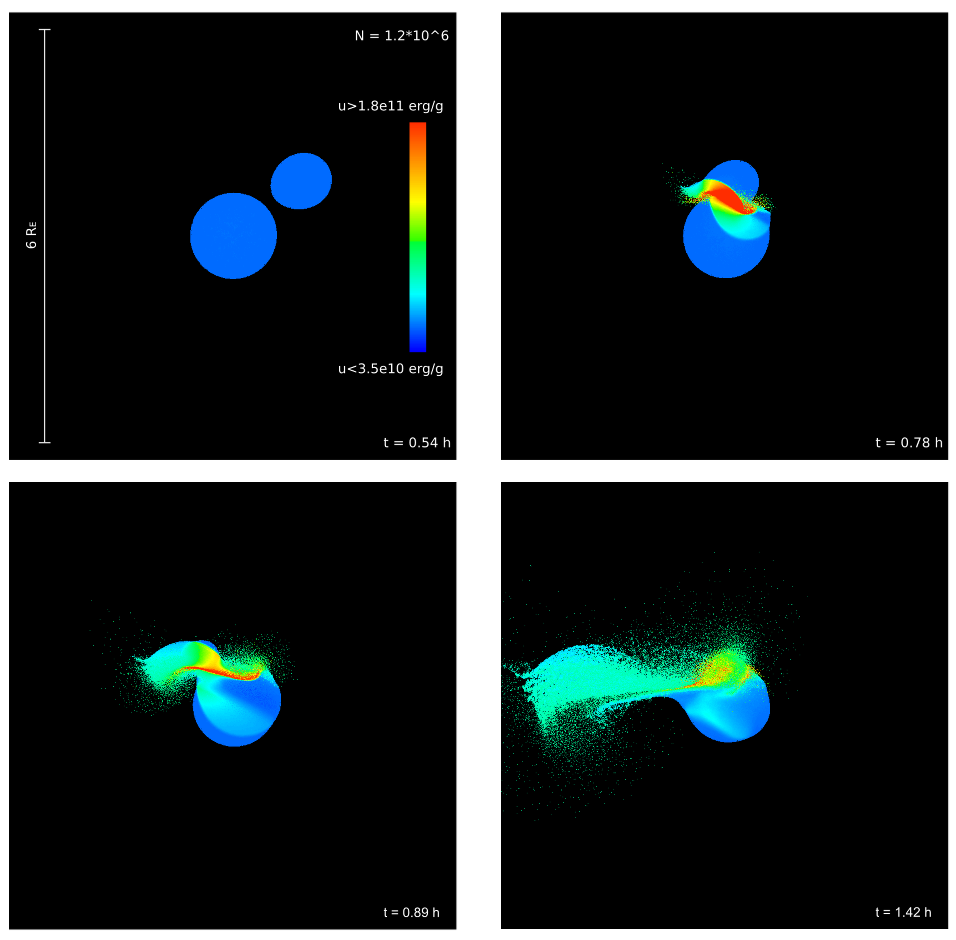
Here we reproduced the main features of Benz pioneering simulations (b = 0.8, vstart = 10 km/s, 2048 particles). The impactor is deformed by tidal forces during the approach and we see a shock wave passing trough both bodies right after the impact and how material is ejected from which a moon could form.

Medium resolution



Increasing the number of particles (b = 0.8, vstart = 10 km/s, 48'000 particles) results in a much better resolved shock wave and we can see that the ejecta starts to form an "arm" like structure. One can also see that the material at the impact site evaporates as soon as its density decreases below the reference density.

High resolution



For more than a million particles (b = 0.8, vstart = 10 km/s, $1.2*10^6$ particles) both the shock wave and the structure of the ejected material are well resolved and we can see how a part of the impactor survives the direct impact and forms a denser core at the end of the arm.

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