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Material loss in two-body collisions during planet formation

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Introduction

During the formation process of a terrestrial planet, a planetary embryo does not only accrete smaller dust particles but also suffers collisions with larger planetesimals. When simulating these collisions, most N-body codes treat them as perfect merging events, i.e. the resulting body's mass is the sum of the previous ones. In our work, we aim to determine whether this assumption is a justified simplification, specifically focusing on bodies containing volatile elements, such as water.

Material Transfer and Loss

Fundamental Questions

- How much does the material transfer in a Hit-and-Run collision differ from a perfect merging event?
- How much is the material transfer influenced by different model parameters?
  We consider the following characteristics:
  - Solid / hydro
  - brittle / no brittle material
  - $\varrho > 0$ / $\varrho < \varrho_{\text{limit}}$ / unconstrained ϱ

Implementation

We have developed our own Smooth Particle Hydrodynamics (SPH) code that includes the following features:

- Self gravity (using a Barnes-Hut tree algorithm)
- Tillotson Equation of State
- Elasto-plastic dynamics (cf. Von Mises)
- Damage model for brittle materials (cf. Benz and Asphaug)

It runs on modern GPU architecture using the Compute Unified Device Architecture (CUDA) which allows for higher resolution in less calculation time.

Simulations

We calculated a hit-and-run collision of two Ceres sized bodies consisting of basalt. One contains a water shell around its core (30wt-%).

Parameter	Value
Number of Particles	200 000
Mass of each body	$9.43 \cdot 10^{20}$ kg
Water Content	30 *wt*-% on one body
Collision Velocity	880 $\frac{\text{m}}{\text{s}}$
Collision Angle	$\approx 60^\circ$

Table 1 Parameter Table

	Mass [10^{20} kg]	r_k [km]	v_k [$\frac{\text{m}}{\text{s}}$]	w_k [wt-%]
F_1	9.55	29 801	278	2
F_2	9.17	31 123	289	27
F_3	0.002 52	20 927	255	29
F_4	0.002 04	5441	62	30
F_5	0.001 77	18 645	219	66
F_6	0.001 56	10 657	120	39

Table 2 Main fragments with mass, distance to center of mass r_k, barycentric velocity and wt-% of ice

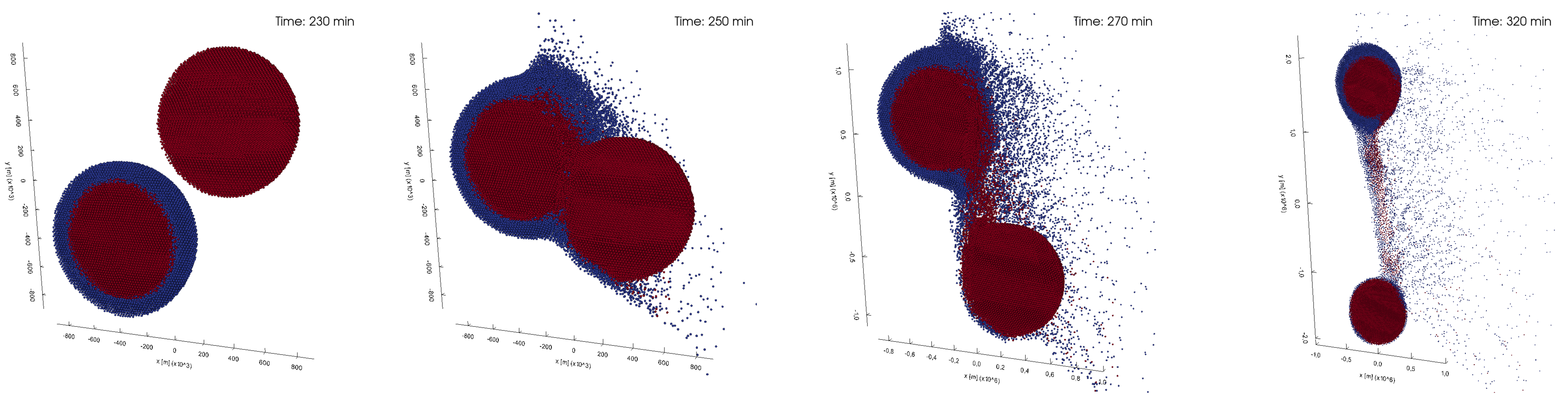


Fig.1 Collision snapshots at different times. The collision itself occurs after 234 minutes. For better visibility of the inside structure we cut open the two bodies along the z = 0 symmetry plane. Basalt is plotted in red, water ice in blue.

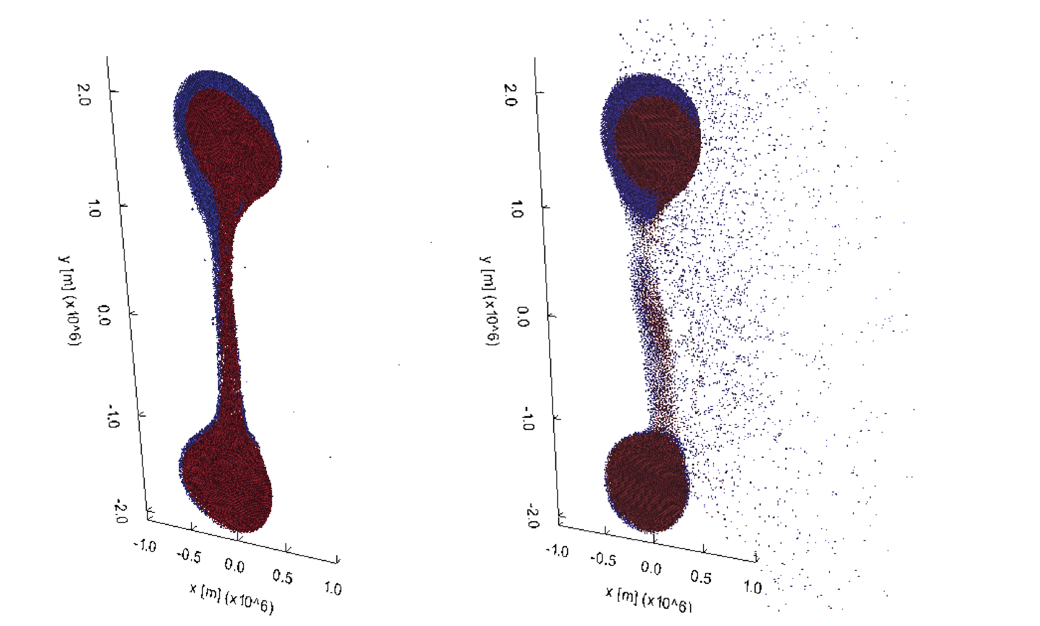


Fig.2 Comparison of two models 86 min after the collision: hydro - no brittle - $\varrho < \varrho_{\text{limit}}$ (left) and solid - brittle - $\varrho < \varrho_{\text{limit}}$ (right)

Focus on Volatile Elements

Fundamental Question

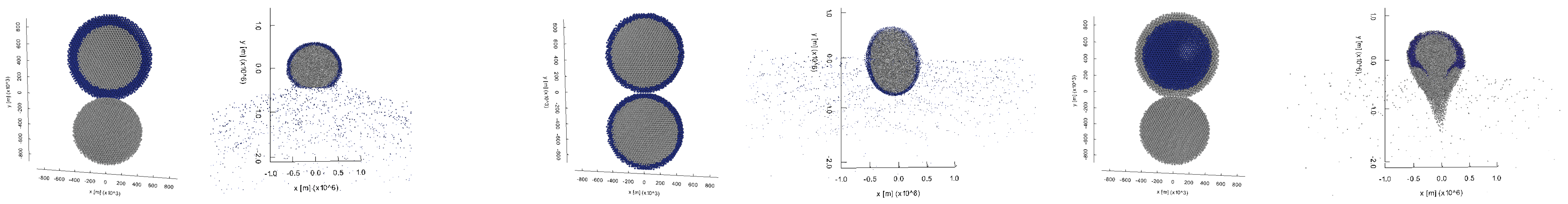
Does the amount of transferred water during a collision depend on its original distribution within the system?

Simulations

Deciding for one fixed set of parameters, we only varied the distribution of the water within the system. For the chosen slow head-on merging event, we analysed three different scenarios: The first had a 30% water shell around one body, the second a 15% shell around both and the third a 30% water core in one body.

Results

For the considered parameters, most of the material is transferred to the resulting body and the variations for the different scenarios are rather small. The first two show similar results of approximately 6% water loss while the third loses none at all. This is due to the protected position of the volatiles at the very inside of the body.
After the collision, the water distribution within the new body shows significant differences: In all scenarios, the water spreads over a much greater radius range than before. This opens up interesting perspectives for subsequent collisions.



a) Scenario 1 b) Scenario 2 c) Scenario 3

Fig.3 Collision snapshots for each of the three scenarios right before the collision and 133 minutes after. For better visibility of the inside structure we cut open the two bodies along the z = 0 symmetry plane. Basalt is plotted in grey, water ice in blue.

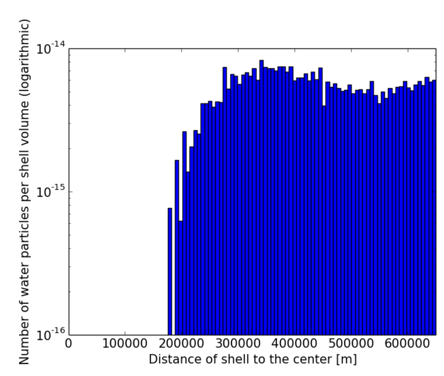
Parameter	Value
Number of Particles	50 000
Mass of each body	$9.43 \cdot 10^{20}$ kg
Total Water Content	30 *wt*-%
Collision Velocity	$\approx 640 \frac{\text{m}}{\text{s}}$
Impact Parameter	0 km
Materials	Basalt and Ice

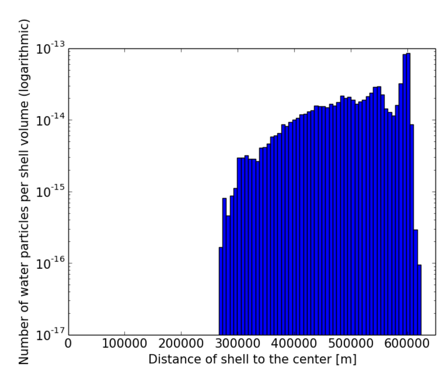
Table 3 Parameter Table

Scenario	Water Distribution	Water Loss
1	30% around one body	5.87%
2	15% around each body	5.95%
3	30% inside one body	0%

Table 4 Water Loss for each Scenario

Fig.4 and **Fig.5** Water Distribution within the newly created fragment for Scenario 1 (left) and Scenario 3 (right)





Conclusion and Future Work

Collisions at higher angles and moderate velocities show a lower material transfer than perfect merging events. Also, modeling brittle materials leads to much more fragmentation and material loss than without a damage model. We will continue to analyse this in more detail and include a wider range of collision scenarios.

References: Barnes, J. & Hut, P. 1986, Nature, 324, 446 - Benz, W. & Asphaug, E. 1995, Comp. Phys. Communications, 87, 253 - Maindl, T. I. et al. 2013, AN, 334, 996 - Monaghan, J. J. 1992, ARA&A, 30, 543 - Tillotson, J. H. 1962, Tech. Rep. General Atomic Rep. GA-3216, General Dynamics, San Diego, CA