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Core Fragmentation of Differentiated Bodies Upon Impacts Into Magma Oceans – Insights From Numerical Modelling

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Introduction: The origin of the relatively high concentration of highly siderophile elements in Earth's mantle [1] is still debated. One possible explanation is the addition of iron rich cores of differentiated impactors during the late accretion phase [2]. Since Earth has most likely had a magma ocean during this period [3], a quantitative understanding of impacts into such targets is of pivotal interest. In particular the answer to the question whether the impactor core material breaks into droplets or remains mostly in one piece is key, since this greatly affects the metal-silicate equilibration and mixing in the magma ocean [4]. This topic has been examined by several experimental as well as numerical studies [5,6,7]. The latter include mesh-free methods like smoothed particle hydrodynamics (SPH [8,9]), which may suffer from insufficient resolution, as well as grid based approaches. To expand on previous studies with such grid based algorithms [7], we implemented a method to improve the resolution and tracking of small material fragments in the simulation. This approach lays the groundwork for detailed studies of the size-frequency distribution of impactor cores in dependency to the impact parameters (core size, impact velocity and angle), as well as target properties (depth, temperature, and viscosity of the magma ocean). In a next step our results can then be used as input for further models studying material mixing in a convecting magma ocean [10].

Methods: We performed simulations of asteroid impacts using the iSALE-2D shock physics code [11,12], utilizing an Euler grid. By adding Lagrangian tracers at defined position at the start of the simulation, more detailed tracking of the material flow is possible. However, the exact fate of the material has to be reconstructed from these tracers in a post processing step, like in the stretching ratio model in [7]. In addition, this approach neglects the fact that small fragments tend to be underresolved and, thus, their motion in the model may suffer from numerical artifacts.

To address these limitations, we developed a method to reduce numerical artifacts as well as improve the tracking of smaller material chunks in iSALE. To this end, we identify and analyze fragments of a chosen material type, in this case the material of the impactor core, in the whole numerical grid during each simulation step. Based on predefined criteria, for example looking at the shape of a fragment or the strain in its individual cells, we determine if each individual fragment is still sufficiently well resolved. If this is not the case, the fragment will be broken up or completely removed by replacing the impactor core material in its cells with that of the surrounding magma ocean matter. The removed mass and volume will be saved in the nearest tracer, which approximates the movement of the fragment based on the surrounding velocities. By effectively freezing mass and volume of a fragment in this way, artificial distortion caused by insufficient numerical resolution for such small fragments is prevented.

The setup of our simulations consists of a 200 km diameter dunite projectile with a 100 km iron core, impacting a dunite half space. The upper 900 km of this target behave purely hydrodynamically without strength or viscosity, approximating a magma ocean. The resolution is varied between 20 and 80 cells per projectile radius (cppr).

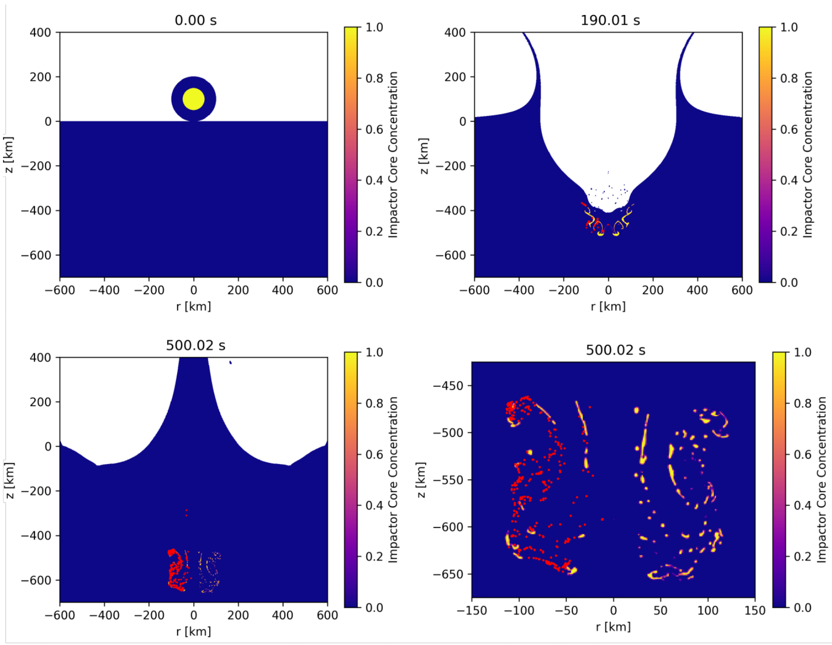

Fig. 1: Impact of a differentiated projectile into a magma ocean at different time steps with (negative x) and without (positive x) the new method. The impactor core is shown in yellow and the tracers used in the new method in red.

Results: Figure 1 shows a comparison between simulations with and without the new method for a cppr of 80 at different time steps. It shows the impactor core material (yellow) as well as the tracers used to save information in the method (red dots). The left side (negative x) of each image shows the results with the new method. It is clearly visible that, as impactor material penetrates deeper into the magma ocean, its core fragments into more and more pieces, the smallest of which are removed into tracers when using the method.

Discussion and Conclusion: The results obtained so far show that the impactor core breaks into many fragments during and after the impact, similar to observations in other studies [7]. The current criteria, based on the concentration in individual cells and their neighbors, as well as on a simplified approximation of the fragment shape, are not entirely sufficient to find all cases in which numerical artifacts occur. To achieve this, physical parameters like the strain inside the fragments have to be considered as well. It is also important to note that the current use of tracers to save the mass and volume of small fragments means that these cannot fragment further and that their interaction with other matter is strongly simplified - tracers follow the velocity field of the surrounding material. Some additional interaction will need to be implemented to evaluate how valid this approximation is.

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References: [1] Walker R. J. (2009) Chem. Erde-Geochem. 69, 101-125. [2] Wood B. J. et al. (2006) Nature 441, 825-833. [3] Tonks W. B. et al. (1993) J. Geophys. Res. 98, 5319-5333. [4] Rubie D. C. et al. (2003) Earth Planet Sc. Lett. 205, 239-255. [5] Daguen R. et al. (2014) Earth Planet Sc. Lett. 391, 274-287. [6] Landeau M. et al. (2016) Nat. Geosci. 9, 786-789. [7] Kendall J. D. et al. (2016) Earth Planet Sc. Lett. 448 24-33. [8] Marchi S. et al. (2020) Sci. Adv. 6(7) eaay2338. [9] Monaghan J.J. (1992) Annu. Rev. Astron. Astrophys. 30, 543-574. [10] Maas C. et al. (2021) Earth Planet Sc. Lett. 554. [11] Collins. G. S. et al. (2004) Meteorics & Planet. Sci. 39, 217-231. [12] Wünnemann K. et al. (2006) Icarus 180, 514-527.