Collisions of planetesimals and formation of planets

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## Abstract

The outcome of numerical simulations of the formation of planets depends a lot on the choice of the initial distribution of planetesimals and planetary embryos after the disappearance of gas in the protoplanetary disk. We take into account that some of these planetesimals of sizes in the order of the mass of the Moon already contain water; the quantity depends on the distance from the Sun - too close and the bodies are dry, but starting from a distance of about 2 AU they can contain substantial amounts of water. We show preliminary results of terrestrial planet formation using on one side classical numerical integrations of hundreds of small bodies on CPUs and on the other side - for comparison reasons - the results of our GPU code with thousands of small bodies which then merge to larger ones. To be able to determine the outcome of collisions we use our SPH code which shows how water is lost during such events.

## Aims

- We simulate the formation of terrestrial planets and consider three models: existing gas giants Jupiter and Saturn (model A), only with Jupiter (model B), and without any giant planet (C). While all three models are important for the understanding of extrasolar planetary systems, we present preliminary results for model A.

The resulting planetary systems are extremely sensitive to initial conditions and even statistical statements are highly biased by them (e.g., surface density, total mass, and dynamical model).

Using SPH computations (smooth particle hydrodynamics) we can already deduce the outcome of collisions depending on mass and size of the bodies, velocity of encounter, and collision angle with respect to (a) merging/fragmentation and (b) the water deficiency (Fig. 4, Maindl et al. 2013, 2014).

- We will run simulations (first tests are shown in Fig. 2) with several thousands of small bodies in the three models defined above on GPUs. As one can see running our GPU-based code is up to two orders of magnitude faster than our CPU n-body integrator (Fig. 3). As very important point this large number of bodies will take care of dynamical friction with a precision not achieved up to now (e.g., O'Brian et al. 2006)

Although — with exception of the last point! — there exist several results from different groups with different underlying assumptions (e.g., Izidoro et al. 2014, Hansen 2009) we believe that independent computations (with others than the usual codes) are desirable for answering the key questions of terrestrial planet formation.

## Preliminary simulation results

Although many results were achieved concerning the formation of planets and also their water content, there are still many open questions (e.g. Raymond et al. 2014). The big problem is that the outcome of numerical simulations is very sensitive to the initial distribution of planetesimals and protoplanets and only small differences lead to completely different results.
In our approach we take the outcome of the last phases of the the Grand Tack scenario (Walsh et al. 2011) as initial conditions for our simulations using the Lie-integration method. This ensures that the encounters and collisions are treated properly because of the built-in automatic step size control (Eggl \& Dvorak 2010).
We are running our codes with Jupiter and Saturn in their actual positions in the Solar System and distribute small bodies in the mass range $3 \times 10^{-9} M_{\odot}<m<3 \times 10^{-7} M_{\odot}$ and semi-major axes $0.4 \mathrm{AU}<a<2.7 \mathrm{AU}$ with small inclinations and small eccentricities. Bodies initially outside 2 AU are assumed to have a water content of 10 percent. In Fig. 1 we show two typical results out of 30 different runs after an integration time of 5 Myrs .

${ }_{a}$ [AU]


Figure 1. Eccentricities (left) and inclinations (right) for two typical scenarios. Different colors indicate the water contents; the circle sizes denote the bodies' masses after 5 Myrs. The largest bodies are of approx. 30 lunar masses.

## Prototype GPU-based results




Figure 2. Preliminary results from our GPU code: 5000 massive bodies +5000 small asteroids merge into 25 massive bodies, the biggest of which has about 2.3 Earth masses and moves on an orbit with semi-major axis $a \approx 1.3 \mathrm{AU}$ and eccentricity $e \approx 0.17$

## GPU computational gain <br> 

Figure 3. The computational gain first grows with the number of bodies involved and settles at a factor of approximately 100.

## Water transport by collisions

Figure 4 (right). SPH simulation of two Ceres-mass bodies colliding at $1 \mathrm{~km} / \mathrm{s}$ and a $62^{\circ}$-angle ( 250 k SPH particles). Blue dots: $30 \mathrm{wt}-\%$ water ice on the target surface, red dots: solid basalt projectile. After the collision some water is transfered.

## References

- Eggl, S., \& Dvorak, R. 2010, Lecture Notes in Physics, 790, 43 - Hansen, B. M. S. 2009, ApJ, 703, 1131

Hansen, B. M. S. 2009, ApJ, 703, 1131 Izidoro, A., Haghighipour, N., Winter, O. C., \& Tsuchida, M. 2014, ApJ, 782, 31 - Izidoro, A., Haghighipour, N., Winter, O. C., \& Tsuchida, M. 2014, ApJ, 782, 31

- Maindl, T. I., Dvorak, R., Schäfer, C., Speith, R. 2014, in IAU Symposium, Vol. - Maindl, T.
310,138


## 310, 13

- Maindl, T. I., Schäfer, C., Speith, R., Süli, Á., Forgács-Dajka, E., Dvorak, R 2013, Astronomische Nachrichten, 334, 996
- O'Brian, D. P., Morbidelli, A., \& Levison, H. F. 2006, Icarus, 184, 39
- Raymond, S. N., Kokubo, E, Morbidelli, A., Morishima, R., \& Walsh, K. J. 2014, in Protostars and Planets VI, 595
- Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., \& Mandell, A. M. 2011, Nature, 475, 7355, 206

Support from the FWF Austrian Science Fund projects S 11603-N16 and P23810-N16 is acknowledged.


