Report on the Thesis “Early phases of formation and evolution of planetary systems” by O. Chrenko.

The thesis presented by O. Chrenko for the obtention of the Ph.D. in physics concerns the evolution of low-mass planets embedded in protoplanetary disks, focusing in particular on the effects of the energy released from the planets due to their vigorous accretion of small particles (pebbles) – the so-called *heating torque*. To perform this investigation, O. Chrenko developed two hydrodynamical codes. The first one, named Thorin, is based on a 2D hydrodynamical code by F. Masset called Fargo, but it required non-trivial modifications. The disk has been extended in the vertical direction assuming hydrostatic equilibrium. The local isothermal approximation has been dropped, with the inclusion of viscous heating and stellar irradiation as heating terms and of radiative diffusion as a cooling term. A two-fluid approach has been implemented to model the distribution of small particles coupled to the gas with back reaction, that planets can accrete releasing as heat the gravitational energy that they acquire. A more sophisticated N-body solver has been interfaced with the hydrodynamical code to study with accuracy the mutual interaction of the planets also during close encounters. The planets evolve in three dimensions. The second code is based on the 3D version of Fargo by Benitez-Llambey, but again with non-trivial modifications to treat the temperature evolution of the gas, the accretion of pebbles by the planets with the consequent release of gravitational energy, and the accurate integration of close encounters. Making and testing thoroughly these two codes required a lot of work and effort and demonstrates that the Ph.D. candidate is an experienced programmer, capable to fully understand and elaborate codes written by others; moreover he has a deep understanding of the dynamics of fluids. These codes have been used in a number of studies, leading to 4 published papers, three of which have the Ph.D. candidate as leading author. Altogether, this constitutes an exceptional performance that definitely deserves the obtention of the Ph.D.

The manuscript is divided in two parts. The first part is an introduction to protoplanetary disks, planet accretion (both classic models and the new pebble-accretion model) and of the equations describing disk evolution and planet-disk interactions. It starts in a soft mode, with a pedagogical presentation for the general public, and then goes into great details, presenting the equations in a self-consistent manner. All the ingredients that are relevant to understand the second part of the thesis are provided. In the second part, the new codes are presented, and the 4 published papers are summarized, highlighting the main results but also openly presenting their limitations. The three papers led by the Ph.D. candidate are included in the manuscript. The tone of the thesis is sober, although the results are clearly important.

The first paper shows that the heat released by planets vigorously accreting pebbles enhances the planets’ orbital eccentricities. This was not known at the time the study was performed, and was independently pointed out by Eklund and Masset. But the paper goes beyond this result, exploring the consequences of the eccentricity enhancement for the evolution of a system of planets coexisting in the disk. The main result is that the eccentricity excitation reduces the ability of planets to get locked in mutual mean motion resonances upon convergent migration. The evolution is consequently much more violent, with multiple planetary close encounters and collisions. This result has been partially tempered later by removing a subtle bug in the code but, although the evolution seems now less violent, the main conclusions subsist. Because the authors plan to publish a corrigendum to their paper, I point out another issue with the code which may affect the results. If I read correctly equations 27-32 of the paper, the pebble accretion rate of a planet does not decrease when its eccentricity increases. In the 2D accretion case (where the height of the pebble layer is smaller that the accretion cross-section of the planet), the pebble accretion rate increases with $v_{rel}^{1/2}$, hence with the eccentricity. This is unphysical. There is in reality another condition: the deflection time for a pebble during an encounter has to be shorter than the encounter time (a.k.a. crossing time). This led Lambrechts et al (2019) to establish condition A.5 in that paper. When the planet's eccentricity increases, t_{cross} decreases and this reduces the accretional cross-section of the planet and the resulting pebble-accretion rate. If this effect is taken into account, my expectation is that the eccentricity enhancement is regulated by the decrease in accretion rate and hence of the released heat. What effect this will have on the evolution of the planets I don't know, but I suspect it will be more regular leading to more frequent resonant captures.

Paper II is not fully presented in the manuscript, given that it is just a "follow-up parametric study of paper I" (words of the author) and not led by the Ph.D candidate, but its main results are summarized. A very crowded system of 120 Mars-mass planets is studied. Through mutual close encounters and the passage through waves launched by the other planets, the eccentricities and inclinations of the system are stirred up, leading to a reduced occurrence of mutual merging events. The planets thus grow mostly by pebble accretion, the least excited ones becoming the more massive, in a negative feedback between mass-growth and excitation.

Paper III starts with a technical modification of the code. The inclination damping of the orbits of the planets is suppressed below $i=10^{-3}$ rad. The rationale is that Eklund and Masset discovered that the energy release from accreting planets enhances the planet's orbital inclinations, counteracting the inclination damping exerted by the disk and leading to equilibrium inclinations of this order of magnitude. With this modification, the simulation presented by the authors finds cases of temporary capture of planets in a binary configuration. The paper then goes off studying the properties of these binaries, how they are formed, and their lifetime. This is very interesting and well conducted. However, it remains unclear (to me at least) why the suppression of the inclination damping should be key to obtain binary planets. It's unfortunate that a parametric study on i_0 (the value of the inclination below which the damping is not applied) is not performed, so the doubt remains that the lack of inclination damping may have been just a mere coincidence.

Paper IV is my preferred one. Using the modified version of Fargo3D, the authors study the effect of the release of energy from an accreting planet in details. With the same set-up of the original paper by Benitez-Llambey et al. (2015) they study more thoroughly the streamlines of the gas, discovering the existence of a convective column of gas above the planet, sucking-in gas from the midplane, that was not noticed in previous papers. Then, by changing the set-up and introducing more realistically the dependence of the gas opacity on temperature (both in the vertical and radial directions) they discover that the heating torque has an oscillating nature, with an almost null average, which was not known before. The authors investigate this behavior with a series of experiments and detailed analyses of the streamlines and provide a rather heuristic but quite convincing explanation of this phenomenon. The idea is that with the vertical dependence of the opacity the disk is more prone to a convective instability; the release of heat from the planet can then generate convection over a much wider neighborhood of the planet, which modifies more substantially the gas distribution and hence the sign of the torque over time. It remains unclear to me, however, why the torque evolution is so cyclic. If we were in presence of a true instability as claimed, I would expect a more chaotic evolution of the torque, which does not seem to be the case. Interestingly, if the planet is let free to migrate, the phenomenon persists. The planet has a net inward migration (as in the case without energy release), but with large oscillations. This result is very relevant because it shows that the importance of the heating torque may have been overestimated in previous studies. I regret that nothing is said on the evolution of the eccentricity and inclination of the planet. What is the impact on the previously presented results of this thesis (particularly Paper I)? I would have appreciated a discussion on this in the conclusions of the thesis, at least to give some perspectives for future studies if a definitive answer is still premature. In the end I remain quite confused on what the consequences of the heating torque really are. This is a rather sad end for a really excellent thesis that I read with interest and pleasure.

Despite I have been critical (but I hope constructive) in some passages, let me summarize by saying that the work performed by O. Chrenko for his thesis is enormous and outstanding. It included code development, the performance of numerous simulations and an intelligent and deep analysis of the results. I think this thesis is well above average and demonstrates the ability and maturity of the candidate.

I don't know if this is customary in the Czech system, but I like to end my report with a list of technical minor remarks, in case the thesis can be amended before its final publication. None of these remarks has substantial importance. All conceptual remarks have been reported above.

It is said at page 29 that, as in Bitsch et al. (2013) the three opacities are assumed to be equal. However, as pointed out in Bitsch et al. (2014) this is not really correct because k_* is related to the temperature of the star, whereas k_r and k_p are related to the temperature of the disk.

At page 30 the notion of two-temperature model is not introduced nor explained.

At the end of page 39, the new paper by Nesvorny et al. (2019) in Nature Astronomy on the prograde/retrograde ratio of Kuiper belt binaries could be reported as a rather definitive proof that planetesimals formed by the streaming instability.

At the top of page 41, the concept of isolation mass is not explained. Because the term isolation mass is also used later for pebble accretion and the two concepts are different, it would be preferable to clarify what each concept refers to.

The second bullet of page 41 is not clear. The occurrence rate of giant planets around stars is approximately 10%, so the fact that planetesimal accretion fails to form giant planet cores in 90% of the cases would not be a problem. I believe Levison et al. (2010) never managed to grow giant planet cores by planetesimal accretion.

At page 46, in addition to Bitsch et al. (2018) and Picogna et al. (2018), a reference to Weber et al. (2018) should be added.

The parameter csi introduced above formula 1.88 is different from the parameter csi in 1.104. It would be good to distinguish the two somehow. It is not obvious which csi enters in 1.122.

At page 58, the terms of vorticity and vortensity are not defined.

Still in 1.122 it is not obvious what b is. Is it the same as b_{sm}?

Second line of page 72: stars should be starts

In the last line of page 77, it is said that because the disk has a vertical extension, the force exerted by the disk on the planet is integrated over (r,theta,phi), which allows to use a much smaller smoothing length than in 2D codes where the H-smoothing is instead required. I agree with this. But which smoothing is used to compute the force of the planet on the disk? I believe in that case a smoothing length that is a substantial fraction of H should still be applied.

A question: given the two-fluid nature of the Thorin code, did you ever see a "pebble torque" as in Benitez-Llambey and Pessah (2018) ?

Fig. 2.1, bottom panel. After the merging event, the evolutions of the blue and red planets look like resonant to me (before and after the orbital switch). Is this the case?

Fig. 2.3. The text says that all planets start at 0.1 Earth masses. But the figure seems to show that some start with a mass that is twice as large.

Fig. 6 and Fig. 7 of paper III. It Is not clear that the orbital elements shown here are for the two planets relative to each other and not for their common orbit relative to the star.

It is said in section 3.7 of Paper III that the gas is removed instantaneously from the simulation. In general this is not a good idea, because the instantaneous removal of gas shocks the system. It is better to remove the gas exponentially, letting the system to adapt adiabatically.

Section 4.5 of Paper III. I'm not sure I agree on how the occurrence rate is estimated. Here, the ratio is taken between the typical lifetime of a binary event and the lifetime of the disk. The rationale is that a binary that is lucky to form at the very end of the disk can survive. But at the very end of the disk there is very little gas. It is not trivial that the formation rate of binaries is the same in a gas starving disk as in the disk studied here. In a gas-less disk, binary formation has never been observed. My guess is that binaries form easily in relatively massive disks, but they last too short to reach the end of the disk. Later on, binary formation is much more rare because there is less gas in the system. If this is true, the occurrence rate would be much smaller than that computer here, possibly even null.

Best regards

Alessandro Morbidelli