Evolution of multiplanet systems in 2D and 3D radiative disks

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Summary

Evolution of planetary systems embedded in disks is driven by planet migration. Its direction and rate delicately depends on radiation-hydrodynamic (RHD) processes in the surrounding gas. We use 2D and 3D RHD simulations to study the outcome of migration in multiplanet systems. Especially, we focus on the effect of heating by pebble accretion which can considerably excite planetary eccentricities and inclinations (Chrenko et al. 2017, Eklund & Masset 2017). Our results of 3D modelling indicate that accreting (hot) low-mass protoplanets probably migrate only inwards. In one of our 2D simulations, we describe a new dynamical effect - formation of a binary planet.

Methods

1) 2D RHD code Fargo_Thorin from Chrenko et al. (2017), based on Fargo (Masset 2000). It includes a one-temperature gas energy equation with simplified irradiation and vertical cooling, a pebble disk modelled using a two-fluid approach, pebble accretion and corresponding heating.
2) 3D RHD code based on Fargo3D (Benítez-Llambay & Masset 2016) with an implementation of two-temperature energy equations from Bitsch et al. (2013) and radialy ray-traced irradiation. Accretion heating is only parametric.
3) Planets are always evolved on 3D orbits using the IAS15 integrator (Rein & Spiegel 2015)

3D: Breaking migration barriers

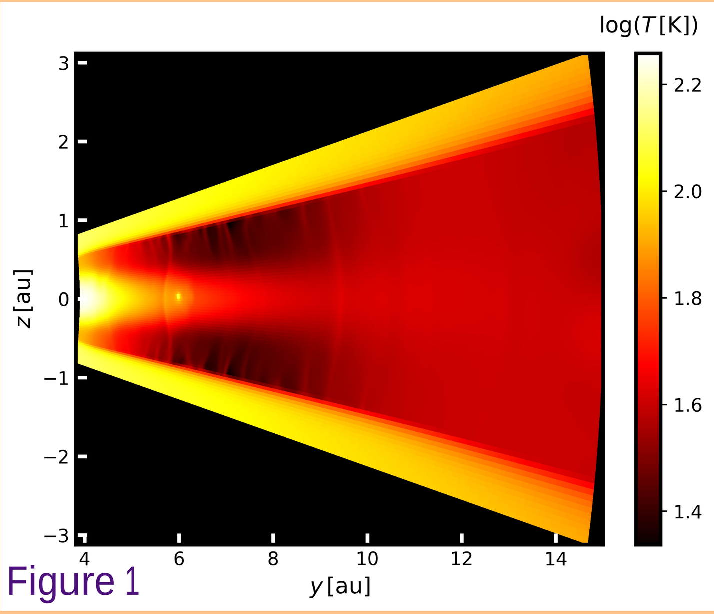

Figure 1

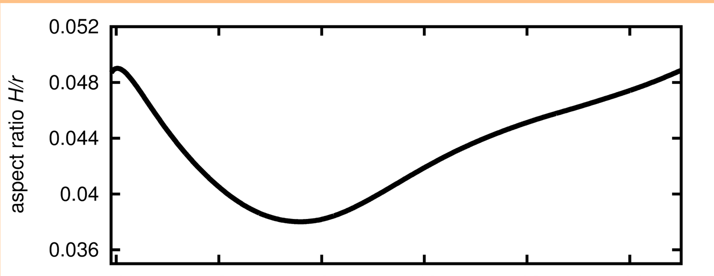

Figure 2

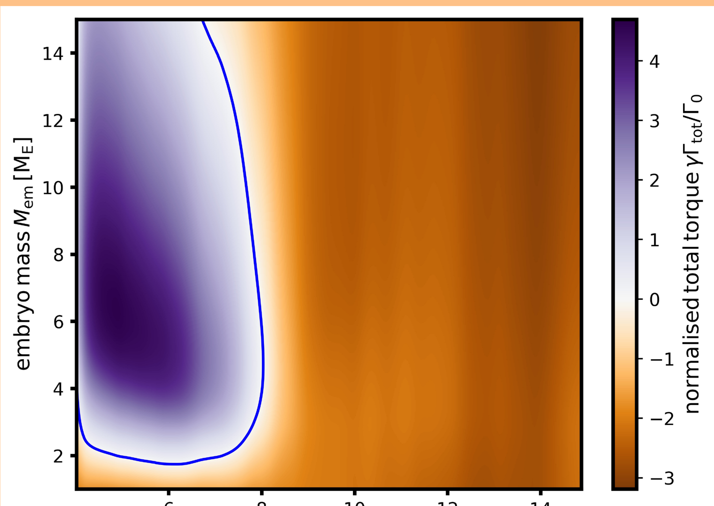

Figure 3

Radiative protoplanetary disks usually have a variable shape, determined by the local balance of heating and cooling processes. The vertical temperature profile of the disk in Figure 1 has an inner viscously heated region which is puffed up and shadows the middle part. The flared outer part extending above the shadow is heated by irradiation which penetrates through an optically thin atmosphere. The hot spot close to 6 au is an embedded accreting planet.

The structural variations also appear in the radial profile of the aspect ratio (disk thickness/radial distance) in Figure 2.

Migration of low-mass planets in such disks is expected to be directed by the corotation torque which depends on radial gradients of thermodynamic quantities. Using analytic formulae for disk torques of Paardekooper et al. (2011) one can construct a migration map as in Figure 3 (positive values indicate outward migration, and vice versa). The map predicts accumulation of planets near 8 au. This accumulation would be basically achieved with migration N-body codes, but the situation becomes different in 3D RHD...

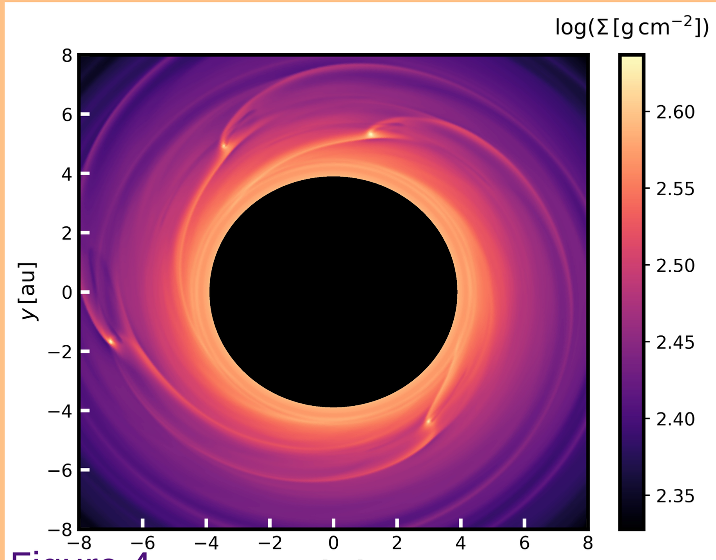

Figure 4

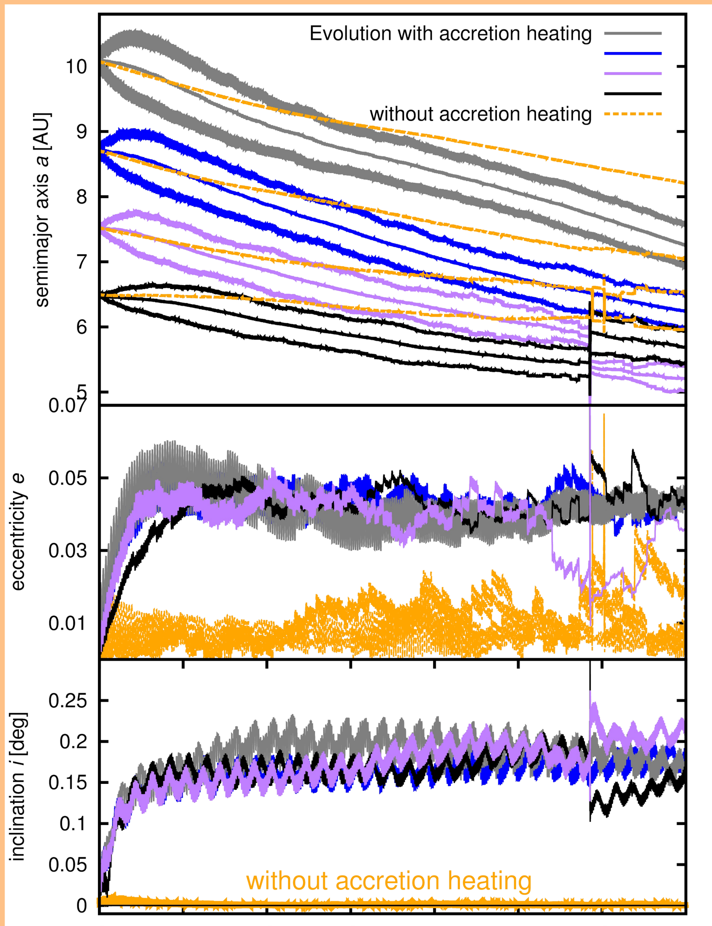

Figure 5

Using a 3D RHD model, we simulated evolution of four protoplanets, each having 4.5 Earth masses and the accretion doubling time 75 kyr. Figure 4 shows a snapshot of the vertically-integrated gas density. Luminous planets create underdense hot trails in the gas (Chrenko et al. 2017, Eklund and Masset 2017) which excite their eccentricities and inclinations.

Figure 5 shows the evolution of the semimajor axes, pericentric and apocentric distances. One can see that the migration is directed inwards and so the prediction of the migration map from Figure 3 breaks down.

The inward migration is a result of excited eccentricities which are also displayed in Figure 5. Eccentric orbits break the positive contribution of the corotation torque (Bitsch & Kley 2010).

Figure 5 also shows a comparative evolution of planets without accretion heating. The torque is also less positive than predicted, but this is due to the cold-finger effect (Lega et al. 2014). Note how the inclinations differ for both cases in Figure 5!

2D: Binary planet formation

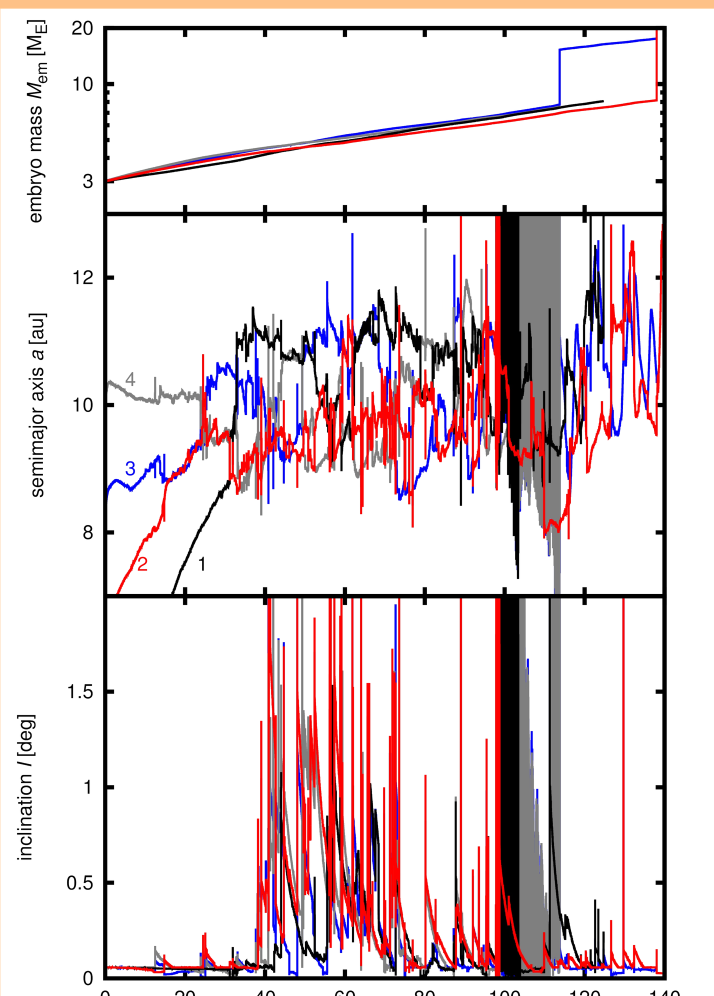

Figure 6

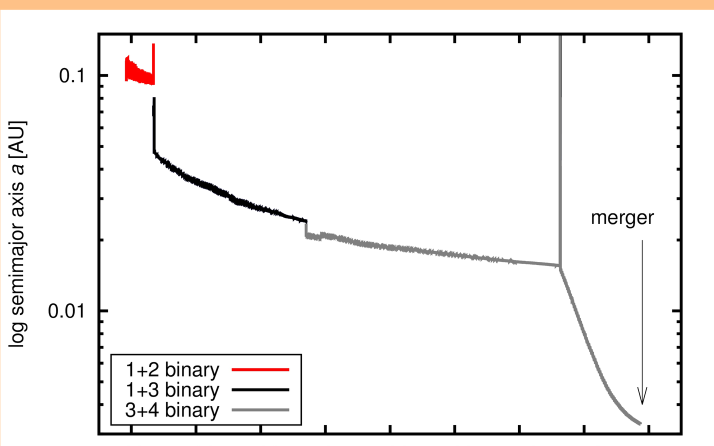

Figure 7

The 2D model is less accurate in reproducing torques found in 3D (convergent migration persists), but it can be used to study long-term evolution. Moreover, pebble accretion is accounted for by adding a second fluid.

To include the effect of non-zero inclinations due to accretion heating, we reduced the efficiency of inclination damping by switching off the Tanaka & Ward (2004) damping formula whenever i < 0.001 rad.

The results in Figure 6 show an unexpected event - a binary planet is formed! Its existence is represented by strong variations of the heliocentric orbital elements between ~98 kyr and ~114 kyr.

The formation mechanism requires a transient capture of two bodies. A gravitationally bound binary planet is formed subsequently in a 3-body encounter with another embryo. The binary planet undergoes other 3-body encounters during which the third body swaps places with one of the binary's components. These events typically diminish the binary separation ('binary hardening'), as shown in Figure 7.

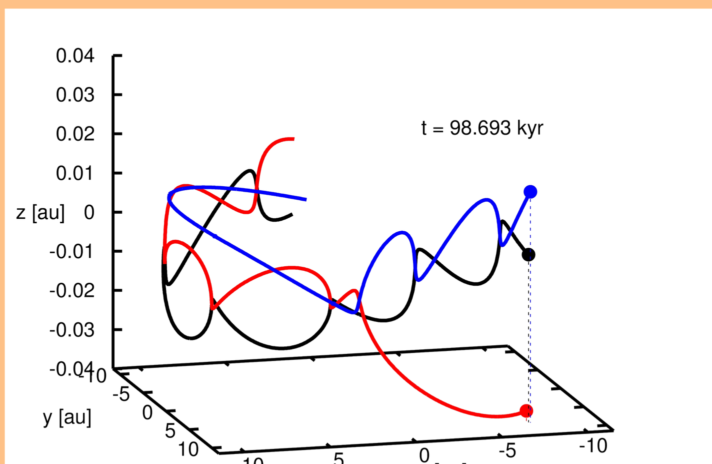

Figure 8

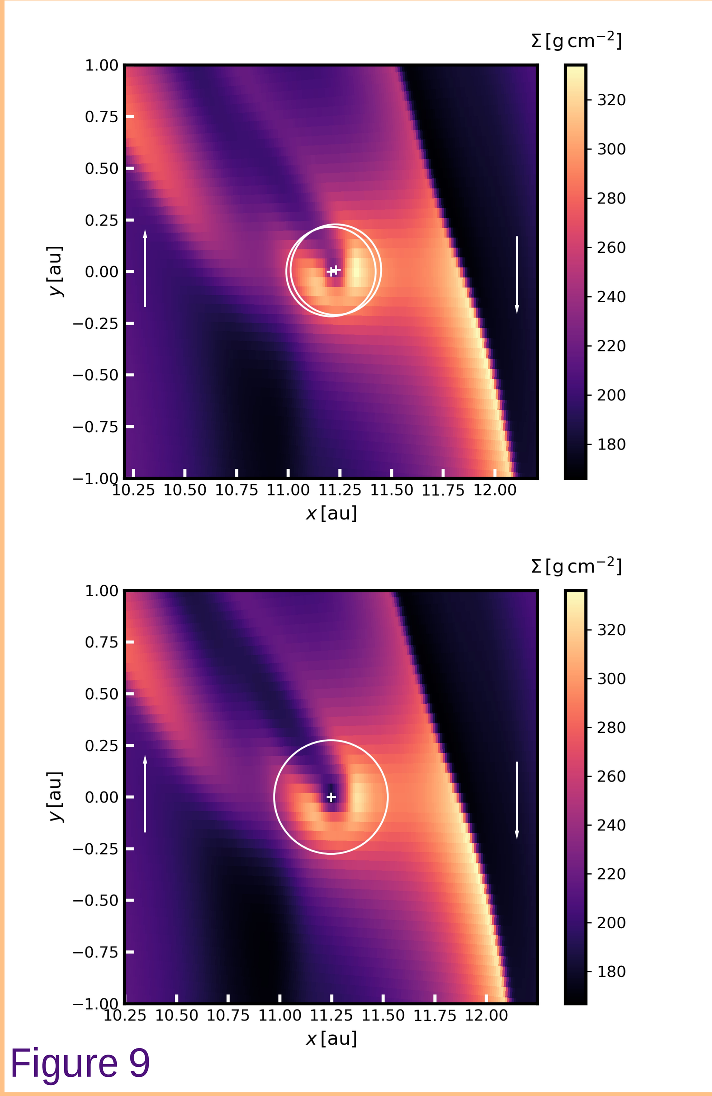

Figure 9

An example of a 3-body interaction in the 3D Cartesian space is shown in Figure 8. The red planet is originally in the binary configuration but it is scattered during the interaction with the blue planet which becomes bound instead.

Although the binary planet did not survive the simulation (it eventually merged), we made a simple estimate of the expected occurrence rate of binary planets (results are to be published in Chrenko et al. subm). The expected fraction of planetary systems containing a binary planet is ~10^{-4}.

Finally, Figure 9 compares the perturbed gas density profile in a vicinity of the binary planet with that of a single equally massive planet.

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