Early instabilities in the systems of planetary embryos heated by pebble accretion

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Motivation & Aims

We present the results of 2D non-isothermal hydrodynamic simulations which include three components of the protoplanetary systems, namely (i) the gaseous disc, (ii) the disc of pebbles and (iii) embedded planetary embryos. Our primary aim is to study in a self-consistent manner the orbital evolution of several migrating planetary embryos while they are accreting pebbles. We also check the following:

- Pebble-accreting embryos are assumed to exhibit short mass doubling times. As described in Benítez-Llambay et al. (2015), fast accretion rate can give rise to so-called heating torque (which is always positive) acting on embryos. We therefore study the effect of the heating torque induced by pebble accretion in our model.
- Packs of planetary embryos orbiting in the regions of convergent Type I Migration tend to form resonant chains. We study the influence of rapidly evolving masses and the heating torque on the stability of such a system.

Model

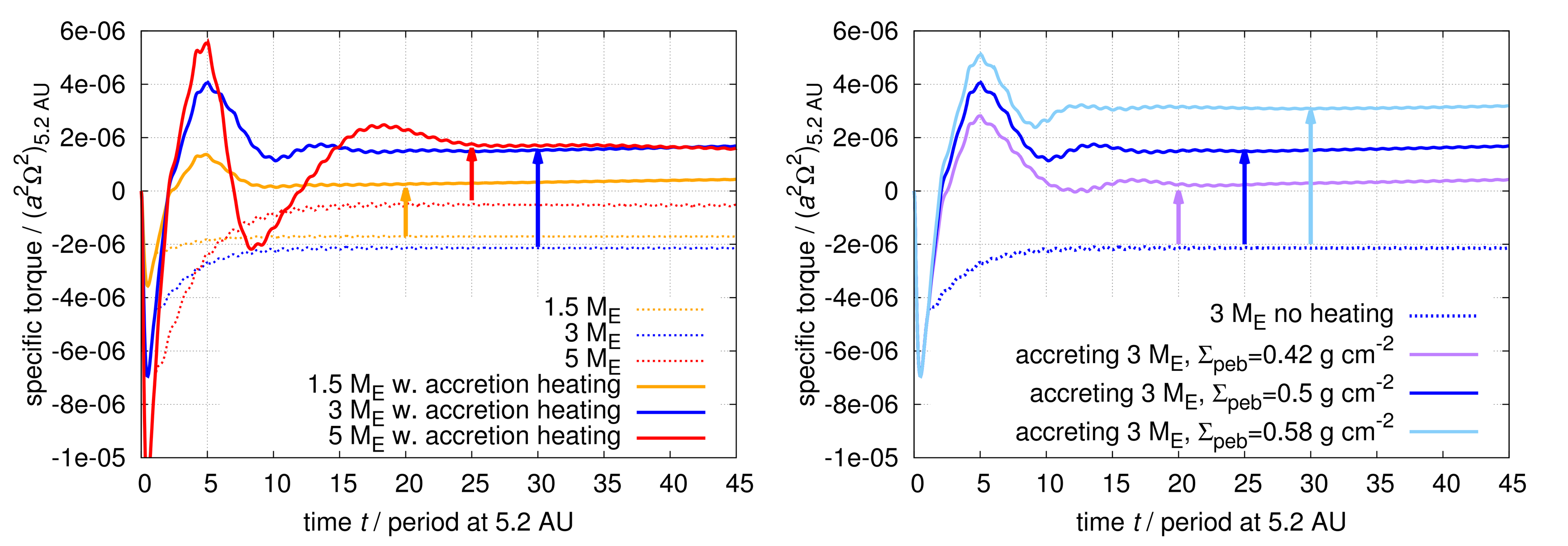
Modifying the **2D FARGO hydrocode** (Masset 2000), we have developed a new tool for modelling the outlined problem. Our code includes:

- Implicit solution of the energy equation with various heating and cooling sources which contribute to the energy budget of the non-isothermal gas:

$$\frac{\partial E}{\partial t} + \nabla \cdot (E\vec{v}) = -P\nabla \cdot \vec{v} + Q_{+}^{\mathrm{visc}} + Q_{+}^{\mathrm{irr}} - Q_{-}^{\mathrm{vert}} - 2H\nabla \cdot \vec{F} \, . \quad (1)$$

  The source terms represent the **compressional heating**, **viscous heating**, **irradiation** by the **protostar** (e.g. Pierens 2015) and the **planets** (Benítez-Llambay et al. 2015), cooling by **vertical escape of the radiation** and **midplane radiative diffusion** treated in the flux-limited approximation (FLD).
- Coupled **Eulerian model of the pebble disc**. Initial conditions are based on the model of Lambrechts & Johansen (2014). The pebble surface density evolution is governed by the Navier-Stokes equation with the gravitational term and the Epstein drag term included. Pebble accretion is self-consistently accounted for as we let the solids which enter the critical accretion radius of an embryo to be immediately added to its mass (embryos act like sinks for pebbles).
- Interface with the **REBOUND integrator package** (Rein & Spiegel 2015), allowing for accurate 3D integration of planetary orbits and collision detection.

Result 1: Heating torque induced by pebble accretion

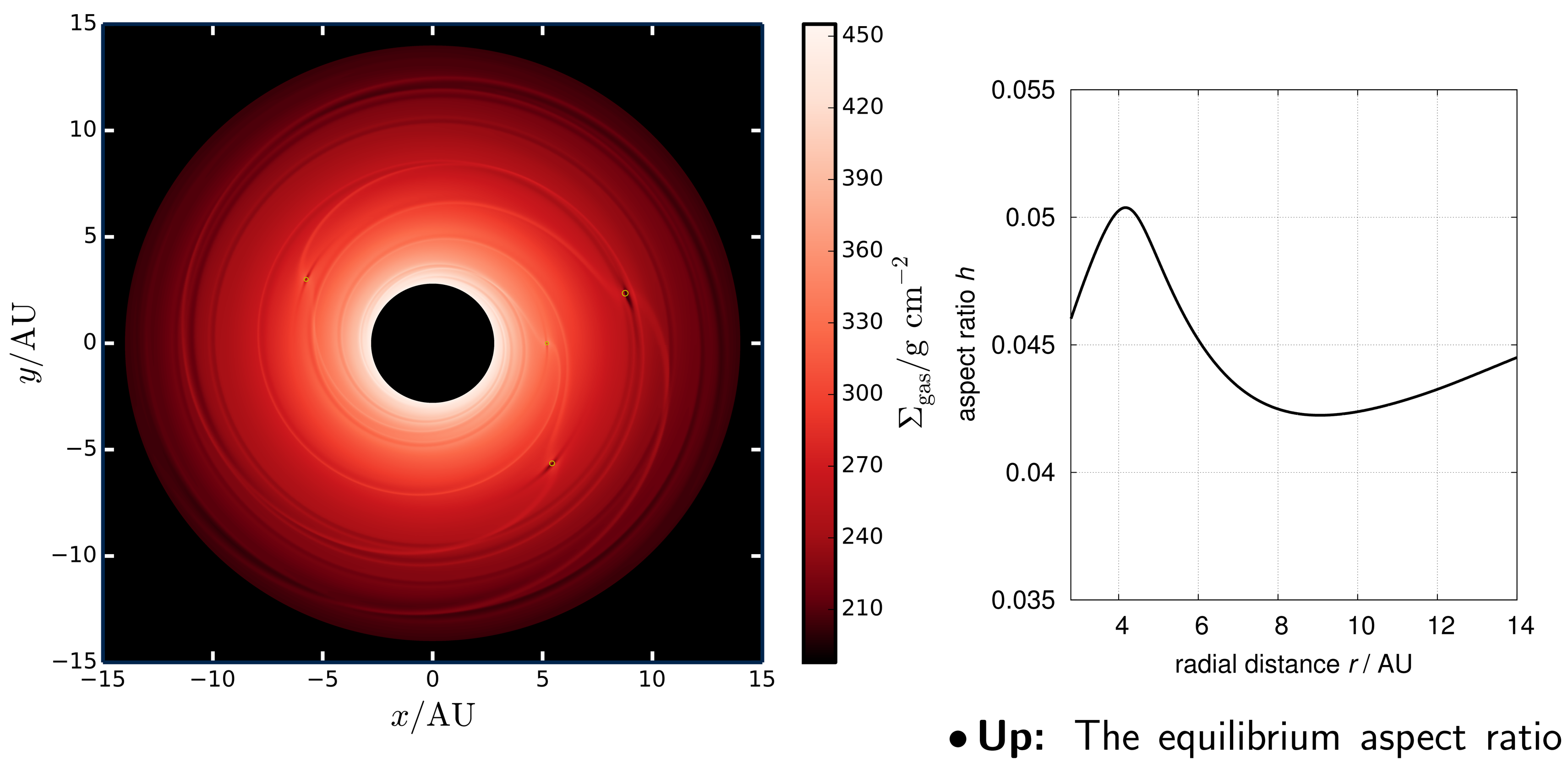


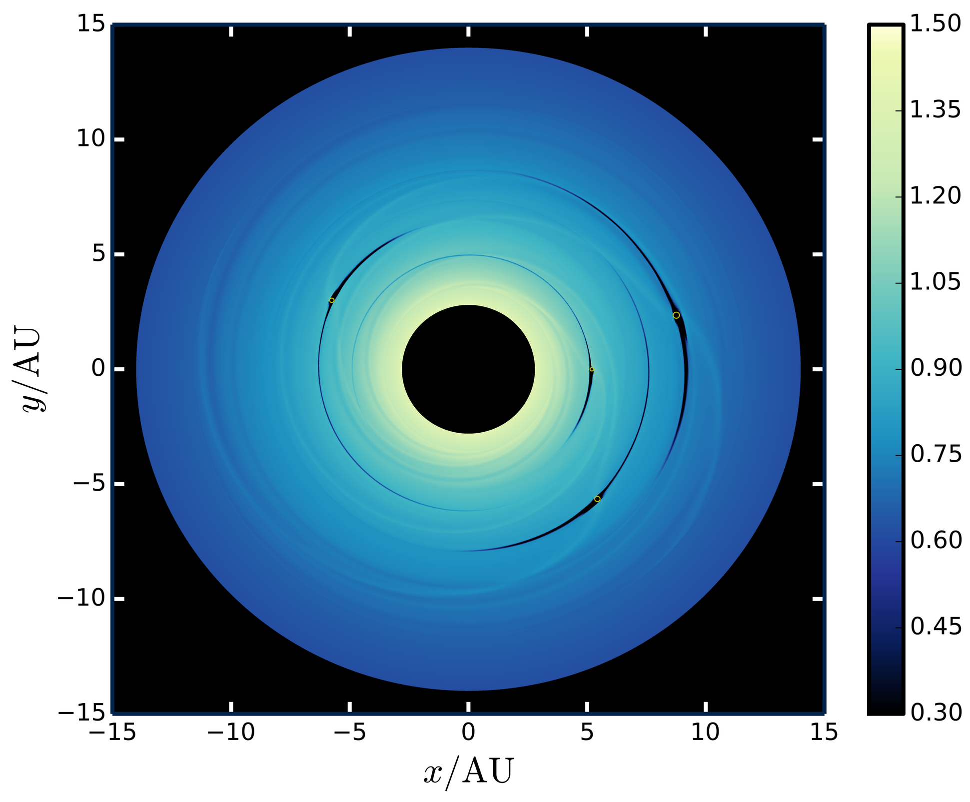
Here we show how the heating torque induced by pebble accretion operates in our 2D global-scale model. The disc parameters in this experiment are similar to Benítez-Llambay et al. (2015). The figures above show the temporal evolution of the total torque exerted by the disc on an embedded embryo.

- **Left:** Embryos of three different masses (1.5, 3 and 5 M_E) evolving in the same disc with the accretion heating switched off (dotted lines) and on (solid lines). The amount of accreted pebbles (=the accretion heat deposit rate) grows with the embryo mass, but the heating torque efficiency is larger for smaller planets. As a result, the heating torque significance peaks for the embryo mass 3 M_E.
- **Right:** The embryo mass is fixed at 3 M_E but we modify the pebble disc density at planet's location. Larger pebble density leads to larger accretion rate (=heating), thus increasing the efficiency of the heating torque.

References:
Benítez-Llambay P., Masset F., Koenigsberger G., Szulágyi J., 2015, Nature, 520, 63.
Kretke K. A., Levison H. F., 2014, AJ, 148, 109.
Lambrechts M., Johansen A., 2014, A&A, 572, 107.
Masset F., 2000, A&AS, 141, 165.
Pierens A., 2015, MNRAS, 454, 2003.
Rein H., Spiegel D. S., 2015, MNRAS, 446, 1424.

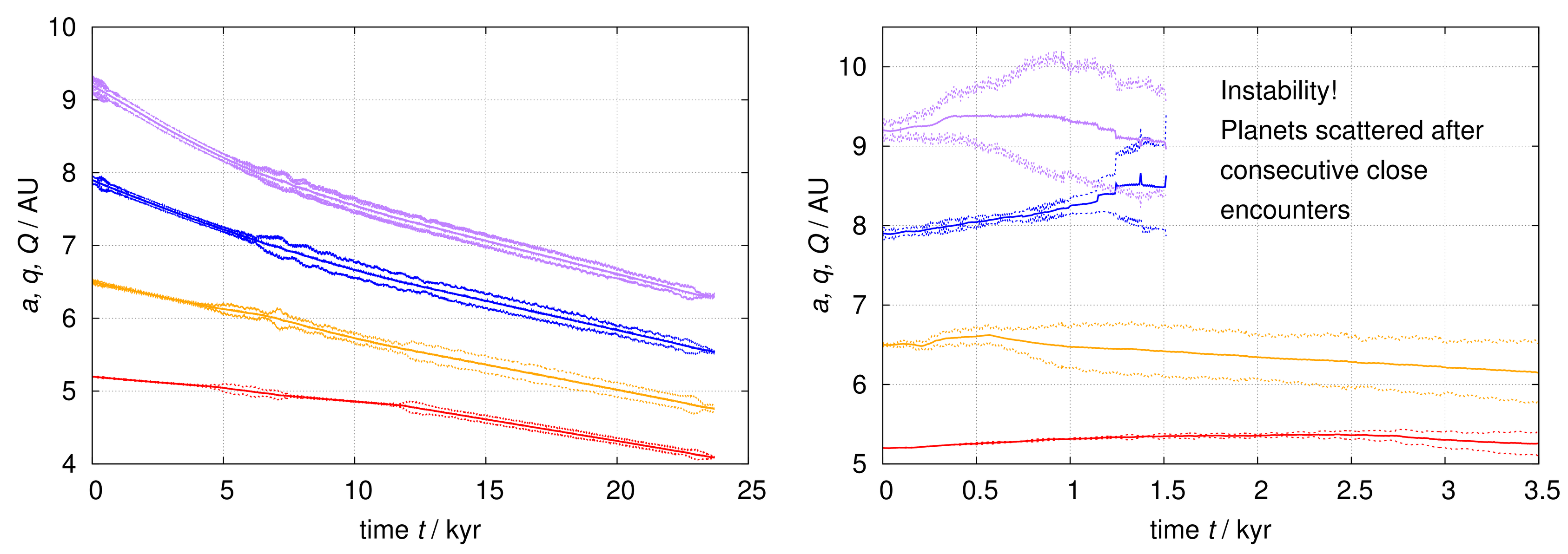
Gaseous and pebble discs





- **Up:** The equilibrium aspect ratio radial profile of the gaseous disc which is used as the initial state in the simulations below. Note the flaring in the outer region caused by the stellar irradiation.
- **Left:** Snapshots of the gas surface density (red) and the pebble surface density (blue) perturbed by four 3 M_E embryos. Note the correspondence of the structures in both discs and the "disappearance" of pebbles in sinks at the positions of embryos.

Result 2: Migration of several pebble-accreting embryos



- **Left:** Temporal evolution of the semi-major axes, pericentric and apocentric distances for four 3 M_E embryos migrating in the disc displayed above. In this case only the **embryo masses are evolving** due to pebble accretion, the accretion heating is switched off. The system migrates inward and develops into a resonant chain. Migration rate is mainly influenced by the eccentricity excitations which damp the corotation torque efficiency. Although the embryos finish with 5 M_E masses, the rapid mass increase does NOT destabilize the resonant chain.
- **Right:** The same initial conditions but the **accretion heating** is now included. Soon after the simulation start, the two outermost embryos undergo several close encounters and are consequently scattered out of the modelled part of the disc.

Conclusions & Future work

Conclusion: We conclude that in realistic systems, in which the formation of planets by pebble accretion is accompanied by effective accretion heating, the **heating torque** strongly affects the migration rates and directions of planetary embryos. These are often driven into mutual **close encounters** which can result in significant **orbital reconfigurations**. This mechanism can pose a natural way to reduce the initial number of planetary embryos. Therefore it could self-consistently help to remove one of the possible drawbacks of the pebble accretion hypothesis which is a formation of too many planetary embryos (e.g. Kretke & Levison 2014).

Future work: We plan to perform a statistically significant study of this type of instabilities in the young planetary systems. The parametric study of the heating torque in our model will also be extended in the future.

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