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

Ondřej Chrenko*, Miroslav Brož

*Institute of Astronomy, Charles University in Prague, Czech Republic
Website: www.sirrah.troja.mff.cuni.cz/chrenko, E-mail: chrenko@sirrah.troja.mff.cuni.cz

Motivation & Aims

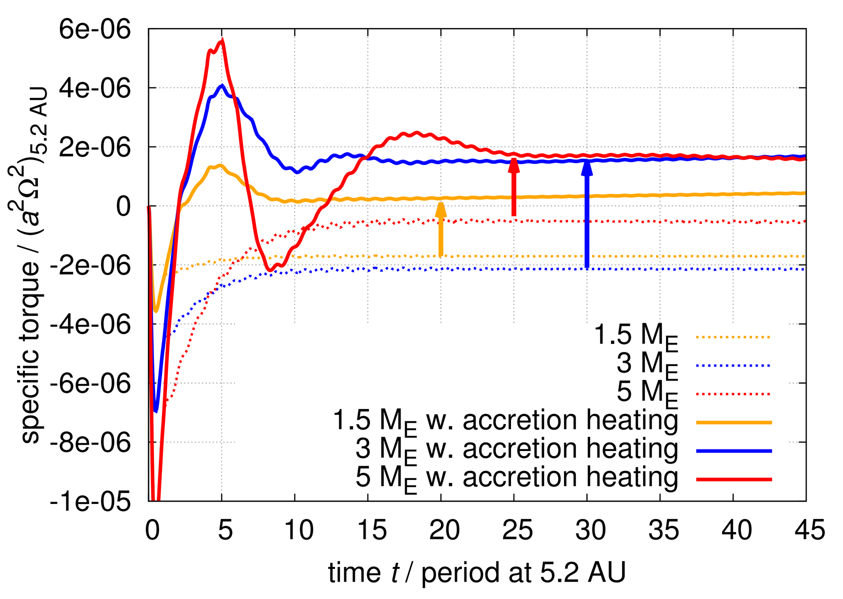
Type I migration: Numerical models imply that the migration histories of multiple planetary embryos are often complex, depending on the structure of the underlying gaseous disc. For example, resonant chains of embryos can form during convergent migration towards the zero-torque radii which are related to opacity transitions and variations of the aspect ratio gradient (e.g. 2DO REF).
Heating torque: A new type of torque acting on planetary embryos has been recently studied by (2DO REF) who demonstrated that fast accretion of material onto the embryos can heat up the surrounding gas, while changing its structure in a way that a new positive heating torque arises.
Pebble accretion: Pebble accretion hypothesis is a promising scenario of the planet formation by the drag-assisted infall of (mm-cm)-sized particles, leading to sufficiently short mass doubling times of the growing bodies.
Aims: Here we attempt to perform global-scale 2D hydrodynamic simulations of the gaseous and pebble disc with several embedded planetary embryos in order to self-consistently account for mutual interactions between these three constituents of the protoplanetary systems. We study the dynamical evolution and stability of the embryos while accounting for the radiative effects in the disc, including the heating torque related to pebble accretion.

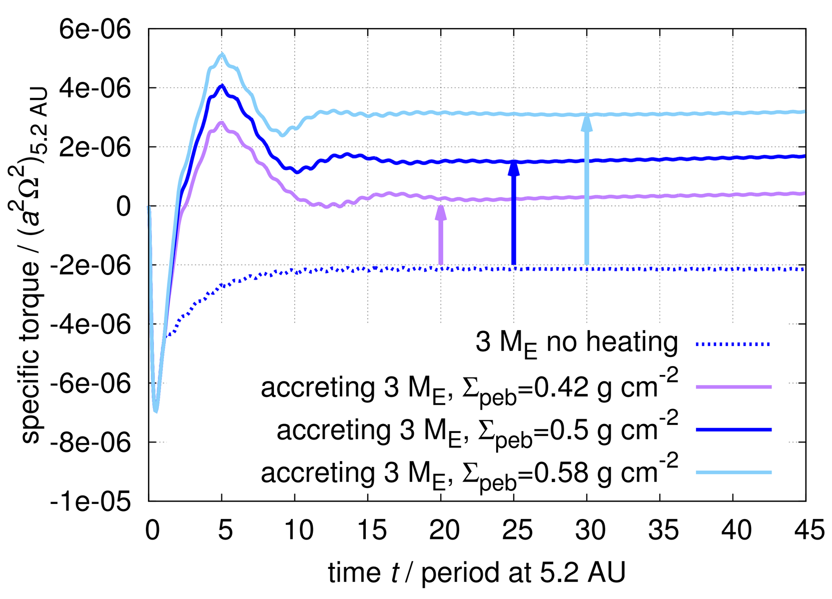
Model

Modifying the framework of the **2D FARGO hydrocode** (2DO REF), 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:
$$\frac{\partial E}{\partial t} + \nabla\cdot(E\vec{v}) = -P\nabla\cdot\vec{v} + Q_+^{\mathrm{visc}} + Q_+^{\mathrm{irr}} - Q_-^{\mathrm{vert}} - 2H\nabla\cdot\vec{F}\,. \qquad (1)$$
Here the right-hand side source terms represent the **compressional heating**, **viscous heating**, **irradiation** by the **protostar** (2DO REF) and the **planets** (2DO REF), cooling by **vertical escape of the radiation** and **radiative diffusion** treated in the flux-limited approximation.
- Coupled **Eulerian model of the pebble disc**. Pebbles are initialized using the model of (2DO REF) and their 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 to be immediately added to the embryo mass (embryos act like a sink for pebbles).
- Interface with the **REBOUND integrator package** (2DO REF). Planetary orbits are integrated in 3D using the hybrid Wisdom-Holman/Gauss-Radau integrator in order to properly resolve close encounters. The direct collision search routines are utilized.

Result 1: Heating torque caused by pebble accretion

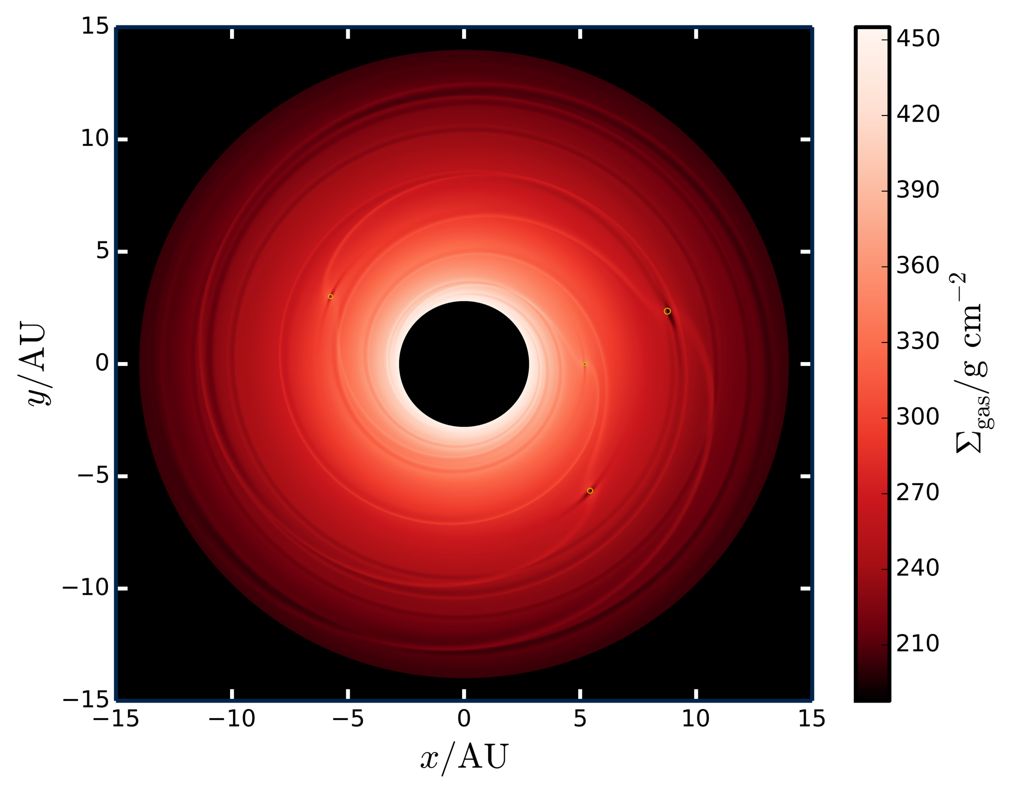


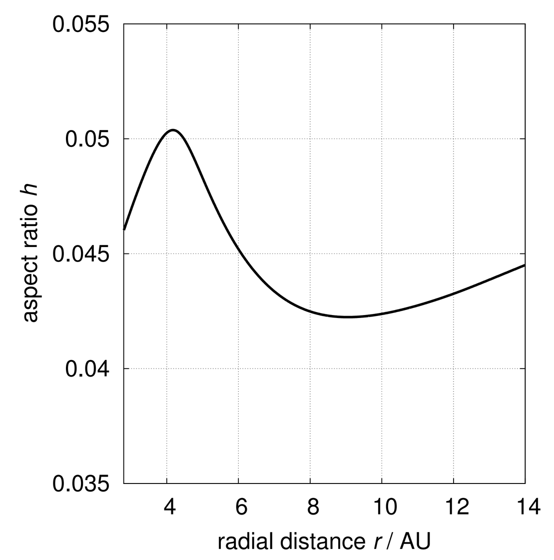


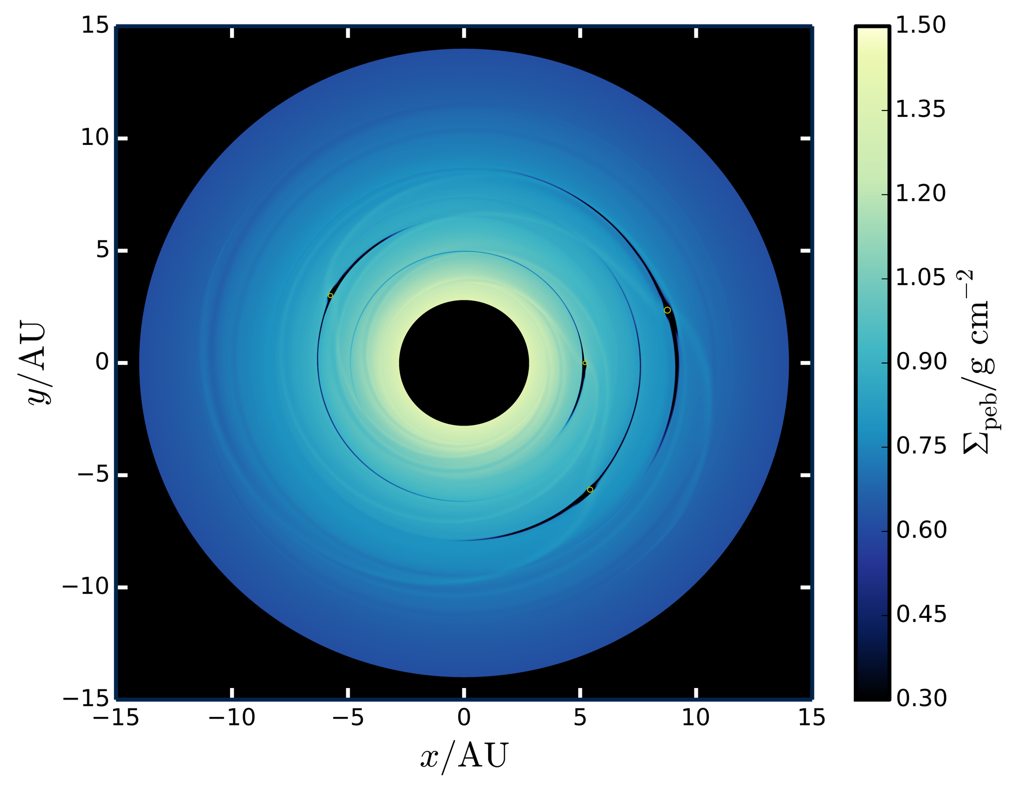
Here we show how the heating torque induced by pebble accretion operates in our 2D global-scale model. The disc parameters in this experiment are similar to (2DO REF).
The figures above show the temporal evolution of the total torque exerted by the disc on an embedded embryo.

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

Gaseous and pebble disc

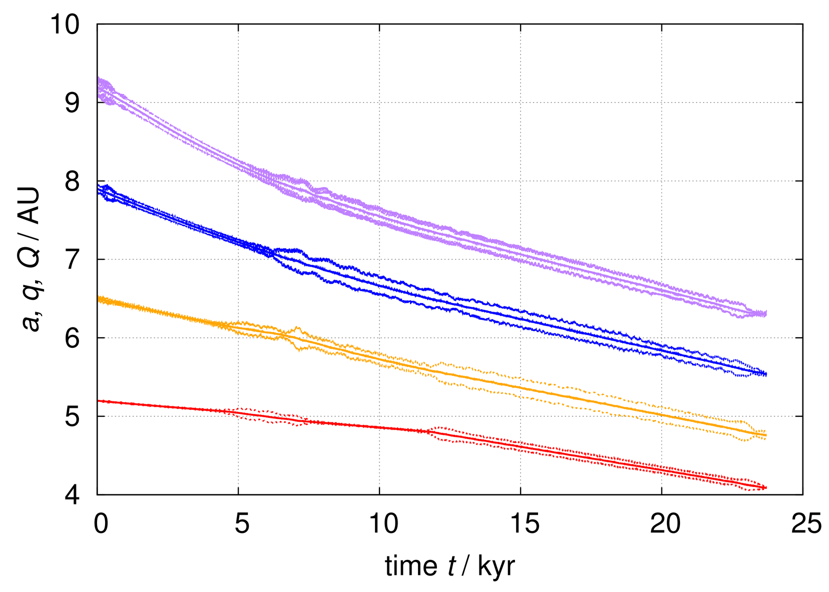


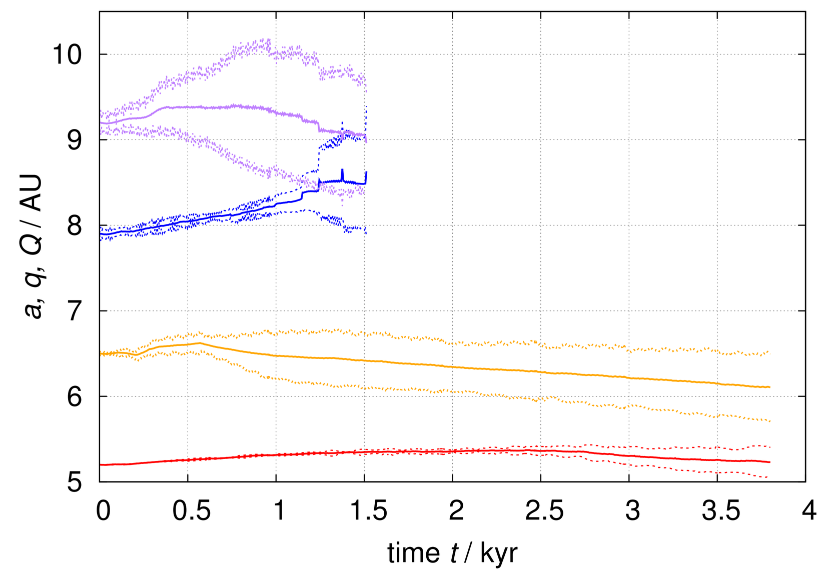




- **Up:** The equilibrium aspect ratio radial profile of the gaseous disc which is used as the initial state in the simulations below. Note the flaring in the outer region caused by the stellar irradiation.
- **Left:** Snapshot of the gas surface density (red) and the pebble surface density (blue) perturbed 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 multiple 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, embryos only **change their masses** 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 excitation which damp the corotation torque efficiency. Although the embryos finish with 5 M_E masses, the rapid mass changes clearly do not destabilize the resonant chain.
- **Right:** The same initial conditions, but the **accretion heating** is at work. Soon after the simulation onset, the two outermost embryos undergo several close encounters and are consequently ejected 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 strong 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 drawbacks of the pebble accretion hypothesis which is a formation of too many planetary embryos (e.g. 2DO REF).
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.