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Radiation Transfer in proto-planetary Accretion Discs with embedded low-mass planets in 3D

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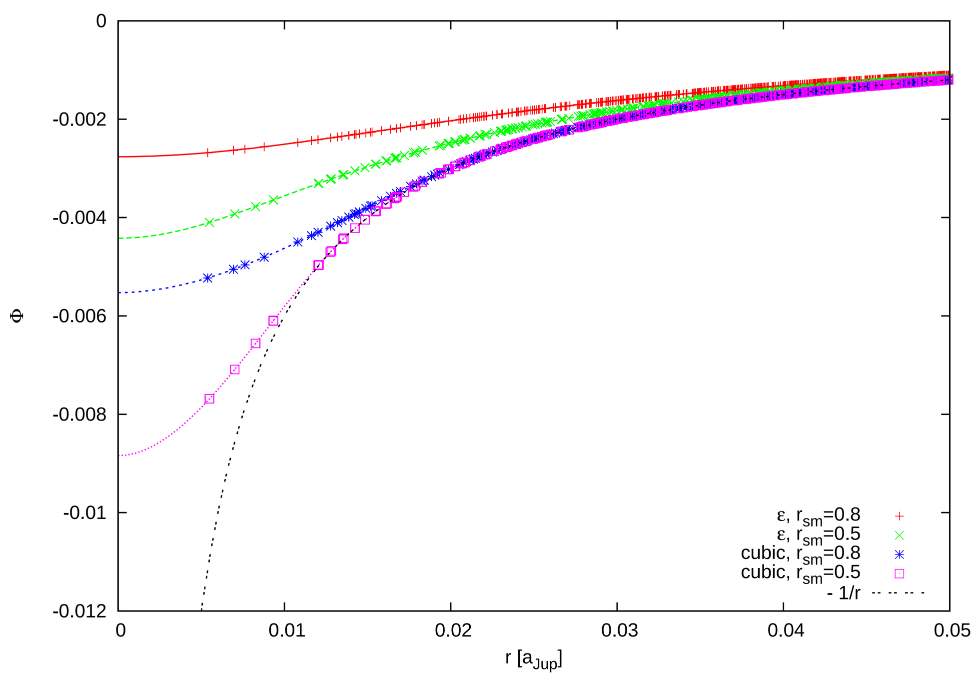
Motivation

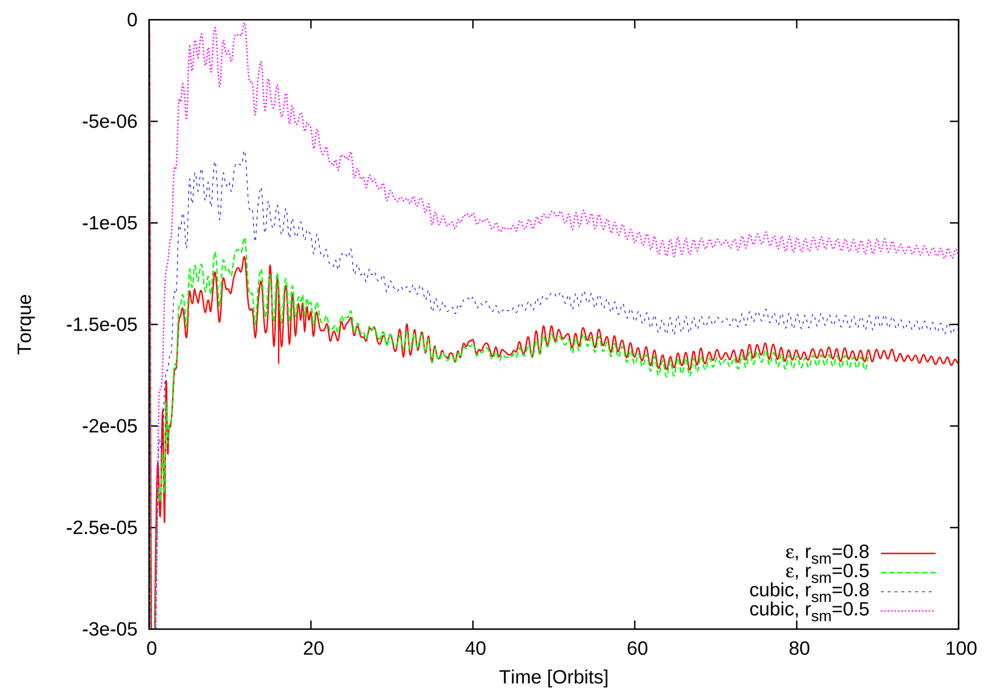
Accretion discs occur in a number of astrophysical environments. Here we are interested in protoplanetary discs around young stars with embedded planets. The orbital evolution (migration) of planets is driven by gravitational planet-disc interaction. The disc's thermal state has been treated in the past primarily in the local isothermal approximation. However, recently it has been found that the magnitude and direction of planet migration depends crucially on the thermodynamics in the disc.
We adopt different numerical planetary potentials in order to find the best approximation for a planet described by a point mass and test its influence on the density distributions near the planet and the torque acting on the planet and thus the migration.
We present for a planet mass of $20M_{Earth}$ a direct comparison of the isothermal and the fully radiative case. We are most interested in the migration of planets, so we finally investigate the torque acting onto the planet for planetary masses ranging from 5 up to $50M_{Earth}$.

Methods and Numerics

- 3D HD equations
- Flux limited diffusion approximation for radiation transport
- SOR for radiation transport
- FARGO (computation in radius dependent co-rotating frame)
- Nirvana-Code (Resolution $266 \times 32 \times 768$ active cells in r, θ, ϕ-direction)

Planetary potentials and corresponding torques

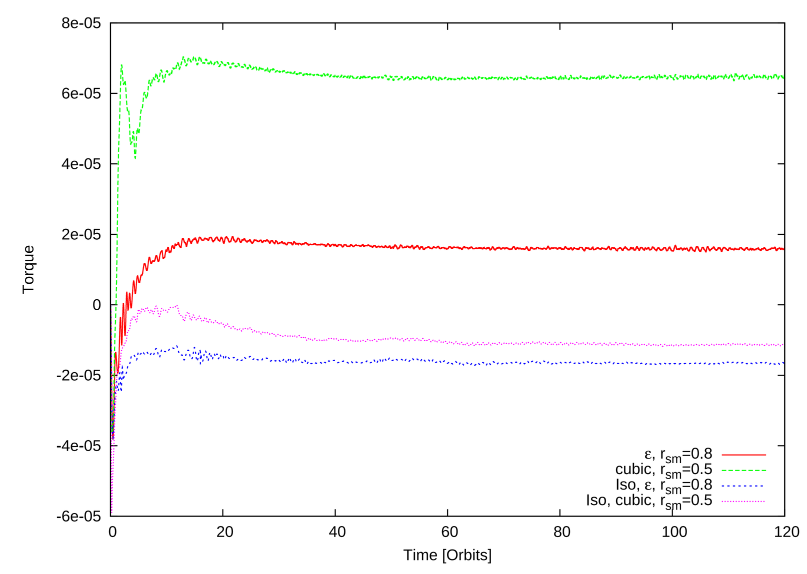




The planet is approximated as a point mass in our simulations. The **cubic** potential equals the physical $(1/r)$ potential outside r_{sm} and is smoothed inside by a cubic polynomial. The classic ϵ-potential is $\propto (r^2 + r_{sm}^2)^{-\frac{1}{2}}$, and influences as such also radii beyond $\epsilon = r_{sm}$. The displayed potentials for two values of r_{sm} for a $20M_{Earth}$ in the picture above. The form of the planetary potential has an influence on the density structure around the planet.

A deeper planetary potential results in a higher density inside the planets roche lobe and a reduced density at the inner half of the horseshoe region. The changed density structures for each planetary potential have an influence on the torques acting on the planet. A deeper planetary potential results in a higher torque acting on the planet, see the figure of torques above (for a $20M_{Earth}$ each) in an isothermal disc.

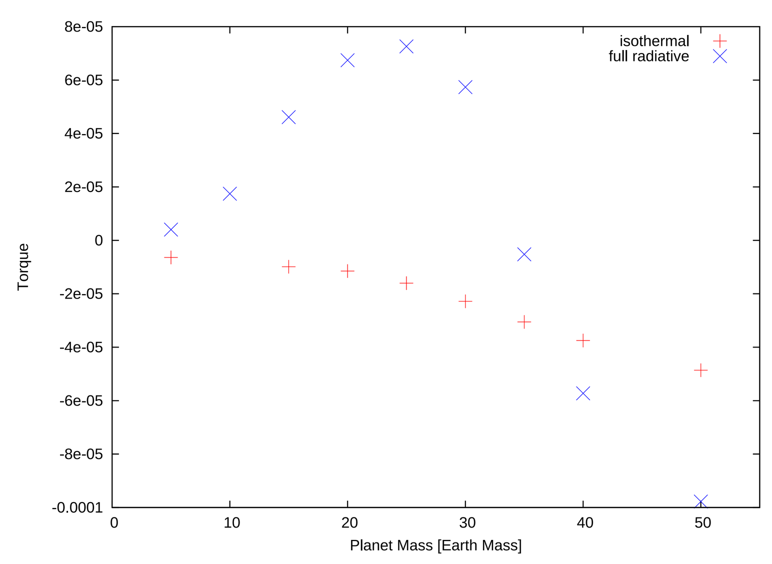
Torques in isothermal & radiative discs



Recent studies of low mass planets in fully radiative discs showed that the planet experiences a positive torque, indicating outward migration, in contrast to a planet in an isothermal disc. For our 3D simulations we find the same result for all our planetary potentials. In the plot above only the torques acting on the planets with the shallowest and deepest potential are shown for the isothermal and fully radiative disc. A deeper planetary potential results for both types of simulations in a higher torque acting on the planet.

Planetary Mass and Torques

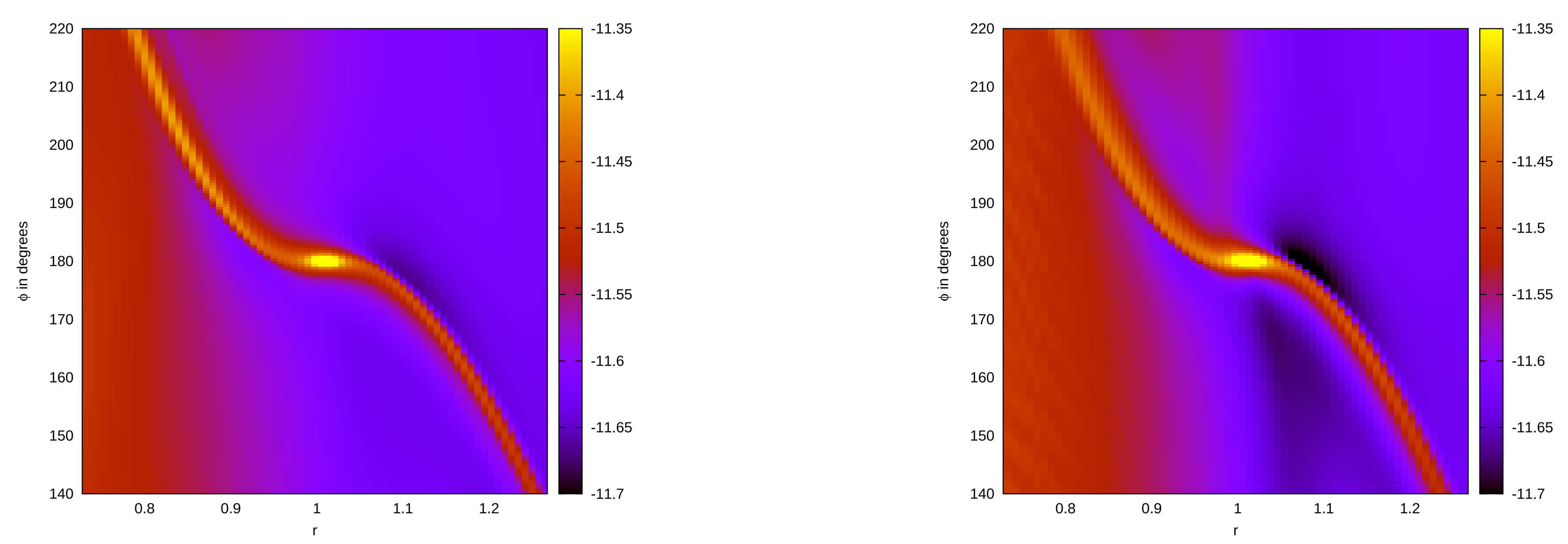
Migration plays an important part in the evolution of planetary systems. Deepending on the planetary mass, a planet undergoes different type of migrations. For low mass planets the (isothermal) Type-I-Migration indicates an inward migration proportional to the planets mass squared. Recent studies of planets in fully radiative discs come to a contrary result: low mass planets do migrate outward. But to what extend do these planets migrate outward? We present here the results of our study of planets with different planetary mass on a fixed planetary orbit (at $r = r_{Jupiter}$) without accretion onto the planet.
For planets with a lower mass than $m \approx 33M_{Earth}$ the torque acting on the planet is positive in a fully radiative disc, while for bigger planets the torque is negative, indicating inward migration. Our reference simulation in the isothermal case gives, as predicted from theory, negative torques. This result is very important for the development of young planetary systems as young growing planetary cores are not lost so easily into the star.



Density distribution in isothermal and fully radiative discs

The density map in the equatorial plane for the isothermal simulation is shown on the left side and for the fully radiative simulation on the right side. Both simulations feature a $20M_{Earth}$ planet with the cubic $r_{sm} = 0.5$ potential. Starting with an isothermal disc model having a fixed $H/r = 0.05$, we find that for our physical disc parameter the inclusion of radiative transport yields discs that are thinner ($H/r = 0.037$ at $r = 1$). Now the thickness depends on the local surface density and the chosen viscosity of the disc.

The different thickness of the protoplanetary discs explains the fact of larger opening angles and higher density for the spiral waves for the isothermal simulations (in thicker discs) compared to the fully radiative simulations (in thinner discs). In discs of the same thickness one should observe larger opening angles for the fully radiative simulation. However the torque acting on the planet is positive for the fully radiative disc indicating outward migration and negative for the isothermal disc.



Conclusions

The planetary potential is a crucial parameter in the calculation of torques acting on the embedded planet. A deeper, more realistic, approximation of the planetary potential results in a stronger torque acting on the planet. For fully radiative discs all planetary potentials indicate outward migration, with the highest torque caused by the deepest planetary potential.
The torque acting onto the planet highly depends on the planetary mass. Our parameter study for planetary masses indicates that planets smaller than $33M_{Earth}$ experience a positive torque and thus outward migration. This result is very important for the first growth phase of planetary systems as it may avoid too early loss into the star.
For more information see the upcoming paper of Kley, Bitsch & Klahr, 2009.