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Migration of massive planets in accreting disks

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Introduction

A very important part to understand the evolution of planetary systems is the migration of the planet while it is still embedded in a protoplanetary disk (Kley & Nelson, 2012). Massive planets that open a gap in the accretion disk are believed to migrate with exactly the viscous speed of the disk, a regime termed type II migration. Even though it is in general slower than type I migration Hasegawa & Ida (2013) argue that type II migration is still too fast. We study the actual migration of massive planets between 0.2 and 10 Jupiter masses in order to compare these migration rates with type II migration.

Setup

- two-dimensional disk approximation
- locally isothermal
- α-viscosity
- code: `NIRVANA` (Ziegler, 1998)
- 251×583 grid cells
- $r = 0.3 \ldots 3.0$ with $r_0 = 5.2\,\mathrm{au}$
- accreting and non-accreting planets

The initial relaxation with a planet on a fixed orbit at $r = 1.0$ is calculated with a reduced resolution for 5000 orbits. Then these results are interpolated to full resolution and can evolve another 290 orbits, until the planet is then released.

Initial and boundary conditions

The initial conditions correspond to an equilibrium disk with constant accretion $\dot{m} = -2\pi r \Sigma u_r$ with

$$u_r = u_r^{\mathrm{visc}} = -\frac{3}{2}\frac{\nu}{r} = -\frac{3}{2}\alpha h^2 r \Omega_{\mathrm{K}}. \qquad (1)$$

This gives

$$\Sigma = \frac{\dot{m}}{3\pi\alpha h^2 \sqrt{GM_*}} r^{-1/2} = \Sigma_0 r^{-1/2}. \qquad (2)$$

We explicitly included accretion through the disk using suitable boundary conditions. At the outer boundary we have an inflow condition with the viscous inflow velocity and a fixed density, thus a given $\dot{m}$ is maintained. At the inner boundary only the outflow velocity is prescribed, the density and thus the outflow of mass is free to change.

Parameter space

We varied the viscosity by the α-parameter, the accretion rate $\dot{m}$ (and thus the disk density) given in $M_\odot$/yr, and the planet mass by the mass ratio $q = M_\mathrm{P}/M_\odot$ where 0.001 corresponds to Jupiter mass M_J. The highlighted row is our standard model. Only one parameter was varied at a time.

α	$\dot{m}$	q
	1×10^{-9}	
	2×10^{-9}	
	5×10^{-9}	
	1×10^{-8}	
	2×10^{-8}	0.0002
0.001	5×10^{-8}	0.0005
0.003	1×10^{-7}	0.001
0.01	2×10^{-7}	0.002
	5×10^{-7}	0.005
	1×10^{-6}	0.01

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Planets on fixed orbits

- gap structure is independent of accretion rate $\dot{m}$
- gaps of accreting planets are deeper by a factor of 2
- flat accretion profile takes very long to develop
- gap does not hinder gas flow in equilibrium
- $\Gamma/\Gamma_0 \propto q^{-1}$ because of the gap becoming wider with increasing planet mass.

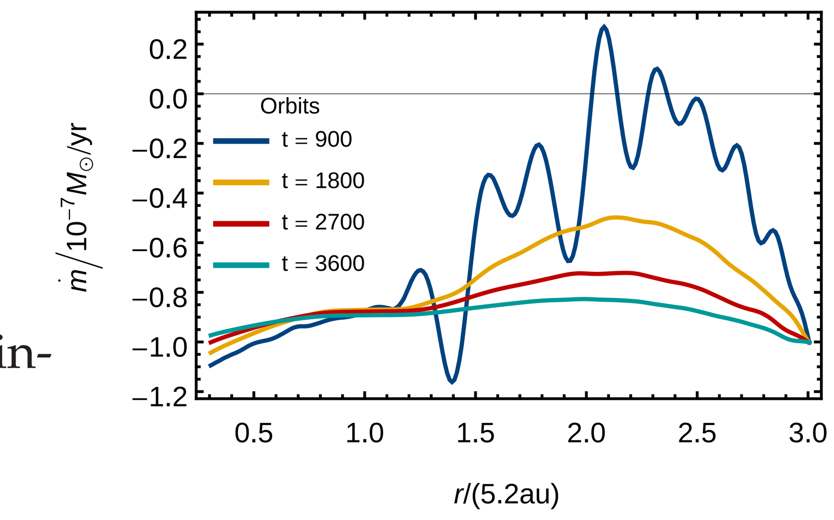

Fig. 1: Accretion rate profile at different times for the standard model. The planet is at $r = 1.0$.

Migrating planets

- planets migrate faster for higher $\dot{m}$
- rapid inward migration at the beginning because the disk has to adapt to moving planets
- type III migration for high disk masses $M_\mathrm{P} \lesssim M_\mathrm{D} = \pi r^2 \Sigma$
- accreting planets migrate about 20 % slower because gas density in the vicinity of the planet is depleted

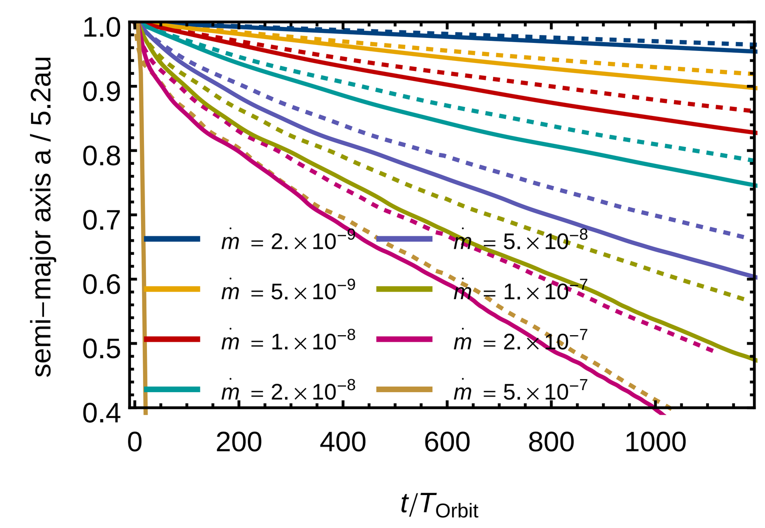

Fig. 2: Migration tracks for Jupiter mass planets with $\alpha = 0.003$ for different accretion rates and hence different disk masses (see Eq. (2)). The dashed lines are for the accreting planets.

- local disk accretion rate in the gap changes with migration rate (migration gets slower with time)
- disk accretion only depends on migration rate
- accretion is positive (outwards) if planets migrates faster than viscous accretion velocity, otherwise reversed

$\Rightarrow$ gap is no barrier for the gas flow

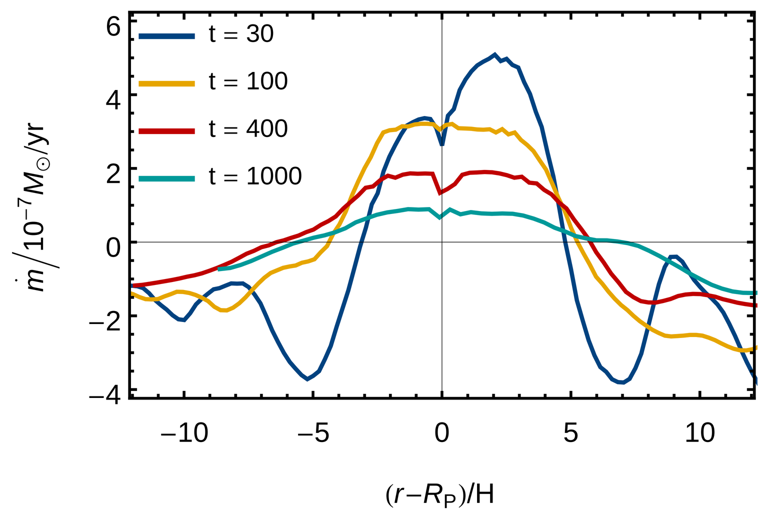

Fig. 3: Accretion rate profile at the position of the planet at different times for the standard model.

- gap structure near the planet independent of $\dot{m}$
- the faster the planets migrate (see Fig. 2) the stronger are the gap deformations: higher density at inner gap edge, lower density at outer gap edge

$\Rightarrow$ gap is dynamically created and follows the position of the planet

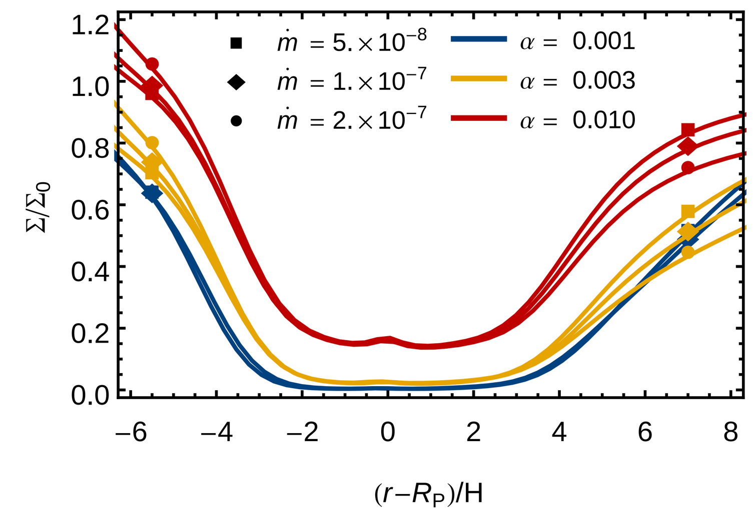

Fig. 4: Gap profiles for different viscosities and accretion rates in case of a Jupiter mass planet.

Comparing to type II migration

- torques are a factor 40 to 400 smaller than in the linear torque regime
- Γ/Γ_0 is constant for light disks as in the linear regime because migration is slow and therefore the gap profiles do not change
- heavier disks lead to faster migration which alters the gap profile and thus weakens the torques
- transition when $\dot{a} \approx u_r^{\mathrm{visc}}$ (see Fig. 6)

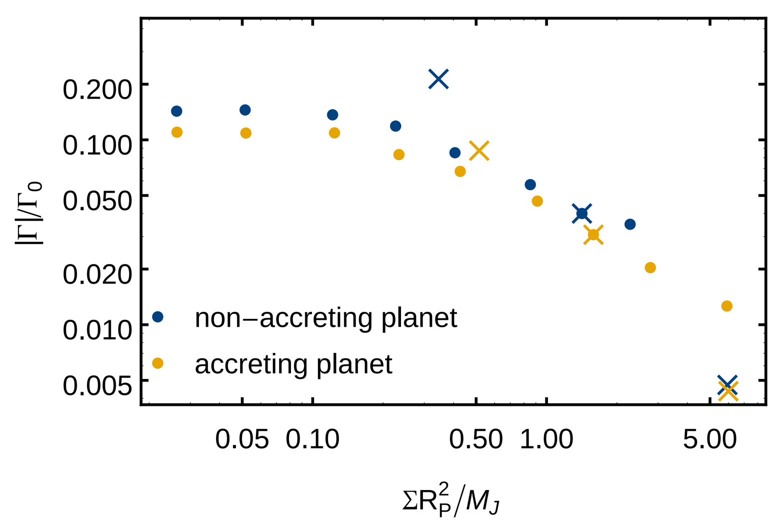

Fig. 5: Normalized torques for different diskmasses varied by the accretion rate and a Jupiter mass planet at $\alpha = 0.003$. The torques were measured between 600 and 700 orbits. The crosses indicate the standard model with $\alpha = 0.01$ (left) and $\alpha = 0.001$ (right).

- migration can be slower or faster than classical type II migration
- for light disks the migration rate is proportional to the disk mass (black line)
- when the migration becomes faster than the viscous inflow velocity the gas near the gap cannot follow the migration and the changed gap profile slows down the increase

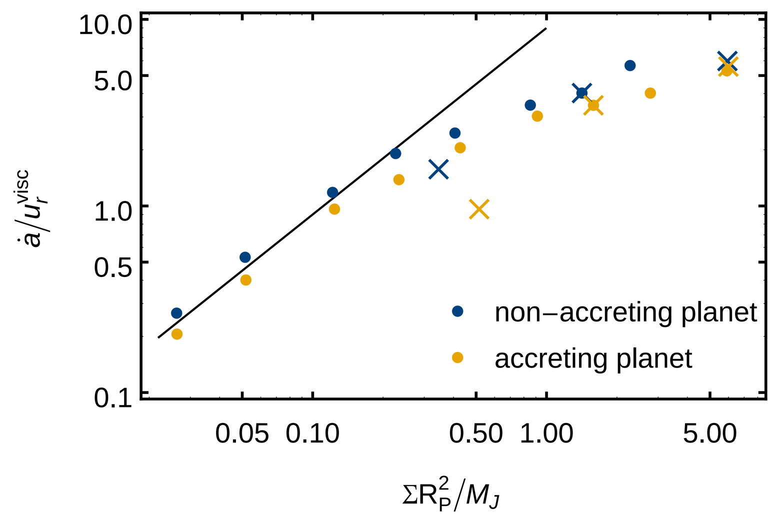

Fig. 6: Migration speeds normalized by the viscous accretion velocity (see Eq. (1)) for the same parameters as Fig. 5.

Conclusion

The inferred migration rate of the planet is determined entirely by the disk torques acting on it and is completely independent of the viscous inflow velocity, so there is no classical type II migration regime. Depending on the local disk mass the migration rate can be faster or slower than type II migration, as also indicated by Duffel et al. (2014).
From the torques and the accretion rate profile in the disk we see that the gap formed by the planet does not separate the inner from the outer disk as necessary for type II migration, rather gas crosses the gap or is accreted onto the planet.

References

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