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PLANET MIGRATION IN MAGNETISED DISKS

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Abstract. Disk/planet interaction in protoplanetary accretion disks causes young planets to migrate inward in the disk. The physical properties of this interaction have been well studied in the past assuming that the disk is laminar. However, it has been known since the early 90s that accretion disks are turbulent because of the magnetorotational instability. In the last few years, the computational power increase has enabled to set up large numerical simulations with the aim to study the effect of MHD turbulence on planet migration. Here, I review the main results obtained though these simulations and then present the coming years perspectives through some recent results.

1 Introduction

The evolution of protoplanets in laminar protoplanetary (PP) disks has been widely studied by many authors in the last few decades (Papaloizou & Terquem 2006, and references therein). A combination of analytical and numerical tools has shown that planets migrate inward because of the tidal torque they exert onto the disk they are embedded in. While low mass planets cause only small perturbations to the PP disk structure, it has also been well established that massive planet clear a gap in the gas around their orbit.

At the same time, observations show ongoing accretion of material onto the central object, which can only be the result of angular momentum transport by turbulence in the disk. At the present time, the most likely mechanism to drive the turbulence is thought to be the magnetorotational instability (MRI; Balbus & Hawley 1998), which destabilise any magnetised rotating fluid when the angular frequency Ω decreases with radius. The nonlinear development of the MRI have been well studied numerically in the last 15 years through local and global numerical simulations and show sustained angular momentum transport for long periods of time, with levels that are roughly consistent with the observations.

While the development of global models of turbulent PP disk is still difficult due to the extremely large computing resources required, it is now feasible, provided some simplifications are made, to study disk/planet interaction in magnetised, and therefore fully turbulent, PP disk. In this paper, I will review recent results obtained using this approach before describing briefly the on–going efforts to relax some of the more stringent approximations made.

2 Planet/disk interaction in turbulent disks

2.1 Disk model

Numerical simulations of planet embedded in turbulent PP disk is challenging for two reasons: first, it requires to develop global disk models for which the resolution requirements are massive. Second, planet/disk interaction occurs on secular timescales. Extremely long integration times are therefore needed. At the present times, such simulations have only been realised by very few groups.

The first of such simulations were presented almost simultaneously by Winters et al. (2003) and Papaloizou & Nelson (2003). To reduce the computational burden, they rely on the so–called cylindrical approximation, first implemented by Armitage (1998). It consists in neglecting the vertical component of the central object gravitational force. Although fully three dimensional, these models have no density stratification in the vertical

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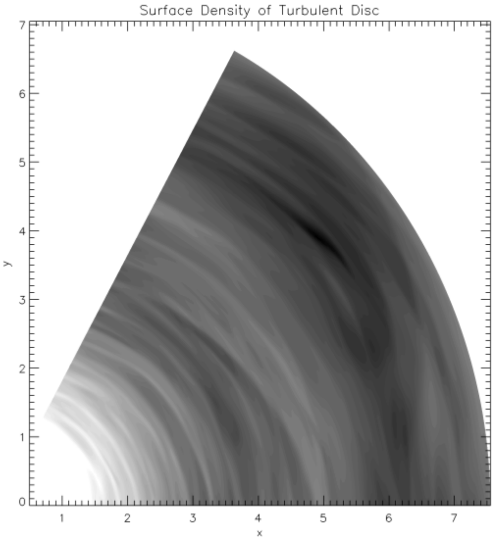

Fig. 1. Surface Density of the disk after turbulence has reach a quasi steady state. Time averaged measures of the Reynolds and Maxwell stress indicate sustained angular momentum transport such that $\alpha \sim 5 \times 10^{-3}$ (from Papaloizou & Nelson 2003).

direction, which significantly reduces the resolution requirements. Even with such a simplification, Papaloizou & Nelson (2003) used a typical resolution $(n_r, n_\phi, n_z) = (335, 100, 60)$ in cylindrical coordinates for a single disk simulation (covering only the range $[0, \pi/3]$ in the azimuthal direction). When subject to a subthermal magnetic field, such a disk is destabilised and the flow breaks down into MHD turbulence. The density structure that results is illustrated on Fig. 1. By calculating the time history of the Reynolds and Maxwell stresses (which measure the correlations respectively between the radial and azimuthal gas velocity components and between the radial and azimuthal magnetic field components), they found $\alpha \sim 5 \times 10^{-3}$. These results are similar to those of Winters et al. (2003).

2.2 Disk/planet interaction

Planets embedded in PP disks create a spiral density wave that propagate in the disk. The gravitational torque exerted by this wave on the planet causes the latter to migrate inward (Ward 1997). Of course, the smaller the mass of the planet, the smaller the density perturbation it creates in the disk. When it is sufficiently small (1–100 earth masses), the turbulent density fluctuations of the background disk can be of the same order as the amplitude of this tidally triggered density wave. This is illustrated on the left panel of Fig. 2, which shows the density in a turbulent disk in the vicinity of a 30 earth mass planet (Nelson & Papaloizou 2004). The wake created by the planet is seen to be strongly perturbed by the turbulence. In this case, the torque exerted by the disk on the planet is still found to be dominated by the spiral wave. For smaller mass planets, however, the "fluctuating" torque created by the turbulent density fluctuations is of the same order as the "systematic" torque due to the spiral wave. Planets in this mass range are therefore observed to do a random walk in the disk. The evolution of their orbital radius depends on the local structure of the disk. This is illustrated by the right panel of Fig. 2, which shows the time history of the semimajor axis of six 10 earth mass planets, released at different radial positions in the disk (Nelson 2005). Some of them migrate inward, some of them barely move at all, while some of them migrate outward. These results have brought forward the idea of "stochastic" migration, which could help increase the typical timescale for type I migration.

As explained above, this effect is only relevant for small mass planets. Larger mass planets strongly perturb the underlying disk and the effect of MHD turbulence becomes less and less important. However, it is of interest to determine whether MHD turbulence has any influence on the processes that leads to gap clearing and finally to the structure of the gap itself. This was studied by Winters et al. (2003) and Nelson & Papaloizou (2003). The results are illustrated on Fig. 3. The left panel shows the effect of a 5 Jupiter mass planet on the structure of the flow. As in a laminar disk, the planet is seen to clear a gap around its orbit. The detailed radial profile

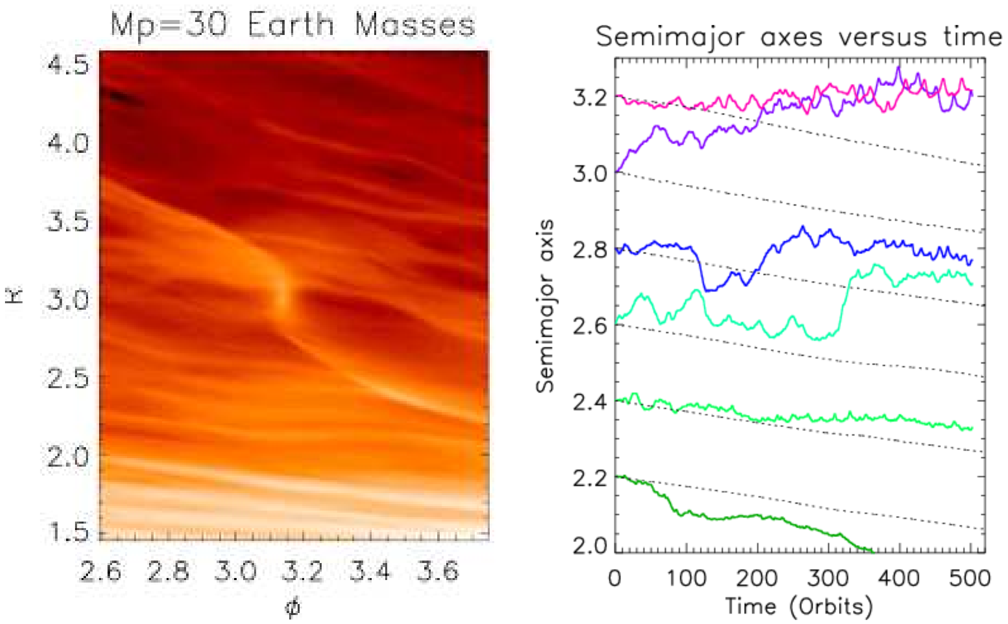

Fig. 2. Left panel: structure of the density field in the equatorial plane of a turbulent disk in the vicinity of a 30 earth mass planet. The spiral wake created by the planet is just visible on top of the turbulent fluctuations (from Nelson & Papaloizou 2004). Right panel: Time evolution of the semimajor axis of six 10 earth mass planets released at different locations in the disk. Significant deviations are found from the expected evolution that would have taken place in a laminar disk, as shown by the dashed lines (from Nelson 2005).

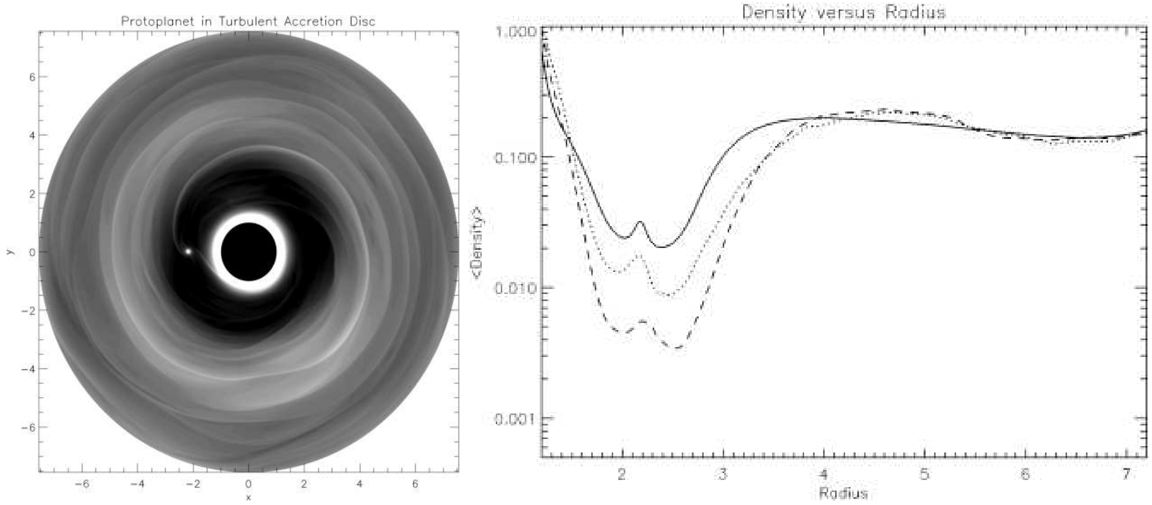

Fig. 3. Left panel: Density in the equatorial plane of a disk perturbed by a 5 Jupiter mass planet in a fixed orbit. Because of its tidal interaction with the gas, the planet has cleared a gap around its orbit. Right panel: Radial profile of the surface density of a disk that contains a 5 Jupiter mass planet. The different curves correspond to a laminar disk with a Navier-Stokes viscosity such that $\alpha \sim 5 \times 10^{-3}$ (solid line), to the turbulent disk model (dotted line) and to a 2D invicid model (dashed line). Both panels are extracted from Nelson & Papaloizou (2003)

of the density is shown on the right panel with the dotted line. It is compared with the result of 2D models computed in a laminar disk with a Navier-Stokes viscosity such that $\alpha = 0$ (dashed line) and $\alpha = 5 \times 10^{-3}$ (solid line). As expected, the gap is more shallow than an inviscid disk, but less than a laminar viscous disk subject to a similar amount of angular momentum transport. The reasons for such a behavior are not fully understood yet.

3 Stratified disk models

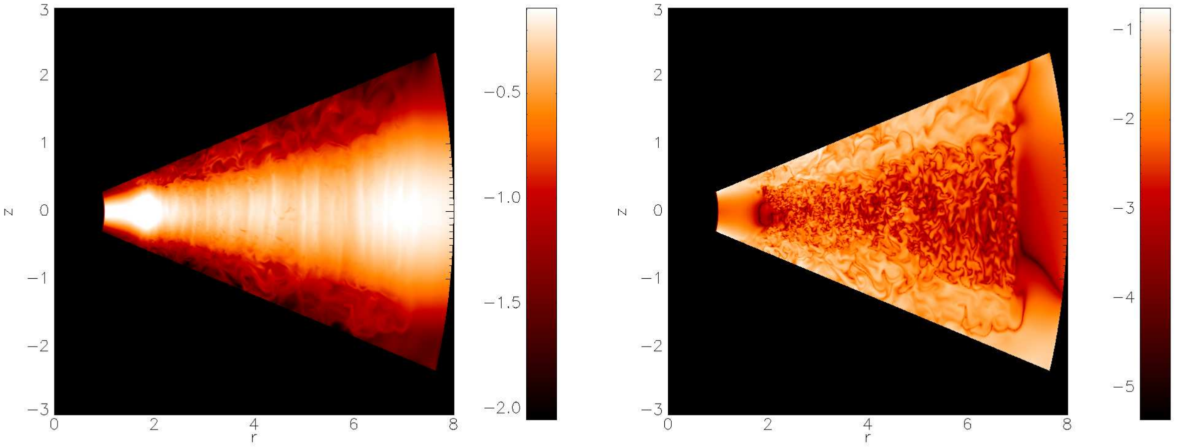

Fig. 4. Left panel: logarithm of the gas density in the $(r-\theta)$ plane of a turbulent and stratified disk model after 400 orbits at the inner edge of the disk. A quasi steady state has been reached with sustained angular momentum transport such that $\alpha \sim 4 \times 10^{-3}$. Right panel: logarithm of the alfvén velocity for the same model. The small scale turbulent structures result from the nonlinear evolution of the MRI and demonstrate that the entire disk has become fully turbulent (from Fromang & Nelson 2006).

The results presented in the previous section consider only cylindrical disk models. Thanks to the increase of computing resources, it is now possible to start to develop more realistic PP disk model, taking the vertical stratification into account. This was done recently by Fromang & Nelson (2006). They found, however, that the resolution requirements are still challenging. To model a PP disk with $H/R = 0.07$, in a computational box that covers $[0, \pi/4]$ in azimuth and 8 scale heights in the vertical direction, the resolution required is $(n_r, n_\phi, n_\theta) = (455, 150, 213)$ in spherical coordinates. With finite difference codes like ZEUS (Stone & Norman 1992a,b) or NIRVANA (Ziegler & Yorke 1997), the corresponding CPU time needed was found to be of the order of 6 years!

The structure of the disk in such a simulation is represented on Fig. 4. The left panel panel shows the logarithm of the density in the (r, θ) plane. The right panel, by showing the logarithm of the Alvén speed, demonstrates that the disk is indeed fully turbulent. Again, measured values of the Reynolds and Maxwell stresses indicate that $\alpha \sim 4 \times 10^{-3}$. In the future, such models will be used to study various problems of planet formation, including planet/disk interaction and their observational signatures, dust dynamics and the influence of a dead zone of global disk properties.

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