EPSC Abstracts
Vol. 6, EPSC-DPS2011-1446-2, 2011
EPSC-DPS Joint Meeting 2011

Planet formation through vortices in layered accretion flow

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Abstract

Large scale anticyclonic vortices concentrate solid material in disks and may thus behave as a route for fast planet formation. The debate over their 3D stability in recent years has lead to the conclusion that they are stable to 3D perturbations provided there is a baroclinic feedback operating. In this contribution, I show how such baroclinic instability interacts with the magneto-rotational instability. Our results indicate that vortices do not survive magnetization, and therefore should exist only inside the dead zone.

1. Introduction

The ill fate of the building blocks of planets in gaseous disks around young stars stands as one of the major unsolved problems in the theory of planet formation. Our current level of understanding indicates that solids in circumstellar disks migrate into the star (Weidenschilling 1977) or are destroyed in collisions on timescales that are much too short to allow the assembly of kilometer sized bodies that can grow further without such problems (Brauer et al. 2008).

The most recent models rely on turbulent motions in the disk in order to breach these barriers (Johansen et al. 2007, Lyra et al. 2008), since turbulent eddies act as particle-trapping high pressure regions (Haghighipour & Boss 2003). Yet, turbulence and angular momentum transport in accretion disks remain a topic of debate. With the disturbing realization that regions of low ionization are robust features of protoplanetary disks (Gammie 1996, Turner & Drake 2009), the search for hydrodynamical sources of turbulence continues. A possible source is the baroclinic instability (BI), which has been shown to exist in unmagnetized non-barotropic disks (Klahr & Bodenheimer 2003, Petersen et al. 2007ab, Lesur & Papaloizou 2010, Lyra & Klahr 2011). I present here simulations of baroclinicly unstable, magnetized, 3D disks, in order to assess the interplay between the BI and the magneto-rotational instability (MRI, Balbus & Hawley 1991), and the role of buoyancy driven flows in the broader picture of the layered accretion paradigm. The implications for planet formation are interesting, since vortices are known to trap solid material efficiently enough to form planetary embryos of Moon to Mars mass (Lyra et al. 2008, 2009).

2. Baroclinic Instability

Vortex formation due to baroclinicity was studied numerically by Klahr & Bodenheimer (2003) and analytically by Klahr (2004). These results were independently confirmed in a definitive study by Petersen et al. (2007ab), Lesur & Papaloizou (2010), and Lyra & Klahr (2011). The BI is a non-linear, local instability triggered by the presence of a global, radial, entropy gradient. Because of this underlying radial gradient, azimuthal disturbances of density and temperature produce non-zero baroclinicity, which in turn generates vorticity locally.

Klahr & Bodenheimer (2003) called it *global baroclinic instability*, where "global" emphasizes the role of the large-scale (global) entropy gradient, and is not related to the (local) nature of the instability. The name is misleading since "global" usually refers to non-local instabilities, i.e., instabilities that depend on boundary conditions. Lesur & Papaloizou (2010) prefer the term *subcritical baroclinic instability*, which emphasizes its non-linear character: the transition to turbulence occurs at a Reynolds number lower than that predicted by linear theory (infinity in this case, since there is no linear instability). We consider the prefix "subcritical" unnecessary, and simply call it *baroclinic instability* (BI).

Four requisites seem to be mandatory for the BI. These are **1.)** *radial entropy gradient and thermal diffusion*, **2.)** *finite amplitude perturbations*, **3.)** *long evolution times*, and **4.)** *high resolution*. The radial entropy gradient may be either positive or negative (Fig. 1). The thermal diffusion is enable thermalization during vortex swing, which is vital to establish azimuthal temperature gradients along the streamline (Petersen et al. 2007ab, Lesur & Papaloizou 2010, Armitage 2010, Lyra & Klahr 2011). These azimuthal temperature gradients, together with the radial entropy gradient, lead to a non-zero baroclinic vector, that in turn generates vorticity growth. Finite amplitude perturbation is needed because the disturbances need to be strong enough to overcome the stabilizing effect of the Keplerian shear that causes perturbations to be heavily dominated by restoring forces in all Reynolds numbers. The instability is *non-linear*. Long evolution times are needed because the growth rate are very small, typically needing hundreds of orbits to achieve saturation. The resolution requirement is tested empirically to be around 32 grid points per radial scale height (H) with the PENCIL CODE. Consider that PENCIL's high order ensure a low degree of numerical dissipation, half-way to spectral, and one would conclude that lower order codes would need even more resolution than 32/H. The resolution requirement is seen to increase when shallower entropy gradients are used. When all these requirements are met, self-sustained vortices are formed in 2D and 3D simulations of unmagnetized protoplanetary disks (Petersen et al. 2007ab, Lesur & Papaloizou 2010, Lyra & Klahr 2011).

2.1 Vortices and planet formation

The saturated state of the BI is characterized by the presence of strong anti-cyclonic vortices. Such vortices radiate inertial-acoustic waves, that vigorously transport angular momentum, yielding alpha values (Shakura & Sunyaev 1973) of $\alpha \approx 5 \times 10^{-3}$ (Lyra & Klahr 2011).

In addition to driving accretion, vortices have two further properties that make them an attractive location for planet formation. The first is that they are equilibrium solutions to the Navier-Stokes equations, and thus are persistent structures in hydrodynamic flows, as seen in the Great Red Spot of Jupiter, a remarkable high pressure vortex stable over three hundred years. The second is that under the influence of the drag force, loosely coupled solid bodies inside an anticyclonic vortex experience a net force towards the vortex eye. While the mechanism is essentially the same mechanism responsible for the radial drift of solids in a laminar disk (Chavanis 2000), the crucial difference is that whereas in a laminar disk the radial drift leads them to the inhospitable flames of the star, radial drift inside an anticyclonic vortex simply makes the particles sink towards the vortex eye. This has the convenient side effect of dramatically enhancing the solids-to-gas ratio, potentially achieving values high enough to form rocky planets by direct gravitational instability of the layer of solids (Safronov 1969, Johansen et al. 2007, Lyra et al. 2009).

It was demonstrated that 2D vortices concentrate boulders strongly enough to allow them to collapse to planets by gravitational instability (Lyra et al. 2008, Lyra et al. 2009). Bursts of planet formation ensue within the vortices, leading to the formation of hundreds of gravitationally bound planetary embryos, with dozens of them being more massive than Mars. The timescale was less than 100 orbits. This efficiency is so high, though, that it approaches implausibility. We suspect that the high efficiency was due to the quiet nature of the 2D vortices. Calculating the collisional velocity history of the particles that compose the embryos, it is found that the vast majority of them never experienced a collision with another particle at speeds faster than $1\ \mathrm{m\,s^{-1}}$. Three-dimensional vortices, on the other hand, display turbulent cores as showed by Lesur & Papaloizou (2009, 2010) and Lyra & Klahr (2011).

2.2 The BI in the layered accretion paradigm

Elliptic streamlines are inherently unstable, decaying spontaneously due to the so-called elliptic instability (EI), a secondary instability that may be connected to the very problem of transition to turbulence (see, e.g., the excellent review of Kerswell 2002). Lesur & Papaloizou (2010) find that unmagnetized vortices find a balance between production of vorticity by the BI and destruction by the EI, leading to "core turbulence" only. In Lyra & Klahr (2011) we extend this result to magnetized vortices, finding that the magneto-elliptic instability (MEI) that ensues (Lebovitz & Zweibel 2004, Mizerski & Bajer 2009) delivers a blow far more powerful than the baroclinic term can withstand. The vortices are completely destroyed as soon as they get magnetized (Fig. 2). We unveil also that in the limit of an infinitely weak vortex, the MEI reduces to the MRI, a result that connects the two instabilities as different manifestations of the same *magneto-elliptic-rotational instability*. As the MEI has roughly the same properties as the MRI, the conclusion is that vortex excitation and sustenance is only viable in regions of low ionization, i.e., the dead zone.

Vortices are also shown to migrate radially (Paardekooper et al. 2010), due to the excitation of spiral density waves, that exert torque on the vortex (see also Fig. 3), similarly to type I migration. This opens the possibility to an interesting global picture of accre-

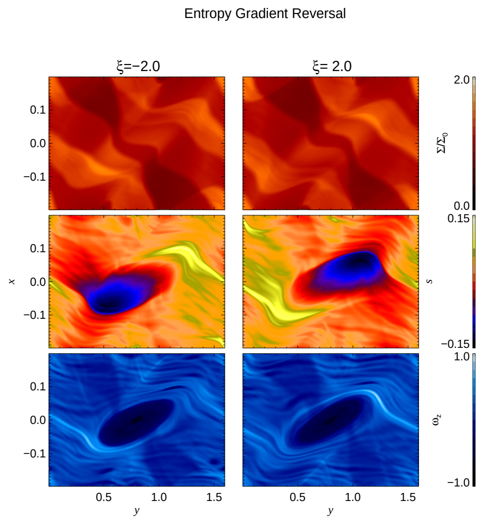

Figure 1: Positive and negative radial entropy gradients yield the same growth rates and saturated state. The flows are perfect mirror-images of each other, owing to a symmetry in the equations. The axis are in units of the scale height.

tion disks. A baroclinicly unstable dead zone should be characterized by the presence of large scale vortices whose cores are elliptically unstable, yet sustained by the baroclinic feedback. As magnetic fields destroy the vortices, and the MRI outweighs the BI, the active layers are unmodified. Vortex migration leads the vortices from their birthplace in the dead zone into the magnetized regions, where they are destroyed. Upon destruction, whatever large bodies formed within the vortex are released in the disk.

3. Summary and Conclusions

We find that vortex excitation and self-sustenance by the baroclinic instability in protoplanetary disks is viable only in low ionization, i.e., the dead zone. A baroclinicly unstable dead zone should be characterized by the presence of large-scale vortices whose cores are elliptically unstable, yet sustained by the baroclinic feedback. Since magnetic fields destroy the vortices and the MRI outweighs the BI, the active layers are unmodified. We also present models of the BI in global disks, in which we see that the vortices developed from the initial perturbations are subject to migration, being lost to the inner boundary of the domain. Without the initial large perturbations to trigger the growth of another vortex, the flow relaminarizes, which implies that the BI needs continuous forcing. Whether the active layers of the MRI can provide such forcing remains and open question. If the MRI and BI are mutually exclusive, a global picture of the dead zone is emerging, where accretion proceeds via MRI alone in the active layers, and by the BI via planet-forming vortices in the magnetically dead zone.

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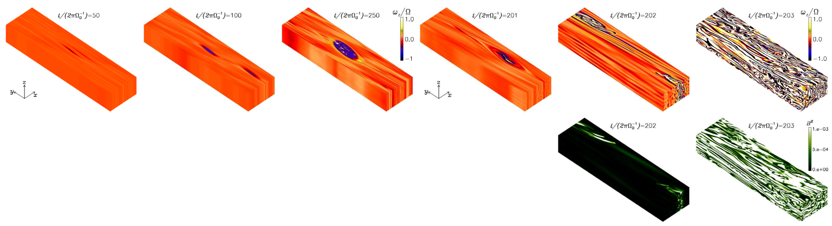

Figure 2: Evolution of vorticity (upper panels) and magnetic energy (lower panels) in 3D. The first three panels show the hydro, unmagnetized, evolution, the last three ones the evolution after the magnetic field is introduced. The vortex is destroyed as the magneto-elliptic instability develops in the vortex core, and the MRI in the box. In a nonmagnetic run, the vortex survives indefinitely.

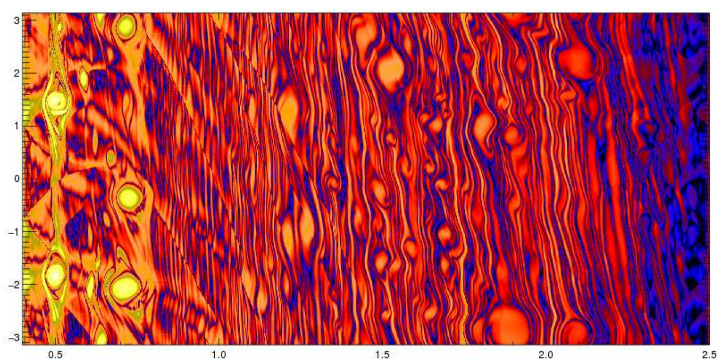

Figure 3: A global model of the baroclinic instability, still in the early stages of growth. The spiral waves radiated by the vortices are apparent. These waves transport angular momentum outward, leading to inward vortex migration. Without finite amplitude perturbations to yield a new generation of vortices, the flow relaminarizes, indicating that the BI needs continuous forcing.