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THE THREE-DIMENSIONAL STRUCTURE OF VORTICES IN PROTOPLANETARY DISKS AND DUST TRAPPING

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Abstract. Protoplanetary disks vortices are of high interest for planetesimals formation as they can accelerate the growing process of the dust. Indeed previous two dimensional studies have shown that they could concentrate the solid particles in their centre. One mechanism proposed to explain the emergence and survival of a vortex in a differentially rotating disk, is the Rossby Wave Instability (RWI). In this context, we present the structure of a three dimensional RWI vortex and we study the concentration of solid particles in this structure. We show that the dust are effectively concentrated in these vortices, and that the concentration depends on the size of the particles.

Keywords: accretion, accretion disks, protoplanetary disks, hydrodynamics, instabilities, methods: numerical

1 Introduction

The growing of dust of sub-μm size toward planet is achieved through multiple steps. The core accretion scenario explains the growth of grains to centimetre or meter scale thanks to electrostatic interactions, but the growth is then halted since solids of this size decouple from the gas and start feeling the headwind of the sub-Keplerian gas. This force them to spiral onto the central star in a highly too short timescale of a few hundreds years. Large-scale and long-lived vortices have been proposed as an alternative to this scenario, as the anticyclonic streamlines induce a drag toward their centre (Barge & Sommeria 1995). This results in a concentration of grains that can highly accelerate the growing process (Inaba & Barge 2006; Lyra et al. 2009) and this is one of the reason why numerous recent studies focus on vortices (Barranco & Marcus 2005; Lesur & Papaloizou 2009; Heng & Kenyon 2010; Paardekooper et al. 2010). The emergence of such vortices, in a differentially rotating disk, stayed unexplained until recently. Whereas different mechanisms have now been explored, we here concentrate on the Rossby wave instability (Lovelace et al. 1999; Tagger 2001) that was proposed by Varnière & Tagger (2006).

This instability can grow, and therefore sustain vortices, in an extremum of the quantity $\mathcal{L} = \frac{\kappa^2}{2\Omega\Sigma}$ that is usually called vortensity or specific vorticity. Here Ω is the rotation frequency, κ is the epicyclic frequency defined as $\kappa^2 = 4\Omega + 2\Omega\partial_r\Omega$ in (r, ϕ, z) coordinates and Σ is the vertically integrated density, called surface density. This extremum can exist at different radius of the protoplanetary disk, such as the edges of the dead-zone (Varnière & Tagger 2006) or the snow line region (Kretke & Lin 2007), that both create a maximum in the density profile.

2 Numerical setup

We have performed two types of numerical simulations, the first one with only a gas disk, and the other one with a mixed gas and solid disk.

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The first one are simulations of unmagnetised and isentropic gas disks. The hydrodynamical equations are solved with the up to date Versatile Advection Code (Tóth 1996) with a cylindrical grid. The mesh has $150 \times 64 \times 64$ cells, on a non-uniform grid that allows to reach a higher resolution on the region of interest. The initial conditions correspond to a radially decreasing density, on which we added a bump to satisfy the RWI criterion. The computational domain goes from (r_i, 0, 0) to ($6r_i$, 2π, r_i), with r_i the radius of the inner boundary of the simulation. The bump is place at a radius of $3r_i$. All the numerical details concerning these simulations are described in our recent paper (Meheut et al. 2010).

Then a second type simulations have been done, with both gas and solid grains. The gas is treated as before, and the dust is considered as a pressureless fluid. The dust evolution equations are solved with a 4^{th} order Runge-Kutta method. The drag force is calculated in the Epstein regime and no back-reaction of the dust on the gas is considered. Yet this bi-fluid version of VAC is not parallelised, and therefore needs a lot of computational time. For this reason, the gas initial conditions are the one obtained at the end of the previous simulation, whereas the dust is initialized with the azimuthally averaged gas density and with a keplerian rotation velocity. The initial azimuthally averaged gas-to-dust ratio is constant over the disk, and fixed to 10^{-2}.

3 Results

The gas simulation has proven the existence of the RWI in a 3D disk, and has shown the emergence and survival of an anticyclonic vortex due to this instability. The detail study of the 3D RWI and its growth are presented in Meheut et al. (2010), here we focus on the vortex structure and its implication for dust trapping.

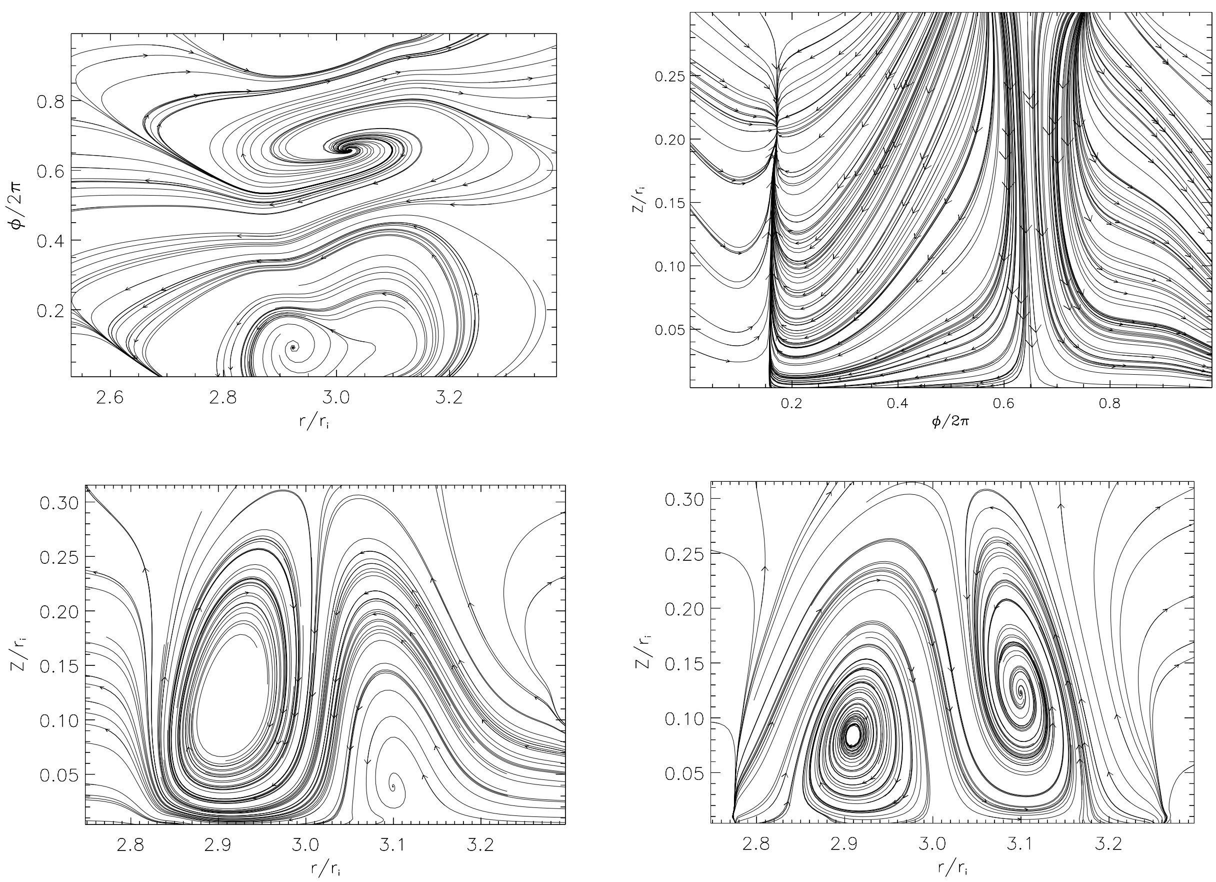

Fig. 1. *Top:* Velocity streamlines in a frame rotating with the disk in the midplane of the disk (*left*) and in the vertical plane at $r = 3r_i$ (*right*). *Bottom:* Velocity streamlines in a vertical frame at $\phi/2\pi = 0.64$ (*left*) and 0.66 (*right*).

The velocity streamlines are presented on Fig. 1. This figure shows the non-axisymetrical part of the velocities. The midplane streamlines confirm the presence of a cyclonic ($\phi/2\pi \sim 0.2$) and anticyclonic ($\phi/2\pi \sim 0.6$) vortex. The converging and diverging streamlines corresponds respectively to upward and downward displacements as can be seen on the vertical cut in the $r = 3r_i$ plane. The vertical structure of the vortex is then more complex than previously thought. This complexity also appears when plotting the radial and vertical velocity streamlines at the centre of the anticyclonic vortex, as shown in the bottom part of the figure. It shows rolls structures on the whole vertical height of the disk, and on each part of the initial density bump that was placed at $r = 3r_i$. The bottom left plot is a vertical cut in the front part of the anticyclonic vortex, it shows accreting streamlines that are vertically modified in the rolls; whereas in the back part of the vortex (bottom right) the streamlines have the opposite direction.

This 3D structure was supposed to modify the dust concentration mechanism: we expected the intermediate size solids to follow the gas in the downward stream but not in the upward stream due to gravity. The bi-fluid simulation confirms this prediction after only approximately one twentieth of an orbit as shown on Fig. 2. One can see that there are two region of dust high density that correspond to the bottom of the upward streamlines. On the other hand, the dust concentration depends on the dust size. The smaller particles follow the gas in its vertical displacement and therefore are less concentrated. The gas drag has a lower effect on the biggest ones that are then less concentrated by the vortex. We then obtained the highest concentration for $500\mu m$ to $1mm$ size dust.

4 Summary and discussion

Here we have presented the first results obtained with our bi-fluid code, allowing to follow gas and dust in a 3D Rossby vortex. The simulation showed that the anticyclonic vortex effectively concentrates the dust and that the highest concentration is obtained for intermediate dust size ($500\mu m$ to $1mm$).

The result presented here only aimed to give a proof of principle of the solid concentration in 3D Rossby vortices but more developments are needed. First, the gas drag should be extended to the Stokes regime to have a better modelisation of the biggest particles. Then the numerical method used to solve the solid evolution equation should be improved with the use of a Riemann solver that will allow to obtain a longer time evolution simulation.

The 3D vortex structure we have obtained also needs to be analyzed analytically as it is only recently that the RWI has started to be analyse in three dimensions. One approach was recently proposed by (Umurhan 2010), but it does not include such 3D vortex structure.

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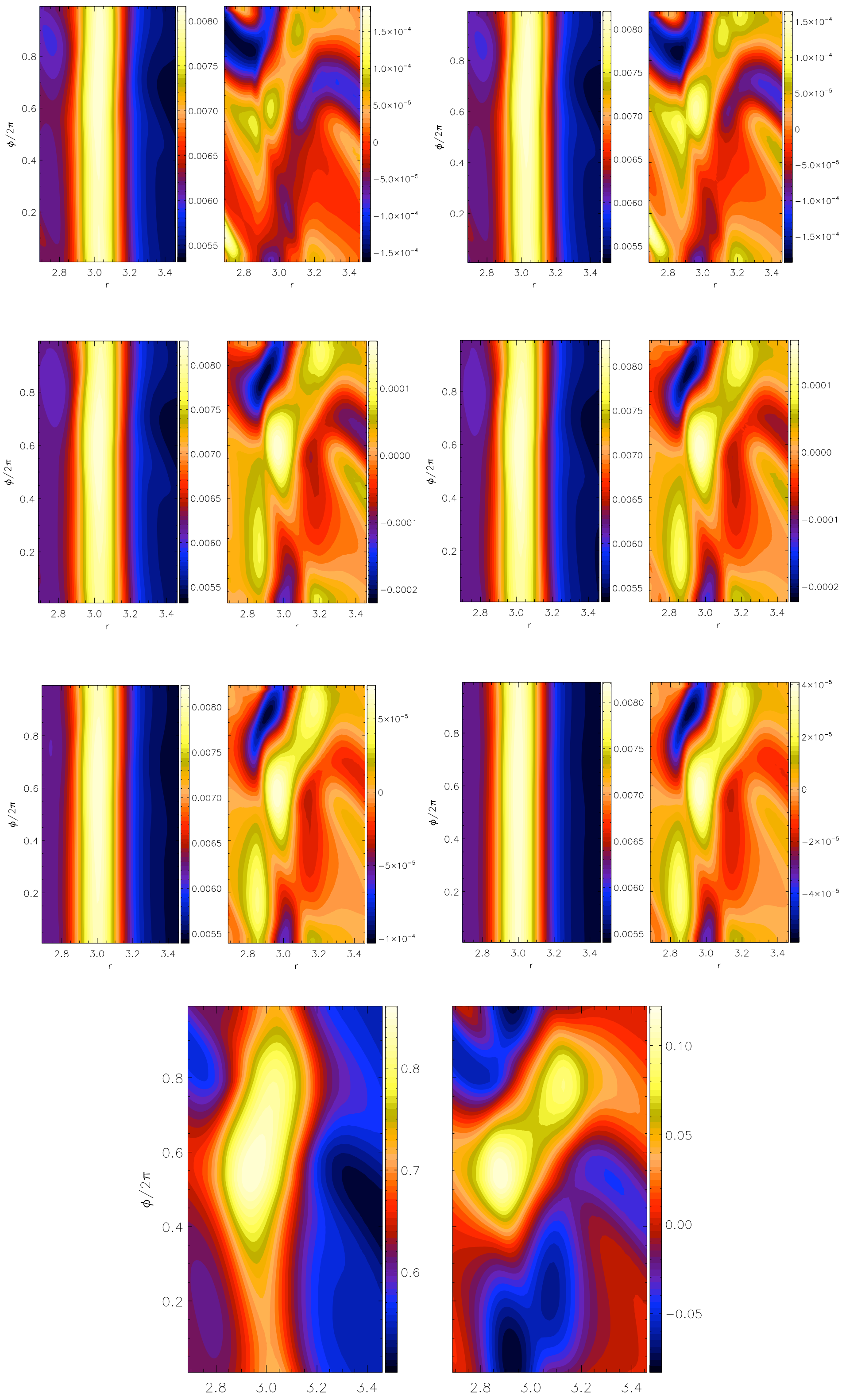

Fig. 2. Density (*left*) and non-axisymetrical part of density (*right*) plotted in the midplane of the disk for different sizes of particles: $10\mu m$, $100\mu m$, $500\mu m$, $1mm$, $5mm$, $1cm$ (from top left to bottom right). The corresponding plot for the gas is also given at the bottom for comparison.