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Concentration of solids in 3D Rossby vortices

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Abstract

Vortices have been proposed as a solution to the "meter-size barrier" in the context of planetesimals formation. Indeed vortices may concentrate the solids in their centres and accelerate grain growth. By this mean, grains may overcome this size barrier without falling onto the central star due to gas drag. The Rossby Wave Instability (RWI) may be a solution to form such vortices again the destructive effect of differential rotation. We present here the first three dimensional (3D) simulations of the concentration of solids in such Rossby vortices.

1. Introduction

One of the most unclear stage for planet formation in the core accretion scenario is the formation of planetesimals. The difficulty resides in the rapid drift of the solid grains, with sizes around 10 cm, toward the central star on a timescale much too small to explain their growth up to sizes where the velocity drift starts to decrease. One proposed solution postulates the trapping of dust in vortices the protoplanetary disc [1, 2]. However such vortices are teared away by differential rotation and one need a stabilising mechanism such as the RWI [4]. Previous studies have shown that this instability can grow at the edge of the poorly ionised region of the disc ("dead-zone") [9] and that the Rossby vortices effectively concentrate the grains [5]. But it is only recently that a full 3D approach of this instability has been proposed [6]. We here present a bi-fluid simulation of the coupled evolution of gas and solids in such Rossby vortices.

2. Methods

To study the coevolution of gas and solids in vortices, we first simulate the formation of the vortices through the RWI ignoring the presence of solids. The initial conditions are similars to the ones presented in [6] and are explained in [8]. When the vortices are fully developed, after ~ 24 orbits at the inner edge of the simulation (r_i), we add the solids. At this stage the grain density is axisymetric and has the same distribution than the gas initially with a bump at $3r_i$. The grains are considered as a fluid without pressure in the Epstein regime and a new module developed for MPI-AMRVAC [3, 7] is used to solve the bi-fluid equations:

$$\begin{cases} \partial_t \rho + \vec{\nabla}\cdot(\rho\vec{v}) = 0 \\ \partial_t \rho\vec{v} + \nabla\cdot(\vec{v}\cdot\rho\vec{v}) + \vec{\nabla}p = -\rho\vec{\nabla}\Phi_G + \vec{f}_d \\ \partial_t \rho_d + \vec{\nabla}\cdot(\rho_d\vec{v}_d) = 0 \\ \partial_t \vec{v}_d + \vec{v}_d\cdot\nabla\vec{v}_d = -\rho\vec{\nabla}\Phi_G - \vec{f}_d \end{cases} \quad (1)$$

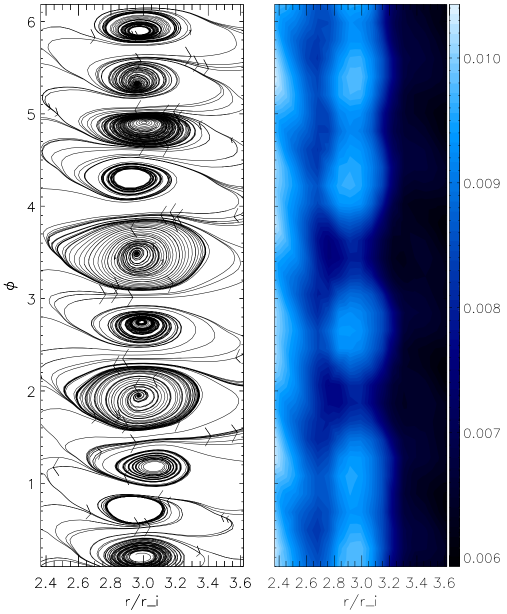

Figure 1: The disc midplane after ~ 25 orbits. *Left:* Gas perturbed velocity streamlines showing cyclonic (anticlockwise rotation) and anticyclonic (clockwise rotation) vortices. *Right:* The density of the solid grains is ploted in color. The solids are concentrated in anticyclonic vortices.

$\vec{f}_d = \sqrt{\frac{8}{\pi}} c_s \frac{\rho_d \rho}{\rho_p s_p}(\vec{v} - \vec{v}_d)$ and $p = 10^{-3}\rho^{5/3}$ with ρ and $\vec{v}$ the density and velocity of the gas, the d subscript refers to the dust, Φ_G is the central gravitational potential. $\vec{f}_d$ is the drag force in the Epstein regime, with ρ_p and s_p the density and size of the individual solid particles and c_s the sound speed. We introduce the nondimensional stopping time at the inner edge $\tau_s = \sqrt{\frac{\pi}{8}} \frac{\rho_p}{\rho(r_i)} \frac{s_p}{r_i} \frac{v_k(r_i)}{c_s(r_i)}$ with v_k the keplerian velocity. $\tau_s = 0.5$ in the simulation presented here.

3. Solids concentration

3.1. Midplane configuration

As predicted theoretically and observed in 2D simulations, we observe dust concentration in anticyclonic vortices. Fig. 1 shows the velocity streamlines of the gas with cyclonic and anticylonic vortices and the density of the dust. The vortices breaks the axisymmetry distribution of the dust with a clear effect of concentration in anticyclonic vortices and depletion in cyclonic vortices.

3.2. Vertical structure

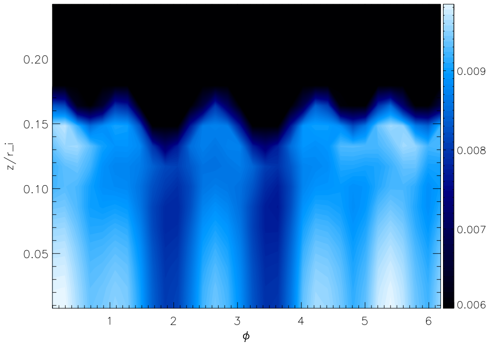

Figure 2: The vertical structure of the dust. The dust density in the $(r = 3r_i, \phi, z)$ plane is plotted. The vertical height of the dust layer is highly modified by the presence of the vortices. However, the variations in height appear here amplified by the different scale in vertical and azimuthal direction. The time is the same than Fig. 1

These 3D simulations allow to investigate the verticale structure of the dust. The Rossby vortices are extended along the whole vertical structure of the disc and tend to concentrate the solids not only in the midplane but also over the height of the dust disc. This effect can be seen it on Fig.2 that shows the dust density over height and azimuth. Moreover, this induces non-axisymmetrical structures in the dust surface, that shows high amplitude variations.

4. Summary

These new simulations have shown the 3D structure of the dust in Rossby vortices, including vertical stratification inside the vortices. We have shown that the dust is concentrated all over the dust disc scale-height in anticyclonic vortices. This induces strong variability of the height of the dust disc over the azimuthal direction. Such variability is of peculiar interest in the scope of the ALMA observatory that may be able to detect such structures in a dust disc.

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