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The Formation of a Planet in the Eye of a Hurricane — Vorticity Generation via the Global Baroclinic Instability in Accretion Disks

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Abstract. Vortices play a crucial role in the formation of planets. They are probably formed naturally in protoplanetary accretion disks from a so called Global Baroclinic Instability that arises if the radial entropy gradient is strong enough. The vortices show up as huge stable anti-cyclonic rotating gas masses, that can be regarded as planetary precursors for two reasons. First they resemble peaks in the gas surface density about four times above the ambient medium, and second they concentrate very efficiently all solid dust above a certain size in their center. This makes it obvious that those vortices are the preferred formation sites for planets. A three-stage formation scenario can be invoked, where the vortices are phase one, dust concentration phase two, and finally gas accretion phase three.

1. Introduction

Anti-cyclonic rotating gas parcels are vortices, that could be the precursors of planetary formation. They can be thought of as pre-protoplanets. The planets could form either by concentration of dust in the centers of the vortices, as was suggested by Barge & Sommeria (1995), Tanga et al. (1996) and Godon & Livio (1999), or by sufficient gas accretion onto a vortex so that it undergoes gravitational collapse (Adams & Watkins 1995).

Klahr & Bodenheimer (2002) discuss the Global Baroclinic Instability as a possible mechanism to form such vortices in protoplanetary accretion disks. This instability arises in rotating systems with a sufficient radial entropy gradient.

2. A Three Phase Model of Planet Formation

The formation of planets is probably characterized by three phases, that depend directly on each other.

- Phase 1: Formation of Anti-cyclonic Vortices as Pre-Protoplanetary Condensations

- Phase 2: Accumulation of solids in Anti-cyclonic Vortices as Protoplanetary Cores
- Phase 3: Accretion of gas onto Protoplanetary Cores

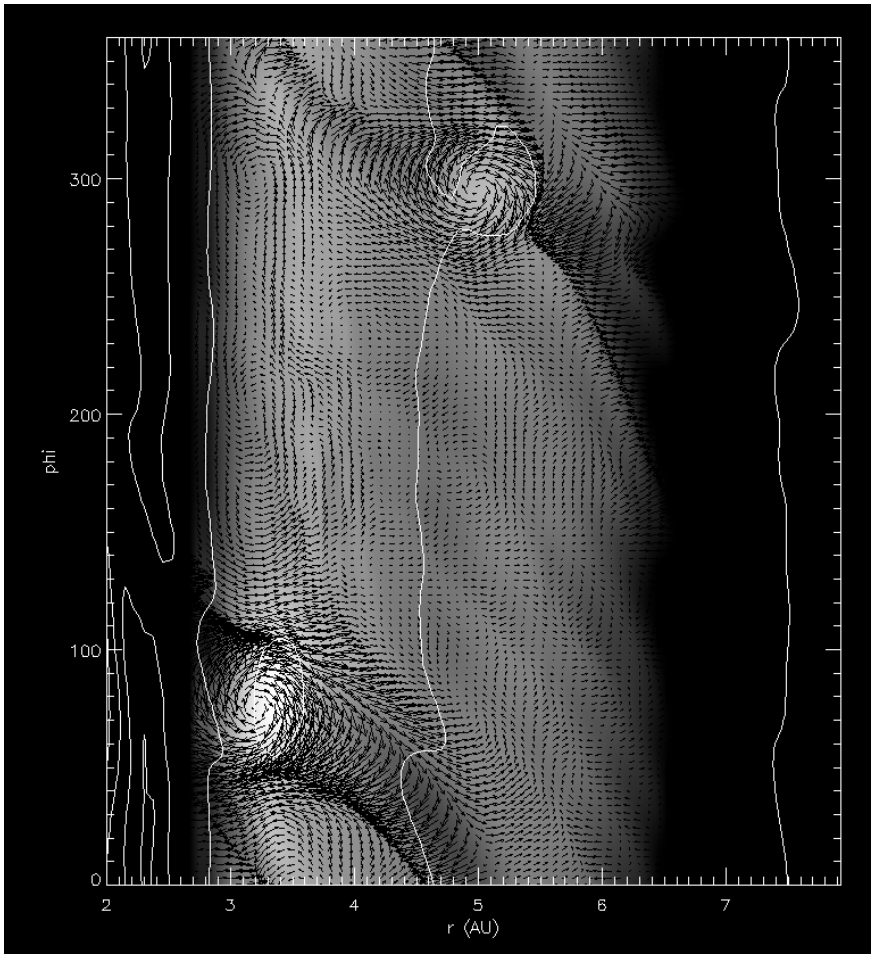

Figure 1. Phase 1 of Planet Formation: Formation of Anti-cyclonic Vortices as Pre-Protoplanetary Condensations. 2D Hydro-Simulation with the TRAMP code. Dark denotes high density and light low density. The contours are lines of constant pressure.

Here we present three Figures which display snapshots of each evolutionary stage. In Figure 1 we show an evolutionary state of protoplanetary disk that extends from 2 to 8 AU around a solar mass star. It has evolved over 10^4yrs. Two vortices have formed and existed already over more than the last 2000 yrs. In those vortices dust gets concentrated efficiently as can be seen in Figure 2. Lastly Figure 3 displays how a solid core starts to open a gap in a disk (not the same calculation as Figures 1 and 2).

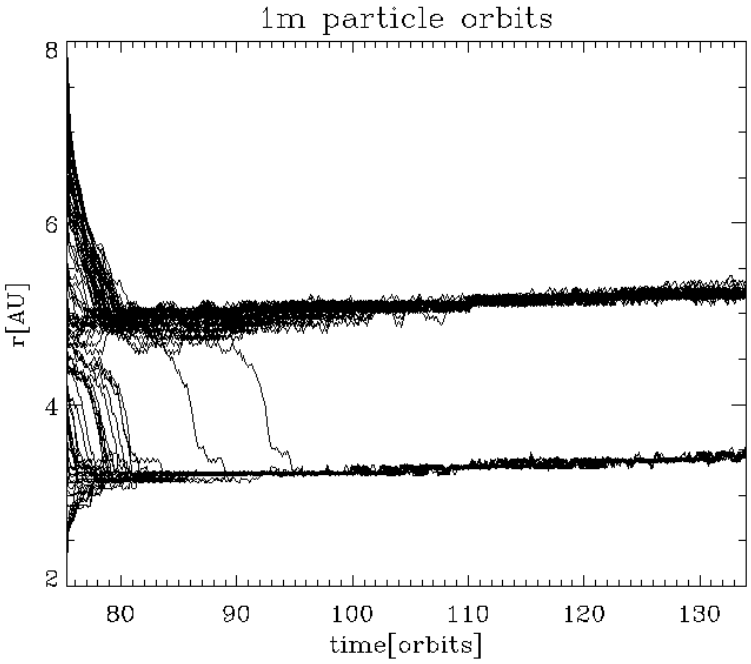

Figure 2. Phase 2 of Planet Formation: Accumulation of solids in Anti-cyclonic Vortices as Protoplanetary Cores. We plot the evolution of the distance of 1m dust particles to the central object over time. One recognizes the individual drift inward, the capturing by the vortices shown in Figure 1, and the slow radial outward drift of the vortex centers.

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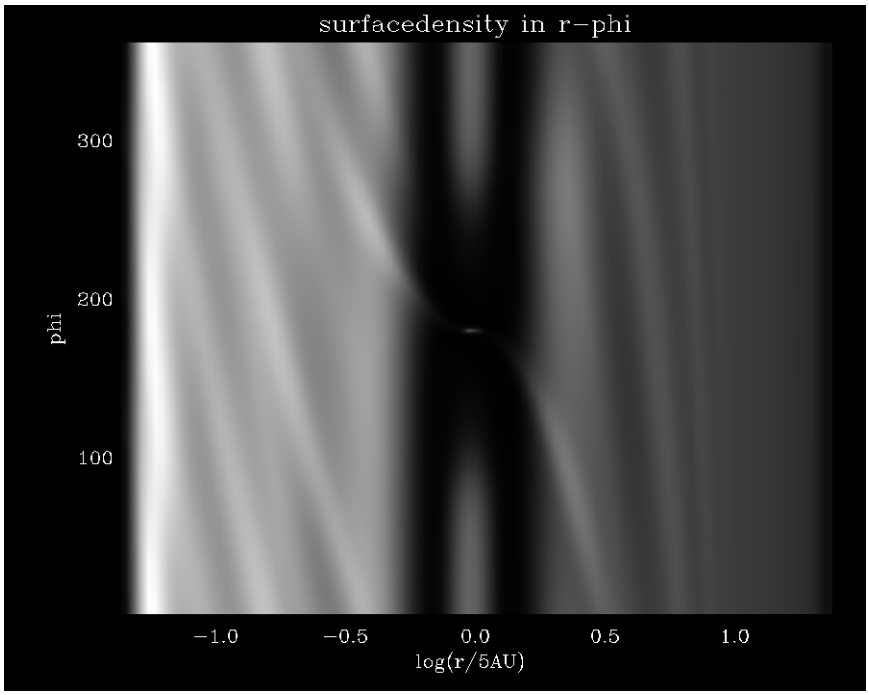

Figure 3. Phase 3 of Planet Formation: Accretion of gas onto a protoplanetary core. One sees the gap which is slowly opened by the planet and the streams of gas which fall onto the planet. 3D-Radiation Hydro Simulation with the TRAMP code. Dark means high and light low surface density.

References

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