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TORNADOS AND HURRICANES IN PLANET FORMATION

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RESUMEN

Estudiamos la formación de un planeta gigante gaseoso por procesos de acrecentamiento y captura de gas, con simulaciones numéricas, bajo la suposición de que el núcleo central se forma en el centro del vórtice de un anticiclón. La presencia del vórtice concentra partículas con tamaños de centímetros a metros del entorno del disco, y acelera la formación del núcleo central. Partiendo de que la formación de un planeta con la masa de Júpiter ocurre a 5 UA de la estrella, el crecimiento debido al vórtice conlleva a tiempos de formación considerablemente más cortos a los encontrados en simulaciones estándar de acrecentamiento central y captura gaseosa. También, la formación de planetas gigantes gaseosos es posible en discos con una masa comparable a la nebulosa solar de masa mínima (MMSN).

ABSTRACT

We study the formation of a giant gas planet by the core–accretion gas–capture process, with numerical simulations, under the assumption that the planetary core forms in the center of an anti-cyclonic vortex. The presence of the vortex concentrates particles of centimeter to meter size from the surrounding disk, and speeds up the core formation process. Assuming that a planet of Jupiter mass is forming at 5 AU from the star, the vortex enhancement results in considerably shorter formation times than are found in standard core–accretion gas–capture simulations. Also, formation of a gas giant is possible in a disk with mass comparable to that of the minimum mass solar nebula (MMSN).

Key Words: **ACCRETION, ACCRETION DISKS — HYDRODYNAMICS — METHODS: NUMERICAL — SOLAR SYSTEM: FORMATION — STARS: CIRCUMSTELLAR MATTER — STARS: PLANETARY SYSTEMS**

1. INTRODUCTION

We present a new formation model for gas giant planets. The general idea is that a giant vortex can accelerate the core formation considerably, even in a low-mass disk. The envelope accretion phase is speeded up also, because once the core has accreted all available solid material, the only energy source available for the gaseous envelope is its own contraction. The main reason for the long formation times for Jupiter in the earlier models of Pollack et al. (1996) was the additional contribution of planetesimal accretion to the energy supply of the envelope, during the first part of the gas accretion phase.

2. HOW DO VORTICES FORM?

In Klahr & Bodenheimer (2003) we presented the global baroclinic instability as a source for vigorous turbulence leading to angular momentum transport in Keplerian accretion disks.

We showed by analytical considerations and three-dimensional radiation hydro simulations that, in particular, protoplanetary disks have a negative radial entropy gradient, which makes them baroclinic. The turbulence in baroclinic disks transports angular momentum outward and creates a radially inward bound accretion of matter. We measured accretion rates in our 2D and 3D simulations of $\dot{M} = -10^{-9}$ to -10^{-7} $M_\odot$ yr^{-1} and viscosity parameters of $\alpha = 10^{-4} - 10^{-2}$, which fit perfectly together and agree reasonably with observations. The turbulence creates pressure waves, Rossby waves, and vortices in the $(R-\phi)$ plane of the disk. We demonstrated in a global simulation that these vortices tend to form out of little background noise and to be long-lasting features, which have already been suggested to lead to the formation of planets (see Figure 1).

Klahr (2004) performed a local linear stability analysis for accretion disks under the influence of a global radial entropy gradient for constant surface density. As a result linear theory predicts a transient linear instability that will amplify perturbations but only for a limited time or up to a certain finite amplification (see Figure 2). So only non-linear effects will lead to a relevant amplification. Nevertheless, it is shown that potential vorticity is generated, which

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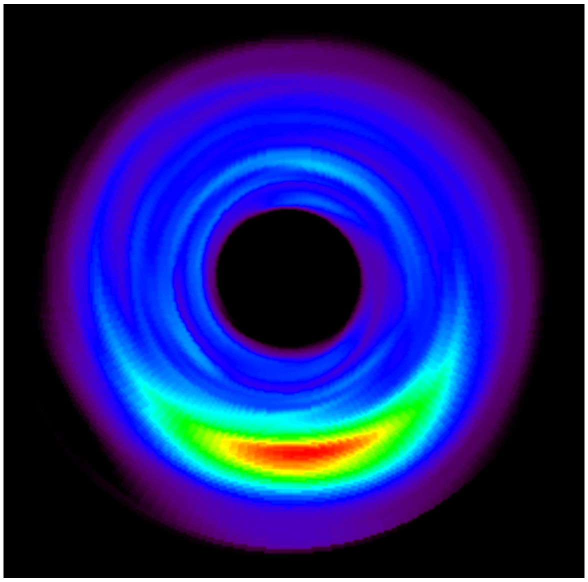

Fig. 1. The "pre-protoplanet" from Klahr & Bodenheimer 2003: Surface density (colors: 650 [red], 550 [yellow], 450 [green], 250 [blue] to < 100 [black] to g/cm^2) in the global model is projected in a cartesian frame after 320 orbits at the outer radius, which corresponds to 10^4 yr.

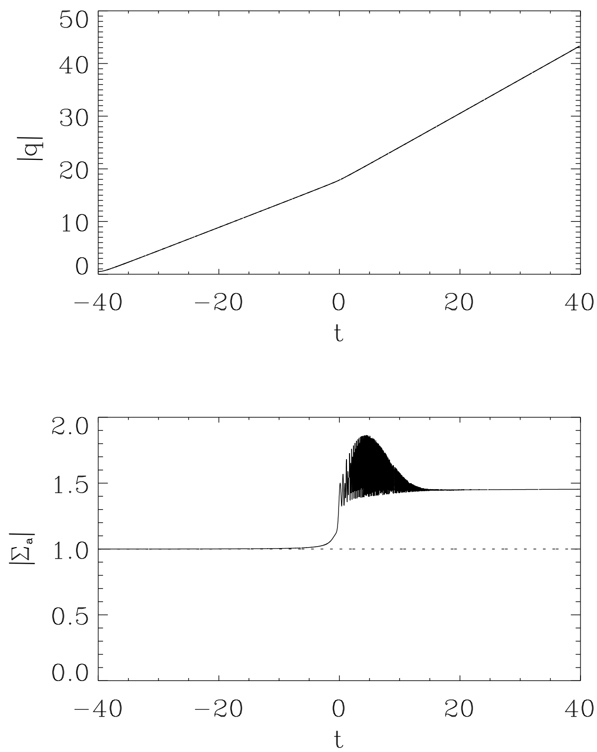

Fig. 2. Evolution of the perturbations in a Keplerian disk with a radial entropy gradient and zero initial vorticity: The amplitudes of surface density Σ_a perturbation and potential vorticity q are plotted.

is the key to explain the formation of vortices (see Figure 2).

3. WHAT IS THE ROLE OF VORTICES?

The idea that planets can form by concentration of dust in the centers of the vortices was already suggested by Barge & Sommeria (1995). We suggest three additional reasons why vortices may be special for the core formation. In contrast to the sub-Keplerian gaseous disk, (1) they orbit at the Keplerian rate, (2) they have no vertical shear, and (3) will not generate turbulence.

3.1. *Vortices move at Keplerian speed.*

First one has to define the center of the vortex, which we take to be given by the maximum in pressure, and which we refer to as the "eye". At a local pressure maximum the radial and azimuthal pressure gradients vanish. Thus, the only forces determining the motion of the gas at the eye of the vortex are gravity and centrifugal force. Consequently the eye must move on a Keplerian orbit and is not bound to the sub-Keplerian motion of the gas outside the vortex.

What are the consequences of this? Once small solid particles have accumulated in the eye of the vortex and have grown to kilometer size, they will decouple from the gas and no longer actively be bound to the vortex eye by the vortical gas motion. However they also will be in Keplerian motion, along with the eye. Thus, as long as there are no additional effects scattering them out of the vortex eye, the planetesimals may well stay in co-orbit with the vortex for many, many orbits.

3.1.1. *Vortices have no vertical shear.*

The vertical shear in an accretion disk is purely an effect of the stronger sub-Keplerian motion of the gas in the midplane than in the upper layers of the disk, because the pressure is the highest in the midplane and thus the radial pressure support the strongest. In contrast, all the way through the vertical extent of the vortex eye, the gas will move at the Keplerian frequency. Of course this vertical direction is not the vertical direction of a cylindrical coordinate system but is given by the local effective gravity in the system co-rotating with the vortex eye, which means that the rotational axis of the vortex bends slightly towards the rotational axis of the accretion disk with increasing height above the midplane. In a thin accretion disk this effect may well be unobservable. The effect of the non-existence of a vertical shear is very interesting. It means that solids can sediment to the midplane and concentrate to a density higher than the critical value where self-gravitational effects become important, without generating a shear layer instability (Cuzzi et al. 1993).

3.2. *Inside a vortex there is no (MHD)-turbulence.*

As is known for hurricanes on earth, the eye of a (anti-) cyclone is quiet. There is probably no turbulence acting in the center of a vortex, because shear is required for the generation of, for instance, the magneto rotational instability. This radial shear is not present in a giant vortex.

As a result of this absence of turbulence there will be very small RMS velocities between the boulders due to turbulent velocity fluctuations. Also, collisions will be gentle and also the likelihood of scattering out of the vortex is small.

4. THE FATE OF CAPTURED SOLIDS.

Basically we think that there are three possibilities concerning what happens to the solids once they are captured in the eye of the anti-cyclone.

4.1. *Single Core*

The naive picture assumes that all captured solids will contribute to one single growing core. This picture has the possibly significant problem that the core might actually leave the vortex once it grows to kilometer size and decouples from the gas. Even though we stated that a strong geostrophic vortex will orbit at the Keplerian rate, as will the kilometer-size planetesimal, there are two sources of danger. First, the vortex is a dynamical feature, and it could migrate in the radial direction by interaction with the ambient disk. Second, even when the core forms from material with basically the same angular momentum as the vortex eye, a small variation in the specific kinetic energy in the azimuthal direction can lead a to slow azimuthal drift of the core out of the eye of the vortex. This problem might be overcome once one starts to investigate the feedback of the core on the gas, via gravity as well as via friction. These effects might stabilize once more the gas around the core.

4.2. *Core Zone*

In a second model one can assume that the boulders that accrete into the vortex interior do not accumulate in the center and form one giant core, but that they form a “core zone”, enriched in solid mass but still containing some gas. This particle layer could then eventually undergo gravitational collapse (Goldreich & Ward 1973), which in this case will not be prevented by vertical shear. This picture has the benefit that all boulders might stay actually captured by the vortex until the core forms in one single collapse. Thus even if the vortex is not 100 percent precisely Keplerian, or if it radially migrates. the solids would follow the vortex and not get ejected.

4.3. *Core region*

In any case we do not expect the physical capturing process to be perfect. Thus probably a smaller or larger fraction of boulders that have decoupled from the gas may get scattered out of the vortex. If this is a minor effect, then this is a wonderful way to produce planetesimals in vortices and then send them to a pool of planetesimals that can be used for the formation of other planets of terrestrial or icy nature, that have formed independently of a vortex.

If this scattering of the planetesimals out of the cyclone is more the rule than the exception, then it will become unlikely to form a planetary core mass inside the vortex. Nevertheless the process would produce 100 m to 1 km planetesimals which are difficult to form by any other means because of the effects of gas drag. Once scattered out of the vortex, the planetesimals will stay at about the same radius. These planetesimals, whose total mass would be 10–20 $M_\oplus$ or more, would thus still be in a radially confined and strongly enriched feeding-zone and could accumulate to a core by collisions and gravitational focusing, as is assumed in the classical picture (Pollack et al. 1996).

If it is the case that only planetesimals are formed in vortices, then the neighborhood of a vortex will be enhanced in metalicity by a factor of a few. This makes the formation of a core for a giant planet more likely at the radial position of a vortex, as the formation time for the core becomes reasonably small. Thus even if a planetary core does not form in a vortex, the presence of the vortex may be very beneficial for planet formation.

Thus we simply assume that sooner or later the accreted solids will provide the potential well for the giant planet formation.

5. GAS ACCRETION ON CORES FORMED IN VORTICES.

We propose that 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 into the vortices to form protoplanetary cores. Phase 3: Accre-

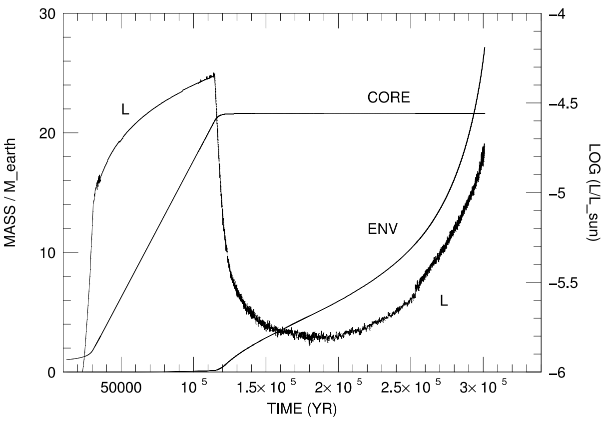

Fig. 3. Evolution of the planet's luminosity (L), core mass (CORE), and envelope mass (ENV) as a function of time. For details see Klahr & Bodenheimer (2004).

tion of gas onto the protoplanetary cores. The assumed mechanism for planet formation is the core accretion – gas capture process. The vortex for Jupiter is assumed to have been formed at 5 AU from the central object. Particles in the 10 cm size range migrate inward in the disk as a result of gas drag and accumulate in the vortex where they quickly spiral toward its center. The vortex is assumed to last long enough so that all the solid particles originally between 5 and 10 AU are captured by it. The procedure for numerically calculating the formation of a planet is described by Pollack et al. (1996). For details please see Klahr & Bodenheimer (2004). There we determine approximately, for the first time, the resulting time scales of such a scenario for the case of Jupiter's formation in a MMSN. If a vortex had been responsible for the formation of Jupiter, the formation time would fall in the range $2 \times 10^5 - 1.3 \times 10^6$ yr (see Figure 3).

6. CONCLUSION

It still needs to be proved that (1) conditions necessary for vortex formation actually commonly occur in disks, and (2) that a vortex actually survives long enough so that a planetary core of 10–20 $M_\oplus$ can form in it. Initial studies by Li et al. (2001) and Klahr & Bodenheimer (2003, 2004) indicate that vortices can form, and work by Godon & Livio (1999a,b) and Johansen et al. (2004) shows that that vortices can survive, at least up to several 10^4 yr at 5 AU. A linear stability analysis shows that vorticity can be generated from entropy gradients in the disk (Klahr 2004) (see Figure 2), which is a necessary condition to form large scale vortices. Further work is required to show how robust the vortex production process is.

Assuming that the above conditions are satisfied, the main benefits of the vortex-core planet formation model are: 1. No need for a solar nebula more massive than minimum mass. 2. No loss of boulders as a result of drift into the central object. 3. No fragmentation of boulders as a result of high impact velocities. 4. Gentle aggregation of a core in the quiet eye of the vortex, which need not be self-gravitating. 5. A formation time far less than the lifetime of the nebula.

We conclude that this model is able to solve outstanding problems in the theory of planet formation, and that further work on the difficult problem of vortex generation, through hydrodynamical simulations with radiation transport in three space dimensions, is warranted.

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