3D Disk - Planet Interactions and Non-Circular Orbits

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Abstract

We present the results of various 3D simulations of protoplanetary accretion disks with an embedded protoplanet. The protoplanet causes distortions in the disk. In the case of a 1 Jupiter mass protoplanet the protoplanet will have opened a gap in the disk and it will send large spiral waves through the disk. These non-axisymmetric features have a severe impact on the development of the protoplanet, most importantly on the accretion rate and the evolution of the orbit. To study these effects we performed numerical simulations using a finite difference scheme. This has been done by many previous authors, but we included a new degree of freedom into the simulations. In contrast to previous 3D simulations that have studied planetary migration on a fixed circular orbits, we do not assume the orbit of the protoplanet is circular or even in the plane of the disk. Instead we investigate the effect of eccentric and inclined orbits on the disk, and the effect of these distortions on the evolution of the planetary orbit.

Introduction

About 120 extrasolar planets have been discovered in the last 10 years. Their masses range from about the mass of Saturn up to 10 Jupiter masses, and because of the way they are discovered, their orbital periods are no longer than a few years. One of the most striking differences with our own solar system is not their tight orbits, which may be due to an observational bias, but that most of the planets are on eccentric orbits, as can be seen in Figure 1.

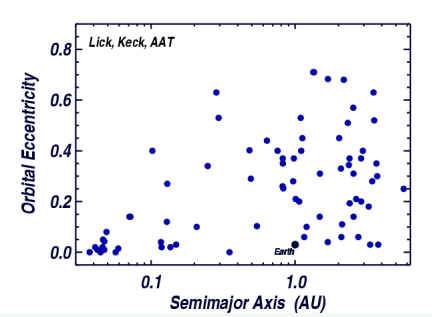

Figure 1: The distribution of eccentricities of extrasolar planets as a function of semimajor axis

There are several theories on how these eccentric orbits arise. Gravitational perturbance from passing stars or companion stars may cause eccentricity (Laughlin and Adams, 1998), however this is unlikely to explain the large quantity of eccentric orbits. A possible cause could be planet-planet interaction, but given the lack of planets on circular orbits this could hardly explain all the planets. Another theory forms Jupiter mass planets not by accretion but by gravitational collapse of a disk instability (Boss, 2000). Here we study the effect a 3D disk has on the eccentricity and inclination of embedded planets.

Physical Model

We solve the Navier-Stokes equations using a three-dimensional finite difference scheme based on the NIRVANA code by Udo Ziegler with subsequent adaptations by Kley and d'Angelo. We use an isothermal equation-of-state, and the planetary orbit is calculated using a 4^{th} order Runge-Kutta solver. The simulations start with a disk with constant surface density and a gap profile near the planet as calculated by Artymowicz (1994). The vertical profile is a Gaussian with scale height $H/r = 0.05$. The inner and outer boundary are managed using a non-reflecting closed boundary. This is set up by choosing a ramp function (with value 1 at the border and 0 at the inner edge of the damping region) that slowly changes the density in the region to its original value. This setup avoids mass loss at the open boundary and on the other hand it damps reflecting waves that will in turn distort the picture near the planet that arise from using closed boundary conditions.

Simulation details

The calculations were performed on a 3-dimensional grid in spherical coordinates grid with 108 cells in the radial direction $(0.4 < r < 2.5)$, 24 cells in the vertical direction $(80° < \theta < 100°)$ and 300 cells in the angular direction $(0° < \phi < 360°)$.

The simulations were run for several hundred orbits. Our standard model starts with a planet on a slightly eccentric and inclined orbit $(e = 0.05, i = 5°)$. The model includes a constant viscosity of $\nu = 10^{-5}$ in dimensionless units, which is equivalent to an α-viscosity of $\alpha = 5 \times 10^{-3}$.
The evolution of the orbital elements over a period of 400 orbits can be seen in Figure 2.

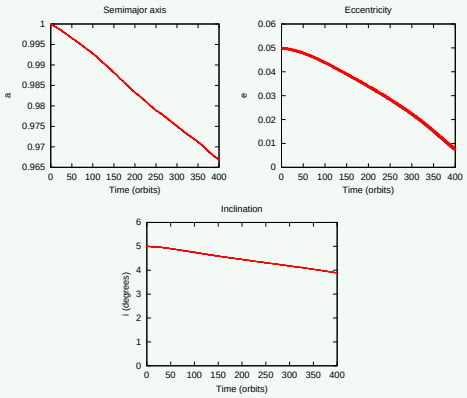

Figure 2: Orbital elements of the protoplanet as a function of time.

There are several interesting features in this plot. First there is the well-known inward migration of the planet. The measured migration time scale $\tau_M = a/\dot{a} = 1 \times 10^5$ years corresponds to the value found with the same model and a circular orbit, as can be found in d'Angelo and Kley (2002). One should not expect this effect to change much because, as can be seen in Figure 3a, the structure of the disk is similar to the situation without inclination and/or eccentricity. The inclination is damped due to interaction with the disk as the momentum is transferred from the planet onto the disk. This induces a warp into the disk as can be seen in Figure 4. In Figure 4 the center of mass of a vertical column is plotted for all values of r and ϕ. As one can see in the plot: The inner part of the disk is located at $\theta > 90°$ and the outer disk at $\theta < 90°$. One can clearly see the Lindblad spirals in this plot: Both the inner and outer spiral start near the planet which is above the disk, and then cross the plane before being integrated in the overall pattern.

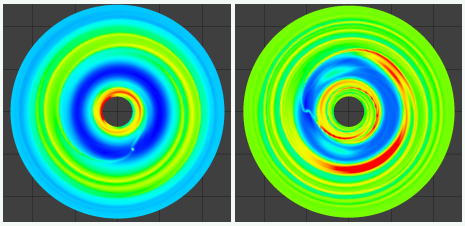

Figure 3: a. 2D slice $(\theta = 90°)$ of a disk with an embedded eccentric planet. b. Vortices in an inviscid calculation.

The eccentricity is also damped. Unless some extra features like vortices are present in the disk the interaction of the protoplanet with the disk is causing the orbit to circularize. If there are vortices in the disk there can be an increase in the eccentricity. An example of such vortices can be seen in Figure 3b, which is the result of inviscid calculations.

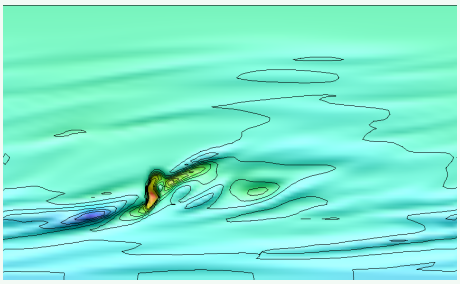

Figure 4: Disk warping due to a protoplanet on an orbit with an inclination of 5°. Red indicates an upward tilt, blue indicates a downward tilt.

Because of the large freedom in global parameters it is unknown if this situation reflects the conditions in real protoplanetary disks.
Other simulations were performed with different values for the viscosity . It turns out that the viscosity parameter performs an important role. If the viscosity is raised by a factor of 10 this has a dramatic effect on the eccentricity. It is no longer damped, it even increases, as can be seen in Figure 5. One can also see that the gap closes if the viscosity increases (the calculations start with an empty gap). Lubow and Ogilvie (2001) suggest that if the viscosity is high enough, there will be a resonance that will pump up the inclination. The same may be true for the eccentricity but this is much harder to check analytically, but one can clearly see the effect in these calculations.

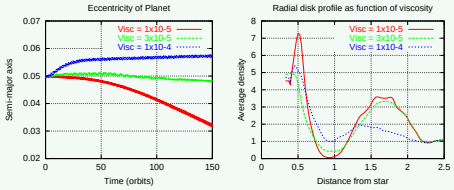

Figure 5: a.The change of eccentricity over time due to the effect of a larger viscosity. The viscosity ν increases from bottom to top. b. The effect of an increased viscosity on the radial profile of the disk.

Conclusions

The evolution of eccentric and inclined orbits is an interesting subject that needs to be studied in much greater detail if we want to understand the nature of these Jupiter-type planets on eccentric orbits. Their abundance is great enough to assume a general principle is at work here. On the other hand we have the numerical simulations that show that under the conditions that are considered standard these orbital features are damped on a timescale similar to the migration timescale. This confirms that we have still not found a way to explain these orbits with the otherwise promising accreting planet model. Further parameter studies will have to be performed and since these 3D calculations are still very time consuming we plan to perform these calculations on as fast a machine as is possible.

We would like to thank the EC Planets Network for this opportunity to present this work. More information about the network can be found at the network website: http://www.usm.uni-muenchen.de/Planets.

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