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DAMPING ECCENTRICITY OF RESONANT EXOPLANETS.

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Abstract. In some exoplanetary systems, pairs of giant planets in Mean Motion Resonance (MMR) are observed. They have relatively small eccentricity, while numerical simulations usually show that their migration in the protoplanetary disk should make their eccentricity increase dramatically, particularly the innermost planet (ex: HD73526, GJ876).

However, the inner disk was never properly taken into account, because its computation is expensive. With extended simulations, we show that the inner disk can play an effective role in damping the eccentricities of the migrating planets, and our results are in agreement with the observations.

1 Introduction

During planets formation in gaseous protoplanetary disks, giant planets open a gap in the disk, and then follow the disk viscous evolution, in what is called type II migration (Lin & Papaloizou, 1986). In this process, the disk drives the giant planet toward the central star. This explains the presence of hot Jupiters, that formed beyond the snow-line and then migrated to their observed orbit close to the star.

If two planets are present in the disk, it could be that the outer one migrates a bit faster than the inner one, so that they have convergent motion. Then, they should lock in MMR, and migrate together in a common gap. In all resonant exoplanetary systems known, the outer planet is more massive, so that it dominates the dynamics : the outer planet is pushed inward by the outer disk and the inner planet is pushed inward by the outer planet through the resonance. This can explain the pairs of hot Jupiters observed. However, during the migration in resonance, the eccentricity of the inner planet should rise far too much according to some numerical simulations. Here, we show that the inner disk (that lies between the orbit of the inner planet and the star) can damp the inner planet eccentricity. We apply this to two systems for which we obtain results in good agreement with the observations.

2 Proof of concept

We put a 2.14 Jupiter mass planet on a fixed orbit of given eccentricity around an inner disk. The code FARGO, by F. Masset (2000a,b) is used. The gas viscosity is given by an α prescription (Shakura & Sunyaev, 1973) with $\alpha = 10^{-2}$. The disk aspect ratio is 0.05. The grid spans between 0.4 and 2 planetary orbits in radius, and is divided in 500 sectors azimuthally and 129 rings, logarithmically spaced. A stationary regime is reached after about a hundred of orbits. After 200 orbits, we measure the power $\dot{E}$ and the torque $\dot{H}$ of the force exerted by the disk on the planet (E and H being respectively the energy and angular momentum of the planet). From this, we compute the effect on the planet eccentricity through the following expression :

$$\dot{e}/e = \frac{e^2-1}{2e}\left(\frac{\dot{E}}{E} + 2\frac{\dot{H}}{H}\right) \tag{2.1}$$

The results are shown on Fig. 1. The damping time $\tau_e = e/|\dot{e}|$ is displayed as a function of the eccentricity. For $e < 0.065$, the measured disk influence on the planet eccentricity is excitation, $\dot{e} > 0$. For $e > 0.065$, damping is observed, in about 1000 orbits. This damping is of course proportional to the gas density, thus the results displayed are normalized by the disk mass in planetary mass unit.

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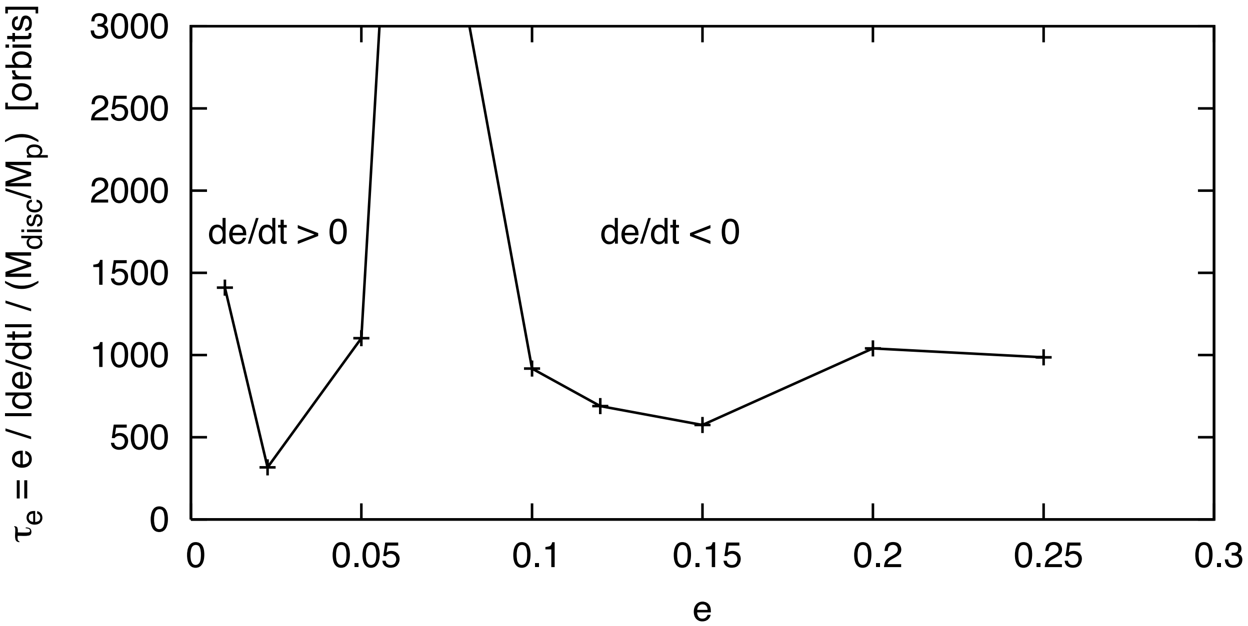

Fig. 1. Damping time of the eccentricity by the inner disk as a function of the planet eccentricity. The time is expressed in orbits. The value is normalized by the disk mass in planetary mass units.

This shows that the inner disk has a non-negligible role on the eccentricity of a giant planet. This role had always been neglected so far, because taking into account the inner disk is really expensive in computing time in hydro simulations. In next sections, we make hydro simulations of two systems, taking into account the inner disk.

3 HD73526

In this system, the two planets are in 2:1 Mean Motion Resonance, with semi major axes of 0.66 and 1.045 AU, with eccentricities 0.26 and 0.16, and masses 2.4 and 2.6 Jupiter masses respectively (Sándor et al 2007).

Figure 2 shows the evolution of these two planets in a gas disk, starting on circular orbits at 2 and 1 AU from the central star. The right panel displays the evolution of the semi major axes. In the red case, there is no inner disk. In the blue case, the grid is extended inward in order to allow the presence of an inner disk. The migration rates do not change much.

On the left panel of Fig. 2, the evolution of the eccentricities is shown. In both cases, after the resonance locking at about 500 orbits, the eccentricity of the outer planet grows to ~ 0.1, and the eccentricity of the inner planet rises very rapidly. If there no inner disk, the inner planet eccentricity goes above 0.4 ; however, in presence of an inner disk, the eccentricity of the inner planet settles at ~ 0.3.

Even if the agreement with the observed orbital elements is not that good, this is shows that the inner disk is likely the explanation for the bounded eccentricity of the inner planet of HD73526. In our simulation, a stable configuration is reached, which is impossible without an inner disk. Other disk parameters would lead to an other damping rate, so that the observed configuration can be achieved.

4 GJ876

In this system, the two planets in 2:1 Mean Motion Resonance have semi major axes of 0.13 and 0.21 AU, eccentricities of 0.22 and 0.025, with masses of 0.62 and 1.93 Jupiter masses respectively. But there is also a third planet in this system, located on a circular orbit at 0.0208 AU from the central star, with a mass of only 0.018 Jupiter masses. Crida & Morbidelli (2007) have shown that the inner disk evolution is strongly dependent on the radius of the inner edge of the disk, and more precisely on the ratio between this radius and the radius of the planetary orbit. Generally, this radius is poorly constrained, and strongly model-dependent. In the case of

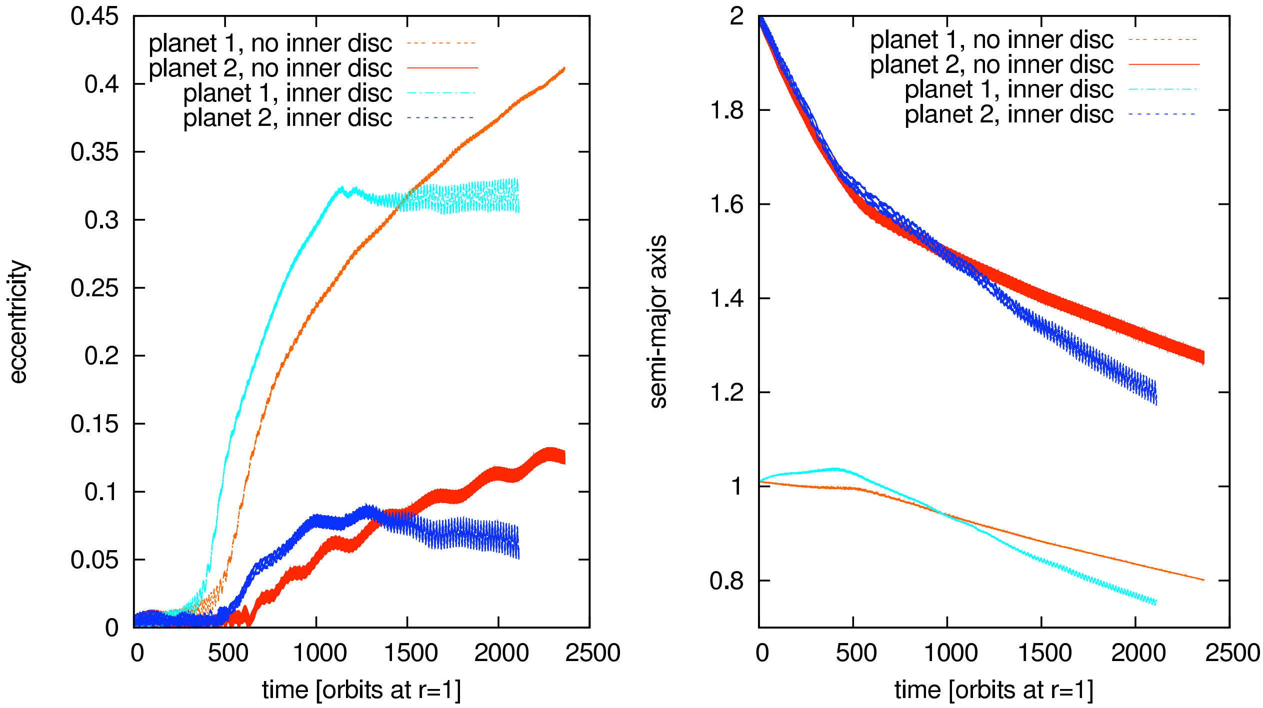

Fig. 2. Eccentricity (right) and semi major axes (left) evolution of the two planets of HD73526 in a gas disk. Red: Without any inner disk. Blue: in presence of an inner disk.

GJ876, the presence of this 'hot Neptune' is a strong constraint for the location of the inner boundary. Indeed, one can imagine that the hot Neptune migrated all the way inward as it was in the disk, in type I migration. Then, it reached the cavity between the gas disk and the star. Once the planet is in the cavity, it feels a negative torque from the disk at its outer Lindblad resonances (Goldreich & Tremaine, 1979). Thus, the planet goes on migrating inward until there is no more gas at the location of its outer 2:1 resonance. In that case, the inner edge of the disk must have been located at the 2:1 resonance with GJ876d, that is at 0.033 AU.

We compute a simulation of the two more massive planets of GJ876 in a gas disk, using an hybrid hydro code in which the classical 2D-grid is surrounded by a 1D-grid (not resolved azimuthally) that spans over the disk physical extension (Crida et al 2005, 2007). The coupling between the two grids allows the realistic computation of the global disk evolution, that is crucial for type II migration and for the description of the inner disk. The open inner edge of the 1D grid is located at 0.33 AU, while the outer boundary is at 10 AU. The 2D grid extends from 0.055 to 0.655, divided in 300 rings themselves divided in 500 sectors. The disk viscosity is given by $\alpha = 5 \times 10^{-3}$ and the aspect ratio is 0.045. The planets start on circular orbits at 0.16 and 0.29 AU. Their evolution in eccentricity and semi major axis is shown on Fig. 3.

The red bottom curve of the bottom panel of Fig. 3 shows the eccentricity of the outer planet. At time 1500, it reaches 0.02, while the semi-major axis is 0.21 AU (red top curve of the top panel). At time 1500, the inner planet has reached 0.13 AU, and its eccentricity is about 0.2 (green middle curve of the bottom panel), which appears to be its limit value from time 800 on. This result is in excellent agreement with the observed orbital elements. We find that the observed eccentricities are obtained in the gas disk phase. If the disk disappears at time 1500 in our simulation, we are left with a planetary system very close to the present one.

For comparison, we have switched off the force of the disk on the inner planet from time 600 on (blue curves). The semi major axis evolution is not affected (the blue and green curves overlap in the top panel), because the outer planet dominates the dynamics. But the eccentricity evolution changes dramatically : it increases up to 0.5 (top curve of the bottom panel). This proves that the inner disk has a major role in damping the eccentricity of planets while they migrate in resonance in a gas disk.

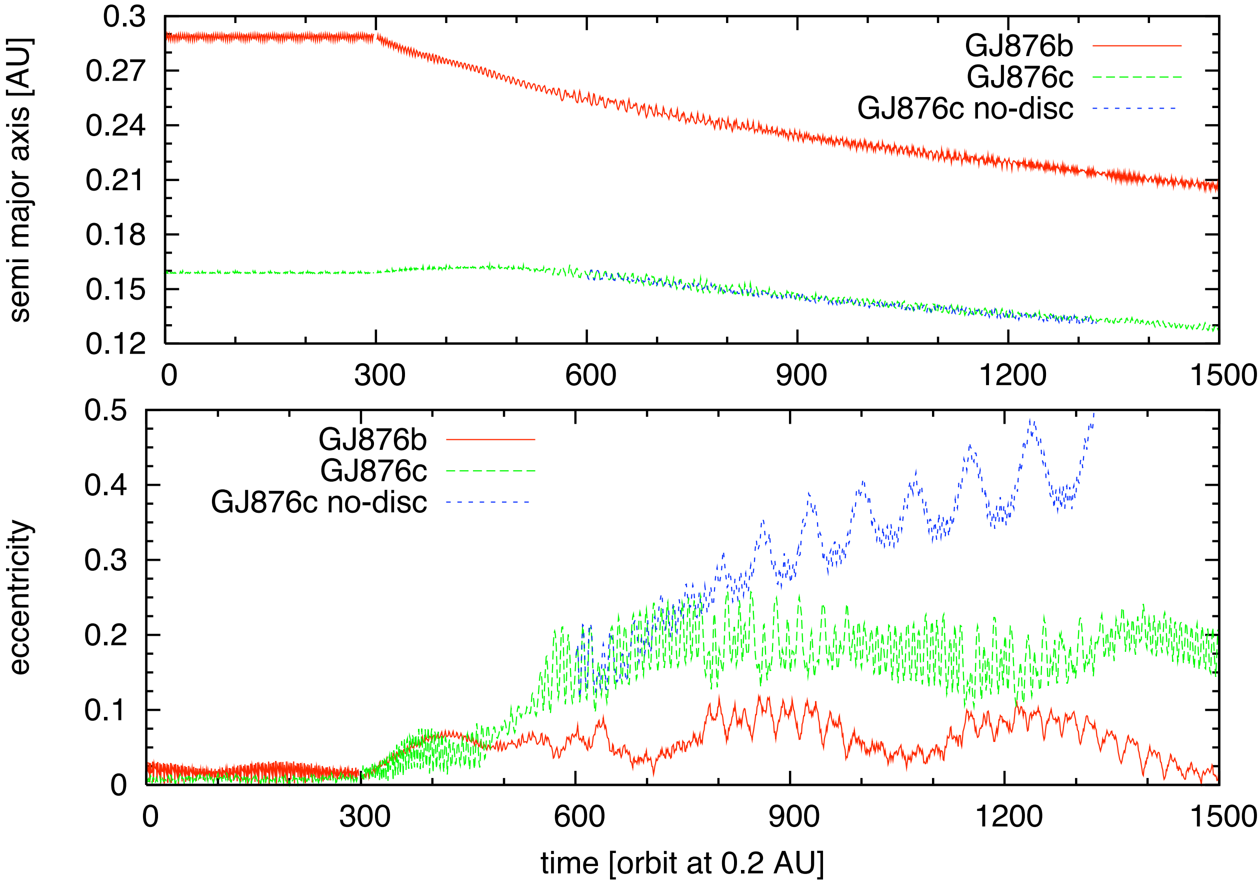

Fig. 3. Eccentricity (bottom) and semi major axes (top) evolution of the two planets of GJ876 in a gas disk. Red: outer planet. Green: inner planet. Blue: inner planet, with disk force switched off.

5 Conclusion

We have studied the problem of the eccentricity of resonant exoplanets. With numerical hydrodynamic simulations, we show that the inner disk damps their eccentricity during their migration in resonance. In the case of the GJ876 system, where the raduis of the inner boundary of the inner disk can be deduced from the presence of a third planet, the result of the simulation is in excellent agreement with the estimated orbital elements, so that the dynamics of this system seems to be a natural outcome of its evolution in the protoplanetary disk.

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