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M. Heydari-Malayeri, C. Reylé and R. Samadi (eds)

MINIMUM MASS SOLAR NEBULÆ AND PLANETARY MIGRATION

Crida, A. [1,2]

Abstract. The Minimum Mass Solar Nebula (MMSN) is a protoplanetary disk that contains the minimum amount of solids necessary to build the planets of the Solar System at the desired location. Assuming that the giant planets formed in the compact configuration they have at the beginning of the "Nice model" (Tsiganis et al, 2005; Gomes et al, 2005), Desch (2007) built a new MMSN, about ten times denser than the standard MMSN by Hayashi (1981).

However, a planet in a protoplanetary disk migrates. With numerical simulations, we show that the four giant planets of the solar system could not survive in Desch's dense disk. In contrast, in a low density disk, planetary migration smoothly brings the planets closer to each other ; then planet-planet interactions may stop migration, in a configuration compatible with the "Nice model" (Crida, 2009).

In fact, planetary migration makes the concept of MMSN irrelevant : planet formation is not a local process. Migration and radial drift of solids should be taken into account when reconstructing the proto-solar nebula.

1 Introduction

The Minimum Mass Solar Nebula (hereafter MMSN) is the protoplanetary disk of solar composition that has the amount of metals necessary to build the eight planets of the Solar System (and the asteroid belts). From the masses and compositions of the planets, a density of solids is derived at several locations of the disk. Then, the solar composition is restored by adding gas, and a smooth protoplanetary disk density profile is derived. The most famous version of the MMSN was provided by Weidenschilling (1977) and Hayashi (1981). Of course, the density profile obtained depends crucially on the position of the planets. They assumed that the planets formed where they presently orbit.

A recent model explains several features of the Solar System (the Late Heavy Bombardment, the orbital distribution of the Trojans of Jupiter, the orbital elements of the giant planets. . .), based on the assumption that the four giant planets were in a compact configuration just after the Solar nebula dissipation (Tsiganis et al., 2005 ; Gomes et al., 2005 ; Morbidelli et al., 2005). If one assumes that this so called "Nice model" is true, then the above nebula is out of date because the planets didn't form where they are now observed. In a recent article, Desch (2007) constructed a new MMSN, assuming that the planets were formed in the disk at their starting position in the Nice model.

However, planets in protoplanetary disks migrate. Here, we study the migration in the dense disk proposed by Desch (2007) and in the older one given by Hayashi (1981). We show that in a dense solar nebula, Jupiter can't avoid migration all the way to the Sun, and that all the giant planets are lost in a short time. In contrast, interactions between the planets enable to save them in a lighter disk.

2 Migration in Desch (2007)'s dense disk

Figure 1 shows the semi-major-axes of the four giant planets as a function of time in a disk of initial surface density profile the one given by Desch (2007) : $\Sigma_0 = 3430 \times (r/10\mathrm{AU})^{-2.168}$ kg.m^{-2}. The temperature is $150 \times (r/1\mathrm{AU})^{-0.429}\,K$, which corresponds to an aspect ratio of $(H/r)_0 = 0.05 \times (r/1\mathrm{AU})^{0.2855}$. The viscosity

[1] CpT-TAT, Universität Tübingen – where this work was done, until december 2008.
[2] D.A.M.T.P., University of Cambridge – since january 2009.
contact: `crida@oca.eu`

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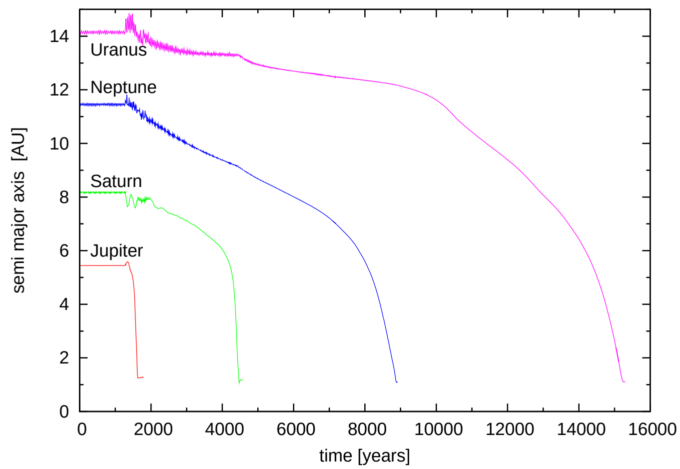

Fig. 1. Migration paths of Jupiter, Saturn, Neptune and Uranus (from bottom to top) in a dense Solar nebula.

is given by an α prescription (Shakura & Sunyaev, 1973), with $\alpha = 4 \times 10^{-4}$. We use the code FARGO-2D1D (Crida et al. 2007, and `http://fargo.in2p3.fr/`), which enables to simulate accurately simultaneously the planet-disk interactions and the global evolution of the disk. For more details on the set-up of the simulations, the reader is refereed to Section 2 of Crida (2009), the paper relative to this work.

As soon as Jupiter is released, it enters in fast, runaway, type III migration inwards. This migration regime can be achieved only if the mass of the gas in the disk in the neighborhood of the planet is larger than the planet mass. It drives Jupiter to 1.5 AU in a few hundred years only, where Jupiter hits the inner edge of the 2D-grid and is removed from the simulation. Then, Saturn migrates to the Sun too, and Neptune and Uranus as well, in type I migration. In 16000 years, the four giants are lost.

In the case presented in Fig. 1, the resolution of the grid is $\delta r/r = \delta\theta = 10^{-2.5}$. The energy equation of the gas is computed, with viscous heating and vertical radiative cooling. Other simulations with locally isothermal equation of state, or different resolution, give similar results.

Changing the aspect ratio and the viscosity, or releasing Jupiter later than Saturn, doesn't change the conclusion that the four planets can not survive in Desch (2007)'s nebula.

3 Migration in a moderate density disk

Figure 2 shows the result of a similar experiment as in previous section, but performed in Hayashi (1981)'s disk, of surface density $\Sigma(r) = 538 \times (r/10\,\mathrm{AU})^{-3/2}$ kg.m^{-2}. This disk is not massive enough for Jupiter to enter in the type III, runaway regime of migration. Consequently, Jupiter is caught up by Saturn and the two planets enter in mean motion resonance after about 10^4 years. This almost stops their migration, as can be seen in the figure and is explained by Masset & Snellgrove (2001) and Morbidelli & Crida (2007). In contrast, Jupiter alone in the same disk would go on migrating inwards in a slow, type II regime, shown by the long dashed, orange curve in the figure, reaching 3 AU in 40 000 years.

Then, Uranus and Neptune, migrating inwards in type I migration are caught in mean motion resonance by Saturn, and stop as well. In the end, we have the four giant planets in a compact configuration, that prevents their migration. This enables to save the giant planets, but this configuration is not similar to the present one, neither to the one required in the original "Nice model" published in 2005. However, such a compact, fully resonant configuration has been proven compatible with the "Nice model" by Morbidelli et al. (2007).

4 Conclusion

Preventing the migration of the giant planets requires interactions between the planets. In the massive disk proposed by Desch (2007), this is impossible. Shortly said, we conclude that this nebula is incompatible with our present knowledge of planetary migration (in particular because of the unavoidable type III migration of Jupiter).

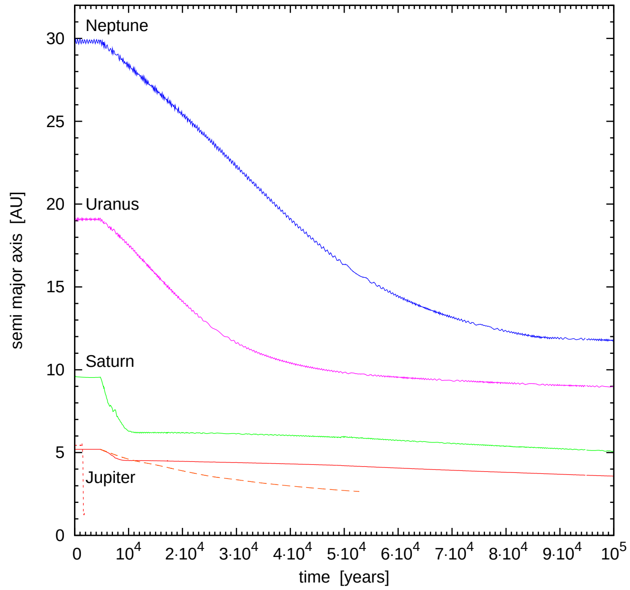

Fig. 2. Migration paths of Jupiter, Saturn, Neptune and Uranus (from bottom to top) in a light Solar nebula. Red dotted curve on the bottom left : migration of Jupiter in Fig. 1, for comparison. Orange, long dashed curve : migration of Jupiter alone, without Saturn.

However, migration can account for planetary formation on a large radial range, followed by a compaction of the configuration of the giant planets, like in Fig. 2. In addition, the solid material that built the giant planets may come not only from the region around their respective orbits : dust drifts inwards in a protoplanetary disk (Weidenschilling 1977), and small bodies migrate as well, so that the giant planets region may be replenished in solids by the outer parts of the disk. This enables the following scenario : (i) formation of Jupiter, Saturn, Uranus and Neptune in a relatively light disk on a large radial range, (ii) migration of the planets to a compact, resonant configuration, (iii) global instability after the gas disk has dissipated, to drive the planets to their presently observed positions (Nice model, see Morbidelli et al. 2007).

In fact, planetary migration makes the concept of the Minimum Mass Solar Nebula irrelevant, because the latter is based on the assumption that planets form locally, from local material, and stay on constant orbits in the disk. Planetary migration has to be taken into account in the reconstruction of the proto-solar nebula. Our result advocates for the density in the solar nebula to be moderate at the time where the giant planets formed, possibly close to Hayashi (1981)'s one. But neither Desch (2007) nor Hayashi (1981) should be considered as the disk out of which the solar system was born.

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