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NEW NUMERICAL MODELS ON GIANT PLANET FORMATION

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RESUMEN

Presentamos nuestros resultados sobre la formación de planetas gigantes dentro del marco del mecanismo de inestabilidad nucleada. Consideramos el régimen de crecimiento oligárquico para el núcleo sólido y una reducción en la opacidad de los granos. Bajo estas suposiciones, la formación de planetas gigantes *in situ* se puede alcanzar en una escala de tiempo más corta que la duración de vida de discos protoplanetarios.

ABSTRACT

We present our results on giant planet formation in the frame of the nucleated instability mechanism. We consider the oligarchic growth regime for the solid core and a reduction in the grain opacity. Under these assumptions, *in situ* giant planet formation is achievable in a timescale shorter than the lifetime of protoplanetary disks.

Key Words: **PLANETS AND SATELLITES: FORMATION**

1. INTRODUCTION

Although a lot of progress has been made in the last decades, the giant planet formation problem is still not completely understood. From the study of our giant planets we know that their interior presents two main components: a solid core and an extended gaseous envelope. Because it can explain this structure, the core accretion model is usually accepted as the main mechanism that gives birth to these objects (Pollack et al. 1996). This scenario suggests a two step process: first, the solid core is formed by accretion of planetesimals from the protoplanetary disk and afterwards, when the core is massive enough, gas is captured from the surrounding nebula to form the characteristic envelope. This scenario explains naturally the existence of the core (this being one of the goals of this theory) but the main drawback are the timescales involved: planets must be formed in the presence of the protoplanetary disk and the disk dissipates in less than 10^7 years. So, giant planet formation timescales are well constrained and, in general, extra hypothesis are needed to complete the formation before the the disk disappears.

In this paper we study the formation of a Jupiter-like object in the frame of the core accretion scenario, but considering that the core grows as prescribed by the oligarchic growth regime instead of the usually assumed - and faster - runaway accretion rate.

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2. THE MODEL AND RESULTS

The main objective of this work is to study the *in situ* formation of a Jupiter like object. This involves the formation of the solid core and the subsequent capture of the surrounding gas from the nebula.

It has been shown by N body numerical simulations (Ida & Makino, 1993) that when colliding planetesimals reach about the Moon's mass (and this takes a very short time), their growth regime changes from the runaway to the oligarchic one. This means that only the more massive planetesimals, the so called *embryos* (the seeds for future planets), go on growing but at a lower rate. Taking this into account, we will consider for the initial model a core of half of the Moon's mass which will grow as prescribed by the oligarchic accretion rate. But the accretion rate also depends on the planetesimals' surface mass density, Σ. We will consider two main reasons for the depletion of planetesimals in the disk: (1) the own accretion by the protoplanet, and (2) the migration of planetesimals due to the nebular gas drag (Thommes et al. 2003).

On the other hand, as the core becomes more massive, it is able to capture gas from the disk. The gas accretion rate is determined by the outer boundary condition: the radius of the planet. Here we define it as usual, $R = min[R_H, R_a]$ where R_H is the Hill's radius and R_a is the accretion radius. This condition must be fullfilled at any time and this means that the gas bound to the planet grows because of the contraction of the outer mass and the enlargement of R as the planet gains mass.

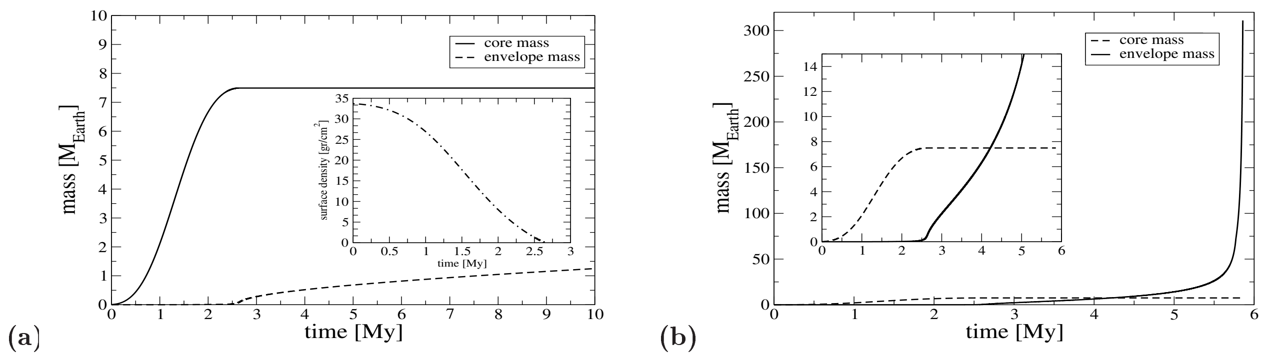

Fig. 1. Core and envelope mass evolution with time. (**a**) First simulation with standard grain opacity. Inside box: disk solid surface density vs. time. Due to planetesimal migration the feeding zone is completely depleted with no further accretion. (**b**) Second simulation with grain opacity reduction. See text for details.

The state of the envelope is calculated with the usual stellar hydrodynamics evolution equations, which are solved with a Henyey code (Benvenuto & Brunini, 2005).

We present here two different simulations considering a protoplanetary disk 10 times more massive than the *minimum mass solar nebula*. In order to take into account for the dissipation of the gaseous part of the nebula we will reduce the gas density as $\rho = \rho_0 e^{t/\tau}$ with $\tau = 10$ My.

Figure 1 (**a**) shows the evolution with time of the core and the envelope mass of the protoplanet. As can be seen, after 2.5 My the core mass stalls on $\sim 7.5 M_\oplus$ because no more accretion is possible. The feeding zone is completely depleted due to the protoplanet accretion and to planetesimal migration. This final mass of the core is in agreement with current models of Jupiter's interior (Guillot, 1999). But after 10 My the gas bound to the core is only $\sim 1 M_\oplus$. However, it has been proposed lately that grain opacity of protoplanet envelopes should be smaller than the corresponding to the interstellar medium due to the convective flows generated in their interior (Podolak, 2003). Then, in order to test the model we have made a reduction in the opacity. As the opacity tables used here correspond to the Rosseland mean opacity, all opacity sources are considered together. So, in order to simulate a lower grain opacity, we have made the reduction in the temperature region where grains dominate (bellow 1500 K). The net effect is a reduction of a half at $T = 1500$ K and it decreases to 1/20 for the lowest temperature at the edge of the planet. Results are depicted in figure 1(**b**). As can be clearly seen, this does not affect the final mass of the core but the formation timescales are reduced in more than an order of magnitude: the complete formation of a Jupiter like planet can be accomplished in less than 6 My, just before the estimated dissipation of the disk.

3. CONCLUSIONS

In our study of an *in situ* Jupiter-like planet formation process, considering the oligarchic accretion rate for the core, several results were found and some of them were shown in the previous section.

From simulations which, unfortunately, we could not show here, we get that the mass of the protoplanetary disk must be, at least, 10 times that of the *minimum mass solar nebula* in order to achieve the complete formation of the planet before the disk disappears. Also, we have found that including planetesimal migration is crucial when studying this problem because the formation of the planet and the lifetime of the disk are both of the same order of magnitude.

In section § 2 we have shown two simulations that differ only in the grain opacity of the envelope. In the first case we considered the full interstellar medium opacity. The formation of the planet is not achievable between the prescribed timescales. But, if the opacity turns out to be really much smaller (as it has been suggested) we are able to compute the whole formation of the planet before the disk disappears and with the oligarchic growth regime as the main core accretion rate.

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