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Simultaneous formation of solar system giant planets

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Abstract

In the framework of the "Nice model" [1], we compute the formation of the solar system giant planets by concurrent accretion of solids and gas, and study the dependence of this process on the surface profile of the protoplanetary disk and the size distribution of the accreted planetesimals. We focus on the conditions that lead to the simultaneous formation of two massive cores, corresponding to Jupiter and Saturn, which should be able to reach the cross-over mass (where the mass of the envelope equals the mass of the core, and gaseous runway starts), while two other cores should be able to grow up to Uranus and Neptune's current masses. We find that the simultaneous formation of the giant planets is favored by flat surface density profiles and by the accretion of relatively small planetesimals.

1. Introduction

The initial configuration of the Nice model [1] represents the orbital configuration of the outer solar system after the gas of the primordial nebula dissipated. This model proposes a compact initial configuration for the location of the giant planets; the giant planet system assumed to be in the range of ~ 5.5 AU to ~ 14 AU.

In our previous work [2], we developed a numerical code to compute the simultaneous formation of giant planets immersed in a protoplanetary disk that evolves with time. We adopted a classical power-law disk for the gaseous and solid component. For the planetesimal disk, we considered a population of non-equal sized bodies. Planetesimals were assumed to follow a size distribution whose radii were between r_p^{min} (free parameter) and 100 km, with steps selected in order that the quotient of masses of consecutive sizes is a factor of two. We considered a number of planetesimals per unit of mass distribution given by $dn/dm \propto m^{-2.5}$ (most of the mass of solids is in the smallest planetesimals). We also took into account planetesimal migration due to nebular gas drag. Therefore the evolution of the planetesimal disk is due to planetesimal migration and accretion onto the forming planets. We assumed that the gaseous component dissipates following an exponential decay with a characteristic timescale of 6 Myr. For the growth of the core, we adopted the oligarchic regime, and planetesimal's relative velocities out of equilibrium were prescribed (e.g. [3]). Finally, the equations governing the evolution of the gaseous envelope were solved coupled self-consistently to the planetesimal's accretion rate, employing a standard finite difference (Henyey) method and the detailed constitutive physics as described in [4], [5] and [2]. We used this code to calculate the *in situ*, but simultaneous formation of the solar system giant planets [6].

2. Results

We assume that the disk surface density profile follows a classical power-law

$$\begin{aligned} \Sigma_s &= \Sigma_0 \left(\frac{a}{5.5\ \text{AU}}\right)^{-p} \eta_{ice} \quad \text{g cm}^{-2} \\ \Sigma_g &= \frac{\Sigma_0}{\text{z}_0} \left(\frac{a}{5.5\ \text{AU}}\right)^{-p} \quad \text{g cm}^{-2}, \end{aligned} \tag{1}$$

where the initial surface density of solids at the location of Jupiter (5.5 AU) is set to $\Sigma_0 = 11$ g cm^{-2}; η_{ice} takes into account the condensation of volatiles beyond the snow line (1 if $a > 2.7$ AU, 1/4 if $a < 2.7$ AU), and $\text{z}_0 = 0.0153$ [7] is the initial abundance of heavy elements in the Sun (we adopt a value for the gas-to-solid ratio of z_0^{-1}).

We proceeded as follows: we first calculated the *isolated* formation of each planet. For each case we ran several simulations only changing the minimum radius of the size distribution of planetesimals, r_p^{min}. The aim of this procedure was to look for an interval in the planetesimal radii where the isolated formation of all the planets occurs in less than 10 Myr. Afterward, and using these results as a guide, we looked for an optimum value of r_p^{min} to calculate the *simultaneous* formation of the four planets. This procedure was repeated for different values of the power index

p that describes the disk's density profile. For steep profiles ($p \sim 2$), we found no common size distribution for the planetesimal radii that would allow the formation of the four planets simultaneously in less than 10 Myr (Fig 1). However, for flat profiles ($p \sim 1$) the isolated formation of the four planets was possible in less than 10 Myr for a common interval of planetesimal sizes, where r_p^{min} could range between 10 m and 200 m (Fig. 1). Therefore, for these cases, we calculated the simultaneous formation of the giant planets for a size distribution of planetesimals between r_p^{min} and 100 km, where we adopted for r_p^{min} several discrete values between 100 m and 200 m. Results are summarized in Fig. 2. For these cases our results for both the cross-over times and cross-over masses of Jupiter and Saturn nicely agree with the disk lifetimes and theoretical estimates of the cores, respectively. The cross-over masses of Uranus and Neptune were larger than their current masses (we allowed Uranus and Neptune continue growing after they reached their current masses), but the core masses at the time they reached their current masses agree with theoretical estimates of their present interior structure. We note the important fact that the formation time-scale of the gas giants was shorter than that of the ice giants. Furthermore, for $r_p^{min} = 100$ m the formation timescale of the four planets was similar.

We conclude that flat density profiles and small planetesimals favor the formation of the giant planets of the solar system. Moreover, their simultaneous formation proceed on appropriate timescales and with core masses within the current theoretical constraints.

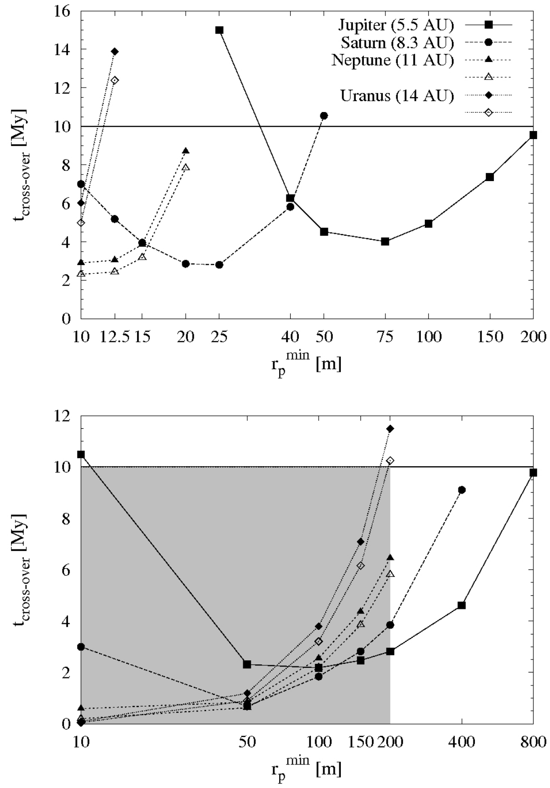

Figure 1: Cross-over time as function of the minimum radius of the planetesimal size distribution for the isolated formation of each planet. **Top:** a disk with surface density profile $\Sigma \propto a^{-2}$. **Bottom:** a disk with surface density profile $\Sigma \propto a^{-1}$. Open triangles (diamonds) correspond to the time at which Neptune (Uranus) achieves its current mass (~ 17 and ~ 14.5 Earth masses, respectively). In grey we show the range of common values of r_p^{min} that are used to calculate the simultaneous formation.

r_p^{min} $[m]$	Jupiter M_{over}^{cross} [$M_\oplus$]	t_{over}^{cross} $[Myr]$	Saturn M_{over}^{cross} [$M_\oplus$]	t_{over}^{cross} $[Myr]$	Neptune M_{over}^{cross} [$M_\oplus$]	t_{over}^{cross} $[Myr]$	Uranus M_{over}^{cross} [$M_\oplus$]	t_{over}^{cross} $[Myr]$
100	32.03	2.14	28.53	1.98	26.97 (15.61)	2.81 (2.27)	24.25 (13.50)	4.18 (3.13)
150	28.87	2.73	23.85	2.80	22.01 (15.23)	4.97 (4.11)	19.08 (12.90)	7.15 (5.90)
200	26.54	2.96	19.17	3.82	18.83 (14.65)	7.68 (6.43)	16.15 (12.40)	11.26 (9.55)

Figure 2: Cross-over mass and cross-over time as function of the minimum radius of the planetesimal size distribution for the simultaneous formation of the solar system giant planets for a disk with a surface density of solids and gas $\propto a^{-1}$.

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