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Core instability models of giant planet accretion and the planetary desert

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ABSTRACT

With the aim of studying the final mass distribution of extrasolar planets, we have developed a simple model based on the core instability model, which allows us to form a large population of planets and make them evolve in circumstellar discs with various initial conditions. We investigate the consequences that different prescriptions for the solid and gas accretion rates would have on this distribution and found that it is strongly dependent on the adopted model for the gas accretion.

Key words: planets and satellites: formation – Solar system: formation.

1 INTRODUCTION

Although we cannot observe the events, which lead to the formation of our Solar system, many information may be inferred by studying its actual structure. Our knowledge of the planets in our own Solar system has constituted the basis for the theory of planetary formation. Nevertheless, observations of other systems are necessary to get a better understanding of this process. Luckily, recent discoveries of extrasolar planets show that 265 planets have been found until 2007 November, since Mayor and Queloz announced in 1995 the discovery of the first extrasolar planet orbiting a near star (Mayor & Queloz 1995). Although this is not a large sample but it is enough for starting to take a glimpse on some common characteristics of planets, which may give us some clues about the process of planetary formation. These clues will be essential to refining theories and getting a more complete understanding of this issue.

According to the standard model, the terrestrial planets and the cores of the giant ones were formed through the accretion of planetesimals, which are rocky and iced particles of many metres in size and formed by dust particles that collided and stuck together. These particles continue to collide until they form first small and then larger bodies orbiting the parent star (Safronov 1969). In the beginning, dynamical friction and gravitational focusing make that larger planetesimals growth faster than the smaller ones (runaway stage). After the cores have acquired a sufficient mass to influence in the dynamic of the small planetesimals, the runaway growth would slow down and the protoplanet-dominated stage begins. This is the dominant stage, studied by Kokubo & Ida (1998), who found that although the cores still grow faster than the planetesimals, the larger ones slow down their growth and, as a result, protoplanets with similar masses grow oligarchically (Ida & Makino 1993). Once a core attains approximately Moon's mass (Mizuno, Nakazawa & Hayashi 1978), it attracts the gas from the surrounding disc, which forms an envelope. When this envelope reaches the critical mass, the hydrostatic equilibrium cannot be sustained, and a run away gas accretion process begins.

Several semi-analytic models of oligarchic planetary growth have been presented in the last years. Thommes, Duncan & Levison (2003) and later Chambers (2006) developed rather sophisticated models in order to reveal the details of the oligarchic growth process in the whole protoplanetary disc. On the other hand, Ida & Lin (2004, hereafter IL04) developed a very simple semi-analytical model of planetary formation (although conserving the relevant physics involved in the process) based on the oligarchic growth regime for the accretion of solid cores and the core instability model (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996) for the accretion of gaseous atmospheres of giant planets, which have allowed them to carry out a huge number of Monte Carlo numerical simulations in order to examine the statistical distribution of extrasolar planets' semi-major axis and mass.

One of the predictions of Ida & Lin's model is the 'planetary desert'. Since planets' masses grow rapidly from 10 to 100 $M_{\oplus}$, the gas giant planets rarely form with asymptotic masses in this intermediate range. This prediction could depend on the prescription they adopt for the accretion of gas. The gaseous envelope of a giant protoplanet contracts on a Kelvin–Helmholtz time-scale when the total mass of the core becomes larger than a certain critical value. Particularly, they based their gas accretion model in pre-existing numerical results of the core instability model (Pollack et al. 1996; Ikoma, Nakazawa & Emori 2000). In this kind of calculation most authors (Pollack et al. 1996; Alibert et al. 2005; Hubickyj, Bodenheimer & Lissauer 2005) usually prescribe as the solid accretion rate that obtained by Greenzweig & Lissauer (1992) which assumes a rapid growth regime for the core. Instead, Fortier, Benvenuto & Brunini (2007) adopt that corresponding to the oligarchic growth of Ida & Makino (1993). With this prescription, a

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very different result regarding the gas accretion rate is obtained, that could have some influence on the characteristics of the ‘planetary desert’ predicted by Ida & Lin’s model.

Based on the considerations, we present a simple model of planet accretion, based mainly in Ida & Lin’s model, but incorporate the solid and gas accretion rates given by Fortier et al. (2007), which will allow us to form a large population of planets and make them evolve in circumstellar discs with various initial conditions, which were taken to match the different observed discs, and determining the final mass distribution. We analyse the influence that these different prescription for the solid and gas accretion rates have on the characteristics of the ‘planetary desert’.

2 THE MODEL

In an attempt to develop a theory for planet formation, we studied the semi-analytic model developed by IL04. They investigated the distribution of masses and semimajor axis of extrasolar planets through an analytical model, based on the nucleated instability model (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996). In this section, we will briefly describe their model, with the aim of comparing with our work later.

IL04 evaluated the cores’ mass-growth rate, $\dot{M}_{\rm c}$, through runaway planetesimal accretion and oligarchic growth. The cores’ accretion rate at an orbital radius a was estimated with a two-body approximation, which in the high-velocity regime, that is when the relative velocity between the protoplanets and the planetesimals is in the dispersion-dominated regime, is

$$\dot{M}_c \sim \pi R^2 \rho_{\rm d} \left(\frac{2GM_c}{R\sigma^2} \right) \sigma \sim 2\pi R^2 \Sigma_{\rm d} \Omega_{\rm K} \left(\frac{GM_c}{R\sigma^2} \right) \quad (1)$$

$$\sim 2\pi \frac{R}{a} \frac{M_c}{M_\star} \left(\frac{a\Omega_{\rm K}}{\sigma} \right)^2 \Sigma_{\rm d} a^2 \Omega_{\rm K}, \quad (2)$$

expression given by Safronov (1969), where $M_{\rm c}$ is the core’s mass, $\Omega_{\rm K} = \sqrt{\frac{GM_\star}{a^3}}$ is the Kepler frequency, $\rho_{\rm d}$ and $\Sigma_{\rm d}$ are the spatial and surface density of solid components, R is a physical radius of the core, $M_\star$ is the stellar’s mass and σ is the relative velocity between the protoplanet and the ensemble of planetesimals inside the feeding zone, which is the region around the protoplanet where it can accrete planetesimals.

In their model, gas accretion process was regulated by the Kelvin–Helmholtz contraction of the planets’ envelope. This process starts when $M_{\rm c}$ becomes larger than $M_{\rm crit}$, and the gas accretion is

$$\frac{{\rm d}M_{\rm g}}{{\rm d}t} \simeq \frac{M_{\rm t}}{\tau_{\rm KH}}, \quad (3)$$

where $M_{\rm t}$ is the total mass which includes both solid mass and the mass of the gaseous envelope, and

$$\tau_{\rm KH} \simeq 10^9 \left(\frac{M_{\rm t}}{M_\oplus} \right)^{-3} \quad {\rm yr} \quad (4)$$

(for more details see Section 3.3). They test different limits to the gas accretion process.

These authors also considered an exponential decay for the disc-gas mass, which occurs on the time-scales between 10^6 and 10^7 yr in agreement with the observation of circumstellar discs. The mass distribution was comparable to those inferred from the observations of circumstellar disc of T Tauri stars.

Finally, in some calculations, Ida & Lin include the effects of type II migration for those giant planets which can acquire an adequate mass to open a gap. In this paper, we neglect this effect because our main aim is only to analyse if different prescriptions for the accretion of gas could lead to substantially different results.

2.1 Results

The results with this model show that the giant planets form mainly just outside the ice boundary at ∼2.7 au. This is because inside the ice boundary the volatile gases cannot condense into grains, as a result, the surface density of heavy elements decays and the critical mass necessary to start the gas accretion is rarely reached by the cores. On the other hand, beyond 10 au, core accretion is so slow that they never reach the critical mass before the gas depletion in the disc.

According to IL04, the $M_{\rm t-a}$ diagram reflects the condition for the process of planetary formation. The mass and semimajor axis distributions generated on their simulations show an absence of planets with masses between 10 and 100 $M_\oplus$, and semi-major axis between 0.2 and 3 au denominated ‘planet desert’. When the embryos reach the critical mass, the gas accretion process began and it is a runaway process, which ends only when there is no residual gas in the disc or a gap form near planet’s orbit. The transition between 10 and 100 $M_\oplus$ is so fast that planets with those masses are very rare.

3 A DIFFERENT ACCRETION MODEL

Fortier et al. (2007) studied the formation and evolution of a protoplanet in a circular orbit around the Sun, in the frame of the nucleated instability model. They improved a numerical code developed by Benvenuto & Brunini (2005), which is an adaptation of stellar binary evolution code based on a Henyey technique. With relation to the calculations made by Pollack et al. (1996), they changed the solid accretion rate, the growth of the gas envelope essentially being the same. The core accretion was modulated in the oligarchic growth frame (Ida & Makino 1993; Kokubo & Ida 1998, 2000), which had not been explored with a self-consistent code for giant planet formation. They also considered the gas drag effect acting on planetesimals inside the planet atmosphere, which increases the collision cross-section of embryos once these have a gaseous envelope. Their results show that the gas accretion into the cores is less sharp than those found by Pollack et al. (1996), so it would have some consequences in the mass distribution.

In this section, we will describe the model we use for computing planet formation.

3.1 Protoplanetary disc structure

The structure of the protoplanetary disc is, essentially, the same used by IL04, and here we briefly summarize it.

The disc is completely determined by the surface density of heavy elements and the gas surface density, $\Sigma_{\rm g}$. Based on the minimum-mass solar nebula model proposed by Hayashi (1981), we adopt the following distribution:

$$\Sigma_{\rm d} = f_{\rm d} \eta_{\rm ice} 10 \left(\frac{a}{1{\rm UA}} \right)^{-\frac{3}{2}} {\rm g\,cm^{-2}}, \quad (5)$$

where $f_{\rm d}$ is a scaling parameter for the total disc mass which takes values between 0.1 and 30, according to the observation of protostellar discs around T Tauri stars (Beckwith & Sargent 1996) and $\eta_{\rm ice}$ is a compositional scaling parameter which expresses the effect of ice condensation across the ice boundary,

$$\eta_{\rm ice} = \begin{cases} 1 & a \leqslant a_{\rm ice} \\ 4.2 & a > a_{\rm ice}, \end{cases} \tag{6}$$

where $a_{\rm ice}$ is the ice condensation radius which corresponds to a temperature of $T = 170^{\circ}$K, $a_{\rm ice} = 2.7(\frac{M_\star}{{\rm M}_\odot})^2$UA

The gas surface distribution is given by

$$\Sigma_{\rm g} = f_{\rm g} 2.4 \times 10^3 \left(\frac{a}{1{\rm UA}}\right)^{-\frac{3}{2}} {\rm g\,cm^{-2}}, \tag{7}$$

where $f_{\rm g}$ is a scaling parameter for the total mass of the gas disc, which is constant throughout the disc, and for simplicity we suppose equal to $f_{\rm d}$.

Finally, to represent the depletion of gas and evolution of the protostellar gas disc, we consider an exponential decay of $\Sigma_{\rm g}$,

$$\Sigma_{\rm g} \simeq \Sigma_{\rm g,0} {\rm e}^{-\frac{t}{\tau_{\rm disc}}}, \tag{8}$$

where $\Sigma_{\rm g,0}$ is the initial distribution and $\tau_{\rm disc}$ is the depletion timescale, which takes values between 10^6 and 10^7 yr, according to observations.

3.2 Core accretion

The formation of terrestrial planets and the cores of Jovian planets began with coagulation of grains; they stick together into larger aggregates. Gravitational forces became more important than gas drag only after objects many metres in size have formed; these are the planetesimals. In this early stage, larger planetesimals grow much faster than the smaller ones, that is because the collision cross-section is enhanced over its geometrical value as a result of gravitational focusing, that is, R is enhanced by a factor

$$1 + \left(\frac{v_{\rm e}}{\sigma}\right)^2, \tag{9}$$

where $v_{\rm e}$ is the mutual escape velocity of the two bodies, which is proportional to R. Then, the effective capture radius is given by

$$R_{\rm eff}^2 = R^2 \left(1 + \left(\frac{v_{\rm e}}{\sigma}\right)^2\right). \tag{10}$$

The cross-section is proportional to R^4, permitting large bodies to grow more rapidly. In addition, dynamical friction makes the random velocities of large planetesimals smaller than those of small planetesimals, and we can also see that the collision cross-section is inversely proportional to the relative velocity, so the smaller this velocity is the larger is its growth rate. This is called runaway growth (Greenberg et al. 1978; Kokubo & Ida 1996).

This runaway growth cannot be sustained indefinitely; Ida & Makino (1993) proposed a two-step growth scenario for a planet. The first stage is the runaway growth, which was already explained, and when the cores become massive enough to increase the velocity distribution of planetesimals, their growth slows down and began the second stage where the planetesimals random velocities lie in the high-velocity regime.

Kokubo & Ida (1998) studied this second stage through 3-D N-body calculations and found that the post-runaway dynamic is dominated by the nascent protoplanets. In this stage, the growth is orderly in the sense that protoplanets tend to have comparable mass cores and their orbital spacing are nearly equal to one another, and $\simeq 10\, r_{\rm H}$, where $r_{\rm H}$ is the Hill radius. They called this stage oligarchic growth. The protoplanet spends most of its growth period in this stage rather than in the runaway growth stage.

As we have already indicated, the runaway growth forms the embryos very quickly and after that the core accretion rate is regulated by the oligarchic growth, this is the real stage where the cores form. So, initially we have a $10^{-5}\, M_\oplus$ embryo and according to Safronov (1969) its accretion rate at an orbital radius a is well described by the particle-in-a-box approximation,

$$\frac{{\rm d}M_{\rm c}}{{\rm d}t} = F \frac{\Sigma_{\rm d}}{2h} \pi R_{\rm eff}^2 \sigma, \tag{11}$$

where h is the solid disc scaleheight, F is a factor introduced by Greenzweig & Lissauer (1992) in order to compensate the accretion rate underestimation ($\simeq$3) in the two-body approximation, compared to the case where the planetesimal population is modelled with Gaussian velocity dispersion by a single eccentricity and inclination equal to the rms values. This factor is adequate in the high-velocity regime. Finally $R_{\rm eff}$ is the effective capture radius given by equation (10).

Their mutual escape velocity is $v_{\rm e}^2 = \frac{2GM_{\rm t}}{R}$, and the relative velocity between the embryo and the planetesimals is determined by

$$\sigma \simeq \sqrt{e^2 + i^2}\, a \Omega_{\rm K}, \tag{12}$$

where $e = \langle e_{\rm m}^2 \rangle^{\frac{1}{2}}$ is planetesimals rms eccentricity, $i = \langle i_{\rm m}^2 \rangle^{\frac{1}{2}}$ is planetesimals rms inclination, both are with respect to the disc and $\Omega_{\rm K}$ is a Kepler frequency. In the high-velocity (high-σ) equilibrium regime, $\frac{i}{e} \simeq \frac{1}{2}$ is a reasonably good approximation, and we also apply the approximation $h \simeq ai$. Then, the accretion rate is

$$\frac{{\rm d}M_{\rm c}}{{\rm d}t} = C\, \Sigma_{\rm d} \Omega_{\rm K} R^2 \left(1 + \frac{2GM_{\rm t}}{R\sigma^2}\right) \tag{13}$$

with $C = F\pi\frac{\sqrt{5}}{2} \simeq 10.53$, and for simplicity we consider $\sigma \sim 10\, r_{\rm H}\, \Omega_{\rm K}$.

The main difference between this relation and the corresponding equation of IL04 model is the factor of 3 introduced by Greenzweig & Lissauer (1992). IL04 apply the approximation $\frac{v_{\rm e}^2}{\sigma^2} \gg 1$.

We have another important difference, which is a correction factor introduced in order to fit the solid accretion rate used by Fortier et al. (2007), which includes the evolution of the planetesimal rms e and i.

When the gravitational perturbation due to the protoplanets is balanced by dissipation due to the gas drag, the planetesimal rms eccentricity attains an equilibrium value, which is obtained by Thommes et al. (2003),

$$e^{\rm eq} (\simeq 2 i^{\rm eq}) \simeq \frac{1.7 m^{\frac{1}{15}} M_{\rm t}^{\frac{1}{3}} \rho_{\rm m}^{\frac{2}{15}}}{b^{\frac{1}{5}} C_{\rm D}^{\frac{1}{5}} \rho_{\rm gas}^{\frac{1}{5}} M_\star^{\frac{1}{3}} a^{\frac{1}{5}}}, \tag{14}$$

where m is the typical planetesimal's mass, $\rho_{\rm m}$ is the planetesimal bulk density ($\sim 1.5 \frac{g}{{\rm cm}^3}$), b is the orbital spacing between adjacent protoplanets($= 10$), $C_{\rm D}$ is a dimensionless drag coefficient which in this case is $\simeq$1, and $\rho_{\rm gas}$ is the gas volume density which is $\simeq 1.5 \times 10^{-10}\,{\rm g\,cm^{-1}}$ when $a = 5.2$ au and $f_{\rm d} = 10$ (which are the values of one of the cases considered by Fortier et al. 2007).

Using this expression, equation (12) can be rewritten as

$$\sigma \simeq 0.5 \times 10 \Omega_{\rm K} r_{\rm H}. \tag{15}$$

When $\frac{v_{\rm e}^2}{\sigma^2} \gg 1$, and considering the above equation, the core accretion rate is approximately 4 times larger than those given by equation (13) in the same case. With this factor of approximately 4, we obtained a very good agreement with the solid accretion rates of all the simulations performed by Fortier et al. (2007), who consider

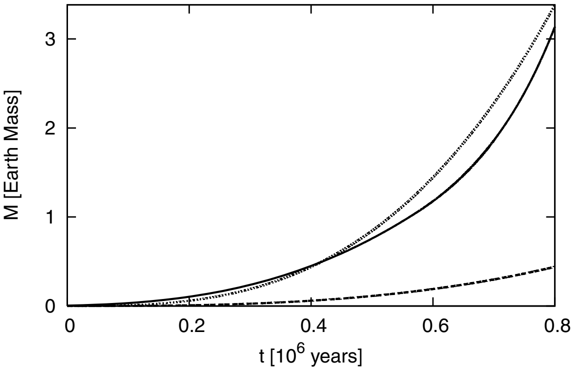


Figure 1. In this figure we plot the growth of the core's mass obtained by Fortier et al. (2007) in the solid line, the dashed line represents the growth when the equation (13) is considered and the dotted line is the mass behaviour with the solid accretion rate fitted by a factor of 4.

different planet locations and densities of the nebular gas without the necessity to introduce a high degree of complexity in the model. In Fig. 1, the solid line shows Fortier et al. (2007)'s results when $f_{\rm d} = 10$ is considered. The dotted line shows the core's mass behaviour in the case of introducing a factor of 4 in those results. Finally, the dashed line shows the growth of the core's mass when a factor of 1 is used for the fit. As seen in the figure, the factor of 4 fits the results much better. The differences between the dotted line and the results of Fortier et al. (2007) are due to different effects considered by them, such as the enhancement of the planet cross-section due to drag with the planet envelope. The introduction of this degree of complexity is beyond the possibilities of a model designed to perform a huge number of simulations like the one presented in this paper.

Finally, the core accretion rate we use is

$$\frac{{\rm d}M_{\rm c}}{{\rm d}t} = 42.12\Sigma_{\rm d}\Omega_{\rm K}R^2\left(1+\frac{2GM_{\rm t}}{R\sigma^2}\right). \qquad (16)$$

The region where the cores can accrete planetesimals directly is called the feeding zone. We consider, according to Kokubo & Ida (1998), that the radial width of the feeding zone during the oligarchic growth stage is given by

$$\Delta a_{\rm c} \simeq 10 r_{\rm H}, \qquad (17)$$

the more massive is the protoplanet, the larger becomes its feeding zone.

The core growth cannot continue indefinitely. As equation (16) shows, the core's accretion rate depends on the planetesimal surface density, $\Sigma_{\rm d}$, on its feeding zone. $\Sigma_{\rm d}$ is not a constant, it changes over time due to depletion of planetesimals by the protoplanet accretion. We consider this effect, which gives us a limiting embryo mass (neglecting radial migration) at which core's growth stops when it consumes all the planetesimals in its feeding zone, or equivalent when $\Sigma_{\rm d} = 0$ in the considered region. Then, we said that the protoplanet reaches its isolation mass. This represents the mass reached by a core whose orbit does not evolve with time, and it has accreted all the nearby planetesimals. It is given by

$$M_{\rm c,iso} = 2\pi \int_{a-\frac{\Delta a}{2}}^{a+\frac{\Delta a}{2}} a\Sigma_{\rm d}\,{\rm d}a. \qquad (18)$$

3.3 Gas accretion on to the core

In this section, we describe the gas accretion model we use for computing planetary formation. This model is equal to that of IL04's, except with a different choice of parameters. This difference, coupled with the use of more adequate solid accretion rates, furnishes very different results than those found by IL04.

The cores have an associate envelope if the molecular velocity is smaller than the escape one. According to Mizuno et al. (1978), once a protoplanet becomes greater than approximately the Moon's mass, the core attracts the neighbouring gas and an envelope forms surrounding it. In the early stages of giant planets formation, the gravity is balanced by the pressure gradient which is maintained by the potential energy released by incoming planetesimals (Mizuno 1980). The stability of this envelope depends on the mass of the protoplanet, when it becomes greater than a critical value, the envelope can no longer be in hydrostatic equilibrium and begins to collapse (Mizuno 1980; Bodenheimer & Pollack 1986), the gas accretion process begins.

Ikoma et al. (2000) found through numerical simulations of quasi-static evolution of the gaseous envelope the characteristic growth time of the envelope mass ($\tau_{\rm g}$) as a power-law function of the grain opacity, κ, and the critical mass of the core, $M_{\rm crit}$,

$$\tau_{\rm g} \simeq b\left(\frac{M_{\rm crit}}{M_\oplus}\right)^{-c}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)\quad {\rm yr}, \qquad (19)$$

with $b \simeq 10^8$ and $c \simeq 2.5$. Ikoma & Genda (2006) found $b \simeq 10^{10}$ and $c \simeq 3.5$ with a more complicated and realistic grain opacity model.

Ida & Lin used a simplified version of equation (19), where the core mass is replaced with the total mass of the protoplanet. As seen on Section 2, $b \simeq 10^9$ and $c \simeq 3.0$ are the values adopted on IL04. Bryden, Lin & Ida (2000) obtained $b \simeq 10^{10}$ and $c \simeq 3.0$ by fitting the results of Pollack et al. (1996) with negligible planetesimal accretion, and we considered $b = 1.64 \times 10^9$ and $c = 1.91$, as a result of generalizing the results of Fortier et al. (2007) by introducing an analytic approximation to their numerical results. We note that our coefficient c is much smaller than the one used by IL04, leading to a slower gas accretion rate.

Equation (19), where $M_{\rm crit}$ is replaced by $M_{\rm t}$, indicates that $\tau_{\rm g}$ depends strongly on $M_{\rm t}$ and moderately on κ. Besides, the amount and size distribution of dust grain in the envelope are not known, based on these considerations we neglect the dependence on κ in our model.

When the core reaches the critical mass, $M_{\rm crit}$, the gas accretion process is triggered. The gas accretion rate is given by

$$\frac{{\rm d}M_{\rm g}}{{\rm d}t} = \frac{M_{\rm t}}{\tau_{\rm g}}. \qquad (20)$$

We need an expression for the critical mass of the core; Ikoma et al. (2000) derived through numerical calculation an approximate expression which is a function of the core accretion rate, $\dot{M}_{\rm c}$, given by equation (16) and κ.

$$M_{\rm crit} \sim 7\left(\frac{\dot{M}_{\rm c}}{10^{-6}M_\oplus\,{\rm yr}^{-1}}\right)^{0.2-0.3}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{0.2-0.3}M_\oplus, \qquad (21)$$

which is an improvement to the formula derived analytically by Stevenson (1982). We consider a simplified formula, where the opacity is neglected and the exponent is taken as 1/4.

Several limits were taken for ending this accretion process: (1) the growth of the envelope ends when the planet consumes all the gas available on its feeding zone; (2) we use a global limit, which stops the process when the total gas present on the disc is 10 times less than the initial one and (3) finally when $\dot{M}_{\rm g} > \frac{1M_\oplus}{100\,{\rm yr}}$.

4 SIMULATION RESULTS

Applying this model, we performed simulations to predict the mass distribution of extrasolar planets, and compare the final distribution to the results obtained with IL04 model.

To favour the comparison, the same initial conditions are used, which are explained next.

As seen on Section 3.1, the distribution of gas and solid surface density is not uniform, so different orbital position goes to different gas and solids to accrete. Since the initial position of the cores has a huge influence on their formation, we assumed that planets form with equal probability per interval of $\log(a)$ to guarantee that different planets will form.

In order to characterize different discs, we assume a Gaussian distribution to represent the f_{d} population. This is a distribution in terms of $\log_{10}(f_{\mathrm{d}})$, with dispersion $\sigma = 1$ and centred at $\log_{10}(f_{\mathrm{d}}) = 0.25$. We adopt a cut-off at $f_{\mathrm{d}} = 30$ because discs with $f_{\mathrm{d}} > 30$ are heavy enough to be gravitationally unstable.

As equation (8) shows, the nebular gas decays exponentially on a time-scale between 10^6 and 10^7 yr, according to observations of circumstellar discs of T Tauri stars (Beckwith & Sargent 1996). In this work the lifetime of the nebular gas is $\tau_{\mathrm{disc}} = 4 \times 10^6$ yr.

In our calculations we consider 1000 initial cores, they evolve 10^7 yr in a circumstellar disc (one core per disc), where the central star's mass is $M_\star = M_\odot$. The solid accretion is truncated when there is no material into their feeding zones (or equivalently the isolation mass is reached). The truncation conditions for the envelope growth are given in Section 3.3.

The mass distribution obtained with our model is shown in Fig. 2(a). While in Fig. 2(b), there is a histogram showing masses for planets formed with IL04 model, the distributions obtained with both models are relatively flat, that is equal number of planets throughout the range of 0.1 to 3500 $M_\oplus$, except the region between 100–1000 (Fig. 2a) and 10–100 (Fig. 2b), where there is a clear lack of planets.

This deficit shows the process of planetary formation. Fig. 3(a) shows the growth of a planet located at 3 au, using the IL04 model. When the gas accretion process begins, the total mass of the planet grows very rapidly from 10 to 100 $M_\oplus$, and this is the reason for the lack of planets with intermediate masses.

Fig. 3(b) shows the evolutionary behaviour of the mass of a planet at an orbital distance of 3 au from the Sun. As seen in the figure, the mass of gas (represented with the dotted line) is less sharp than those found by IL04, as a consequence, the 'crossover mass' (which is the planet mass when the mass of the envelope is approximately equal to the core's mass) is reached at $\sim$100 $M_\oplus$ instead of $10 M_\oplus$. Although 100 $M_\oplus$ seems to be too large to begin the runaway gas accretion of gas, the model 'State of the art' developed by Fortier et al. (2007) shows that this is possible.

This result shows that the final mass distribution is strongly dependent on the gas accretion model used.

5 CONCLUSIONS

In this work, we have analysed the influence that a different prescription for the solid and gas accretion rates would have on the final mass distribution of extrasolar planets.

We have developed a simple model for computing planetary formation, based on the standard core instability model for giant planet formation. The core accretion was modelated through the process of oligarchic growth, and we include a factor of approximately 4 which is taken to consider the evolution of the planetesimal rms e and i (this value was obtained by fitting the results of Fortier et al. 2007).

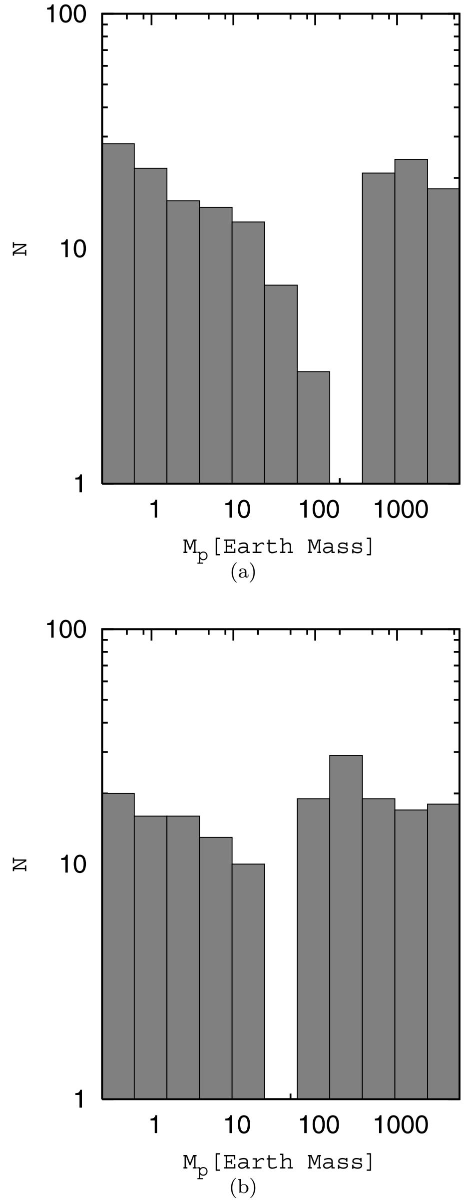
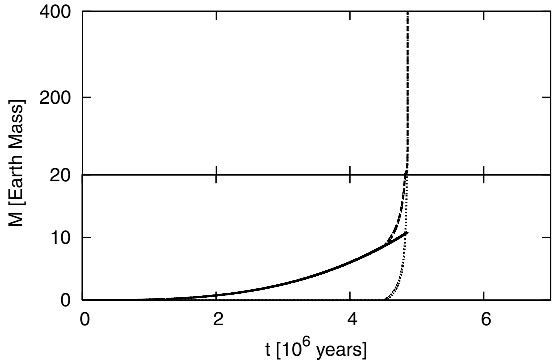


Figure 2. Histograms showing final planet mass distributions obtained with our model (a) and IL04 model (b).

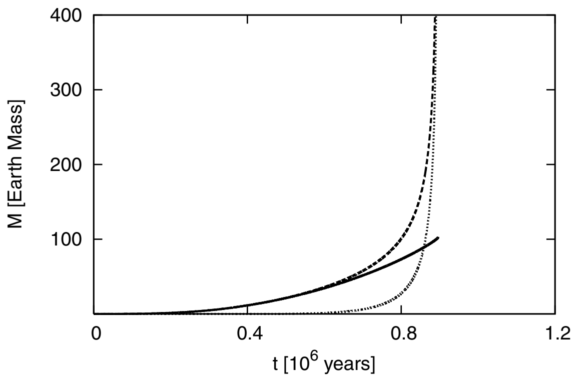
In the models of this work, the core accretion rate is so high that the energy transport in the envelope is largely convective. However, equation (16) holds true when the energy transport is mostly radiative, but since the aim of this work is to show the consequences that different accretion models have on the masses distribution, it might not be important.

Once the core reaches the critical mass (given by equation 21), the gas accretion process begins. This process was modelated by fitting the results of the self-consistent code for giant planet formation developed by Fortier et al. (2007).

Our results show that the gas accretion into the core is less sharp than the one obtained by using a Kelvin–Helmholtz contraction model. As a consequence, the run away gas accretion process is



(a)



(b)

Figure 3. The mass evolution of a planet located at 3 au is shown in the figures.(a) shows the growth of a planet using IL04 model and the masses behaviour obtained with our model is represented in (b). The dashed line represents the total mass, the mass of the envelope is shown with the dotted line, and the solid line is the core's mass. In both cases, we can see that the total mass grows really fast when the runaway accretion of gas begins, but it starts at different masses depending on the gas accretion model considered (see text).

reached by the cores at a larger mass, fact that modifies the location of the 'planetary desert'. According to IL04's results, the region where a deficit of planets is found is located between 10 and 100 $M_\oplus$, but we found that this region was moved beyond 100 $M_\oplus$.

This result shows that the 'desert' found on the final mass distribution of extrasolar planets is strongly dependent on the gas accretion model considered.

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