

Orbital migration and the period distribution of exoplanets

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Abstract. We use the model for the migration of planets introduced in Del Popolo et al. (2003, MNRAS, 339, 556) to calculate the observed mass and semimajor axis distribution of extra-solar planets. The assumption that the surface density in planetesimals is proportional to that of gas is relaxed, and in order to describe disc evolution we use a method which, using a series of simplifying assumptions, is able to simultaneously follow the evolution of gas and solid particles for up to 10^7 yr. The distribution of planetesimals obtained after 10^7 yr is used to study the migration rate of a giant planet through the model described in the present paper. The disk and migration models are used to calculate the distribution of planets as function of mass and semimajor axis. The results show that the model can give a reasonable prediction of planets' semi-major axes and mass distribution. In particular there is a pile-up of planets at $a \approx 0.05$ AU, a minimum near 0.3 AU, indicating a paucity of planets at that distance, and a rise for semi-major axes larger than 0.3 AU, out to 3 AU. The semi-major axis distribution shows that the more massive planets (typically, masses larger than $4 M_J$) form preferentially in the outer regions and do not migrate much. Intermediate-mass objects migrate more easily whatever the distance at which they form, and that the lighter planets (masses from sub-Saturnian to Jovian) migrate easily.

Key words. planets and satellites: general – planetary system – planets and satellites: formation

1. Introduction

The number of currently known extra-solar planets exceeds 100. This is a statistically significant sample from which it is possible to determine meaningful distributions of planetary characteristics (Udry et al. 2003; Marcy et al. 2003), and useful constraints for planet-building models, and then to possibly discriminate between the different proposed scenarios. Some features in the period versus mass diagram start to emerge and provide strong observational constraints for the migration scenario.

After the discovery of solar-like stars showing evidences of planets orbiting around them (Mayor & Queloz 1995; Marcy et al. 2000; Vogt et al. 2000; Butler et al. 2001) a number of questions about the formation mechanisms of such systems have been raised. The properties of these planets, most of which are Jupiter-mass objects¹, and with orbits ($r < 1$ AU) very close to their stars, are difficult to explain using the standard model for planet formation (Lissauer 1993; Boss 1995), which predicts nearly circular planetary orbits and giant planet distances ≥ 1 AU from the central star, where the temperature in the protostellar nebula is low enough for icy materials to

condense (Boss 1995, 1996; but see also Wuchterl 1993, 1996). Thus, in the case of close-in giants, it is very unlikely that such planets were formed at their present locations: the most natural explanation for this paradox and for planets on very short orbits is that these planets formed further away in the protoplanetary nebula and migrated afterwards to the small orbital distances at which they are observed (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Murray 2002; Goldreich & Tremaine 1979, 1980; Ward 1986; Lin et al. 1996; Ward 1997; Del Popolo et al. 2001 (hereafter DP1)). Recent studies based upon the quoted sample have shown some peculiar features that could be used to constraint theoretical models (migration models), and have generated new puzzles that should be solved². Some of the emerging observational properties are the following (Udry et al. 2003):

1) The more massive planets (typically, masses larger than $4 M_J$) form preferentially in the outer regions where there is

² In the list of new problems, a noteworthy role can be given to the origin of eccentricities for single planets and the steep planet mass distribution. Plausible mechanisms include gravitational interactions between the planet and other planets, stellar companion, or the protoplanetary disk (Rasio & Ford 1996; Lin & Ida 1997; Marzari & Weidenschilling 2002; Goldreich & Sari 2002; Chiang 2003). The dynamical processes that lead to resonances remain under study.

¹ Note that the Doppler method measures only $M \sin i$, and in the following when we refer to planet masses, we mean $M \sin i$.

- a large-enough material reservoir and do not migrate much. None are observed within (≈ 100 days) of the central star.
- 2) The clear emergence of a gap in the 10 and 100-days periods (the “period valley” following Udry et al. 2003), due to the light candidates ($M_p \sin i \leq 2 M_J$).
 - 3) The apparent lack of very light planets ($M_p \sin i \leq 0.75 M_J$) with periods larger than ≈ 100 days. Most of them are found in the very central regions. None is observed with $P \geq 100$ days.

The semi-major axes distribution shows:

- i) A pile-up of planets at $a \approx 0.05$ AU.
- ii) A minimum near 0.3 AU.

The different features pointed out above in the observed mass versus period and in semi-major axes distribution can be used to check the processes proposed to explain the observed distribution of mass and periods for extra-solar planet candidates, and fix some constraints for the planet migration models as a function of the planet mass, in single star systems.

Some studies have tried to reproduce the quoted behaviors. The lack of massive planets on short-period orbits can be explained by means of a low migration efficiency for higher mass planets. When the mass of the planet becomes of the order of a significant fraction of the characteristic disc mass with which it interacts, the inertia of the planet becomes important and slows down the orbital evolution (e.g. Trilling et al. 1998; Nelson et al. 2000). Using a model assuming a simple impulse approximation for the type II migration, no ad-hoc stopping mechanism in the center and neglecting type I migration, Trilling et al. (2002) showed that, for identical initial disk conditions, close-in surviving pseudo-planets have smaller masses and distant surviving pseudo-planets have larger masses. Armitage et al. (2002) extended the work of Trilling et al. (2002) including a physical mechanism for disc dispersal into a model for the formation and migration of massive planets, and made quantitative comparisons with the observed distribution of planetary orbital radii. They found good agreement with the Trilling work.

A recent study by Masset & Papaloizou (2003) gives some insight into the observed lack of small-mass planets ($M_p \sin i \leq 0.75 M_J$) on intermediate-period orbits ($P \geq 100$ days) (see the Results section of the present paper, for details).

The aim of the present paper is to check the predictions of the migration model introduced in DP1, for the semi-major axes and mass distribution of extra-solar planets, and to compare them with the observed distribution of known extra-solar planets. This goal is reached by allowing giant planets to evolve and migrate in circumstellar disks with various initial conditions (different values of planet mass, disk mass, viscosity, etc.), assuming one planet per disk, and determining the final semi-major axis and mass distributions. The fundamental differences to previous studies in literature lie in the disk model used and the migration model.

A fundamental issue in studying planet migration is the disk model. From Del Popolo et al. (2001) to Del Popolo et al. (2003) (hereafter DP3), there was a noteworthy improvement in the disk model used. In the current work, as in DP3, the disk model we used is a time-dependent accretion disk, and

moreover we relaxed the assumption of Del Popolo & Ekşi (2002) (hereafter DP2) that the surface density in planetesimals remains proportional to that of gas: $\Sigma_s(r, t) \propto \Sigma(r, t)$. It is well-known that the distribution of planetesimals emerging from a turbulent disk does not necessarily reflect that of gas (e.g., Stepinski & Valageas 1996, 1997).

In order to take into account that the evolution of the distribution of solids is also governed by coagulation, sedimentation and evaporation/condensation, we use the method developed in Stepinski & Valageas (1997) which is able to simultaneously follow the evolution of gas and solid particles for up to 10^7 yr.

The second fundamental issue in studying planet migration is the migration mechanism. A detailed discussion of the mechanisms that have been proposed to explain the presence of planets at small orbital distances are summarized in DP1 and DP2, and in those papers we showed that dynamical friction between a planet and a planetesimal disk is an important mechanism for planet migration. Coupling the two models to obtain the migration rate of planets is possible, as shown in DP1, DP2, and DP3, and this can be used to calculate the distribution in terms of semimajor axes and mass.

This paper is organized as follows. In Sect. 2, we revise the disk and migration model used to obtain the radial distribution of the planetesimals. In Sect. 3, we describe our results. Section 4 is devoted to conclusions.

2. Disk and migration models

2.1. Distribution and evolution of gas and solids

In this section, we summarize the models used for the disk and migration. Interested readers are referred to DP3, and previous papers of the same author, for more details.

In order to obtain a better description of the planets' migration, it is necessary to model how the structure of the disk changes in time. This cannot be handled by the minimum-mass model nor by steady-state models. Observations of circumstellar disks surrounding T Tauri stars support the view of disks having a limited life-span and characterized by continuous changes during their life. This evidence has led to a large consensus about the nebular origin of the Solar System. In addition, one also needs to describe the global evolution of the solid material which constitutes, together with the gas, the protoplanetary disk. The knowledge of this distribution and its time evolution is important both to understand how planets form and to calculate the migration rate.

The time evolution of the surface density of the gas Σ is given by the familiar equation (e.g., Stepinski & Valageas 1997):

$$\frac{\partial \Sigma}{\partial t} - \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} (r^{1/2} \nu_t \Sigma) \right] = 0 \quad (1)$$

where ν_t is the turbulent viscosity. Since ν_t is not an explicit function of time, but instead depends only on the local disk quantities, it can be expressed as $\nu_t = \nu_t(\Sigma, r)$ and Eq. (1) can be solved subject to boundary conditions on the inner and outer edges of the disk. The opacity law needed to compute ν_t is obtained from Ruden & Pollack (1991). Then, Eq. (1) is solved by

means of an implicit scheme. Note that the evolution of the gas is computed independently of the evolution of particles (which only make up $\sim 1\%$ of the gas mass). Next, from $\Sigma(r, t)$ we can algebraically find all other gas disk variables.

Next, as described in Stepinski & Valageas (1997) the evolution of the surface density of solid particles Σ_s is given by:

$$\frac{\partial \Sigma_s}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} (v_s \Sigma_s r^{1/2}) \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[\frac{2r \Sigma_s \langle \bar{v}_\phi \rangle_s}{\Omega_k t_s} \right] \quad (2)$$

where the effective viscosity v_s is given by:

$$v_s = \frac{v_t}{Sc} \quad \text{with} \quad Sc = (1 + \Omega_k t_s) \sqrt{1 + \frac{\bar{v}^2}{V_t^2}} \quad (3)$$

where Sc is the Schmidt number, which measures the coupling of the dust to the gas turbulence, \bar{v} is the relative velocity between a particle and the gas, V_t the turbulent velocity, Ω_k is the Keplerian angular velocity and t_s the so-called stopping time.

The first diffusive term in Eq. (2) is similar to Eq. (1), the second advective term in Eq. (2) arises from the lack of pressure support for the dust disk compared to the gas disk. Thus, it is proportional to the azimuthal velocity difference \bar{v}_ϕ between the dust and the gas. The average $\langle \dots \rangle_s$ refers to the vertical averaging over the disk height weighted by the solid density. We refer the reader to Stepinski & Valageas (1997) for a more detailed presentation, see also Kornet et al. (2001).

In addition to the radial motion described by Eq. (2), the dust surface density also evolves through evaporation/condensation and coagulation. The method used to incorporate these processes into calculations relies on keeping Eq. (2) as the principal mathematical description of the global evolution of particles, but freeing its parameters from constraints of single-size and thermal indestructibility assumptions. Thus, the method can be characterized as solving a radial advection-diffusion problem modulated by coagulation, with the possibility of a cut-off by the evaporation. This method requires that the mass distribution of particles at any given radial location of a disk is narrowly peaked about a mean value particular for this location and a given time instant. Such an assumption may appear quite arbitrary; however, it has a reasonable physical justification as collisions with small particles do not significantly increase the size of a test particle and the bulk of the solid mass is concentrated in the largest particles. This is supported by numerical simulations (Mizuno et al. 1988) of grain growth in protoplanetary disks which clearly show that although a broad size distribution is maintained, most of the mass is nevertheless always concentrated in the largest particles. Therefore, we assume that the mass distribution of particles at any given radial location r is narrowly peaked about the mean value $m_d(r, t) = (4/3)\pi s^3(r, t)\rho_s$, where $s(r, t)$ is the size. The goal is to evaluate the functional dependence of s on r and t . Particles are assumed to be spheres with a bulk density of ρ_s . The density of matter concentrated into solid particles is $\rho_s(r)$. Then, within this approximation, coagulation does not influence the dust surface density Σ_s since it conserves the total mass of solids. Thus, the coagulation of solid particles only appears through the evolution of the radial distribution $s(r, t)$ of the typical size of the dust grains. We model this process as

Table 1. Properties of the initial gas disk.

M_d	J_{50}	Σ_1	r_1	Σ_2
10^{-1}	911	22	200	100
10^{-2}	85	1.7	200	100
10^{-3}	5.5	1.2	50	30
10^{-4}	0.46	0.2	50	2.8

in Stepinski & Valageas (1997). We only consider collisional coagulation and we disregard gravitational interactions which would come into play at late times when large planetesimals have formed.

On the other hand, we take into account the evaporation of solid particles which takes place at the radius r_{evap} where the temperature reaches T_{evap} . We also include the condensation of the vapor below T_{evap} onto the solid grains. As in DP3, we consider only one species of solid particles: high-temperature silicates with $T_{\text{evap}} = 1350$ K and a bulk density $\rho_{\text{bulk}} = 3.3$ g cm $^{-3}$. Thus, in our simplified model we follow the evolution of three distinct fluids: the gas, the vapor of silicates and the solid particles.

In this fashion, we obtain the radial distribution of the planetesimal swarm after 10^7 yr. This yields the surface density of solids $\Sigma_s(r, t)$ and the mid-plane solid density $\rho_s(r, t)$. We also obtain the size distribution $s(r, t)$ reached by hierarchical coagulation. Of course, at these late times where planetesimals have typically reached a size of a few km or larger, gravitational interactions should play a dominant role with respect to coagulation. However, if these interactions do not significantly affect the radial distribution of solids (note that the radial velocity of such large particles due to the interaction with the gas is negligible) we can still use the outcome of the fluid approach described above to study the migration of giant planets, as detailed below.

As in Stepinski & Valageas (1997), we consider an initial gas surface density of the form:

$$\Sigma_0(r) = \Sigma_1 \left[1 + (r/r_1)^2 \right]^{-3.78} + \Sigma_2 (r/1 \text{ AU})^{-1.5}. \quad (4)$$

The quantities Σ_1 , r_1 and Σ_2 are free parameters which we vary in order to study different disk masses. The values we use are given in Table 1, where M_d is the gas disk mass (in units of M_\odot), J_{50} is the disk angular momentum (in units of 10^{50} g cm 2 s $^{-1}$), Σ_1 and Σ_2 are in g cm $^{-2}$ and r_1 is in AU. The first term in Eq. (4) ensures that there is some mass up to large distances from the star, while the second term corresponds to the central concentration of the mass and sets the location of the evaporation radius. Note however that the evaporation radius for the high-temperature silicates we study here remains of the order of 0.1 AU. As previously explained, we consider only one species of solid: high-temperature silicates with $T_{\text{evap}} = 1350$ K. We initialize the dust subdisk at time $t = 10^4$ yr (i.e. after the gas distribution has relaxed towards a quasi-stationary state) by setting the solid surface density Σ_s as: $\Sigma_s(r, t = 10^4 \text{ yr}) = 6 \times 10^{-3} \Sigma(r, t = 10^4 \text{ yr})$, similarly to Stepinski & Valageas (1996, 1997), in order to account for cosmic abundance.

The assumed initial surface density profile is arbitrary. Fortunately, the specific form of the profile does not influence the subsequent evolution of the gas, inasmuch as the process governed by Eq. (1) is diffusive in nature and the details of initial distribution are forgotten after a time short in comparison with the evolutionary timescale.

Taking advantage of the “memory” of the gaseous component, we introduce solid particles into the calculation only after 10^4 yr during which the gas evolves alone to remove the arbitrariness in the initial conditions. Upon introduction, the solid particles all have the same size, $s = 10^{-3}$ cm.

The calculations are carried out for up to $t = 10^7$ yr, a period of time equal, within an order of magnitude, to observationally deduced lifetimes of protoplanetary disks (Strom & Edwards 1993).

As shown in DP3, after times of the order of 10^6 – 10^7 yr, the coagulation process gives rise to large particles ($>10^5$ cm) which have a small radial velocity, and hence a negligible radial motion. This leads to a freezing of the solid surface density to the value reached at times of the order of 10^7 yr. In other words, once solids are in the form of planetesimals, the gas coupling becomes unimportant and the radial distribution of solids does not change and can only change on a much longer timescale by processes not considered in our model (like mutual gravitational interactions between planetesimals first proposed by Safronov 1969)³. This is why we do not need to calculate its evolution for times longer than 10^7 years.

2.2. Migration model

With regard to the migration model, we consider a planet revolving around a star of mass $M_* = 1 M_\odot$. The equation of motion of the planet can be written as

$$\dot{\mathbf{r}} = \mathbf{F}_\odot + \mathbf{R} \quad (5)$$

where the term \mathbf{F}_\odot represents the force per unit mass from the star, while \mathbf{R} is the dissipative force (i.e. the dynamical friction term – see Melita & Woollson 1996). Then, the frictional drag on the test particles may be written as

$$\mathbf{R} = -k_{\parallel} v_{\parallel} \mathbf{e}_{\parallel} - k_{\perp} v_{\perp} \mathbf{e}_{\perp} \quad (6)$$

where \mathbf{e}_{\parallel} and \mathbf{e}_{\perp} are two unit vectors parallel and perpendicular to the disk plane, and $k_{\parallel} v_{\parallel}$ and $k_{\perp} v_{\perp}$ are given in DP3. We assume a disk-shaped matter distribution with constant velocity dispersions σ_{\parallel} (parallel to the plane) and σ_{\perp} (perpendicular to the plane) and with a ratio simply taken to be 2:1 (i.e. $\sigma_{\parallel} = 2\sigma_{\perp}$). Since the damping of eccentricity and inclination is more rapid than radial migration (Ida 1990; Ida & Makino 1992; DP1), we only deal with radial migration and we assume that the planet has negligible inclination and eccentricity ($i_p \sim e_p \sim 0$) and that the initial distance from the star to the planet is 5.2 AU. The planet was set at an initial distance

³ Note that 10^6 yr is the time required for Σ_s (or ρ_s) to converge everywhere. However, this convergence is not uniform and can be achieved on a time scale as short as 10^4 yr in the innermost disk where the dust density is highest.

of 5.2 AU for similarity with choices made in previous papers (e.g., Murray et al. 1998; Trilling et al. 1998)

In the calculation, we consider a two-component system, consisting of one protoplanet and many equal-mass planetesimals. The velocity dispersion of planetesimals in the neighborhood of the protoplanet depends on the mass of the protoplanet. When the mass of the planet, M_p , is $\leq 10^{25}$ g, the value of $\langle e_m^2 \rangle^{1/2}$ (e_m being the eccentricity of the planetesimals) is independent of M_p therefore:

$$e_m \simeq 20(2m/3M_\odot)^{1/3} \quad (7)$$

(Ida & Makino 1993) where m is the mass of the planetesimals. When the mass of the planet reaches values larger than 10^{25} – 10^{26} g at 1 AU, $\langle e_m^2 \rangle^{1/2}$ is proportional to $M_p^{1/3}$:

$$e_m \simeq 6(M_p/3M_\odot)^{1/3} \quad (8)$$

(Ida & Makino 1993). As a consequence, the dispersion velocity in the disc is also characterized by two regimes, being connected to the eccentricity by the equation:

$$\sigma_m \simeq (e_m^2 + i_m^2)^{1/2} v_c \quad (9)$$

where i_m is the inclination of planetesimals and v_c is the Keplerian circular velocity. Following Stern (1996) and Del Popolo et al. (1999) we assume that $\langle i_m^2 \rangle = \langle e_m^2 \rangle/4$. In the simulation we assume that the planetesimals all have equal masses, m , and that $m \ll M_p$. This assumption does not affect the results, since dynamical friction does not depend on the individual masses of these particles but on their overall density (see DP3). Therefore, we do not need to follow the evolution of the size distribution of planetesimals. We merely use the planetesimal density ρ_s reached after 10^7 yr, assuming that the height of the planetesimal disk does not evolve significantly.

Other details, and a discussion about the back reaction of the planet on the swarm, can be found in DP1, DP2, DP3.

2.3. Further assumptions and the distribution calculation method

In order to determine the distribution of semimajor axes and mass, it is necessary to investigate the dependence of the giant planet migration on the properties of the protoplanetary disk and planet mass M_p . Similarly to what we did in DP3, we integrated the model introduced in the previous sections for several values of the initial disk surface density (i.e. several disk masses), different values of α , and planet mass. In this way, it was possible to obtain a semimajor axis corresponding to a given value of α , disk mass, and M_p . As previously reported, the assumptions and model are the same as in DP3.

Since, similarly to DP3, we are mainly interested in studying the planet migration due to the interaction with planetesimals, we assume that the gas is almost dissipated when the planet starts its migration. We know that, usually, while the gas tends to be dissipated, (some evidence shows that the disk lifetimes range from 10^5 yr to 10^7 yr, see Strom et al. 1993; Ruden & Pollack 1991), the coagulation process induces an increase

of the density of solid particles with time and gives rise to objects of increasing dimensions. Clearly the effect of the presence of gas should be that of accelerating the loss of angular momentum of the planet and to reduce the migration time. In our case, there is still gas after 10^7 yr, but it is in quantity inferior to that of planetesimals, especially in the case of lower mass discs, in which it can be even two order of magnitude less than planetesimals. Moreover, as noticed by Kominami & Ida (2002) dynamical friction and gravitational gas drag are essentially the same dynamical process and the effect of the gravitational gas drag is incorporated in that of dynamical friction. In our case, other forces, such as aerodynamical gas drag, can be neglected when compared to gravitational gas drag (Kominami & Ida 2002).

In order to calculate the fraction of planets in terms of semi-major axes and mass, we used the model described in the previous section, and we have performed a statistical study of planet migration in systems in which both disk mass and disk viscosity are varied in turn. The initial orbital semi-major axes of all planets are 5.2 AU. Initial planet masses are taken to be fractional values of Jupiter masses, between 0.1 and 18 Jupiter masses (with intervals of $0.1 M_J$), considering one planet per system. As in Trilling et al. (2002), for the varied parameters, we adopt nominal values and vary each parameter over a given range. In the case of disk mass, we adopt a nominal disk mass of $0.02 M_\odot$ (after Beckwith et al. 2000), and calculate model cases between $10^{-4} < M_d < 0.6 \times 10^{-1} M_\odot$ (with intervals of $0.01 M_\odot$). This range spans disk masses from less than the minimum mass disk for a system containing a Jupiter, to a disk so massive that direct binary star production is more likely than giant planet formation (see, for example, reviews by Beckwith & Sargent 1993 and Beckwith et al. 2000). Similarly, we use a nominal α viscosity of 3×10^{-3} (Shakura & Sunyaev 1973; Trilling et al. 1998) and test parameter values in the range of $10^{-4} < \alpha < 10^{-1}$ (with intervals of 0.01α) (the values used by Trilling et al. 2002 are almost the same, $10^{-4} < \alpha < 9 \times 10^{-2}$). Each model run has one parameter varied while the other two are given their nominal values. This very fine sampling of disk parameters allows us to simulate a continuum of physical properties of planet-forming systems.

For each value of the planet mass, we obtain a three-dimensional grid of models, based on the nominal values and spanning the range of parameter space. To produce a Gaussian statistical population the significance of each model run was weighted by the Gaussian probability of the value of the varied parameter according to the standard Gaussian formalism:

$$P(y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}[(y-y_0)]^2/\sigma^2} \quad (10)$$

where $y = \log x$ and $y_0 = \log x_0$, where x is equal to the value of the varied parameter, x_0 is the nominal value for the parameter being varied, and where σ (describing the width in log space of the Gaussian parameter distribution) is equal to 0.5. In other words, the half-width of the Gaussian physical parameter distribution is a factor of $\sqrt{10}^4$. We use this Gaussian

⁴ Thus, a parameter value which is $\sqrt{10}$ times greater or less than the nominal value has a probability one half of the probability that of the nominal value: $P(y_k) = \frac{1}{2}P(y_0)$ for $y_k = y_0 \pm 0.5$.

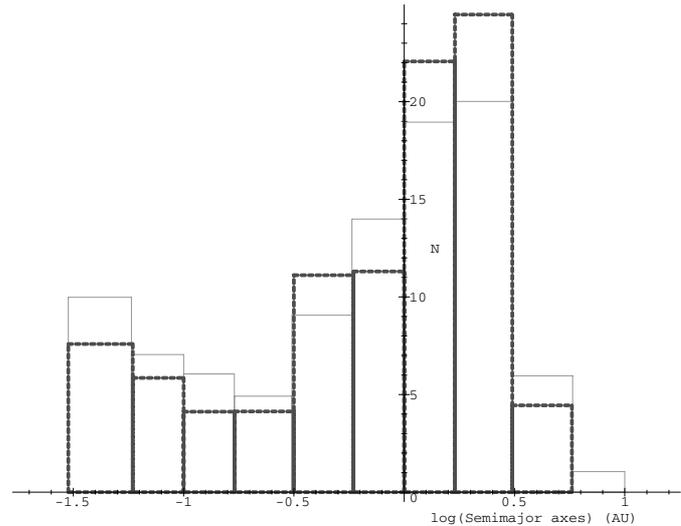


Fig. 1. Orbital semi-major axes for observed (solid line), and model (dashed thick line) Extra-solar Giant Planets (EGPs). The solid line represents the semi-major axes distribution obtained with the data given at www.exoplanets.org, while the dashed thick line is the distribution obtained with the model of this paper.

weighting in all results discussed in this paper. Weighting is achieved by assigning a significance to each planet as $P(y)$. Thus, planets from extreme disks which survive but whose initial conditions are extremely unlikely are not overrepresented in the statistical results. Note that because probabilities are assigned after all model runs are completed and are simple functions of the nominal values and a description of a Gaussian distribution, other probability weightings can be installed to represent other experiments. Future work includes deriving both x_0 and σ more directly from observations (see, e.g., Gullbring et al. 1998; Hartmann et al. 1998) and testing non-Gaussian probability distributions.

3. Results

3.1. Semi-major axis distribution

The results of the model of the previous section are plotted in Figs. 1–3. In the first, we represent the distribution of semi-major axis of planets. In Fig. 1, the light solid line represents the semi-major axis distribution obtained with the data given at www.exoplanets.org (see also Fig. 3 of Marcy et al. 2003) while the dashed thick line is the distribution obtained with the model of this paper.

The plot in Fig. 1 shows that we obtain a reasonable agreement with the data. However, the main point of Fig. 1 is to show that the observed distribution of orbital periods can be easily recovered from our model, and with reasonable values for α and M_d .

The plot shows that at $a \approx 0.05$ AU there is a pile-up of planets. This pile-up seems not to be an artifact of observational selection (see Kuchner & Lecar 2002 and Sect. 3.3), and it suggests that some mechanism must be responsible for halting the migration of planets at an orbital period of 3 days.

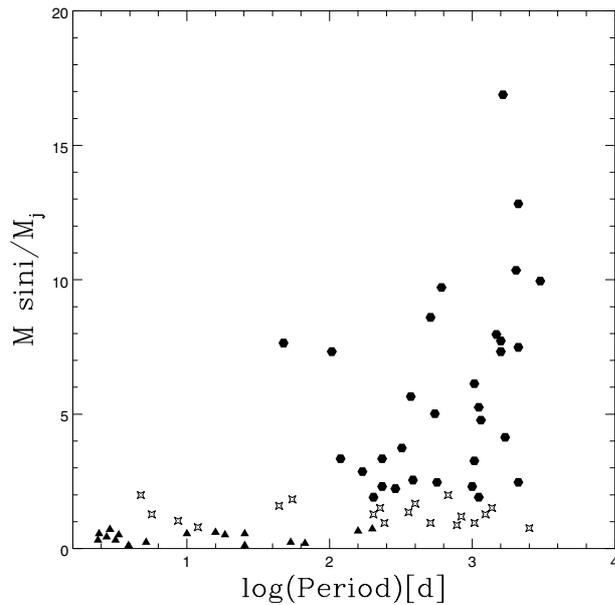


Fig. 2. Mass versus period of planets calculated according to the model of the current paper. Filled symbols represent massive ($M_p \geq 2 M_J$) planets, open symbols represent intermediate-mass planets ($0.75 \leq M_p \leq 2 M_J$) and filled triangles lighter ($M_p \leq 0.75 M_J$) planets.

As stressed by Kuchner & Lecar (2002), phenomena like the interaction between two planets and a star, that can leave a planet trapped by stellar tides into a circular orbit of ≈ 0.04 AU (Rasio & Ford 1996), or halting of planet migration by loss of mass to the star (Trilling et al. 1998), are rare. The migration through resonant interaction with planetesimals in the disk (Murray 2002) provides a natural way of halting the planet but unfortunately to change the orbit of a Jupiter-mass planet requires approximately a Jupiter mass of planetesimals and a too massive disk. The other possibility to explain the pile-up of planets seen in Fig. 1 (see also DP3) is a gas disk truncated at a temperature of 1500 K by the onset of Magneto-Rotational instability (Kuchner & Lecar 2002). Thus, disk temperature determines the orbital radii of the innermost surviving planets. In our model, the distribution of internal planets is naturally connected to the evaporation of planetesimals at very short radii. As stressed in DP1, DP2, this model does not have the drawback of Murray (2002), namely that of requiring a too-large disk mass for migration, and at the same time it has the advantage of Murray (2002) of having an intrinsic natural mechanism that provides halting of migration. As shown in DP3, the same model used in this paper is able to explain the peak at 3–4 days for the orbital period.

A second feature visible in Fig. 1 is a minimum near 0.3 AU, indicating a paucity of planets at that distance. One interpretation of this minimum is that the migration mechanism rarely allows them to stop near 0.3 AU (Jones et al. 2003). There is the suggestion of a rise for semi-major axes larger than 0.3 AU, out to 3 AU. Beyond 3 AU, the Doppler surveys have had inadequate lifetimes (≈ 8 yr) to securely detect planets in the correspondingly long orbital periods (the decrease observed

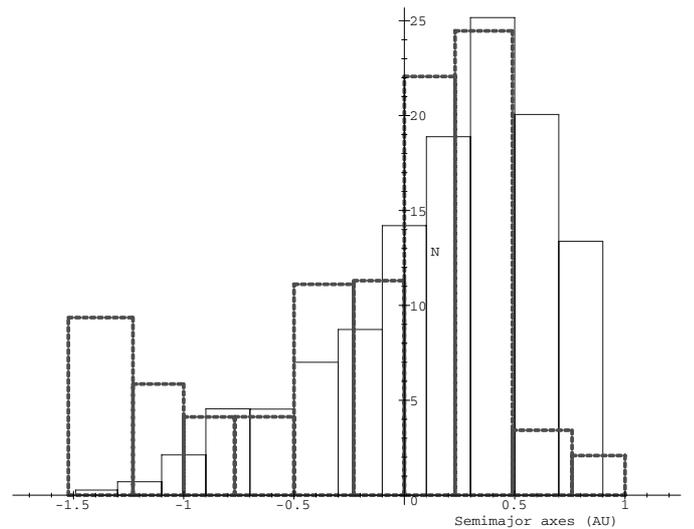


Fig. 3. Orbital semi-major axes for EGPs obtained in the model of this paper (thick dashed line) compared to the model of Trilling et al. (2002) (solid line).

after 3 AU is due at least in part to observational bias)⁵. Thus, observations summarized in Fig. 1 strongly indicate the existence of a rise in the distribution of planets with increasing orbital distance from the host star. The increasing numbers of planets in larger orbits is consistent with models that invoke orbital migration, like that of this paper, and a contemporaneous clearing of the gaseous disk to explain the final positions of giant planets (Trilling et al. 2002). If we have planets that initially reside at 5 AU or at larger distances, and if the disk clears its gas on a time scale shorter than the migrational time scale, then giant planets beyond 5 AU could be more numerous than the extrasolar planets discovered so far.

In conclusion, we can tell that the disk model and migration mechanism used in this paper are able not only to predict the planet distribution at short semi-major axes, with a peak at 3–4 days, but also the distribution of planets at larger distances.

3.2. Mass versus period

In Fig. 2, we plot planet mass vs. orbital semi-major axis. There is a lack of massive planets having small semi-major axes. Within ≈ 0.3 AU (≈ 60 days) there are no planets with masses larger than $\approx 4 M_J$ and moreover there are few massive planets with semi-major axis < 1 AU.

With now more than 100 extra-solar planets discovered, the lack of short-period massive planetary companions becomes even clearer, as seen in Fig. 2. When we neglect the multiple-star systems⁶, a complete void of candidates is observed in the diagram for masses larger than $\approx 2 M_J$ and periods smaller than ≈ 100 days.

⁵ Indeed, there is poor detectability of planets for semi-major axes greater than 2 AU, where planets with $M_p < 1 M_J$ are currently difficult to detect, given the precision and duration of surveys.

⁶ In these systems the planetary formation or evolution could follow different paths (Zucker & Mazeh 2002; Udry et al. 2003).

This feature can be explained by several processes:

- 1) Type II migration.
- 2) Processes related to planet-star interactions when the planet reaches the central regions (see Udry et al. 2003).
- 3) Multi-planet chaotic interactions (Rasio & Ford 1996; Weidenschilling & Marzari 1996).

In relation to type II migration, the feature can be explained assuming that the migration process has a low efficiency (planets rarely migrate inward) or too high an efficiency (planets migrate all the way into the star) for massive planets (mass $> 4 M_J$). The first alternative (low efficiency) is the most probable. This view is supported by simulations of single-planet migration and by the model of this paper. More massive planets create larger gaps than smaller planets (Trilling et al. 1998). For the most massive planets, the length of time it takes to fully form the gap can be quite long and during gap formation there is no Type I migration since the planet has already opened a gap; there is also little Type II migration because most Lindblad resonances already fall within the growing gap. If the timescale for gap growth is longer than the disk lifetime, then the planet will not migrate far. Therefore, overall, close-in surviving model planets have smaller masses and distant surviving models planets have larger masses.

The explanation of the lack of short-period massive planetary companions is similarly explained in our model. As discussed in DP2, DP3 (in connection with the back reaction of the planet on the swarm), when the protoplanet becomes massive enough (10^{25} – 10^{26} g) to influence the velocity distribution of small planetesimals, the random velocities and velocity dispersion of planetesimals are heated by the protoplanet and become larger than in the early stage. Furthermore, the protoplanet would scatter neighboring planetesimals and give rise to a gap in the spatial distribution of planetesimals (see Fig. 3 of Ida & Makino 1993, and Fig. 1a of Tanaka & Ida 1997). The effect on the drift velocities can be easily predicted observing that the increase in velocity dispersion of planetesimals around the protoplanet decreases the dynamical friction force and consequently increases the migration time-scale.

As shown in DP3, the drift velocity behaves as:

$$\frac{dr}{dt} \propto \begin{cases} M & M \leq 10^{25} \text{ g} \\ \text{constant} & M > 10^{25} \text{ g} \end{cases} \quad (11)$$

The linear dependence on the planet's mass of the drift velocity corresponds to the *type I* drift in the density wave approach (Ward 1997), while the part independent of the planet's mass corresponds to *type II* drift. The transition between the two regimes entails a velocity drop of between one to three orders of magnitude (according to the value of α). As the threshold is exceeded, the motion fairly abruptly converts to a slower mode in which the drift velocity is independent of mass⁷. The

⁷ The conclusion that migration timescales are independent of planet mass is valid in the limit that the planets mass is small compared to the disk mass. In the case of a finite mass ratio between planet and disk, however, there is a feedback torque from the planet onto the disk, and the planetary migration timescale is seen to be a function of planetary masses (Lin & Papaloizou 1986; Trilling et al. 1998;

phenomenon is equivalent to that predicted in the density wave approach (Goldreich & Tremaine 1980; Ward 1997). This leads to similar conclusions obtained by Trilling et al. (2002), with a type II migration model: higher mass planets migrate on longer timescales. More massive planets preferentially form in the outer regions where a larger amount of building material is available, and that from those distances they need longer times to migrate towards the inner region.

The migration calculated in the case the disc mass, M_d , is smaller than that of the protoplanet. One can think that less massive discs are not able to move a more massive planet. This idea is not completely correct. As we know, when the planet mass is less than or comparable to the local disc mass, the planet behaves as a representative particle in the disc, as shown by Lin & Papaloizou (1986). When the protoplanet has a mass larger than that of the disc, the satellite acts as a dam against the viscous evolution of the disc, and can lead to a substantial change in the disc structure in the vicinity of the planet. The coupled disc-planet evolution in this case has been studied by Syer & Clarke (1995) and by Ivanov et al. (1999), who showed that the inertia of the planet plays an important role in this case (see Nelson et al. 2000, Eq. (9)). The effect of the interaction between the secondary and the disc leads to accumulation of the disc matter in the region behind the protoplanet (see Eqs. (12) and (39) of Syer & Clarke 1995). In order to calculate the migration in our model, we used the surface density given in Ivanov et al. (1999).

As shown in Fig. 2, another very interesting feature comes out of the period/separation distribution: there is a shortage of planets with periods between roughly 10 and 100 days. This observational property is mainly due to the light candidates ($M_p \sin i \leq 2 M_J$). As seen in the previous section, massive planets orbiting single stars are almost exclusively found on longer-period orbits. They probably form and stay further out. On the other hand, lighter planets ($0.75 \leq M_p \sin i \leq 2 M_J$), are found at all distances from their stars, unlike massive planets.

A third feature emerging from the mass-period diagram is the apparent lack of very light planets ($M_p \sin i \leq 0.75 M_J$) with periods larger than ≈ 100 days. Assuming that it is not produced by small number statistics, an explanation of this feature has been advanced by Masset & Papaloizou (2003), Udry et al. (2003). Masset & Papaloizou (2003) studied the effect of co-orbital corotation torque on migrating protoplanets. In particular they showed that if the mass deficit created by the radial drift with the planet of the material trapped in the co-orbital region is larger than the planet mass, the migration rate undergoes a runaway which can rapidly vary the protoplanet semi-major axis by a large amount (50% over a few tens of orbits). This typically corresponds to planet masses in the sub-Saturnian to Jovian mass range embedded in massive protoplanetary disks.

Moreover, the simulations by Masset & Papaloizou (2003) show that the limit in planetary mass for the appearance of the

Bryden et al. 2000; Nelson et al. 2000; Kley 2000; D'Angelo et al. 2002). In the regime in which we are working, planetary migration timescales are functions of planet masses in the sense that, in general, smaller planets migrate faster and more massive planets migrate more slowly.

runaway regime is very steep (their Figs. 12–14). There is a critical mass relatively well-constrained ($M_{\text{crit}} \approx 1 M_J$) under which runaway is likely provided that the protoplanetary disk is not too lightweight, and above which runaway is impossible. In Fig. 2, it is shown that in the calculations of this paper, light planets, $M_p \sin i \leq 0.75 M_J$, are found predominantly at periods shorter than 100 days, but some planets are found also at larger distances. In other words, following the mass trend seen for other planets, smaller mass planets migrate to smaller periods, but differently from observations, some light planets, $M_p \sin i \leq 0.75 M_J$, are observed also at periods larger than 100 days. This suggests that if there is a larger probability of finding light planets with smaller periods, it is also possible that some light planets can be found on larger orbits, depending on particular characteristics of the disk. The fact that in the sample of ≈ 100 planets we have now the light planets are found exclusively on periods shorter than 100 days can be related to the fact that the detection probability decreases with increasing distances and with decreasing mass: light planets $M_p \sin i \leq 0.75 M_J$ are more and more difficult to detect at larger distances. In other words, this feature could be related to the observational bias (see Sect. 3.3) inherent to the radial-velocity technique for planet search that makes the detection more difficult for distant and/or lighter planets (but see also Udry et al. 2003).

P. J. Armitage (private communication) suggested that the probability that the observational evidence of the lack of planets with $M_p \sin i \leq 0.75 M_J$ with $P > 100$ days is a real effect is only marginal. This comes from the fact that plotting the mass vs. semi-major axis distribution, the lower edge of the distribution nearly follows the line defined by constant stellar radial velocity amplitude (i.e. $\propto \sqrt{a}$). If there is a lack of low mass planets present at 1 AU separation, there are only maybe one or two planets “missing”, leading to the conclusion that the planet lack quoted is definitely connected to small number statistics.

3.3. Bias and significance of the data.

Here we add some statements about the significance of the observational data, in general. No massive planets ($M \sin i \geq 2 M_J$) are found on short periods orbits ($P \leq 100$ d) around single stars. This feature has been pointed out by Udry et al. (2002) and Zucker & Mazeh (2002). The same authors verified its statistical significance and examined the possible influence of binarity on the mass-period relation of exoplanets, an indication of potentially different formation and evolution processes for planets in binaries and planets around single stars. The observed feature is most probably not an observational bias since these objects are the easiest to detect.

The second important feature that emerges from observations is a planet shortage in the 10 and 100-day periods, the “period valley”, following Udry et al. (2003). The features appearing in the planetary period distribution peak at short periods and rising at intermediate periods seem significant and not due to observational biases. The peak at short periods is formed by the pile-up of migrating planets, stopped close to the central star. The rise of the distribution at longer

periods is more clearly emerging thanks to the increase of the timebase of the radial-velocity surveys. More and more long period planets are being detected. This rise is significant in the sense that, for a given mass range, similar planets on shorter period orbits would have been easier to detect than the actual ones. The other, previously quoted feature is the lack of planets with $M_p \sin i \leq 0.75 M_J$ with $P > 100$ days. This feature could be related to the observational bias inherent to the radial-velocity technique for planet search that makes the detection more difficult for distant and/or lighter planets. In order to check the statistical significance of the effect, Udry et al. (2002) performed Monte-Carlo simulations. They conclude that the considered region is indeed empty of planets with a confidence level of about 99.97%. This conclusion is only valid if the observational biases are correctly taken into account. For example, activity-induced radial-velocity jitter may screen planet detection. Another concern relates to the difficulty encountered when trying to actually derive the values for the orbital elements, which are different to just detecting radial-velocity variability.

As previously observed, a different point of view is that the probability that the effect is a real effect is only marginal. This comes from the fact that plotting the mass vs semi-major axis distribution, the lower edge of the distribution is close to following the line defined by constant stellar radial velocity amplitude (i.e. $\propto \sqrt{a}$).

More quantitative constraints for the different mass regimes will require a better detection by the surveys, to diminish the effect of the observational bias in the distributions and thus increase the confidence we can put in the derived trends, especially for the lower-mass planets.

3.4. Comparison with other studies

A comparison with Trilling et al. (2002) is performed in Fig. 3. In this plot the thick dashed line represents the model of this paper while the light solid line Trilling’s prediction. As previously reported, using a model assuming a simple impulse approximation for the type II migration, no ad-hoc stopping mechanism in the center and neglecting type I migration, Trilling et al. (2002) show that, for identical initial disk conditions, close-in surviving pseudo-planets have smaller masses and distant surviving pseudo-planets have larger masses. They also find that planets forming farther out migrate less rapidly and that higher-mass planets migrate on longer timescales. Thus, there should be more massive planets at intermediate and large semi-major axes than found close-in. Conversely, the population of short-period planets should be dominated by smaller-mass planets, as is indeed observed.

Similarly to Trilling et al. (2002), the present paper concludes that close-in surviving pseudo-planets have smaller masses and distant surviving pseudo-planets have larger masses. Differently from Trilling et al. (2002), in the model of this paper the pile-up of planets at small periods is naturally explained. In our model, the distribution of internal planets is naturally connected to the evaporation of planetesimals at very short radii. In Trilling et al. (2002), the observed peak at small

separations is not reproduced because they have not introduced any process to stop migration close to the central star.

The lack of a peak in Trilling's result at small separation is clearly visible in Fig. 3 (light solid line), this last figure also shows that for $r \geq 3$ AU Trilling's simulations give a larger number of planets than the present paper. In other words, the model of this paper gives a better prediction, with respect to Trilling's model, of the distribution of planets observed to date both at small and large radii, while at small radii the model of this paper is probably a better description of data, at larger radii future surveys may help determine whether the model of this paper or Trilling's is a better description of data. As is known, the radial velocity technique is most sensitive to planets at small semi-major axes, because the magnitude of the stellar wobble is greatest for close-in planets. Additionally, since the highest precision radial velocity surveys have relatively short baselines of data, planets with longer periods are only beginning to be identified (e.g., 55 Cnc d, with ≈ 15 year orbit (Marcy et al. 2002)). Thus, a large population of Jupiter-like planets could be as yet undetected.

Armitage et al. (2002) extended the work of Trilling et al. (2002). They include a physical mechanism for disc dispersal into a model for the formation and migration of massive planets, and make a quantitative comparison with the observed distribution of planetary orbital radii. The results are comparable to those of Trilling et al. (2002).

Another interesting comparison is with Udry et al. (2003). The authors showed that:

- 1) No massive planets ($M_p \sin i \geq 2 M_J$) are found on short-period orbits ($P \leq 100$ days) around single stars.
- 2) The maximum mass of detected planets per period interval increases with distance to the central star (their Fig. 6).
- 3) The migration rate of planets decreases with increasing mass of the planetary companion.
- 4) Up to now, no planet candidates with very low masses ($M_p \sin i \leq 0.75 M_J$) have been detected in orbits with periods longer than ≈ 100 days.
- 5) There is a shortage of planets with periods in the 10–100 days range.

The previous results are in agreement with the results of this paper, except, partially, with point 4. In this paper, low-masses planets ($M_p \sin i \leq 0.75 M_J$) tend to move towards small periods, but some can be found at periods larger than 100 days. This could be due to the fact that planet detectability is poorer for increasing values of semi-major axis and small planet mass. If this feature is confirmed in future studies, showing a sharp feature in the period versus mass diagram, this could provide a proof of the importance of the runaway migration process recently studied by Masset & Papaloizou (2003).

Our model, similarly to that of Trilling et al. (2002), does not deal with the distribution of orbital eccentricities of the known radial velocity companions. The discussion of whether radial migration in gaseous or particulate disks produces eccentric orbits is an ongoing one (e.g., Ward 1997a,b; Bryden et al. 1999; Kley 2000; Papaloizou et al. 2001; Murray et al. 2002). The presence of high eccentricities suggests that multiple giant planet formation may be the norm, and that interactions

among giant planets after disk migration ends may increase the orbital eccentricities. The stochastic nature of such interactions precludes their inclusion in an analysis such as the one we present. Further, until the orbital inclinations can be determined, an important clue to the genesis of the eccentricities is missing. Regardless of the mechanism(s) by which eccentricity is created, except for extreme cases, our results regarding the semi-major axis distribution are hardly affected⁸. Additional modest semi-major axis evolution associated with eccentricity pumping does not alter our results significantly. Dramatic three-planet interactions that would leave giant planets in vastly altered orbits and greatly affect our statistics are arguably rare. In summary, while we do not calculate eccentricities induced by gas drag in our one-dimensional model, the results based on the statistics of semi-major axis distribution remain robust.

We recall that Woolfson (2003) showed that even in a model of planet formation that produces planets on extensive eccentric orbits, the presence of a disk-like resisting medium can explain all types of planetary orbits that have been observed, when parameters are varied in a systematic manner.

4. Conclusions

In this paper, we have studied the period and mass distribution of extra-solar planets, obtained using the migration model introduced in DP1. The results show several features of those distributions that are in almost all cases in agreement with observations. In the case of period distribution, the paper shows:

- 1) A pile-up of planets at $a \approx 0.05$ AU. This pile-up is clearly significant, and it suggests that some mechanism must be responsible for halting the migration of planets at an orbital period of 3 days. According to DP3 and this paper, the distribution of internal planets is naturally connected to the evaporation of planetesimals at very short radii.
- 2) There is a minimum near 0.3 AU, indicating a paucity of planets at that distance.
- 3) There is the suggestion of a rise for semi-major axes larger than 0.3 AU, out to 3 AU. The increasing number of planets in larger orbits is consistent with models that invoke orbital migration and a contemporaneous clearing of the gaseous disk to explain the final positions of giant planets.

In the case of mass distribution, we have that:

- i) The more massive planets (typically, masses larger than $4 M_{Jup}$) form preferentially in the outer regions and do not migrate much.
- ii) Intermediate-mass objects migrate more easily whatever the distance where they form and they are observed at almost all distances.
- iii) The lighter planets (masses from sub-Saturnian to Jovian) migrate easily. They are not confined to regions of period < 100 days.

The results obtained are in agreement with observations except item iii. In this study, we do not find that lighter planets

⁸ Our statistical results regarding planet formation frequency hinge on the frequency of the close-in giant planets versus those farther out.

are confined in regions of period <100 days. Future observations could be decisive, showing whether mechanisms like the runaway process studied by Masset & Papaloizou (2003) are needed to explain this sharp feature in the observed mass period diagram.

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References

- Armitage, P. J., Livio, M., Lubow, S. H., & Pringle, J. E. 2002, *MNRAS*, 334, 248
- Beckwith, S. V. W., & Sargent, A. I. 1993, in *Protostars and Protoplanets III*, ed. E. H. Levy, & J. I. Lunine (Tucson: University of Arizona Press), 521
- Beckwith, S. V. W., Henning, T., & Nakagawa, Y. 2000, in *Protostars and Planets IV*, ed. Mannings et al. (Tucson: University of Arizona), 533
- Boss, A. P. 1995, *Science*, 267, 360
- Boss, A. P. 1996, *Lunar & Planetary Science*, 27, 139
- Bryden, G., Chen, X., Lin, D. N. C., Nelson, R. P., & Papaloizou, J. C. B. 1999, *ApJ*, 514, 344
- Butler, R. P., Tinney, C. G., Marcy, G. W., et al. 2001, *ApJ*, 555, 410
- Chiang, E. I. 2003, *ApJ*, in press
- D'Angelo, G., Henning, T., & Kley, W. 2002, *A&A*, 385, 647
- Del Popolo, A., & Ekcisi, Y. E. 2002, *MNRAS*, 332, 485 (DP2)
- Del Popolo, A., Spedicato, E., & Gambera, M. 1999, *A&A*, 350, 685
- Del Popolo, A., Gambera, M., & Ercan, E. N. 2001, *MNRAS*, 325, 1402 (DP1)
- Del Popolo, A., Yesilyurt, S., & Ercan, E. N. 2003, *MNRAS*, 339, 556
- Goldreich, P., & Tremaine, S. 1979, *ApJ*, 233, 857
- Goldreich, P., & Tremaine, S. 1980, *ApJ*, 241, 425
- Goldreich, P., & Sari, R. 2002, *ApJ*, submitted [arXiv:astro-ph/0202462]
- Gullbring, E., Hartmann, L., Briceno, C., & Calvet, N. 1998, 492, 323
- Hartmann, L., Calvet, N., Gullbring, E., & D'Alessio, P. 1998, *ApJ*, 495, 385
- Ida, S. 1990, *Icarus*, 88, 129
- Ida, S., & Makino, J. 1992, *Icarus*, 98, 28
- Ivanov, P. B., Papaloizou, J. C. B., & Polnarev, A. G. 1999, *MNRAS*, 307, 79
- Jones, H. R. A., Butler, R. P., Tinney, C. G., et al. 2003, *MNRAS*, submitted
- Kley, W. 2000, *MNRAS*, 313, L47
- Kominami, J., & Ida, S. 2002, *Icarus*, 157, 43
- Kornet, K., Stepinski, T. F., & Rózycka, M. 2001, *A&A*, 378, 180
- Kuchner, M. J., & Lecar, M. 2002 [arXiv:astro-ph/0206232]
- Lin, D. N. C., & Papaloizou, J. 1986, *ApJ*, 309, 846
- Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, *Nature*, 380, 606
- Lin, D. N. C., & Ida, S. 1997, *ApJ*, 477, 781
- Lissauer, J. J. 1993, *ARA&A*, 31, 129
- Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, *ApJ*, 536, L43
- Marcy, G. W., Butler, R. P., Fisher, D. A., et al. 2002, *ApJ*, 581, 1375
- Marcy, et al. 2003, in *Scientific Frontiers in Research on Extrasolar Planets*, ed. D. Deming, & S. Seager, ASP Conf. Ser., in press
- Marzari, F., & Weidenschilling, S. J. 2002, *Icarus*, 156, 570
- Masset, F., & Papaloizou, J. 2003, *ApJ*, submitted [arXiv:astro-ph/0301171]
- Mayor, M., & Queloz, D. 1995, *Nature*, 378, 355
- Melita, M. D., & Woolfson, M. M. 1996, *MNRAS*, 280, 854
- Mizuno, H., Markiewicz, W. J., & Völk, H. J. 1988, *A&A*, 195, 183
- Murray, N., Hansen, B., Holman, M., & Tremaine, S. 1998, *Science*, 279, 69 (see also preprint SISSA [arXiv:astro-ph/9801138])
- Murray, N., Paskowitz, M., & Holman, M. 2002, *ApJ*, 565, 608
- Nelson, R., Papaloizou, J., Masset, F., & Kley, W. 2000, *MNRAS*, 318, 18
- Papaloizou, J. C. B., Nelson, R. P., & Masset, F. 2001, *A&A*, 366, 263
- Rasio, F. A., & Ford, E. 1996, *Science*, 274, 954
- Ruden, S. P., & Pollack, J. B. 1991, *ApJ*, 375, 740
- Safronov, V. S. 1969, in *Evolutsiia doplanetnogo oblaka (Evolution of the protoplanetary cloud and formation of the Earth and planets)* (Moscow: Nauka press)
- Sasselov, D. D., & Lecar, M. 2000, *ApJ*, 528, 995
- Shakura, N. I., & Sunyaev, R. A. 1973, *A&A*, 24, 337
- Stepinski, T. F., & Valageas, P. 1996, *A&A*, 309, 301
- Stepinski, T. F., & Valageas, P. 1997, *A&A*, 319, 1007
- Stern, S. A. 1996, *A&A*, 310, 999
- Strom, S. E., Edwards, S., & Skrutskie, M. F. 1993, in *Protostars and Planets III*, ed. E. H. Levy, & J. I. Lunine (Tucson: Univ. Arizona Press), 837
- Syer, D., & Clarke, C. J. 1995, *MNRAS*, 277, 758
- Strom, S. E., & Edwards, S. 1993, in *Planets around Pulsars*, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni, ASP Conf. Ser., 36, 235
- Trilling, D. E., Benz, W., Guillot, T., et al. 1998, *ApJ*, 500, 428
- Trilling, D., Lunine, J., & Benz, W. 2002, *A&A*, 394, 241
- Udry, S., Mayor, M., & Queloz, D. 2003, in *Scientific Frontiers in Research on Extrasolar Planets*, ed. D. Deming, & S. Seager, ASP Conf. Ser., in press
- Vogt, S. S., Marcy, G. W., Butler, R. P., & Apps, K. 2000, *ApJ*, 536, 902
- Ward, W. R. 1986, *Icarus*, 67, 164
- Ward, W. R. 1997a, *ApJ*, 482, L211
- Ward, W. R. 1997b, *Icarus*, 126, 261
- Weidenschilling, S. J., & Marzari, F. 1996, *Nature*, 384, 619
- Woolfson, M. M. 2003, *MNRAS*, 340, 43
- Wuchterl, G. 1993, *Icarus*, 106, 323
- Wuchterl, G. 1996, *BAAS*, 28, 1108
- Zucker, S., & Mazeh, T. 2002, *ApJ*, 568, L113