The potential for Earth-mass planet formation around brown dwarfs

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ABSTRACT
Recent observations point to the presence of structured dust grains in the discs surrounding young brown dwarfs, thus implying that the first stages of planet formation take place also in the substellar regime. Here, we investigate the potential for planet formation around brown dwarfs and very low-mass stars according to the sequential core accretion model of planet formation. We find that, for a brown dwarf mass $0.05 \, M_\odot$, our models predict a maximum planetary mass of $\sim 5 M_\oplus$, orbiting with semimajor axis $\sim 1$ au. However, we note that the predictions for the mass–semimajor axis distribution are strongly dependent upon the models chosen for the disc surface density profiles and the assumed distribution of disc masses. In particular, if brown dwarf disc masses are of the order of a few Jupiter masses, Earth-mass planets might be relatively frequent, while if typical disc masses are only a fraction of Jupiter mass, we predict that planet formation would be extremely rare in the substellar regime. As the observational constraints on disc profiles, mass dependencies and their distributions are poor in the brown dwarf regime, we advise caution in validating theoretical models only on stars similar to the Sun and emphasize the need for observational data on planetary systems around a wide range of stellar masses. We also find that, unlike the situation around solar-like stars, Type II migration is totally absent from the planet formation process around brown dwarfs, suggesting that any future observations of planets around brown dwarfs would provide a direct measure of the role of other types of migration.

Key words: stars: low-mass, brown dwarfs – planetary systems: formation.

1 INTRODUCTION
Observations of planets proceed apace: currently there are 232 extra solar planets known in 199 different planetary systems.1 As is well known, many, if not all, of these systems are radically different from the Solar system (Beer et al. 2004), often posing challenges to theories of planet formation. As time has progressed, a number of planets have begun to be observed around low-mass stars ($M_\star \sim 0.2-0.3 \, M_\odot$), thus begging the natural question of whether this trend will continue and whether similar planetary systems are to be expected at even lower masses, down in the brown dwarf regime.

Observations suggest that there does not seem to be any discontinuity between the properties of the discs around stars and those around brown dwarfs: Spitzer observations by Luhman et al. (2005) found that disc fractions for stars and brown dwarfs in the IC 348 and Chamaeleon I clusters were similar, thus suggesting a similar disc lifetime (see also Sterzik et al. 2004). The measurement by Scholz, Jayawardhana & Wood (2006) of the Taurus star-forming region indicates that many of the discs around brown dwarfs must be relatively large in size, extending beyond 10 au, and have masses up to 12 per cent of the central brown dwarf, with the average being 2.6 per cent, compared with an average value of 1.9 per cent for low-mass main-sequence stars (note, however, that such disc mass estimates are very uncertain). Hence it appears that discs around brown dwarfs have similar properties and are as ubiquitous as discs around main-sequence stars.

Observations indicate that grain growth, the precursor to planet formation in the sequential core accretion model, can occur efficiently in the small discs surrounding brown dwarfs (Apai et al. 2005). This then poses such questions as: what is the potential to form planets around very low-mass stars; what would be their mass–semimajor axis distribution and would they be detectable? If formed or forming planets could be observed around brown dwarfs, these would provide highly valuable, low-mass calibration points for the assessment of planet formation models over a wide range of stellar masses. In view of this, and in view of forthcoming missions such as the Terrestrial Planet Finder and Darwin, aimed at looking for Earth-like planets, it is important to estimate the likelihood of the presence of planets around stars of different masses, and in particular around brown dwarfs.

Planet formation models currently fall into two categories: (i) the sequential core accretion model, which can account for the
2 PLANET FORMATION MODEL

The model we adopt here is primarily based on the model of sequential accretion presented in IL1, IL2 and IL3. In this section we initially briefly recount the principle components which pertain to our investigation before going on to discuss in more detail the refinements and additions which are required to extend the model down to the brown dwarf regime. Readers requiring more detail on the original model construction should refer to IL1, IL2 and IL3.

2.1 Disc properties and initial conditions

The protoplanetary disc is modelled using a two component surface density profile, \( \Sigma = \Sigma_d + \Sigma_g \), to account for the dust and gas, with:

\[
\Sigma_d = 10 f_0 n_{\text{ice}} \left( \frac{a}{1 \text{ au}} \right)^k \left( \frac{M_*}{M_\odot} \right)^n \text{ g cm}^{-2},
\]

\[
\Sigma_g = 2.4 f_0 \times 10^3 \left( \frac{a}{1 \text{ au}} \right)^k \left( \frac{M_*}{M_\odot} \right)^n e^{-a/\text{disc}} \text{ g cm}^{-2},
\]

where \( M_* \) is the mass of the central star, \( a \) is the radial distance from it, and \( n_{\text{ice}} \) is a step function accounting for the increase in dust density at the snow line such that \( n_{\text{ice}}(a < a_{\text{ice}}) = 1 \) and \( n_{\text{ice}}(a > a_{\text{ice}}) = 4.2 \). The radial location of the snow line \( a_{\text{ice}} \) is set to core growth caused by various effects, such as isolation and migration.

Whilst this kind of modelling is admittedly oversimplified, the models of IL1, IL2 and IL3 do succeed in reproducing several features of the observed distribution of extrasolar planets, such as the metallicity dependence for the probability of planet formation, the dependency on stellar mass of the distribution of planetary masses as well as giving realistic mass ranges for the outcome of the planet formation process. However, the models experience problems in reproducing observations of intermediate-mass planets with semimajor axes less than 3 au. It is possible that these difficulties stem from the neglect of Type I migration in these models – see Sections 2.4 and 3.2 for further consideration.

Clearly a self-consistent disc processing and core growth model for multiple interacting planets would be more appropriate (e.g. Laughlin, Bodenheimer & Adams 2004; Alibert et al. 2005; Papaloizou & Nelson 2005; Papaloizou & Terquem 2006; Terquem & Papaloizou 2007). But given that the models of IL1, IL2 and IL3 are currently the only extant attempt at providing a general framework for examining the outcome of the planetary formation and migration mechanism, they provide a useful framework for the exploration of the extensive parameter space and they allow us to start examining in a statistical manner the potential for planet formation in discs around brown dwarfs and the potential for practical observations in the near future.

To address the issue of planet formation around brown dwarfs under the core accretion model, we therefore extend the core accretion model of IL1, IL2 and IL3 down to the low-mass regime. Once the basic structure of the model is in place, it can be used to investigate the effect on the planetary mass–semimajor axis distribution of varying key physical parameters. These include: the surface density profile of the disc, the size and mass of the disc, the rate of disc clearance, the effect of stellar mass and luminosity as well as migration.

formation of both rocky planets and gas giants and (ii) the gravitational instability model, which can only account for the formation of massive gas giants. The sequential core accretion model of planet formation (Pollack et al. 1996) assumes that planets form through a process in which first dust grains initially present in the protoplanetary disc condense to form kilometre-scale planetesimals; the collisional accumulation of planetesimals forms the basis for the runaway growth of a protoplanetary core of rock and/or ice (Safronov 1972; Wetherill 1980), and finally if a critical mass has been reached, the protoplanetary cores can begin to rapidly accrete a gaseous envelope (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996). The gravitational instability model does not need to form the initial rocky core, and assumes that the protoplanetary disc may become gravitationally unstable and hence form gas giants via gravitational collapse of high-density regions in the disc (Boss 1998, 2000; Mayer et al. 2004). Whilst it is possible that some of the observed planets formed via a gravitational instability scenario (and indeed also planetary mass companions to brown dwarfs. See e.g. the case of 2MASS1207B, Chauvin et al. 2005; Lodato, Delgado-Donate & Clarke 2005), the results of Matsumo et al. (2007) suggest that around 90 per cent of the observed extrasolar planets have a mass–semimajor axis relation consistent with the core accretion model and that the metallicity dependence of the distribution of these planets can only be explained using the core accretion model.

In a series of papers, Ida & Lin 2004a,b; Ida & Lin (2005, henceforth IL1, IL2; IL3) attempted to construct a semi-analytic model of the combined core accretion and migration process which would allow quantitative comparison to be made between the observed distribution of extrasolar planets and that predicted by the theoretical core accretion model. They concentrated on investigating the effect on the planetary mass–semimajor axis distribution of varying key physical parameters. These include: the surface density profile of the disc, the size and mass of the disc, the rate of disc clearance, the effect of stellar mass and luminosity as well as migration.

Figure 1. Mass–semimajor axis distribution of all currently known extrasolar planets.
by the stellar luminosity, \(L_\star\), such that (Hayashi 1981)

\[ a_{\text{isc}} = 2.7 \left( \frac{L_\star}{L_\odot} \right)^{1/2} \text{au}. \] (3)

The factors \((M_*/M_\odot)^n\) allow an investigation of the dependence of the disc mass on stellar mass (here we examine the cases \(n = 1\) and 2). The dissipation of the gaseous component is modelled as a simple exponential decay with characteristic time-scale, \(\tau_{\text{disc}}\), chosen to be \(\sim 10^6 - 10^7\) yr, as suggested by observations of the infrared excess in young stellar objects (Haisch, Lada & Lada 2001). The dust component is assumed to be time independent. Setting the parameters \(f_0 = 1\) and \(k = -3/2\) would give the minimum mass nebula model (Hayashi 1981). We investigate the effect of varying the absolute surface density of the disc by varying \(f_0\).

While IL1, IL2 and IL3 only consider the case where the surface density profile is a power law with index \(k = -3/2\), here we also investigate the effects of having \(k = -1\) (see Section 3.4.1 for motivation and discussion).

It should also be noted that the simple exponential decay of the gaseous disc is the only evolution of the disc to be considered. The solid component is taken to be constant and neither component is modelled self-consistently with the growing mass of the planet. A self-consistent disc processing and core growth model would clearly be more appropriate (e.g. Alibert et al. 2005), but would also be more computationally demanding, so we adopt the simplified approach in this investigation.

To investigate the formation of planets around brown dwarfs, it is clear that we need to extend the semi-analytic model down to \(M_* \lesssim 0.084 M_\odot\). However, the model depends on \(M_*\) in two main ways: (i) direct dependence on \(M_*\) via \(\Sigma \propto M_*^{1/2}\) and (ii) indirect dependence on \(M_*\), e.g. the dependence of \(a_{\text{isc}}\) and hence \(\Sigma_0\) on \(L_*\). The detailed effects of varying \(L_*\) are discussed below in Sections 2.3 and 3.4.3.

2.2 Core growth and gas accretion

We follow the prescription for core growth and gas accretion as presented in IL1, with a core accretion time-scale for a planet of mass \(M\) of (Kokubo & Ida 2002)

\[ \tau_c = 1.2 \times 10^7 \left( \frac{\Sigma_a}{10 \text{g cm}^{-2}} \right)^{-1/3} \left( \frac{a}{1 \text{au}} \right)^{5/3} \left( \frac{M}{M_\oplus} \right)^{1/3} \left( \frac{M_*}{M_\odot} \right)^{-1/6} \times \left( \frac{\Sigma_g}{2.4 \times 10^5 \text{g cm}^{-2}} \right)^{-2/5} \left( \frac{m}{10^{18} \text{g}} \right)^{2/15} \text{yr}, \] (4)

where \(m = 10^{18} \text{g}\) is the assumed mass of the planetesimals accreted by the planetary core.

Ikoma, Nakazawa & Emori (2000) find that once a critical core mass of

\[ M_{\text{crit}} = 10 \left( \frac{\dot{M}}{10^{-6} M_\oplus \text{yr}^{-1}} \right)^{0.25} M_\oplus \] (5)

has been reached, gas accretion can commence at a rate of

\[ \tau_{\kappa-H} = 10^{-10} \left( \frac{M}{M_\oplus} \right)^{-3} \text{yr}. \] (6)

Once a planet has grown to such as size that it opens a gap in the disc, the gas accretion rate is regulated by the rate at which the disc can process material and supply it across the gap to the planet. IL1 use a mass transfer rate given by the inferred rate for protostellar discs on T-Tauri stars (Hartmann et al. 1998; Calvet, Hartmann & Strom 2000)

\[ \dot{M}_{\text{disc}} = 10^{-3} M_\oplus \left( \frac{t}{\tau_{\text{disc}}} \right)^{-3/2} \text{yr}^{-1}. \] (7)

However, once the gap is opened, the accretion rate is reduced to values of the order of \(0.1 \times \dot{M}_{\text{disc}}\) (Artymowicz & Lubow 1996; Lubow & D’Angelo 2006). Here we have considered both the case described in equation (7), appropriately scaled down for brown dwarfs, and the case where accretion is further reduced due to gap opening, and found that this had little effect on the final distribution of planet masses and semimajor axes. Indeed, the details of gas accretion do not strongly affect our conclusions, since in most cases, as discussed below, we observe only very limited gas accretion in brown dwarf protoplanets.

We again acknowledge that these growth models are probably oversimplified. The form for \(\tau_c\) given in equation (4) neglects the effects of core migration on the accretion rate of planetesimals on to the protoplanetary core (e.g. Rice & Armitage 2003; McNeil, Duncan & Levison 2005). The treatment of gas accretion giving rise to the expressions for \(\dot{M}_{\text{disc}}\) and \(\tau_{\kappa-H}\) in equations (5 and 6) is also highly approximate, neglecting the effects of opacity (Adams, Bodenheimer & Laughlin 2005; Ikoma et al. 2000) and all the details evidenced by a numerical treatment of the problem (Pollack et al. 1996; Bryden, Lin & Ida 2000).

2.3 Luminosity evolution

The models of IL1, IL2 and IL3 treat the central star as a purely static object, with a fixed luminosity \(L_\star\) equal to that on main sequence, scaling such that \(L_\star/L_\odot = (M_*/M_\odot)^{5/4}\). For brown dwarfs, a constant-luminosity model would be completely inappropriate, as no constant luminosity is ever reached, and we need to take this into account.

We allow stellar luminosity evolution to take place, accounting for this using the pre-main-sequence evolution simulations of Tout, Livio & Bonnell (1999). Some sample evolutionary tracks are shown in Fig. 2. Compared to a static luminosity model, the net effect of the inclusion of luminosity evolution is to raise the luminosity at earlier times.

It should be noted that the core accretion model considered here, with an initial swarm of planetesimals of mass \(10^{18} \text{g}\), may have required \(\sim 10^4\) yr for the planetesimals to form, although theoretical models vary considerably (Weidenschilling & Cuzzi 1993; Supulver

![Figure 2. Luminosity evolution profiles from Tout et al. (1999) for (top to bottom) \(M_*/M_\odot = 1.5, 1.0, 0.6, 0.4, 0.2, 0.084\) and 0.05, respectively.](https://example.com/figure2.png)
et al. 1997; Rice et al. 2004, 2006). Hence we set the zero of time in our model to correspond to $10^4$ yr in Fig. 2.

2.4 Planetary migration

Protoplanetary cores embedded within a gaseous disc interact with the gas and are thus subject to gravitational torques which cause them to migrate away from their initial position. For small core masses the interaction is linear and the corresponding migration regime is called Type I, while for larger core masses (typically above $1 M_{\oplus}$, for planets forming around a solar type star), a gap is opened in the disc and the resulting migration regime is called Type II (Ward 1997).

Type I migration is important for a number of reasons. (i) It is well known (Papaloizou & Terquem 2006) that the inclusion of Type I migration in models of planet formation around solar-mass stars completely prevents the formation of massive gas giants (unless the disc mass is sufficiently small Thommes & Murray 2006), as all the planetary cores rapidly migrate into the central star, and thus Type I migration is generally neglected. However, simulations by Nelson & Papaloizou (2004) suggest that, in a turbulent disc, Type I migration may actually follow a random walk, potentially providing a mechanism to ameliorate this problem. (ii) It may help to explain the presence of intermediate-mass planets at small semimajor axes, by providing an additional migratory mechanism. In this paper, we have run models both including and neglecting the effect of standard (Ward 1997) Type I migration.

Type II migration occurs when the planet becomes massive enough to open a gap in the disc, the subsequent orbital evolution of the planet becoming firmly coupled to the viscous evolution of the disc (Lin & Papaloizou 1985). A gap is opened up when the planetary mass exceeds

\[
\frac{40 \nu}{\alpha^2 \Omega_K} M_\ast = 40 \alpha \left( \frac{c_s}{V_\kappa} \right)^2 M_\ast
\]

\[
= 3 \left( \frac{\alpha}{10^{-4}} \right) \left( \frac{a}{1 \text{ au}} \right)^{1/2} \left( \frac{L_*}{L_{\odot}} \right)^{1/4} M_{\odot},
\]

where we have used the \( \alpha \) parametrization for the effective viscosity, \( \nu = \alpha H_F \Omega_K \) of Shakura & Sunyaev (1973) and we use \( c_s^2 \propto T \).

However, hydrodynamical simulations (Lin & Papaloizou 1985; IL1) suggest that the onset of Type II migration occurs somewhat later, when the planet has grown to a larger mass. Type II migration is therefore taken to begin when the planet exceeds 10 times the gap opening mass.

In general, in any viscously evolving gaseous disc, the inner parts move in and accrete, while the outer parts move out and take up the angular momentum lost by the accretion material (Lynden-Bell & Pringle 1974). The direction of Type II migration is therefore determined by the position of the planetary core with respect to the radius which marks the transition from the inner to the outer disc, which we obtain from the appropriate self-similar solution of Lynden-Bell & Pringle (1974).

2.5 Methodology

Given the above semi-analytic prescription for protoplanetary growth, if we specify \( M_\ast, k, n, f_0, \tau_{\text{disc}} \) and the initial semimajor axis \( a_i \), we can then allow the planet to grow from an initial mass of \( 10^2 \) g. If we then perform a Monte Carlo simulation, allowing the parameters \( f_0, \tau_{\text{disc}} \) and \( c_i \) to vary, we can build up a picture of the potential for planet formation for a wide range of protoplanetary discs around a wide range of stars.

Because the initial size distribution is unknown for brown dwarf discs, the dissipation time-scale is also unknown. Attempts at estimating this time-scale have been made by Alexander & Armitage (2006) based on the \( M-M\) relation (Natta et al. 2004), and they argue that \( t \sim M_{\ast}^{-1} \). However, it is not clear whether such observational scalings really reflect some intrinsic properties of the initial protostellar disc population, nor how much are they affected by selection effects (Clarke & Pringle 2006), so we have kept the same time-scale for solar mass stars and brown dwarfs (but we do allow for a relatively large spread in time-scale, as suggested by Clarke (2007)). We therefore allow \( \tau_{\text{disc}} \) to be evenly distributed in logarithmic scale over \( 10^6-10^{10} \) yr.

We take \( f_0 \) to be lognormally distributed (centred on \( \log f_0 = 0 \) and with variance equal to 1) and then demand that the disc mass within 100 au be less than \( 0.35M_\ast \), to ensure that the disc is gravitationally stable out to 100 au. We thus end up with a distribution of disc masses such that the maximum disc/stellar mass fraction is \( <0.35 \), with an average significantly below this value. Note that Rodríguez et al. (2005) have observed protostellar disc masses as high as \( 0.35M_\ast \), indicating that the above upper limit is reasonable. Finally, we distribute the initial orbital semimajor axes evenly in log scale over \( 0.1-100 \) au and terminate all migration at \( 0.04 \) au.²

3 RESULTS

Before discussing our results on planet formation around brown dwarfs, we initially test our model by reproducing some of the main results of IL1, IL2 and IL3 for planets around solar-type stars. Our standard model assumes a disc profile with \( \Sigma \propto a^{-3/2} \) and \( f_0 \propto (M_\ast/M_{\odot})^2 \) and considers only Type II migration. We then extend our standard model down to the brown dwarf regime, adding in also the effect of luminosity evolution (Section 3.3). Finally, we investigate the impact of varying our main parameters on the potential for planet formation (Section 3.4).

3.1 Planet formation around solar mass stars

Fixing \( M_\ast = M_{\odot} \), we reproduce in Fig. 3 the mass–semimajor axis distribution as found in IL1, fig. 12c. The model uses our standard scalings such that \( k = -3/2 \) in \( \Sigma \propto (a/1 \text{ au})^k \) and the distribution of values of \( f_0 \) is such that the maximum disc mass is \( 0.35M_\ast \), with an average of 0.05\( M_\ast \). We use the following nomenclature, approximately equivalent to that of IL1, to label the planets:

(i) gaseous: \( M_\text{f} > 10M_\text{e} \);
(ii) intermediate: \( M_\text{f} < M_\text{g} < 10M_\text{e} \);
(iii) rocky: \( M_\text{g} < M_\text{e} \);

where \( M_\text{f} \) is the final gas mass and \( M_\text{e} \) is the core mass, such that the total planet mass is \( M = M_\text{g} + M_\text{e} \).

The model distribution presented in Fig. 3 faithfully reproduces that of IL1, fig. 12c: They both display the characteristic 'lanet desert' for \( a < 4 \) au and \( 10 < M < 100M_{\odot} \) and both have a maximum gas giant mass of \( \sim 3000M_{\odot} \). In addition, the distribution of planet types within the diagram is very similar (although the precise definition of planet-type-labels may differ slightly).

² While in general, for solar-type stars, this radius corresponds to the stellar magnetospheric radius, there is no strong reason for assuming that the termination radius in brown dwarf discs would be the same, but as we show later, we find little or no migration around brown dwarfs, so its exact value is effectively unimportant.
Planet formation around brown dwarfs

Note the high density of massive planets at $a = 0.04$ au caused by the inward Type II migration being arbitrarily halted at this distance.

Note also that below the $1 \, M_{\oplus}$ line, there is a vast tail of small-mass planets produced by the simulations; planets which grew only very slowly and/or were growing in a disc whose mass was very small.

3.2 Planet formation around intermediate-mass stars

The results of Fig. 3 are in good general agreement with observed extrasolar planets, the exception being the problematic observations of intermediate-mass planets at small semimajor axes. IL3 note that their results indicate that close-in, intermediate-mass planets cannot form around F, G and K dwarfs, but may form around M dwarfs and note that the formation of dynamically isolated low-mass planets around such stars would likely be attributable to Type I migration or the effect of sweeping secular or mean motion resonances.

In Fig. 4 we focus on the observed planetary systems around Gl-581 and Gliese 876, both of which have $M_\star \sim 0.3 \, M_\odot$. We thus plot the observed planets on the same scale as our numerical results, using models that do not include Type I migration. We consistently find it very difficult to produce close-in, intermediate-mass planets (such as Gl-581-c Udry et al. 2007), if we do not include some form of Type I migration in the process.

However, as mentioned above, the simple introduction of the fast Type I migration (Ward 1997) would generally preclude the formation of the high-mass ($\sim 100 \, M_{\oplus}$) planets observed in these systems, unless the migration rate is significantly slower than the standard analytic form (Nelson & Papaloizou 2004; Thommes & Murray 2006). It thus appear that, while some additional form of planetary core migration is needed in order to reproduce the above-mentioned observations, its rate should be substantially reduced with respect to the simple analytical estimates. In the rest of the paper we will therefore consider the two extreme cases in which we neglect completely Type I migration and in which we include standard Type I migration.

3.3 Planet formation around brown dwarfs

If we now allow the central stellar mass $M_\star$ to vary down below $0.084 \, M_\odot$, we can to investigate the potential for planet formation in the brown dwarf regime. As noted in Section 2.3, this extension requires the implementation of a luminosity evolution model for brown dwarfs.

In Fig. 5 we plot the mass–semimajor axis distribution resulting from our numerical simulation of the planet formation process around brown dwarfs of mass $0.05 \, M_\odot$ – note the change in scale compared to Fig. 3. We keep the standard disc profile of Section 3.1 and assume that the disc surface density scales as $M_\star^2$ (i.e. we assume $n = 2$ in equation 2). This effectively makes the $0.35 \, M_\star$ cut-off unnecessary, as the maximum disc mass is now $0.21 \, M_\star$. 

Figure 3. Planet masses $> 1 \, M_{\oplus}$ for $M_\star = M_\odot$ with static luminosity. The different symbols, respectively, label: open circles – ‘gaseous’ ($M_g > 10 \, M_c$); filled triangles – ‘intermediate composition’ ($10 \, M_c > M_g > M_c$); crosses – ‘rocky’ ($M_g < M_c$).

Figure 4. Planet masses $> 1 \, M_{\oplus}$ for $M_\star = 0.3 \, M_\odot$ with only Type II migration present. Labels are as in Fig. 3, with the addition of observed planets plotted as filled squares.

Figure 5. Planet masses for brown dwarf with $M_\star = 0.05 \, M_\odot$. Labels are as in Fig. 3.
masses unchanged from the standard model in

Changing the slope of the surface density profile at

maximum = −1, dotted lines \( k/\Sigma_1 \odot \) average C_1 model is to increase both the average and maximum planet masses, whilst \( M = 0.05 \) model leaves the average mass unchanged from the standard model, but suppresses the production of terrestrial planets. This result can be simply understood based on the fact that, for a given disc mass, with a shallower surface density profile the disc density is decreased at small radii and increased at large radii. Note that Raymond, Quinn & Lunine (2005) looked at terrestrial planet formation at small radii and found it was suppressed in discs with shallower profiles, in agreement with our result.

At \( M_\star = M_\odot \), moving to a \( k = -1 \) model leaves the average and maximum disc masses unchanged from the standard model in Section 3.1. However, a comparison between Fig. 6 (which shows the planet mass–semimajor axis distribution in this case) and Fig. 3 shows that for semimajor axes <10 au, the change in model gives very similar results for the distribution of Jupiter-mass planets, but suppresses the production of terrestrial planets. Fig. 7 shows the average and maximum planetary masses at different radii for the various cases. This shows that both the maximum and average planet mass inside 10 au (which are dominated by the gas giants) are similar for these models, but beyond 10 au, the effect of the \( k = -1 \) model is to increase both the average and maximum planet masses. This result can be simply understood based on the fact that, for a given disc mass, with a shallower surface density profile the disc density is decreased at small radii and increased at large radii.

Let us now turn to analyse the case of brown dwarf. Fig. 8 shows the planet mass–semimajor axis distribution for \( k = -1 \) (cf. Fig. 5). The effect of moving to a \( k = -1 \) model, similarly to the case of

higher stellar mass, is to suppress the formation of rocky planets. This is further evidenced in Fig. 9, which shows a comparison of the maximum and average planet mass at different radii for the two cases \( k = -1 \) (solid line) and \( k = -3/2 \) (dashed line). Unlike the case of solar-type stars, these histograms are now dominated by rocky planets, and indeed moving to a shallower surface density profiles results in a reduction of both the maximum and average mass planet formed, preventing the formation of any planets with masses greater than \( 1 M_\odot \).

3.4 Impact of parameter variation on planet formation

3.4.1 Surface density dependence on semimajor axis

It was assumed in Section 3.3 that the disc profile varied as \( \Sigma \propto a^{-3/2} \). In this section we explore the effect of having a shallower density profile, with \( \Sigma \propto a^{-1} \), while keeping the scaling with stellar mass as \( (M_\star/M_\odot)^2 \), and allowing only Type II migration. We find that at both solar mass and lower masses of \( M_\star = 0.05 M_\odot \), the effect of moving to \( k = -1 \) is significant.

At \( M_\star = M_\odot \), moving to a \( k = -1 \) model leaves the average and maximum disc masses unchanged from the standard model in Section 3.1. However, a comparison between Fig. 6 (which shows the planet mass–semimajor axis distribution in this case) and Fig. 3 shows that for semimajor axes <10 au, the change in model gives very similar results for the distribution of Jupiter-mass planets, but suppresses the production of terrestrial planets. Fig. 7 shows the average and maximum planetary masses at different radii for the various cases. This shows that both the maximum and average planet mass inside 10 au (which are dominated by the gas giants) are similar for these models, but beyond 10 au, the effect of the \( k = -1 \) model is to increase both the average and maximum planet masses. This result can be simply understood based on the fact that, for a given disc mass, with a shallower surface density profile the disc density is decreased at small radii and increased at large radii.

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3.4.2 Surface density dependence on stellar mass

Disc masses estimates for brown dwarfs are very uncertain and only known for a handful of objects (Scholz et al. 2006). In our standard
objects being able to form Earth-like planets. Indeed, planets with mass larger than 0.3 M⊕ are formed now in ≈10 per cent of the cases for k = −3/2 and in ≈2 per cent of the cases for k = −1.

In this case, the cores are growing faster, but still none of them grow quickly enough to start accreting gas before it dissipates. Thus, despite the increased potential for planet formation, no object is able to accrete a significant gaseous envelope, and the maximum planet mass is only slightly enhanced, the maximum now being 5 M⊕, in the most favourable case (i.e. k = −3/2).

The maximum planetary mass obtained is also slightly dependent on the upper limit on the disc mass in order for the disc to be gravitationally stable. For example, if we only allowed discs less massive than 10 per cent of the central brown dwarf mass, the maximum resultant planetary mass would be decreased to 1 M⊕ and it would be raised to 9 M⊕, with some very limited gas accretion occurring, if the discs are allowed to be half as massive as the brown dwarf.

Clearly, an important parameter in the determination of the final planet population is the disc surface density. For a given total disc mass, a more compact disc, with an outer radius significantly smaller than the 100 au assumed above, would have a larger surface density and therefore an enhanced chance of forming planets. We have thus rerun the most favourable case for planet formation (i.e. the one with n = 1 and k = −3/2), assuming the same distribution of total disc mass, but with significantly smaller disc sizes (this, in turn, implies increasing the factor f0 in equations 1 and 2). The results are shown in Fig. 12, for an outer disc radius Rout = 50 au (left-hand panel) and 20 au (right-hand panel). While the reduction of Rout to 50 au only results in a slightly increased maximum planet mass, in the case of Rout = 20 au we do see the appearance of a number of gas giants in a limited number of cases. However, we regard these cases as extremely unlikely, since they correspond to the upper tail of the disc mass distribution, with disc masses of the order of several Jupiter masses, confined within a region as small as 20 au.

3.4.3 Introduction of luminosity evolution

As mentioned above, the models that we use for planet formation around brown dwarfs also include the effect of the evolution of the (sub)stellar luminosity with time. The stellar luminosity has two main effects on our models: (i) it determines the temperature of the gas and (ii) it sets the location of the snow line, inside which the solid density is significantly reduced (we neglect here any other possible effect related to changes in the efficiency of angular momentum transport within the discs). Since there is little or no gas accretion on protoplanets around brown dwarfs in our model, and no planet becomes massive enough to open up a gap and start migrating, the first of the above effects actually has essentially no impact on the final outcome. The second effect is indeed present, but it turns out not to affect deeply the final results, and simulations performed without taking into account the luminosity evolution of the brown dwarfs only show relatively small differences.

3.4.4 Introduction of planetary migration

As IL3 have already noted, since low-mass cores do not undergo Type II migration, any detection of close-in super-Earths around low-mass stars, as in the case of Gl-581-c (a 5.5 M⊕ planet orbiting a 0.3 M⊙ star, Udry et al. 2007), would need the inclusion of other types if migration. In our models of planetary formation around brown dwarfs in which Type I migration is neglected, we always
predict a peak in the distribution at 1 au, irrespective of the other parameter variations in the model.

As discussed in Section 3.2, we now consider the addition of a form of Type I migration to our model. In particular, we consider the model for Type I migration as derived by Tanaka, Takeuchi & Ward (2002) for a three-dimensional isothermal gaseous disc, where the migration rate is of the form

$$\tau_I \approx 1 \times 10^5 \left( \frac{M}{M_\odot} \right)^{-1} \left( \frac{M_\star}{M_\odot} \right)^{3/2} \left( \frac{\Sigma_0}{2 \times 10^3 \text{ g cm}^{-2}} \right)^{-1} \text{ yr.}$$

We find that in general the effects of Type I migration around brown dwarfs are less significant than around solar type stars. This is mostly due to the fact that planetary cores around brown dwarfs grow at a much slower rate, and therefore the migration time-scale in this case is relatively longer. For the $n = 1, k = -3/2$ model (see Fig. 13), the maximum planet mass at $\sim 1$ au is very slightly reduced, whilst the average value at this radius (and the efficiency of the planet formation process) is reduced as a large number of the cores are swept into the inner boundary.

Since Type II migration effectively never occurs around brown dwarfs, any observational evidence of a secondary peak/excess in the radial distribution of planetary semimajor axes inside the main distribution peak at $\sim 1$ au would provide a clean, direct insight into the nature and extent of Type I migration.

4 DISCUSSION AND CONCLUSIONS

We have extended standard core accretion models for planet formation down to the brown dwarf regime and investigated the potential for planet formation in protoplanetary discs around objects with masses $\sim 0.05 M_\odot$. We looked at the impact on the predicted planetary mass–semimajor distribution of varying fundamental parameters, like the total disc mass and its radial distribution.

In line with previous results (IL1), at higher stellar masses ($M_\star \sim 1 M_\odot$, Fig. 3), we found that the full range of extant planet
Planet formation around brown dwarfs

Figure 12. Planet mass versus semimajor axis for $M_\star = 0.05 M_\odot$, $n = 1$ and $k = -3/2$, with outer disc radius equal to 50 au (left-hand panel) and 20 au (right-hand panel). While in the case of $R_{\text{out}} = 50$ au, the final distribution of planet mass is very similar to the case of $R_{\text{out}} = 100$ au, some gas giants appear in the case $R_{\text{out}} = 20$ au. These latter cases, however, correspond to the very unlikely case of a massive disc ($M_{\text{disc}} \gtrsim$ a few Jupiter masses) with a very small outer radius.

Figure 13. Effect of analytic Type I migration on brown dwarfs with $M_\star = 0.05 M_\odot$ and $n = 1$, $k = -3/2$. Labels are as in Fig. 3.

types is produced, including rocky and icy cores up to $10^2 M_\oplus$, rock and ice giants spanning a range $10^1$–$10^3 M_\oplus$ and gas giants extending from $10^2$ up to $10^6 M_\oplus$. In addition, we have found that a shallower surface density profile results in a reduced efficiency of the formation of rocky planets at radii $\lesssim 10$ au.

Our main result is the determination of the likelihood of planet formation around brown dwarfs, with $M_\sim 0.05 M_\odot$. Our main findings can be summarized as follows. (i) Giant planet formation is completely inhibited in this case. In none of our standard simulations did any planet accrete a significant gaseous envelope. This occurs despite the fact that in a few cases relatively massive cores do form (in principle massive enough to start runaway gas accretion), because such massive cores, when they form, only do so at a late time, when most of the gaseous component of the disc has dissipated. This means that Jupiter mass companions to brown dwarfs, as sometimes observed, have to be formed through a different – binary like – mechanism, i.e. either core or disc fragmentation. While this had already been discussed for very wide extremely low-mass binaries, like 2MASS1207 (Lodato et al. 2005), we can now extend this conclusion to closer binaries. (ii) The formation of Earth-like planets is possible even around brown dwarfs, and the maximum planet mass that we have found is $\approx 5 M_\oplus$. However, the likelihood of this process is critically dependent on what the typical disc masses are in this regime. In particular, if typical brown dwarf disc masses are of the order of a few Jupiter masses (which is consistent with a linear scaling of disc mass with stellar mass), then up to 10 per cent of brown dwarfs might possess planets with masses $> 0.3 M_\oplus$, while on the other hand if typical brown dwarf disc masses are only a fraction of a Jupiter mass (consistent with a quadratic scaling of disc mass with stellar mass), then even the formation of Earth-like planets would be essentially prohibited. We note that current estimates of brown dwarf disc masses are only available for a small number of objects and are very close to our boundary between planet-forming and non-planet-forming systems, with upper limits at the level of a few Jupiter mass (Scholz et al. 2006). In order to answer the question of the occurrence of planets around brown dwarfs it is therefore essential to improve the statistics and the accuracy of disc mass measurements in the very low-mass regime.

Finally, we note that the lack of any gas accretion in the planet formation process around brown dwarfs and the concomitant lack of any Type II migration means that the radial distribution of the planets will be determined purely by the initial mass distribution in the disc and the subsequent effects of Type I migration. Given that the underlying disc models tend to produce the most massive planets at $a \sim 1$ au, irrespective of the specific model, then any excess/secondary peak (or lack thereof) in the number of detected planets inside this radius would give clear evidence of the nature of Type I migration.

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REFERENCES

Adams F. C., Bodenheimer P., Laughlin G., 2005, Astron. Nachr., 326, 913
Alexander R. D., Armitage P. J., 2006, ApJ, 639, L83
Alibert Y., Mordasini C., Benz W., Winnisoerffer C., 2005, A&A, 434, 343
Apaï D., Pascucci I., Bouwman J., Natta A., Henning T., Dullemond C. P., 2005, Sci, 310, 834
Artymowicz P., Lubow S. H., 1996, ApJ, 467, L77
Beer M. E., King A. R., Livio M., Pringle J. E., 2004, MNRAS, 354, 763
Bodenheimer P., Pollack J. B., 1986, Icarus, 67, 391
Bodenheimer P., Pollack J. B., 1986, Icarus, 67, 391
Boss A. P., 1998, Nat, 393, 141
Bosch A. P., 2000, ApJ, 536, L101
Bryden G., Lin D. N. C., Ida S., 2000, ApJ, 544, 481
Calvet N., Hartmann L., Strom S. E., 2000, Protostars and Planets IV. Univ. of Arizona Press, Tucson, p. 377
Chauvin G., Lagrange A.-M., Dumas C., Zuckerman B., Mouillet D., Song I., Beuzit J.-L., Lowrance P., 2005, A&A, 438, L25
Clarke C. J., 2007, MNRAS, 376, 1350
Clarke C. J., Pringle J. E., 2006, MNRAS, 370, L10
Crafts K. E., Jr, Lada E. A., Lada C. J., 2001, ApJ, 553, L153
Hartmann L., Calvet N., Gullbring E., D’Alessio P., 1998, ApJ, 495, 385
Hayashi C., 1981, Prog. Theor. Phys. Suppl., 70, 35
Ida S., Lin D. N. C., 2004a, ApJ, 604, 388 (IL1)
Ida S., Lin D. N. C., 2004b, ApJ, 616, 567 (IL2)
Ida S., Lin D. N. C., 2005, ApJ, 626, 1045 (IL3)
Ikoma M., Nakazawa K., Emori H., 2000, ApJ, 537, 1013
Kokubo E., Ida S., 2002, ApJ, 581, 666
Laughlin G., Bodenheimer P., Adams F. C., 2004, ApJ, 612, L73
Lin D. N. C., Papaloizou J., 1985, in Black D. C., Matthews M. S., eds, Protostars and Planets II. Univ. of Arizona Press, Tucson, p. 981
Lodato G., Delgado-Donate E., Clarke C. J., 2005, MNRAS, 364, L91
Lubow S. H., D’Angelo G., 2006, ApJ, 641, 526
Lubman K. L., et al., 2005, ApJ, 631, L69
Lynden-Bell D., Pringle J. E., 1974, MNRAS, 168, 603
McNeil D., Duncan M., Levison H. F., 2005, AJ, 130, 2884
Matsuo T., Shibai H., Ootsubo T., Tamura M., 2007, ApJ, 662, 1282
Mayer L., Quinn T., Wadsley J., Stadel J., 2004, ApJ, 609, 1045
Mizuno H., 1980, Prog. Theor. Phys., 64, 544
Natta A., Testi L., Muzerolle J., Randich S., Comerón F., Persi P., 2004, A&A, 424, 603
Nelson R. P., Papaloizou J. C. B., 2004, MNRAS, 350, 849
Papaloizou J. C. B., Nelson R. P., 2005, A&A, 433, 247
Papaloizou J. C. B., Terquem C., 2006, Rep. Prog. Phys., 69, 119
Pollack J. B., Hubickyj O., Bodenheimer P., Lissauer J. J., Podolak M., Greenzweig Y., 1996, Icarus, 124, 62
Raymond S. N., Quinn T., Lunine J. I., 2005, ApJ, 632, 670
Rice W. K. M., Armitage P. J., 2003, ApJ, 598, L55
Rice W. K. M., Lodato G., Pringle J. E., Armitage P. J., Bonnial I. A., 2004, MNRAS, 355, 543
Papaloizou J. C. B., Terquem C., 2007, ApJ, 654, 1110
Thommes E. W., Murray N., 2006, ApJ, 644, 1214
Tout C. A., Livio M., Bonnial I. A., 1999, MNRAS, 310, 360
Udry S. et al., 2007, A&A, 469, 43
Ward W. R., 1997, Icarus, 126, 261
Weidenschilling S. J., Cuzzi J. N., 1993, in Levy E. H., Lunine J. I., eds, Protostars and Planets III. Univ. of Arizona Press, Tucson, p. 1031
Wetherill G. W., 1980, ARA&A, 18, 77

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