

# Substellar companions and isolated planetary-mass objects from protostellar disc fragmentation

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## ABSTRACT

Self-gravitating protostellar discs are unstable to fragmentation if the gas can cool on a time-scale that is short compared with the orbital period. We use a combination of hydrodynamic simulations and  $N$ -body orbit integrations to study the long-term evolution of a fragmenting disc with an initial mass ratio to the star of  $M_{\text{disc}}/M_* = 0.1$ . For a disc that is initially unstable across a range of radii, a combination of collapse and subsequent accretion yields substellar objects with a spectrum of masses extending (for a Solar-mass star) up to  $\approx 0.01 M_{\odot}$ . Subsequent gravitational evolution ejects most of the lower mass objects within a few million years, leaving a small number of very massive planets or brown dwarfs in eccentric orbits at moderately small radii. Based on these results, systems such as HD 168443 – in which the companions are close to or beyond the deuterium burning limit – appear to be the best candidates to have formed via gravitational instability. If massive substellar companions originate from disc fragmentation, while lower-mass planetary companions originate from core accretion, the metallicity distribution of stars which host massive substellar companions at radii of  $\sim 1$  au should differ from that of stars with lower mass planetary companions.

**Key words:** accretion, accretion discs – planets and satellites: formation – stars: low-mass, brown dwarfs – planetary systems: protoplanetary discs – stars: pre-main sequence.

## 1 INTRODUCTION

Protostellar discs formed during the early phases of star formation can be cool and massive enough that self-gravity plays an important role in their evolution (Cassen & Moosman 1981; Lin & Pringle 1990; Bate, Bonnell & Bromm 2003, though see also Krasnopolsky & Königl 2002). Self-gravity leads to the formation of spiral structure, which in turn can drive angular momentum transport and accretion (Adams, Ruden & Shu 1989; Laughlin & Bodenheimer 1994; Laughlin & Rozyczka 1996; Laughlin, Korchagin & Adams 1997; Pickett et al. 1998; Nelson et al. 1998; Nelson, Benz & Ruzmaikina 2000). Alternatively, a sufficiently unstable disc may fragment into bound objects, which in a protostellar disc would have planetary or brown dwarf masses.

Whether a gravitationally unstable gas disc will fragment or stably transport angular momentum depends upon the efficiency of radiative cooling from the disc's surfaces (Pickett et al. 2000, 2003; Gammie 2001; Boss 2001, 2002b; Rice et al. 2003). Efficient disc

cooling – on a time-scale comparable to the orbital period – robs transient overdensities of pressure support and allows them to collapse into bound substellar objects. Quantitatively, Gammie (2001) showed using analytic considerations and local numerical simulations that fragmentation occurs if the local cooling time is  $\lesssim 3\Omega_K^{-1}$ , where  $\Omega_K$  is the Keplerian angular velocity. A similar fragmentation boundary was obtained in global simulations of cooling, self-gravitating discs (Rice et al. 2003). For discs with mass substantially smaller than that of the star, fragmentation leads immediately to the formation of a number of substellar objects (Mayer et al. 2002; Rice et al. 2003).

The conditions in the outer regions of protostellar discs at early epochs are not well known, so it is uncertain whether the rapid cooling required for fragmentation occurs frequently, rarely, or never. Here, we assume that the conditions in the disc are such that fragmentation occurs, and investigate the subsequent evolution of the system, which will initially comprise a number of substellar objects embedded within the remaining disc gas. Qualitatively, it is fairly clear how such a system evolves post-fragmentation. The gas will be accreted – either by the planets or by the star – while gravitational interactions amongst the planets or brown dwarfs will eject most of

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them while leaving a handful of survivors on eccentric orbits (e.g. Armitage & Hansen 1999). Numerical integrations of unstable multiple planet systems (Lin & Ida 1997; Papaloizou & Terquem 2001; Terquem & Papaloizou 2002; Adams & Laughlin 2003) show that the final planetary systems can be strikingly similar to some of those observed in radial velocity surveys (Marcy & Butler 1998), though extremely close in planets such as that orbiting 51 Peg (Mayor & Queloz 1995) almost certainly require additional migration mechanisms (Lin, Bodenheimer & Richardson 1996).

In this Letter, we study the long-term evolution of a fragmenting protostellar disc using a two-step approach. We first extend our previous hydrodynamic simulation of a fragmenting disc (Rice et al. 2003) until most of the gas has been swept up and incorporated into bound objects. This allows us to estimate the mass spectrum of substellar objects produced as a consequence of disc fragmentation. We then isolate the population of substellar objects, and evolve them under purely gravitational forces (using methods similar to Papaloizou & Terquem 2001, and obtaining comparable results) until a stable final system is obtained. In doing this we are able to study self-consistently the formation and evolution of a planetary system.

## 2 METHODS

We use smoothed particle hydrodynamics (SPH) (e.g. Benz 1990; Monaghan 1992) to consider a  $0.1\text{-}M_{\odot}$  disc, with a radius of 50 au, surrounding a  $1\text{-}M_{\odot}$  star. The disc is modelled, in three dimensions, using 250 000 SPH particles, while the star is represented by a sink particle on to which gas particles may accrete if they approach to within an accretion radius of 0.5 au (Bate, Bonnell & Price 1995). Disc self-gravity is included and a tree is used to determine gravitational forces between gas particles and between gas particles and point masses. The gravitational force between point masses is computed directly.

The disc temperature ( $T$ ) and surface density ( $\Sigma$ ) are taken, initially, to have radial profiles of  $T \propto r^{-0.5}$  and  $\Sigma \propto r^{-1}$ . The temperature is normalized to give a minimum Toomre (1964)  $Q$  parameter of 2 at the outer disc edge. Since the disc stability depends on both heating and cooling we use an adiabatic equation of state, with adiabatic index  $\gamma = 5/3$ , and impose a radially dependent cooling time. The imposed cooling time has the form  $t_{\text{cool}} = 3\Omega^{-1}$ , where  $\Omega$  is the angular frequency. The motivation for choosing this cooling time is provided by both local and global simulations (Gammie 2001; Rice et al. 2003) which show that a self-gravitating accretion disc will fragment into gravitationally bound objects for  $t_{\text{cool}} \leq 3\Omega^{-1}$ . The form of this imposed cooling time can be related, at least approximately, to the real physics of an accretion disc. For an optically thick accretion disc in equilibrium it can be shown (e.g. Pringle 1981) that the cooling time is given by

$$t_{\text{cool}} = \frac{4}{9\gamma(\gamma - 1)} \frac{1}{\alpha\Omega} \quad (1)$$

where  $\gamma$  is the adiabatic index, and  $\alpha$  is the Shakura & Sunyaev (1973) viscosity parameter.

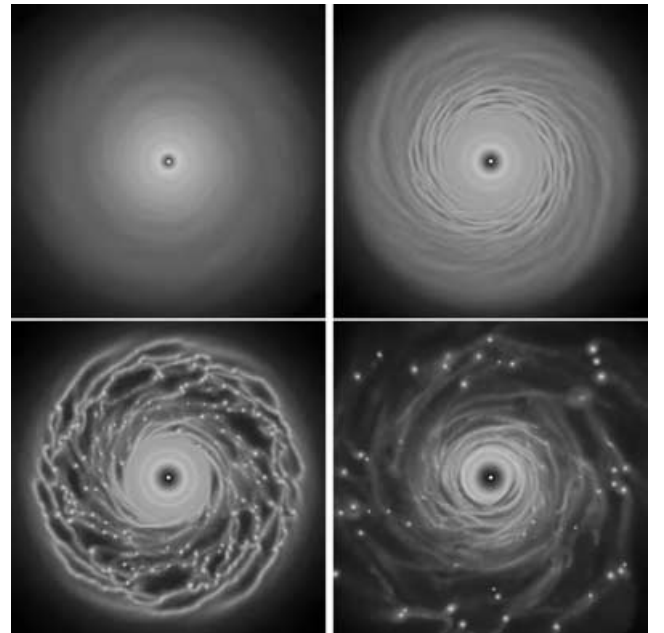
The fragmentation of the disc produces gravitationally bound regions with densities significantly higher than the initial disc density. Continuing to follow the internal evolution of these fragments – which cannot be done reliably in any case – tends to slow the code down significantly. To continue simulating the fragmenting disc, we allow sufficiently dense regions, containing  $\sim 50$  SPH particles, that are gravitationally bound to be converted into sink particles (Bate et al. 1995). Since we are simulating a  $0.1\text{-}M_{\odot}$  disc using 250 000

SPH particles, we have a minimum sink particle mass of  $\sim 2 \times 10^{-5} M_{\odot}$ . Gas particles may accrete on to the sink particles if they approach to within a predefined accretion radius. The accretion radius is taken to be 0.02 au and is approximately the Hill radius of a minimum mass sink particle at 1 au. We are therefore able not only to simulate the fragmentation of the disc, but also to continue following the subsequent growth of the gravitationally bound fragments.

## 3 DISC EVOLUTION

Fig. 1 shows the surface density structure of the gaseous protoplanetary disc at four different times. All four figures have  $x$  and  $y$  axes that run from  $-60$  au to  $60$  au and have the star in the centre. At early times ( $t = 140$  yr), the surface density is reasonably smooth and unstructured. As the disc evolves ( $t = 420$  yr) spiral structures that are due to the growth of the gravitational instability are evident. Since the cooling time in this particular simulation is short, heating through the growth of the gravitational instability is unable to balance the imposed cooling without the disc fragmenting into gravitationally bound objects. After 644 yr there is clear evidence of fragmentation with a number of high density regions present in the disc. After 956 yr, there is still fragmentation of the outer regions of the disc.

We continue to evolve the hydrodynamical simulation for a further 10640 yr, at which point 83 substellar objects have formed through fragmentation of the disc gas. All 83 objects have been converted into point masses (Bate et al. 1995), and 87 per cent of the gas (217362 SPH particles) has been accreted on to either



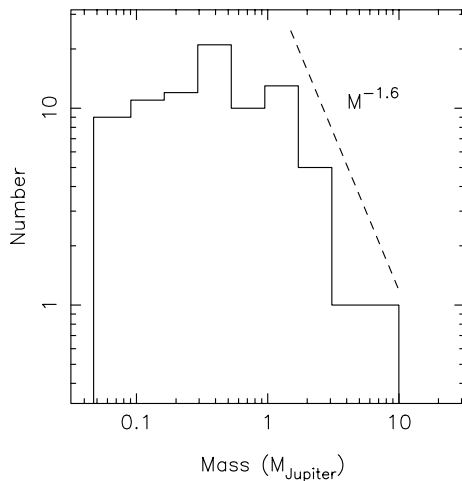
**Figure 1.** Disc surface densities at four different times during the hydrodynamical simulation. After 140 yr (top left) the disc is still reasonably smooth and unstructured. As the disc evolves ( $t = 420$  yr – top right) spiral structures, owing to the growth of the gravitational instability, are evident. The low cooling time means that heating through the growth of the gravitational instability is unable to balance the imposed cooling without the disc fragmenting. Gravitationally bound fragments are clearly present after 644 yr (bottom left). The bottom right figure shows the disc after 956 yr and shows fragmentation taking place in the outer regions of the disc while the inner fragments have been converted into point masses.

these substellar objects or the central star. The central star has increased in mass from 1 to  $1.011 M_{\odot}$ , an accretion rate of  $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$ . At this stage, we remove the remaining gas and evolve the 84 point masses (central star plus 83 substellar objects) using an  $N$ -body code. We primarily use NBODY3 (Aarseth 1999), which is fast and uses chain regularization to treat close encounters and binary systems efficiently, but we also compare our results using HNBODY (Rauch & Hamilton 2002) and MERCURY (Chambers 1999).

An obvious limitation of our simulations is that the derived fragmentation time-scale (around  $10^4$  yr) is significantly shorter than the time-scale on which the disc is assembled. Unless instability in the disc is radiatively triggered, for example by a sudden change in the illumination of the outer disc by the central star, this disparity in time-scales implies that disc fragmentation should properly be studied within the larger context of the star and disc formation process. This is extremely difficult. Although simulations of star formation within molecular clouds (Watkins et al. 1998; Bate, Bonnell & Bromm 2002) already support the view that brown dwarfs may form within protostellar discs, they do not yet have the resolution or treatment of the thermal physics to follow the fragmentation process in the same detail as is possible for an isolated disc.

#### 4 SUBSTELLAR MASS FUNCTION

Fig. 2 shows the substellar initial mass function (IMF) immediately following disc fragmentation (i.e. prior to subsequent modification by planet–planet and planet–star collisions). Between  $\sim 3 \times 10^{-2} M_{\text{Jupiter}}$  and  $\sim 1 M_{\text{Jupiter}}$ , the IMF is reasonably flat with  $\sim 60$  substellar objects having masses less than  $1 M_{\text{Jupiter}}$ . There is a turnover at  $\sim 1 M_{\text{Jupiter}}$  above which the mass function falls off steeply with  $dN/d \log M \propto M^{-1.6}$ . In this particular case we have a maximum mass of  $7.8 M_{\text{Jupiter}}$ . The slope of the IMF cut-off, and the maximum mass, are likely to depend on the disc properties. Although we have not performed any kind of parameter survey, a second simulation, with the same total disc mass but a steeper surface density profile, produced objects that were slightly more massive. The maximum mass is also likely to depend on the disc mass. Our simulation is essentially scale-free. We could, equally well, have assumed a stellar mass of  $M_* = 2 M_{\odot}$ , giving a disc mass of  $0.2 M_{\odot}$  and increasing the masses of the substellar objects by a factor of 2. The



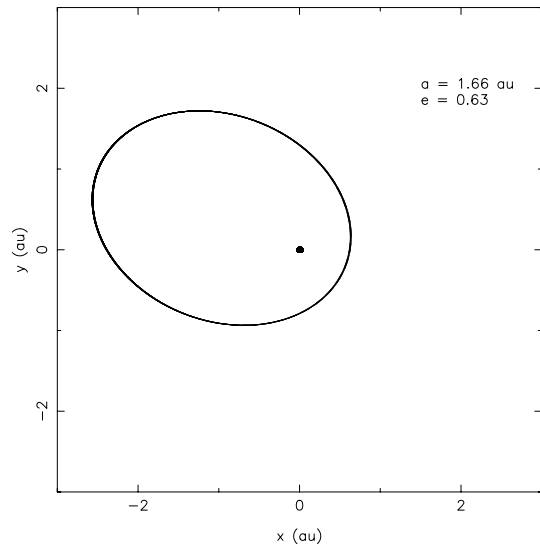
**Figure 2.** Substellar initial mass function (IMF). There is a turnover at  $\sim 10^{-3} M_{\odot}$  with a slope, above  $10^{-3} M_{\odot}$ , of  $dN/d \log M \propto M^{-1.6}$  and a maximum mass of  $7.8 M_{\text{Jupiter}}$ .

maximum mass would then be  $15.6 M_{\text{Jupiter}}$ . Similarly, simulations by Boss (1998) show that a more massive disc around a star with the same mass ( $1 M_{\odot}$ ) also result in substellar objects with masses in excess of  $10 M_{\text{Jupiter}}$ . Since only reasonably massive discs will become sufficiently gravitationally unstable for fragmentation, it seems likely that the maximum mass of objects produced in discs via fragmentation would also be reasonably high ( $\sim 10 M_{\text{Jupiter}}$  or greater).

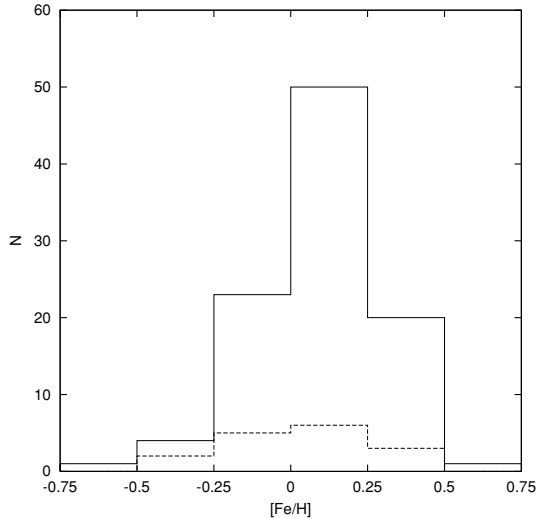
#### 5 N-BODY EVOLUTION

After 11 618 yr, 87 per cent of the disc gas has been accreted on to the 83 substellar objects, or on to the central star. At this stage we remove the remaining gas and evolve the 84 point masses (central star plus 83 substellar objects) in an  $N$ -body fashion using NBODY3 (Aarseth 1999), which we normalize in the standard way by setting the radius and total mass to 1. The velocities are then normalized to recover the original virial ratio. The system is evolved for 21 Myr. Of the 83 substellar objects, 74 are ejected from the system and would become, unless captured by another system, free-floating planets (e.g. Lin & Ida 1997; Papaloizou & Terquem 2001; Smith & Bonnell 2001; Terquem & Papaloizou 2002; Hurley & Shara 2002). Of these 74 ejected objects, 19 have masses in excess of  $1 M_{\text{Jupiter}}$ , with the most massive having a mass of  $3.6 M_{\text{Jupiter}}$ .

Most of the substellar objects that remain bound have large semi-major axes ( $a > 500$  au) and eccentricities, and (depending on the stellar environment) would probably be removed by encounters with other stars. If, however, they were able to remain bound, they would be good candidates for direct imaging surveys for extrasolar planets, either during the late pre-main-sequence phase, around main-sequence stars, or once the central star has evolved into a white dwarf (Burleigh, Clarke & Hodgkin 2002). Two of the objects, however, are left on orbits close to the central star. One of these objects has an orbit that approaches to within a solar radius and so would collide with the star were the stellar radius included in the calculation. The other, which was the most massive substellar object ( $7.8 M_{\text{Jupiter}}$ ), had a final semimajor axis of 1.66 au, and an eccentricity of 0.63. These orbital parameters fall well within the range of observed values (Marcy & Butler 2000). Fig. 3 shows the orbit of this object. It



**Figure 3.** Orbit of the only remaining substellar object within 10 au. This is the most massive object, with a mass of  $7.4 M_{\text{Jupiter}}$ , and has a semimajor axis of 1.66 au and an eccentricity of 0.63.



**Figure 4.** Metallicity distribution for all planet-bearing stars (solid line), compared with those that have at least one companion with a mass in excess of  $5M_{\text{Jupiter}}$ , a semimajor axis greater than 0.1, and an eccentricity greater than 0.2 (dashed line). It does appear that the systems preselected on the basis of companion mass, semimajor axis and eccentricity are not as metal-rich as planet-bearing systems in general.

therefore seems that the evolution of a system in which disc fragmentation produces planetary mass objects, can result in a final state consistent with that currently observed.

The same calculation was also performed using `HNBODY` (Rauch & Hamilton 2002) and `MERCURY` (Chambers 1999), in both cases using the Burlisch–Stoer integrator provided with those codes. Comparable results were obtained from all three codes, provided that each was set to model strictly point-mass evolution. In this limit, the most massive ( $7.8M_{\text{Jupiter}}$ ) object was left in an orbit with a semimajor axis of between 1.6 au and 1.8 au, and an eccentricity in excess of 0.3. We note, however, that this final result is sensitive to close encounters between planets and between planets and the star. Rerunning the integration, using `MERCURY`, with reasonable values for the planetary density, and a stellar radius of  $1 R_{\odot}$ , we obtained a final orbit for the most massive object that was significantly wider ( $\sim 10$  au). This may be due to the reduced population of low-mass scatterers, many of which collided with the central star.

As a further test of these  $N$ -body results, we performed 10  $N$ -body simulations in which we randomized the positions of the 83 substellar objects, keeping the energy and angular momentum of each body constant. In 9 of the 10 cases, the results were consistent with the original  $N$ -body calculation. The  $7.8M_{\text{Jupiter}}$  body was left in an orbit with semimajor axis between 1.49 and 1.81 au, and eccentricity between 0.28 and 0.82. The exception was a case in which the  $7.8M_{\text{Jupiter}}$  body was ultimately ejected from the system while two less massive objects merged with the central star. In general, however, it does seem that the final state will be one in which the most massive body remains bound to the star with a modest semimajor axis and a reasonably large eccentricity ( $\sim 0.3$  or greater).

## 6 DISCUSSION

We have used global hydrodynamic simulations to follow the long term fate of a self-gravitating disc that is unstable to fragmentation (according to the results of Gammie 2001; Rice et al. 2003). For our choice of parameters (disc radius of 50 au, disc mass  $0.1 M_{\odot}$

around a  $1 M_{\odot}$  star), we find that fragmentation is largely complete within about  $10^4$  yr. By this epoch, 87 per cent of the disc gas had been accreted, and in excess of 80 substellar objects formed. The substellar IMF immediately following fragmentation is found to be roughly flat below a Jupiter mass, with a steep fall off ( $dN/d \log M \propto M^{-1.6}$ ) at higher masses. For our specific simulation, the most massive object had a mass of  $7.8M_{\text{Jupiter}}$ . Since gravitationally unstable discs are likely to have at least as much mass as that simulated here, it is likely that the most massive object formed as a result of gravitational instability will typically be either a very massive planet or a low-mass brown dwarf.

To continue evolving the system toward an observable epoch, we removed the (small) residual gas fraction and integrated the multiple planet system using  $N$ -body methods. Generically, one expects that the most massive object will often survive as a bound planet or brown dwarf, while most of the lower mass objects are ejected. This was indeed the outcome. The  $7.8M_{\text{Jupiter}}$  planet ended up in an orbit with a semimajor axis of 1.5–1.8 au and a large eccentricity; 7 lower mass planets were left as distant companions ( $a > \sim 500$  au); and most of the rest were ejected. These results are consistent with those of Papaloizou & Terquem (2001) and Adams & Laughlin (2003). They suggest that the extrasolar planetary systems most likely to be the products of gravitational instability are those in which one or two very massive planets (or low mass brown dwarfs) orbit at modest radii in highly eccentric orbits. HD 168443 represents an observed example of such a system (Marcy et al. 2001).

For observations, our results have three main implications. First, they suggest that gravitational instability, if it occurs, is likely to populate preferentially the very high-mass end of the planetary mass function. There is no reason to expect that the metallicity dependence of stars hosting massive companions formed via disc fragmentation would be the same as that for stars with lower-mass planetary companions originating from core accretion (Boss 2002a). It is now generally accepted that stars with planetary companions are generally metal-rich (Laughlin 2000; Santos, Israelian & Mayor 2001; Murray & Chaboyer 2002; Santos et al. 2003; Fischer & Valenti 2003). Using the currently available data base of known extrasolar planets (see <http://cfa-www.harvard.edu/planets/cat1.html>), we have compared the metallicity distribution for all planet bearing stars with that for systems in which there is a companion having a mass in excess of  $5M_{\text{Jupiter}}$ , a semimajor axis in excess of 0.1 au, and an eccentricity greater than 0.2. The result is shown in Fig. 4 and illustrates that the systems chosen using the above criteria (dashed line) do not appear to be as metal-rich as planet-bearing stars in general (solid line). Although this is preliminary and inconclusive, a *different* metallicity distribution for stars hosting the most massive planets, compared with stars hosting lower-mass companions, would provide circumstantial evidence that massive planets formed from disc fragmentation. Secondly, our integrations indicate that additional massive planets could be present at very large orbital radii in systems with the most massive extrasolar planets or close brown dwarf companions. Although these distant companions are vulnerable to disruption by encounters with passing stars, they are potentially detectable via direct imaging. Finally, we find that a significant fraction of the initial gas content of the disc can end up being ejected from the system in the form of isolated planetary-mass objects. Constraining the numbers – and especially the masses – of free-floating substellar objects in star-forming regions is not straightforward for the young objects of relevance here (e.g. Baraffe et al. 2002). However, an absence (or small number) of free-floating sub-Jupiter mass planets would provide a new way to limit the fraction of stars with

discs that underwent large-scale gravitational collapse of the sort simulated here.

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