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Numerical results on low mass star and brown dwarf multiplicity

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Abstract. We have undertaken a series of hydrodynamic + N-body simulations in order to explore the properties of young stars. Our results suggest that the IMF may be sensitive to environment in its substellar region, with more brown dwarfs being formed where clusters are denser or more compact. We find that multiple stars are a natural outcome of collapsing turbulent flows, with a high incidence of $N > 2$ multiples. We find a positive correlation of multiplicity with primary mass but a companion frequency that decreases with age. Binary brown dwarfs are rarely formed, in conflict with observations. Brown dwarfs as companions are predominantly found orbiting binaries or triples at large separations.

Key words. Star Formation – Binary Stars – Initial Mass Function – Brown Dwarfs

1. Introduction and Motivation

Most stars are known to be members of binary or even higher-order multiple systems (Duquennoy & Mayor 1991). Thus, any good star formation theory must be a theory of (at least) binary star formation. Currently we can hope to do more than produce multiple stars by imposing some multi-armed instability on a collapsing core. Turbulent initial conditions, for example, allow star formation to be triggered in a less predictable way (e.g. Bate et al. 2003). In addition, it has become computationally affordable to study the statistics of star pairing beyond simple N-body integration (Delgado-Donate et al. 2003). These two steps forward have made it possible to perform calculations which both resolve the fragmentation and collapse of molecular clouds (accounting fully for the hydrodynamics) and which produce a statistically significant number of stellar systems, thus opening the door to a direct comparison with observations of the IMF and multiplicity properties of young stars (Delgado-Donate et al. 2004a,b). In this paper we present the results from the first hydrodynamic calculations to produce a statistically significant number of *stable* multiple systems in the separation range $1 - 1000$ AU. We will concentrate our attention mostly on those aspects pertaining to the multiplicity properties of stars and brown dwarfs.

2. Numerical Scheme and Initial Conditions

We have performed 10 calculations of small fragmenting clouds, using the SPH technique to solve the fluid equations. Our version of

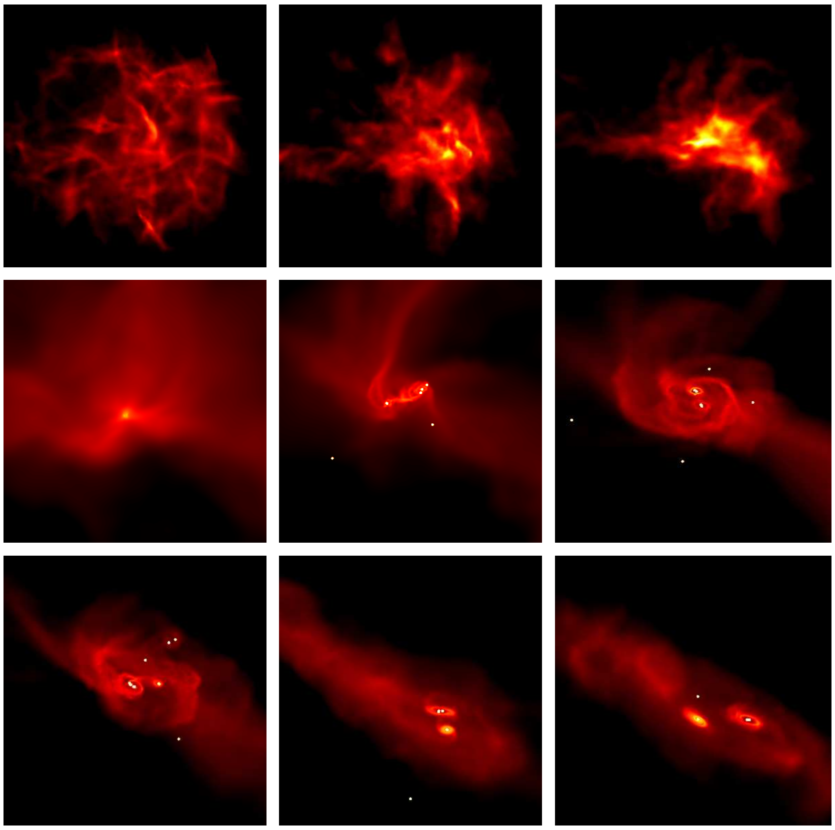

Fig. 1. Evolution of a typical $\alpha = -3$ cloud

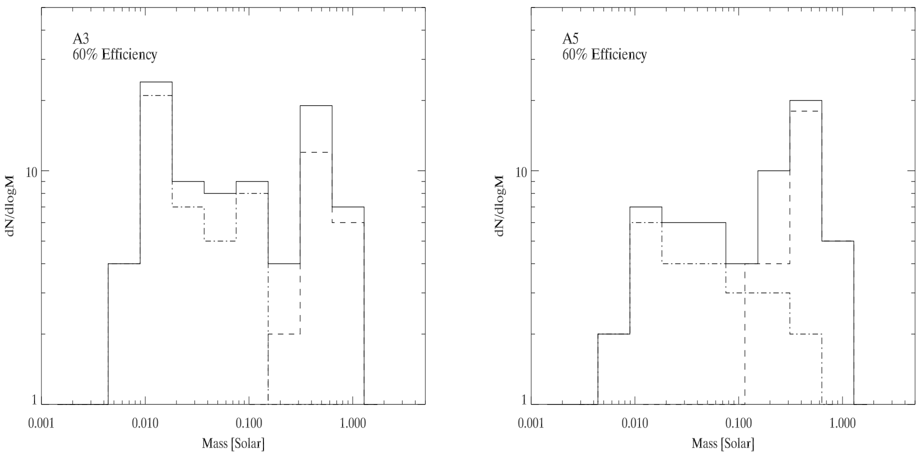

Fig. 2. Mass Functions. Left, $\alpha = -3$; right $\alpha = -5$. The solid line includes all objects

SPH uses individual smoothing lengths and timesteps. Sink particles replace bound blobs after a critical density is reached (Bate et al. 1995). We apply standard viscosity with $\alpha = 1$ and $\beta = 2$, and a binary tree to find nearest neighbours and calculate self-gravity. The opacity limit for fragmentation (see e.g. Low & Lynden-Bell 1976) is modeled using a barotropic equation of state $p \propto \rho^{\gamma}$, so that the gas is isothermal at low densities ($\leq 10^{-13}$ g cm^{-3}) and polytropic with $\gamma = 5/3$ at higher densities.

Each cloud is initially spherical, has radius of $\approx 10^4$ AU, 5 $M_\odot$ and density and temperature of $\approx 10^{-18}$ g cm^{-3} and 10 K respectively. These values for ρ and T imply an initial Jeans mass of ≈ 0.5 $M_\odot$, typical of molecular clouds. We follow Bate & Burkert (1997) and use at least 100 SPH particles to resolve the minimum Jeans mass that can occur in the calculation (a few M_J), thus resulting in a total of 3.5×10^5 SPH particles.

We impose a random 'turbulent' velocity field on each calculation, defined by a power-law spectrum. The power-law exponent α is set to -5 in 5 of the simulations and to -3 in the other half (the former index corresponds to shifting the balance to having even more power in large scales than in the $\alpha = -3$ case). These values of α bracket the observed uncertainties in Larson's *velocity dispersion-size* relationship. The velocity field is normalised so that there is equipartition of kinetic and gravitational energy initially. The velocity field is allowed to decay freely. We are imposing a parameterised initial velocity field which approximately reproduces observed bulk motions in molecular clouds (often described as 'turbulent' motions) but this term ('turbulence') should not be taken to imply that we are modeling what a fluid dynamicist would recognise as fully developed turbulence.

The gravitational force between sink particles is smoothed at short distances. Therefore, binaries with semi-major axis $\lesssim$ 1 AU cannot form. A more detailed description of the code and the initial conditions can be found in Delgado-Donate et al. (2004a).

The calculations are run until star formation no longer occurs (see Figure 1 for snapshots of an $\alpha = -3$ calculation). This translates into $\approx$ 0.5 Myr of time or 60% efficiency in terms of the amount of gas converted into stars. At this point the remaining gas is removed and the stellar system is evolved as a pure N-body system, using NBODY2 (Aarseth 1999). After 10 Myr we find that 95% of the multiples have decayed into stable configurations (using the criterion by Eggleton & Kiseleva 1995), and we stop the integration. The calculations have been performed using the United Kingdom Astrophysical Fluids Facility (UKAFF).

3. Results: IMF

Overall, the calculations produce 145 stars and brown dwarfs after 0.5 Myr, an average of $\approx$ 15 objects per calculation (a number comparable to the initial number of Jeans masses). For the vast majority of objects, the accretion rates are very low and so one expects the objects masses to be representative of their *final* masses. Overall, 40% of the objects are brown dwarfs and 60% stars. But the percentage changes depending on the initial value of the turbulent spectrum slope. A higher fraction, nearly 50% of the objects in the $\alpha = -3$ calculations are brown dwarfs for $\approx$ 30% in the $\alpha = -5$ case.

The MFs derived from the two sets of calculations can be seen in Figure 2. A KS test confirms that the MFs are different at the substellar regime, at a 2σ level, while the stellar MFs are indistinguishable. Notice that the upper-end of the MFs cannot be directly compared with a Salpeter IMF as the MFs we present proceed from calculations of clouds of the *same* mass, whereas the high-mass end of the observed IMF is probably a reflection of the cloud mass function, which is likely a power-law, non-flat distribution. It is natural that the $\alpha = -3$ calculations produce a higher number of brown dwarfs. These calculations have less kinetic energy in large scales relative to the $\alpha = -5$ simulations and thus the action tends to concentrate in dense, compact clusters near the cloud centre. This leads to much more frequent dynamical interactions and consequently ejection of low-mass objects, thus enhancing the fraction of brown dwarfs. Other initial condi-

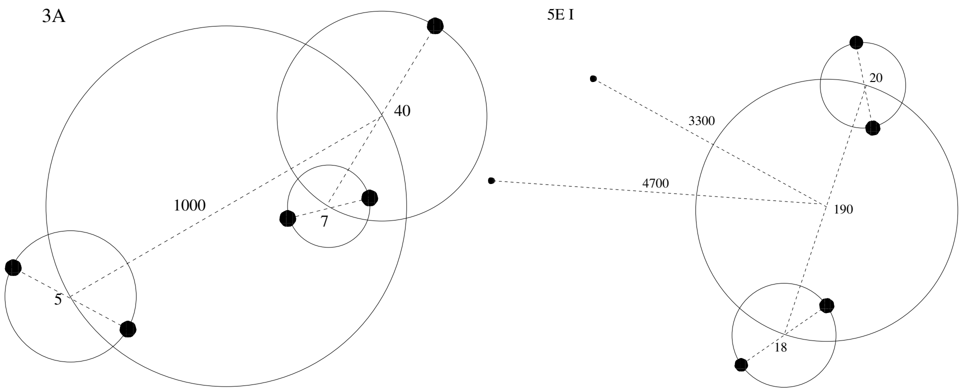

Fig. 3. Examples of some of the *exotic* multiples that form in our calculations. Binary orbiting a triple and binary orbiting a binary plus some outliers.

tions (e.g. a denser cloud, see Bate this volume) can also lead to a disparity in the fraction of brown dwarfs formed. Thus, the substellar IMF appears as the region of the IMF most sensitive to environment. Observational hints to this conclusion can be found in the literature, e.g. Briceño et al. (2002) find a paucity of brown dwarfs in Taurus relative to denser SFRs like Orion (Slesnick et al. 2004).

4. Results: Multiplicity Properties

Our simulations produce a wealth of multiple systems. The multiplicity fraction at 0.5 Myr after the initiation of star formation is close to 100%. The systems can adopt a variety of configurations, like binaries orbiting binaries or triples (see Figure 3). It is apparent that multiple star formation is a major channel for star formation in turbulent flows.

4.1. Multiplicity as function of primary mass

The companion frequency decreases during the first few Myr of N-body evolution, as many of the multiples are unstable. This internal decay affects mostly low-mass outliers, which are released in vast amounts to the field. We expect that in a real cluster the multiplicity would drop even further as star forming cores do not form in isolation but close to one another. Some of our binaries orbiting binaries might not have survived in a more realistic environment. The predicted decrease in the multiplicity frequency has been quantitatively observed by Duchêne et al. (2004).

The properties of our multiples and the dependence of the binary fraction on primary mass is best illustrated by a direct comparison with the infrared colour-magnitude diagram of the 600 Myr old Praesepe cluster (Figure 4). This comparison summarises the conclusions obtained from a wider cross-check with observations. The cluster was observed by Hodgkin et al. (1999) and our masses were converted to magnitudes using the tracks by Baraffe et al. (1998). Binaries with less than 200 AU separation (the spatial resolution of Hodgkin et al.'s measurements) are considered one object.

Two features from Figure 4 are worth noting: first, the simulated cluster shows a binary sequence whose width is comparable to that of the Praesepe, except for systems redder than $I - K = 2.5$. This seems to suggest that the formation of a significant minority of triples, quadruples, etc. may indeed be common in real clusters. Second, although our binary fraction for G stars is in agreement with observations, our models fail to produce as many low-mass binaries as observed. For example, at least a binary fraction of 15% is seen among brown dwarfs (e.g. Bouy et al. 2003).

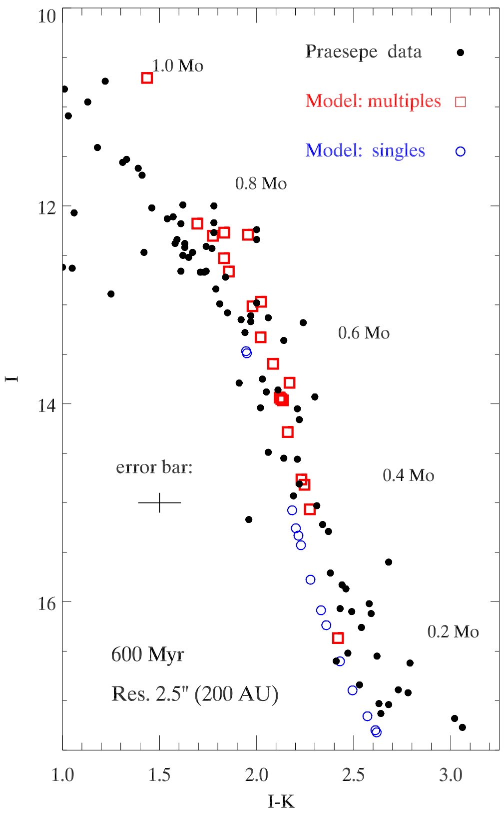

Fig. 4. Colour-magnitude diagram (I vs $I - K$) for the Praesepe clusters and superimposed our results. Symbols as in legend. Resolution at 200 AU.

4.2. Where do we find brown dwarfs

During the first few $\times 10^5$ yr most brown dwarfs are locked in multiple systems, often orbiting a binary or triples in eccentric orbits at large separations. Most of these systems are unstable and decay in a few Myr, releasing individual brown dwarfs to the field. Only a few substellar objects survive bound to stars. Of these, the majority orbit a binary or triple at distances greater than 100 AU. One case out of 4 consists of a brown dwarf orbiting an M star at 10 AU. Our results are in agreement with the observed brown dwarf desert at very small separations (see e.g. Forveille, this volume). However, more than a dozen substellar objects companion to stars at wide separations are known (Gizis et al. 2001). According to our results, we would expect that a large fraction of the primaries in these wide systems should turn out, in closer examination, to be $N \geq 2$ multiples.

5. Conclusions

We have undertaken the first hydrodynamical + N-body simulations of multiple star formation to produce a statistically significant number of stable hierarchical multiple systems, with components separations in the range 1 – 1000 AU. We have shown that a high multiplicity fraction is typical of the very early stages, a few $\times 10^5$ yr after star formation begins, with many different possible multiple configurations. At later stages, a few Myr, most systems have decayed, ejecting brown dwarfs to the field and decreasing the companion frequency. Both the high initial multiplicity and its dependence with age seem to be in accord with resent observations. In addition we have probed different power spectra for the initial random velocity field and found that a larger fraction of brown dwarfs is produced when the initial conditions favour a more compact, dense distribution of stars. Our findings, taken together with others found in the literature, seem to suggest that the substellar regime is where it is most likely that the universality of the IMF might break down.

We find a positive dependence of multiplicity with primary mass, with few low-mass stars being primaries. The paucity of brown dwarf binaries in our simulations indicate that the models need finer tuning. Brown dwarfs are found, however, orbiting binaries or triples at large distances, and thus we suggest that a good test of our models is to look into the primaries of wide brown dwarf companions in search of multiplicity.

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