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Numerical simulations of the formation of brown dwarfs

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Abstract. The results of recent large-scale hydrodynamical simulations of star formation are discussed, focusing on the formation mechanisms and properties of brown dwarfs, including the dependence of the abundance of brown dwarfs on environment and the velocity dispersion, binarity and discs of brown dwarfs.

Key words. Brown dwarfs – IMF – Binaries

1. Simulations of star formation

Two of the main questions in star formation are which process dominates the origin the the stellar initial mass function (IMF), and how does the IMF vary with environment?

Over the past three years, my collaborators and I have been tackling these questions through direct hydrodynamical simulations of star cluster formation. These simulations each formed a large enough number of objects that their statistical properties could be derived in a meaningful way. At the same time, they were followed long enough that most of the objects had finished evolving, and they had enough resolution to resolve large circumstellar discs and most binary systems. They also resolved the fragmentation of molecular gas down to the 'opacity limit for fragmentation' (e.g. Low & Lynden-Bell 1976), when collapsing molecular gas departs from isothermality and begins to heat up. Fragmentation at higher densities is thought to be inhibited (Boss 1989; Bate 1998) and, thus, the calculations should capture the formation of all stars and brown dwarfs. The opacity limit is thought to set a minimum for the mass of a brown dwarf of a few times the mass of Jupiter, M_J (Low & Lynden-Bell 1976).

To investigate the origin of stellar properties, we performed four large-scale star formation simulations, each beginning with different initial conditions.

1. Calculation 1 (Bate, Bonnell & Bromm 2002a, 2002b, 2003) followed the collapse of a 50-$M_\odot$ cloud with an initial mean thermal Jeans mass of 1 $M_\odot$. An initial supersonic 'turbulent' velocity field was imposed on the gas by generating a divergence-free random Gaussian field with a power spectrum $P(k) \propto k^{-4}$. The velocity field was normalised so the kinetic energy was equal to the magnitude of the gravitational potential energy. A barotropic equation of state was used to mimic the opacity limit for fragmentation. Below densities of $\rho = 10^{-13}$ g cm^{-3}, the gas was isothermal, while above this density the pressure increased as $p \propto \rho^{7/5}$.

2. Calculation 2 (Bate & Bonnell 2004) was identical to the first except the initial radius of the cloud was reduced by a factor of

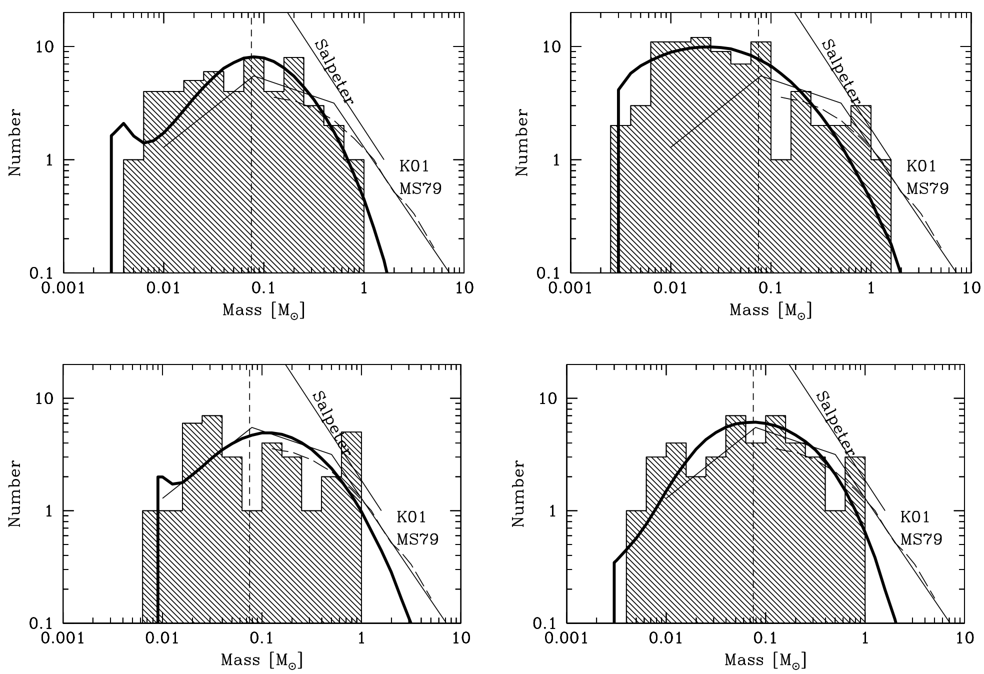

Fig. 1. The IMFs produced from the four hydrodynamical calculations (histograms). The thick solid lines give the IMFs produced by the simple accretion/ejection model discussed in Section 2. These give good fits to the hydrodynamical IMFs. The Salpeter (1955) slope and the IMFs of Kroupa (2001) and Miller & Scalo (1979) are also plotted. The vertical dashed line marks the boundary between stars and brown dwarfs.

2.08 so the mean thermal Jeans mass was a factor of 3 lower.

3. Calculation 3 was identical to the first except the opacity limit occured at a lower density of $\rho = 1.1 \times 10^{-14}$ g cm^{-3} so that the minimum brown dwarf mass was increased by a factor of 3.

4. Calculation 4 was identical to the first except the initial velocity power spectrum was $P(k) \propto k^{-6}$ (i.e. their was more energy on larger scales initially).

2. The IMF and brown dwarfs

Each calculations was evolved to the same number of initial cloud free fall times ($t = 1.4t_{\rm ff}$). Figure 1 gives the IMFs produced by each calculation. There is a clear difference between the IMFs from calculations 1 and 2. Calculation 2, with the lower mean thermal Jeans mass, produces many more brown dwarfs. A Kolmogorov-Smirnov test on the two cumulative IMFs show that there is only a 1.9% chance that they are drawn from the same underlying IMF. By contrast, there is little difference between the IMFs produced from calculations 1, 3, and 4, except that, as expected, calculation 3 does not produce very low-mass brown dwarfs (the lowest mass is 9 M_J compared to calculations 1, 2, and 4 in which the lowest mass objects are 5, 3 and 5 M_J, respectively). In particular, we note that a large change in the initial velocity power spectrum has no significant effect on the IMF even though the gas distribution through out calculation 4 is much more filamentary than in the other calculations. Thus, the IMF does not

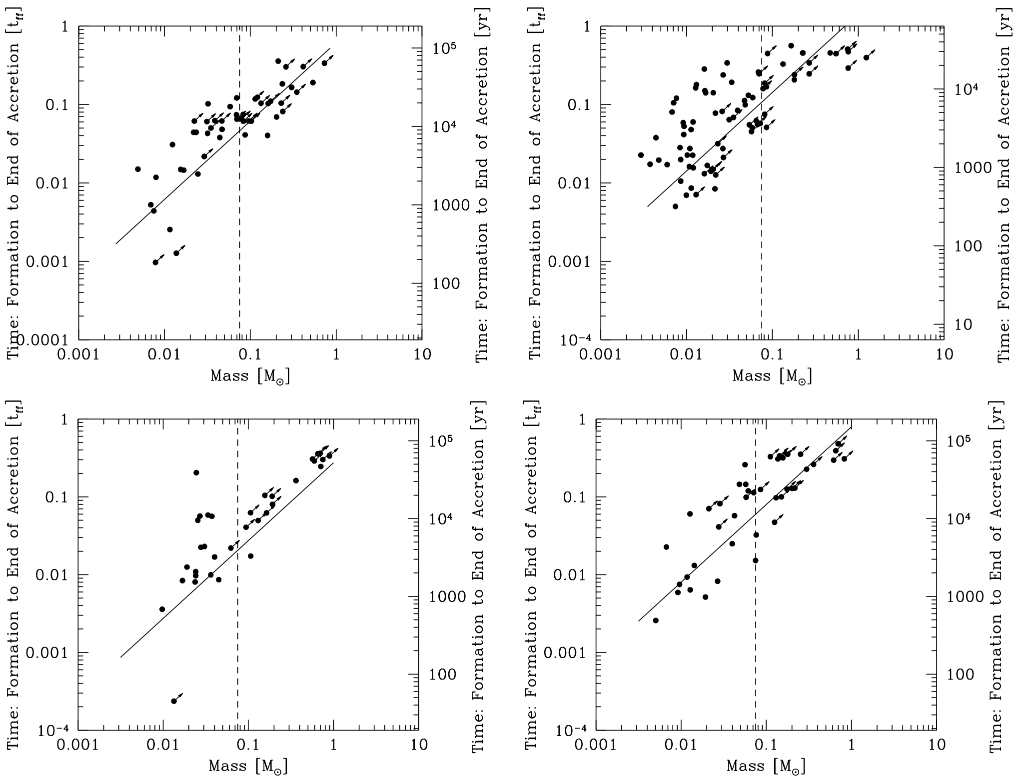

Fig. 2. For each object in each the four hydrodynamical calculations we plot the time between the formation of the object and the termination of its accretion versus its final mass. Note that in all four calculations there is a linear correlation (the longer an object accretes, the greater its final mass). The solid lines denote the loci along which objects accreting at the mean accretion rate (for each calcuation) would lie.

seem to be particularly sensitive to the density structure in molecular clouds.

What then determines the origin of the IMF? In Figure 2, we plot the time between the formation of an object and the termination of its accretion versus the final mass of the object. There is a clear linear correlation. Bate & Bonnell (2004) also show an object's accretion is usually terminated by the dynamical ejection of an object from the dense gas in which it formed. Thus, *stars and brown dwarfs form in the same way*, but brown dwarfs are those objects that happen to be ejected from small$-N$ groups soon after they form and before they reach a hydrogen-burning mass. Stars may also be ejected during the dissolution of the small groups but, by definition, not until their mass has exceeded the hydrogen-burning mass.

From the hydrodynamical simulations, Bate & Bonnell (2004) proposed a simple accretion/ejection IMF model, assuming

- All objects begin with masses set by the opacity limit for fragmentation (e.g., ≈ 3 M_J) and then accrete at a fixed rate $\dot{M}$ until they are ejected.
- The accretion rates of individual objects are drawn from a log-normal distribution with a mean accretion rate given by $\overline{\log(\dot{M})} = \overline{\log(\dot{M})}$ and a dispersion of σ dex.

– The ejection of protostars from an N-body system is a stochastic process and that there is a single parameter, $\tau_{\rm eject}$, that is the characteristic timescale between the formation of an object and its ejection from the cloud. The probability of an individual object being ejected is then $\exp(-t/\tau_{\rm eject})$ where t is the time elapsed since its formation.

There are essentially only three free parameters in this model. These are the mean accretion rate times the ejection timescale, $\overline{M} = \overline{\dot{M}}\tau_{\rm eject}$, the dispersion in the accretion rates, σ, and the minimum mass provided by the opacity limit for fragmentation, $M_{\rm min}$. If $\overline{M} >> M_{\rm min}$, $\overline{M}$ is the characteristic mass of the IMF.

The above parameters can all be measured directly from the hydrodynamical simulations. Using these values, four synthetic IMFs can be generated from the simple accretion/ejection model and compared with the IMFs from the hydrodynamical calculations (thick lines, Figure 1). In all cases, the simple accretion/ejection model provides a good fit to the hydrodynamical IMFs, showing that this simple model gives a good description of the origin of the IMF in the hydrodynamical calculations.

Furthermore, the mean accretion rate of a protostar may be expected to scale as $\sim c_{\rm s}^3/G$, where $c_{\rm s}$ is the sound speed in the cloud, and the timescale for ejection from a small group of stars may be expected to scale with the crossing time of the group which should in turn scale with the density, ρ of the cloud as $\propto 1/\sqrt{G\rho}$. Thus, the characteristic mass of the IMF should scale as $c_{\rm s}^3/\sqrt{G^3\rho}$ which, neglecting constants of order unity, is the definition of the mean thermal Jeans mass of the cloud. Recalling that the mean thermal Jeans mass of calculation 2 was a factor of 3 smaller than that for calculation 1, we do indeed find that the median (characteristic) mass of the stars and brown dwarfs formed in calculation 2 is a factor of 3.04 smaller than in calculation 1.

Thus, the peak of the IMF in star-forming clouds with lower values of the initial mean thermal Jeans masses (i.e. denser or cooler clouds) should shift to lower masses (i.e. those clouds should produce a higher fraction of brown dwarfs). The recent observation (Briceno et al. 2002; Slesnick et al. 2004; Luhman 2004b) that the Orion Trapezium Cluster (a dense star-forming region) appears to have a factor of ≈ 1.5 fewer brown dwarfs than Taurus (a low-density star-forming region) may indicate such a dependence of the IMF on the mean Jeans mass in molecular clouds.

3. The properties of brown dwarfs

3.1. Velocity dispersion

When Reipurth & Clarke (2001) proposed that brown dwarfs may be ejected stellar embryos that had not been able to accrete to stellar masses, they suggested a signature of this formation mechanism might be that brown dwarfs had higher velocities than stars. However, the hydrodynamical calculations show there is no significant dependence of the velocity dispersion of stars and brown dwarfs on their mass (Bate et al. 2003; Bate & Bonnell 2004). The reason is that both brown dwarfs and stars are ejected by dynamical encounters. Brown dwarfs are simply ejected sooner after they form, before they reach stellar masses. Observations also support this lack of dependence of the velocity dispersion on mass (Joergens & Guenther 2001; White & Basri 2003).

3.2. Binarity

The ejection model for brown dwarf formation implies that any binary brown dwarf (BBD) systems should be close to avoid being disrupted in the encounter (Reipurth & Clarke 2001; Bate et al. 2002a) and those that do survive are likely to be rare. Indeed, of the ≈ 20 brown dwarfs formed in calculation 1, there was only one BBD system (separation ≈ 6 AU) giving a frequency of $\approx 5\%$ (Bate et al. 2002a, 2003).

Calculation 2 produced three BBD systems and a further two systems composed of a very low-mass (VLM) star (mass less than 0.09 $M_\odot$) and a brown dwarf (Bate & Bonnell 2004), giving a frequency of very-low-mass binaries of $\approx$ 8%. One of the BBDs and one of the VLM+BD systems had been ejected from the cloud and, thus, had reached their final states. Surprisingly, both were wide systems (66 AU and 126 AU, respectively). These systems were not ejected as binaries. Instead they formed when two objects were ejected from the same group of protostars at roughly the same time and with similar velocities. Thus, they were bound. The remaining three systems were still accreting when the calculation was stopped and were all close (separations of 2, 15 and 21 AU).

Calculations 3 and 4 each produced $\approx$ 20 brown dwarfs. Calculation 3 produced no binary brown dwarfs, but calculation 4 produced one with a separation of 26 AU that had been ejected.

In summary, there is a clear preference from the simulations for BBDs to be close, but, contrary to expectations, wide ejected systems can be formed by nearly simultaneous ejections. Such wide systems are likely to be rare, however, because they require special timing of the ejections. These are only likely from reasonably large groups of protostars ($N \sim 20 - 30$).

Observationally, most known very low mass binaries are close (e.g. Reid et al. 2001; Close et al. 2002) with separations less than $\approx$ 15 AU. Their frequency seems to be $\approx$ 15% which is roughly a factor of two higher than the results of the hydrodynamical simulations. This agreement is reasonable given that the simulations are still limited to small numbers of objects, very close dynamical interactions and small circumstellar discs are not resolved, and the calculations are stopped before all of the multiple systems have finished evolving. Luhman (2004a) has recently reported the discovery of a wide ($\approx$ 240 AU) binary brown dwarf system. Clearly the frequency of binary brown dwarfs is a crucial test of the models, but more work needs to be done on both the theoretical and observational sides to obtain more accurate measurements of the separation distributions of binary brown dwarfs.

3.3. Discs

The ejection mechanism for brown dwarf formation also implies they are unlikely to have large discs. There are two reasons for this. First, during a dynamical encounter, an existing disc will be truncated to $\approx 1/3$ of the minimum distance during the encounter (e.g. Hall, Clarke & Pringle 1996). Second, the fact that the brown dwarf is ejected soon after it forms means that it does not have much time to accumulate a large disc. The first material to be accreted by a protostar from the envelope in which it is embedded tends to have the lowest specific angular momentum. Material with high specific angular momentum tends to fall in later. If the object does not get the chance to accrete gas with high specific angular momentum it will not assemble a large disc.

The hydrodynamical calculations cannot resolve circumstellar discs with radii less than $\approx$ 20 AU. Together, the four calculations the produce approximately 90 brown dwarfs that have been ejected from the cloud and will not evolve further. Of these, only one (from calculation 1) has a resolved disc. Its radius is $\approx$ 50 AU. Thus, most brown dwarfs are expected to have discs with radii less than $\approx$ 20 AU. The only caveat to this statement is that, due to computational limitations, all four hydrodynamical simulations performed to date have been of high-density star-forming clouds (stellar densities of $\sim 10^3 - 10^4$ stars/pc^3). In low density star-forming regions, dynamical interactions may be wider allowing somewhat larger discs to survive.

Observationally, many brown dwarfs are observed to have circumstellar discs (e.g. Natta & Testi 2001; Pascucci et al. 2003; White & Basri 2003). As yet, their sizes are unknown, but there are at least indications that brown dwarf discs may have lower masses than their stellar counterparts because their accretion rates seem to be much lower (Natta, this proceedings). However, disc sizes will probably only be measured with new high-resolution sub-millimetre or millimetre instruments such as the SMA or ALMA.

4. Conclusions

Recent hydrodynamical simulations of star cluster formation have provided several predictions for the abundances and properties of brown dwarfs. They predict that brown dwarfs should be more abundant in star-forming clouds with lower values of the mean thermal Jeans mass (i.e. denser or cooler clouds). They predict that the velocity dispersions of brown dwarfs should be indistinguishable from those of stars. They predict that binary brown dwarfs should be reasonably rare and that most systems should be close (less than ≈ 30 AU). They predict that most young brown dwarfs should have small discs (less than ≈ 20 AU in radius).

While the frequency of binary brown dwarfs derived from the calculations appears to be roughly factor of two lower than is observed, and it is not currently possible to measure the sizes of brown dwarf discs, there is nevertheless broad agreement between the calculations and current observations. In particular, there are indications that brown dwarfs may be more abundant in denser star-forming regions, measurements of the velocities of brown dwarfs and stars show no obvious differences, and most observed binary brown dwarfs have small orbital separations. However, further observations and theoretical calculations with still higher resolution (to better resolve discs and binaries) are still required.

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