Brown Dwarfs
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The Formation Mechanism and Resulting Properties of Brown Dwarfs

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Abstract. We present results from the most complex hydrodynamical star formation calculation performed to date. It follows the collapse and fragmentation of a large-scale turbulent molecular cloud to form dozens of stars and brown dwarfs. It resolves all fragmentation down to the opacity limit, binary stars with separations as small as 1 AU, and circumstellar disks with radii down to ≈ 10 AU. In this proceedings, we examine the formation mechanism of the brown dwarfs and compare the initial mass function and the properties of the brown dwarfs with observations.

1. Introduction

Recent observations show that brown dwarfs are common, perhaps as numerous as stars (e.g. Reid et al. 1999). Despite their abundance, however, the formation mechanism of brown dwarfs is currently a mystery. The typical thermal Jeans mass in molecular cloud cores is ≈ 1 M$_\odot$. Thus, the gravitational collapse of molecular clouds might be expected to form stars, not brown dwarfs.

There are two obvious routes by which brown dwarf systems (i.e. brown dwarfs without stellar companions) may form. First, they may result from the collapse of low-mass cores (masses $\lesssim 0.1$ M$_\odot$) that are smaller (radii $\lesssim 0.05$ pc) and denser ($n(\mathrm{H}_2) \gtrsim 10^7$ cm^{-3}) than the cores that are typically observed (i.e. they have low masses yet are still Jeans unstable). Thus, brown dwarfs would be 'low-mass stars'. The second possibility is that brown dwarfs form in higher-mass cores but are prevented from accreting enough mass to exceed the hydrogen-burning limit. If such a core fragments to form an unstable multiple system, this may be achieved by the dynamical ejection of a fragment from the core, cutting it off from the reservoir of gas, and thus preventing it from accreting to a stellar mass. In this case, brown dwarfs would be 'failed stars'. This ejection mechanism has been proposed by Reipurth & Clarke (2001).

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We presents results from the first hydrodynamical calculation to follow the collapse and fragmentation of a large-scale turbulent molecular cloud to form a stellar cluster, while resolving beyond the opacity limit for fragmentation (Low & Lynden-Bell 1976). The opacity limit occurs when molecular gas ceases to collapse isothermally and begins to heat up. The dynamical collapse is stopped and a pressure-supported fragment forms with an initial mass of ≈ 0.01 $M_\odot$ and radius of ≈ 5 AU (Larson 1969). The fragment cannot collapse further to form a star (or brown dwarf) until its central temperature exceeds that required for molecular hydrogen to dissociate. This allows a 'second collapse' to form the star. Fragmentation during this second phase of collapse is thought to be inhibited by the high thermal energy content of the gas and angular momentum transport via gravitational torques (Bate 1998; Bate, in preparation). Thus, the opacity limit results in a minimum mass for the initial mass function and resolving the calculation down to the opacity limit should allow us to model all potential fragmentation, including that resulting in binary and multiple systems.

2. Calculations

2.1. The code and initial conditions

We performed the calculation using a parallelised version of the smoothed particle hydrodynamics (SPH) code described in Bate, Bonnell, & Price (1995) on the United Kingdom Astrophysical Fluids Facility (UKAFF). High-density bound objects (the pressure-supported fragments that become stars and brown dwarfs) consisting of many SPH gas particles are replaced by 'sink' particles. These interact with the rest of the calculation only via gravity and accrete any SPH gas particles that come within an accretion radius of 5 AU.

The initial conditions consist of a 50-$M_\odot$, uniform-density, spherical cloud of molecular gas with diameter ≈ 0.375 pc. At the temperature of 10 K, the mean thermal Jeans mass is 1 $M_\odot$. We impose a supersonic divergence-free random Gaussian velocity field on the cloud with a power spectrum $P(k) \propto k^{-4}$. In three-dimensions, the velocity dispersion varies with distance, λ, as $\sigma(\lambda) \propto \lambda^{1/2}$, in agreement with the observed Larson scaling relations for molecular clouds.

2.2. Resolution

To mimic the opacity limit for fragmentation, our equation of state changes from isothermal to barotropic with a polytropic index of $\eta = 7/5$ at $\rho = 10^{-13}$ g cm^{-3} (Bate, Bonnell & Bromm 2003). Once the density in a pressure-supported fragment passes $\rho_s = 10^{-11}$ g cm^{-3}, we replace the fragment with a 'sink' particle. We cannot follow a fragment's collapse to the actual formation of a star (as done in Bate 1998) while simultaneously following the evolution of the large-scale cloud: the range of dynamical timescales would be too large.

We must resolve the local Jeans mass throughout the calculation (Bate & Burkert 1997). The minimum Jeans mass occurs at the maximum density during the isothermal phase of the collapse, $\rho = 10^{-13}$ g cm^{-3}, and is 0.0011 $M_\odot$ (1.1 Jupiter masses). The Jeans mass must be resolved by a minimum of ≈ 75 SPH particles (Bate, Bonnell, & Bromm 2003). Thus, we use 3.5×10^6 particles to model the 50 $M_\odot$ cloud.

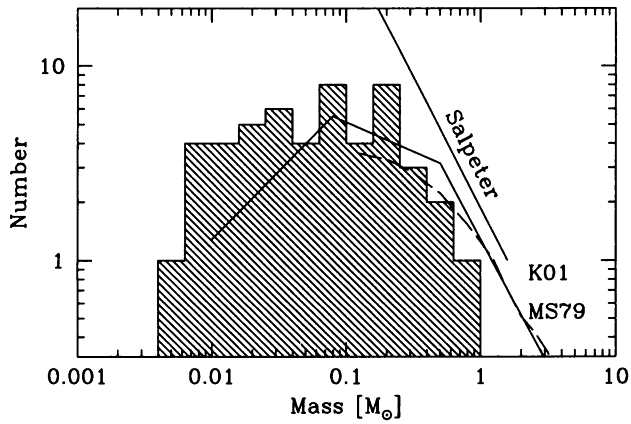

Figure 1. The IMF obtained from the calculation, compared with the Salpeter slope, Miller & Scalo (1979), and Kroupa (2001).

3. Results and Discussion

3.1. Cloud evolution

We evolve the cloud for 1.40 free-fall times (2.66×10^5 years) as the turbulent energy decays in shocks and dense self-gravitating cores form and collapse to produce stars and brown dwarfs. In all, 23 stars and 18 brown dwarfs are formed. An additional 9 objects have substellar masses when we stop the calculation, but are still accreting. Further details can be found in Bate, Bonnell & Bromm (2002a, 2002b, 2003). Animations of the calculation can be downloaded from http://www.astro.ex.ac.uk/people/mbate and http://www.ukaff.ac.uk

3.2. The initial mass function

In Figure 1, we plot the initial mass function (IMF) obtained from the calculation. This is the first initial mass function to be determined from a hydrodynamical calculation that resolves objects down to the opacity limit for fragmentation. Hence, it predicts both the stellar and substellar IMF.

We obtain a mass function consistent with $\mathrm{d}N/\mathrm{dlog}M = M^\Gamma$ where $\Gamma = -1.35$ for $M > 0.5$ $M_\odot$, $\Gamma = 0.0$ for $0.006 < M < 0.5$ $M_\odot$, and there are no objects below the opacity limit for fragmentation (≈ 0.005 $M_\odot$). The Salpeter slope is $\Gamma = -1.35$. This initial mass function is consistent with recent determinations of the IMF in young stellar clusters and star-forming regions (e.g. Luhman et al. 2000). Furthermore, roughly equal numbers of stars and brown dwarfs are produced, a result also supported by observations (Reid et al. 1999).

3.3. The formation mechanism of brown dwarfs

Although the mean Jeans mass in the cloud is 1 $M_\odot$, the calculation produces many brown dwarfs. The formation mechanism of the brown dwarfs is discussed in detail by Bate, Bonnell, & Bromm (2002a). We find that the brown dwarfs form in dense gas where the local Jeans mass is lower than that in the

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cloud as a whole. Roughly three quarters form via the fragmentation of massive gravitationally-unstable circumstellar disks, while the remainder form in dense filaments of molecular gas. However, in either case, the objects must avoid accreting to stellar masses. This is accomplished by the objects forming in, or quickly falling into, unstable multiple systems where they are dynamically ejected from the cloud before they have been able to accrete to stellar masses. This formation mechanism has been discussed by Reipurth & Clarke (2001), although they could only speculate on its efficiency and the ways in which the multiple systems might form. We show that this mechanism is capable of producing the observed numbers of brown dwarfs.

3.4. The properties of brown dwarfs

The close dynamical interactions that occur during the ejection process have two important implications for the properties of brown dwarfs. First, we find that binary brown dwarf systems should be rare. None of the 18 definite brown dwarfs are binaries. One close ($\approx$ 6 AU) binary brown dwarf exists at the end of the calculation, but it is part of an accreting unstable multiple system. If this system survives, the frequency would be $\approx$ 5%. Current observations suggest a frequency of $\approx$ 20% (Close, this proceedings). With only $\approx$ 20 brown dwarfs, we are limited by small numbers since with the currently observed probability there is a $\approx$ 6% probability of observing 20 systems and finding only one binary brown dwarf (i.e. our result differs from observations at only the 2σ level).

Second, we find the frequency of young brown dwarfs with large circumstellar disks (greater than $\approx$ 20 AU in radius) should also be low at $\approx$ 5% as only one of the definite brown dwarfs has a resolved disk (radius $\approx$ 60 AU). There are two main reasons for this. First, to avoid becoming stars the brown dwarfs must be ejected from the cloud soon after their formation and, thus, many do not have time to accrete the high angular momentum gas required to form large disks. Second, the majority of the dynamical encounters that eject the brown dwarfs occur at separations $<$ 20 AU so that any existing large disk is truncated.

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