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UNDERSTANDING THE FORMATION OF STARS AND BROWN DWARFS

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RESUMEN

Reseñamos resultados recientes que emanan de cálculos hidrodinámicos sobre la formación de cúmulos estelares jóvenes. Los cálculos presentan un panorama altamente dinámico de la formación estelar, donde la función de masa se origina de un acrecentamiento competitivo entre protoestrellas y la eyecciónes dinámicas que detienen el acrecentamiento. Basados en cálculos que resultan de la fragmentación más allá del límite de opacidad, examinamos el origen de la función inicial de masa y su dependencia en metalicidad y en la masa térmica media de Jeans de nubes moleculares. Encontramos que la masa estelar promedio es relativamente independiente de la masa térmica promedio de Jeans y depende más del límite de opacidad para fragmentación. Sin embargo, nubes con una menor masa térmica promedio de Jeans producen una mayor fracción de enanas marrones.

ABSTRACT

We review recent results from hydrodynamical calculations of the formation of young stellar clusters. The calculations present a highly dynamical picture of star formation where the mass function of stars originates from competitive accretion between protostars and dynamical ejections that halt accretion. Using calculations that resolve fragmentation beyond the opacity limit, we examine the origin of the stellar initial mass function and its dependence on the metallicity and mean thermal Jeans mass of molecular clouds. We find that the mean 'stellar' mass is relatively independent of the mean thermal Jeans mass and depends more on opacity limit for fragmentation. However, progenitor clouds with a lower mean thermal Jeans mass do produce a greater fraction of brown dwarfs.

Key Words: **STARS: FORMATION — STARS: STATISTICS**

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1. INTRODUCTION

Hydrodynamical calculations of star cluster formation are very computationally intensive and have only recently become possible. Chapman et al. (1992) performed the first hydrodynamical calculations to follow the formation of large numbers of protostars. However, they could not follow the evolution until these objects had reached their final states. Bonnell et al. (1997, 2001a,b, 2002) ignored the initial fragmentation process and performed calculations that began with protoclusters consisting of 10-1000 protostars deeply embedded in molecular gas. They were interested in how the masses of the protostars evolved as they accreted gas. They found that even starting with equal-mass objects, competitive accretion between stars quickly produced a distribution of masses similar to the stellar initial mass function (IMF). Klessen et al. (1998, 2000, 2001), performed calculations that began with clumpy and turbulent molecular clouds, each forming ~ 100 objects. They were able to follow their evolution until most of the gas had been used up in the star formation process. They found that the IMF of their objects originated from a combination of fragmentation, competitive accretion, and dynamical interactions that would eject objects from the dense gas. The resulting IMFs were roughly log-normal, reminiscent of the stellar IMF, with a mean mass of order the mean Jeans mass of the cloud. However, these calculations did not have the resolution to follow small-scale fragmentation, most binaries, or circumstellar discs.

In this proceedings, we review results from recent hydrodynamical calculations of cluster formation that resolve beyond the opacity limit for fragmentation (Low & Lynden-Bell 1976) and, thus, capture the formation of all stars and brown dwarfs. 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 ≈ 0.005 $M_\odot$ (Larson 1969). Subsequent fragmentation is not thought to occur due to the high thermal energy content of the gas and/or angular momentum transport via gravitational torques (Boss 1988; Bate 1998). Thus, the opacity limit results in a minimum mass for the 'stellar' initial mass function of ~ 5 Jupiter masses (M_J).

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2. CALCULATIONS

2.1. *The code and initial conditions*

The calculations were performed 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). Between 50,000 and 95,000 CPU hours were used per calculation. 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 their accretion radii.

The initial conditions consist of uniform-density, spherical molecular clouds at temperatures of 10 K. Each cloud contains 50 $M_\odot$ of gas. We impose supersonic divergence-free random Gaussian velocity fields with power spectra $P(k) \propto k^{-4}$. In three-dimensions, these power spectra result in velocity dispersions that vary with distance, λ, as $\sigma(\lambda) \propto \lambda^{1/2}$, in agreement with the observed Larson scaling relations for molecular clouds.

2.2. *Resolution and equation of state*

The calculations are fully-resolved in the sense that fragmentation is followed down to the opacity limit for fragmentation (masses of a few Jupiter masses). Thus, all stars and brown dwarfs that should form in the clouds are modelled. To mimic the opacity limit for fragmentation, the calculations use an equation of state that changes from isothermal to barotropic with a polytropic index of $\eta = 7/5$ at $\rho = 10^{-13}$ g cm^{-3} (Bate, Bonnell & Bromm 2003) or $\rho = 1.1 \times 10^{-14}$ g cm^{-3} in the third calculation. Once the density in a pressure-supported fragment exceeds 100 times these critical densities, we replaced the fragment with a 'sink' particle. We can not 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 is too large. The calculations model binaries as close as 1 AU, and resolve circumstellar discs with radii $\gtrsim 20$ AU.

The local Jeans mass is resolved (Bate & Burkert 1997) throughout the calculations. 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 M_J). The Jeans mass must be resolved by a minimum of ≈ 75 SPH particles (Bate et al. 2003). Thus, we use 3.5×10^6 particles to model the 50 $M_\odot$ clouds.

During the conference, a suggestion was made that this resolution may not be sufficient to correctly model fragmentation and may promote the fragmentation of gravitationally unstable discs. After the conference, we performed calculations of isolated stars surrounded by gravitationally unstable discs at both the resolution suggested by Bate & Burkert (1997) and using five times as many particles (i.e. 100 and 500 particles per minimum Jeans mass). There were no significant differences in the fragmentation between these high and low resolution calculations. Still higher resolution calculations are currently underway, but at this stage it appears that artificial disc fragmentation is not a problem in the calculations discussed in this proceedings.

3. THE DEPENDENCE OF STAR FORMATION ON THE INITIAL CONDITIONS

We report the results from three separate calculations of star cluster formation. The first calculation was the first fully-resolved calculation of star cluster formation, published in Bate, Bonnell & Bromm (2002a,b; 2003). Animations of the calculation can be downloaded from http://www.astro.ex.ac.uk/people/mbate. The initial cloud for this calculation had a mean thermal Jeans mass of 1 $M_\odot$ and the equation of state, mimicking the opacity limit for fragmentation, changed at a density of 10^{-13} g cm^{-3} giving a minimum object mass of ≈ 4 M_J. The calculation had converted 5.89 $M_\odot$ of gas into 50 stars and brown dwarfs when it was stopped at 1.40 initial free-fall times.

The second calculation (Bate & Bonnell 2004) was identical to the first calculation, except that the initial cloud was nine times denser. Thus, the mean thermal Jeans mass was only 1/3 $M_\odot$. The equation of state was identical to the first calculation. At 1.40 initial free-fall times, 7.92 $M_\odot$ of gas had been converted into 79 stars and brown dwarfs.

The third calculation (Bate 2004) was identical to the first calculation, except that the equation of state changed from isothermal to barotropic at 1/9 the density (i.e. 1.1×10^{-14} g cm^{-3}). This calculation can be thought of as having a lower metallicity (see below). This increased the minimum object mass by a factor of ≈ 3 to 10 $M_\odot$. The initial mean thermal Jeans mass, and indeed the entire evolution of the cloud up to the formation of the first star, was identical to that in the first calculation. At 1.40 initial free-fall times, 6.88 $M_\odot$ of gas had produced 34 stars and brown dwarfs.

The first calculation (Bate et al. 2002a,b; 2003) began with a reasonable estimate for the conditions

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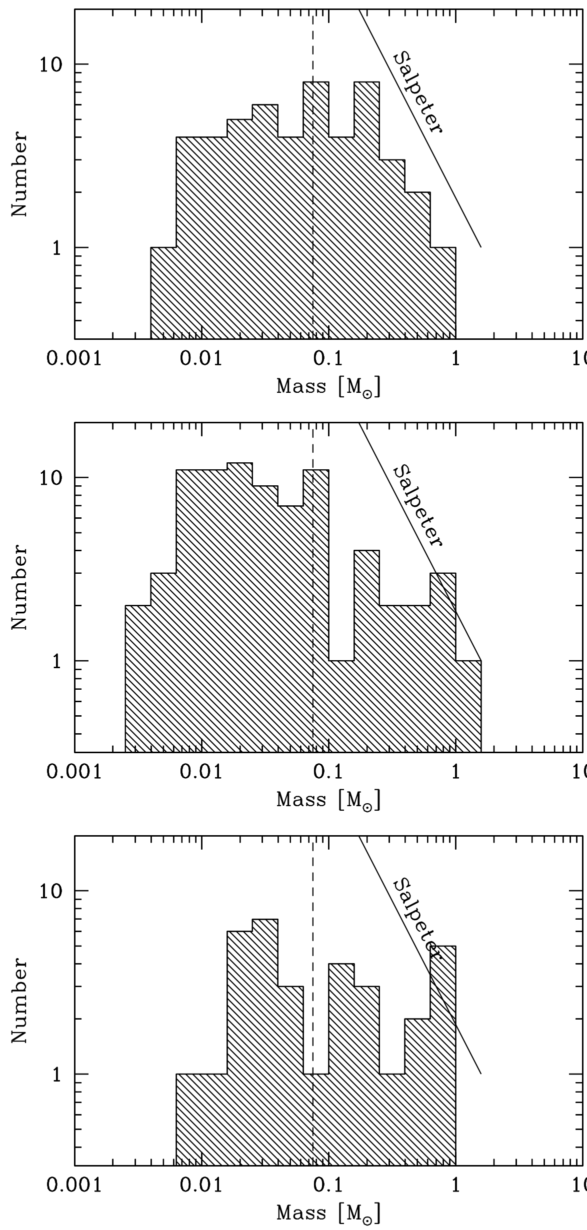

Fig. 1. The IMFs obtained from the three calculations discussed in the text. The progenitor clouds had mean thermal Jeans masses of 1 $M_\odot$ (top and bottom) and 1/3 $M_\odot$ (middle). The opacity limit for fragmentation set in at a density nine times lower in the bottom calculation, increasing the minimum mass from $\approx$ 4 to $\approx$ 10 M_J. The solid line shows the Salpeter slope, $\Gamma = -1.35$. The dotted line gives the stellar/brown dwarf boundary.

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in molecular clouds and obtained stellar properties in reasonable agreement with observations. The IMF resulting from the calculation is shown in the top panel of Figure 1. It is 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 (≈ 0.004 $M_\odot$). This 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, there are roughly equal numbers of stars and brown dwarfs, a result also supported by observations (Reid et al. 1999).

The IMF obtained from the second calculation is presented in the middle panel of Figure 1. This calculation, with a lower mean thermal Jeans mass, produces a larger fraction of brown dwarfs. A Kolmogorov-Smirnov test on the mass functions from the first two calculations shows that this result is significant at the 98.1% level (i.e. 2.4 σ). However, despite a reduction in the mean thermal Jeans mass by a factor of 3, the mean object mass is only 15% lower in the second calculation. Thus, although the mean 'stellar' mass does seem to depend on the mean thermal Jeans mass in the progenitor cloud, it is only a very weak dependence. The dependence on the mean Jeans mass is consistent with the results of Briceno et al. (2002) who find there is a factor of two fewer brown dwarfs in Taurus compared to the Orion Trapezium Cluster, the latter of which has a higher mean density and hence a smaller inferred Jeans mass.

The third calculation investigates the dependence of the IMF on the opacity limit for fragmentation. The small number of objects formed makes it difficult to drawn any conclusions on the form of the IMF (see the bottom panel of Figure 1). However, there are two important differences between this IMF and those of the first two calculations. First, as expected, the lowest mass object has a mass of roughly three times the lowest mass object in the other calculations due to the change in the equation of state. Second, although the mean mass of the objects is not a factor of three higher than in the first calculation, as it would be if it were directly linked to the minimum object mass, it has increased by a factor of 1.7. Thus, the mean 'stellar' mass is more sensitive to changes in the minimum object mass than changes in the mean thermal Jeans mass of the cloud.

The sensitivity of the mean stellar mass to the minimum mass implies a higher mean stellar mass at lower metallicities. However, the effect is predicted to be relatively weak. Low & Lynden-Bell (1976) found that the minimum mass due to the opacity limit for fragmentation should scale with metallicity, Z, as $Z^{-1/7}$. Thus, for globular clusters with a metallicity of [Fe/H] $= -2$, the minimum object mass would only be expected to increase by factor of 2 and, according to the above results, the mean mass by a somewhat lower factor, perhaps 1.5. We note there is weak evidence that the peak in the IMF may be at a slightly higher mass in globular clusters than in local, higher metallicity, star-forming regions (Paresce & De Marchi 2000; Chabrier 2003).

4. THE FORMATION MECHANISM AND PROPERTIES OF BROWN DWARFS

Although the mean Jeans mass in the clouds ranges from 1/3 to 1 $M_\odot$, all the calculations produce many brown dwarfs. The formation mechanism of the brown dwarfs was discussed in detail by Bate et al. (2002a). They found that the brown dwarfs formed in dense gas where the local Jeans mass was lower than that in the cloud as a whole. In the first calculation, roughly three quarters formed via the fragmentation of massive gravitationally-unstable circumstellar discs, while the remainder formed in dense filaments of molecular gas. However, in either case, the objects had to avoid accreting to stellar masses. This was accomplished by the objects forming in, or quickly falling into, unstable multiple systems where they were dynamically ejected from the cloud before they had been able to accrete to stellar masses. This formation mechanism was discussed by Reipurth & Clarke (2001), although they could only speculate on its efficiency and the ways in which the multiple systems might form. Bate et al. (2002a) showed that this mechanism is capable of producing the observed frequency of brown dwarfs.

The close dynamical interactions that occur during the ejection process have two important implications for the properties of brown dwarfs. First, binary brown dwarf systems should be rare. The above calculations give binary brown dwarf frequencies of $5-10\%$. Current observations suggest a frequency of $15 \pm 7\%$ (Close et al. 2003). Second, the frequency of young brown dwarfs with large circumstellar discs (greater than ≈ 20 AU in radius) should also be low at $\sim 5\%$. 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 discs. Second, the majority of the dynamical encounters that eject the brown dwarfs occur at separations < 20 AU so that any existing large disc is truncated.

5. CONCLUSIONS

The calculations discussed here indicate that the origin of the IMF is complex, involving competitive accretion and dynamical interactions between objects. Furthermore, the IMF does not appear to be related in a simple way to global quantities such as the mean thermal Jeans mass in a molecular cloud or the opacity limit for fragmentation. A fourth calculation investigating the dependence of stellar properties on the properties of the turbulence in the molecular cloud is currently being performed. Future similar, and even larger-scale, calculations should dramatically increase our understanding of the star formation process and the origin of the properties of stars and brown dwarfs.

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