The Formation of a Cluster of Stars and Brown Dwarfs in a Turbulent Molecular Cloud

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Abstract. We present preliminary results from the first hydrodynamic calculation to follow the collapse and fragmentation of a large-scale turbulent molecular cloud into a stellar cluster while resolving beyond the opacity limit for fragmentation. The calculation produces a mixture of single and binary stars with comparable numbers of stars and brown dwarfs. Without exception, the brown dwarfs are formed by ejection from unstable multiple systems. The calculation produces a stellar initial mass function in agreement with observations. However, at this stage in the calculation, no high-mass (> 0.03 M$_\odot$) brown dwarfs have been formed because they are ejected too soon after formation to have accreted much mass.

1 Introduction

The collapse and fragmentation of molecular cloud cores to form single stars and bound multiple stellar systems has been the subject of many numerical studies, e.g. [1–7]. These calculations have resulted in the adoption of fragmentation as the favoured mechanism for the formation of the majority of binary stars, since it can produce a wide range of binary properties (as observed) through simple variations of the pre-collapse initial conditions.

However, while individual binary systems can be reproduced by such fragmentation calculations, it is extremely difficult to predict the statistical properties of stellar systems that should result from the fragmentation model. There are two main reasons for this. First, most fragmentation calculations have only considered the formation of binaries or small multiple systems and not the large numbers of stars for which statistical properties can be determined. Second, the results of these calculations depend primarily on the initial conditions chosen. For example, in forming a binary system, the system's final mass is determined by the mass of the initial cloud core, its separation is determined by the initial angular momentum, and so forth. Thus, the statistical properties of stellar systems such as the frequencies of single, binary and higher-order multiple systems, the initial mass function (IMF), and the distribution of binary separations cannot be determined from such calculations. In order to obtain theoretical predictions of the statistical properties of stellar systems, we must both form a greater number of stars and begin with more realistic initial conditions.

The first such calculation [8] modelled the collapse of a large-scale clumpy molecular cloud to form $\sim$ 60 protostellar cores. It was found that the mass function of the cores could be fit by a lognormal mass function that has a similar width to the observed stellar initial mass function. The core masses were determined by a combination of the initial density structure, competitive accretion (see [9,10] for indepth studies of how competitive accretion leads to an initial mass function), and dynamical interactions. Further calculations [11,12] confirmed the lognormal mass function and showed that the mean mass of the protostellar cores was similar to the mean initial Jeans mass in the cloud.

Unfortunately, while these calculations help us to understand the processes that may determine the initial mass function, they only allow the very widest binaries to be resolved. We do not know which of the unresolved protostellar cores will fragment to form binaries or what their properties will be. Thus, we are also unable to determine the true stellar initial mass function (only the 'system' mass function) or what role multiple systems play in the evolution of a young cluster.

This proceedings presents results from the first calculation to follow the collapse and fragmentation of a large-scale turbulent molecular cloud to form a stellar cluster, while resolving down to the opacity limit for fragmentation [13]. The opacity limit occurs approximately at the point when the centre of a collapsing cloud of molecular gas becomes optically-thick to infrared radiation and begins to heat up. This heating stops the dynamic collapse near the cloud's centre and forms a quasistatic core with a size of $\sim$ 5 AU [14]. The quasistatic core cannot collapse further to form a star until it has accreted more gas and 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 [15,16]. Thus, resolving the calculation up to and beyond 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

The calculation is being performed using a parallelised version of the three-dimensional smoothed particle hydrodynamics (SPH) code described in [17] on the United Kingdom Astrophysical Fluids Facility (UKAFF), a 128-processor SGI Origin 3000. The code uses a tree structure to calculate gravity and neighbouring particles. High-density gravitationally-bound objects consisting of many SPH gas particles are replaced during the calculation by 'sink' particles. These massive particles interact with the rest of the calculation only via gravity and accrete any SPH gas particles that come within a predefined accretion radius.

The initial conditions consist of an initially uniform-density, spherical cloud of molecular gas with mass of 50 $M_\odot$ and a radius of ≈ 0.2 pc. At a temperature of 10 K, this results in a mean thermal Jeans mass of 1 $M_\odot$ (i.e. the cloud contains 50 initial Jeans masses). Although the cloud is uniform in density, we impose an initial supersonic turbulent velocity field on it in the same manner as [18]. We generate a divergence-free random Gaussian velocity field with a power spectrum $P(k) \propto k^{-4}$. In three-dimensions, this results in the velocity dispersion varying with distance, λ, as $\sigma(\lambda) \propto \lambda^{1/2}$ in agreement with the observed Larson scaling relations for molecular clouds [19]. Burger's supersonic turbulence also produces this power spectrum.

2.2 Resolution

One of the goals of this calculation is to resolve the collapse beyond the density at which the gas becomes non-isothermal so that we reach the opacity limit for fragmentation. To model the thermal behaviour of the gas, we use an equation of state that changes from isothermal to barotropic with an adiabatic index of $\gamma = 7/5$ at $\rho = 10^{-13}$ g cm^{-3} (see [15]). Then, once the density in an optically-thick quasistatic core passes $\rho \approx 10^{-11}$ g cm^{-3}, we replace the quasistatic core with a 'sink' particle having an accretion radius of 5 AU. We cannot follow the collapse of quasistatic cores all the way to the actual formation of the stars (as done in [15]) while simultaneously following the evolution of the large-scale cloud: the range of dynamical timescales would be too large.

We must ensure that we have sufficient resolution to resolve the local Jeans mass throughout the calculation [6,7]. The minimum Jeans mass occurs at the maximum density during the isothermal phase of the collapse, $\rho = 10^{-13}$ g cm^{-3}, and is 0.0014 $M_\odot$ (1.4 Jupiter masses). The Jeans mass must be resolved by a minimum of ≈ 100 SPH particles [6]. Thus, we use 3.5×10^6 particles to model the 50 $M_\odot$ cloud.

3 Results and discussion

The divergence-free turbulent velocity field quickly evolves to produce converging flows that result in shocks. Initially, the dense structures formed by the shocks are transient, but as the turbulence decays, dense, self-gravitating cores begin to form. The largest of these cores (≈ 0.05 pc across) undergoes collapse first and forms filamentary structures in which 'stars' form (Figure 1). The stars begin as very low-mass fragments (~ 0.01 $M_\odot$, set by the opacity limit) that accrete up to their final masses. First to form is a binary system with a separation of ≈ 30 AU surrounded by a circumbinary disc that later fragments to form 3 objects. Two of these are quickly ejected in a chaotic interplay which terminates their accretion and fixes their masses to be in the brown dwarf regime. In other parts of the core, four single stars – each surrounded by a disc of radius ~ 100 AU – and another multiple system form. Such a mixture of single and multiple systems and the sizes of the circumstellar discs are consistent with observed pre-main-sequence systems. Eventually, 16 objects form. Most fall together into a small cluster which subsequently breaks up by ejecting the low-mass members.

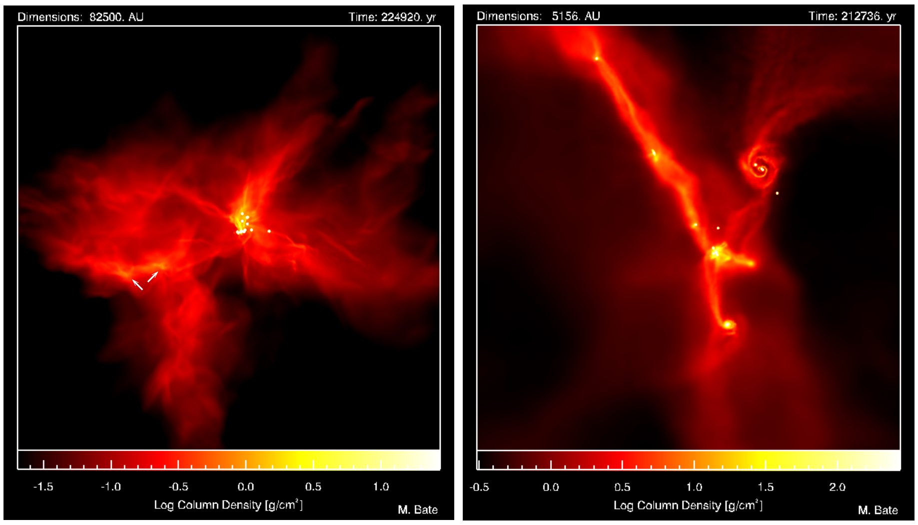

Fig. 1. Column density plots of the molecular cloud during the calculation. *Left:* A view of the entire cloud. The most massive dense core (*near the centre*) forms 10 stars and 6 brown dwarfs. The two smaller cores (*arrows*) are about to form more stars. *Right:* A snapshot of the fragmentation inside the most massive core. A multiple system with circumstellar disc is clearly visible with several single stars and another multiple system forming in the 'filament'.

Of the 16 objects formed in the collapse of the most massive core, 10 have stellar masses and 6 are brown dwarfs. The brown dwarfs contain only 3% of the total mass of these objects. The these numbers are consistent with current observations of stellar clusters [20] (i.e. a large number of brown dwarfs that do not contain a significant fraction of the mass).

An unsolved problem in the field of star formation is how brown dwarfs form. The typical Jeans mass in molecular clouds is thought to be ~ 1 $M_\odot$ or greater. Thus, a typical collapsing molecular cloud core should have roughly this mass. Although the cloud core collapses inhomologously, forming one or more low-mass quasistatic cores at the opacity limit for fragmentation, the majority of the envelope should subsequently accrete onto these objects, increasing their masses to those of stars. Thus, there are two possible ways to form field brown dwarfs. Either they must form from particularly dense, low-mass cloud cores (since to have a low total mass while remaining gravitationally unstable they must be very dense), or they must form in typical cores but somehow avoid accreting much of the envelope. The latter is possible if a brown dwarf forms in a multiple system and is quickly ejected (e.g. Reipurth, this volume). In the calculation presented here, without exception, the brown dwarfs are formed in dynamically-unstable multiple systems and are ejected before they can accrete much gas.

The calculation produces both single stars and multiple systems with masses ranging from 0.6 to 0.008 $M_\odot$. However, there are some potential problems which

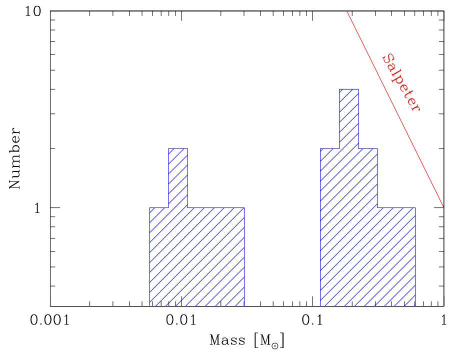

Fig. 2. The mass distribution of the 10 stars and 6 brown dwarfs produced in the calculation thus far. The stellar mass function peaks at ~ 0.2 $M_\odot$, in agreement with observations, but all of the brown dwarfs have very low masses resulting in a gap in the range $0.03 - 0.10$ $M_\odot$.

bear watching as we continue the calculation. Figure 2 gives the mass function of the 16 objects. While the stellar mass function peaks at ~ 0.2 $M_\odot$ in reasonable agreement with observations, all of the brown dwarfs have very low masses. Indeed, there are no objects with masses between $0.03 - 0.10$ $M_\odot$. The brown dwarfs seem to be ejected too quickly, before they have accreted much mass at all. Furthermore, all of the brown dwarfs are single, whereas several binary brown dwarf systems have been found [20]. This is perhaps the most serious problem with the ejection scenario for brown dwarf formation – how are binary brown dwarfs ejected? It is essential that further surveys of field brown dwarfs are performed in order to determine their binarity accurately.

Another potential problem with the calculation is that, although the initial fragmentation of the largest core produces 4 single stars, 2 multiple systems, and discs with radii ~ 100 AU, the stars fall together to form a small bound cluster. This cluster subsequently breaks up into 12 single objects and 2 binary systems and all but two of the large circumstellar discs are destroyed by dynamical interactions (note that we cannot resolve discs smaller than ≈ 10 AU). The high number of single objects is worrying as most stars are observed to be members of binary systems [21]. On the other hand, if only the stellar-mass objects are considered, we have 6 single stars and 2 binaries which, given the small numbers, is reasonable. Again we return to the question of the true frequency of binary brown dwarf systems.

We stress that the results given above are preliminary in that only 6% of the total cloud mass has been converted to stars and brown dwarfs thus far. In particular, there are two lower-mass cores that will shortly form stars. Since each of these cores is likely to produce fewer objects than the largest core, we expect that they may also produce stars with a higher binary fraction. We are continuing the calculation to clarify this.

4 Conclusions

We have presented preliminary results from the first hydrodynamical calculation to follow the collapse and fragmentation of a large-scale turbulent molecular cloud core to form a stellar cluster while resolving beyond the opacity limit for fragmentation. We find

- the initial fragmentation produces a mixture of single stars and multiple systems with typical circumstellar disc sizes of ~ 100 AU
- stars and brown dwarfs are formed in roughly equal numbers, but the stars contain the vast majority of the mass
- all of the brown dwarfs are formed via ejections from multiple systems before they have been able to accrete much mass, but they all have very low masses
- the stellar mass function is in agreement with the observed stellar IMF.

This calculation and similar calculations in the future will allow us to obtain theoretical predictions of the statistical properties of stellar systems for the first time. It is essential that these properties are determined observationally so that the models can be tested and refined. The VLT and other large telescopes will play an important role in obtaining these observations.

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