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The formation mechanism of brown dwarfs

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ABSTRACT

We present results from the first hydrodynamical star formation calculation to demonstrate that brown dwarfs are a natural and frequent product of the collapse and fragmentation of a turbulent molecular cloud. The brown dwarfs form via the fragmentation of dense molecular gas in unstable multiple systems and are ejected from the dense gas before they have been able to accrete to stellar masses. Thus, they can be viewed as 'failed stars'. Approximately three-quarters of the brown dwarfs form in gravitationally unstable circumstellar discs while the remainder form in collapsing filaments of molecular gas. These formation mechanisms are very efficient, producing roughly the same number of brown dwarfs as stars, in agreement with recent observations. However, because close dynamical interactions are involved in their formation, we find a very low frequency of binary brown dwarf systems ($\lesssim 5$ per cent) and that those binary brown dwarf systems that do exist must be close, $\lesssim 10$ au. Similarly, we find that young brown dwarfs with large circumstellar discs (radii $\gtrsim 10$ au) are rare (≈ 5 per cent).

Key words: accretion, accretion discs – hydrodynamics – binaries: general – circumstellar matter – stars: formation – stars: low-mass, brown dwarfs.

1 INTRODUCTION

The existence of brown dwarfs was incontrovertibly demonstrated for the first time by the discovery of Gliese 229B (Nakajima et al. 1995), a cool brown dwarf orbiting an M dwarf. In the same year, other candidates later confirmed to be free-floating brown dwarfs were announced (e.g. Teide 1 by Rebolo, Zapatero-Osorio & Martin 1995), along with PPl 15 which was later discovered to be a binary brown dwarf (Basri & Martin 1999). Observations now suggest that brown dwarfs are as common as stars, although stars dominate in terms of mass (e.g. Reid et al. 1999).

Despite the abundance of brown dwarfs, their formation mechanism is currently a mystery. The typical thermal Jeans mass in molecular cloud cores is $\approx 1\,M_\odot$ (Larson 1999 and references therein). Thus, the gravitational collapse of these cores 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 [$n(H_2) \gtrsim 10^7\,cm^{-3}$] 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'. Such low-mass bound cores have not yet been observed, but they would be difficult to detect because of their small sizes and low masses, and rarely detected owing to their short dynamical time-scales ($\sim 10^4$ yr). Observations are beginning to reach this mass regime (e.g. Motte, André & Neri 1998), although the low-mass clumps found thus far probably are not gravitationally bound (Johnstone et al. 2000).

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) and Watkins et al. (1998b).

In this Letter, we present results from the first hydrodynamical calculation to demonstrate that a large number of brown dwarfs can be formed during the fragmentation of a molecular cloud. All the brown dwarfs are formed by the ejection of fragments from unstable multiple systems. In Section 2, we briefly describe the numerical method and the initial conditions for our calculation. In Section 3, we present results from our calculation and compare them with observations. Finally, in Section 4, we give our conclusions.

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2 COMPUTATIONAL METHOD AND INITIAL CONDITIONS

The calculation presented here was performed using a three-dimensional, smoothed particle hydrodynamics (SPH) code based on a version originally developed by Benz (Benz 1990; Benz et al. 1990). The smoothing lengths of particles vary in time and space, such that the number of neighbours for each particle remains approximately constant at $N_{\rm neigh} = 50$. We use the standard form of artificial viscosity (Monaghan & Gingold 1983) with strength parameters $\alpha_{\rm v} = 1$ and $\beta_{\rm v} = 2$. Further details can be found in Bate, Bonnell & Price (1995). The code has been parallelized by M. Bate using OpenMP.

2.1 Opacity limit for fragmentation and the equation of state

When the collapse of a molecular cloud core begins, the gravitational potential energy released easily radiates away so that the collapsing gas is approximately isothermal (e.g. Larson 1969). Thus, the thermal pressure varies with density ρ as $p \propto \rho^{\eta}$ where the effective polytropic exponent, $\eta \equiv {\rm d}\log[p]/{\rm d}\log[\rho] \approx 1$. Fragmentation is allowed because the Jeans mass decreases with increasing density if $\eta < 4/3$.

The opacity limit for fragmentation occurs when the rate at which energy is released by the collapse exceeds the rate at which the gas can cool (Low & Lynden-Bell 1976; Rees 1976). The gas then heats up with $\eta > 4/3$, the Jeans mass increases, and a Jeans-unstable collapsing clump quickly becomes Jeans-stable so that a pressure-supported fragment forms. The gas begins to heat significantly at a density of $\approx 10^{-13}\,{\rm g\,cm^{-3}}$ (Masunaga & Inutsuka 2000).

The pressure-supported fragment initially contains several Jupiter masses ($\rm M_J$) and has a radius of ≈ 5 au (Larson 1969). Such a fragment is expected to be embedded within a collapsing envelope; thus, its mass grows with time. Although these fragments later undergo another phase of collapse due to the dissociation of molecular hydrogen (Larson 1969) in order to become stars (or brown dwarfs), they are unlikely to sub-fragment (e.g. Boss 1989; Bate 1998; Bate, in preparation). Thus, the opacity limit sets a minimum fragment mass of $\approx 10\,\rm M_J$ (Boss 1988).

To model the opacity limit for fragmentation without performing full radiative transfer, we use a gas equation of state given by $p = K\rho^{\eta}$, where K is a measure of the entropy of the gas. The value of η varies with density as

$$\eta = \begin{cases} 1, & \rho \le 10^{-13}\,{\rm g\,cm^{-3}}, \\ 7/5, & \rho > 10^{-13}\,{\rm g\,cm^{-3}}. \end{cases} \tag{1}$$

We take the mean molecular weight of the gas to be $\mu = 2.46$. The value of K is defined such that when the gas is isothermal $K = c_{\rm s}^2$, with $c_{\rm s} = 1.84 \times 10^4\,{\rm cm\,s^{-1}}$ at 10 K, and the pressure is continuous when the value of η changes.

This equation of state reproduces the temperature–density relation of molecular gas during spherically symmetric collapse (as calculated with frequency-dependent radiative transfer) to an accuracy of better than 20 per cent in the non-isothermal regime up to densities of $10^{-8}\,{\rm g\,cm^{-3}}$ (Masunaga & Inutsuka 2000). Thus, our equation of state should model collapsing regions well, but may not model the equation of state in protostellar discs particularly accurately due to their departure from spherical symmetry.

2.2 Sink particles

The opacity limit results in the formation of distinct pressure-supported fragments. As these fragments accrete, their central density increases, and it becomes computationally impractical to follow their internal evolution due to the short dynamical time-scales involved. Therefore, when the central density of a fragment exceeds $10^{-11}\,{\rm g\,cm^{-3}}$, we insert a sink particle into the calculation (Bate et al. 1995). Gas within radius $r_{\rm acc} = 5$ au of the centre of the fragment (i.e. the location of the SPH particle with the highest density) is replaced by a point mass with the same mass and momentum. The fragment is only replaced if it is gravitationally bound. Any gas that later falls within this radius is accreted by the point mass if it is bound. Thus, we can only resolve discs around sink particles if they have radii $\gtrsim 10$ au.

Since all sink particles are created from the pressure-supported fragments, their initial masses are $\approx 10\,\rm M_J$, as given by the opacity limit for fragmentation. Subsequently, they may accrete large amounts of material to become higher-mass brown dwarfs ($\lesssim 75\,\rm M_J$) or stars ($\gtrsim 75\,\rm M_J$).

The gravitational acceleration between two sink particles is Newtonian for $r \ge 4$ au, but is softened within this radius using spline softening (Benz 1990). The maximum acceleration occurs at a distance of ≈ 1 au; therefore, this is the minimum binary separation that can be resolved.

2.3 Initial conditions

The initial conditions consist of a large-scale, turbulent molecular cloud. The cloud is spherical and uniform in density with a mass of $50\,\rm M_\odot$ and a diameter of 0.375 pc. At the temperature of 10 K, the mean thermal Jeans mass is $1\,\rm M_\odot$ (i.e. the cloud contains 50 thermal Jeans masses). An initial supersonic turbulent velocity field is imposed on the cloud in the same manner as Ostriker, Stone & Gammie (2001). We generate a divergence-free random Gaussian velocity field with a power spectrum $P(k) \propto k^{-4}$, where k is the wavenumber. In three dimensions, this gives a velocity dispersion that varies with distance, λ, as $\sigma(\lambda) \propto \lambda^{1/2}$ in agreement with the observed Larson scaling relations for molecular clouds (Larson 1981). The velocity field is normalized so that the kinetic energy of the turbulence equals the magnitude of the gravitational potential energy of the cloud.

2.4 Resolution

The local Jeans mass must be resolved throughout the calculation to model fragmentation correctly (Bate & Burkert 1997; Truelove et al. 1997; Whitworth 1998). Bate & Burkert (1997) found that this requires $\gtrsim 2N_{\rm neigh}$ SPH particles per Jeans mass; $N_{\rm neigh}$ is insufficient. We have repeated their calculation using different numbers of particles and find that $1.5N_{\rm neigh} = 75$ particles is also sufficient to resolve fragmentation (Bate, Bonnell & Bromm, in preparation). The minimum Jeans mass in the calculation presented here occurs at the maximum density during the isothermal phase of the collapse, $\rho = 10^{-13}\,{\rm g\,cm^{-3}}$, and is $\approx 0.0011\,\rm M_\odot$ ($1.1\,\rm M_J$). Thus, we use 3.5×10^6 particles to model the 50-$\rm M_\odot$ cloud. The calculation required approximately 95 000 CPU hours on the SGI Origin 3800 of the United Kingdom Astrophysical Fluids Facility (UKAFF).

3 RESULTS

3.1 Evolution of the cloud

The hydrodynamical evolution of the cloud produces shocks that decrease the turbulent energy that initially supported the cloud. In parts of the cloud, gravity begins to dominate and dense self-gravitating cores form and collapse. These dense cores are the sites where the formation of stars and brown dwarfs occurs. In all, 23 stars and 18 brown dwarfs are produced. An additional nine objects have substellar masses when we stop the calculation, but are still accreting. Three of these are likely to remain substellar, but the other six would probably become stars. The evolution of the cloud and the properties of the stars and brown dwarfs will be discussed in detail in subsequent papers. In this Letter, we concentrate on the mechanism by which the brown dwarfs form.

3.2 The formation of brown dwarfs

Although the thermal Jeans mass is initially $1\,M_{\odot}$, the cloud produces roughly equal numbers of brown dwarfs and stars. By what mechanism(s) do these brown dwarfs form?

As mentioned in Section 2.2, all the stars and brown dwarfs begin as fragments whose initial masses are given by the opacity limit for fragmentation. Thus, *all the objects begin with masses of a few Jupiter masses*. Those that become stars subsequently accrete large quantities of gas from the dense cores in which they form, while those that remain as brown dwarfs do not.

Without exception, we find that those objects that end up as brown dwarfs begin as opacity-limited fragments in dynamically unstable multiple systems and are ejected before they can accrete enough gas to become stars. In no case does a dense core collapse to form a single brown dwarf or a binary brown dwarf system alone. This general mechanism has been proposed by Reipurth & Clarke (2001) and Watkins et al. (1998b), but the main processes involved in the formation of the unstable multiple systems and the resulting properties of the brown dwarfs could only be conjectured.

By tracing the evolution of the brown dwarfs in our calculation back to their fragmentation out of the gas, we find that brown dwarfs form in two different ways. Roughly three quarters (14 of the 18 definite brown dwarfs) form via the fragmentation of gravitationally unstable circumstellar discs (e.g. Fig. 1, opposite p. L68). The discs fragment due to rapid accretion (e.g. Bonnell 1994; Bonnell & Bate 1994a,b; Whitworth et al. 1995; Burkert, Bate & Bodenheimer 1997) and/or tidal-perturbations during stellar encounters (Boffin et al. 1998; Watkins et al. 1998a,b). The fragments destined to become brown dwarfs then interact with the stars and brown dwarfs to which they are bound until they are ejected from the dense gas, limiting their masses to be substellar. The remaining brown dwarfs (4 of the 18) originate from the fragmentation of dynamically collapsing, filamentary molecular gas (e.g. Fig. 2, opposite p. L68; Bonnell et al. 1991). The fragments initially form on their own, but quickly fall into unstable multiple systems and are ejected from the dense gas before they can attain stellar masses. This latter mechanism is similar to that discussed by Reipurth & Clarke (2001).

Although the initial thermal Jeans mass in the cloud is $1\,M_{\odot}$, the gas in the circumstellar discs and dynamically collapsing gas is at a much higher density. Thus, the local Jeans mass and Jeans length are much smaller (both scale with density as $\rho^{-1/2}$). Consequently, when gravitational collapse occurs in such an environment, the opacity-limited fragment that forms has a very limited reservoir of gas from which to accrete. In order to attain a large mass it must accrete most of its mass from distances much greater than the Jeans length of the gravitationally unstable clump from which it formed. However, since it is in a multiple system it must compete for the gas (e.g. Bonnell et al. 1997). Furthermore, in an unstable multiple system, the most frequently ejected object is that having the lowest mass (van Albada 1968). These two constraints frequently conspire to eject a low-mass fragment from the dense gas in which it forms before it has accreted enough gas to become a star.

If brown dwarfs are produced by ejection from multiple systems, one might expect the fraction of binary brown dwarfs to be low since the binary must be ejected without being disrupted. However, a close binary brown dwarf might be ejected from a multiple system and avoid disruption if the other components of the system were widely separated.

This calculation does not produce any definite binary brown dwarfs, but at the end of the calculation there is a close binary brown dwarf within an unstable multiple system. The system consists of seven objects. The close binary brown dwarf (semimajor axis 6 au) is in a hierarchical binary (semimajor axis 84 au, eccentricity 0.20) with a close stellar binary (semimajor axis 7 au). This quadruple system orbits a triple system at 330 au with an eccentricity of 0.18. The triple system consists of a close (9 au) stellar binary orbited by a brown dwarf companion (semimajor axis 90 au, eccentricity 0.82). This system is dynamically unstable and will undergo further evolution. Unfortunately, we are unable to follow it any further. Since the binary brown dwarf is very close, it is possible that it will survive the dissolution of this multiple system. Even so, this would result in only one binary brown dwarf system and ≈ 20 single brown dwarfs. We therefore conclude that the formation of close binary brown dwarfs may be possible, but the fraction of brown dwarfs with a brown dwarf companion is very low ($\lesssim 5$ per cent).

Observationally, the frequency of brown dwarf binaries is not yet clear. Reid et al. (2001) find that four out of 20 brown dwarf primaries have companions giving a fraction of ≈ 20 per cent. However, this survey is magnitude-limited rather than volume-limited and is therefore likely to overestimate the true frequency of brown dwarf binaries. It is interesting to note that none of the binary brown dwarf systems currently known has projected separation > 10 au (Reid et al. 2001). This is consistent with their having survived ejection from unstable multiple systems.

Similarly, the survival of large discs around brown dwarfs is not an obvious outcome of the ejection mechanism of brown dwarf formation. Of the 18 definite brown dwarfs, most have close dynamical encounters ($\lesssim 20$ au for 14 of the 18). Of the remaining four, three are ejected before they can accrete gas with the high specific angular momentum required to form large discs. Only one brown dwarf is ejected with a resolved disc (radius ≈ 60 au). The other brown dwarfs are likely to possess smaller discs, but in this calculation we are unable to resolve discs with radii $\lesssim 10$ au (Section 2.2). Muench et al. (2001) find that ≈ 65 per cent of brown dwarfs in the Orion Trapezium cluster have infrared excesses indicative of discs. Our results show that if brown dwarfs are formed by the ejection mechanism, most of these discs should have radii $\lesssim 10$ au.

Most brown dwarfs in our calculation are produced via gravitational instabilities in massive discs. The ease with which disc fragmentation occurs depends primarily on the rate at which it accretes mass from the surrounding cloud (Bonnell 1994) and the equation of state of the disc (e.g. Pickett et al. 2000). The density of the gas in the discs that fragment to form brown dwarfs is high enough that the gas is in the $\eta = 7/5$ regime (Section 2.1). Thus, the gas resists fragmentation far more than it would if an isothermal equation of state was used, although our equation of state does not include heating from shocks. On the other hand, because the flattened disc geometry may allow more rapid cooling than a spherically symmetric geometry, real discs may be cooler and more unstable than those we model here. Hence, the number of brown dwarfs may be even greater. Another factor is that stars and brown dwarfs cannot merge in our calculation. Mergers may reduce the final number of brown dwarfs. In summary, a more definitive prediction will have to wait until a large-scale calculation is performed with radiative transfer and even higher resolution. For the present, we have demonstrated that the fragmentation of a turbulent molecular cloud is capable of forming similar numbers of brown dwarfs and stars. This is in agreement with observational surveys of brown dwarfs in the solar neighbourhood (Reid et al. 1999) and in clusters (e.g. Luhman et al. 2000 and references therein).

4 CONCLUSIONS

We have presented results from the first calculation to demonstrate the formation of brown dwarfs from the fragmentation of a turbulent molecular cloud. The calculation resolves the opacity limit for fragmentation and follows numerous brown dwarfs until accretion onto them has ceased.

We find that the star formation process produces roughly equal numbers of stars and brown dwarfs, in agreement with recent observations. Examining the mechanisms by which the brown dwarfs form, we find that they are the result of the ejection of fragments from the dense gas in which they form by dynamical interactions in unstable multiple systems. This occurs before they are able to accrete to stellar masses. Three quarters of the brown dwarfs fragment out of gravitationally unstable discs, while the remainder form in collapsing filamentary flows of high-density gas.

The calculation indicates that close binary brown dwarf systems (separations $\lesssim 10$ au) might be able to survive the ejection process. However, such systems should be very rare (frequency $\lesssim 5$ per cent) because of the close dynamical interactions that are involved in the ejection of brown dwarfs. Similarly, large discs (radii $\gtrsim 10$ au) around young brown dwarfs should also be rare (frequency ≈ 5 per cent). Observations show that close binary brown dwarfs and circumstellar discs surrounding brown dwarfs do exist, but more detailed surveys are required to test the predictions made here.

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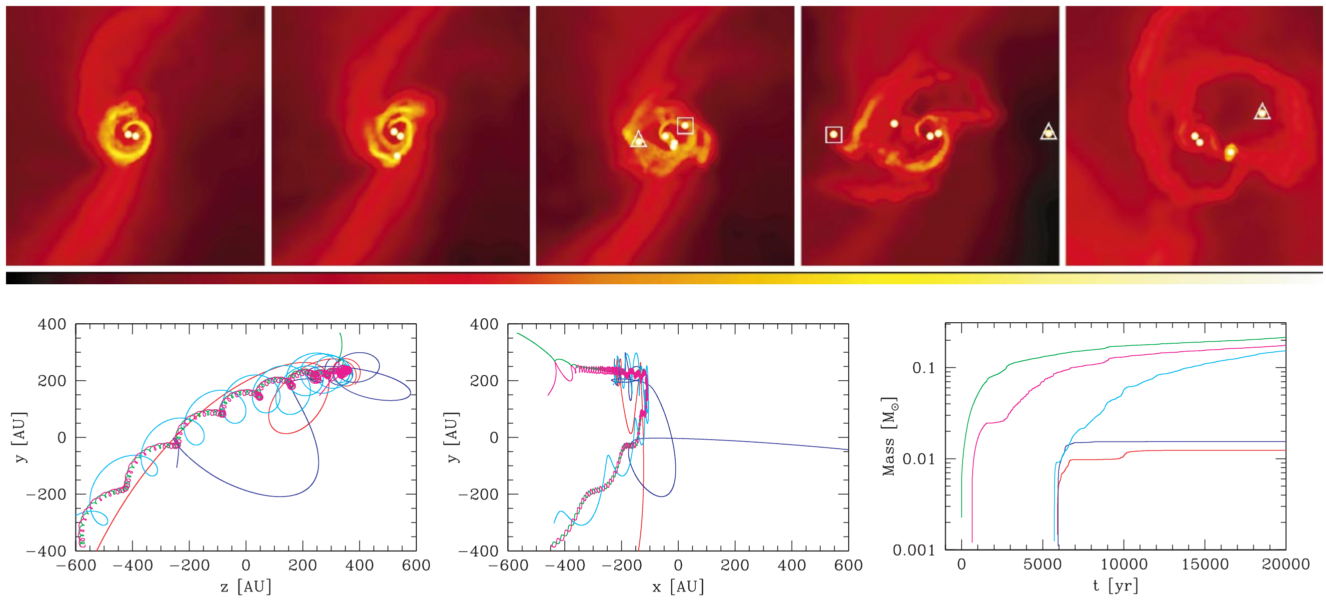

Figure 1. Top panels: time sequence showing the formation of two brown dwarfs via disc fragmentation. Spiral density waves in a gravitationally unstable circumbinary disc (panel 1; $t = 5160$ yr) fragment to form a third star (panel 2; $t = 5735$ yr) and two brown dwarfs (panel 3; $t = 6020$ yr). The resulting multiple system undergoes chaotic evolution. The first brown dwarf (box; red lines) is eventually ejected from the system, while the second is put into a highly eccentric orbit (panel 4; $t = 10\,490$ yr). Much later the second brown dwarf (triangle; blue lines) is also ejected (panel 5; $t = 17\,340$ yr) leaving a hierarchical triple system. Each panel is 600 au across. The colour scale shows the logarithm of column density ranging from 3×10^{-1} to 3×10^{3} g cm^{-2}. Lower panels: the trajectories and masses of the five objects during the ejection of the two brown dwarfs. The left panel has the same orientation as the time sequence. The centre panel shows the third dimension. The right panel shows the evolution of the masses of the objects. When the brown dwarfs are ejected from the dense gas accretion on to them is halted and they are consequently unable to attain stellar masses. Times are given in years from the beginning of star formation in the cloud.

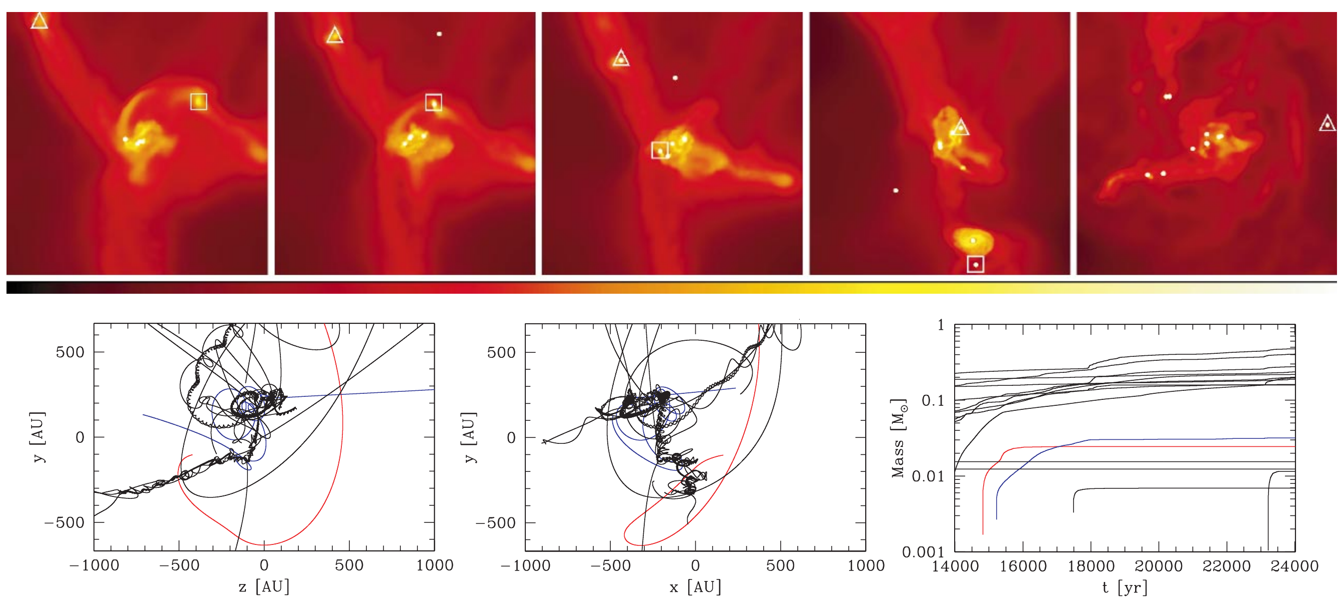

Figure 2. Top panels: time sequence showing the formation of two brown dwarfs via the fragmentation of collapsing filaments of molecular gas. Two brown dwarfs (box, triangle; red and blue lines) fragment out of filaments (panels 1, 2 and 3; $t = 14\,300$, $14\,870$ and $15\,440$ yr). Both fall towards an existing multiple system, one almost radially along its filament (triangle). The first brown dwarf (square; red line) is quickly ejected from the multiple system (panels 3 and 4; $t = 15\,440$ and $17\,150$ yr). Much later, after several crossing times of the multiple system, the second brown dwarf (triangle; blue line) is also ejected (panel 5; $t = 23\,710$ yr). Each panel is 1000 au across. The colour scale shows the logarithm of column density ranging from 3×10^{-1} to 3×10^{3} g cm^{-2}. Lower panels: The trajectories and masses of the objects during the ejection of the two brown dwarfs. The left panel has the same orientation as the time sequence. The centre panel shows the third dimension. The right panel shows the evolution of the masses of the objects. When the brown dwarfs are ejected from the dense gas, accretion onto them is halted and they are consequently unable to attain stellar masses. Times are given in years from the beginning of star formation in the cloud. For clarity, only the trajectories of the two brown dwarfs are coloured.