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How do brown dwarves form?

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Abstract. We review and evaluate four mechanisms for forming brown dwarves: (i) dynamical ejection of a stellar embryo from its placental prestellar core; (ii) opacity-limited fragmentation of a shock-compressed layer; (iii) gravitational instabilities in discs, triggered by impulsive interactions with other discs or naked stars; and (iv) photo-erosion of pre-existing cores. All these mechanisms can produce free-floating brown dwarves, but only (ii) and (iii) are likely to produce brown dwarves in multiple systems, and (i) has difficulty delivering brown dwarves with discs.

Key words. Star Formation - Brown Dwarves

1. Introduction

The existence of brown dwarves was first proposed on theoretical grounds by Kumar (1963a,b) and by Hayashi & Nakano (1963). However, more than three decades passed before brown dwarves were observed unambiguously (Rebolo et al., 1995; Nakajima et al., 1995; Oppenheimer et al., 1995). Brown dwarves are now observed routinely (McCaughrean et al., 1995; Luhman et al. 1998; Wilking et al. 1999; Luhman & Rieke, 1999; Lucas & Roche, 2000; Martín et al., 2000; Luhman et al., 2000; Béjar et al., 2001; Martín et al., 2001; Wilking et al., 2002; McCaughrean et al., 2002; etc.), and so it is appropriate to ask how such low-mass objects are formed. In particular, astronomers are concerned with the question of whether brown dwarves form in the same way as more massive stars, and whether there is a dividing line between the mechanisms that produce stars and those that produce planetary-mass objects.

This paper is concerned with four possible mechanisms for forming brown dwarves. Section 2 considers the possibility that brown dwarves are formed when low-mass protostellar embryos are ejected from their placental prestellar cores before they can accrete sufficient mass to ignite hydrogen (Reipurth & Clarke, 2001). Section 3 considers the possibility that brown dwarves are formed by opacity-limited fragmentation in turbulent molecular clouds. Section 4 considers the possibility that brown dwarves are formed by gravitational instabilities in circumstellar discs, in particular circumstellar discs which are subject to impulsive perturbations due to interactions with other discs or with naked stars. Section 5 considers the possibility that brown dwarves are formed by the photo-erosion of more massive cores which find themselves overrun by HII regions (Hester. 1997). Section 6 summarizes our main conclusions

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2. Ejection

The collapse and fragmentation of a prestellar core is unlikely to lead to the formation of a single star. Even quite modest levels of turbulence (e.g. Goodwin, Whitworth & Ward-Thompson 2004a) and/or global rotation (e.g. Cha & Whitworth, 2003; Hennebelle et al. 2003, 2004) are sufficient to ensure the formation of a small-N cluster of protostars, which then grow by competitive accretion and interact dynamically (Whitworth et al., 1995; Bonnell et al., 2001). Protostars that get ejected from the core before they have had time to grow to $0.08\,\mathrm{M}_\odot$, end up as brown dwarves (Reipurth & Clarke, 2001). It seems inescapable that this mechanism occurs, since all that is required is the formation and coexistence of more than two protostars in a core, with one of them being less massive than $0.08\,\mathrm{M}_\odot$; N-body dynamics will then almost inevitably eject one of the stars, and usually the least massive one.

Several numerical simulations have been performed, using SPH with sink particles, to demonstrate this mechanism at work, both in cores with very high levels of turbulence (Bate, Bonnell & Bromm, 2002; Delgado-Donate, Clarke & Bate, 2003, 2004), and in cores with more modest levels of turbulence (Goodwin, Whitworth & Ward-Thompson, 2004a,b,c).

The main concern with these simulations is that, by invoking sink particles, protostellar embryos are instantaneously converted into point masses. This predisposes them to dynamical ejection, and prohibits them from merging or fragmenting further. Therefore the efficiency of the mechanism may have been overestimated, although probably not by much.

Additional support for the mechanism comes from the recent paper by Goodwin et al. (2004b), which presents an ensemble of simulations of the collapse and fragmentation of cores having a mass spectrum, density profiles, and low levels of turbulence, matched to those observed in Taurus. These simulations reproduce rather well the unusual stellar mass function observed in Taurus (Luhman et al., 2003), including the relative paucity of brown dwarves. As far as we are aware, these are the first simulations to demonstrate a direct causal connection between the core mass spectrum and the stellar initial mass function.

However, ejection is unlikely to be the only mechanism forming brown dwarves, since it seems very unlikely to produce brown dwarves in multiple systems. It is also unclear whether ejected brown dwarves can retain the discs which seem to be needed to explain the significant fraction of brown dwarves having IR excesses and other signatures of on-going accretion.

3. Opacity-limited fragmentation

Conventionally, the minimum mass for star formation has been evaluated on the basis of the 3D hierarchical fragmentation picture developed by Hoyle (1953). In this picture, a large protocluster cloud becomes Jeans unstable and starts to contract. As long as the sound speed in the gas remains approximately constant, the increasing density reduces the Jeans mass, and eventually separate parts of the cloud (subclouds) become Jeans unstable and can contract independently of one another. This process repeats itself recursively, breaking the cloud up into ever smaller and denser subsub...subclouds, until the gas becomes so opaque that it can no longer radiate away the gravitational energy being released by contraction. At this stage the gas starts to heat up, and fragmentation ceases. This yields a minimum mass in the range $M_{\rm MIN} \sim 0.007\,\mathrm{M}_\odot$ to $M_{\rm MIN} \sim 0.015\,\mathrm{M}_\odot$ (e.g. Rees, 1976; Low & Lynden-Bell, 1976; Silk, 1977).

However, it appears that 3D hierarchical fragmentation does not work. There is no evidence of its occuring in nature, nor does it occur in numerical simulations of star formation. Therefore one must question estimates of $M_{\rm MIN}$ based on 3D hierarchical fragmentation. The reason 3D hierarchical fragmentation does not work probably has to do with the fact the timescale on which a fragment condenses out in 3D is always longer than the timescale on which the parent cloud (of which it is part) is contracting. Therefore fragmentation, if it occurs at all, is only temporary, and the fragments are then merged by the overall contraction of

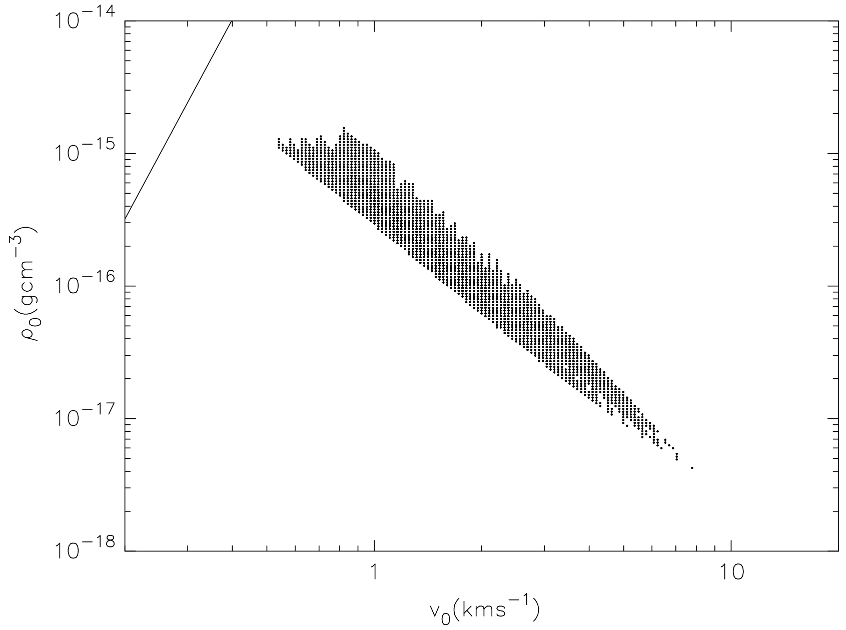

Fig. 1. A log/log plot of the (ρ, v) plane. The dots mark combinations of pre-shock density. ρ, and collision speed, v, for which the fastest growing fragment has a mass less than 0.005 $M_\odot$; we assume that the effective post-shock sound speed is $\sigma = 0.2\,\mathrm{km\,s^{-1}}$, corresponding to molecular gas at 10 K. The irregularities in the boundaries of this region reflect the tendency of low-mass fragments to undergo pulsations before they collapse. The solid line is the locus below which ρ must fall if our treatment of the radiation from the accretion shock is to be valid; see Boyd & Whitworth (2004) for details.

the parent cloud. The only way to avoid this is to start with proto-fragments which are widely spaced, but then the rate of accretion onto a fragment is very high, and even if it starts off with mass $M_{\rm FRAG} \sim M_{\rm JEANS}$, it will have grown much more massive by the time its contraction becomes non-linear.

We have therefore revisited the question of the minimum mass for star formation, but now using a model which invokes 2D one-shot fragmentation of a shock-compressed layer. We argue that this model is more relevant to the contemporary picture of 'star formation in a crossing time' (Elmegreen, 2000). In this picture star formation occurs in molecular clouds wherever two – or more – turbulent flows of sufficient density collide with sufficient ram pressure to produce a shock-compressed layer out of which prestellar cores can condense. This model is 2D because fragmentation of a shock-compressed layer is in effect two-dimensional (the motions which initially assemble a fragment are in the plane of the layer), and it is 'one-shot' in the sense of not being hierarchical or recursive.

A shock compressed layer is contained by the ram pressure of the inflowing gas, and until it fragments it has a rather flat density profile. Normally it fragments whilst it is still accumulating, at time $t_{\rm FRAG}$, and the fastest growing fragment has mass $m_{\rm FRAG}$, radius $r_{\rm FRAG}$ (in the plane of the layer) and half-thickness $z_{\rm FRAG}$ (perpendicular to the plane of the layer) given by

$$t_{\rm FRAG} = (\sigma / G \rho v)^{1/2} , \qquad (1)$$

$$m_{\rm FRAG} = \left(\sigma^7 / G^3 \rho v\right)^{1/2} , \qquad (2)$$

$$r_{\rm FRAG} = \left(\sigma^3 / G \rho v\right)^{1/2} , \qquad (3)$$

$$z_{\rm FRAG} = \left(\sigma^5 / G \rho v^3\right)^{1/2} , \quad (4)$$

where σ is the net velocity dispersion in the shock-compressed layer, ρ is the pre-shock density in the colliding flows, and v is the relative speed with which the flows collide. We note (a) that the fragments are initially flattened objects ($r_{\rm FRAG}/z_{\rm FRAG} \sim v/\sigma \gg 1$), and (b) that $m_{\rm FRAG}$ is not simply the 3D Jeans mass evaluated at the post-shock density and velocity dispersion – it is larger by a factor $(v/\sigma)^{1/2}$.

2D one-shot fragmentation has the advantage that the fastest-condensing fragment has finite size, i.e. fragments with initial radius $\sim r_{\rm FRAG}$ condense out faster than either larger or smaller fragments. Moreover we can analyze the growth of a fragment in a shock-compressed layer, taking account of the continuing inflow of matter into the fragment. Hence we can identify the smallest fragment which can cool radiatively fast enough to dispose of *both* the *PdV* work being done by compression of the fragment, *and* the energy being dissipated at the accretion shock where matter continues to flow into the fragment; these two sources of heat turn out to be comparable. We find (Boyd & Whitworth, 2004) that for shocked gas with temperature $T \sim 10\,{\rm K}$ and no turbulence (i.e. velocity dispersion equal to the isothermal sound speed, $0.2\,{\rm km\,s^{-1}}$), the smallest fragment which can condense out is less than $0.003\,{\rm M_\odot}$, and fragments with mass below $0.005\,{\rm M_\odot}$ condense out for a wide range of pre-shock density ρ and shock speed v (as illustrated on Figure 1). We emphasize that this analysis is more robust than the standard one based on 3D hierarchical fragmentation, on two counts. (i) The fragments have condensation timescales shorter than all competing length-scales (a well-known property of layer fragmentation), so they do not tend to get merged by the overall contraction of a parent fragment. (ii) Ongoing accretion is taken into account; indeed the smallest fragment of all starts off with mass $0.0011\,{\rm M_\odot}$ and grows to $0.0027\,{\rm M_\odot}$ before its contraction becomes non-linear. We conclude (Boyd & Whitworth, 2004) that brown dwarves and planetary-mass objects with masses down to $0.003\,{\rm M_\odot}$ can condense out of shock-compressed layers, along with more massive stars.

4. Disc instabilities

Brown dwarves may also form via gravitational instabilities in massive protostellar discs. If we consider a massive disc in isolation, there is some doubt as to whether it will fragment gravitationally, spawning low-mass companions to the central primary protostar, or whether spiral instabilities will act to quickly redistribute angular momentum, thereby stabilizing – and ultimately disspating – the disc before it can fragment. However, if a massive protostellar disc interacts impulsvely with another disc, or with a naked star, then it can be launched directly into the non-linear regime of gravitational instability and fragmentation is then much more likely. Such interactions must be quite frequent in the dense proto-cluster environment where stars are born; for example, young massive protostellar discs extend out to several hundred AU, and 40% of stars are born in binary systems with semi-major axes less than 100 AU. Boffin et al. (1998) and Watkins et al. (1998a,b) have simulated parabolic interactions between two protostellar discs, and between a single protostellar disc and a naked protostar. The protostars all have mass $M_\star = {\rm M_\odot}$, and the discs also have $M_{\rm DISC} = {\rm M_\odot}$ (so these are very young protostars with very massive discs). All possible mutual orientations of spin and orbit are sampled. The critical parameter turns out to be the effective shear viscosity in the disc. If the Shakura-Sunyaev parameter is low, $\alpha_{\rm SS} \sim 10^{-3}$, the interactions produce mainly planetary-mass companions, i.e. objects in the range $\sim 0.001\,{\rm M_\odot}$ to $\sim 0.01\,{\rm M_\odot}$. Conversely, if $\alpha_{\rm SS}$ is larger, $\alpha_{\rm SS} \sim 10^{-2}$, interactions produce mainly brown-dwarf companions, i.e. objects in the range $\sim 0.01\,{\rm M_\odot}$ to $\sim 0.1\,{\rm M_\odot}$. The formation of low-mass companions is most efficient for interactions in which the orbital and spin angular momenta are all parallel; on average 2.4 companions are formed per interaction in this case. If the orbital and spin angular momenta are randomly oriented with respect to each other, then on average 1.2 companions are formed per interaction. This is evidently a good way of producing brown dwarves and planetary-mass objects as companion objects. It can also produce brown dwarves with discs.

5. Photo-erosion of pre-existing prestellar cores

Another mechanism for producing brown dwarves is to start with a standard prestellar core (one which if left to its own devices is destined to form an intermediate- or high-mass star), and have it overrun by an HII region (Hester, 1996). As a result, an ionization front (IF) starts to eat into the core, 'photo-eroding' it. At the same time, a compression wave (CW) advances into the core ahead of the IF. When the CW reaches the centre, a protostar is created, which then grows by accretion. At the same time, an expansion wave (EW) is reflected and propagates outwards, setting up the inflow which feeds accretion onto the central protostar. The outward propagating EW soon meets the inward propagating IF, and shortly thereafter the IF finds itself ionizing gas which is so tightly bound to the protostar that it cannot be unbound by the act of ionization. All the material interior to the IF at this juncture ends up in the protostar. On the basis of a simple semi-analytic treatment, Whitworth & Zinnecker (2004) show that the final mass is given by

$$M \simeq 0.01\,\mathrm{M}_\odot \left(\frac{a_{\mathrm{I}}}{0.3\,\mathrm{km\,s^{-1}}}\right)^6 \times \left(\frac{\dot{\mathcal{N}}_{\mathrm{LyC}}}{10^{50}\,\mathrm{s^{-1}}}\right)^{-1/3} \left(\frac{n_0}{10^3\,\mathrm{cm^{-3}}}\right)^{-1/3} ,$$

where a_{I} is the isothermal sound speed in the neutral gas of the core, $\dot{\mathcal{N}}_{\mathrm{LyC}}$ is the rate at which the star(s) exciting the HII region emit hydrogen-ionizing photons, and n_0 is the density in the ambient HII region.

The mechanism is rather effective, in the sense that it produces brown dwarves for a wide range of conditions. Indeed, the EGGs identified in M16 by Hester et al. (1996) would appear to be pre-existing cores being photo-eroded in the manner we describe. However, the mechanism is also very inefficient, in the sense that it usually takes a rather massive initial prestellar core to form a single very low-mass brown dwarf or planetary-mass object. Moreover, the mechanism can only work in the immediate vicinity of an OB star, so it cannot explain the formation of all brown dwarves, only free-floating brown dwarves in HII regions. Brown dwarves formed in this way are likely to be single. They should have no difficulty retaining small discs.

6. Conclusions

Four mechanisms for forming brown dwarves have been described. The question of which, if any, of these mechanisms contributes to brown dwarf formation in nature may be settled once the binary statistics of brown dwarves are known accurately, and the frequency of accretion discs around brown dwarves is established. If any of these four mechanisms are important, this suggests that the formation of brown dwarves forms a continuum with the formation of more massive stars.

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