A Dynamical Origin for Brown Dwarfs

Bo Reipurth\textsuperscript{1,2}, Cathie Clarke\textsuperscript{3}, & Eduardo Delgado-Donate\textsuperscript{3}

Abstract.
Brown dwarfs may have such low masses because they are prematurely ejected from small unstable multiple systems, while the members are still actively building up their masses. We demonstrate that this scenario is consistent with all currently existing observations of brown dwarfs, and propose further observational tests. We review the status of the latest realistic numerical simulations of disintegrating small \( N \) clusters, which show that many of the ejected members end up with masses that are substellar, drifting away from their birth region with velocities rarely exceeding 2 km s\(^{-1}\).

1. Introduction

It is commonly assumed that brown dwarfs are formed the same way as stars, except under conditions that lead to stellar objects with very small masses, i.e. from clouds that are very small, very dense, and very cold. However, with the growing realization that brown dwarfs may be as common as stars, it is becoming disturbing that such special physical conditions are not readily found in the molecular clouds of our Galaxy (although they may exist elsewhere, see Elmegreen 1999).

Alternatively, Lin et al. (1998) suggested that the encounter between two protostars with massive disks could fling out tidal filaments with lengths of about 1000 AU, out of which a brown dwarf might form. However, the fact that brown dwarfs are increasingly discovered also in loose T Tauri associations like Taurus, where such encounters should be extremely rare, suggests that this mechanism is unlikely to be a major source of brown dwarfs.

Taking another approach, we have recently proposed that brown dwarfs have such extremely low masses because they were ejected from small clusters of nascent stellar embryos (Reipurth \& Clarke 2001). This can occur because the timescale for dynamical interactions and ejection is comparable to the timescale for collapse and build-up of a star. In the following, we outline the basic aspects of this model, and summarize the status of current efforts to numerically model such ejections.

\textsuperscript{1}Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, USA

\textsuperscript{2}Present address: Institute for Astronomy, University of Hawaii, Honolulu, USA

\textsuperscript{3}Institute of Astronomy, University of Cambridge, UK
2. Multiplicity of Newborn Stars

Observations over the last decade have established that young T Tauri stars have the same or a slightly higher binary frequency than at the main sequence (e.g. Reipurth & Zinnecker 1993; Ghez et al. 1993; Köhler & Leinert 1998). A small, although not very well determined, fraction of both young and more evolved stars are also triple or higher-order multiple systems. The situation is much less clear among the very youngest, still embedded stars, due to the difficulties of probing into the heavily shrouded environment of such objects. However, new high resolution infrared techniques from the ground and space, as well as centimeter interferometry with e.g. the VLA, are beginning to yield results. In a detailed study of 14 driving sources of giant Herbig-Haro (HH) flows, Reipurth (2000) found that more than 80% are binaries, and of these half are higher order systems. It should be noted that these are the actually observed frequencies, without corrections for the considerable incompleteness of the observations, and so the results are in fact consistent with the possibility that all giant HH flow sources may be binary or multiple systems. These embedded outflow sources are of the order of $10^5$ yr old or less, and it follows that some of these systems must decay to reach the lower observed frequencies at later evolutionary stages. It is well established that non-hierarchical triple systems undergo rapid dynamical evolution and evolve into either a binary with a distant companion, i.e. a hierarchical triple system, or into a binary and an unbound, escaping third member (see Section 3). The binary system that is formed in this dynamical process is highly eccentric, and given that the triple disintegration is likely to take place while the stars are still actively accreting gas from an infalling envelope, it follows that the circumstellar disks will interact on an orbital timescale, which will lead to shrinkage of the orbit (e.g. Artymowicz & Lubow 1996). These interactions are again likely to cause cyclic variations in the accretion rate, with consequent pulses in the outflow production, and the giant HH flows may therefore represent a fossil record of the birth and early evolution of binary systems (Reipurth 2000). Altogether, it appears that the generation of giant HH flows, the birth of a binary, and the formation of brown dwarfs may all be different aspects of a single event, namely the dissolution of a small multiple system.

3. Dynamical Interactions in Multiple Systems

If the dominant mode of star formation involves the splitting of a core into $N = 3$ or more fragments then important new ingredients enter the dynamics which are not encountered in the cases $N = 1$ or $N = 2$. The reason for this is simply that most $N > 2$ body configurations are dynamically unstable; over several dynamical timescales the components exchange energy through the action of gravitational forces until they attain a stable equilibrium. In practice, this generally means that the mini-cluster disintegrates, the energy for this process being derived from the formation of at least one binary system. After a number of dynamical timescales, therefore, the core no longer consists of a bound stellar system, but of a mixture of binary and single stars that drift apart so as to mingle with the ambient stellar field.
Figure 1. Snapshots showing the ejection of a $0.06 M_\odot$ brown dwarf with a final speed of $\sim 1.5 \text{ kms}^{-1}$, from a simulation by Delgado-Donate. The sequence, which covers a time span of $\sim 10,000 \text{ yr}$, displays the typical features of this kind of models: the escape of a light object expelled from an unstable multiple system together with the subsequent recoil of its tightest bound members. The brown dwarf has been highlighted with an arrow.

Below we summarise the progress that has been made to date in quantifying such behaviour. We would like to know what is the mass spectrum of the stars (and brown dwarfs) that are produced in this way, what are their binary statistics, how much circumstellar material young stars can bring with them as they emerge from such a core? We would also like to know what are the kinematic properties of the resulting stars and brown dwarfs. Unfortunately, the answers to these questions can be most readily obtained in the case of simulations that omit a vital ingredient (i.e. gas); and it is only recently that it has been possible to address these issues in hydrodynamical simulations. Even so, the twin demands of simulations that are both well resolved and can be performed a large number of times (in order to obtain statistically meaningful results) takes us close to the limits of what is computationally viable at the present time. Here we describe the results of simulations that are progressively more realistic, starting with pure N-body experiments and ending with what represents the current state of the art - gas dynamical simulations starting from turbulent initial conditions. Although these results will give a flavour of the physical processes involved, it should be stressed that we are not yet at a stage where statistical results can
be derived from the most realistic experiments. This inevitably means that the observational predictions (described in Section 4) remain somewhat provisional.

The simplest possibility conceptually (which is however not likely to be even approximately true in practice) is if all the gas is instantly accreted on to each protostar so that the ensemble evolves thereafter as a system of point masses. This situation is straightforward to model as an Nbody system and has been analysed by many authors (e.g. van Albada 1968; Sterzik & Durisen 1998). The usual outcome of such simulations is that the two most massive members of the system form a binary, whereas the remainder are ejected as single stars. The ejection velocity of stars is related to their orbital velocity during a close three body encounter. For example, in Sterzik and Durisen’s simulations, the typical separation between stars is initially around 100 AU, and typical ejection velocities of single stars are 3-4 km s\(^{-1}\). If the same system of point masses had been set up with separations a factor 10 greater (say), the resulting ejection velocities would be a factor \(10^{1/2}\) smaller. Sterzik and Durisen also quantified the dependence of ejection velocity on stellar mass, and found that for \(N > 3\), such a dependence is very weak; they however found a significant difference in the final velocities of single stars and binaries, with the centre of mass velocity of binaries being typically a factor \(3\) – \(6\) less than that of singles.

The above simulations have all the advantages of computational simplicity and yield well defined predictions for the fraction of stars of various masses that end up in binaries (McDonald & Clarke 1993). They however take no account of the fact that the fragments will not interact as point masses but will instead have their interactions mediated by the presence of circumstellar disks. This situation is less straightforward to model numerically, since there are well known numerical difficulties in maintaining disks for many internal orbital timescales against the dispersive action of viscosity. Some insight into the expected role of disks can be obtained from the calculations of McDonald & Clarke (1995), who included the effect of star-disk interactions in a parameterised form (see also Clarke & Pringle 1991). The main role of disks is to harden temporary binaries so as to protect them against disruptive encounters with other cluster members. As a result, more than one binary can be formed in each cluster; although the most massive cluster member is always in a binary, its companion is now picked at random from the cluster members. Thus the net effect of star-disk interactions is to boost the numbers of lower mass stars that end up in binaries (either as primaries or secondaries) relative to the dissipationless (Nbody) case.

However, neither of the sorts of simulations described above can say anything about the stellar initial mass function, since stellar masses are assigned at the outset of the simulation. Such instantaneous mass assignment is of course a very poor approximation to the behaviour of real fragmenting cores: the interactions that lead to the formation of binaries and break up of the cluster occur over a few dynamical times, but the infall of mass onto each of the stars happens on a comparable timescale. Thus realistic simulations need to address the whole process as a hydrodynamic one and follow through the evolution of a core that is initially 100% gas.

To date, some progress has been made on this issue by setting up cores in which ‘seeds’ of collapsed gas have been planted (Bonnell et al 1997; Bonnell et al. 2001). These seeds grow in mass due to gas accretion in an inequitable
Figure 2. The final velocity of ejected stars (diamonds = singles, asterisks = binaries) versus mass, from the simulations of Delgado-Donate. These simulations model cores of mass $0.5M_\odot$ consisting initially of 5 ‘seeds’ each of mass $0.025M_\odot$, and the remaining 75% of the core mass in gas. The initial virial velocity of the cores is $\sim 0.2 \text{ km s}^{-1}$.

manner - their orbital histories determine whether they spend much time in the densest central regions of the core and hence how much mass they acquire. Such simulations vividly demonstrate how ‘competitive accretion’ works: seeds that get an early headstart in the race for mass tend to settle into the cluster core and thereby acquire more mass, whereas seeds that do not grow much initially are more likely to be flung out of the core and hence be prevented from further growth. Thus competitive accretion provides a ready mechanism for obtaining a large dynamic range of final stellar masses from arbitrary initial conditions.

Recent simulations by Delgado-Donate (in preparation) have begun to quantify the IMF produced by competitive accretion during the break up of small clusters (Figure 1) and find that it is broadly compatible with the observed IMF. (Note that in these simulations no disks are formed around the protostars due to the absence of small scale turbulence in the initial core. Thus although these simulations model the accretion of gas on to the stars as they form, and the consequent shrinkage of the protostellar separations, they do not model the effects of star-disk interactions). The dynamical outcome of such disintegrations shares many qualitative similarities with the dissipationless (Nbody) results of Sterzik and Durisen. As in their simulations, there is no appreciable dependence of final velocity on resulting stellar mass (see Figure 2), but the binaries attain speeds that are a factor $\sim 5$ less than the typical ejection speeds of the single stars. One notable difference, however, is the relationship between the typical ejection
speeds and the initial parameters of the core. In the dissipationless simulations, the final velocities of ejected stars are of the same order as the virial velocity of the initial core. In the gas dynamical simulations, there are also many objects that are ejected early on with such velocities, as shown in Figure 2, where the initial virial velocity of the parent core is around 0.2 km s\(^{-1}\). However, Figure 2 also shows that many stars are ejected with velocities much greater than this: about half the stars attain velocities greater than 3 times the initial virial velocity (the corresponding number for Sterzik and Durisen’s simulations is less than 1%) and there is also a significant minority that attain velocities more than a factor 10 greater than the initial virial value. This may be readily understood inasmuch as in the gas dynamical simulations, the systems shrink as the gas is accreted, so that later interactions are much closer and produce correspondingly larger velocity kicks. Thus in these gas dynamical simulations (where the typical initial separations of protostars are 10\(^4\) AU), the ejection velocities are similar to Sterzik and Durisen’s dissipationless calculations in which the stars are initially separated by only of order 100 AU.

These simulations also give some insight into the binary pairing characteristics of the resulting stars. The outcome of each five star simulation is the production of a binary (sometimes a triple). (Note that these simulations do not give reliable results for the separations of the resultant binaries, since they do not include star-disk interactions, which will tend to harden the binaries considerably). It is notable that these simulations produce extreme mass ratio pairs (e.g. 10 : 1) quite readily, which contrasts strongly with pure Nbody results, where such an outcome is almost unknown.

A further step towards reality can be obtained by abandoning the artificial distinction between seeds and smoothly distributed background gas in the above simulations. A more physical approach is to start with gas that is subject to a supersonic turbulent velocity field which rapidly generates a richly non-linear density structure in the gas (Klessen et al. 2000; Klessen 2001). Such simulations follow not only the competitive accretion between contending ‘stars’ and their dynamical interactions, but also the very formation of the stars from pockets of Jeans unstable gas. The most ambitious simulation to date is that of Bate (see Bate et al. 2001) which models a system that will form of the order of a hundred stars, with the capacity to resolve structures forming down to mass limits of a few Jupiter masses. This system readily demonstrates the formation of small N ensembles in which the sort of behaviour described above (binary formation, competitive accretion, ejection of low mass members) is observed to occur. Such a one-off simulation cannot be used to generate statistical results however, and so follow up simulations, tracing the evolution of large numbers of small N ensembles are required.

4. Observational Tests

*Brown Dwarfs and Early Stellar Evolution*

Small N-body systems still in the process of accumulating mass from an infalling envelope would observationally be seen as a Class 0 or perhaps a Class I source with strong outflow activity. If brown dwarfs are formed by the disintegration of small N-body systems, it follows that the very youngest, indeed newborn,
brown dwarfs should be found in the immediate vicinity of such sources. As a small triple or multiple system breaks up, its members start to drift out of the nascent envelope, and may on relatively short time scales (of order a couple of thousand years) emerge from being deeply embedded infrared sources with ample far-infrared and sub-mm emission to being optically visible T Tauri like stars. In this radically different picture of early stellar evolution, the gradual and smooth transition between Class 0 and Class II sources can be replaced by a rather abrupt transition, and the main accretion phase for the members of a multiple system is terminated not by the infalling envelope running out of gas, or outflow blowing away the last parts of the envelope, but by the newborn members “leaving the nest” (Reipurth 2000). Considering the rapidly increasing evidence for multiplicity among the youngest stars, it is interesting to review the early idea by Larson (1972) that all single low mass stars may have formed in dynamical interactions among newly born multiple systems.

One observational test of the dynamical formation model of brown dwarfs would be to study carefully the statistics of brown dwarfs in the vicinity of Class 0 sources. To get a practical sense of the observed separation between a nascent brown dwarf and its siblings, assume that it is observed at a time \( t \) [yr] after ejection and moving with the space velocity \( v \) [km s\(^{-1}\)] at an angle \( \alpha \) to the line-of-sight in a star forming region at a distance \( d \) [pc]. Then the projected separation \( s \) in arcsec is \( s = 0.21 \cdot v \cdot t \cdot d^{-1} \cdot \sin \alpha \). For a velocity of 1 km s\(^{-1}\), a brown dwarf moving out of a nearby (\( d \sim 130 \) pc) cloud at an angle of 60° to the line-of-sight will already be 5 arcmin away after \( 2 \times 10^5 \) yr. Also, half of all ejected brown dwarfs will move into the cloud from which they formed. Such objects will be detectable only as highly extincted and weak infrared sources.

**Brown Dwarfs with Stellar Companions**

It has been known for some time that brown dwarfs are only rarely found as close (less than 3 AU) companions to low mass stars (the “brown dwarf desert”). But recent work by Gizis et al. (2001) has demonstrated that brown dwarfs are commonly companions to normal stars at large separations (greater than 1000 AU). The separation distribution function of brown dwarfs in binary systems contains important information about their formation, and establishing its form more precisely will form a crucial test for any theory of brown dwarf formation. The ejection hypothesis readily explains the currently available observations: brown dwarfs should rarely be found as close companions to stars, as in this environment they would, except for special circumstances, have continued to accrete mass at almost the same rate as their stellar companions, thus pushing through the substellar/stellar boundary at almost the same time. On the other hand, distant brown dwarf companions are readily expected, because not all ejections will lead to unbound systems.

A further test of the ejection scenario comes from studies of the binarity of brown dwarfs. A number of brown dwarfs have been found to be binaries (e.g. Martín, Brandner, & Basri 1999), but, intriguingly, they appear to be rather close binaries, whereas wide pairs (many hundreds of AU) have so far not been found. In the ejection scenario, if two stellar embryos are ejected as a pair, they have to be relatively close in order to survive as a binary. Obviously, the precise limit for survival depends not only on the mass of the pair, but also on

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whether the ejection occurs from a compact or a wider configuration of embryos. Numerical simulations will help to quantify this.

**Kinematics of Brown Dwarfs**

When a small N-body cluster dissolves, its members drift apart and blend with the other young stars in the general star forming environment, whether it is an association or a rich cluster. The velocities of young stars are generally assumed to be similar to the turbulent velocity of the gas out of which they formed, i.e. of the order of a km per second. If all stars are formed in small multiple systems (Larson 1972), then to this we must add the mean velocity of the dispersing members.

If brown dwarfs are ejected stellar embryos, they must carry kinematic evidence reflecting their origin in small multiple systems. To first order, the ejected member from such a system acquires a velocity comparable to the velocity attained at pericenter in the close triple encounter. An observational test of the ejection scenario would therefore be to compare observed velocities of brown dwarfs with velocities derived in realistic numerical simulations. However, the brown dwarfs studied must be young and belong to loose associations. In denser clusters, two body relaxation will soon dominate the kinematics of its members, and field brown dwarfs will be dominated by objects that have evaporated from clusters and thus are similarly affected.

As discussed in Section 3, and illustrated in Figure 2, the most recent, realistic simulations show that the majority of brown dwarfs are ejected with space velocities of less than 1 km s\(^{-1}\), and only a small fraction have velocities larger than 2 km s\(^{-1}\). One-dimensional velocities (radial or tangential) are correspondingly smaller.

It follows that a kinematical test of the ejection scenario will be very difficult to carry out. In the first kinematical study of brown dwarfs, Joergens & Guenther (2001) found that the radial velocity dispersion of nine brown dwarfs in Cha I is 2.0 km s\(^{-1}\), whereas for T Tauri stars in the same region it is 3.6 km s\(^{-1}\). These numbers should be compared to the velocity dispersion of the gas, which is 1.2 km s\(^{-1}\) in the region. As illustrated in Figure 2, there is virtually no dependence of the ejection velocity on mass, i.e. if most or all single stars have been ejected, then there should be little if any kinematic difference between brown dwarfs and surrounding young stars. The existing, limited observations are thus consistent with our current understanding of the kinematics of ejected brown dwarfs and low mass stars.

One possible kinematic signature which may be unique to the ejection scenario is that the binaries that recoil from a dissolving small N cluster will have significantly smaller velocities than the ejected single objects. Once a young stellar association has been carefully studied to identify all binaries, this could be an interesting test.

**Signatures of Youth in Brown Dwarfs**

The expulsion of an “unfinished” hydrostatic core from an infalling envelope may place limits on the amount of circumstellar material that can be brought with it. Freely floating brown dwarfs will therefore have finite reservoirs from which they can accrete and form planets. However, it is only the outermost regions of a circumstellar disk that will be truncated, the precise values depending on the impact parameters in the close triple encounter that triggers the expulsion.
The innermost disk regions will be unaffected, and it is these regions that are responsible for the near-infrared excesses and T Tauri like characteristics that are observed in very young brown dwarfs (e.g. Muench et al. 2001). Brown dwarfs are therefore expected to show mostly the same characteristics of youth as T Tauri stars, and may even be able to form planets, but because of the limited amount of gas they carry with them, the period during which they display T Tauri like characteristics may be more short-lived than for their heavier stellar siblings.

5. Brown Dwarfs and Extrasolar Planets

The discovery in recent years of numerous giant extrasolar planets orbiting other stars (e.g. Marcy, Cochran & Mayor 2000), as well as a large number of low-luminosity objects that have been suggested to be freefloating giant planets (e.g. Lucas et al. 2001) suggests that a continuum may exist between such giant planets and brown dwarfs. By its definition as an object that cannot attain hydrogen burning, a brown dwarf must have a mass of less than about 0.08 M⊙, or 80 M_jupiter, weakly dependent on metallicity (Chabrier & Baraffe 2000). Most of the extrasolar planets found around other stars have masses of order \( M_{\text{sin}} \leq 10 M_{\text{Jupiter}} \). The difference between the masses of giant extrasolar planets and brown dwarfs is therefore about an order of magnitude, much less than the three orders of magnitude spanned by stellar masses. With no clear dividing line between brown dwarfs and giant extrasolar planets, it is thus of considerable interest to ask which, if any, differences exist between these two classes of objects, and whether they perhaps could have a common origin.

It is indeed a possibility that freefloating giant planets are formed the same way as brown dwarfs, i.e. as ejectae from unstable multiple systems of forming stars. Boss (2001) has advocated precisely such a scenario, suggesting that magnetic field tension in the collapse process has the effect of splitting the infalling material into very closely spaced fragments, from which objects as small as a Jupiter-mass can be immediately ejected by dynamical interactions. Another possibility is that freefloating giant planets are formed like the giant planets in our own solar system, i.e. by later condensing out of material in a circumstellar disk. Subsequently, dynamical relaxation may ultimately kick one or more of the giant planets out of their nascent planetary system (e.g. Papaloizou & Terquem 2001). Obviously both mechanisms, despite their very different nature, may create freefloating planetary sized objects, which observationally do not appear to be easily distinguishable. Because ejected objects lose most traces of their pre-history by their expulsion, attempts to compare brown dwarfs and giant extrasolar planets should not be done on the basis of freefloating objects.

On the other hand, bound systems, in which giant planets or brown dwarfs are orbiting a star, may retain critically important memories of their formation processes. And for such objects major differences exist between the two classes of objects. As discussed earlier, brown dwarfs are commonly found bound to stars only at very large separations. Their formation history clearly do not commonly permit them to exist closely bound to a star, as expected and readily explained by the ejection scenario. This is in marked contrast to the increasingly well determined statistics for giant extrasolar planets orbiting other stars, which show
that such objects are often located at extremely small separations, in regions that are off-limits to brown dwarfs in the ejection scenario. If the observed separations were a smooth function of mass between the two categories of objects, one could possibly have argued that orbital evolution had led the smallest mass objects to migrate to locations close to their stars. But given that the two populations are strictly separated in the way they orbit their stars, we conclude that brown dwarfs and giant extrasolar planets, although both arguably having sizable free-floating populations, are likely to be formed in very different manners. In this interpretation, giant planets are formed at later times out of circumstellar disks and their growth is limited by how much disk material is available, whereas brown dwarfs are failed stars, which due to their expulsion could not take full advantage of their rich supply of inflowing gas to grow beyond the hydrogen burning limit.

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