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The distribution of ejected brown dwarfs in clusters

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Abstract. We examine the spatial distribution of brown dwarfs produced by the decay of small-N stellar systems as expected from the embryo ejection scenario. We model a cluster of several hundred stars grouped into 'cores' of a few stars/brown dwarfs. These cores decay, preferentially ejecting their lowest-mass members. Brown dwarfs are found to have a wider spatial distribution than stars, however once the effects of limited survey areas and unresolved binaries are taken into account it can be difficult to distinguish between clusters with many or no ejections. A large difference between the distributions probably indicates that ejections have occurred, however similar distributions sometimes arise even with ejections. Thus the spatial distribution of brown dwarfs is not necessarily a good discriminator between ejection and non-ejection scenarios.

Key words: Stars: formation; stars: binaries : general ; stars: low-mass, brown dwarfs

1. Introduction

Brown dwarfs are observed to constitute some 15–25% of the objects in young star forming regions (e.g. Briceño et al. 2002; Muench et al. 2003; Luhman et al. 2003; Luhman 2005). However, the formation mechanism(s) of brown dwarfs are currently unclear. The two most popular models are that (a) brown dwarfs form like stars but in very low-mass cores (e.g. Greaves this volume; Padoan this volume), or (b) brown dwarfs are stellar embryos that are ejected before than can accrete sufficient mass to become stars (Reipurth & Clarke 2001,2003). (Also see Whitworth & Goodwin (2005) and Whitworth & Goodwin (this volume) for a review of other possible mechanisms).

Probably the most popular model for brown dwarf formation (at least among theorists) is the ejection scenario (Reipurth & Clarke 2001). This model appears to be supported by simulations of star formation in turbulent cores (e.g. Bate et al. 2002, 2003; Delgado Donate et al. 2004; Goodwin et al. 2004a,b).

The ejection scenario has three significant problems. Firstly, it is not clear if ejected brown dwarfs are able to retain the significant discs which are observed around at least some young brown dwarfs (e.g. Jayawardhana et al. 2003). Secondly, whilst ejections do produce some brown dwarf-brown dwarf binary systems (e.g. Bate et al. 2002) a large population of brown dwarf-brown dwarf binaries would be difficult to explain via the ejection scenario (this problem has recently become more acute with evidence that the brown dwarf binary fraction may be significantly higher than previously thought (Pinfield et al. 2003; Jeffries & Maxted this volume). Finally, brown dwarfs are ejected with velocities of order 1 km s^{-1} and it may be expected that brown dwarfs are more widely distributed than stars, in contrast to observations (Briceño et al. 2002; see also Luhman 2005).

In this paper we concentrate on the final problem - the spatial distribution of brown dwarfs. In the ejection scenario, cores form several objects in an unstable high-order multiple system. Dynamical interactions typically eject the lowest-mass members of the system until a stable binary or hierarchical multiple remains. We perform N-body simulations of a cluster of decaying small-N 'cores' to examine if the distributions of brown dwarfs and stars are different or if the velocity dispersion between cores effectively conceals the ejection of brown dwarfs and low-mass stars.

2. Method

We simulate the N-body evolution of a cluster containing many 'cores' containing several stars using the NBODY6 code (Aarseth 2003).

A core is a small-N system of stars and brown dwarfs in which we assume accretion has finished and the gas reservoirs have been exhausted *before* dynamical evolution occurs. This is a simplification to avoid dealing with the complex gas dynamics of the combined accretion/ejection phase (e.g. Delgado Donate et al. 2004; Goodwin et al. 2004a,b; see Umbreit et al. 2005 for an N-body treatment of this problem). However, we believe that it retains the key physics of the current problem - the ejection of low-mass members of cores which are moving relative to one-another within a cluster.

A cluster is initially composed of $N_{\rm core}$ cores each containing N_* stars and/or brown dwarfs (so that the total number of stars in the cluster is $N_{\rm tot} = N_{\rm core} \times N_*$). For a typical distribution the inter-core velocity dispersion is around 1 km s^{-1} (of order the ejection velocities of low-mass stars and brown dwarfs - see below).

Within a core the masses of stars (for brevity 'stars' generally means both stars *and* brown dwarfs) are randomly sampled from a Kroupa (2002) IMF of the form

$$N(M) \propto \begin{cases} M^{-0.3} & 0.02 < M/M_\odot < 0.08 \\ M^{-1.3} & 0.08 < M/M_\odot < 0.5 \\ M^{-2.3} & 0.5 < M/M_\odot < 5 \end{cases}$$

The N_* stars are distributed randomly within a region of radius $R_{\rm core}$ and given random velocities which are scaled such that the core is in virial equilibrium. We note that a random sampling of the IMF in this way may not reproduce the correct (post-ejection) multiple system properties (Kroupa this volume).

We choose $R_{\rm core} = 200$ au as the typical scale on which stars are expected to form (e.g. Goodwin & Kroupa 2005). This is the scale at which a collapsing core will reach the critical density at which the minimum mass for fragmentation is reached ($\sim 10^{-13}$ g cm^{-3}). We note that such a length scale has an observational basis as the peak of the T Tauri binary separation distribution occurs at ~ 100 au (e.g. Mathieu 1994; Patience et al. 2002).

The cores so established are expected to decay on a timescale of < 0.1 Myr rapidly if $N_{\rm star} > 2$ by ejecting the lowest-mass members of the system until a stable hierarchical system or a binary is formed (Anosova 1986; see also Sterzik & Durisen 2003; Hubber & Whitworth 2005; Goodwin & Kroupa 2005; Umbreit et al. 2005). We ignore the interaction of the protostars and the ambient gas, as all we are interested in is the post-ejection velocity distribution and we find that the ejection velocities of low-mass stars and brown dwarfs are of order 1 km s^{-1}, similar to that found in more detailed simulations including gas (e.g. Umbreit et al. 2005).

Cores are then placed within the star cluster by positioning them within a virialised Plummer sphere with a virial radius of 1 pc following the prescription of Aarseth et al. (1974).

3. Results

We analyse the relative distributions of brown dwarfs and stars by comparing the distances to the nearest neighbours (following Brinceño et al. 2003); using the mean distances to the nearest neighbour (nearest neighbour distance, or NND).

There are two important observational biases that must be included when analysing the data. The first is unresolved binaries, which we include by ignoring the secondary component of any system if it is within 250 au of the primary (roughly 2 arcsec at the distance of Taurus). The second is that surveys are over limited areas: cluster members at great distances from the cluster centre will normally not be found in surveys, and - even if they are - would be difficult to unambiguously relate to the cluster without additional proper motion studies. Therefore we restrict ourselves to stars and brown dwarfs within a projected distance of 5 pc from the cluster centre (this corresponds to an area of 13 square degrees at the distance of Taurus).

In Fig. 1 we compare the stellar and brown dwarf NNDs for clusters with a total of $N_{\rm tot} = 400$ stars and $N_* = 1$ (ie. no decay of groups within cores) and $N_* = 4$ (generally decay into a binary and two single stars).

When $N_* = 1$, the NNDs of the stars and brown dwarfs are indistinguishable, over the 20 Myr of cluster evolution that is followed, the NNDs increase somewhat as the cluster expands slightly through 2-body interactions. Over a significant time, we would expect the brown dwarf NND to become larger than the stellar NND as low-mass stars and brown dwarfs gain a higher velocity dispersion as equipartition is established through 2-body encounters (however, in reality the cluster will probably disperse long before this becomes important).

In contrast, when $N_* = 4$, the effect of the very rapid decay of the small-N cores is to produce a population of more widely dispersed brown dwarfs and low-mass stars with a larger NND. (It should be noted that not accounting for unresolved binaries and limited survey areas makes these differences significantly more extreme). Towards the end of the simulation the NND for brown dwarfs is seen to drop significantly. This is caused by a number of brown dwarfs escaping from the cluster at late times, either because they were ejected with an initially low velocity or have gained velocity due to later encounters in the cluster.

Thus it would appear that the ejection of brown dwarfs from small-N cores can produce a significant and observable effect in the spatial distributions. However, ejections do not always produce a significant difference in the spatial distributions. In Fig. 2 we show four more simulations with $N_* = 4$ (making 5 in total including the simulation from Fig. 1). The only difference between these simulations is the random number seed used to generate the initial conditions. In the final simulation in particular there is no significant difference between brown dwarfs and stars at any time.

The most extreme differences between the NNDs of brown dwarfs and stars occurs at 5 - 10 Myr: after ejections have had time to significantly disperse the brown dwarfs, but before most of them have escaped the inner regions of the cluster (travelling at 1 km s^{-1} this should take ~ 5 Myr). However, most young clusters are observed at ages of ~ 1 Myr (e.g. the Taurus observations of Briceño et al. 2002) at which point only 1 of the 5 simulations shows a very significant difference.

4. Conclusions

When ejections are not important ($N_* = 1$) the spatial distributions of stars and brown dwarfs are (unsurprisingly) very similar. When ejections become important ($N_* = 4$) then the spatial distributions can show significant differences. However, these differences can disappear altogether in some clusters depending on the exact details of the initial clustering. In addition, at the young age of most well-studied young clusters a significant difference in the spacial distributions is seen in only 1 out of 5 simulations.

Thus if brown dwarfs and stars have different spatial distributions it is probably a signature of ejections, however the lack of a difference does not necessarily exclude the ejection scenario.

We suggest that binarity is a far stronger discriminator between models since (as yet) there is no way in which to make significant numbers of brown dwarf-brown dwarf binaries from ejections. However, we are currently investigating if a more sophisticated statistical analysis of positions may yield a more robust discriminator.

The discovery of many more brown dwarfs in Taurus extending over a wide area (Guieu et al. this volume) does suggest that ejections may have been responsible for at least some of the Taurus brown dwarfs.

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References

Aarseth, S. J., Henon, M. & Wielen, R. 1974, A&A, 37, 183
Aarseth, S. J. 2003, 'Gravitational N-body Simulations' (CUP: Cambridge)
Anosova, J. P. 1986, Ap&SS, 124, 217
Bate, M. R., Bonnell, I. A. & Bromm, V. 2002, MNRAS, 332, L65
Bate, M. R., Bonnell, I. A. & Bromm, V. 2003, MNRAS, 339, 577
Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R. & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Delgado-Donate, E., Clarke, C. J. & Bate, M. R. 2004, MNRAS
Goodwin, S. P., Whitworth, A. P. & Ward-Thompson, D. 2004a, A&A, 414, 633
Goodwin, S. P., Whitworth, A. P. & Ward-Thompson, D. 2004b, A&A, 423, 169
Goodwin, S. P. & Kroupa, P. 2005, A&A, in press
Hubber, D. A. & Whitworth, A. P. 2005, A&A, 437, 113
Jayawardhana, R., Ardila, D. R., Stelzer, B., Haisch, K. E. Jr. 2003, AJ, 126, 2009
Luhman, K. L., Briceño, C., Stauffer, J. R., Hartmann, L., Barrado y Navascués, D. & Nelson, C. 2003, ApJ, 590, 348
Luhman, K. L. 2005, ApJ, 617, 1216
Mathieu, R. D. 1994, ARA&A, 32, 465
Muench, A. A., Lada, E. A., Lada, C. J. & Alves, J. 2002, ApJ, 573, 366
Patience, J., Ghez, A. M., Reid, I. N. & Matthews, K. 2002, AJ, 123, 1570
Pinfield, D. J., Dobbie, P. D., Jameson, R. F., Steele, I. A., Jones, H. R. A., Katsiyannis, A. C. 2003, MNRAS, 342, 1241
Reipurth, B. & Clarke, C. J. 2001, AJ, 122, 432
Reipurth, B. & Clarke, C. J. 2003, in 'Brown Dwarfs' IAU symposium 211, eds. E. Martín (ASP: San Francisco), p13
Sterzik, M. F. & Durisen, R. H. 2003, A&A, 400, 1031
Umbreit, S., Burkert, A., Henning, T., Mikkola, S. & Spurzem, R. 2005, ApJ, in press (astro-ph/0501075)

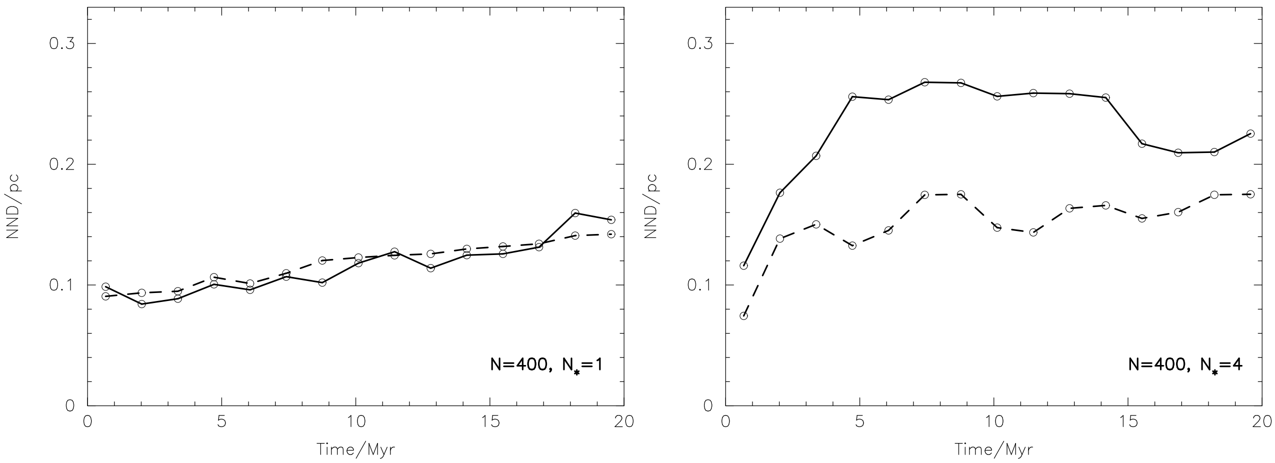

Fig. 1. The average nearest neighbour distances (NND) of stars (dahsed-line) and brown dwarfs (full line) for clusters with $N_{\mathrm{tot}} = 400$ with $N_* = 1$ (left panel) and $N_* = 4$ (right panel).

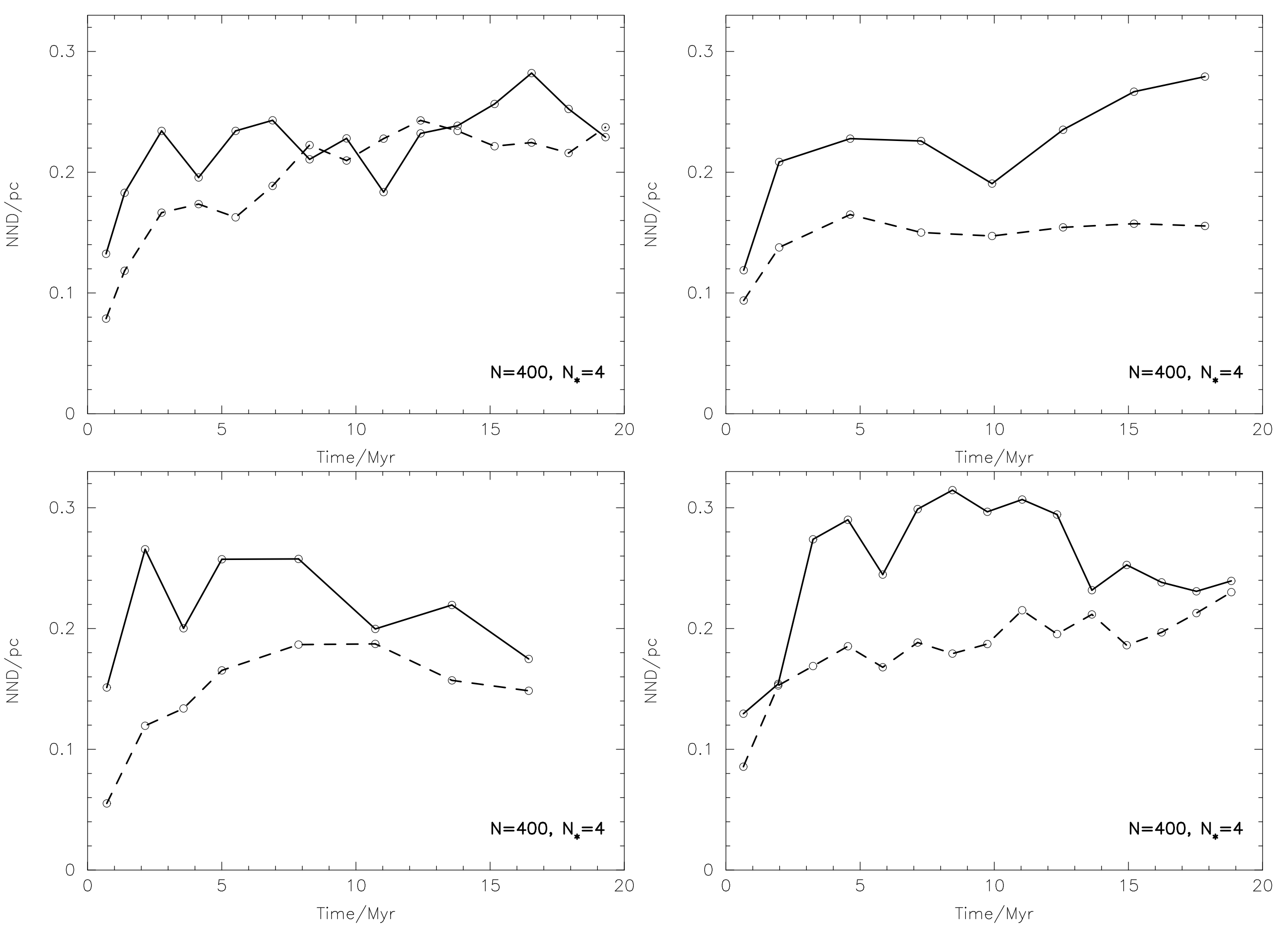

Fig. 2. The average nearest neighbour distances (NND) of stars (dashed-line) and brown dwarfs (full line) for clusters with $N_{\mathrm{tot}} = 400$ and $N_* = 4$ for four different realisations (different random number seeds).