Mem. S.A.It. Vol. 76, 265
© SAIt 2005

Memorie della

Brown dwarfs in young open clusters

E. Moraux[1,⋆], J. Bouvier[2] and C. Clarke[1]

[1] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
[2] Laboratoire d'Astrophysique de Grenoble, BP 53, Grenoble Cedex 9, France

Abstract. From the detection of several tens of brown dwarfs using wide-field cameras, we derive new estimates of the present day mass function (PDMF) of 3 young open clusters (the Pleiades, NGC 2516, Blanco 1) from 10 $M_{\odot}$ down to 30 Jupiter masses. The PDMF of the 3 clusters are remarkably similar, suggesting little impact of specific conditions (stellar density, metallicity, early dynamical evolution). We then compare the observed spatial distribution of the substellar cluster population to results predicted by N-body simulations and we discuss the implications on the brown dwarf formation process.

Key words. Stars: low-mass, brown dwarfs – Stars: mass function – Open clusters and associations: individual: Blanco 1, Pleiades, NGC 2516 – Stellar dynamics

1. Introduction

Since the first brown dwarf discovery in 1995, new perspectives have opened regarding the formation of condensed objects in molecular clouds. Today more than one thousand brown dwarfs (brown dwarfs) are known but their mode of formation is still controversial and the theoretical framework describing the stellar and substellar formation process(es) is far from being satisfactory. How do brown dwarfs form ? Is there a lower mass limit for an object to be formed ? A way to tackle these questions is to determine the mass spectrum resulting from the stellar formation process, i.e. the initial mass function (IMF), down to the substellar regime.

Young nearby open clusters are ideal environments for such a purpose. Their youth ensures that brown dwarfs are still bright enough for being easily detected and their rich well-known stellar populations complement the recent discoveries of cluster brown dwarfs to yield a complete mass function from the substellar domain up to massive stars. Moreover masses can be determined relatively easily as cluster members constitute a uniform population. Extinction is most often insignificant and scatter in their intrinsic properties (age, distance, metallicity) minimal – nearby cluster age and distance are usually known to better than 20% and sometimes to within a few percent. Cluster member masses can thus be derived converting their luminosity with the help of a *unique* mass-luminosity relationship delivered by evolutionary models.

The determination of bias-corrected mass functions of young open clusters of similar age (∼ 100 Myr) over nearly 3 decades of masses, from 0.03 to $10 M_{\odot}$, is presented in this contribution. We briefly describe the wide-field surveys we conducted to look for the substellar

---

Send offprint requests to: E. Moraux
⋆ e-mail: `moraux@ast.cam.ac.uk`
Correspondence to: IoA, Madingley Road, Cambridge CB3 0HA, UK

Cluster	Age (Myr)	Distance (pc)	Richness (known stellar members)	[Fe/H]	Covered area (sq.deg.)
Blanco 1	100	260	> 200	+0.14	2.5
Pleiades	120	125	~1200	0.0	6.4
NGC 2516	150	350	~2000	-0.3–0.0	2.0

Table 1. Properties of the 3 surveyed young open clusters.

population in Section 2 and the resulting mass functions (MF) are presented in Section 3. We then discuss some implications of our study on the kinematics of brown dwarfs at birth in Section 4.

2. brown dwarfs in young open clusters

We performed deep, wide-field photometric surveys using the CFH12K camera or ESO 2.2m/WFI of 3 nearby young open clusters whose properties are summarized in Table 1. Beyond their proximity, they have been selected as having a similar age (100-150 Myr) but different richness and possibly metallicity. We covered a large fraction of each cluster down to $I \sim z \sim 24$ which corresponds to a mass between 30 and 50 Jupiter masses depending on the distance of the cluster. We selected from tens to a few hundreds of very low mass star and brown dwarf candidates on the basis of their location in the $(I, I-z)$ colour magnitude diagram and we assessed their membership using a combination of criteria: proper motion, lithium absorption, surface gravity index, infrared photometry and spectroscopy. (see Fig. 1 as an illustration).

Using those large and unbiased samples of probable members, we then derived the mass function of the 3 clusters in the mass range 0.030-0.50 $M_\odot$ and we completed our study to $\sim 10 M_\odot$ with data from the literature. Multiple systems are not resolved at the distance of the cluster and we did not attempt to correct it.

3. The mass function of young open clusters

In a Salpeter-like power-law representation ($\xi(m) = dn/dm \propto m^{-\alpha}$), we derive $\alpha = 0.6 \pm 0.1$ for the *system* mass distribution of the Pleiades (Moraux et al. 2003) and Blanco 1 over 0.030-0.50$M_\odot$ and $\alpha = 0.4 \pm 0.2$ for NGC 2516 over 0.050-0.20$M_\odot$. On a broader mass range, from 30 Jupiter masses to the most massive stars, the system MF of young open clusters is reasonably well fitted by a Scalo-like log-normal distribution

$$\xi_L(m) = \frac{dn}{d\log m} \propto \exp\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2}\right]$$

with $(m_0, \sigma) \simeq (0.3 M_\odot, 0.5)$ (see Fig. 2). The high mass part of the MFs was built from published data (Pilliterri et al. 2003, Jeffries et al. 2001, Stauffer & Prosser cluster database). The MFs of the 3 studied clusters appear quite similar whith a characteristic system mass around 0.3$M_\odot$. The fraction of brown dwarfs compared to stars in each cluster is about 10-15% which corresponds to a substellar mass of only $\sim 1\%$ of the cluster mass. This result suggests that the cluster MF may be invariant under various initial conditions (stellar density, metallicity).

The cluster mass distributions are also similar to the field system MF (Chabrier 2003, Moraux, Kroupa & Bouvier 2004). Small differences may exist with a characteristic mass possibly slightly higher in clusters than in the field and consequently a larger brown dwarf to star ratio in the field.

4. Kinematics of brown dwarfs at birth

The broad similarity between the cluster present day mass functions and the field MF suggests that the cluster dynamical evolution had little effect on its mass content and that there is *no* significant loss of brown dwarfs during at least the first 100 Myr. This brings some

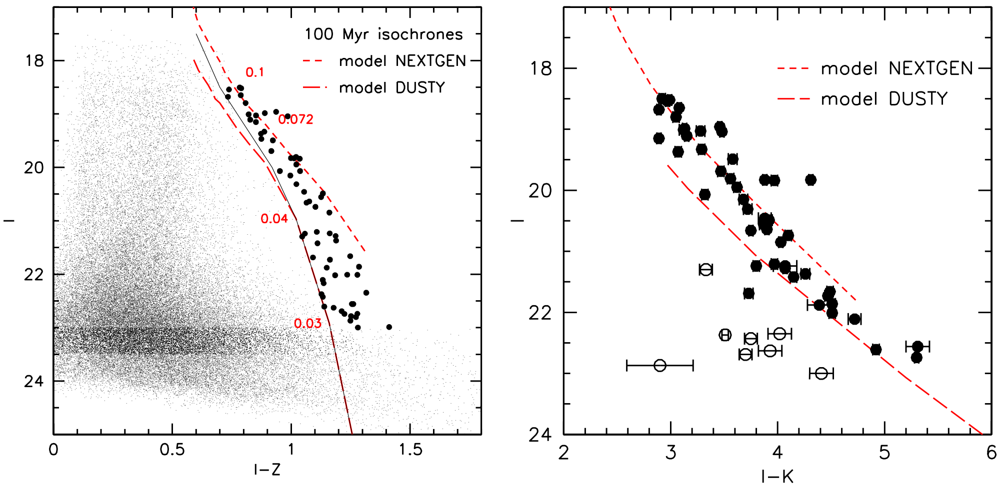

Fig. 1. *Left:* Optical colour magnitude diagram (CMD) of the Blanco 1 cluster. The 100 Myr NextGen and DUSTY isochrones from the Lyon group (Baraffe et al. 1998, Chabrier et al.2000) are labelled with mass. On the red side of our selection line (solid) the cluster candidates are shown as filled dots. *Right:* Infrared CMD of the Blanco 1 cluster candidates. Objects lying on the blue side of the isochrones are rejected as non members (open circles). (From Moraux et al. 2005)

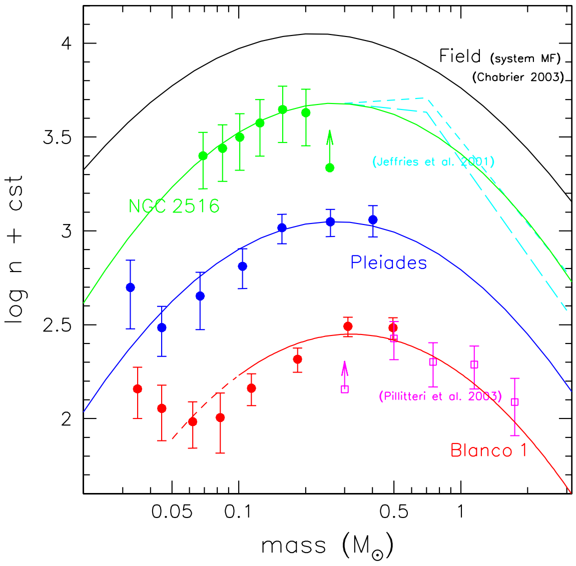

Fig. 2. The mass function of Blanco 1, the Pleiades and NGC 2516 from low mass brown dwarfs to the most massive stars. The large dots are our data points completed in the more massive star domain by literature data. Each cluster MF is fitted by a log-normal distribution. The field system MF from Chabrier (2003) is shown for comparison.

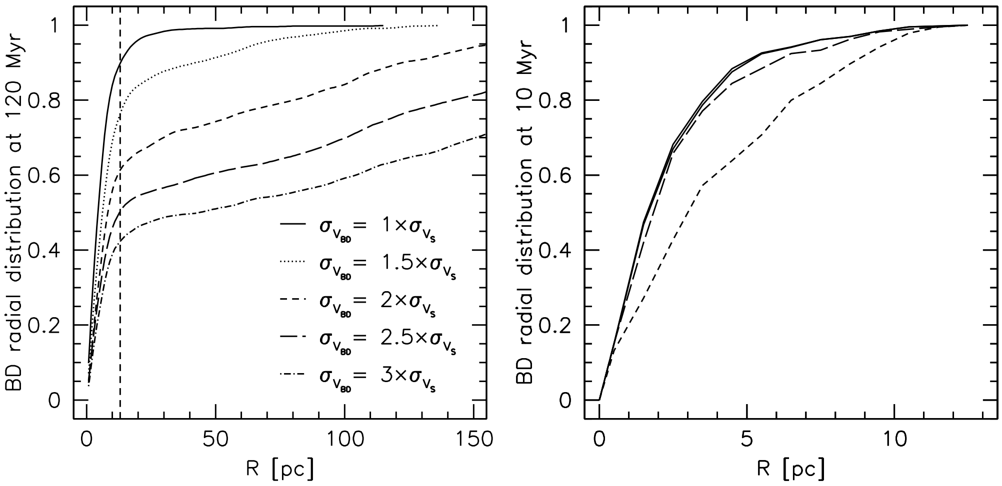

Fig. 3. *Left:* Cumulative radial distribution of brown dwarfs after ~ 120 Myr calculated by our NBODY2 numerical simulations of the dynamical evolution of a Pleiades-like cluster. The vertical dashed line represents the extent of the Pleiades cluster. All the objects located at larger radii are in reality lost by the cluster. *Right:* Radial distribution of low mass stars (solid) and brown dwarfs (dashed) inside the cluster after 10 Myr. The long-dashed line corresponds to $\sigma_{V_{\rm BD}} = \sigma_{V_\star}$ and the short-dashed line to $\sigma_{V_{\rm BD}} = 2 \times \sigma_{V_\star}$. (From Moraux & Clarke 2004)

constraints on the kinematics of brown dwarfs at birth and thus on the substellar formation process itself.

Two main competing scenarios have been proposed so far to account for the formation of substellar objects. One assumes that brown dwarfs form like solar-mass stars by gravitational collapse of small, dense molecular cloud core and subsequent accretion. The supporting argument is that in the opacity limited regime the Jeans mass can be as low as a few Jupiter masses (Low & Lynden-Bell 1976, Boyd & Whitworth 2004). The alternative view assumes that brown dwarfs are "stellar embryos" ejected from unstable protostellar multiple systems as proposed by Reipurth & Clarke (2001). In this scenario, molecular cloud cores fragment to form small *N* body systems which decay dynamically. The lowest mass fragments are ejected from their birth place and deprived of surrounding gas to accrete remain substellar objects. The substellar properties predicted by these two different formation scenarios may in principle be quite different. In the former case, both stars and brown dwarfs form predominantly as single or binary systems whereas in the latter scenario the gravitational interplay that precedes the break up of the small *N* body systems into stable entities implies a potentially strong mass dependence for resulting properties like the binary fraction and kinematics. In particular it has been suggested that low mass objects (e.g. brown dwarfs) ejected from such protostellar multiple systems would have a larger velocity dispersion than higher mass objects.

The relative kinematics of stars and brown dwarfs – and of single stars and binaries – can therefore shed some light on the conditions in star forming cores and could ultimately answer the question of whether stars (and brown dwarfs) are formed as isolated single and binary systems, as small *N* aggregates containing typically one binary, or as aggregates containing more than one binary.

Direct observations of the kinematics of young stars and brown dwarfs are unlikely to be fruitful however. The differences in velocity dispersion predicted by theoretical models (Delgado et al. 2003, Sterzik & Durisen 2003) are small, of the order of a km/s. We propose here another approach to detect any mass dependence of the kinematics of stars and brown dwarfs at birth. We examine the statistical consequences of such an effect on the spatial distribution of stars and brown dwarfs in clusters using 'toy' N-body models.

We performed numerical simulations of the dynamical evolution of a Pleiades-like cluster using the code NBODY2 (Aarseth 2001). At time $t = 0$, the model of cluster we used conforms to a Plummer model containing 1900 objects whose masses are distributed over a mass function corresponding to the Pleiades MF presented in the previous section. In our toy model brown dwarfs are introduced with an initial velocity dispersion that is a variable multiple of the stellar velocity dispersion, $\sigma_{V_{\rm BD}} = k \times \sigma_{V_\star}$ whith $k \in [1.0 - 3.0]$ (see Moraux & Clarke 2004 for more details). Then we let the cluster evolve dynamically under the effect of gravitational interactions between members over 12 crossing times, corresponding to about the age of the Pleiades. Thus, we can follow the evolution of the star and brown dwarf population within the cluster from their birth to the age of the Pleiades depending on their initial kinematics.

Figure 3, left panel, illustrates the effect of the initial velocity dispersion of brown dwarfs on their spatial distribution at the age of the Pleiades. If the stellar and substellar initial velocity dispersion are similar ($k = 1.0$), then as many brown dwarfs as low mass stars have been lost after 120 Myr (about 10%) - which is consistent with the simulations performed by de la Fuente Marcos & de la Fuente Marcos (2000). However, as soon as $k \geq 2.0$ then 40% or more of the initial brown dwarf population have left the cluster. The broad agreement between the brown dwarf fraction in the field and in the Pleiades suggests that there was *no* significant loss of brown dwarfs in 120 Myr, which indicates that the substellar velocity dispersion at birth has to be less than twice the stellar one (see Fig. 3, left panel), i.e. cannot exceed a few km/s in the Pleiades cluster.

Then, in order to discern more subtle differences between the kinematics of brown dwarfs and stars at birth, we investigated whether the radial distribution of the residual brown dwarfs in the cluster was sensitive to $\sigma_{V_{\rm BD}}$. We found, however, that by the age of the Pleiades, two body relaxation is sufficiently important so as to have erased any "memory" of the initial brown dwarf velocity dispersion. Instead we need to look at clusters that are only about a crossing time old. This expectation is borne out by Figure 3, right panel, which compare the normalised distributions of stars and brown dwarfs within a Pleiades-like cluster at an age of 10 Myr for two different ratios of $\sigma_{V_{\rm BD}}$ to $\sigma_{V_\star}$. When the stellar and substellar velocity dispersions are similar then the radial distributions are also the same, whereas this is not the case for $\sigma_{V_{\rm BD}} = 2 \times \sigma_{V_\star}$. This evidences that, at this age, two-body relaxation is ineffective in producing a more diffuse brown dwarf distribution and any differences in the spatial distribution of stars and brown dwarfs at such a young age would be indicative of different velocity distributions at birth.

5. Conclusions

Deep wide-field photometric surveys of brown dwarfs in three young open clusters (Blanco 1, Pleiades and NGC 2516) having about the same age (∼ 100 Myr) allowed us to estimate their present day *system* mass function across the stellar/subtellar boundary. We found that they can be approximated by a power-law $dn/dm \propto m^{-\alpha}$ with an exponent $\alpha \simeq -0.6 \pm 0.10$ over the mass range 0.030-0.50 $M_\odot$, and by a log-normal distribution

$$\xi_{\rm L}(m) \propto \exp\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2}\right]$$

with $(m_0, \sigma) \simeq (0.3M_\odot, 0.5)$ over the entire mass range. There is no significant differences in the shape of the MF between the various clusters, regardless of their precise age, metallicity or richness. The shape of the Galactic disk MF is also similar to these results. This suggests that there is a characteristic system mass $m_0 \sim 0.2{-}0.3M_\odot$ issued from the star formation process which does not depend much on the environmental conditions.

The agreement between the cluster and the field MFs indicates that the cluster dynamical evolution has had little effect on its mass content at an age of about 100 Myr and that there was *no* significant loss of brown dwarfs. Using numerical N-body simulations, we find that this result constrains the substellar velocity dispersion at birth to be less than twice the stellar one, i.e. cannot exceed a few km/s in the Pleiades cluster. To discern whether the velocity distribution of brown dwarfs at birth may still be slightly higher than the star one, we need to look at clusters that are much less dynamically evolved than the Pleiades. One might especially seek evidence of high velocity brown dwarfs at birth by examining spatial distribution of stars and brown dwarfs in clusters that are about a crossing timescale old.

References

Aarseth, S. J. 2001, New Astronomy, 6, 277

Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P.H. 1998, A&A, 337, 403

Boyd, D.F.A. & Whitworth, A., 2004, accepted by A&A

Chabrier, G., Baraffe, I., Allard, F., Hauschildt, P.H. 2000, ApJ, 542, 464

Chabrier, G. 2003, PASP, 115, 763

Jeffries, R.D., Thurston, M.R., Hambly, N.C., 2001, A&A, 375, 863

Delgado-Donate, E. J., Clarke, C. J., & Bate, M. R. 2003, MNRAS, 342, 926

de la Fuente Marcos, R., & de la Fuente Marcos, C., 2000, Ap&SS 271, 127

Low, C. & Lynden-Bell, D. 1976, MNRAS, 176, 367

Moraux, E. & Clarke, C. 2004, A&A, in press

Moraux, E., Kroupa, P., Bouvier, J. 2004, A&A, 426, 75

Moraux, E., Bouvier, J., Stauffer, J., Cuillandre, J.-C. 2004, A&A, submitted

Moraux, E., Bouvier, J., Stauffer, J., Cuillandre, J.-C. 2003, A&A 400, 891

Pilliterri, I., Micela, G., Sciortino, S., & Favata, F. 2003, A&A, 399, 919

Reipurth, B. & Clarke, C. 2001, AJ, 122, 432

Sterzik, M. F. & Durisen, R. H. 2003, A&A, 400, 1031