Part 4

Observations of Young Brown Dwarfs (age $\sim$ 50–200 Myr)

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The Lower Mass Function of Young Open Clusters

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Abstract. We report new estimates for the lower mass function of 5 young open clusters spanning an age range from 80 to 150 Myr. In all studied clusters, the mass function across the stellar/substellar boundary ($\sim$ 0.072 $M_\odot$) and up to 0.4 $M_\odot$ is consistent with a power-law with an exponent $\alpha \simeq -0.5 \pm 0.1$, i.e., $dN/dM \propto M^{-0.5}$.

1. Introduction

Young open clusters are ideal locations to search for isolated brown dwarfs. Their youth ensures that substellar objects have not yet cooled down to undetectable levels, and the rich stellar populations of the nearest open clusters complement the recent discoveries of cluster brown dwarfs to yield a complete mass function for coeval systems from the substellar domain up to massive stars.

Nearby clusters have been surveyed by various groups in an effort to build statistically significant samples of young brown dwarfs and derive reliable estimates of the substellar mass function. In this contribution, we present the latest results obtained from the CFHT Pleiades wide-field survey (Section 2) and estimates of the lower mass function for several other open clusters (Section 3). We then briefly discuss the potential effects of cluster dynamical evolution on the shape of the mass function (Section 4).

2. The CFHT 2000 Pleiades survey

A Pleiades survey performed in 1996 with the UH 8K camera led to a preliminary estimate of the cluster mass function which was found to be consistent with a

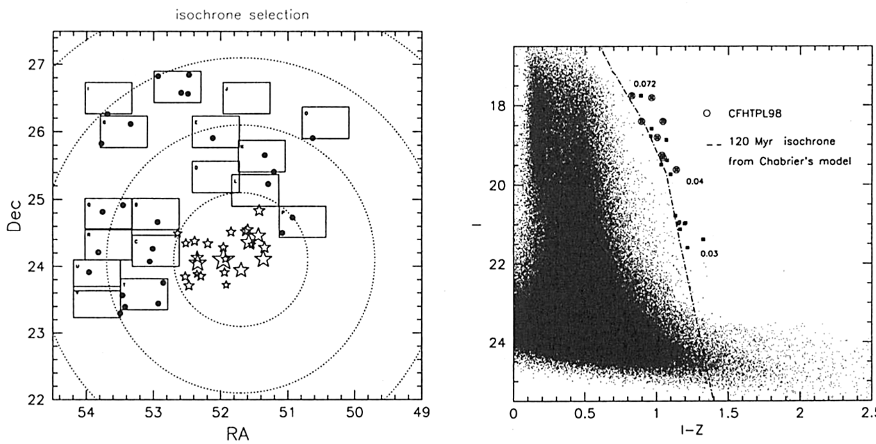

Figure 1. *Left Panel:* Area of the sky covered by the CFHT 2000 Pleiades survey. Each rectangle corresponds to one CFHT12K field. The star symbols indicate the 25 brightest stars of the cluster which have been avoided to prevent CCD saturation. Filled dots show the location of detected Pleiades brown dwarf candidates. *Right panel:* A (I, I-z) CMD for all stellar-like objects identified on the long exposure images. The 120 Myr isochrone of Chabrier et al.'s (2000) models shifted to the distance of the Pleiades is shown as a dash-dotted line labelled with mass (in $M_{\odot}$ unit). Candidate brown dwarfs are identified as lying on or above the isochrone. Brown dwarfs detected in the first CFHT survey and recovered here are shown as encircled squares while other candidates are new (adapted from Moraux et al. 2002).

power-law $dN/dM \propto M^{-0.6}$ over the mass range from 0.04 to 0.3 $M_{\odot}$ (Bouvier et al. 1998). Proper motion measurements and follow-up observations in the near-IR of the brown dwarf candidates detected in this survey subsequently confirmed this estimate (Martín et al. 2000, Moraux et al. 2001).

A new Pleiades survey was performed with the CFHT12K camera (Cuillandre et al. 2000) in December 2000 covering a wider area (6.4 sq.deg.) and going deeper (down to 0.025 $M_{\odot}$) than the original survey. Figure 1 illustrates the surveyed area on the sky (left) and the resulting (I, I-z) color-magnitude diagram (CMD, right). New brown dwarf candidates are selected from the CMD as lying on or above the 120 Myr isochrone of Chabrier et al.'s (2000) models. Pending follow-up observations of the lowest-mass candidates, the photometric selection of substellar objects is stopped at 0.030 $M_{\odot}$ where contamination by field stars becomes significant.

Taking into account the contamination of photometrically-selected brown dwarf candidates by field dwarfs (cf. Moraux et al. 2001), the number of brown dwarfs detected in each magnitude bin is directly converted into a mass function using the (I magnitude, Mass) relationship of Chabrier et al.'s (2000) 120 Myr model. The mass function (MF) derived for the cluster across the stellar/substellar boundary is shown in Figure 2. The data points in the stellar

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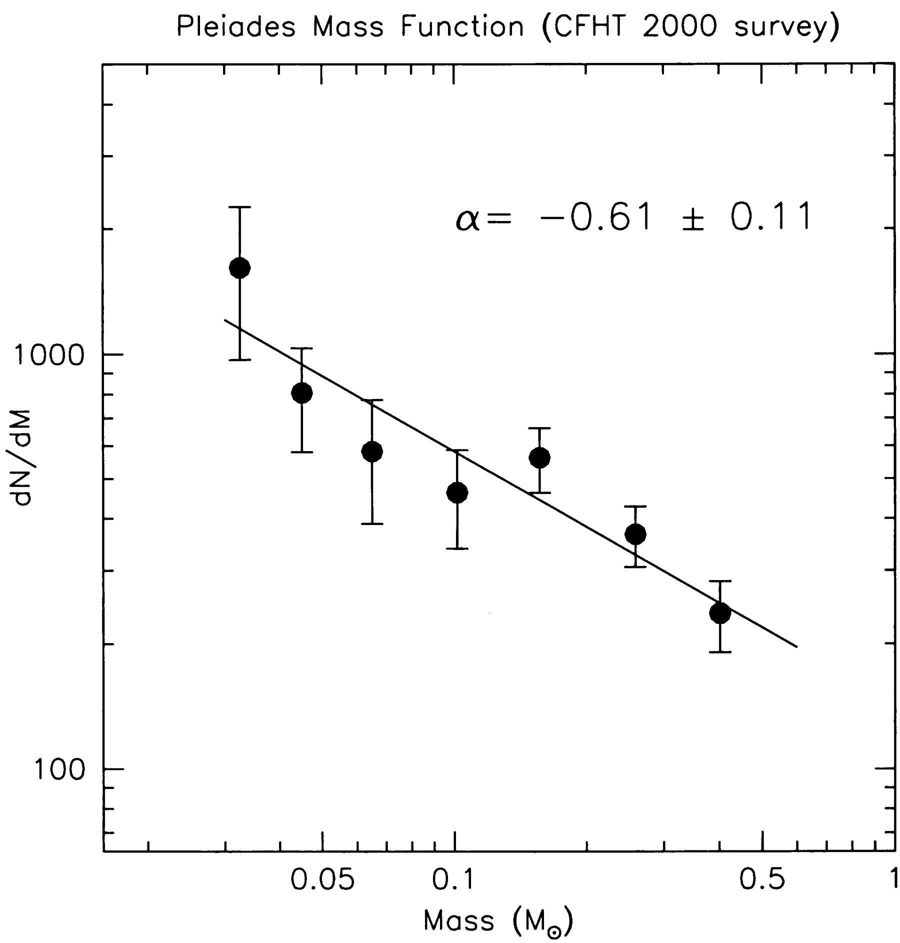

Figure 2. The Pleiades mass function across the stellar/substellar boundary. Note that all data points are derived from the same survey, using short exposures for the stellar domain and long exposures for the substellar regime. This provides a consistent determination of the slope of the cluster's mass function in the mass range from 0.030 to 0.4 $M_{\odot}$. A least-square fit to the data point yields a power-law exponent $\alpha = -0.61 \pm 0.11$. (adapted from Moraux et al. 2002)

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domain have been derived from short exposures while the derivation of the MF in the substellar domain is obtained from the long exposures CMD shown in Figure 1. Over more than a decade in mass, from 0.030 to 0.4 $M_\odot$, the observed mass function is reasonably well-fitted by a power-law $dN/dM \propto M^{-0.61\pm0.11}$, consistent with previous determinations (Bouvier et al. 1998, Hambly et al. 1999, Martín et al. 2000, Moraux et al. 2001).

3. The lower mass function of Pleiades-age open clusters

Apart from the Pleiades, a handful of other galactic open clusters are young and close enough to allow deep brown dwarf searches (cf. Stauffer & Barrado y Navascués, this volume). Figure 3 shows current determinations of the lower MF for M35 (~150 Myr, Barrado y Navascués et al., in prep.), Alpha Per (~80 Myr, Barrado y Navascués et al. 2002) and for NGC 2516 and Blanco 1 (~150 Myr, Moraux et al., in prep.).

The MF estimates have been derived from optical CMDs in a similar fashion as for the Pleiades (see above) over a mass range extending from low mass stars down to the stellar/substellar boundary and below it for the youngest/nearest clusters. When approximated by a power-law, the slope of the MF over this restricted mass range is strikingly similar for the various clusters, with a power-law index $\alpha \simeq -0.5 \pm 0.1$ within uncertainties.

The main uncertainties associated with these preliminary results are related to small number statistics (shown as Poisson error bars in Figure 3) and, for some clusters, to the contamination of the photometrically selected BD candidates by field dwarfs. Follow-up observations are being acquired to confirm the BD status of some of the photometric candidates. In the meantime, vertical arrows drawn in Figure 3 at the low mass end of the MF indicate the current 3σ upper limit to the total number of candidates.

Pending the resolution of these uncertainties, there is presently no evidence for significant differences in the mass function between the Pleiades cluster itself and other Pleiades-type open clusters studied so far across the stellar-substellar boundary.

4. Dynamical effects and the origin of brown dwarfs

The main objective in determining the lower mass function is to constrain the star and brown dwarf formation process(es). A pressing issue is then whether the MF derived for young open clusters is representative of the initial mass function (IMF), i.e. the distribution of the masses of condensed objects resulting from their formation process. In other words, is the cluster population observed at an age of about 100 Myr representative of the initial population of the cluster at the time it formed ?

If the details of the star-formation process are not relevant to the subsequent evolution, and if brown dwarfs are formed like stars, then the difference between the IMF and the observed MF is only due to "classical" dynamical evolution. As the cluster evolves, dynamical processes act to deplete its lowest mass members. Weak gravitational encounters lead to mass segregation and to the evaporation of the lowest mass objects. Yet, current models predict that only about 10% of the

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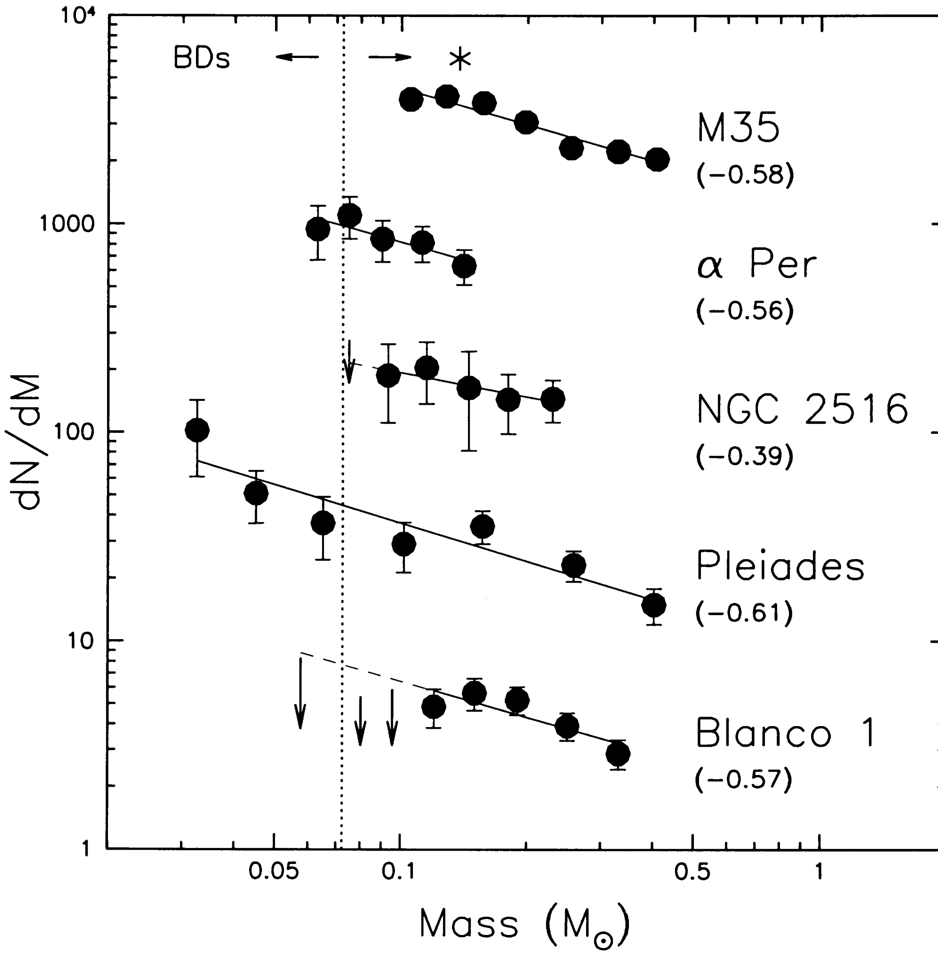

Figure 3. The mass function of young open clusters across the stellar/substellar boundary. Each cluster is identified by its name and the index α of a power-law fit to the mass function ($dN/dM \propto M^{\alpha}$, shown as a solid line) is given within parentheses. Vertical arrows at the low mass end of NGC 2516's and Blanco 1's MF indicate 3σ upper limits. dN/dM of each cluster has been vertically scaled for clarity.

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low mass stars and brown dwarfs will have escaped a Pleiades-like cluster at an age of 100 Myr by this process (e.g., de la Fuente Marcos & de la Fuente Marcos 2000). Furthermore, the predicted loss rate is nearly the same for substellar objects and low mass stars (since there is no dynamical boundary between the stellar and substellar regimes), so that the shape of the mass function will not be affected across the stellar/substellar boundary. Hence, the secular dynamical evolution of stellar clusters is not expected to significantly deplete the IMF at low masses during the early evolutionary stages.

However, in some theoretical models, dynamical processes intimately linked to the star-formation process are predicted to significantly influence the observed MF at Pleiades age. In the scenario Reipurth & Clarke (2001) proposed for the formation of isolated brown dwarfs, the lowest mass fragments of protostellar aggregates are dynamically ejected and may rapidly leave the cluster if their ejection velocity exceeds the escape velocity. Several models of dynamical ejection have been developed along these lines and all suggest ejection velocities of order of a few km/s, though the output of each particular model differs in the details (cf. Sterzik & Durisen 1998, Bate et al. 2002, Delgado et al., in prep.).

Following this scenario, Figure 4 shows the results of a N-body 2 numerical simulation of the dynamical evolution of a Pleiades-like cluster (Moraux & Clarke, in prep.). The simulation includes 1600 objects whose mass distribution follows a prescribed mass function, with the initial velocity dispersion of brown dwarfs being scaled relative to that of stars, and assuming the whole system is virialized. The various curves in Figure 4 illustrate the computed spatial distribution of brown dwarfs at an age of 120 Myr depending on their initial velocity distribution. Note that the Pleiades cluster ($r_{tidal} \simeq 16$ pc) is entirely contained in the very first 2 bins. It is seen that half or more of the initial cluster brown dwarfs will have left the cluster by an age of 120 Myr if their initial velocity dispersion exceeds that of stars by a factor of 2.

Such dynamical processes may be expected to significantly modify the lower mass function of young open clusters in a way which sensitively depends upon the specific properties of each cluster, such as initial stellar density and radius, thus presumably leading to different lower MF for different clusters. Yet, no significant difference is found so far between the lower MF of the studied clusters. Also, the lower MF of young open clusters appears similar to that of star forming regions such as Orion Trapezium (Luhman et al. 2000) or σ Ori (Béjar et al. 2001). These results then suggest that dynamical processes are not in fact predominant in the formation and early evolution of open clusters and that the MF derived for the Pleiades and Pleiades-like clusters may indeed be representative of the IMF.

5. Conclusions

Deep wide-field photometric surveys of brown dwarfs in nearby young open clusters have yielded estimates of the mass function across the stellar/substellar boundary. The best studied cluster so far is the Pleiades whose lower mass function can be approximated by a power-law with an exponent $\alpha = -0.6 \pm 0.1$ (i.e. $dN/dM \propto M^{-0.6}$) over the mass range 0.03-0.4 $M_{\odot}$. Though the determination of the mass function in other Pleiades-age clusters (M35, Alpha

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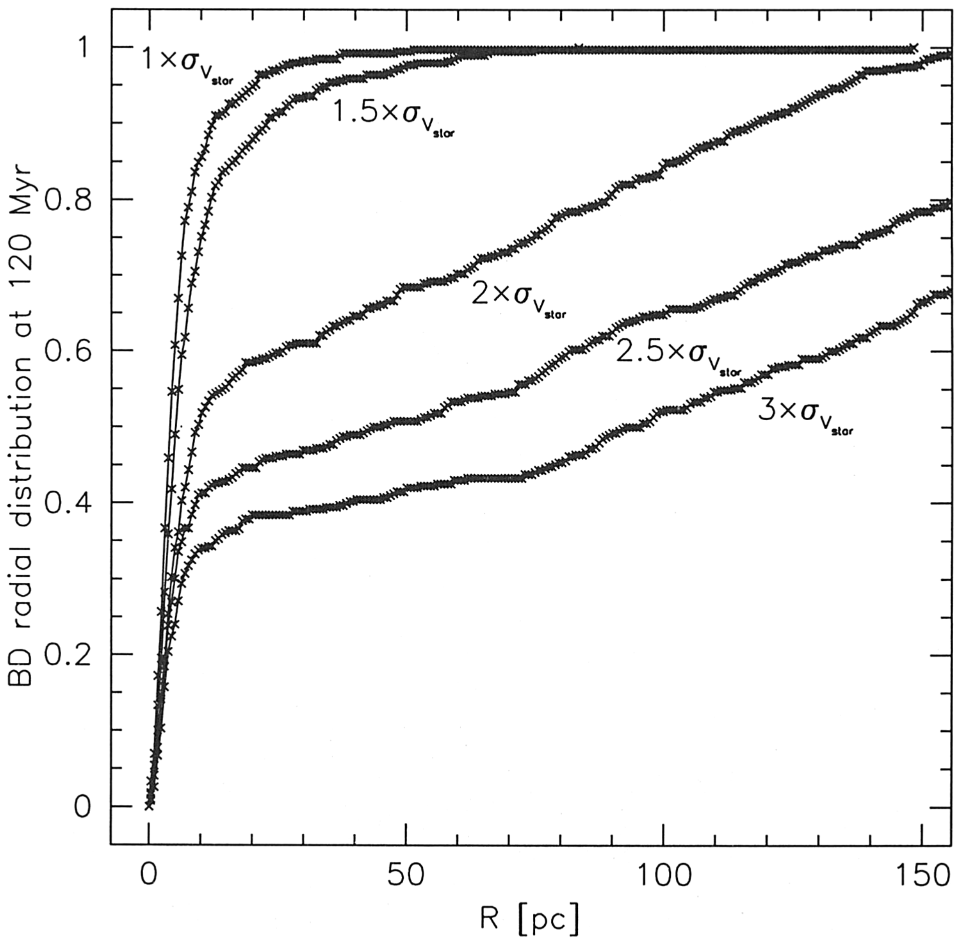

Figure 4. The radial distribution of brown dwarfs at an age of 120 Myr computed from the numerical simulation of the dynamical evolution of a Pleiades-like cluster. From top to bottom the cumulative distributions illustrate the effect of increasing the initial velocity dispersion of cluster BDs. Note that the Pleiades cluster, with a tidal radius of about 16 pc, is entirely contained in the first 2 bins on the x-axis.

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Per, NGC 2516, Blanco 1) is not yet as precise as for the Pleiades itself, current estimates suggest that there is no appreciable differences in the shape of the lower MF between the various clusters, regardless of their precise age, metallicity or richness. This might be an indication that the currently measured mass function of these clusters at an age of about 100 Myr is representative of their initial mass function (IMF) and thus provides a quantitative constraint to the formation scenarios for stars and brown dwarfs.

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From left to right: Emmanuel Caux, Jean-Louis Monin, Jerome Bouvier, and Nicolas Lodieu

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