The substellar mass function in the central region of the open cluster Praesepe from deep LBT observations

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Abstract. Studies of the mass function (MF) of open clusters of different ages allow us to probe the efficiency with which brown dwarfs (BDs) are evaporated from clusters to populate the field. Surveys in old clusters (age ≳ 100 Myr) do not suffer so severely from several problems encountered in young clusters, such as intra-cluster extinction and large uncertainties in BD models. Here we present the results of a deep photometric survey to study the MF of the old open cluster Praesepe (age 590^{+150}_{-120} Myr and distance 190^{+6}_{-5.8} pc), down to a 5σ detection limit at i ∼ 25.6 mag (∼40 MJup). We identify 62 cluster member candidates, of which 40 are substellar, from comparison with predictions from a dusty atmosphere model. The MF rises from the substellar boundary until ∼60 MJup and then declines. This is quite different from the form inferred for other open clusters older than 50 Myr, but seems to be similar to those found in very young open cluster, whose MFs peak at ∼10 MJup. Either Praesepe really does have a different MF from other clusters or they had similar initial MFs but have differed in their dynamical evolution. We further have identified six foreground T dwarf candidates towards Praesepe, which require follow-up spectroscopy to confirm their nature.

1. Introduction

The mass functions (MFs) of stellar and substellar populations have been determined from optical and near-infrared surveys for several open clusters at different ages, such as the Orion Nebula Cluster, σ Orionis, ρ Ophiuchi, Taurus, IC 348, IC 2391, M35, the Pleiades, and the Hyades. Studies of relatively old open clusters (age > 100 Myr) are important for the following two reasons in particular: first, they allow us to study the intrinsic evolution of basic properties of BDs, e.g. luminosity and effective temperature, and to compare the evolution with structural and atmospheric models; second, we may investigate how the BD and low-mass star populations as a whole evolve, e.g. the efficiency with which BDs and low-mass stars evaporate from clusters. Such an
investigation has been carried out for the Hyades (Bouvier et al. 2008, and references therein) and for Praesepe (Boudreault et al. 2010, and references therein).

Boudreault et al. (2010, hereafter B2010) observed a significant difference between the MFs of Praesepe and Hyades: While the Hyades MF is observed to have a maximum at $\sim 0.6 \, M_\odot$ (Bouvier et al. 2008), the MF of Praesepe continues to rise from $0.8 \, M_\odot$ down to $0.1 \, M_\odot$. This is surprising, as both clusters share similar physical properties (ages, mass, metallicity, and tidal radii). Disagreement between the Praesepe and Hyades MFs could arise from variations in the clusters' initial MFs, or from differences in their dynamical evolution (Bastian et al. 2010). Although different binary fractions could cause the observed (system) MFs to differ, there is no clear evidence for varying binary fractions from measurements published in the literature (B2010).

2. Observations and analysis

The Large Binocular Cameras (LBCs) are two wide-field, high-throughput imaging cameras, namely Blue (LBCB) and Red (LBCR), located at the prime focus stations of the Large Binocular Telescope (LBT). Each LBC has a wide field of view ($23^\prime \times 23^\prime$), with four CCD detectors of $2048 \times 4608$ pixels each, providing images with a sampling of $0.23^\prime$/pixel. The optical design and detectors of the two cameras are optimized for different wavelength ranges: one for ultraviolet-blue wavelengths (including the Bessel $U$, $B$, $V$ and Sloan $g$ and $r$ bands), and one for the red-infrared bands (including the Sloan $i$, $z$ and Fan $Y$ bands). In the full binocular configuration, both cameras are available simultaneously, and both point in the same direction of the sky, thus doubling the net efficiency of the LBT. The survey was carried out with the $r$ filter using LBC-blue and the $izY$ filters using LBC-red, covering the central $0.59 \, \text{deg}^2$ area of Praesepe.

The standard data reduction steps for the LBT data were performed using the IDL astronomy package and IRAF. An astrometric solution was achieved using the Sloan Digital Sky Survey (SDSS) catalogue as a reference. The root mean square accuracy of our astrometric solution is $0.10-0.15$ arcsec. To correct for Earth atmospheric absorption on the photometry, we calibrated the infrared data using the $r$, $i$ and $z$ band values of SDSS objects which were observed in the science fields. In order to calibrate our $Y$ band photometry, we used our LBT $i$ and $z$ photometry and the $Y$ band photometry from the United Kingdom Infrared Telescope Infrared Deep Sky Survey (UKIDSS).

3. Candidate Selection Procedure and mass determination

The candidate selection procedure and the mass determination introduced by Boudreault & Bailier-Jones (2009) and B2010 were adopted in the present work. We use the evolutionary tracks from (Chabrier et al. 2000) and the atmosphere models from (Allard et al. 2001) assuming a dusty atmosphere (the AMES-Dusty model), to compute an isochrone for Praesepe using an age of $590^{+150}_{-120}$ Myr, a distance of $190^{+6.0}_{-5.8}$ pc, a solar metallicity and we neglecting the reddening.

3.1. Candidate Selection using colour-magnitude and colour-colour diagrams

Candidates were first selected from our CMD by keeping all objects which are no more than $0.28$ mag redder or bluer than the isochrones in all CMDs. This number accommodates errors in the magnitudes and uncertainties in the model isochrones. We also
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Figure 1. Colour-magnitude diagram (Left) and colour-colour diagram (Right) used for the first and second selection procedures. Solid lines are the isochrones computed from an evolutionary model with a dusty atmosphere (AMES-Dusty). The dashed lines delimit our selection band. The numbers indicate the masses (in $M_{\odot}$) on the model sequence. In the right panel, the theoretical colours of six galaxies and of red giants are shown as thin lines and as thick lines, respectively. The six galaxies are two starbursts, one Sab, one Sbc, and two ellipticals of 5.5 and 15 Gyr, with redshifts from $z=0$ to $z=2$ in steps of 0.25 (evolution not considered). We assume that all red giants have a mass of 5 $M_{\odot}$, $0.5 < \log g < 2.5$ and $2000 \, \text{K} < T_{\text{eff}} < 6000 \, \text{K}$.

include the errors from age and distance of Praesepe. We additionally include objects brighter than the isochrones by 0.753 mag in order to include unresolved binaries. In Figure 1(left) we show the CMD where candidates were selected based on $z$ vs. $i-z$.

The second stage of candidate selection involves retaining just those objects which lie within 0.28 mag of the isochrone in the colour-colour diagram. This value reflects the photometric errors and uncertainties in the model isochrones. In addition, we also include the uncertainty in the age estimation of Praesepe. The colour-colour diagram with the selection limits is shown in Figure 1(right), with the theoretical colours for red giants using the atmosphere models of Hauschildt et al. (1999) and theoretical colours of six galaxies with redshift from 0 to 2 from K. Meisenheimer et al. (in prep.) overplotted. Neither the red giants nor the galaxies are expected to be a significant source of contamination; most of the low redshift galaxies can be easily rejected through visual inspection. As these are the dominant potential contaminants, we conclude that there is no significant contamination of non-Praesepe members in our sample (Praesepe is at a Galactic latitude of $b = +32.5^\circ$).

3.2. Observed magnitude vs. predicted magnitude

Our determination of $T_{\text{eff}}$ is based on the spectral energy distribution of each object and is independent of the assumed distance. The membership status of an object can therefore be assessed by comparing its observed magnitude in a band with its magnitude predicted from its $T_{\text{eff}}$ and the Praesepe’s isochrone (which assumes a distance and an
This selection step is only a verification of the consistency between the physical parameters obtained of the photometric cluster candidates with the physical properties assume for the cluster itself when computing the isochrones. In order to avoid removing unresolved binaries that are real members of the cluster, we keep all objects with a computed magnitude of up to 0.753 mag brighter than the observed magnitude. This selection procedure is illustrated in Fig. 2.

4. Results

4.1. Selected photometric candidates

62 photometric candidates survive the selection procedures (based on isochrones assuming dusty atmospheres). This corresponds to \( \sim 105 \) objects per square degree. Our survey saturation occurs at \( \sim 18 \) mag in \( z \) band, corresponding to \( \sim 100 \, M_{\text{Jup}} \). Therefore, most of the low mass candidates discovered in previous surveys (e.g. Pinfield et al. 1997, Hambly et al. 1995) saturate in our LBT images. Only a few faint BDs classified by Pinfield et al. (1997), González-García et al. (2006) and by B2010 are rediscovered by the current survey.

There are also some targets which are previously identified as cluster members but rejected by our selection procedures or visual inspection. For example, ten candidates identified by B2010 are detected (not saturated) in our LBT survey, but six of them are rejected by the \( z \) vs. \( i-z \) CMD, because they are bluer than the isochrones area. Another
one is obviously not a point-like source in the LBT image, and another is rejected because its observed $J$ magnitude is not consistent with its model-predicted magnitude. Only the remaining two targets are confirmed to be cluster dwarf stars. As the current work employed more photometric bands than B2010 did, it is not surprising that we achieve a more conservative selection.

Most of our candidates are in the substellar regime, and other than these ten, no other accurate photometric observations are available from past epochs. This precludes using proper motions as a mean of cluster membership assessment at this time.

4.2. Contamination by non-members
As mentioned before, the two main sources of contamination are the background red giants and unresolved galaxies. Red giants occupy the high mass end of this study, as seen in the $i - J$ vs. $z - K_s$ diagram. Although some types of galaxies share similar colours with Praesepe cluster members more massive than 60 $M_{\text{Jup}}$, such low-redshift galaxies are in general extended sources and therefore easily rejected by our visual inspection. Among the 74 candidates that passed our selection procedures, we identify four as galaxies through their LBT images. Other possible sources are field L dwarfs and high redshift quasars (for instance at $z \sim 6$; Caballero et al. 2008). However, as such quasars have spectral energy distributions similar to mid-T dwarfs whereas our faintest candidates have colours of early L dwarfs, and given that they are rare (0.25 quasars at $5.5 < z < 6.5$ in a 0.59 deg$^2$ survey, Stern et al. 2007), the MF should not be affected by quasar contamination.

The contamination by L dwarfs is also unimportant. Caballero et al. (2008) have collected possible field dwarf contaminants covering spectral type from M3 to T8 from the literature. From their Table 3, the spatial density for L dwarfs in the solar neighbourhood is $\sim 7 \times 10^{-3}$ pc$^{-3}$. Given that Praesepe has a Galactic latitude of $+32.5$ deg and distance of 190 pc, the nearby spatial density of L dwarfs Praesepe should be $\sim 6 \times 10^{-3}$ pc$^{-3}$, assuming an exponential decrease for stellar density perpendicular to the Galactic disk and a scale height of 500 pc. If we define a volume corresponding the area of our survey, and use the distance uncertainties to the cluster as its depth, the total volume is $\sim 80$ pc$^3$. Therefore, we estimate that we have $\sim$0.5 L dwarf contaminants near the cluster, which amounts to a negligible contamination of merely 0.7%. A similar calculation shows that we would have $\sim$4 M dwarf contaminants, about 6%.

We conclude that various contaminants are not important for this study and the MF we derive for Praesepe should be accurate.

5. Mass function of very low mass and substellar population of Praesepe
The mass function, $\xi(\log_{10} M)$, we present here is the total number of objects per square degree in each logarithmic mass interval $\log_{10} M$ to $\log_{10} M + 0.1$. Since we do not make any corrections for binaries, we compute here a system MF.

Our optical photometry reaches lower masses than the NIR photometry that we used. To compute the MF of Praesepe to the lowest mass bin, we first computed a MF using only the optical $iz$ photometry. This MF is presented on Fig. 3 as filled dots. We computed a second MF from the list of candidates that pass the three selections criteria which are also detected in the survey of B2010 in the NIR $J$ and $K_s$ bands (presented on Fig. 3 as filled triangles). For each mass bin, we computed the number of object removed because of adding the $J$ and $K_s$ filters to our selection process and mass
determination (plotted as a function of mass in Fig. 3, top panel). We fitted a linear function to estimate the number of objects that would be removed if we had additional J and $K_s$ photometry down to 40–45 $M_{\text{Jup}}$. The corresponding extension of the MF with $izJK_s$ photometry is given as a large triangle on Fig. 3.

Figure 3. Bottom. MFs based (a) on our survey LBT $i$ and $z$ photometry (dots), and (b) also combined with the J and $K_s$ photometry from B2010 (triangles). Error bars are Poissonian arising from the number of objects in each bin, except for the last bin, for which the error bar is mostly from the linear fit in top panel. The vertical dotted line is the saturation mass. The vertical long and short dashed lines are the masses at the 5σ detection limits of our optical LBT data and of the B2010 NIR data. Top. Difference of the number of objects in each mass bin, between the MF computed using the LBT $iz$ data and the MF computed using the combination of the $iz$ data from the B2010 NIR $JK_s$ data. The dotted line is a linear fit to the discrepancies.

Our derived MF of Praesepe (presented in Fig. 3) shows a rise from 105 $M_{\text{Jup}}$ to 60 $M_{\text{Jup}}$ and then a turn-over at $\sim$60 $M_J$. We note that in the second mass bin at $\sim$ 48 $M_{\text{Jup}}$, the MF is very low. This is probably because at this mass we reach the 5σ detection limit of the J-band of our Ω2k photometry, so we suspect this is not a real feature. However, the turn-over at $\sim$60 $M_{\text{Jup}}$ occurs well above the 5σ of either $iz$ bands or $JK_s$ bands (e.g., at $\sim$60 $M_{\text{Jup}}$, $i \sim 22$, completeness$\sim 100\%$) and therefore should not be caused by incompleteness. This is the first time one observes a clear rise in the substellar MF in old open cluster.

We collected some results for other clusters for comparisons, as plotted in Fig. 4. This includes: IC 2391 by (Boudreault & Bailer-Jones 2009), ONC by (Hillenbrand & Carpenter 2000), $\sigma$ Orionis by (Bihain et al. 2009) and the Hyades from (Bouvier et al. 2008).
Figure 4. Mass functions of various open clusters. From top to bottom: $\rho$ Oph ($\sim 1$ Myr); S 106 ($\sim 1$ Myr, middle panel for example); Trapezium ($\sim 0.8$ Myr); IC2391 ($\sim 50$ Myr); ONC ($\sim 5$ Myr); $\sigma$ Ori ($\sim 3$ Myr); Hyades ($\sim 625$ Myr); Praesepe ($\sim 590$ Myr, from this work). We also show the Galactic field star MF from Chabrier (2003) as a dashed line. All the MFs are normalized to the lognormal fit of Chabrier (2003) at the substellar limit ($\sim 72 M_{\text{Jup}}$).

The MF of Praesepe is quite different from either IC 2391 (age of $\sim 50$ Myr) or the Hyades ($\sim 625$ Myr). Either the ‘dynamical evaporation’ does not have the same effect on those three clusters, or they have a different initial mass function. Another alternative possibility is that Praesepe has a different binary fraction. Further studies would be necessary to clarify these points.

The continuing rise of the MF into the substellar regime which we observe has also been observed in young clusters (as shown in Fig. 4), specifically in $\sigma$ Orionis (Bihain et al. 2009), Trapezium (Muench et al. 2002, turn-over at $\sim 10$–20 $M_{\text{Jup}}$), $\rho$ Oph (Marsh et al. 2010, MF rising to $\sim 10 M_J$) and in the very low luminosity young cluster in S106, where the MF increases or at least remains flat down to $\sim 10 M_{\text{Jup}}$ (Oasa et al. 2006). If we assumed a universal IMF, then it seems that the substellar MF of Praesepe has not evolve significantly since it the cluster formed.

6. Conclusions

We have carried out the deepest survey to date of the open cluster Praesepe, covering the central 0.59 deg$^2$ in the $rizY$ bands. The survey probed a mass range from $\sim 100$ to $40 M_{\text{Jup}}$ at 5$\sigma$ detection limit. Our $iz$-bands data, combined with the $\Omega 2k$ NIR ($J$ & $K_s$) band observations from B2010, are compared with theoretical loci of cluster members based on a dusty atmosphere (the AMES-Dusty model), in order to clarify cluster member candidates. Our final sample comprises 62 photometric candidates. We estimate the contamination by field L dwarfs to be less than 1%, and that by galaxies and red giants also to be negligible. About two thirds of our candidates have theoretical masses below the Hydrogen-burning limit at 0.072 $M_\odot$, and are therefore BD candidates.
The mass function we have inferred for Praesepe is consistent with that inferred by B2010 at a mass just below the substellar boundary, but deviates by ~0.4 dex in the next lowest mass bin, which may indicate either a significant number of objects missing in the Boudreault et al. 2010 survey, or a higher concentration of substellar objects in the centre of Praesepe (as the Boudreault et al. survey is at a larger cluster radius). The latter possibility suggests that the dynamical evolution of very low mass stars is not efficient in this cluster, as proposed by B2010, for explaining the discrepancy between the Praesepe MF and Hyades MF.

The steady rise of the Praesepe MF until ~60 $M_{\text{Jup}}$ was unexpected. Such a significant peak has never been observed in any other cluster older than 50 Myr, but has been observed in several very young open clusters such as σ Orionis or clusters in star forming regions (e.g. Trapezium). This suggests that the dynamical interactions in Praesepe have very little effect on MFs, if we assume there is a universal initial MF.

The results reported here will be presented with further details in an future publication submitted to A&A (Wang et al. 2010, submitted).

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