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Brown Dwarfs in the Pleiades*

A deep IJK survey

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Abstract. An area large enough (180 arcmin^2) to put constraints on a possible low mass brown dwarf population in the Pleiades has been surveyed to very faint magnitudes in I, J and K. The completeness limit, I=21.6, corresponds to a mass of 0.01 M$_\odot$ for a cluster age of 70 Myr and 0.035 M$_\odot$ for 120 Myr. The result is consistent with previous investigations at higher masses that the brown dwarf initial mass function is a m^{-1}, or even less steep, power law. Thus low mass brown dwarfs cannot contribute significantly to the Pleiades' mass. One new possible Pleiades member was found, mass $\sim$ 0.08 M$_\odot$ (age 120Myr).

Key words: stars: late-type – stars: low-mass, brown dwarfs – stars: luminosity function, mass function – open clusters and associations: individual: Pleiades

1. Introduction

Brown dwarfs (BDs) are stellar-like objects. The only difference from ordinary stars is that the mass is too low to bring up the central temperature to the level of stable hydrogen burning, thus the BD luminosity decreases with time. As an example, from 70 Myr to 10 Gyr, a 0.08 M$_\odot$ object at the hydrogen burning limit would decrease a factor 15 in luminosity, while a 0.06 M$_\odot$ would go a factor 700 (Burrows et al. 1993). The ideal target for a BD search thus is a fairly young, nearby and rich star cluster. The Pleiades is the obvious choice in the northern hemisphere, being at $\sim$ 125 pc and 70-120 Myr old. Several recent authors have proposed an age above 100 Myr. In this paper 120 Myr is adopted. The mean distance modulus of the cluster used is 5.53 (see Basri et al. 1996 for a discussion).

Whether BDs could be a significant part of the local dark matter is a subject of controversy. Several recent photometric surveys have found a significant drop in the luminosity function from M_V = 12 to M_V = 14, leading to a turnover in the initial mass function (IMF, $dN_{\rm stars} = const * m^n * dm$ (m = mass; n = IMF-index)) at $\sim$ 0.3 M$_\odot$ (see e.g. Gould et al. 1996; Tinney 1993) or a continued rise towards the hydrogen burning limit (see e.g. Kirkpatrick et al. 1994) depending on the choice of mass-luminosity relation. Kroupa (1995) showed that the difference between the nearby stellar luminosity function (LF), measured by parallax and the more distant LF, measured by photometry alone, can be explained by undetected binary companions in the distant sample. From a recently derived mass-luminosity relation (Chabrier et al. 1996) and the well-known photometric LF (see e.g. Gould et al. 1996), Mera et al. (1996) concluded that the IMF for low mass stars continues to rise to the hydrogen burning limit. However the number of known field stars at the low mass end of the main sequence is small. To clearify this item it is necessary to discover more low mass stars and BDs, preferrably at a known distance and age.

In Sect. 2, observations, reductions and a short discussion on photometry and completeness limits is given. In Sect. 3, the extraction of Pleiades members is described. Sect. 4 discusses contamination and overall observing strategy. In Sect. 5 the implications of this paper on the IMF-index is discussed and compared to other authors.

2. Observations and reductions

All observations for this program were obtained at the 2.56 m Nordic Optical Telescope (NOT), La Palma. The observed area covers 180 arcmin^2 in IJK and is centred at RA 3$^{\rm h}$48$^{\rm m}$3.6$^{\rm s}$, Dec 23° 44′13.1” (J2000.0).

The I data was taken with BROCAM1 (TEK1K), operated in cassegrain focus with 0.176”/pixel and 3’x3’ field. For future proper motion measurements, the astrometry errors due to nonuninform pixels and possible effects of rotator position were reduced by using four different position angles for each I-field (0, 90, 180 and 270 degrees) exposing 5 min at each position. Debiassing and flatfield corrections were done in a standard

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* Based on observations made with the Nordic Optical Telescope, La Palma.

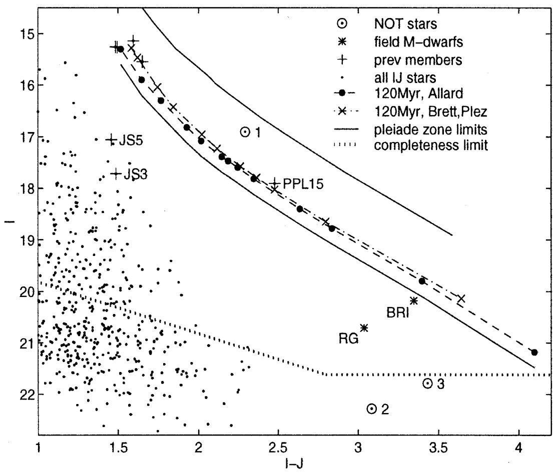

Fig. 1. Colour-magnitude diagram for all stars detected in both I and J. NOT1 is a Pleiades candidate and other NOT stars are probable background M-dwarfs. Ticks ($M_{\odot}$): 0.035, 0.045, 0.055, 0.060, 0.070, 0.075, 0.078, 0.080, 0.090, 0.100, 0.125, 0.150, 0.200 (Allard) and 0.045, 0.060, 0.070, 0.075, 0.080, 0.090, 0.100, 0.125, 0.150, 0.200, 0.220 (Brett,Plez). The two field stars are BRI0021-0214 (>M9.5V) and RG0050-2722 (M8V), reduced in the same way as the program fields. The models and the two field stars have been shifted to the distance and general reddening of the Pleiades.

fashion within IRAF (Image Reduction and Analysis Facility)[1]. Median seeing was $\sim$ 0.6", varying from 0.46" to 0.80".

The JK observations were done with the ARNICA NICMOS3 (256x256) array, which was made available at NOT via a collaboration with Arcetri Astrophysical Observatory, Florence. The last third of 6 nights in Aug-Sep95 was used. Unfortunately the pixel size (0.55") was not very well matched to the seeing ($<$ 0.8") and all images were undersampled. Another problem was that focus changed across the field, which due to astigmatism in the NOT optics led to stars of slightly different elongation across the field. Apparently this was caused by the chip not being perpendicular to the optical axis which could be seen as a slight change in pixel scale across the field.

The J data could be treated the same way as I, but high and rapidly varying background in K necessitated a different approach. The sky for each K-image was defined as the median of the four images nearest in time and subtracted from the image, which then was flatfielded by a differential flat.

2.1. Classification of objects

A major problem in this kind of survey is to distinguish stars from distant galaxies at faint magnitudes. The whole area was visually inspected and all objects were classified as stars, galaxies, binaries or unclassifiable (too faint for a meaningful classification). 1411 objects out of 3800 were classified as stars. Since the seeing conditions were excellent it is estimated that the discrimination between stars and galaxies is reliable to $I \sim 22$.

2.2. Photometry

Since point spread functions (PSFs) were undersampled in JK it was not suitable to use ordinary PSF fitting. For single aperture photometry it is necessary to always keep the same aperture radius. However for the JK data centering errors and focus shifts are non-negligible, thus in order to maximize the signal to noise ratio it was desirable to change aperture radius from one object to another. A new, more robust, method (used also in I) was developed, brief outlines:

1. All objects were measured in a series of 80 apertures, with radii ranging from 0.05" to 4" in steps of 0.05".
2. From the "best" stars in each field a growth curve (Stetson 1990) was constructed, i.e. magnitude shift as function of aperture radius.
3. Each objects' curve was subtracted by that frames' growth curve. Ideally this curve is completely flat, but due to centering errors, errors in the sky level etc... that is generally not the case. However, there is normally an almost flat part of the curve at $\sim 1-2$ FWHM. The magnitude difference was taken as the mean level of that part. The advantage with this method is that the right mean level will be found even if objects are differently focussed or elongated as compared to the reference growth curve.

Transformation of JK instrument magnitudes to the CIT system was done by observations of IR standard stars and transformation equations provided by the ARNICA team (Hunt et al. subm.). I instrument magnitudes were transformed to the Kron-Cousins system via observations of Landolt (1992) standard stars. Typical internal errors are 0.1 mag (I = 21.9; J = 19.3; K = 16.9) and 0.02 mag (I = 19.8; J = 16.7; K = 14.9). The zeropoint errors are $\sim$0.05 mag in J and $\sim$0.08 mag in K. In I they are estimated to be less than 0.02 mag. Zeropoint errors are not included in Table 1 and Table 3.

All objects recognized as binaries or stars very close to a galaxy in I were, as a check, also measured by PSF-fitting. For a few objects that were resolved in I, but not in JK, the whole system was measured as one object in all bands, thus getting the binary system correct in the colour magnitude diagrams.

2.3. Completeness limits

In this kind of surveys it is important to know the magnitude limit to which the survey is complete. The number of detected stars as a function of magnitude increases exponentially and gives a straight line in a $\log(N_{stars})$ vs mag plot as long as the survey is complete. The point at which the curve turns away from the straight line should be regarded as the completeness limit. Thus I = 21.6, J = 18.9 and K = 16.7 are the completeness limits of this survey (magnitude error $\sim$ 0.08 mag). The 50 % limit is $\sim$ 0.7 mag fainter.

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[1] IRAF is distributed by National Optical Observatories (NOAO), which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

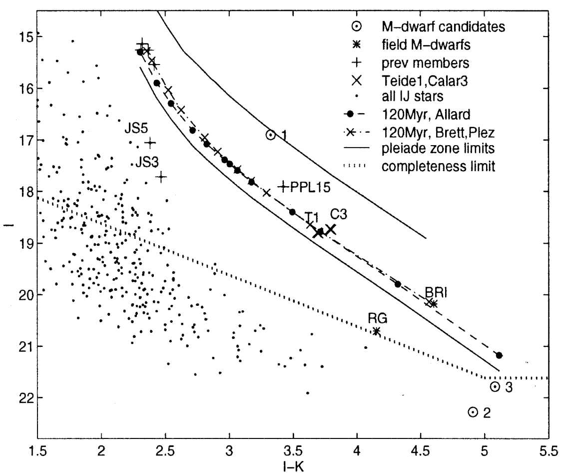

Fig. 2. All stars detected in both I and K. Symbols are the same as in Fig. 1.

Table 1. Photometry of potential Pleiades members. Magnitude errors are internal.

id	I_{KC}	J_{CIT}	K_{CIT}
HHJ424	saturated	saturated	10.99 (0.01)
HHJ336	saturated	12.74 (0.01)	11.99 (0.01)
HHJ288	saturated	13.25 (0.01)	12.36 (0.01)
HHJ152	15.14 (0.01)	13.55 (0.01)	12.82 (0.01)
HHJ188	15.26 (0.01)	13.78 (0.01)	12.95 (0.01)
HHJ156	15.26 (0.01)	13.77 (0.01)	12.90 (0.01)
HHJ122	15.55 (0.01)	13.90 (0.01)	13.13 (0.01)
NOT1	16.91 (0.01)	14.61 (0.01)	13.58 (0.01)
PPL15	17.91 (0.01)	15.43 (0.01)	14.48 (0.02)
JS3	17.72 (0.05)	16.23 (0.01)	15.25 (0.02)
JS5	17.06 (0.05)	15.60 (0.01)	14.68 (0.02)

3. Analysis

3.1. Extraction technique

Several different kinds of errors define the zone of potential Pleiades members in the colour magnitude diagram. The maximum error in the absolute magnitude of a single Pleiades member is not likely to exceed 0.2 mag because of uncertainty of its distance. The photometric error for $I < 21.0$ is less than 0.1 mag. For binaries, the worst case is considered. Two identical companions get 0.75 mag brighter than a single star of the same colour. Therefore the bright edge is raised by 0.75 mag. The age of the Pleiades is also a source of error. Basri et al. (1996) argue that the age is $\sim$ 115 Myr while the "canonical" age deduced from the upper main sequence turn-off is 75 Myr. To account for the worst possible case, the 70 Myr sequence -1.05 mag defines the bright limit, and the 120 Myr model +0.30 mag defines the faint limit. An extension of the model colours in Chabrier et al. (1996) based on the Brett (1995) models was kindly provided by Plez (1996). Next generation models from Allard et al. (1996) were also included. Both models show excellent agreement with the data (Fig. 1 and 2).

Note the clear gap between the background field stars and the Pleiades sequence and that all previously known members within the field were detected with this technique.

3.2. Extracted objects

As shown in Fig. 1 and 2, 6 objects in the sample ($I > 15$) can be regarded as potential cluster members (Table 1). Of these, 5 were previously known as proper motion members (Hambley et al. 1993; Rebolo et al. 1995). The new candidate (NOT1) is very close to a much brighter star, discovered only as a consequence of the excellent seeing conditions during the observations. A finding chart and coordinates of NOT1 are given in Fig. 4. Its colours and magnitude indicate a binary of equally sized components, each of $\sim 0.08 M_\odot$, slightly heavier than PPL15 (Basri et al. 1996). It is, however, also consistent with being a foreground M-dwarf (see Sect. 4).

The last two stars in Table 1 were previously regarded as Pleiades candidates from RI photometry (Jameson & Skillen 1989), but can be judged as clear nonmembers from Fig. 1, which is the same result as Zapatero Osorio et al. (1996) got from their RI survey.

3.3. Comparison with other works

Several papers have recently been published on the Pleiades. The proper motion survey by Hambley et al. (1993), using POSS and UKSTO Schmidt plates, covered most of the cluster, complete to $I \sim 16.5$, corresponding to a star of 0.10 $M_\odot$, slightly above the hydrogen burning limit. Their limiting magnitude was $\sim$ 1 mag fainter and they reached objects of $\sim$ 0.08 $M_\odot$, right at the BD limit.

Jameson & Skillen (1989) imaged 175 arcmin^2 in RI. Some of their fields overlap with ours and after checking their original data, we concluded that their completeness limit is $I \sim 20.7$ and $R \sim 23.1$. Their R limit corresponds to $I \sim 20.3$ on the Pleiades sequence. They found 9 BD candidates, all of which later have been shown to fall significantly below the Pleiades sequence in colour magnitude diagrams (Zapatero Osorio et al. 1996). Rebolo et al. (1995) announced the discovery of a BD (Teide1) in the Pleiades as a result of a CCD survey, 175 arcmin^2. This survey was later extended to 578 arcmin^2, complete to $I \sim 19.5$, and another candidate (Calar3) was found (Zapatero Osorio et al. 1996). Both candidates have passed all membership tests hitherto, including the lithium test (Rebolo et al . 1996) and can be regarded as genuine BDs. Stauffer et al. (1994) surveyed $\sim$ 1500 arcmin^2. Their survey is complete to $V \sim 22$ corresponding to $I \sim 18$ in the Pleiades domain of the V vs $V-I$ diagram. They found 15 very red Pleiades candidates, among them PPL15, which for a cluster age of 75 Myr would be of mass $\sim$ 0.06 $M_\odot$. However, Basri et al. (1996) observed PPL15 at Keck and suggested, based on the lithium line strength, that its age is around 115 Myr, thus increasing the mass from 0.065 $M_\odot$ to 0.077 $M_\odot$. Basri also concludes,

Table 2. The number of Pleiades candidates in the magnitude interval $16 < I < 19$ from five different surveys and as expected from four different IMF-indices. The rightmost column is scaled to 500 arcmin^2. Normalization of the IMF was deduced from proper motion members in $15.0 < I < 16.4$ (Hambley et al. 1993). Statistical errors are within the parenthesis.

origin	arcmin^2	candidates	scaled
this paper	180	2 (2)	5.6 (4)
Jameson & Skillen 1989	175	0 (-)	0 (-)
Simons & Becklin 1992	200	22 (10)	55 (25)
Stauffer et al. 1994	1500	9 (3)	3.0 (1)
Williams et al 1996	400	8 (3)	10 (3)
Zapatero O et al. 1996	578	5 (2)	4.3 (2)
IMF-index, $n = -2.8$	—	——	37-56
-2.0	—	——	16-22
-1.0	—	——	6-7
-0.0	—	——	2-3

Table 3. M-dwarf candidates, including the Pleiades candidate NOT1. Magnitude errors are internal. Distance errors are of the order of 10%.

id	$I_{\rm KC}$	$I - J_{\rm CIT}$	$I - K_{\rm CIT}$	d(pc)
NOT1	16.90 (0.01)	2.29 (0.01)	3.15 (0.01)	70
NOT2	22.29 (0.11)	3.08 (0.23)	4.91 (0.24)	330
NOT3	21.79 (0.13)	3.43 (0.14)	5.08 (0.15)	250

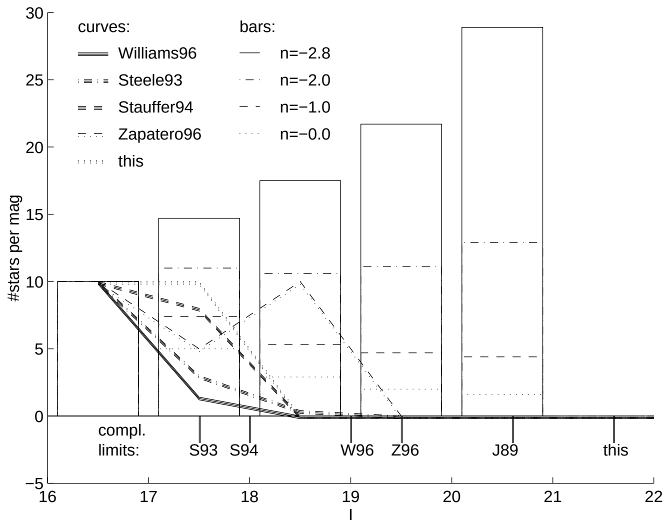

Fig. 3. Comparing LF predicted for four different IMF-indices (bars) and five recent surveys (curves). All LFs were normalized to 10 counts in $16 < I < 17$). Indicated are also approximate completeness limits for the surveys. Jameson & Skillen (1989) (J89) is only indicated for completeness limit, since all of their candidates fall 1.5 - 2 mag below the Pleiades sequence.

based on the non-detection of lithium in the BD candidate HHJ3 (Hambley et al. (1993)), that it cannot be younger than 110 Myr. Thus the Pleiades age is confined approximatively between 110 Myr and 125 Myr. Simons & Becklin (1992) used I vs $I - K$ diagrams and compared fields within the cluster to reference fields outside the cluster. They found an excess of 22 ± 10 BD candidates in 200 arcmin^2 in the cluster field. Williams et al. (1996) found 8 stars in the magnitude interval $16 < I < 19$, using V and K instead of IJK, a result consistent with ours. Steele et al. (1993) present ~ 35 candidates with IJK photometry in the same magnitude range, a subsample from Hambley et al. (1993), complete to $I \sim 16.5$ and therefore not included in Table 2. All surveys except Simons & Becklin (1992) agree reasonably well within error bars.

4. Discussion

Photometry alone can not extract Pleiades members to a very high confidence level, but is the most time-efficient tool for finding potential members, whose proper motion later can be measured. In this survey it is shown that the I vs $I - J$ diagram clearly sorts out the Pleiades sequence from the background. As an example of efficiency, consider the completeness limit of this survey (I = 21.6), reached in 20 minutes integration at seeing 0.6". The same BD in V ($V \sim 26$) would demand ~ 8 hours and in R ($R \sim 24$) ~ 1 hour. In J it takes only ~ 1 minute. Thus even though CCDs have larger surface area, they cannot compete with IR-arrays for objects as red as presumed BDs. In case of K, the needed integration time is ~ 6 minutes. Adding more complicated reductions to that and the fact that I and J is enough to extract the Pleiades sequence there is no need for K data in the first step of a survey like this.

Possible contamination of the Pleiades candidates could come from reddened background giants, M-dwarfs and unresolved galaxies. The number of contaminating background giants in the surveyed area was estimated from the model by Bahcall & Soneira (1984) to be ~ 0.03, thus being negligible. The interstellar extinction adopted was A_I = 0.57 mag/kpc ($E_{I-K} \sim 0.43$ mag/kpc) (Lucke 1978; Cardelli et al. 1989) out to 2 kpc, then decreasing exponentially with the same scale-factor as for the giants, which is expected to be an upper limit of the possible extinction, and thus gives an upper limit of the number of contaminating giants. Due to the excellent seeing during the observing run it is believed that the contamination by galaxies on the stellar sample is negligible for $I \lesssim 22$.

The LF from Gould et al. (1996) was used to estimate the number of foreground M-dwarfs for $I - J > 2.2$ to < 0.2. Thus it is not likely, although possible, that NOT1 is a foreground M-dwarf. Since late M-dwarfs are presumed to be rare, it is interesting that a few candidates turn up in this survey, see Table 3. Both NOT2 and NOT3 appear quite close to the Pleiades zone in Fig. 2. Could they be low mass Pleiades BDs? NOT3 was in a part of the field that was also covered by Jameson & Skillen (1989). It was found in their original data, however far too faint for astrometry of sufficiently high accuracy for a proper motion measurement. NOT2 and NOT3 will though be observed in future runs.

Towards this part of the Pleiades the total reddening is $E_{B-V} \sim 0.04$ mag (Stauffer & Hartmann 1987), which cor-

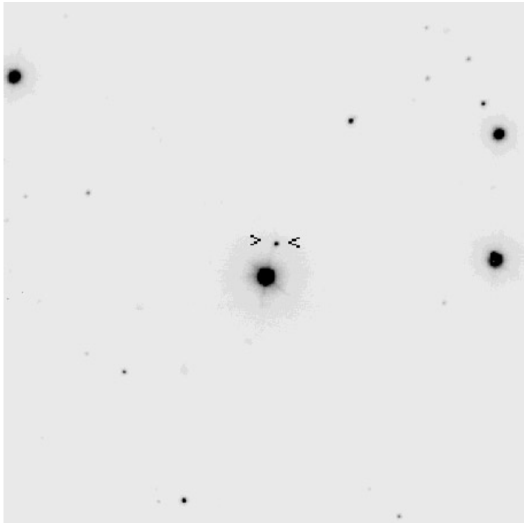

Fig. 4. Finding chart for the Pleiades candidate NOT1 (RA $3^{h}48^{m}3.61^{s}$, Dec $23^{\circ}44'13.1''$ (J2000.0, Epoch 1995.9), errors $\sim$ 1” in both coordinates). The size of the field is $\sim$ 2’x2’. North is down. East is right.

responds to $E_{I-J} \sim 0.02$ mag (Cardelli et al. 1989). Thus if these stars really are M-dwarfs, E_{I-J} is less than 0.1 mag even for the most distant candidate and does not affect classification significantly.

5. Conclusions

Our goal was not to cover as large an area as possible, but to reach very faint magnitudes in order to investigate the presence of a population of low mass BDs in the Pleiades. This survey is complete to I = 21.6, corresponding to 0.035 $M_\odot$ (120 Myr) or 0.01 $M_\odot$ (70 Myr). In Fig. 3, LFs from recent surveys are compared to LFs deduced from 4 different IMF-indices. It is clear from previous surveys that an IMF-index close to or even above 0 is favored at least down to $I \sim 18$. This survey, complete to I = 21.6 in the Pleiades domain, one magnitude fainter than any previous survey does not give one single object below I = 18. Thus $n = -2.8$ (Simons & Becklin 1992) can be rejected with 99.8% confidence, $n = -2$ with 96.9%. Corresponding figures for $n = -1$ is 75.1% and for $n = 0$ 45.0%. The final conclusion is that if low mass BDs ($M < 0.05$ $M_\odot$) exist in the Pleiades, they follow an IMF with index less steep than $n = -1$, and cannot comprise a very large part of the cluster’s mass.

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