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ASTRONOMY AND ASTROPHYSICS

Brown dwarfs in the Pleiades cluster

II. J, H and K photometry*

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Abstract. We have obtained near-infrared observations of some of the faintest objects so far known towards the Pleiades young stellar cluster, with the purpose of investigating the sequence that connects cluster very low-mass stars with substellar objects. We find that infrared data combined with optical magnitudes are a useful tool to discriminate cluster members from foreground and background late-type field stars contaminating optical surveys. The bottom of the Pleiades sequence is clearly defined by the faint HHJ objects as the very low-mass stars approaching the substellar limit, by the transition object PPl 15, which will barely ignite its hydrogen content, and by the two brown dwarfs Calar 3 and Teide 1.

Binarity amongst cluster members could account for the large dispersion observed in the faint end of the infrared colour-magnitude diagrams. Two objects in our sample, namely HHJ 6 and PPl 15, are overluminous compared to other members, suggesting a probable binary nature. We have reproduced the photometric measurements of both of them by combining the magnitudes of cluster very low-mass stars and brown dwarfs and using the most recent theoretical evolutionary tracks. The likely masses of the components are slightly above the substellar limit for HHJ 6, while they are 0.080 and 0.045±0.010 $M_{\odot}$ for PPl 15. These masses are consistent with the constraints imposed by the published lithium observations of these Pleiads.

We find a single object infrared sequence in the Pleiades cluster connecting very low-mass stars and brown dwarfs. We propose that the substellar mass limit ($\sim$0.075 $M_{\odot}$) in the Pleiades ($\sim$120 Myr) takes place at absolute magnitudes $M_{\rm I}$ = 12.4, $M_{\rm J}$ = 10.1, $M_{\rm H}$ = 9.4 and $M_{\rm K}$ = 9.0 (spectral type M7). Cluster members fainter by 0.2 mag in the I-band and 0.1 mag in the K-band should be proper brown dwarfs. The star-brown dwarf frontier in the Hyades cluster (600 Myr) would be located at $M_{\rm I}$ = 15.0, $M_{\rm J}$ = 11.6, $M_{\rm H}$ = 10.8 and $M_{\rm K}$ = 10.4 (spectral type around M9). Fon an age older than 1000 Myr we estimate that brown dwarfs are fainter than $M_{\rm K}$ = 10.9 (spectral type later than M9.5).

Key words: stars: pre-main sequence – stars: late-type – stars: low-mass, brown-dwarfs – open clusters: Pleiades

1. Introduction

The search for free-floating brown dwarfs (hereafter referred to as BDs) has finally been proved successful. After years of continuous efforts to detect intrinsically fainter and less massive objects both in the field and in open star clusters (see e.g. the reviews by Jameson 1995 and Reid 1995), the recent photometric survey of a small sky area in the Pleiades (age 70–120 Myr) by Zapatero Osorio, Rebolo & Martín (1997) (hereafter Paper I) has provided objects that according to all available evolutionary models are beyond the substellar limit (Rebolo, Zapatero Osorio & Martín 1995; Martín, Rebolo & Zapatero Osorio 1996). The genuine BD nature of two of them has been confirmed by the detection of high lithium abundances in their atmospheres (Rebolo et al. 1996). The re-appearance of lithium in objects at the bottom of the Pleiades main sequence (MS) has helped to empirically define the borderline that separates very low-mass stars from BDs. At present, both sides of the substellar limit are populated with several objects which may allow us to establish qualitative and quantitative differences between them and also with respect to other field objects with similar spectral types. Martín et al. (1996) have started to approach this issue using intermediate-resolution optical spectroscopy. In this paper, we examine this problem using near-infrared photometry. We have obtained J, H and K magnitudes for some Pleiades very low-mass stars selected from the literature, as well as for the most interesting objects in the optical survey presented in Paper I. We will focus here on the utility of combining both optical and infrared photometry to identify true Pleiades BDs, disentangle binarity effects and discriminate cluster members from contaminants that appear in optical surveys. These observations

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* Based on observations made with the William Herschel Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias (IAC), Spain.

are mainly aimed at characterizing the cluster substellar borderline and studying the infrared sequence that connects Pleiades least massive stars with BDs.

2. Sample selection. Observations

Our sample is presented in Table 1 where we have avoided the term "Pleiades" for those objects taken from Paper I. All objects in the sample have measured spectral types equal or later than M6, and they could be located around the substellar limit in the Pleiades cluster according to their I magnitudes and $(R-I)$ colours. PPl 15 (discovered by Stauffer, Hamilton & Probst 1994) is the M6.5-type Pleiad that at present defines the borderline which separates very low-mass stars from BDs in the cluster. This is based on the fact that PPl 15 has preserved some of its initial lithium content. The comparison with theoretical models (Basri, Marcy & Graham 1996; Rebolo et al. 1996) yields that the most likely mass of PPl 15 is $\sim$0.08 $M_\odot$. HHJ 2 (M6.5), HHJ 3 (M6) and HHJ 6 (M6.5) are proper motion members taken from Hambly, Hawkins & Jameson (1993). Their optical-infrared magnitudes and spectral types (Steele & Jameson 1995) place these objects close to the substellar limit, but still on the stellar domain. HHJ 3 has depleted its lithium (Marcy, Basri & Graham 1994). In fact, none of the HHJ objects in our sample shows lithium in their atmospheres (Basri 1996, private communication), implying that all of them have masses larger than 0.08 $M_\odot$ and therefore, they are among the least massive stars in the cluster. There are no lithium observations available for PPl 1 (M6.5) (Stauffer et al. 1989), but it has a photometry very similar to that of HHJ 3, and a radial velocity consistent with membership. The remaining objects in our sample are taken from the optical survey of Paper I from which two genuine BDs have emerged, namely Teide 1 (M8) and Calar 3 (M8). Both have successfully passed the lithium test (Rebolo et al. 1996). According to their radial velocities and spectral types, Calar 1 (M9), Calar 2 (M6), Calar 5 (M6.5) and Roque 1 (M7) seem to be non-members of the Pleiades (Martín et al. 1996). The infrared photometry will shed new light on their membership in the cluster.

The J, H and K observations were performed in 1996 February 9 at the 4.2 m William Herschel Telescope (WHT, Observatorio del Roque de los Muchachos on the Island of La Palma, Spain), using the WHIRCAM infrared camera equipped with an InSb (256$\times$256) detector array. This detector provided 0".24 pixels and a field of view of $\sim 1' \times 1'$. The standard J, H and K' infrared filter set was used. The total integration time per object and per filter was 50 s, where each final image actually consisted of 5 co-added 10 s exposures. Raw data were processed using standard techniques within the IRAF[1] environment. Dark frames were first substracted from the images before combining them in order to obtain good flat-fields for each filter. Then, individual frames were divided by the normalized, mean flat-field.

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

Table 1. Infrared photometry

Name	SpT^a	J	H	K	I^b-K	R^c-I
HHJ 6	M6.5	14.77	14.08	13.59	3.41	2.35
HHJ 2	M6.5	15.33	14.71	14.31	2.99	2.08
HHJ 3^d	M6	15.21	14.50	14.23	3.18	2.15
PPl 1	M6.5	15.44	14.68	14.32	3.21	
PPl 15	M6.5	15.36	14.66	14.14	3.66	2.25
Calar 1	M9	16.01	15.41	14.95	3.23	2.93
Roque 1	M7	16.22	15.65	15.21	3.22	2.50
Calar 2	M6	16.55	15.81	15.55	3.11	2.50
Calar 3	M8	16.29	15.45	14.94	3.79	2.54
Teide 1	M8	16.37	15.55	15.11	3.69	2.74
Calar 5	M6.5	17.07	16.23	15.88	3.13	2.33

NOTES.
[a] Spectral types for the HHJ objects are taken from Steele & Jameson (1995), whereas for the remaining objects spectral types come from Martín et al. (1996).
[b] I magnitudes come from Steele & Jameson (1995) for the HHJ objects; from Stauffer et al. (1989) for PPl 1; from Stauffer et al. (1994) for PPl 15; from Paper I for Roque 1, Teide 1 and Calar objects.
[c] R magnitudes are taken from Hambly et al. (1993) for the HHJ objects; from Paper I for PPl 15, Roque 1, Teide 1 and Calar objects.
[d] H and K magnitudes for HHJ 3 are taken from Steele et al. (1993).

The photometric analysis was carried out using routines within DAOPHOT. Weather conditions during the campaign were always fairly photometric. Instrumental aperture magnitudes were corrected for atmospheric extinction and transformed into the UKIRT system using observations at different airmasses of the standards FS 9 and FS 12 (Casali & Hawarden 1992). The K' data were converted to the K-band magnitudes using the transformation equation given in Wainscoat & Cowie (1992). We estimate that the accuracy in the final magnitudes is 0.05 mag at each wavelength. The final J, H and K photometry of the sample is provided in Table 1. Our magnitudes are in good agreement within $\pm$0.1 mag with those found in the literature for the objects in common (HHJ and PPl objects), except for the K-band of PPl 15, where a difference of 0.18 mag is observed with respect to Basri et al.'s (1996) data in the sense that our result is brighter. We have only a J measurement for HHJ 3; for completeness in Table 1, H and K magnitudes in the UKIRT system were taken from Steele, Jameson & Hambly (1993).

3. Infrared diagrams and cluster membership

The K vs $(I-K)$ colour-magnitude diagram for our sample (filled symbols) and some of the Pleiades least massive objects discovered to date (open symbols) is shown in Fig. 1. We also plot previously known proper motion cluster members observed at these wavelengths by Steele et al. (1993) using the revised I photometry published in Steele & Jameson (1995). We have also included the BD candidates proposed by Stauffer et al. (1989) and Williams et al. (1996). Different symbols are used for clarity and no de-reddening has been applied. The solid line is an averaged MS derived from the photometry of field stars taken

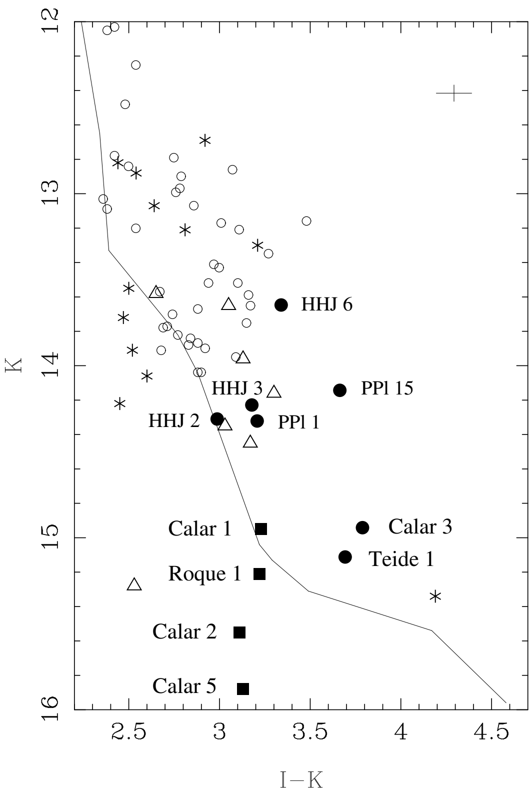

Fig. 1. K vs $(I-K)$ colour-diagram for our sample and other Pleides low-mass objects. Filled circles denote cluster members whereas filled squares denote non-members (see text for explanation). Asterisks stand for the BD candidates of Williams et al. (1996), and triangles for those of Stauffer et al. (1989). Proper motion HHJ objects (data taken from Steele et al. 1993, and Steele & Jameson 1995) are shown as open circles. The line represents the MS as derived from the photometry of field late-type dwarf stars (Leggett 1992), shifted to the Pleiades distance and reddening. Error bars for our photometry are indicated at the top right corner

from Leggett (1992), shifted to an assumed Pleiades distance modulus of $(m-M)_{\circ}$ = 5.53 mag and adopting $A_{\rm V}$ = 0.12 mag (Crawford & Perry 1976); $A_{\rm I}$ and $A_{\rm K}$ were then derived using the relationships of Rieke & Lefobski (1985).

Only objects with spectral types later than M3 ($(I-K) \geq$ 2.2) are displayed in Fig. 1. As expected, young Pleiades members have not reached the field MS (Stauffer 1984; Steele & Jameson 1995), thus lying above it. This is basically what is observed except for a few exceptions, like PPl 3 (Stauffer et al. 1989), also named as JS1 (Jameson & Skillen 1989), which is located 1.7 mag below the MS line. The infrared photometry rules out its membership in the cluster, a fact that is consistent with our proper motion measurement in Paper I. Five very low-mass stars proposed by Williams et al. (1996) around $(I-K)$ = 2.5 and $K \sim 14$ lie also below the field MS and are indeed fainter in the K-band than proper motion Pleiades of the same colour, suggesting that they are unlikely members based on their infrared photometry.

Two other objects in our sample, Calar 2 and Calar 5, are clearly located below the MS by $\sim$1 mag in Fig. 1. Both of them have infrared colours that resemble those of field stars of similar spectral types within the errors in photometry and classification (e.g., see the $(I-K)$ vs spectral type diagram of Fig. 2). Although found with $(R-I)$ values and radial velocities consistent with other cluster members, Calar 2 and Calar 5 are non-members on the basis of their infrared photometry, confirming the suspicions of Martín et al. (1996). These objects do not fit in the sequence described by the cluster members in Fig. 4 in Martín et al.'s work, being fainter in I than expected for Pleiads of these spectral types. Calar 2 and Calar 5 are therefore likely background reddened low-mass stars. Infrared observations allow an easy discrimination of contaminants that could arise in optical photometric surveys from true Pleiads.

Roque 1 appears very close to the MS in Fig. 1, but slightly below it implying that it is a likely non-member. By inspecting Fig. 2 and allowing for the photometric uncertainties, this object fits in the $(I-K)$ colour-spectral type diagram for solar metallicity field stars. From the comparison of its photometry and spectral type with the absolute magnitudes published in Kirkpatrick & McCarthy (1994) we conclude that this object may be located at approximately the Pleiades distance. Nevertheless, given its high radial velocity ($v_{\rm r}$ = 151$\pm$30 km s^{-1}), it was suggested in Martín et al. (1996) that Roque 1 could be part of the old galactic population, but neither its R, I and J, H, K colours nor its optical spectrum show any evidence of significant low-metallicity. Roque 1 still awaits further investigation that confirms its membership in an old population.

Calar 1 sits on the MS in Fig. 1. However, its location is highly unexpected given its spectral type and $(R-I)$ colour. This object was found to be the reddest BD candidate in the optical survey of Paper I with $(R-I)$ = 2.9, and surprisingly, it appears rather blue in the infrared (see Fig. 2). Apart from being one of the few M9 dwarfs known in the whole sky, it is the first one to our knowledge that behaves so rarely at infrared wavelengths. Leggett (1992) states that for very cool dwarfs no obvious metallicity effects are discernable in optical diagrams, but that they become apparent in infrared plots. Metal-poor objects are well known to have bluer colours than solar metallicity ones. Calar 1 may be a metal-deficient dwarf located foreground to the Pleiades, a fact that is supported by its high radial velocity ($v_{\rm r}$ = 85$\pm$30 km s^{-1}, Martín et al. 1996). The proper motion and parallax determinations would help to understand the nature of this object. Calar 1, Calar 2, Calar 5 and Roque 1 are excluded from further discussion in this paper as very unlikely members of the cluster.

The remaining objects in our sample (HHJ 2, HHJ 3, HHJ 6, PPl 1, PPl 15, Teide 1 and Calar 3) do follow the sequence described by the proper motion cluster members in Fig. 1. Particularly, Teide 1 and Calar 3 define the present faint end of the Pleiades, which lies 0.3–0.45 mag above the MS in the K-band. Objects with similar photometry should be considered as probable BDs in the cluster. The object in Williams et al. (1996) labelled as No. 13 could be a BD based on its photom-

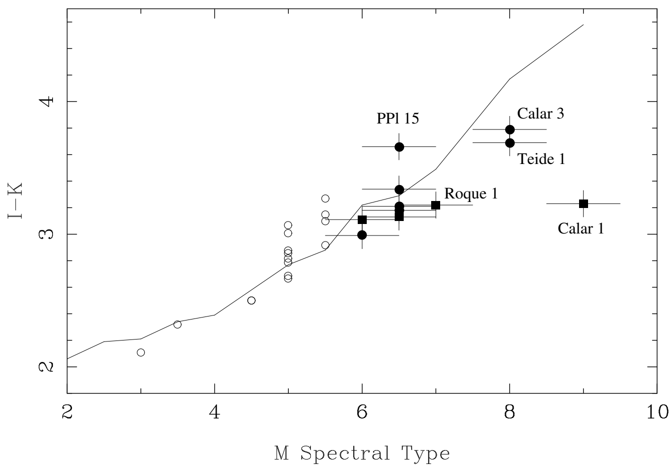

Fig. 2. $(I-K)$ vs spectral type diagram for our sample. Symbols are as in Fig. 1. Spectral types have been taken from Steele & Jameson (1995), Martín et al. (1994), and Martín et al. (1996). The line represents the relationship for solar metallicity field stars (Kirkpatrick & McCarthy 1994). Error bars are half a spectral subclass (as stated by the authors), and ±0.1 mag for the photometric colour. Some objects have been labeled for clarity

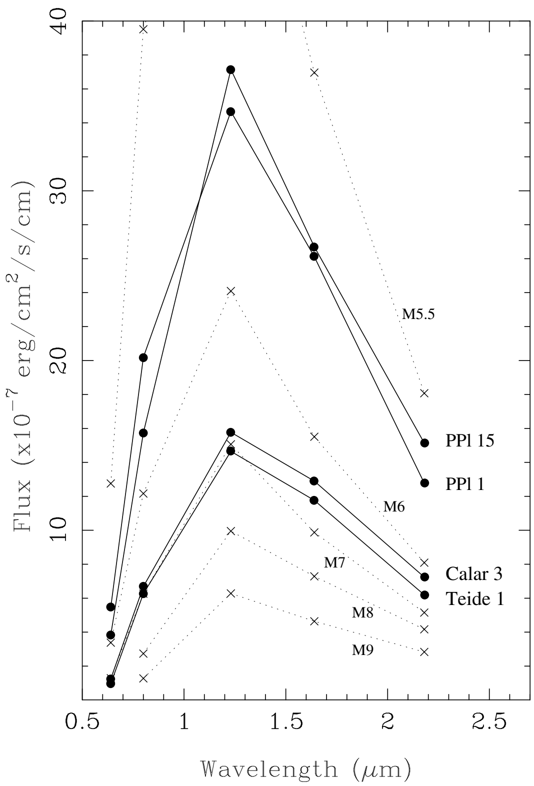

Fig. 3. Broad-band energy distributions at R, I, J, H and K wavelengths. Pleiades members are denoted as circles and full lines. The spectral distributions of M5.5–M9 field dwarfs are also plotted for comparison (crosses and dotted lines). Errors in flux conversion could be as large as 20%.

etry. However, we have recently obtained deep images in the I-band which show that it is likely an extense object.

3.1. Broad-band energy distributions

We have combined optical (R and I) and infrared magnitudes of the Pleiades objects in our sample in order to obtain the general shape of their energy distributions and compare them with those of field stars with similar spectral types. We adopted the absolute magnitudes for M dwarfs given in Kirkpatrick & McCarthy (1994) as representative of the field, and the distance modulus and extinction of the Pleiades to convert the observed magnitudes to absolute magnitudes for the cluster members. The zero-magnitude fluxes and center-wavelengths (Cousins for R and I, UKIRT for J, H and K) are taken from Mead et al. (1990).

In Fig. 3 we plot the final broad-band spectral distributions for PPl 1, PPl 15, Teide 1, and Calar 3. PPl 1 is the only object in our sample which has no R magnitude available. We have estimated it using the mean $(R-I)$ colour of the other three M6.5 Pleiads in our sample (the mean coincides with that given by Kirkpatrick & McCarthy 1994 for a field star of the same spectral type). Overplotted are the distributions of stars from M5.5 to M9 (for spectral types M8 and M9 Kirkpatrick & McCarthy 1994 do not provide data at the R-band). This plot clearly shows how important infrared emission is to study these extremely late-type objects since most of their bolometric flux is emitted at these wavelengths. Less than a few per cent is emitted blueward of the R-band.

Given a spectral type, a Pleiades member having the same effective temperature and hence a very similar energy distribution than a field star, should emit more at each wavelength due to its youth; i.e., it should move up along the flux-axis in Fig. 3. PPl 1 and PPl 15 appear to have energy distributions that resemble within uncertainties in flux conversion and observed magnitudes those of the old M6–M7 stars, except that the formers (which have similar optical spectral types) are twice (0.3 dex) more luminous. Teide 1 and Calar 3 show cooler energy distributions that are much alike to M8-type field stars, but the two Pleiades BDs are overluminous by a factor 1.6 (0.2 dex). These results agree with expectations for cluster members.

The accurate determination of bolometric luminosities for our objects would require the use of spectroscopic data covering the whole optical and infrared regions. Integrating the broad-band flux distributions always overestimates the luminosity, because the spectra of these late-type objects are dominated by deep molecular and absorption features that are not precisely described by the photometry. The overestimation (less than 10% according to Reid & Gilmore 1984 and Tinney et al. (1993) seems to be constant through all the spectral types, although perhaps slightly larger for M9 stars. This allow us to be confident on the fact that relative luminosities within our sample are not strongly influenced by molecular absorption effects. We have integrated the flux distributions of our Pleiades members and evaluated the differences in luminosity with respect to Teide 1 (the least luminous object in our sample). The result-

Table 2. Differences in log $(L/L_{\odot})$ relative to Teide 1

HHJ 6	HHJ 2	HHJ 3	PPl 1	PPl 15	Calar 3
0.63	0.41	0.45	0.36	0.37	0.05

ing values are provided in Table 2. We estimate that they are affected by an error of $\pm$0.04 dex which mainly comes from uncertainties in the photometry.

In the Pleiades cluster stars of spectral type M6.5 are 2.29$\pm$0.25 times (0.36$\pm$0.04 dex) more luminous than M8-type objects. We have computed the mean luminosities for field stars of the same spectral types averaging the data from Tinney et al. (1993) and Bessell & Stringfellow (1993), and found that M6.5 field stars are overluminous by a factor 1.78 (0.25 dex) with respect to M8 stars. It is remarkable that the factor for the Pleiades is larger by $\sim$0.1 dex. This offset in luminosity takes into account differences in radii. The fact that the ratio $R_{\rm M6.5}/R_{\rm M8}$ is greater in the Pleiades cluster than in the field could be explained by a larger mass difference between a M6.5 object and a M8 object in the former than in the latter. This result was expected from theoretical evolutionary models. It would be desirable to define a consistent spectral type classification using objects that belong to a cluster to take advantage of the coeval formation as well as of the homogeneous metallicity.

4. Binarity amongst the faintest Pleiades members

One of the most noteworthy features in the colour-magnitude diagram of Fig. 1 is the large scatter observed among the Pleiades objects. As a possible explanation it was suggested that an age spread could account for such an effect (Eggen & Iben 1989; Steele et al. 1993). However, this is a controversial subject (e.g. Stauffer, Liebert & Giampapa 1995). Recently, Steele & Jameson (1995) have argued that the scatter could be interpreted in terms of a single and a binary star sequence, both of the same age. These authors found that 46% of the fainter HHJ stars are likely binary systems, a figure which compares well with those given for low-mass stars (Bessell & Stringfellow 1993, and references therein). According to Steele & Jameson (1995), the binary sequence of M stars at the age of the Pleiades is expected to lie $\sim$0.75 mag above the single sequence. It is obvious from Fig. 1 that two Pleiads (HHJ 6 and PPl 15) in our sample are too bright by a similar quantity in the K-band, thus suggesting that they are binary sistems. We will take advantage of what is already known for these two cluster members and try to estimate the most likely masses of the components. We will show that it is possible to reproduce the observed magnitudes and colours of HHJ 6 and PPl 15 by co-adding those of other members of different masses located on the sequence of likely single objects, which is defined by HHJ 2, HHJ 3, PPl 1, Calar 3 and Teide 1. These members can be used as photometric and mass templates.

HHJ 3 does not show lithium in its atmosphere implying that its mass is greater than 0.08 $M_{\odot}$. PPl 1 has a very similar photometry both in the optical and in the infrared, and therefore it could be considered as a "twin" of HHJ 3. For Calar 3 and Teide 1, Rebolo et al. (1996) inferred a likely mass of 0.055$\pm$0.015 $M_{\odot}$ based on the comparison of their lithium abundance and luminosity with the theoretical models of Chabrier, Baraffe & Plez (1996) that predict the destruction of this element as a function of time. The authors adopted a cluster age of 120 Myr (see Basri et al. 1996 for a further discussion). For the following analysis we have taken the same age as well as the theoretical evolutionary tracks of Chabrier et al. (1996) (those based on the 'NextGen' model atmospheres of Allard & Hauschildt 1996). We have computed the magnitude offsets for different masses in the range 0.10–0.04 $M_{\odot}$ relative to an object of 0.055 $M_{\odot}$, and applied them to the photometry of Teide 1. We have built a grid of apparent magnitudes that describe very low-mass single stars and BDs in the cluster. The comparison of the photometry of HHJ 3 and PPl 1 with the grid yields a mass of 0.09$\pm$0.01 $M_{\odot}$, consistent with the high destruction of lithium observed in them.

HHJ 6 is massive enough to be a star since it has depleted its lithium content. Its magnitudes are brighter than those of HHJ 3 and PPl 1 which have the same spectral type, whereas their colours are not different within error bars (see Fig. 2). This suggests that if HHJ 6 is a binary system, the components should have roughly equal masses. Steele & Jameson (1995) and Steele et al. (1995) obtained the optical and infrared spectra, respectively, of this Pleiad and claimed that their spectroscopic data do not show any evidence for a companion of different mass. Following the same approach described above and taking the 0.09 $M_{\odot}$ stars as templates, we find that the combination of two objects of 0.085$\pm$0.010 $M_{\odot}$ each reproduces well the magnitudes and colours measured for HHJ 6. The number of possible pairs that comply with the purpose of obtaining the photometry of a presumed binary object is not unique, but the current spectroscopic knowledge on the candidate constrains the result. Nevertheless, given the error bars, other combinations of objects with masses around 0.09 and 0.08 $M_{\odot}$ are possible (e.g., 0.090 and 0.085 $M_{\odot}$; 0.09 and 0.08 $M_{\odot}$).

4.1. A likely brown dwarf companion to PPl 15

PPl 15 is a M6.5 Pleiad that shows at infrared wavelengths too red colours for its spectral type (see Fig. 2), even taking into account the difference in the K-band magnitude between Basri et al.'s (1996) measurement and ours. This object, however, fits well the single sequence of cluster members in the V versus $(V-I)$ (Stauffer et al. 1994) and in the I versus $(R-I)$ (Paper I) diagrams. A possibility that could explain the observed excess in the infrared colours of PPl 15 is the existence of a residual extinction dust shell around this object. According to previous J, H and K data (Stauffer 1982, 1984; Steele & Jameson 1995), low-mass Pleiades stars have colours that resemble those of field dwarfs. This suggests that if a circumstellar disc exists its size should be small and hence, it hardly contributes to the total luminosity of the object. The anomalous colours of PPl 15 may be attributable to binarity, however. The supposed secondary must be significantly less massive than the primary. Its contribution to the total integrated flux would be hence more important at redder wavelengths. The flux emitted at J, H and K by PPl 15 is larger than that emitted by PPl 1, occurring just the opposite at R and I wavelengths as shown in Fig. 3. Following the technique of the relative differences in colour previously described, we find that a combination of objects of 0.080 and 0.045±0.010 $M_{\odot}$ matches the photometry of PPl 15.

It is of interest to calculate the contribution of such a low-mass companion to the total luminosity of the PPl 15 system as well as to the observed magnitude in each filter. According to Rebolo et al. (1996), the luminosity of PPl 15 is log $L/L_{\odot}$ = –2.80±0.10, about 20% of it could come from the secondary. Its contribution to the R-band is only 5%. Thus, the effect of this companion on the "unresolved" optical spectrum obtained by Basri et al. (1996) is nearly undetectable, in particular implying that the observed lithium line at λ670.8 nm is due to the primary component, for which we have estimated a mass just on the substellar limit. To date, there is no report on the variabililty of the radial velocity of PPl 15. It would be desirable to obtain near infrared spectroscopy of this object in order to test its possible binarity. At these wavelengths (1–2.5 μm) the low-mass companion is expected to contribute with 25–30% of the total flux, and hence its effects on molecular bands such as CO and H_2O should be noticeable (Steele et al. 1995).

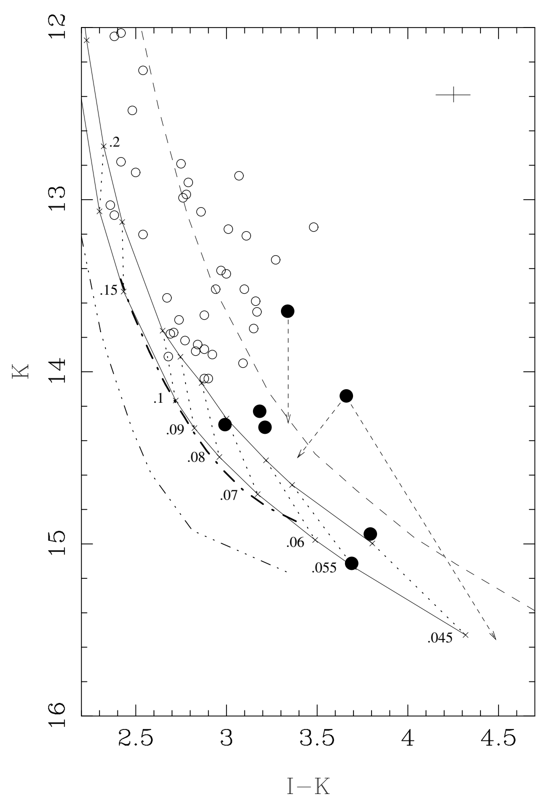

Fig. 4. K vs $(I-K)$ colour-diagram for the Pleiades members. Symbols are as in Fig. 1. Superimposed to the data are the isochrones of Baraffe et al. (1995) based on the 'Base' models atmospheres (Allard & Hauschildt 1995, dashed line, 120 Myr), and those of Chabrier et al. (1996) based on the "NextGen" model atmospheres (Allard & Hauschildt 1996, solid lines, 70 and 120 Myr). Numbers denote masses in solar units for these models, and evolutionary tracks are shown as dotted lines. Isochrones of Burrows et al. (1993) and D'Antona & Mazzitelli (1994) are denoted by a dot-dashed line and by a dot-dot-dot-dashed line, respectively, both for an age of 70 Myr. The mass range depicted for these models is 0.15–0.04 $M_{\odot}$. An indication of the location of the likely components of HHJ 6 and PPl 15 is given by dashed arrows

5. The infrared sequence from very low-mass stars to brown dwarfs

The final K versus $(I-K)$ diagram for the least massive Pleiades members known so far is displayed in Fig. 4. We have only plotted objects for which cluster membership has been established by other means than photometry, such as proper motion and radial velocitiy measurements, and/or the presence of lithium in their spectra. Superposed on the data we have drawn theoretical evolutionary tracks of Baraffe et al. (1995) based on the 'Base' model atmospheres of Allard & Hauschildt (1995), and those of Chabrier et al. (1996) based on the most recent 'NextGen' model atmospheres of Allard & Hauschildt (1996) for solar metallicity and ages of 70 and 120 Myr. We have also included the isochrones for 70 Myr of Burrows et al. (1993) (Model X) and D'Antona & Mazzitelli (1994) (Table 5). Baraffe et al. and Chabrier et al. have estimated magnitudes (V, R, I in the Cousins system and J, H, K in the CIT system) as a function of mass and age. We have used the equations given in Leggett (1992) to convert the infrared magnitudes into the UKIRT system. Burrows et al. (1993) and D'Antona & Mazzitelli (1994) do not provide magnitudes for their models; thus, we have computed them using the $(I-K)$ and K bolometric correction versus effective temperature relationships that can be obtained from Tables 2, 6 and 7 of Leggett et al. (1996).

All isochrones reproduce qualitatively the general trend of the observational data. However, within the age range assumed for the Pleiades (70–150 Myr), the models of Burrows et al. (1993) and D'Antona & Mazzitelli (1994) predict rather blue $(I-K)$ colours and/or faint K magnitudes. Only for very young ages, those isochrones would fit the Pleiades data, implying that cluster members like the faintest HHJ objects should have preserved lithium, clearly in desagreement with the lithium observations of these stars. This discrepancy for very low-masses was also noted in terms of effective temperature and luminosity in the α Persei cluster by Zapatero Osorio et al. (1996). The 70 Myr evolutionary track of Burrows et al. (1993) seems to coincide with that of the 'NextGen' 120 Myr isochrone of Chabrier et al. (1996). For a given age, Burrows et al.'s models predict effective temperatures that are hotter by 150–100 K than those predicted by Chabrier et al., and luminosities that are slightly brighter by 0.03–0.015 dex in the mass range in common for both theoretical models. The differences between the two sets of isochrones of Baraffe et al. ('Base') and Chabrier et al. ('NextGen') are remarkable, e.g., given an age and a mass the $(I-K)$ offset could be as large as 0.5 mag. The 'Base' model atmospheres have been improved recently by including more accurate molecular line lists, yielding the 'NextGen' mod-

Table 3. Absolute magnitudes defining the substellar limit (0.080–0.075 $M_{\odot}$, solar metallicity) at different ages

Age (Myr)	M_R	M_I	M_J	M_H	M_K	SpT
Pleiades (120)	14.4–14.7	12.2–12.4	10.0–10.1	9.3–9.4	8.9–9.0	M6.5–M7
Hyades (600)	17.2–17.9	14.5–15.0	11.4–11.6	10.6–10.8	10.3–10.4	M8.5–$\gtrsim$M9
Field (1000)	18.0–18.9	15.1–15.8	11.8–12.1	10.9–11.2	10.6–10.9	$\gtrsim$M9–>>M9
Field (5000)	18.9–20.5	15.8–17.2	12.1–13.0	11.3–12.1	10.9–11.8	>>>M9

els. These are claimed to reproduce the observations better than previous sets of computations (see Allard et al. 1996; Baraffe & Chabrier 1996; Chabrier et al. 1996). However, the masses that are inferred from the comparison of our data with the 'NextGen' models in Fig. 4 are lower by a factor ∼1.25 than those obtained from the lithium test. This is basically due to the apparent different age that is derived from the isochrones in Fig. 4 (70 Myr, the canonical age of the cluster), and from the combination of lithium and luminosity of objects close to the substellar limit (120 Myr, Basri et al. 1996). Since the input molecular line lists for computing synthetic spectra for cool temperatures are incomplete, colours and magnitudes measured on these spectra are hampered by uncertainties of ∼0.5 mag (Chabrier et al. 1996). On the other hand, masses obtained from lithium are more reliable because they are based on the simpler physics of the interior of fully-convective objects (Magazzù, Martín & Rebolo 1993; Bildsten et al. 1996). In order to bring the masses obtained from the K vs $I-K$ diagram into agreement with those inferred from the lithium test for an age of 120 Myr, it would be required to shift the 'NextGen' isochrone by about 0.4 mag towards redder colour, which is within the theoretical uncertainties estimated by Chabrier et al. 1996.

The sequence of very low-mass stars and BDs in the Pleiades is depicted in Fig. 4. Our suggested decomposition for HHJ 6 and PPl 15 is indicated. The location of the likely companions nicely fits the sequence of single members. We consider that the primary of PPl 15 defines the transition region between stars and BDs, i.e. masses within 0.08–0.075 $M_{\odot}$, and we propose that its photometry could be adopted as indicative of the location of the substellar limit in the Pleiades. The derived absolute magnitudes are listed in Table 3, where the interval of values corresponds to the above mass range. We have estimated the star-BD frontier for older clusters like the Hyades, as well as for objects of different ages in the field using the isochrones of Chabrier et al. (1996) ('NextGen' model atmospheres) normalized to the primary of PPl 15. We consider the theoretical magnitude differences associated to different ages in order to evolve from the Pleiades to 600, 1000 and 5000 Myr. We have also inferred the spectral types of the objects at the substellar limit – shown in the last column of Table 3 – by comparing our $I-J$, $I-K$ and $J-K$ colours with those of Kirkpatrick & McCarthy (1994) for field objects. We obtain fainter magnitudes and cooler spectral types than suggested by the mass-luminosity and mass-spectral type relationships proposed by Henry & McCarthy (1993) and Kirkpatrick & McCarthy (1994) respectively. Our results are in better agreement with those of Baraffe & Chabrier (1996). At the age of the Hyades, the substellar limit has moved to M9 spectral type; for example, cluster objects with the mass of the primary of PPl 15 might show a spectrum similar to a field M9 dwarf, whereas those like Teide 1 would have become much cooler. Field very late-M dwarfs (M7–M10) are likely older than 1000 Myr and, therefore, most of them should be very low-mass stars rather than substellar objects. It is possible that photometric surveys reveal nearby young BDs with spectral types earlier than M9–M10 in the solar neighbourhood. Because of their recent formation they will be less numerous than stars of similar spectral types in the field, but their relatively higher luminosity will favour detection in all-sky near-infrared surveys like DENIS and 2MASS. The probability of finding these field young BDs will depend on the mass function for very low-masses and on the mixture of ages (see Martín, Zapatero-Osorio & Rebolo 1997). The lithium test will be useful in order to establish their substellar nature.

6. Conclusions

We have presented near-infrared J, H and K photometry for some of the least luminous objects so far known in the Pleiades cluster. They are very low-mass stars approaching the substellar limit, transition objects, and massive BDs (HHJ and PPl objects, and Calar 3 and Teide 1). In addition, we have also included in our sample four of the BD candidates proposed in Paper I (Calar 1, 2, 4, 5 and Roque 1) in order to asses their membership on the basis of the infrared data. We have made use of all the available spectroscopic and photometric knowledge on our final list of objects to characterize the sequence that cluster members around the substellar limit and beyond do follow in the infrared colour-magnitude diagrams. This sequence is clearly defined by the faintest HHJ objects, PPl 1, PPl 15, Calar 3 and Teide 1, lying 0.3–0.4 mag above the field MS for spectral types later than M6. Objects found in future surveys with similar photometry (optical and infrared) should be considered as likely cluster members.

Undoubtely, infrared data is highly useful to discriminate those objects that are true Pleiades members from those that are not. Optical surveys could be contaminated by background objects that although fitting in the cluster sequence at these wavelengths, may suffer from interestellar reddening. As extinction affects much less infrared magnitudes, consequently these objects do not match the J, H and K photometry expected for the Pleiades (this is the case of Calar 2 and Calar 5). Foreground late-type stars are also possible contaminants in photometric surveys, although its contamination is expected to be considerably smaller. However, in the optical survey of Paper I two of these field stars were detected, Roque 1 and Calar 1, both having very high radial velocities (Martín et al. 1996). The reddest object in optical wavelengths, Calar 1 (M9), appears to have rather bluer infrared colours than expected for its spectral type. This together with its high radial velocity suggests membership to an old population.

The large dispersion observed in the infrared photometry of Pleiades members is likely attributable to binarity effects. Two objects in our sample, namely HHJ 6 and PPl 15, lie $\sim$0.7 mag above the single cluster sequence in infrared diagrams. Adopting an age of 120 Myr for the cluster and using the photometric data of very low-mass Pleiades stars and BDs as well as the theoretical tracks of Chabrier et al. (1996), we have reproduced the photometry of both, finding that the likely masses of the components are 0.085 and 0.085$\pm$0.010 $M_{\odot}$ for HHJ 6, 0.080 and 0.045$\pm$0.010 $M_{\odot}$ for PPl 15. These results are in fairly good agreement with those obtained from the lithium test. Follow-up infrared spectroscopic observations of PPl 15 should be made to try to detect the effects of the companion on the spectrum, which are expected to be detectable. Since the primary of PPl 15 would be exactly located at the transition region between stars and BDs in the Pleiades, we have used it to define the empirical location of the substellar limit in infrared diagrams, for which we have corrected the observed magnitudes from the contribution of the secondary. We have estimated that the star-BD frontier on the single Pleiades sequence is located at magnitudes I = 17.8–18.0, J = 15.6–15.7, H = 14.9–15.0 and K = 14.5–14.6 and at optical spectral types M6.5–M7. New Pleiades objects that are found fainter along the photometric sequence defined in this paper might be BDs indeed. Based on this result, we estimate that the hydrogen-burning mass limit occurs at spectral types around M9 in the Hyades cluster.

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