Brown Dwarfs in the Pleiades Cluster.

III. A deep $IZ$ survey*

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Abstract. We present the results of a deep CCD-based $IZ$ photometric survey of a $\sim 1$ deg$^2$ area in the central region of the Pleiades Galactic open cluster. The magnitude coverage of our survey (from $I \sim 17.5$ down to 22) allows us to detect substellar candidates with masses between 0.075 and 0.03 $M_\odot$. Details of the photometric reduction and selection criteria are given. Finder charts prepared from the $I$-band images are provided.

Key words: Stars: low-mass, brown dwarfs – Stars: pre-main sequence – Galaxy: open clusters and associations: Pleiades – Astronomical data bases: surveys

1. Introduction

The Pleiades star cluster is an ideal hunting ground for substellar objects mainly due to its richness of members, young age, proximity and scarce interstellar absorption. Taking advantage of these properties, several photometric searches aimed at finding brown dwarfs (BDs) have been performed during the last decade (see Hambly [1998] for a review). The recent spectroscopic confirmations of Pleiades objects at the stellar-substellar boundary and genuine substellar members (Basri et al. [1996], Rebolo et al. [1996], Martin et al. [1998], Stauffer et al. [1998]) previously discovered as a result of optical photometric surveys in small areas suggest that a numerous population of very low-mass objects may be found in this cluster. This encourages future surveys to discover BDs cooler and less massive than those (0.075–0.05 $M_\odot$) previously detected by these surveys. The Pleiades offers a unique opportunity to establish the observational properties of these rather elusive objects and to characterize the initial mass function in the substellar mass regime.

1.1. The survey

As part of an on-going search for BDs in the Pleiades, we have conducted a deep CCD-based $IZ$ survey using the 2.5 m Isaac Newton Telescope (INT) located on the Observatorio del Roque de los Muchachos (ORM, island of La Palma). The area covered was 1.05 deg$^2$ within the central region of the cluster (a small fraction of the total area was also observed using the $R$ filter). More than 40 faint ($I \geq 17.5$), very red ($I-Z \geq 0.5$) objects have been detected down to $I \sim 22$. Their location in the colour-magnitude diagram suggests cluster membership. In this paper we report on the details of this survey along with the selection criteria. We provide $IZ$ magnitudes, coordinates and finder charts for all candidates. Preliminary results of this survey were presented in Zapatero Osorio et al. [1997a, 1998a]. An extensive discussion on the membership of the candidates and derivation of the initial mass function will be given in a forthcoming paper (Zapatero Osorio et al. [1998b]).

2. Observations and data reduction

All of our CCD survey was carried out during 1996 in two campaigns which took place on February 9–12 and on September 19–20. We used the TEK (1024×1024 pixel$^2$) detector mounted on the prime focus of the telescope, with a field of view of 10×10 arcmin$^2$. A total of 40 fields, with center coordinates listed in Table I, were observed with the Harris ($R$)$I$ and RGO $Z$ broad-band filters providing...
Table 1. Field (100 arcmin^2) center coordinates

| RA (J2000) | DEC | Date (1996) | Sep. ^a (arcmin) | Filters |
|------------|-----|-------------|------------------|---------|
| 3 43 35    | 24 30 00 | 21 Sep | 53.02 | IZ     |
| 3 43 43    | 24 45 00 | 12 Feb | 58.69 | RI     |
| 3 44 15    | 23 40 30 | 21 Sep | 46.15 | IZ     |
| 3 44 30    | 23 55 00 | 21 Sep | 36.32 | IZ     |
| 3 45 00    | 24 40 00 | 20 Sep | 47.44 | IZ     |
| 3 45 15    | 23 54 35 | 20 Sep | 27.02 | IZ     |
| 3 45 30    | 24 10 00 | 20 Sep | 17.37 | IZ     |
| 3 45 45    | 24 46 00 | 20 Sep | 42.55 | IZ     |
| 3 46 15    | 23 45 00 | 20 Sep | 20.00 | IZ     |
| 3 46 30    | 24 25 00 | 20 Sep | 35.89 | IZ     |
| 3 46 30    | 24 37 00 | 21 Sep | 30.77 | IZ     |
| 3 47 20    | 23 25 00 | 21 Sep | 42.25 | IZ     |
| 3 47 22    | 22 39 40 | 13 Feb | 87.48 | RIZ    |
| 3 47 30    | 24 26 00 | 20 Sep | 20.19 | IZ     |
| 3 47 52    | 24 10 00 | 21 Sep | 12.23 | IZ     |
| 3 48 00    | 24 00 00 | 21 Sep | 15.39 | IZ     |
| 3 48 00    | 24 34 00 | 9 Feb  | 30.25 | RIZ    |
| 3 48 05    | 23 39 32 | 9 Feb  | 31.24 | RIZ    |
| 3 48 05    | 23 45 00 | 20 Sep | 40.76 | IZ     |
| 3 48 15    | 23 32 30 | 21 Sep | 38.55 | IZ     |
| 3 48 15    | 24 28 00 | 21 Sep | 27.06 | IZ     |
| 3 48 19    | 23 52 00 | 11 Feb | 86.85 | RI     |
| 3 48 20    | 23 45 00 | 20 Sep | 28.62 | IZ     |
| 3 48 30    | 23 57 00 | 21 Sep | 22.87 | IZ     |
| 3 48 40    | 23 22 00 | 13 Feb | 88.07 | RIZ    |
| 3 48 40    | 24 45 00 | 20 Sep, 13 Feb | 44.27 | IZ |
| 3 48 45    | 24 40 00 | 20–21 Sep | 36.15 | IZ |
| 3 48 57    | 23 18 00 | 21 Sep | 28.84 | IZ     |
| 3 49 15    | 24 31 00 | 20 Sep | 38.97 | IZ     |
| 3 49 20    | 23 32 00 | 21 Sep | 47.48 | IZ     |
| 3 49 20    | 24 45 00 | 20 Sep | 49.54 | IZ     |
| 3 49 35    | 23 55 00 | 21 Sep | 37.40 | IZ     |
| 3 49 41    | 25 15 40 | 21 Sep | 77.72 | RI     |
| 3 50 00    | 24 28 00 | 20 Sep | 46.03 | IZ     |
| 3 50 15    | 23 40 00 | 21 Sep | 52.18 | IZ     |
| 3 50 25    | 24 05 00 | 21 Sep | 46.83 | IZ     |
| 3 50 30    | 23 50 00 | 21 Sep | 50.94 | IZ     |
| 3 53 30    | 23 40 00 | 11 Feb | 93.29 | RI     |

Fig. 1. Location of our fields (squares) within 3°.5 × 3°.5 of the Pleiades area. Open squares stand for those fields observed with IZ filters while the shaded squares depict the four fields observed with RI filters. Central coordinates (indicated with a cross) are 3h 47m, +24° 7' (Eq. 2000). The five fields which may have some amount of extra reddening according to the CO contours shown by Breger (1987) are indicated with an arrow. Filled star symbols stand for stars brighter than 6th magnitude, and filled circles for proper motion M members (Hambly et al. 1993) with I magnitudes in the range 13–18. The vertical gap in the M star distribution around 3h 51m is due to the fact that there were no overlaps between the first and second epoch plates used by the authors, causing the lack of proper motion measurements for stars in that strip. The relative brightness is represented by symbol diameters. North is up and East is left.

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a Separation from the cluster center (3h 47m, +24° 7').
We adopted the $IZ$ broad-band filters for several reasons. One of our goals was to detect objects fainter and less massive than the two cluster BDs Teide 1 and Calar 3 ($M_8, I \sim 19, R - I \sim 2.6, \sim 0.055 M_\odot$, Rebolo et al. 1993; Martín et al. 1996). Theoretical evolutionary models (which do not include grain formation in very cool atmospheres) predict that these objects become much redder with colours ($R - I \geq 3$ (Chabrier et al. 1996)). Thus, they might be extremely faint in $R$ wavelengths, greatly hindering their detection. On the other hand, field stars do exhibit a turn-off in ($R - I$) at around M7 spectral type, with stars of later types having bluer colours (Bessell 1991). The fluxes and colours of the Pleiades BDs fainter than Teide 1 and Calar 3 are unknown, but we expect them to have spectral energy distributions which resemble those of the coolest objects in the field. It could turn out that the ($R - I$) colour is no longer useful to discriminate low luminosity cluster members from field objects. The ($I - J$) colour, however, gets monotonically redder for lower temperatures (both for observed and theoretical predictions), implying that the slope of the spectral pseudocontinuum between $I$ and $J$ wavelengths clearly increases. As the $Z$ filter is centered at 920nm, we expect a similar behaviour with $I$ and $Z$. Although the efficiency of the CCD drops considerably in the $Z$-band, this effect is compensated by the increased brightness of BDs at these near-IR wavelengths. The ($I - Z$) colour has been shown to be a useful discriminator for Pleiades BDs by Cossburn et al. (1997).

Other photometric searches for substellar objects in the Pleiades carried out with $R$ and $I$ (Jameson & Skillen 1988; Zapatero Osorio et al. 1997b, Paper I) provide a high number of mid- and late-M stars that do not belong to the cluster and are contaminating the surveys. It is desirable to find a strategy which avoids these field contaminants and facilitates a more efficient tool for detecting true members. In Paper I the success rate was only 25%: two out of the eight proposed cool candidates have been confirmed as genuine Pleiades BDs (Rebolo et al. 1996). The authors argue that this was due to the detection of reddened late-M dwarfs (Zapatero Osorio et al. 1997c, Paper II). The use of longer wavelength filters would help to jump over this obstacle.

Raw frames were processed using standard techniques within the IRAF1 (Image Reduction and Analysis Facility) environment, which included bias subtraction, flat-fielding and correction for bad pixels by interpolation with values from the nearest-neighbour pixels. The photometric PSF fitting analysis was carried out using routines within DAOPHOT, which provides image profile information needed to discriminate between stars and galaxies. Instrumental $RI$ magnitudes were corrected for atmospheric extinction and transformed into the $RI$ Cousins system using observations of standard stars from Landolt’s (1992) list. Special care was taken in including red standard stars in order to ensure a reliable transformation for the reddest candidates: the field SA 98 contains many photometric standards covering colours from A0 to M7 spectral type. The calibration of $Z$ magnitudes required more observational effort as there are no real data for standards available in the literature. We have not performed an absolute flux calibration for this filter, but obtained ($I - Z$) colours with respect to a given spectral type. Using the same Landolt fields as observed through the other two filters at culmination (airmass = 1.1), we set $Z = I$ for those standard stars with ($R - I$) $\sim 0$ (A0-type). The adopted ($I - Z$) colours are shown in Table 2. Observations of these fields at different elevations allowed us to correct $Z$ instrumental magnitudes for atmospheric extinction. Errors for $Z$ instrumental magnitudes as provided by IRAF routines are plotted in Fig. 2. The best power law fit to the errors in $I$ for the bulk of data is superimposed in the figure for comparison. Summarizing, uncertainties in the INT photometry range from $\leq 0.05$ mag at $I, Z \sim 20.5, 19.7$ to about $0.15$ mag at $22, 21$ mag, respectively. We present in Fig. 3 the resulting $I$ vs. ($I - Z$) diagram where data for the Pleiads HHJ 3, PPl 15 and Teide 1 (which are present in three of our fields) are combined with the new observations. We remark that $Z$ magnitudes are not on a standard system. Completeness and limiting

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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.
The candidate BD members of the Pleiades are characterized by their infrared excess and their position in the I-Z colour-magnitude diagram. These objects are fainter than the classical M stars and are classified as brown dwarfs. The table below lists the adopted (I - Z) colours for the photometric standard stars used in the calibrations.

| SA Star | (R - I)a | Ia | (I - Z)b |
|---------|----------|----|----------|
| 98 642  | 0.393±0.002 | 14.594±0.026 | 0.15±0.09 |
| 98 650  | 0.086±0.002 | 12.105±0.003 | 0.02±0.02 |
| 98 652  | 0.339±0.024 | 14.201±0.025 | 0.07±0.04 |
| 98 653  | 0.008±0.001 | 9.522±0.002 | 0.00±0.02 |
| 98 670  | 0.653±0.001 | 10.555±0.003 | 0.23±0.03 |
| 98 671  | 0.494±0.004 | 12.315±0.006 | 0.13±0.03 |
| 98 675  | 1.002±0.002 | 11.314±0.004 | 0.39±0.03 |
| 98 676  | 0.673±0.022 | 11.716±0.005 | 0.24±0.02 |
| 98 682  | 0.352±0.003 | 13.032±0.006 | 0.26±0.05 |
| 98 685  | 0.280±0.002 | 11.384±0.005 | 0.05±0.02 |
| 98 L5   | 2.60±0.04   | 12.05±0.20   | 1.1±0.2 |

a RI magnitudes and their errors taken from Landolt (1992).
b 1-σ errors come from uncertainties in I-band and the dispersion in the calibration.

In Table 3 we list the names, magnitudes, colours and positions for the proposed Pleiades BD candidates. They are named after the Roque Observatory followed by the word Pleiades and numbered according to their decreasing I-band apparent magnitude (second column of Table 3). Hereafter, we will use an abridged version of the names which omits the term ‘Pleiades’. The names of the candidates adopting the IAU rules are also provided (first column), where the acronymn “RPL” stands for Roque Pleiades. Three of the four faintest candidates have slightly larger fwhm than the average value for our frames. Presumably this is an indication that they are not a point source. It is expected that distant galaxies

![Fig. 3. IZ colour-magnitude diagram for our 1.05 deg² survey in the Pleiades. Z magnitudes are not on a standard system (see text for details). Previous known members are labelled along with the completeness (dashed line) and limiting (full horizontal line) magnitudes. Suspected extended objects are shown with asterisks, and the seven candidates previously studied in Zapatero Osorio et al. (1997a) are indicated with filled triangles. Masses according to the NG Chabrier et al.’s (1996) model for solar metallicity and 120 Myr are labelled on the right side.](image-url)
### Table 3. Coordinates and photometry for the candidates

| IAU Name<sup>a</sup> | Abridged name | RA (J2000) | DEC | Epoch | \(I\) | \(I - Z\) | \(R - I\) | Other names<sup>b</sup> |
|----------------------|--------------|------------|-----|-------|------|--------|--------|-----------------|
| RPL J034741+2244.5   | Roque 48     | 3 47 41.3 | 22 44 33 | 1996.123 | 17.31 | 0.56   | 1.73   |                  |
| HHJ 3<sup>c</sup>    |              | 3 48 50.4 | 22 44 30 | 1989.9 | 17.33 | 0.71   | 2.21   |                  |
| RPL J034904+2333.7   | Roque 47     | 3 49 04.8 | 23 33 40 | 1996.726 | 17.74 | 0.62   |        |                  |
| RPL J034723+2242.6   | Roque 17     | 3 47 23.9 | 22 42 38 | 1996.123 | 17.78 | 0.81   | 2.31   |                  |
| RPL J034739+2436.4   | Roque 16     | 3 47 39.0 | 24 36 22 | 1996.112 | 17.79 | 0.69   | 2.24   | CFHT-PL-11      |
| RPL J034541+2354.2   | Roque 15     | 3 45 41.2 | 23 54 10 | 1996.723 | 17.82 | 0.73   |        | PPl 11          |
| RPL J034953+2359.0   | Roque 48     | 3 49 53.7 | 23 59 01 | 1996.726 | 17.92 | 0.56   |        |                  |
| RPL J034738+2238.7   | Roque 44     | 3 47 38.7 | 22 38 41 | 1996.123 | 18.12 | 0.62   | 2.01   |                  |
| RPL J034541+2424.9   | Roque 43     | 3 45 41.2 | 24 24 51 | 1996.723 | 18.21 | 0.61   |        |                  |
| RPL J034939+2242.6   | Roque 17     | 3 49 39.3 | 22 42 38 | 1996.123 | 18.23 | 0.62   |        |                  |
| RPL J034746+2403.7   | Roque 27     | 3 47 46.9 | 24 03 42 | 1996.726 | 18.06 | 1.00   |        |                  |
| RPL J034843+2245.9   | Roque 26     | 3 48 43.9 | 22 45 51 | 1996.123 | 21.13 | 1.01   | 1.98   |                  |
| RPL J034830+2444.9   | Roque 25     | 3 48 30.6 | 24 44 50 | 1996.123 | 21.17 | 1.03   | 2.75   |                  |
| RPL J034951+2355.5   | Roque 24     | 3 49 51.4 | 23 55 31 | 1996.117 | 21.31 | 2.1    | ≥2.1   |                  |
| RPL J034737+2338.7   | Roque 23     | 3 47 37.5 | 23 38 22 | 1996.123 | 21.56 | 1.20   |        |                  |
| RPL J034853+2359.0   | Roque 48     | 3 48 53.7 | 23 59 01 | 1996.726 | 21.13 | 1.01   | 1.98   |                  |
| RPL J034738+2238.7   | Roque 44     | 3 47 38.7 | 22 38 41 | 1996.123 | 21.17 | 1.03   | 2.75   |                  |
| RPL J034541+2424.9   | Roque 43     | 3 45 41.2 | 24 24 51 | 1996.723 | 21.13 | 1.01   | 1.98   |                  |
| RPL J034939+2242.6   | Roque 17     | 3 49 39.3 | 22 42 38 | 1996.123 | 21.17 | 1.03   | 2.75   |                  |
| RPL J034746+2403.7   | Roque 27     | 3 47 46.9 | 24 03 42 | 1996.726 | 21.06 | 1.00   |        |                  |
| RPL J034843+2245.9   | Roque 26     | 3 48 43.9 | 22 45 51 | 1996.123 | 21.13 | 1.01   | 1.98   |                  |
| RPL J034830+2444.9   | Roque 25     | 3 48 30.6 | 24 44 50 | 1996.123 | 21.17 | 1.03   | 2.75   |                  |
| RPL J034951+2355.5   | Roque 24     | 3 49 51.4 | 23 55 31 | 1996.117 | 21.31 | 2.1    | ≥2.1   |                  |
| RPL J034737+2338.7   | Roque 23     | 3 47 37.5 | 23 38 22 | 1996.123 | 21.56 | 1.20   |        |                  |

<sup>a</sup> “RPL” stands for Roque Pleiades, and “TPL” for Teide Pleiades.

<sup>b</sup> References: PPl objects from Stauffer et al. (1989); JS objects from Jameson & Skillen (1989); NPL objects from Festin (1998); CFHT-PL objects from Bouvier et al. (1998).

<sup>c</sup> Coordinates for HHJ 3 taken from Hambly et al. (1993); for PPl 15 from Stauffer et al. (1994); coordinates and RI photometry for Teide 1 taken from Paper I.

<sup>d</sup> These objects appear slightly extended in the IZ images.

: For error bars in the photometry see text. Those measurements labelled with a “;” have rather large uncertainties.
fainter than $I = 21$ will begin to contaminate the number counts of objects. Those candidates labelled as extended are shown with a different symbol in Fig. 4. By reference to the reddening map provided in Breger (1987), Roque 3, 5, 15, 18 and 32 could suffer from a somewhat enhanced extinction as they lay within or very near to the CO contours given by the author.

In addition to the INT data, we have obtained $R$-band photometry for five of the candidates at the 2.5 m Nordic Optical Telescope (BroCam1, NOT) on 1996 October 10–11 (Roque 17, 11 and 4), and at the 1 m Jacobus Kapteyn Telescope (JKT) on 1996 September 12–13 (Roque 16 and 13), both telescopes at the ORM. The CCDs used were a Tektronix 1024×1024 providing fields of view of 3.0 and 5.5 arcmin$^2$, respectively. Exposure times were typically 15 min at NOT and 30 min at JKT. Landolt’s (1992) standard stars were observed just before and after the targets. Reduction of the raw frames and photometry of the candidates has been performed as described above. Uncertainties in $R$ magnitudes range from 0.07 mag for the brightest objects to 0.15 mag for the faintest ones. Considering the $R − I$ photometry from Table 2 and from other deep surveys (Paper I; Bouvier et al. 1998) Roque 44 and Roque 26 are not likely to be Pleiades members as they seem to deviate towards bluer colours from the sequence defined by other candidates.

Astrometry for all Roque objects has been performed by the triangles fitting method using the APM Sky Catalogue. Several stars close to every candidate were identified and they served as a reference for the astrometric calibration. Coordinates are accurate to approximately ±2″. The location of our candidates in the surveyed area is depicted in Fig. 4. Their distribution around the cluster center appears quite homogeneous. However, we note that the number of fields (9) with ≥ 3 BD candidates is surprisingly large compared to the expectations from a random distribution. The study of possible spatial inhomogeneities within the cluster still awaits membership confirmation. Seven of the Roque BD candidates have also been identified in other surveys. The last column of Table 3 gives cross-identifications. Our $I$ magnitudes seem to be on average 0.25 mag brighter than those available in the most recent literature. This is likely due to an effect of the colour-dependence of the Harris filters we used in our observations; although a red standard star was considered, it is poorly calibrated and consequently does not provide an accurate determination of the colour-term in the photometric calibration. Cossburn et al. (1998) have found that the colour-term for the transformation from Harris $I$ to Cousins is indeed rather significant for very red objects. In the case of Roque 33 (NPL 40) the difference found is −0.58 mag which might be due to contamination from a nearby very bright star (and saturated in our frames). Figure 2 provides the $I$-band finder charts (2′ × 2′ in extent) for all Roque objects ordered as listed in Table 3.

According to the “NextGen” (NG) theoretical evolutionary models of Chabrier et al. (1996), and adopting solar metallicity, an age of 120 Myr (Basri et al. 1996; Martin et al. 1998; Stauffer et al. 1998) and a distance of 127 pc for the Pleiades cluster, our survey has detected objects in the mass interval from roughly 0.08 $M_\odot$ down to 0.03 $M_\odot$. The completeness magnitudes correspond to 0.035 $M_\odot$ as indicated in Fig. 3. Chabrier et al.’s models provide absolute magnitudes as a function of mass, metallicity and age obtained by direct integration of theoretical atmospheres which do not incorporate grain formation and dust absorption (Allard et al. 1997). However, the effects of condensation become important for temperatures cooler than about 2500 K (Tsui et al. 1997). Although the temperature range partially covered by our survey (Pleissmüller, private communication) show that models considering dust formation and opacities predict brighter $I$ magnitudes and subsequently slightly lowers the mass determination by ∼ 8 %.

Membership and therefore the real nature of our candidates on the basis of $JHK$ photometry and spectroscopy and the Pleiades mass function will be addressed in a forthcoming paper (Zapatero Osorio et al. 1998b). Seven of them (Roque 17, 16, 15, 14, 13, 11 and 4) with $I$ magnitudes in the range 17.8–19.5 (masses in the interval 0.08–
0.045 \( M_\odot \) have already been studied to some extent by Zapatero Osorio et al. (1997a). They are shown in Fig. 3 with a different symbol. The authors conclude that given their \( K \) magnitudes, radial velocities, spectral types and weakness of some atomic features these candidates should be considered as Pleiades members. The number of remaining candidates in our \( IZ \) survey deserve further investigation as there are large enough to ensure that follow-up observations will confirm more Pleiades substellar objects. Among the faintest ones, there could be BDs with masses as low as 0.03 \( M_\odot \). These studies will make it possible to derive the cluster mass function well into the substellar regime.

3. Conclusions

We have imaged about 1 deg\(^2\) in the central region of the Pleiades young cluster using \( IZ \) broad-band filters, and identified more than 40 brown dwarf candidates with \( I \) magnitudes ranging from 17.5 to 22 (completeness is given by \( I \sim 21 \) mag). This corresponds to a mass interval starting roughly at the substellar mass limit down to 0.03 \( M_\odot \) according to recent non-dusty evolutionary models by Chabrier et al. (1996). Follow-up IR and spectroscopic observations of seven of these candidates (Zapatero Osorio et al. 1997a) have revealed that they are very likely to be cluster brown dwarfs. Further data for the remaining candidates should definitely establish or refute cluster membership in the Pleiades. These studies will provide a solid foundation for deriving the cluster substellar mass function.

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Fig. 5. Finder charts (2′ × 2′ in extent) taken from the I-band images for all Roque candidates. North is up and East is left
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