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An HST/WFPC2 Survey for Brown Dwarf Binaries in the αPersei and the Pleiades Open Clusters

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ABSTRACT

We present the results of a high-resolution imaging survey for brown dwarf binaries in two open clusters. The observations were carried out with the Wide Field Planetary Camera 2 onboard the Hubble Space Telescope. Our sample
consists of 8 brown dwarf candidates in αPersei and 25 brown dwarf candidates in the Pleiades. We have resolved 4 binaries in the Pleiades with separations in the range 0″.094–0″.058, corresponding to projected separations between 11.7 AU and 7.2 AU. No binaries were found among the αPersei targets. Three of the binaries have proper motions consistent with cluster membership in the Pleiades cluster, and for one of them we report the detection of Hα in emission and LiI absorption obtained from Keck II/ESI spectroscopy. One of the binaries does not have a proper motion consistent with Pleiades membership. We estimate that brown dwarf binaries wider than 12 AU are less frequent than 9% in the αPersei and Pleiades clusters. This is consistent with an extension to substellar masses of a trend observed among stellar binaries: the maximum semimajor axis of binary systems decreases with decreasing primary mass. We find a binary frequency of 2 binaries over 13 brown dwarfs with confirmed proper motion membership in the Pleiades, corresponding to a binary fraction of 15±5%. These binaries are limited to the separation range 7-12 AU and their mass ratios are larger than 0.7. The observed properties of Pleiades brown dwarf binaries appear to be similar to their older counterparts in the solar neighborhood. The relatively high binary frequency (≥ 10%), the bias to separations smaller than about 15 AU and the trend to high mass ratios (q≥0.7) are fundamental properties of brown dwarfs. Current theories of brown dwarf formation do not appear to provide a good description of all these properties.

Subject headings: stars: low mass, brown dwarfs, binaries: visual, techniques: high angular resolution, surveys

1. Introduction

Brown dwarfs (BDs) are very low-mass objects that do not stabilize on the hydrogen-burning main sequence because they develop degenerate cores. They are akin to giant planets in that their luminosity and temperature drop continuously with time, and ultimately they become extremely cool and faint. The borderline between stars and BDs has been known for 40 years to be at about 0.08 solar mass (M⊙) for solar metallicity (Hayashi & Nakano 1963; Kumar 1963). Recent calculations yield a substellar limit at 0.072 M⊙ (e.g. Baraffe et al. 1998).

For many years BDs eluded firm detection, but since 1995 (Nakajima et al. 1995; Rebolo, Zapatero Osorio, & Martín 1995) there has been a plethora of discoveries. The evidence for BDs is based on observations of lithium, luminosity and surface temperatures of
faint dwarfs, as well as astrometric and radial velocities of main sequence stars. Dynamical measurements of BD masses are becoming available with the study of nearby binaries where both components are substellar (Martín et al. 2000b; Lane et al. 2001).

Recent censuses of BDs in young open clusters indicate that they are numerous (Béjar et al. 2001; Moraux et al. 2003). With increasing age, BDs cool down and reach very faint luminosities, becoming indeed very difficult to detect. Young stellar associations and open clusters have provided a gold mine for BD searches because these objects are still in the early phase of gravitational contraction. Hence, they are brighter and warmer than older BDs.

Several processes of BD formation have been studied in some detail in the last few years. They can be divided in two main groups: (1) Failed star-formation model: BDs are ejected from unstable multiple systems during the collapse and fragmentation of a turbulent molecular cloud (Reipurth & Clarke 2001, 2003; Sterzik & Durisen 2003); (2) Small star-formation model: BDs result from the collapse of small cores of substellar mass in supersonically turbulent molecular clouds (Padoan & Nordlund 2002).

These processes lead to different outcomes in the overall properties of a brown dwarf population which result in observable effects. Hydrodynamical simulations show that the failed star-formation model produces a very low frequency (<5%) of BD binaries, which must be limited to systems closer than 10 AU (Bate et al. 2002; Durisen, Sterzik & Pickett 2001; Delgado-Donate & Clarke 2003). The consequences of the small star-formation model for the properties of the BD binary population have not been explored, but it is reasonable to expect a higher frequency of binaries than in the previous scenario.

Using the high-resolution capability of the Hubble Space Telescope (HST), Keck, and Adaptive Optics (AO) on large ground-based telescopes, the first very low-mass binaries have been resolved (Martín et al. 1998a, 1999, 2000a,b; Bouy et al. 2003; Burgasser et al. 2003; Close et al. 2002, 2003; Gizis et al. 2003; Koerner et al. 1999; Reid et al. 2001). Most of the work has concentrated on nearby field ultracool dwarfs. However, the field targets represent a mix of ages, distances, primary masses and metallicities. Hence, the results are difficult to interpret. In contrast, an open cluster sample has well-known age, distance, primary masses and metallicity. In this paper we present the first confirmed cluster BD binaries resolved with HST.

The paper is organized as follows: In Section 2 we describe the target selection and observations. In Section 3 we present the photometric and point-spread-function (PSF) analysis. Section 4 contains the discussion of our results, and in Section 5 we present our final remarks and suggestions for future work.
2. Target Selection and Observations

The targets were compiled from several lists of very low-mass (VLM, $M < 0.1 \, M_\odot$) candidate members. For the Pleiades we used the information provided in the works of Martín et al. (1996, 1998b), Rebolo et al. (1996) and Zapatero Osorio et al. (1997) for Calar objects; Zapatero Osorio et al. (1999) for Roque objects; Bouvier et al. (1998), Stauffer, Schultz & Kirkpatrick (1998) and Martín et al. (2000a) for CFHT-PL objects; Hambly et al. (1999) for IPMBD objects; and Festin (1998a,b) for NPL objects. These compilations include most of the known Pleiades VLM stars and brown dwarf candidates (BDCs) that had not been previously observed with HST. Of the 29 objects originally proposed for this program, 26 have been observed. One of them turned out to be a duplication because NPL 40 is the same object as Roque 33. This object was observed twice. The remaining 3 Pleiades targets were not scheduled for observation. For αPer we used the data in Rebolo, Martín & Magazzù (1992), Prosser (1994), Basri & Martín (1998), and Stauffer et al. (1999). We selected 14 VLM stars and BDCs, and 8 were observed. The other 6 were withdrawn.

Observations were carried out between July 2000 and August 2001 as part of an HST Snapshot (SNAP-8701, HST Cycle 9) program designed to fill short intervals between accepted GO observations. Each BDC was centered in the PC1 chip of the Wide-Field Planetary Camera 2 (WFPC2). With a plate-scale of $0''.0455$ per pixel, the PC1 has a field of view of $36''$ in diameter. Assuming a distance of 125 pc for the Pleiades, this provides a physical separation of 2250 AU from each BDC to search for companions. The observations were made in two broadband filters, the F814W and the F785LP with central wavelengths at 792.4 nm and 862.1 nm respectively. The filters were chosen to provide high throughput and a clear color separation between BDs and background stars and galaxies. Two exposures were taken in each filter to allow for proper cosmic ray rejection, yielding total integration times of 600 s and 280 s in the F814W and F785LP filters, respectively.

The binarity of IPMBD 25 was noticed in an early analysis of a subset of our WFPC2 dataset reported by Dahm & Martín (2003). In order to confirm the cluster membership, we decided to apply the lithium test (Magazzù, Martín & Rebolo 1993). We observed IPMBD 25 on 15 November 2001 with the Echellette Spectrograph and Imager (ESI, Sheinis et al. 2002) mounted on the Cassegrain focus of the Keck II telescope. We used the echellette mode to cover the entire spectrum from 0.39 to 1.1 mm. The spectral resolution given by the $0''.6$ slit was 6500. Three exposures of 1200 s were obtained. Data reduction was made using IRAF’s echelle tasks. The spectra were bias subtracted, flat fielded, and combined. Wavelength calibration was made using a CuAr lamp spectrum obtained the same night.
3. Data Analysis and Products

3.1. HST/WFPC2 data

We used the data reduced by the HST pipeline. Aperture photometry was accomplished using the IRAF\textsuperscript{1} phot task in daophot. Photometry was completed for all point sources in the PC1 chip using the recommended aperture of 11 pixels, corrected for finite aperture (subtract 0.1 mag). Magnitudes are given in Table 1 in the VEGA system using the zeropoints provided in the WFPC2 User Manual (F814W=21.639, F785LP=20.688). Roque 33 was observed twice because it was also entered in the target list as NPL 40. We report the average values of the photometry for both observations. Our photometric measurements are in good agreement with those reported in the literature, except for those given by Zapatero Osorio et al. (1999) which are systematically brighter. Jameson et al. (2002) noted that the Zapatero Osorio et al.’s $I$-band data lies on the Harris system, and they provide a conversion to the Cousins system. Our F814W data is a good approximation to the $I$-band Cousins system. We estimate that the 5 $\sigma$ limiting magnitude for the survey is approximately $I_C \sim 22.5$ and was constrained by the lower throughput and shorter exposure times of the F785LP images.

All images have been inspected visually to search for obviously resolved companions. There were not any companion BDCs in the PC1 chip for separations larger than 3 pixels, i.e. $0''.13$ for a nominal scale of $0''.0455$ pix$^{-1}$. We first identified the binary candidates as objects with larger FWHM than average using the IRAF task imexam. Figure 1 illustrates the results of the FWHM analysis for the F814W filter. The results for the F785LP filter were very similar. We identified 4 binary candidates with FWHM$>$2 pixels in both the F814W and F785LP filters, namely CFHT-Pl-12 and 19, IPMBD 25 and 29.

We used a custom-made PSF fitting program to compute the precise separation, position angle and flux ratio of each candidate binary system. This program is identical to that used by Bouy et al. (2003), and it is fully described in that paper. A brief summary is given here for completeness: The PSF fitting routine builds a model PSF using 8 different PSF stars in each filter coming from different WFPC2 images. A cross correlation between the model and the binary system yields the best values for five free parameters (flux ratio and the pixel coordinates of the two components of the binary system). By using non-linear PSF fitting we were able to push the limit of detection down to $\sim 0''.060$ arcsec for non-equal luminosity systems. Figure 2 displays one example of the PSF fitting technique. The uncertainties and limitations of this technique are discussed in Bouy et al. (2003). The final

\textsuperscript{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.
best solutions for the binary parameters are summarized in Table 2.

3.2. Keck II data

We report the detection of H\(_\alpha\) in emission (equivalent width = 13.1 ±0.2 Å), and LiI resonance line in absorption (equivalent width = 0.55 ±0.10 Å) in the ESI spectrum of IPMBD 25 (shown in Figure 3). The lithium depletion boundary (LPD) in the Pleiades is located at \(I=17.8±0.1\) (Stauffer et al. 1998). Cluster members fainter than the LPD are expected to have preserved a measurable amount of lithium in their photosphere. Cluster members brighter than the LPD are expected to have depleted their lithium abundances to a level that cannot be detected. The apparent \(I\) magnitude of IPMBD 25 is 17.67 (Hambly et al. 1999), which is brighter than the lithium boundary. However, the apparent magnitude of the primary is \(I=17.93±0.09\), which is fainter than the boundary. Thus, our lithium detection confirms the membership of IPMBD 25 in the cluster, and is consistent with the previously established LPD. The LiI equivalent width that we measured in our ESI spectrum of IPMBD 25 is very similar to Stauffer et al.’s measurement for CFHT-Pl-11.

4. Discussion

4.1. Cluster membership and binary frequency

Two proper motion studies of VLM stars and BDs in the Pleiades are available (Hambly et al. 1999; Moreaux et al. 2001). 14 of our targets have confirmed proper motion membership. 10 do not have proper motion information available. 2 do not have proper motions consistent with cluster membership. The proper motion nonmembers are: CFHT-Pl-15 and CFHT-Pl-19. The first one has lithium (Stauffer et al. 1998) but we do not consider the Li detection to be sufficient to rank it as a \textit{bona fide} cluster member. Young BDs are not uncommon in the general direction of the Pleiades cluster. CFHT-Pl-15 may be one more example of a scattered population of young BDs in the Taurus-Auriga region (Oppenheimer et al. 1997). CFHT-Pl-19 is a binary. It is unlikely that the binarity has affected the proper motion measurement of Moreaux et al. (2001). Furthermore, its position in the H-R diagram is not consistent with being a cluster binary (Martín et al. 2000a).

We consider CFHT-Pl-12, IPMBD 25 and 29 as \textit{bona fide} Pleiades binaries. All of them have proper motion membership. CFHT-Pl-12 and IPMBD 25 have lithium detections. The lithium test has not been applied in IPMBD 29.
IPMBD 25 and 29 were found in a shallower and wider survey than CFHT-Pl-12. IPMBD 25 A has $I=17.93±0.09$ which is brighter than the sensitivity limit of Hambly et al.’s survey ($I=18.4$). However, IPMBD 29 A has $I=18.70±0.15$ which is fainter than the survey limit. IPMBD 29 was found by Hambly et al. (1999) because it is a binary. Thus, we must exclude it from our binary frequency statistics.

Our sample of bona fide cluster members includes 13 objects, which include 2 resolved binaries. Thus, we derive a binary frequency (defined as number of binaries divided by total number of objects in the sample) of $15.3^{+15}_{−5}$% for our proper motion selected subset. Statistical uncertainties ($1\,\sigma$) throughout this paper were calculating using Poisson statistics for a small sample in the manner discussed by Burgasser et al. (2003).

Our proper motion sample includes objects in the $I$ magnitude range 17.74–20.05. We note that the two primaries of our binaries have $I$ brighter than 18.5. We define magnitude limited bins of proper motion members as follows: (1) between $I = 17.74–18.50$ we have 9 objects and 2 binaries; (2) between $I = 18.50–21.00$ we have 4 objects and 0 binaries. We also note that 4 of the 10 Pleiades BDCs without proper motion data lie in the second magnitude bin. The rate of success in confirming BDs among the BDCs found in the CFHT survey (Bouvier et al. 1998) in the magnitude bin of subset (2) has been 55% (6 proper motion members out of 11 candidates, Moraux et al. 2001). If the success rate is similar for the NPL and Roque surveys, we expect 2 of the 4 BDCs to be confirmed. Thus, we add 2 objects to the sample in bin (2) and we get 0 binaries for 6 objects.

To summarize, we get the following binary frequencies for the separation range 7-12 AU: $F_b = 2/13 = 15^{+15}_{−5}$% for the sample of proper motion members in the magnitude range $I = 17.74–20.05$; $F_b = 2/9 = 22^{+19}_{−8}$% in the magnitude bin $I = 17.74–18.50$ for proper motion members; and $F_b = 0/6$ implying $F_b < 23$% in the magnitude bin $I = 18.50–21.00$ for targets with confirmed proper motion membership (4 objects) plus targets without proper motion information (2 out of 4 objects).

Our survey is not sensitive to separations smaller than 7 AU in the Pleiades and smaller than 10.5 AU in $\alpha$Per. We do not find any companions with separations larger than 12 AU among the sample of 13 Pleiades proper motion members, and we do not find any binaries with separations larger than 10.5 AU among the sample of 8 $\alpha$Per candidate members. No proper motions are available for the $\alpha$Per objects, but 4 of them have lithium detections (Basri & Martín 1999; Stauffer et al. 1999). We estimate that BD binaries with separations larger than 12 AU are less frequent than 1/21, i.e. $<9$% in the $\alpha$Per and Pleiades open clusters. This result is consistent with the low frequency ($<2$%) of ultracool binaries in the solar neighborhood with separations larger than 15 AU (Bouy et al. 2003; Close et al. 2003; Gizis et al. 2003; Reid et al. 2001).
4.2. Comparison with theoretical models: Mass estimates

In Figure 4 we show a color-magnitude diagram (CMD) for the sample of proper motion
Pleiades members included in our survey. The components of the 3 binaries are plotted indi-
vidually. Note that the photometric uncertainties are higher for these objects (Table 2). The
synthetic WFPC2 photometry from the Nextgen (Baraffe et al. 1998) and Dusty (Chabrier
et al. 2000) isochrones for ages 70 and 120 Myr are shown. These ages bracket the range of
cluster ages estimated for the Pleiades in the literature (Stauffer et al. 2003 and references
therein).

The Nextgen isochrones give a better fit to the cluster sequence for \( I < 18.5 \), and the
Dusty isochrones provide a better fit for fainter objects. The agreement between the models
and data is quite good within the error bars.

We have estimated masses for the objects using an age of 120 Myr (LDB age, Stauffer
& Barrado y Navascués 2003) and the Nextgen models for \( I < 18.5 \). For fainter objects we
used the Dusty models. The masses derived for the components of the 3 binaries are given in
Table 2. CFHT-Pl-12 and IPMBD 29 have estimated orbital periods of less than a century.
Orbital motion should be measurable in a few years. The dynamical masses of BD binaries
of known age constitute an important test to the accuracy of evolutionary models.

4.3. Binary properties as a function of primary mass

We have compiled all the known resolved (separation > 7 AU) stellar binaries in the
Pleiades from the following papers: Abt et al. (1965); Anderson, Stoeckly & Kraft (1966);
Bouvier, Rigaut, & Nadeau (1997); Jones, Fischer & Stauffer (1996); Mason et al. (1993);
Mermilliod et al. (1992); Raboud & Mermilliod (1998); Rosvick, Mermilliod, & Mayor
(1992a,b); Stauffer (1982); and Stauffer et al. (1984). Their primary masses are plotted in
Figure 5 with respect to their projected semimajor axis. There is a strong trend for the
upper envelope of maximum separations to decrease with primary mass. A similar effect has
been noted among binaries in the field (Burgasser et al. 2003 and references therein). The
lack of BD binaries in the αPer and Pleiades open clusters, and in the solar vicinity, with
separations larger than 15 AU, may be a natural continuation of this effect, already present
in stellar binaries, toward substellar masses. In order to check if there is any sudden change
in the distribution of semimajor axis across the substellar boundary, a survey for binaries
among M-type Pleiades members is needed.

In section 4.1 we obtained a binary frequency for the semimajor axis range 7–12 AU of
\( F_b = 22^{+19}_{-8} \% \) in the magnitude bin \( I = 17.74–18.50 \), which corresponds to primary masses
in the range $0.072 - 0.05 \, M_\odot$ according to the Nextgen models for an age of 120 Myr. We also derived a binary frequency for the same range of semimajor axis of $F_b < 23 \%$ in the magnitude bin $I = 18.50 - 21.00$, corresponding to primary masses between $0.050 \, M_\odot$ and $0.030 \, M_\odot$ according to the Dusty models for an age of 120 Myr. The difference between these two mass bins is not statistically significant, but it suggests that lower mass BD binaries may be tighter than the resolution limit of our WFPC2 survey. The trend seen in Figure 5 may continue into the substellar domain. A larger sample of binaries is needed to improve the statistics.

Figure 6 displays the mass ratios of resolved binaries in the Pleiades cluster, including the 3 BD binaries found in this survey. We note the lack of mass ratios equal to unity among the BD binaries. This may be an effect of low number statistics. We also note that there are no BD binaries with $q<0.7$. The sensitivity of our survey is $I = 22.5$, which translates into a mass of $0.027 \, M_\odot$ using the Dusty models for an age of 120 Myr. Thus, we are sensitive to mass ratios $q>0.37$ for our most massive primaries ($M_p \sim 0.07 \, M_\odot$), and larger $q$ for lower mass primaries. However, all our BD binaries were found at close separations where the sensitivity limit is only about 3 magnitudes (Bouy et al. 2003). The lack of BD binaries in our survey with mass ratios in the range $q=0.7 - 0.4$ may be an observational effect. Since our survey is not as sensitive to low mass ratios as other surveys (e.g., Bouvier et al. 1997), our BD binary frequencies may be underestimated if there is a significant number of BD binaries with mass ratios $q<0.7$ which we have missed. Nevertheless, we note that high-resolution surveys of nearby ultracool dwarfs have also failed to find binaries with $q<0.7$ in larger samples (Bouy et al. 2003; Close et al. 2003; Gizis et al. 2003). So, there could be a real trend for VLM binaries to have mass ratios larger than $q=0.7$.

In Figure 7 we plot the frequency of binaries wider than 7 AU as a function of primary mass in the Pleiades cluster. The binary frequency for brown dwarfs does not appear to be lower than for stars, although the error bars are still high due to low number statistics.

5. Final remarks and future prospects

In a survey carried out with HST/WFPC2, we have found 4 binaries in a sample of 25 candidate VLM members in the Pleiades cluster and no binaries in a sample of 8 candidate VLM members in the α Persei cluster. We argue that 3 of the Pleiades binaries are cluster members and one is not on the basis of the available proper motion and spectroscopic information. Component masses and orbital periods are estimated from theoretical evolutionary models. Follow-up observations will yield orbital parameters in a timescale of about a decade, and will provide powerful tests to the theory of substellar-mass objects.
No binaries are detected with separations larger than 12 AU among the VLM population of the αPersei and Pleiades clusters. We estimate a frequency of <9% for VLM binaries with separations larger than 12 AU in these clusters. This result agrees with the scarcity of VLM binaries wider than 15 AU in the solar neighborhood (<2%, Bouy et al. 2003; Close et al. 2003; Gizis et al. 2003). We show that in the Pleiades there is a decrease in the upper envelope of binary separations with decreasing primary mass. The VLM binaries may be a natural continuation of this effect. We note that there is a significant lack of data of binaries for masses in the range 0.3-0.1 M⊙ in the Pleiades. A study of binarity in those stars is needed to fill the gap between the cool stars and the VLM objects.

We find that the binary frequency among Pleiades BDs with confirmed proper motion membership in the mass range 0.072 – 0.030 M⊙ and separations larger than 7 AU is 15%. It is similar to that the binary fraction of stellar binaries for the same separation range. We divide our Pleiades sample in two mass bins. We estimate a binary frequency of $22^{+19}_{-8}$% for primary masses in the range 0.072 – 0.050 M⊙. For primary masses between 0.050 M⊙ and 0.030 M⊙ we derive an upper limit of <23%. Although our study is hampered by low number statistics, we suggest that low mass BD binaries may be systematically tighter than high-mass BDs, and thus are not detected in our HST survey. Studies of larger samples of BDs are needed to test our suggestion.

The BD binary frequency appears to be larger than 10% in the Pleiades cluster and in the solar neighborhood. Such a relatively high binary frequency does not support hydrodynamical models of BD formation that predict a very low (<5%) BD binary frequency (Bate et al. 2002). Within the error bars, our results may be consistent with dynamical decay models of evolution in open clusters with random pairing (Sterzik & Durisen 2003). However, such models predict a flat mass ratio distribution which does not seem to agree with the observed lack of VLM binaries with q<0.7. Models of BD formation should take into account the fundamental observational constrains that BD binaries are numerous, and that they are biased toward separations smaller than 15 AU and that the mass ratios tend to be larger than 0.7.

Interferometric imaging and radial velocity studies of the Pleiades VLM population are needed to discover short period binaries such as PPl 15 (Basri & Martín 1999) and determine their frequency and mass ratio distribution. Larger samples of BDs in clusters should be studied to improve the statistical significance of the BD binary properties.

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Fig. 1.— Full width half maximum (FWHM) measurements in the F814W filter for our program objects (asterisks) and for reference stars in the PC1 field of view (empty hexagons). The four objects with FWHM>2 are binaries.
Fig. 2.— The 0\".065 BD binary CFHT-Pl-12 in the Pleiades cluster resolved with our PSF analysis of WFPC2 F814W observations. Upper left: Binary PSF. Upper right: Model PSF. Lower right: Residual after subtraction of model PSF for primary object. Lower left: Residual after subtraction of model PSF for secondary object.
Fig. 3.— A portion of the ESI spectrum of IPMBD 25 showing the detection of H$_\alpha$ in emission and LiI absorption.
Fig. 4.— Color-magnitude diagram for proper motion Pleiades members included in our WFPC2 survey. The components of 3 resolved binaries share the same symbols: CFHT-Pl-12 (asterisks), IPMBD 25 (open hexagons) and IPMBD 29 (filled hexagons). Unresolved targets are denoted with filled triangles. The following theoretical isochrones are overplotted from right to left: Nextgen–70 Myr (dotted line), Nextgen–120 Myr (solid line), Dusty–70 Myr (short dashed line), and Dusty–120 Myr (long dashed line). Masses obtained from the Nextgen–120 Myr (0.072 and 0.060 $M_{\odot}$) and the Dusty–120 Myr (0.050 and 0.040 $M_{\odot}$) are labelled. A typical errorbar for the photometric data is shown in the lower left corner.
Fig. 5.— Primary mass versus semimajor axis for resolved (separation > 7 AU) binaries in the Pleiades cluster.
Fig. 6.— Primary mass versus mass ratio for resolved binaries in the Pleiades cluster.
Fig. 7.— Frequency of binaries wider than 7 AU as a function of primary mass in the Pleiades cluster. The right panel is a zoom on the substellar-mass regime of this diagram.
Table 1. Data for program objects

| Name         | F814W | FWHM | F785LP | FWHM | I_c | R - I_c | SpT | Li | PMM |
|--------------|-------|------|--------|------|-----|---------|-----|----|-----|
| Calar 3      | 19.00 | 1.70 | 18.19  | 1.83 | 19.00| 2.50    | M8  | Y  | Y   |
| CFHT-Pl-9    | 17.74 | 1.66 | 17.05  | 1.81 | 17.71| 2.18    | M6.5| N  | Y   |
| CFHT-Pl-10   | 17.81 | 1.83 | 17.12  | 1.97 | 17.82| 2.21    | M6.5| N  | Y   |
| CFHT-Pl-12   | 17.93 | 2.10 | 17.14  | 2.15 | 18.00| 2.47    | M8  | Y  | Y   |
| CFHT-Pl-15   | 18.73 | 1.85 | 17.96  | 1.85 | 18.62| 2.34    | M7  | Y  | N   |
| CFHT-Pl-19   | 18.99 | 2.30 | 18.30  | 2.27 | 18.92| 2.51    | na  | na | N   |
| IPMBD 11     | 18.00 | 1.80 | 17.25  | 1.99 | 18.07| na      | na  | na | Y   |
| IPMBD 21     | 17.85 | 1.60 | 17.15  | 1.80 | 17.85| na      | na  | na | Y   |
| IPMBD 22     | 17.86 | 1.65 | 17.20  | 1.86 | 17.90| na      | na  | na | Y   |
| IPMBD 25     | 17.67 | 2.19 | 16.97  | 2.12 | 17.82| na      | na  | na | Y   |
| IPMBD 26     | 18.04 | 1.93 | 17.40  | 1.79 | 18.11| na      | na  | na | Y   |
| IPMBD 29     | 18.38 | 2.05 | 17.49  | 2.10 | 18.35| na      | na  | na | Y   |
| IPMBD 43     | 18.06 | 1.60 | 17.33  | 1.73 | 18.1: | na      | na  | na | Y   |
| NPL 36       | 18.56 | 1.80 | 17.79  | 2.00 | 18.66| na      | M7  | na | na  |
| NPL 38       | 19.20 | 1.83 | 18.38  | 1.84 | 19.18| na      | M8  | na | na  |
| NPL 43       | 21.77 | 1.91 | 21.05  | 1.82 | 21.79| na      | na  | na | na  |
| Roque 5      | 20.05 | 1.78 | 19.29  | 1.72 | 19.71| na      | M9  | na | Y   |
| Roque 7      | 19.39 | 1.92 | 18.68  | 1.85 | 19.50| 2.61    | M8.5| na | Y   |
| Roque 18     | 21.41 | 1.84 | 20.85  | 1.81 | 21.11| na      | na  | na | na  |
| Roque 20     | 21.62 | 1.89 | 22.31  | 1.59 | 22.2:| na      | na  | na | na  |
| Roque 23     | 22.01 | 1.84 | 21.73  | 1.83 | 21.75| na      | na  | na | na  |
| Roque 24     | 22.14 | 1.76 | 21.02  | 1.79 | 21.56| na      | na  | na | na  |
| Roque 30     | 20.92 | 1.67 | 20.40  | 1.86 | 20.31| na      | na  | na | na  |
| Roque 33     | 20.39 | 1.81 | 19.65  | 1.75 | 20.26| na      | M9.5| na | na  |
| AP 270       | 17.80 | 1.80 | 17.01  | 1.75 | 17.83| na      | M6  | Y  | na  |
| AP 275       | 17.31 | 1.84 | 16.62  | 1.66 | 17.25| 2.20    | M6  | N  | na  |
| AP 300       | 17.86 | 1.73 | 17.17  | 1.93 | 17.85| 2.18    | M6  | Y  | na  |
| AP 310       | 17.71 | 1.85 | 17.08  | 1.71 | 17.80| 2.33    | M6  | N  | na  |
| AP 318       | 17.42 | 1.61 | 16.75  | 1.64 | 17.45| 2.16    | M6  | N  | na  |
| AP 323       | 17.57 | 1.56 | 16.92  | 1.77 | 17.50| 2.13    | na  | Y  | na  |
| AP 324       | 18.11 | 1.72 | 17.44  | 1.63 | 18.10| 2.36    | M6.5| Y  | na  |
| AP 325       | 17.74 | 1.89 | 16.94  | 1.78 | 17.65| 2.30    | M7  | Y  | na  |

b The $R_C$ and $I_C$ photometric data, spectral types, lithium detections and proper motion memberships come from the literature cited in Section 2.

na = not available.
Table 2. Data for Binary Systems.

| Name   | F814W(A)   | F814W(B)   | F785LP(A)  | F785LP(B)  | Sep (arcsec) | Sep (AU)   | P.A.   | M_p^a | q   | P(yr)^b |
|--------|------------|------------|------------|------------|--------------|------------|--------|-------|----|--------|
| CFHT-Pl-12 | 18.34±0.11 | 19.32±0.11 | 17.57±0.11 | 18.48±0.11 | 0.062±0.002  | 7.75       | 266.7±1.7 | 0.054 | 0.70 | 76     |
| CFHT-Pl-19 | 19.40±0.11 | 20.38±0.11 | 18.79±0.11 | 19.57±0.11 | 0.066±0.003  | 262.7±1.8  |        |       |    |        |
| IPMBD 25  | 17.93±0.09 | 19.38±0.09 | 17.22±0.09 | 18.74±0.09 | 0.094±0.003  | 11.75      | 340.5±2.1 | 0.063 | 0.62 | 126    |
| IPMBD 29  | 18.70±0.15 | 19.95±0.15 | 17.81±0.11 | 19.06±0.11 | 0.058±0.004  | 7.25       | 103.0±4.5 | 0.045 | 0.84 | 68     |

^a Masses for primaries (M_p) are given in solar masses (see text for details).

^b Orbital periods are estimated for circular orbits using Kepler’s third law and are given in years. No masses and periods are estimated for CFHT-Pl-19 because it is thought to be a nonmember.