Discovery of a Very Low-Mass Binary with HST/NICMOS

E.L. Martín and G. Basri
Astronomy Department, University of California, Berkeley, CA 94720

W. Brandner
Jet Propulsion Laboratory/IPAC, Mail Code 100-22, Pasadena, CA 91125

J. Bouvier
Observatoire de Grenoble, B.P.53, F-38041 Grenoble Cedex 9, France

M. R. Zapatero Osorio and R. Rebolo
Instituto de Astrofísica de Canarias, 38200 La Laguna, Spain

J. Stauffer
Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138

F. Allard and I. Baraffe
CRAL, Ecole Normale Superieure, 46 Alee d’Italie, Lyon, 69364 France

and

S. T. Hodgkin
Astronomy Group, Department of Physics and Astronomy, Leicester University, University
Road, Leicester, LEI 7RH, England, UK

contact e-mail address: ege@popsicle.berkeley.edu

Received ________________; accepted ________________

accepted by ApJ Letters
Hubble Space Telescope NICMOS observations are presented of six brown dwarf candidates in the Pleiades open cluster. One of them, namely CFHT-Pl-18, is clearly resolved as a binary with an angular separation of 0”.33. The very low density of contaminating background stars in our images and the photometry of the components support that this system is a physical binary rather than a chance projection. All the available photometric and spectroscopic data indicate that the CFHT-Pl-18 system is likely a member of the Pleiades cluster, but a final confirmation will have to wait until lithium can be detected. Assuming cluster membership, we compare our NICMOS photometry with evolutionary models, and find that the inclusion of the effects of dust grains is necessary for fitting the data. We estimate that the masses of the components are about 0.045 M\(_\odot\) and 0.035 M\(_\odot\). The binary system has a projected separation of 42 AU (for a distance of 125 pc) that is common among stellar binaries.

**Subject headings:** surveys — binaries: general — stars: formation — stars: evolution — stars: low-mass, brown dwarfs — open clusters and associations: individual (Pleiades)
1. Introduction

Brown dwarfs (BDs; substellar objects with masses lower than about 0.075 M⊙) cool down with increasing age to very low temperatures and faint luminosities, becoming very difficult to detect. Ten cool Pleiades members have been shown to have strong resonance Li I lines that confirm their BD status and provide a nuclear age of 120 Myr for the cluster (Basri, Marcy & Graham 1996; Rebolo et al. 1996; Martín et al. 1998a; Stauffer, Schultz & Kirkpatrick 1998). Thus, the substellar borderline and the cluster sequence into the BD realm is now well established. The substellar limit in the Pleiades is located at I ~17.8 and spectral type M6–M6.5 (Martín, Rebolo & Zapatero Osorio 1996; Stauffer et al. 1998).

Recent deep CCD surveys in the Pleiades have been successful in revealing a numerous population of BD candidates (Zapatero-Osorio et al. 1997a; Bouvier et al. 1998; Festin 1998). The density of BD candidates uncovered by these surveys indicates that the mass function (MF) of the Pleiades does not turnover in the stellar domain. Martín, Zapatero Osorio & Rebolo (1998) and Bouvier et al. (1998) have shown that the Pleiades MF can be approximated to a power law M^{−α} with α in the range 0.5 to 1.2 for masses between 0.4 M⊙ and 0.04 M⊙.

The substellar MF of the Pleiades cluster has not been corrected for binaries because nothing is known about the multiplicity of brown dwarfs. The effect of binarity is to increase the number of BDs, and thus the MF slope α should be revised upward if there are many BD companions. Recently it has been shown that the Pleiades object PP 15 is a double-lined spectroscopic binary (Basri & Martín 1998) composed of two brown dwarfs. Since very few BDs have been checked for radial velocity variations, this suggests a high binary fraction among BDs. With the aim of finding more BD binaries, we selected a sample of 30 targets with high likelihood of being Pleiades members with masses between 0.09 M⊙ and 0.04 M⊙ for an imaging survey with the NICMOS camera on the Hubble
Space Telescope (HST). This paper reports on the observations of the first 6 objects of our program. One of them has been clearly resolved into two components and we argue that it probably constitutes the first resolved BD–BD binary.

2. Observations, Results and Discussion

The HST observations of our first 6 targets were obtained between 1998 February 17 and 1998 March 31. The objects were selected randomly among our total list of 30 targets that were chosen to be representative of all known Pleiades BD candidates. Our sample includes ‘Calar’ and ‘Teide’ objects from Zapatero Osorio et al. (1997b) and Martín et al. (1998a); ‘CFHT’ objects from Bouvier et al. (1998); ‘HHJ’ objects from Hambly, Hawkins & Jameson (1993); ‘MHO’ objects from Stauffer et al. (1998b); and ‘Roque’ objects from Zapatero Osorio et al. (1997a).

We used the NICMOS camera 1 (NIC1) in multiple-accumulate mode with filters F110M, F145M, and F165M (Thompson et al. 1998). The integration times were 896 s in F110M and 768 s in the other two filters. The limiting sensitivities are 0.012 mJy in F110M, 0.017 mJy in F145M and 0.016 mJy in F165M (corresponding to $J=20.0$ and $H=19.4$). They were derived based on the assumption that we would detect a source if the counts in the central pixel of its PSF are at least 3 times the sigma of the background. Each target was observed during only one orbit (visibility 52 min).

In Figure 1 we show the NIC1 images of five targets. All of them are consistent with being unresolved single objects except for CFHT-Pl-18, which is clearly resolved into two components. The separation between them is $0.334\pm0.001$ arcsec and the position angle is $351.3\pm0.2$ degrees. At the distance of the Pleiades cluster (125 pc) the observed angular separation corresponds to a projected binary axis distance of 41.75 AU. Flux values for
all the targets were computed based on the header keyword PHOTFNU and are given in Table 1. These values should be used with caution because the values for PHOTFNU are valid for sources with a constant flux per unit wavelength across the band pass, which might not be the case for our sources. Other limiting factors in the accuracy of the fluxes are that we used model PSF for fitting the data that did not provide a perfect match to the observed PSF, and uncertainties in the NICMOS darks and resulting spatial variations in the background. We used on-orbits darks (as opposed to the model darks used in the standard NICMOS pipeline) to improve the photometric accuracy, but it was still not perfect.

We obtained near-IR photometry of CFHT-Pl-18 at the 3.6 m CFHT telescope on 13-15 January 1998. Using zero-points from UKIRT faint standards we obtained the following magnitudes: J=15.95±0.02; H=15.23±0.04 and K=14.80±0.07. After discovering the binary nature of CFHT-Pl-18 in the NIC1 data, we applied for service observations at the Keck observatory. On 1998 August 8, an LRIS spectrum was obtained at Keck II by the staff of the observatory. The 1200/7500 grating was used with a 1" slit. One exposure of 1800 s was obtained. The CCD frame was reduced and wavelength calibrated using standard IRAF routines. The spectral dispersion, FWHM resolution and range recorded are: 1.26 Å, 2.4 Å and 664.6–793.3 nm, respectively.

The RIJHK photometric measurements of CFHT-Pl-18 support the membership to the Pleiades cluster because they are similar to the benchmark BDs Calar 3 and Teide 1 (Zapatero-Osorio et al. 1997c). Additional evidence for cluster membership is provided by the LRIS spectrum. In Figure 2 we compare the spectra of CFHT-Pl-18 and Teide 1 (Rebolo et al. 1995, 1996). We do not find any significant difference between them. We obtained a heliocentric radial velocity for CFHT-Pl-18 of 2.3±10.5 km s⁻¹ by cross-correlation with an LRIS spectrum of VB 10 (Vₚ=35 km s⁻¹) obtained in another run. This radial velocity is
fully consistent with cluster membership, but does not rule out that CFHT-Pl-18 could be a field young disk star. Our spectrum of CFHT-Pl-18 is unfortunately too noisy to attempt a detection of the lithium resonance line at 670.8 nm. We intend to obtain higher quality spectra soon.

Zapatero Osorio et al. (1997b) discussed the different kinds of objects that could contaminate the Pleiades photometric sequence and found that only very-low mass (VLM) foreground stars could be important. We have estimated the probability that CFHT-Pl-18 could be a field VLM star. The Keck spectrum yields a spectral type of M8 using the indices defined by Martín et al. (1996). If it were a main-sequence M8 dwarf, it would have to be at a distance of about 90 pc. The local density of M8 dwarfs is about 0.0024 pc$^{-3}$ (Kirkpatrick et al. 1994). The number of expected M8 dwarfs in a distance range between 80 pc and 100 pc in the total area of the CFHT CCD survey (2.5 deg$^2$; Bouvier et al. 1998) is $\sim$0.8. Since there are 6 BD candidates in the CFHT survey with magnitudes in the range $I$=18.6 and 19.0, the probability that CFHT-Pl-18 is a contaminating foreground star is $\sim$15% . Thus, it is much more likely that CFHT-Pl-18 is a young BD binary system rather than an old field VLM stellar binary, and our measured radial velocity is a positive consistency check of Pleiades membership. Eventually it would be good to have proper motion confirmation.

CFHT-Pl-18 is likely to be a physical binary rather than a chance coincidence in the sky of two unrelated objects because of three reasons: The density of contaminating stars in our NIC1 images is very low (Figure 1). The fainter component of CFHT-Pl-18 is redder than the primary and probably has stronger water absorption. The F145N filter is strongly affected by water vapour. The B/A ratio in this filter is lower (0.480±0.011) than in the F110M filter (0.488±0.010), indicating stronger water absorption in the B component than in the A component, consistent with being cooler.
In order to derive the luminosities and masses of the CFHT-Pl-18 components we assume that it belongs to the Pleiades. This fixes the age, distance and metallicity at 120 Myr, 125 pc and solar, respectively. In Figure 3, we present a comparison of our data with state of the art models. The “Dusty” models include dust grains in the equation of state and the opacities, and the “Cond” models include grains in the equation of state but not in the opacities. The NextGen models (Allard et al. 1997; Baraffe et al. 1998) do not have any grains and they are systematically redder than the Dusty and Cond models, even in the stellar domain, because they were computed with a different water molecule data set. The NextGen models provide a good fit to the data for the higher masses (0.08–0.06 M⊙), but the Cond models fit better the lower masses (0.06–0.03 M⊙). Our models should be considered preliminary because they do not do a very good job reproducing the H bandpasses of very cool dwarf spectra (Allard et al. 1998). We plan in the future to make a detailed comparison between models and the NICMOS data of our whole sample. Presently, we note that the low-mass Pleiades BDs are likely to be dusty, and that the masses estimated for them depend on the details of the models. Taking into account the observational error bars and the theoretical uncertainties, we estimate masses of M/M⊙=0.046±0.006 and M/M⊙=0.035±0.007 for CFHT-Pl-18 A and B, respectively.

Bouvier et al. (1997) have performed a search for close multiple systems to G- and K-type Pleiades members. They found companions with separations in the range 0.08″–6.9″ and a contrast in the H-band up to 5 magnitudes. They derived a binary frequency of 28±4% in the orbital period range from 4.2 to 7.1 log(days) after correction for incompleteness. Such binary frequency is similar to that of nearby field G-type dwarfs (27%). The separation of the components of the CFHT-Pl-18 system lies around the maximum of the distribution of binary separation among different kinds of low-mass stars. If the multiplicity frequency of BDs is similar than for solar-type stars (a hypothesis that will be tested with our observations) we expect to find at most 8 binaries among our 30
primaries, depending on the mass-ratio distribution of brown dwarf binaries. So far we have
found 1 binary out of 6 candidate primaries (16% detection rate), consistent with the field
dwarf results. The study of the multiplicity in our sample is important for constructing
the MF below the substellar limit. The Pleiades cluster is the first site where a sufficient
number of BDs can be studied in order to derive a substellar mass function. The recent La
Palma and CFHT surveys strongly indicate that the MF rises below the substellar limit
(Zapatero Osorio et al. 1997a; Martín et al. 1998b; Bouvier et al. 1998). The effect of
unresolved binaries is an important uncertainty in the computation of the MF (Kroupa
1995). The fact that PPl 15 and CFHT-Pl-18 are binaries indicates that BD companions
suggests that binary BDs may be frequent. We plan to discuss the binary statistics in a
future paper when our HST program has been completed.

The binary CFHT-Pl-18 may have formed via the gravitational collapse and late
fragmentation of a very low-mass molecular core. Since the opacity limit for gravitational
collapse is thought to be as low as $\sim 0.01 M_\odot$ (Kanjilal & Basu 1992), there is no reason why
the BDs should form in a manner different from stars unless such fragmentation does not
proceed to completion. This latter point has been an important question to be addressed
by the discovery of brown dwarfs. Now that many free-floating BDs have been found,
hierarchical fragmentation might be considered a viable hypothesis, and the discovery of
this binary suggests that the process of binary formation could be similar in the substellar
and stellar mass ranges.

Acknowledgments: This research is based on data collected at the Hubble Space
Telescope, the Canada-France-Hawaii telescope and the Keck II telescope. We are
grateful to the staff of the Keck observatory for carrying out LRIS service observations of
CFHT-Pl-18. We thank G. Chabrier for his help in developing the models used in this
paper. EM acknowledges the support from the F.P.I. program of the Spanish Ministry of
Education and Culture. GB acknowledges the support of NSF through grant AST96-18439. FA was supported by NASA through grants 110-96LTSA and NAG5-3435. Funding for this publication was provided by NASA through Proposal GO-7899 submitted to the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
REFERENCES

Allard, F., Hauschildt, P. H., Alexander, D. R. & Starrfield, S. 1997, ARAA, 35, 137

Allard, F., Baraffe, I., Chabrier, G. & Hauschildt, P. H. 1998, A&A, in press

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P.H. 1998, A&A, 337, 403

Basri, G., Marcy, G., & Graham, J. R. 1996, ApJ, 458, 600

Basri, G., & Martín, E.L. 1998, in Brown Dwarfs and Extrasolar Planets, eds. R. Rebolo, E. L. Martín & M. R. Zapatero Osorio, ASP Conf. Series, 134, 284

Bouvier, J., Stauffer, J. R., Martín, E.L., Barrado y Navascués, D., Wallace, B. & Béjar, V.J.S. 1998, A&A, 336, 490

Festin, L. 1998, A&A, 333, 497

Hambly, N. C., Hawkins, M. R. S., & Jameson, R. F. 1993, A&AS, 100, 607

Kanjilal, T. & Basu, B. 1992, Ap&SS, 193, 17

Kirkpatrick, J.D., McGraw, J.T., Hess, T.R., Liebert, J. & McCarthy, D.W. 1994, ApJS, 94, 749

Kroupa, P. 1995, MNRAS, 453, 358

Martín, E. L., Rebolo, R., & Zapatero Osorio, M. R. 1996, ApJ, 469, 706

Martín, E. L., Basri, G., Gallegos, J. E., Rebolo, R., Zapatero Osorio, M. R. & Béjar, V. J. S. 1998a, ApJ, 499, L61

Martín, E. L., Rebolo, R. & Zapatero Osorio, M. R. 1998b, in Brown Dwarfs and Extrasolar Planets, eds. R. Rebolo, E. L. Martín and M. R. Zapatero Osorio, ASP Conf. Series, 134, 507
Rebolo, R., Martín, E. L., Basri, G., Marcy, G. W., & Zapatero Osorio, M. R. 1996, ApJ, 469, L53

Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, Nature, 377, 129

Stauffer, J. R., Schultz, G. & Kirkpatrick, J.D. 1998a, ApJ, 499, L199

Stauffer, J. R., Schild, R., Barrado y Navascués, D., Backman, D. E., Angelova, A. M., Kirkpatrick, J. D., Hambly, N. & Vanzi, L. 1998b, ApJ, 504, 805

Thompson, R.I., Rieke, M.J., Schneider, G., Hines, D. & Corbin, M.R. 1998, ApJ, 492, L95

Zapatero Osorio, M. R., Rebolo, R., Martín, E. L., Basri, G., Magazzù, A., Hodgkin, S. T., Jameson, R.F. & Cossburn, M. R. 1997a, ApJ, 491, L81

Zapatero Osorio, M. R., Rebolo, R., & Martín, E. L. 1997b, A&A, 317, 164

Zapatero Osorio, M. R., Martín, E. L., & Rebolo, R. 1997c, A&A, 323, 105

This manuscript was prepared with the AAS \LaTeX{} macros v4.0.
**Figure Captions:**

Fig. 1.— Mosaic of reduced HST/NIC1 images.

Fig. 2.— The optical spectrum of CFHT-Pl-18 compared with Teide 1 (Rebolo et al. 1996). Both spectra have similar spectral resolution and have been smoothed with a boxcar of 3 pixels. The spectrum of CFHT-Pl-18 has been normalized in the same region (∼690 nm) as the spectrum of Teide1, and shifted upward by 5 units.

Fig. 3.— A color-magnitude with the NICMOS filters. The two components of CFHT-Pl-18 are marked with filled hexagons. The other program objects are marked with empty circles. The solid line is the 120 Myr isochrone for NextGen model atmospheres (Allard & Hauschildt 1995). The dotted and dashed lines are isochrones for the same age but including dust effects and a different water line list (see text for details). The asterisks on the isochrones denote the position of models with masses 0.075 and 0.040 M☉.
Table 1.  HST data for our program objects

| Name     | F110M    | F145M    | F165M    | Separation |
|----------|----------|----------|----------|------------|
| CFHT-Pl-18 A | 0.321±0.020 | 0.382±0.011 | 0.519±0.018 | 0.334±0.001 |
| CFHT-Pl-18 B | 0.157±0.020 | 0.183±0.011 | 0.266±0.018 | ≤0.08      |
| CFHT-Pl-20  | 0.263±0.012 | 0.353±0.010 | 0.459±0.008 | ≤0.08      |
| HHJ8      | 1.193±0.022 | 1.452±0.013 | 1.800±0.017 | ≤0.08      |
| MHO6      | 0.800±0.029 | 0.960±0.018 | 1.234±0.023 | ≤0.08      |
| Roque 11  | 0.428±0.012 | 0.505±0.009 | 0.706±0.013 | ≤0.08      |
| Roque 12  | 0.450±0.021 | 0.566±0.012 | 0.767±0.014 | ≤0.08      |

The fluxes are given in mJy and the separations in arcsec. For unresolved objects an upper limit is given for companions up to 3 magnitudes fainter than the primary. The error bars are 1 σ standard deviations.
