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A *HUBBLE SPACE TELESCOPE* ADVANCED CAMERA FOR SURVEYS SEARCH FOR BROWN DWARF BINARIES IN THE PLEIADES OPEN CLUSTER

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ABSTRACT

We present the results of a high-resolution imaging survey for brown dwarf binaries in the Pleiades open cluster. The observations were carried out with the Advanced Camera for Surveys (Pavlovsky and coworkers) on board the *Hubble Space Telescope*. Our sample consists of 15 bona fide brown dwarfs. We confirm two binaries and detect their orbital motion, but we did not resolve any new binary candidates in the separation range between 5.4 and 1700 AU and masses in the range 0.035–0.065 $M_\odot$. Together with the results of our previous study (Martín and coworkers), we can derive a visual binary frequency of $13.3^{+13.7}_{-4.3}$ % for separations greater than 7 AU, masses in the range 0.055–0.065 $M_\odot$, and mass ratios in the range $0.45–0.9 < q < 1.0$. The other observed properties of Pleiades brown dwarf binaries (distributions of separation and mass ratio) appear to be similar to their older counterparts in the field.

Subject headings: binaries: general — globular clusters: general — globular clusters: individual (M45, Pleiades) — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. INTRODUCTION

Young open clusters offer the advantage that both the age and distance are precisely known so that brown dwarf candidates are more easily identified from their positions in color-magnitude diagrams (CMDs), relative to the expected position of the cluster's substellar isochrone. Over the last few years, a large number of authors have published results of large surveys looking for substellar members of the Pleiades (Nagashima et al. 2003; Moraux et al. 2003; Dobbie et al. 2002a; Jameson et al. 2002). Using theoretical models (Chabrier et al. 2000), the magnitude of an object can be readily converted to a mass (given the age and distance of the cluster) and the resulting initial mass function (IMF) estimated. While detailed studies of the IMF of the Pleiades' very low mass stars and brown dwarfs have already been performed (see, e.g., Dobbie et al. 2002b; Jameson et al. 2002; Hambly et al. 1999), the contribution of multiple systems to the IMF has rarely been taken into account. In this study we obtained high angular resolution images of a sample of brown dwarfs in the Pleiades cluster in order to investigate the occurrence of multiple systems among substellar objects and its implications on (1) the formation and evolution processes of brown dwarfs, (2) the properties of these multiple systems in comparison with those of the field and in star-forming regions, and (3) the contribution of substellar objects to the IMF.

The Pleiades is one of the best-studied open clusters. Its age (105–140 Myr; Martín 2006) and distance ($d = 135$ pc; see, e.g., Pan et al. 2004; Munari et al. 2004) are well known and its IMF has been well studied over the stellar mass range. All the targets come from the same star-forming region: they formed under similar initial conditions and are now following identical evolutionary paths, which is not the case for field brown dwarfs, for which in general we know neither the age nor the distance precisely. Moreover, the Pleiades cluster offers two important advantages for our study in comparison with other clusters, star-forming regions, or associations. First of all, there exists a relatively large sample of confirmed brown dwarfs, which is of prime importance in making a good statistical study, and secondly because the cluster is not so far away as to exclude a search for close visual binaries. These considerations make this cluster the ideal place for a complementary study to the field ultracool dwarfs presented by Siegler et al. (2005), Bouy et al. (2003),

TABLE 1
Pleiades Sample

Name	R.A. (J2000.0)	Decl. (J2000.0)	I (mag)	$I-Z$ (mag)
Cl* Melotte 22 CFHT-Pl 11[a]	03 47 39.0	+24 36 22.1	17.91	...
Cl* Melotte 22 CFHT-Pl 12[a,b]	03 53 55.1	+23 23 36.4	17.87	1.04
Cl* Melotte 22 CFHT-Pl 13[a]	03 52 06.72	+24 16 00.76	17.82	0.90
Cl* Melotte 22 CFHT-Pl 15[a]	03 55 12.5	+23 17 38.0	18.62	...
Cl* Melotte 22 CFHT-Pl 16[a]	03 44 35.3	+25 13 44.0	18.47	1.11
Cl* Melotte 22 CFHT-Pl 17[a]	03 43 00.2	+24 43 52.1	18.47	0.96
Cl* Melotte 22 CFHT-Pl 21[a]	03 51 25.6	+23 45 21.2	18.88	1.07
Cl* Melotte 22 CFHT-Pl 23[a]	03 52 18.64	+24 04 28.41	19.32	1.11
Cl* Melotte 22 CFHT-Pl 24[a]	03 43 40.29	+24 30 11.34	19.38	1.12
Cl* Melotte 22 CFHT-Pl 25[a]	03 54 05.37	+23 33 59.47	19.69	1.21
Cl* Melotte 22 CFHT-Pl-IZ 2141[a]	03 44 31.29	+25 35 14.42	21.88	1.14
Cl* Melotte 22 CFHT-Pl-IZ 2[a]	03 55 23.07	+24 49 05.01	17.81	0.90
Cl* Melotte 22 CFHT-Pl-IZ 23[a]	03 51 33.48	+24 10 14.16	20.30	1.10
Cl* Melotte 22 CFHT-Pl-IZ 26[a]	03 44 48.66	+25 39 17.52	20.85	1.20
Cl* Melotte 22 CFHT-Pl-IZ 28[a]	03 54 14.03	+23 17 51.39	21.01	1.23
Cl* Melotte 22 CFHT-Pl-IZ 4[a]	03 41 40.92	+25 54 23.0	17.82	0.96
Cl* Melotte 22 IPMBD 29[a,b]	03 45 31.3	+24 52 48.0	18.35	...
Cl* Melotte 22 CFHT-Pl-IZ 10	03 51 44.97	+23 26 39.47	18.66	1.03
Cl* Melotte 22 CFHT-Pl-IZ 1262	03 44 27.27	+25 44 41.28	22.47	1.23
Cl* Melotte 22 CFHT-Pl-IZ 13	03 55 04.4	+26 15 49.3	18.94	1.14
Cl* Melotte 22 CFHT-Pl-IZ 14	03 53 32.39	+26 07 01.2	18.94	1.14
Cl* Melotte 22 CFHT-Pl-IZ 161	03 51 29.43	+24 00 36.79	22.32	1.35
Cl* Melotte 22 CFHT-Pl-IZ 17	03 51 26.69	+23 30 10.65	19.44	1.08
Cl* Melotte 22 CFHT-Pl-IZ 19	03 56 16.37	+23 54 51.44	19.56	1.10
Cl* Melotte 22 CFHT-Pl-IZ 21	03 55 27.66	+25 49 40.72	19.80	1.17
Cl* Melotte 22 CFHT-Pl-IZ 25	03 52 44.3	+24 24 50.04	20.58	1.16
Cl* Melotte 22 CFHT-Pl-IZ 29	03 49 45.29	+26 50 49.88	21.03	1.27
Cl* Melotte 22 CFHT-Pl-IZ 300	03 51 15.6	+23 47 05.38	22.1	1.18
Cl* Melotte 22 CFHT-Pl-IZ 31	03 51 47.65	+24 39 59.51	21.05	1.26
Cl* Melotte 22 CFHT-Pl-IZ 51	03 46 36.24	+25 33 36.21	22.59	1.24
Cl* Melotte 22 CFHT-Pl-IZ 7	03 48 12.13	+25 54 28.4	18.46	1.12
Cl* Melotte 22 IPMBD 25[b]	03 46 26.1	+24 05 10.0	17.82	...

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Observed objects.
[b] Binaries.

Burgasser et al. (2003), Close et al. (2003), and Gizis et al. (2003).

In a first attempt to investigate brown dwarf binaries, Martín et al. (1998, 2000) surveyed 34 very low mass Pleiades members with the *Hubble Space Telescope* (*HST*) and adaptive optics at the Canada-France-Hawaii Telescope (CFHT). They found only one binary at a resolution of 0.″2 or larger (27 AU), but it failed the lithium test and was therefore not confirmed as a Pleiades member. More recently, Martín et al. (2003) used the *HST* WFPC2 and found only four binary candidates at a resolution of ∼0.″060 or larger (8.1 AU at 135 pc) among a total sample of 25 objects. In this paper we present the results of our complementary, higher resolution ACS observations. In § 2 we present the new sample, the observations, and the data analysis. In § 3 we present the results on the resolved multiple systems. In §§ 4 and 5 we discuss the confirmed and unresolved photometric binary candidates. In §§ 6 and 7 we calculate and discuss the binary frequency.

2. OBSERVATIONAL STRATEGY AND TECHNIQUES

In order to refine the previous studies of Pleiades brown dwarf binaries (Martín et al. 2000, 2003), we used the higher angular resolution provided by *HST* ACS-HRC (program SNAP-9831, P.I. Bouy). Using point-spread function (PSF) fitting, the observations we obtained with *HST* ACS allow us to resolve multiple systems with separations as low as ∼0.″040 (∼5.4 AU at the distance of the Pleiades). This is more than 5 times better than the NICMOS study of Martín et al. (2000) and 1.5 times as good as the WFPC2/PC study of Martín et al. (2003). Moreover, the sensitivity of *HST* ACS in the chosen filter is ∼5 times greater than the WFPC2/PC (see Biretta 2002). This allows us to investigate systems with close companions and with low flux ratios between the companion and the primary.

2.1. *Sample*

The initial sample consists of 32 brown dwarfs (spectral types later than M7) in the magnitude range $I = 18.0$–22.9 mag, identified from deep, wide-field surveys of the Pleiades cluster (Moraux et al. 2001, 2003; Hambly et al. 1999; Bouvier et al. 1998). Six objects (the binaries CFHT-PL-12, IPMBD 25, and IPMBD 29 and the unresolved objects CFHT-PL-15, CFHT-Pl-21, and CFHT-Pl-24) had already been observed with WFPC2 by Martín et al. (2003), and two more (CFHT-Pl-11 and CFHT-Pl-13) with NICMOS by Martín et al. (2000). All targets have been identified as brown dwarfs using near-infrared and optical photometry analysis and/or spectroscopy. The sample covers a mass range from 0.025 to 0.080 $M_\odot$ (see Table 1). The membership of our targets has been already confirmed by proper-motion measurements or spectroscopy (Moraux et al. 2001, 2003).

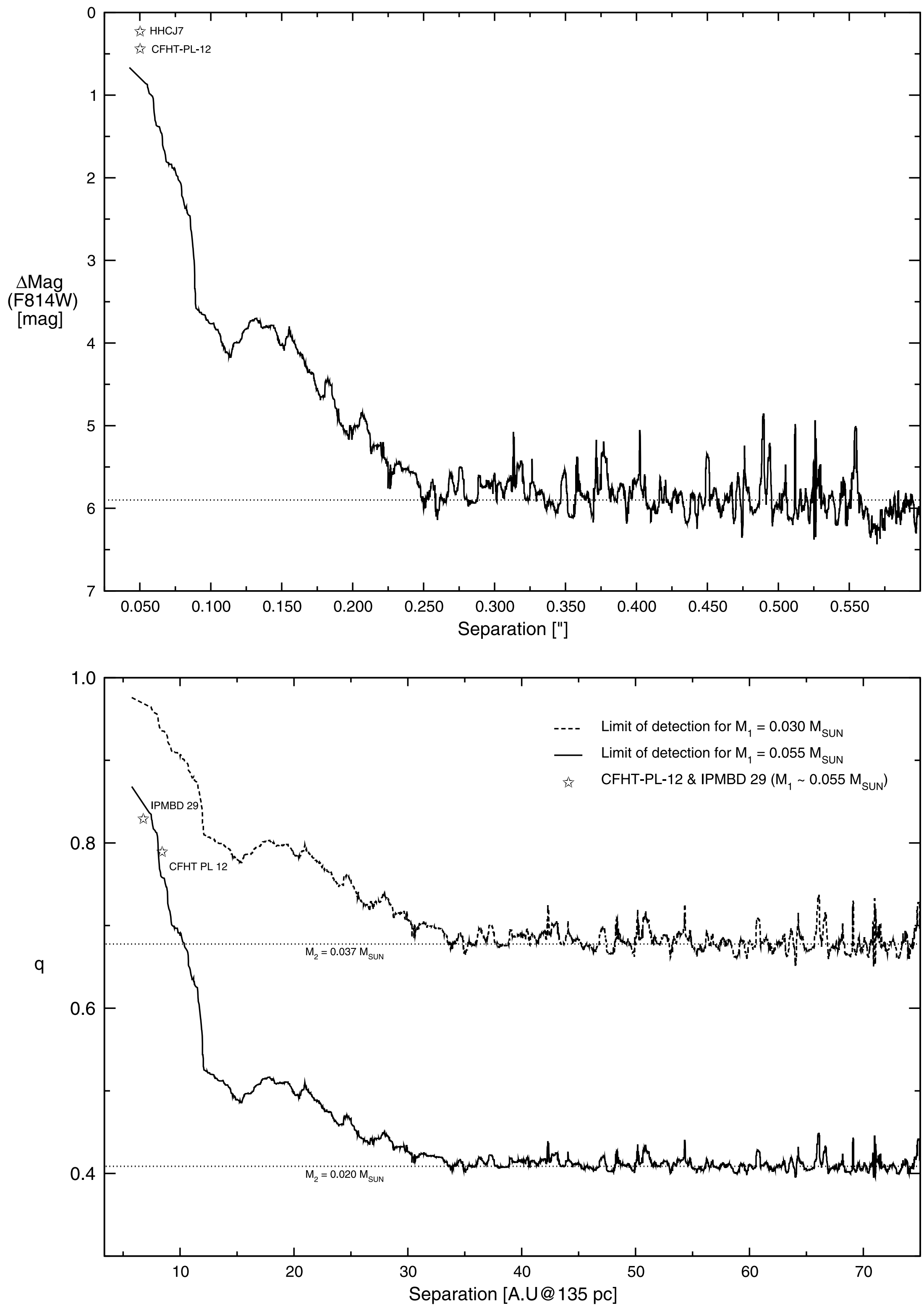

Fig. 1.—Limit of detection of our ACS/HRC observations. *Top*: ΔMag vs. angular separation. The solid line represents the largest detectable difference of magnitude in the F814W band between the primary and the secondary, as a function of the projected separation. The line was computed from the average of the 3 σ noise measurements in the images. At separation greater than 0″250, we were sensitive to companions 5.9 mag fainter than the primary (*dotted line*). The two stars indicate the two resolved binaries in this sample. *Bottom*: Same as the top panel, but for the mass ratio vs. the physical separation. The mass ratios have been computed for two different primary masses characteristic of our sample, using the top panel line and DUSTY models convolved with the *HST* filters for the mass-luminosity relation. The physical separations have been calculated assuming an average distance of 135 pc.

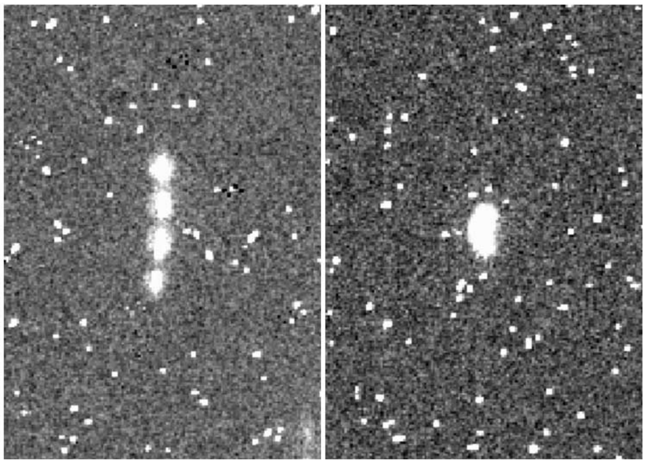

FIG. 2.—A problem in the FGS during the acquisition resulted in moved and useless exposures. *Left*: CFHT-Pl-23. *Right*: CFHT-Pl-24.

2.2. *Observations*

Observations were carried out during cycle 12 between 2003 July and 2004 August as part of the *HST* Snapshot SNAP-9831 program. Each object was observed in the F814W filter, which provides the best compromise between the efficiency, the sensitivity to our cold objects, and the signal-to-noise ratio (S/N). Only one band was obtained in order to maximize exposure times, minimize the visit times, and thus optimize schedulability.

Diffraction-limited imaging with ACS-HRC at 814 nm gives us a spatial resolution of 0$''$.085. With its 0$''$.027 pixel scale, the ACS-HRC thus provides the required critical sampling of the PSF, which was not the case for the WFPC2/PC camera. Using PSF fitting, we are thus able to resolve even closer companions than in the case of WFPC2. Integration times were 400 s, spread over four exposures in CR-SPLIT mode (Pavlovsky et al. 2003). Figure 1 shows that we are sensitive to companions 5.9 mag fainter than their primary (3 σ detection limit), corresponding to a lower limit on the mass ratio between 0.4 and 0.7 at separations greater than 0$''$.250, depending on the brightness of the primary. Considering the total field of view of the ACS camera ($26'' \times 29''$), we were sensitive to companions up to separation as high as $\sim$1700 AU.

A total of 17 objects among the 33 submitted have been observed, but in 2 cases a problem with the guidance sensor resulted in moved exposures, as shown in Figure 2. The corresponding images are useless. We thus obtained images for 15 targets, 2 of which were already known binaries.

2.3. *Data Analysis*

2.3.1. *Search for the Multiple Systems*

In order to look for multiple systems, we used the same method as described in Bouy et al. (2005). Briefly, it consists of a quantitative analysis of the relative intensity of the residuals after PSF subtraction. Any multiple system is expected to show higher residuals than an unresolved one. The technique and its limitations are fully described in the above-mentioned article. Figure 3 shows the result of this analysis. Two systems appear to have clearly higher residuals, indicating that they are very likely to be multiple. These two objects had already been resolved in a previous *HST* program (see Martín et al. 2003). Some objects at lower S/N also show slightly higher residuals (at about $\sim$1 σ), but a careful visual inspection of the images and of the PSF subtraction does not show any convincing evidence of multiplicity. As a sanity check, all images have been inspected visually.

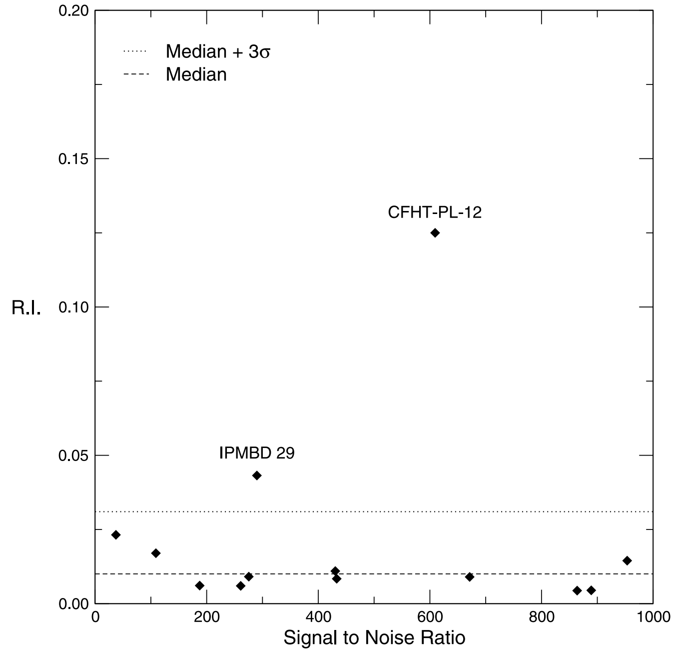

FIG. 3.—Relative intensity of the residuals after PSF subtraction as a function of the S/N. The two binary candidates show clearly higher residuals, above the median + 3 σ value.

2.3.2. *PSF Fitting*

The ACS-HRC data have been processed with the same PSF fitting program described in Bouy et al. (2003), adapted to ACS-HRC. Briefly, the program performs a dual-PSF fit of the binary, fitting both components at the same time. The relative astrometry and photometry are obtained when the residuals reach their minimum value. The method and its limitations are fully described in Bouy (2004) and Bouy et al. (2003).

3. RESULTS FOR THE INDIVIDUAL OBJECTS

We confirm two binaries previously discovered by Martín et al. (2003) and report no new binary in the angular separation 0$''$.045–0$''$.26 and apparent brightness range $18 < I_C < 22.8$.

Considering the relatively high proper motion of the Pleiades cluster ($\mu_\alpha \cos\delta = 19.15$ mas yr^{-1}, $\mu_\delta = -45.72$ mas yr^{-1}; Robichon et al. 1999) and the small relative motion of their respective components (see Tables 2 and 3), we conclude that CFHT-PL-12AB and IPMBD 29AB are common proper-motion pairs. Tables 2 and 3 show the astrometric measurements of the two objects. For both binaries the separation measured in 2003 is smaller than that measured in 2000. This is an effect of the eccentricity of the orbits and a selection bias due to the resolution limit of the WFPC2 survey.

3.1. *Cl* Melotte* 22 *CFHT-Pl* 12

Cl* Melotte 22 CFHT-Pl 12 is a binary with a separation of 0$''$.062 $\pm$ 0$''$.002 and a position angle (P.A.) of 266°.7 $\pm$ 1°.7 (2000 November 14), corresponding to a physical separation of 8.4 $\pm$ 0.3 AU at 135 pc. Correcting for a statistical factor of 1.26 as explained in Fischer & Marcy (1992), it leads to a semimajor axis of 10.5 $\pm$ 0.3 AU. Its proper motion and the presence

TABLE 2
Relative Astrometry and Photometry of Cl* Melotte 22 CFHT-PL 12

Date	Instrument	Separation (mas)	P.A. (deg)	ΔMag	Filter
2000 Nov 14...........	WFPC2	62 ± 3	266.7 ± 4.5	0.98 ± 0.15	F814W
2003 Nov 07...........	ACS	50 ± 3	251.4 ± 0.75	0.43 ± 0.15	F814W

Notes.—The difference of magnitude is different at the two epochs. They agree within 2 σ, but the WFPC2 value should be considered with more caution than the ACS value. The ACS image is indeed much better sampled (the pixel scale of ACS is twice that of WFPC2). We therefore consider the ACS value more accurate.

of Li absorption in its spectrum indicate that it is substellar and belongs to the Pleiades cluster (Stauffer et al. 1998; Moraux et al. 2001). Table 4 gives a summary of its astrometric and photometric properties. Using the NextGen models for the primary and the DUSTY models for the fainter (and therefore cooler) secondary and assuming an age of 120 Myr, we can estimate the masses of each component to be $M_A = 0.066 \pm 0.001\ M_\odot$ and $M_B = 0.052 \pm 0.002\ M_\odot$, corresponding to a mass ratio of $q = 0.79$ (see Fig. 4). According to Kepler's third law (Kepler 1609), the corresponding period is $\sim$99 ± 5 yr. The small relative motion of 15° in 3 yr corresponds to an orbital period of $\sim$70 yr, which is of the same order as the orbital period derived from the theoretical masses and the semimajor axis, but a more precise comparison between dynamical masses and theoretical masses requires more astrometric monitoring.

3.2. *Cl* Melotte* 22 *IPMBD* 29

Cl* Melotte 22 IPMBD 29 was confirmed as a Pleiades member via proper-motion measurements by Hambly et al. (1999). It was observed twice: the first time with WFPC2 (2000 September 18) and the second time with ACS (2003 December 13). Table 3 gives a summary of the astrometric and photometric properties measured at both epochs. Unfortunately, a satellite crossed the field of our ACS image exactly on the target (see Fig. 5). The flux of the satellite track is relatively low. Measuring the number of counts in an area of 11 pixels around the source and in another area centered on the satellite track away from the source, we can estimate that the flux of the satellite track corresponds to less than 5% of that of the source. The elongation and the duplicity are nevertheless real, since it appears clearly on the three individual exposures of the CR-SPLIT that have not been affected by the satellite track. It is moreover confirmed by the previous detection in the WFPC2 image 3 yr earlier, with consistent relative astrometry of the two components. The difference of magnitude is different at the two epochs. They agree within 3 σ, but the WFPC2 value should be considered with more caution than the ACS value. The ACS image is indeed much better sampled (the pixel scale of ACS is twice as good as that of WFPC2), and the separation is below the sampling limit of WFPC2, while it is above that of ACS. We therefore consider that the ACS value is more reliable than the WFPC2 one. Uncertainties on the relative photometry at such short separations should always be considered with caution, since we are much below the diffraction limit of *HST* at this wavelength. The difference between the measurements obtained with two different instruments on board *HST* illustrates the limitations of the PSF fitting.

Cl* Melotte 22 IPMBD 29 is a binary with a separation of 0.″050 ± 0.″003 and P.A. of 85.°6 ± 0.°75, corresponding to a physical separation of 6.75 ± 0.4 AU at 135 pc. Correcting for a statistical factor of 1.26 as explained in Fischer & Marcy (1992), it leads to a semimajor axis of 8.5 ± 0.5 AU. Using the NextGen models for the primary and the DUSTY models for the fainter secondary and assuming an age of 120 Myr, we can estimate the masses of each component to be $M_A = 0.056 \pm 0.002\ M_\odot$ and $M_B = 0.047 \pm 0.002\ M_\odot$, corresponding to a mass ratio of $q = 0.83$ (see Fig. 4). According to Kepler's third law, the corresponding period is $\sim$77 ± 9 yr. The small relative motion of 5° yr^{-1} corresponds to an orbital period of $\sim$75 yr, consistent with the period derived from Kepler's laws.

4. CONFIRMED PHOTOMETRIC BINARY CANDIDATES

From its position in the H-R diagram, Moraux et al. (2003) suspected CFHT-Pl-12 to be a brown dwarf binary. Similarly, from their photometric analysis, Pinfield et al. (2003) suspected this object to be multiple. Using our WFPC2 and ACS images, we resolve CFHT-Pl-12 and calculate a mass ratio consistent with the one they derive from the photometry.

It is interesting to note that the two resolved binaries IPMBD 25 and IPMBD 29, which have I_C and K photometric measurements available, fall just on the binary sequence of the K versus $(I_\mathrm{C} - K)$ CMD defined by Pinfield et al. (2003), as shown in Figure 6, although they were not included in their study. From this diagram we can predict a mass ratio of 0.6–0.9 for IPMBD 25, very similar to that of CFHT-Pl-12 since the two objects are very close in the diagram, and consistent with the mass ratio we derive from the relative photometry of the two components. Similarly, the CMD predicts a mass ratio of 0.7–1.0 for IPMBD 29,

TABLE 3
Relative Astrometry and Photometry of Cl* Melotte 22 IPMBD 29

Date	Instrument	Separation (mas)	P.A. (deg)	ΔMag	Filter
2000 Jul 18.............	WFPC2	58 ± 3	103 ± 4.5	1.25 ± 0.15[a]	F814W
2003 Dec 13...........	ACS	50 ± 3	85.6 ± 0.75	0.22 ± 0.30[a]	F814W

[a] The difference of magnitude is different at the two epochs. They agree within 3 σ, but the WFPC2 value should be considered with more caution than the ACS value. We consider the ACS image more reliable than the WFPC2 one.

TABLE 4
Properties of the Unresolved Photometric Binary Candidates

Object	$q_{\rm phot}$	I_C (mag)	ΔMag (mag)	Limit on Separation (AU)
CFHT-Pl-16.......	0.75–1.0	18.7	0.0–6.0	<5.4–34.0
CFHT-Pl-21.......	0.5–0.7	19.0	3.5–8.8	<13.0–34.0
CFHT-Pl-23.......	∼1	19.3	∼0.0	<5.4
CFHT-Pl-25.......	<0.75–1.0	19.7	>0.0–3.5	<5.4–13.0

Notes.—Parameter $q_{\rm phot}$ is the mass ratio reported by Pinfield et al. (2003) from their photometric study. I_C is from Moraux et al. (2003). Parameter ΔMag is obtained using I_C, $q_{\rm phot}$, and the DUSTY evolutionary models. The limit on the separation is then derived using Fig. 1.

in good agreement with the one we derive from the relative photometry of the two components.

5. UNRESOLVED PHOTOMETRIC BINARY CANDIDATES

From their positions in the H-R diagram, Moraux et al. (2003) suspected CFHT-Pl-16 to be a brown dwarf binary. It is not resolved in our ACS images. From their photometric study, Pinfield et al. (2003) also classify this object as binary and derive a mass ratio of about 0.75–1. According to the DUSTY models, this mass ratio corresponds to a difference of magnitude in the range 0.0 mag $\leq \Delta$mag $\leq$ 6 mag in the I band, thus just at/above the limit of sensitivity of our study. This indicates that, if multiple, this system should have a separation less than 5.4–34 AU depending on the flux ratio (see Fig. 1 and Table 5).

Due to its peculiar proper motion, Moraux et al. (2001) suggested that CFHT-Pl-15 might be a multiple system. Martín et al. (2000) found evidence for high residuals after PSF subtraction on their NICMOS image and suspected the presence of a companion at a separation less than 0.″22. Using ACS, we do not resolve any companion at separation larger than 0.″040. If multiple, this object should have a separation smaller than 5.4 AU

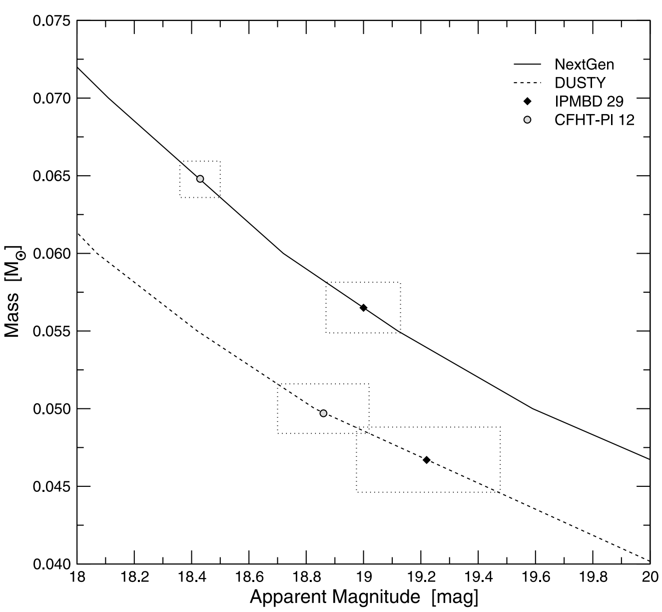

Fig. 4.—Mass vs. apparent magnitude diagram. The 120 Myr isochrones of the DUSTY and NextGen models are represented together with the measurements we obtained for CFHT-Pl 12 and IPMBD 29, assuming a distance of 135 pc. The propagated uncertainties on the magnitude translate into uncertainties on the mass. These uncertainties are indicated by boxes.

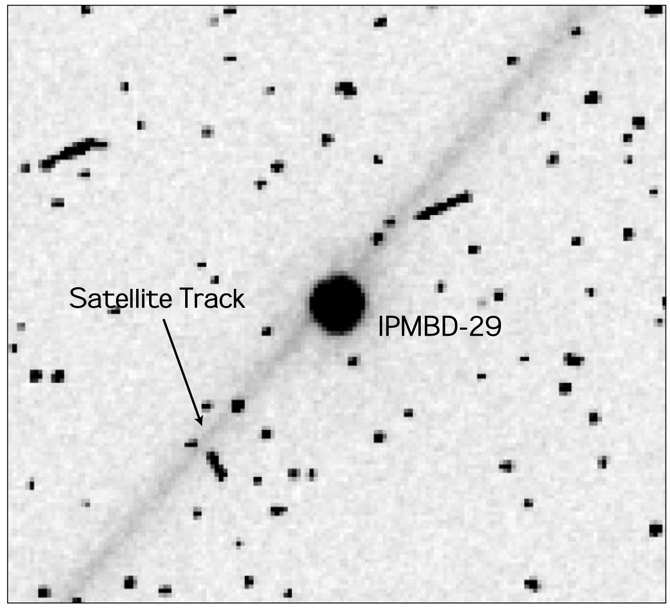

Fig. 5.—Satellite track on the ACS image of Cl* Melotte 22 IPMBD 29. Very unfortunately the path of a satellite crossed the field exactly on the position of the target. The corresponding flux is nevertheless relatively small but might explain part of the ΔMag difference reported in Table 3.

and/or a difference in magnitude larger than 5.9 mag in the F814W band.

From their photometric analysis, Pinfield et al. (2003) suspected CFHT-Pl-25, CFHT-Pl-23, and CFHT-Pl-21 to be binaries. Using our ACS images, we do not find any evidence of companions around these three objects. Pinfield et al. (2003) also predict mass ratios of $q \sim 1$ for CFHT-Pl-23, $q < 0.75$–1 for CFHT-Pl-25, and $0.5 < q < 0.7$ for CFHT-Pl-21, corresponding to differences of magnitude of, respectively, 0, >0–3, and 3.3–8.8 mag. Together with our ACS study, this constrains the separation of CFHT-Pl-23 to be smaller than 5.4 AU and that of CFHT-Pl-25 to be smaller than ∼5.4–13 AU, while that of CFHT-Pl-21 should be less than 13 AU (see Fig. 1). Spectroscopic studies would be currently the only way to test the possibility that these objects are binaries. Table 5 summarizes this analysis.

6. ANALYSIS: BINARY FREQUENCY

Our sample of bona fide brown dwarf Pleiades members includes 15 objects. Two of them were previously known binaries and should therefore be excluded from the statistics. This gives an observed visual binary frequency of <7.7% for separations greater than 5.4 AU and primary masses in the range 0.030–0.065 $M_\odot$. The binary frequency is defined here as the number of binaries divided by the total number of objects in the sample. Upper limit uncertainty is derived as explained in Burgasser et al. (2003).

Martín et al. (2003) noticed that the primaries of the only two binaries resolved with WFPC2 are brighter than $I = 18.5$ mag, suggesting breaking the statistical analysis into two bins of magnitudes. In the first bin, in the range 17.7 mag $< I <$ 18.5 mag corresponding to 0.055 $M_\odot < M <$ 0.065 $M_\odot$, they reported a binary frequency of 22^{+19}_{-8} %, with two binaries among a sample of nine objects. In the same magnitude bin and over the same separation range (>7–12 AU), we have six new objects and zero new binaries. The combination of the two results gives a total of two binaries over 15 objects, leading to a refined binary

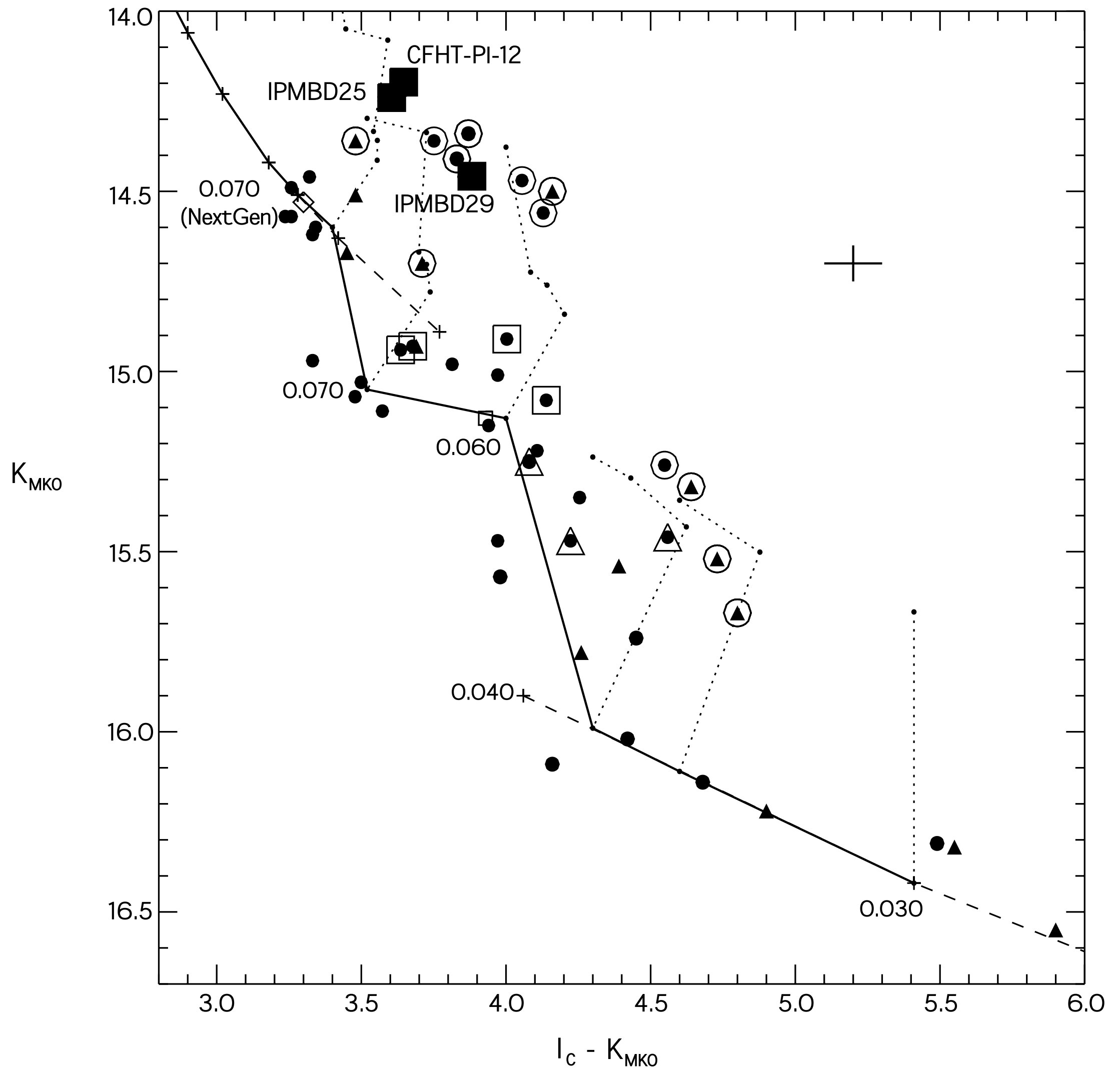

FIG. 6.—K vs. $I_C - K$ from Pinfield et al. (2003) plus the resolved binaries CFHT-Pl-12, IPMBD 25, and IPMBD 29 (*large filled squares*; values from Hambly et al. 1999). The symbols mean the same as in Pinfield et al. (2003): circled objects are *IK* binary candidates, and objects overplotted with an open square or triangle are, respectively, a *JK* or *JHK* binary candidate. Dashed lines are the NextGen and DUSTY models. Solid and dotted lines are the cluster single and binary star sequences, respectively. Typical uncertainties are indicated. Corresponding masses (in units of solar masses) from the DUSTY models are indicated. The 0.070 $M_\odot$ point around $K = 14.5$ is the NextGen model prediction for a 125 Myr isochrone. The two resolved binaries fall on the binary sequence.

TABLE 5

VISUAL BINARY FREQUENCY MEASURED IN SUCCESSIVE STUDIES

Reference	$N_{objects}$	$N_{binaries}$	Separation Range (AU)	Mass Range[a] ($M_\odot$)	Sensitivity[b] (q_{min})	Binary Frequency[c] (%)
Martín et al. (2000)	34	0	>24	>0.090	0.6	<3
Martín et al. (2003)	13	2	>7–12	0.040–0.065	0.45–0.9	15^{+15}_{-5}
Martín et al. (2003)	9	2	>7–12	0.055–0.065	0.45–0.9	22^{+19}_{-8}
ACS + Martín et al. (2003).......	15	2	>7–12	0.055–0.065	0.45–0.9	$13.3^{+13.7}_{-4.3}$
This ACS study	6	0	>5.4–7.0	0.055–0.065	0.9	<16.7
Martín et al. (2003)	6	0	>7–12	0.035–0.055	0.45–0.9	<16.7
This ACS study	5	0	>7–12	0.035–0.055	0.45–0.9	<20.0
ACS + Martín et al. (2003).......	11	0	>7–12	0.035–0.055	0.45–0.9	<9.1

[a] For the primary.
[b] Range of sensitivity to lower mass companions, expressed as the minimum mass ratio $q = M_2/M_1$ to which the observations were sensitive.
[c] Binary frequency defined as $N_{binaries}/N_{objects}$.

TABLE 6
Results for Pleiades Binary Systems

Name	Magnitude F814W A	Magnitude F814W B	Magnitude F875LP A	Magnitude F875LP B	Separation (arcsec)	Separation (AU)	P.A. (deg)	M_A ($M_\odot$)	q	P (yr)
CFHT-Pl 12	18.34 ± 0.11	19.32 ± 0.11	17.57 ± 0.11	18.48 ± 0.11	0.062 ± 0.002	10.5 ± 0.3	266.7 ± 1.7	0.066	0.79	99
IPMBD 25	17.93 ± 0.09	19.38 ± 0.09	17.22 ± 0.09	18.74 ± 0.09	0.094 ± 0.003	16.0 ± 0.5	340.5 ± 2.1	0.063	0.62	200
IPMBD 29	18.70 ± 0.15	19.95 ± 0.15	17.81 ± 0.11	19.06 ± 0.11	0.058 ± 0.004	8.6 ± 0.5	103.0 ± 4.5	0.056	0.83	77

Notes.—F875LP magnitudes are from Martín et al. (2003). Orbital periods are estimated for circular orbits using Kepler's third law and a distance of 135 pc and are given in years.

frequency of $13.3^{+13.7}_{-4.3}$ %. In the second magnitude bin, in the range $18.5 < I < 21.0$ corresponding to $0.035\ M_\odot < M < 0.055\ M_\odot$, Martín et al. (2003) reported zero binaries among a total of six objects. In the same magnitude bin and over the same separation range (>7–12 AU), we report five new objects and zero new binaries. The combination of the two results gives a total of zero binaries over 11 objects, leading to a refined limit on the visual binary frequency of $f_{\rm vis} < 9.1\%$.

In the new separation range that we were able to investigate with ACS, in the range 5.4–7.0 AU (for the brightest objects only, 17.7 mag $< I <$ 18.5 mag or $0.055\ M_\odot < M < 0.065\ M_\odot$; see Fig. 1), we report zero binaries among a total of six objects, leading to a limit on the visual binary frequency of $f_{\rm vis} < 16.7\%$, consistent with that reported in the separation range 7–12 AU for the same range of masses.

To summarize, we obtain the following binary frequencies: in the separation range >5.4–7.0 AU and in the range of mass $0.055\ M_\odot < M < 0.065\ M_\odot$, we report a visual binary frequency of $f_{\rm vis} = 0/6 < 16.7\%$. In the separation range >7–12 AU and in the mass range $0.055\ M_\odot < M < 0.065\ M_\odot$, we report a visual binary frequency of $f_{\rm vis} = 2/15 = 13.3^{+13.7}_{-4.3}$ %. In the separation range >7–12 AU and in the mass range $0.035\ M_\odot < M < 0.055\ M_\odot$, we report a visual binary frequency of $f_{\rm vis} = 0/11 < 9.1\%$. Table 6 gives an overview of these results.

The three binaries observed in the WFPC2 study all have separations less than 12 AU. The mass ratios are all larger than 0.62. PPL 15, the spectroscopic binary brown dwarf discovered by Basri & Martín (1999), has a semimajor axis of 0.03 AU and a mass ratio of 0.87. Although this sample is too small for allowing any meaningful statistical study, it is interesting to note that these results are consistent with those obtained in the field for slightly more massive objects, for which a cutoff in the separation range at 20–30 AU and a possible lack of small mass ratios[1] are observed ($q \leq 0.5$; Siegler et al. 2005; Bouy et al. 2003; Close et al. 2003; Gizis et al. 2003).

7. DISCUSSION

7.1. *Properties of Multiplicity and the Mass*

Both the present ACS study and Martín et al. (2003) WFPC2 study suggest that there might be an important change in the properties of multiplicity within the brown dwarf regime. Although statistically inconclusive because of the small number statistics and the relatively large uncertainties, the binary fractions in the two ranges of mass 0.035–0.055 $M_\odot$ ($f_{\rm vis} < 9.1\%$) and 0.055–0.065 $M_\odot$ ($f_{\rm vis} = 13.3^{+13.7}_{-4.3}$ %) seem to be notably different. This could mean that the brown dwarf binaries at lower masses are tighter, as already suggested by Close et al. (2003), and therefore were not resolved by any of the ACS or WFPC2 studies. The small separations reported for the three field binary T dwarfs currently known (all in the range 0–2.7 AU; Burgasser et al. 2003; McCaughrean et al. 2004) are consistent with this result.

7.2. *Properties of Multiplicity and the Environment*

Figure 7 shows that the observed binary frequency among the Pleiades brown dwarfs ($13.3^{+13.7}_{-4.3}$ %) for separation greater than 7–12 AU is similar to the values reported in the field (1) for slightly more massive objects (see Siegler et al. 2005; Bouy et al. 2003; Close et al. 2003; Gizis et al. 2003; 10%–15% of late M and L dwarfs) and (2) for field brown dwarfs, as reported by Burgasser et al. (2003; 9^{+15}_{-4} % for T5 to T8 field brown dwarfs).

This indicates that the statistical properties, and therefore the formation and evolution processes, of field and Pleiades binary brown dwarfs are probably similar. This would imply that the evolution processes of very low mass binaries do not depend much on the age after 120 Myr, as expected. The formation, the evolution, and, possibly, the disruption of binaries responsible for the low rate of binaries and the cutoff in the separation range would thus have to occur during the early stages of the cluster, when its density and the probability of gravitational encounters are higher. *N*-body simulations performed by Kroupa (1995a, 1995b) have shown that in dense stellar clusters, such as the Pleiades during its early stages, the binary fraction could drop from 100% to ~50% in less than 1 Myr. More recent hydrodynamical simulations undertaken by Delgado-Donate & Clarke (2005) led to similar conclusions, with a typical decay time for multiple systems of ~10 Myr, consistent with the preliminary conclusion we draw here.

In their numerical simulations of the dynamical interactions in stellar clusters, Sterzik & Durisen (2003) show that the different properties cited above (binary fraction and distribution of separation) can be nicely reproduced when considering a small-*N* cluster model ($N < 10$) where stars and brown dwarfs form from progenitor clumps. Choosing specific clump and stellar mass spectra, they were able to generate a cluster with an IMF consistent with that observed. Using Monte Carlo simulations, they could then study the small-*N* cluster decay dynamics and compute the properties of brown dwarfs and brown dwarf binaries. Their study shows that a simple gravitational point-mass dynamics, with weighting factors for the pairing probabilities as a function of the mass evaluated in the first of a two-step process, gives results consistent with the observations over the entire range of mass. In particular, they obtain a binary fraction for brown dwarfs of 8%–18%, consistent with the binary fraction we report here ($13.3^{+13.7}_{-4.3}$ %). They also model a distribution of separation in remarkable agreement with that reported for the field brown dwarfs and for the three Pleiades binaries of our study, with a peak around 4 AU and most (~85%) objects with separations less than 20 AU. On the other hand, they produce a flat

[1] The latter result might be due to observational biases.

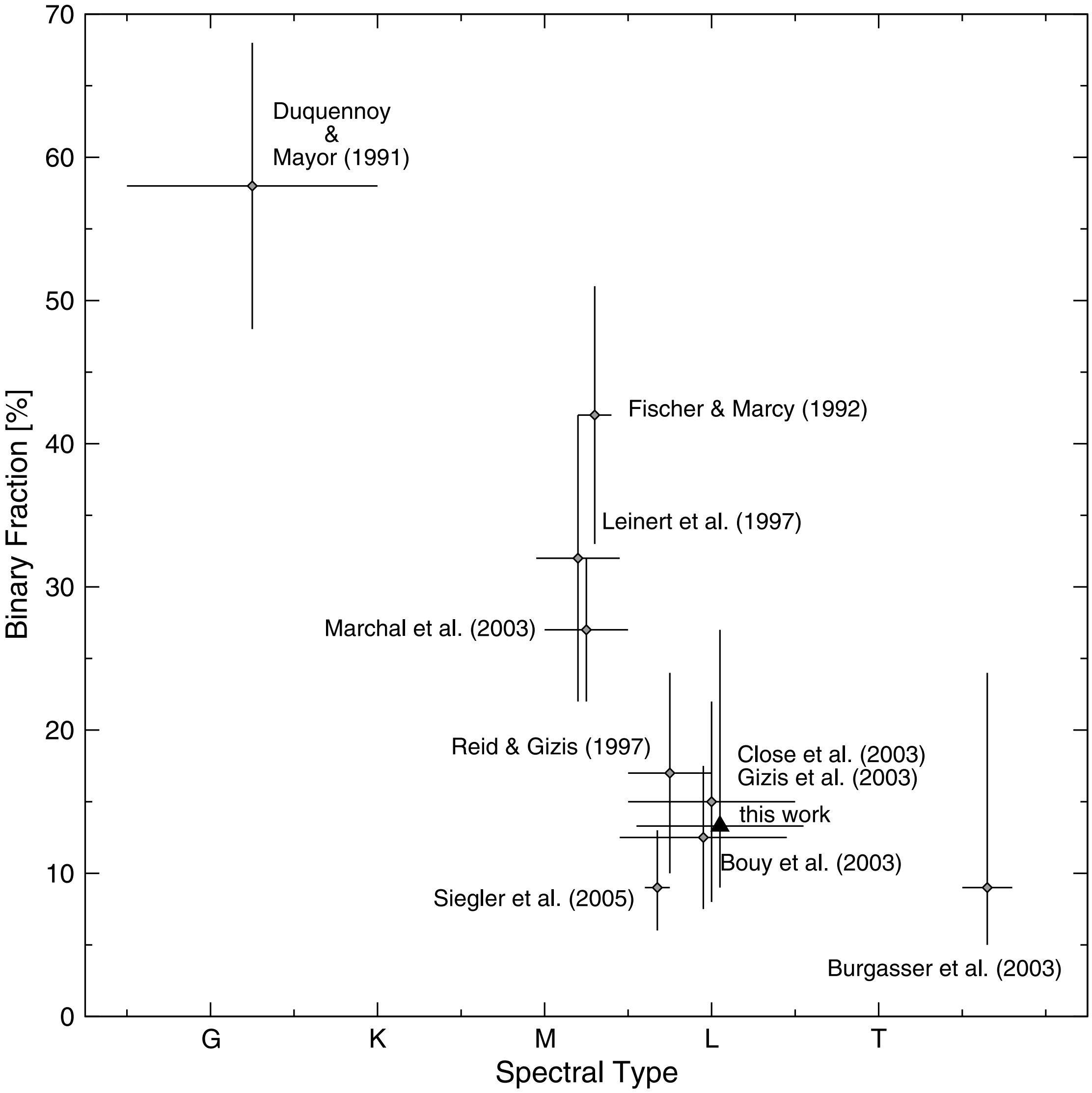

Fig. 7.—Binary frequency as a function of the spectral type in the field and in the Pleiades. The value reported in the present work is indicated by a black triangle, while other results for field objects are represented by gray diamonds. The values for spectral types later than M5 are upper limits and do not cover the same ranges of mass ratio and separation as the studies for earlier spectral types, and a direct comparison between the two is not correct. Some points have been slightly shifted (±0.5 spectral class) to make the figure more clear.

distribution of mass ratio in the range $0.2 < q < 1.0$, which is apparently not observed in the field and in the Pleiades. Siegler et al. (2005), Bouy et al. (2003), Burgasser et al. (2003), Close et al. (2003), and Gizis et al. (2003) showed that their observations in the field, although statistically incomplete, suggest that there is a preference for equal-mass systems. Halbwachs et al. (2003) showed also that the mass ratio distribution of spectroscopic binaries among field and Pleiades F–G dwarfs is not flat but bimodal. Finally, in a similar recent study performed on the decay of accreting[2] triple systems, Umbreit et al. (2005) show that they are also able to reproduce nicely the distribution of separation observed for field brown dwarfs, with a cutoff around 20 AU.

7.3. *Photometric Binary Frequency*

Our work allows the measurement of the binary frequency among brown dwarfs in the Pleiades open cluster for separations greater than 7 AU, masses in the range 0.055–0.065 $M_\odot$, and mass ratios in the range $0.45–0.9 < q < 1$, with $f_{\rm vb} = 13.3^{+13.7}_{-4.3}$ % (visual binaries). We compare this result to that obtained for slightly more massive objects by Pinfield et al. (2003) via the study of binary sequences in CMDs.

The results of Pinfield et al. (2003) do not agree with the observations we report here. From their study of *IK*, *JK*, and *JHK* CMDs, they measure a binary frequency of 50^{+11}_{-10} % for brown dwarfs in the Pleiades in the mass range 0.05–0.07 $M_\odot$ with mass ratio in the range $0.5 < q < 1.0$, thus comparable to the ranges covered by our study. This result is much higher than any of the two values reported in our WFPC2 and ACS studies. If correct, these results together would imply that most (∼85%) of the Pleiades brown dwarf binaries in the range 0.055–0.065 $M_\odot$ and $0.5 < q < 1.0$ have separations less than 7 AU. From their simulations, Maxted & Jeffries (2005) have recently shown that the spectroscopic binary fraction might be as high as 17%–30% for separations less than 2.6 AU. This value, together with the one we report for separations greater than 7 AU, adds up to 30%–43% for objects with separations less than 2.6 AU or greater than 7 AU (with a gap between the two). Over the whole separation range,

[2] Sterzik & Durisen (2003) simulations were purely dynamical, neglecting accretion, but considering small-*N* clusters rather than triple systems.

it probably adds up to a binary fraction close to that reported by Pinfield et al. (2003). On the other hand, a recent spectroscopic survey among Cha I brown dwarfs (Joergens 2005; no binary candidate out of a sample of 10 objects) shows that the spectroscopic binary fraction seems to be relatively low at young ages.

If confirmed by spectroscopic surveys, it would contrast with the results obtained for late-type G–K dwarfs in the Pleiades and for early M dwarfs in the field. Mermilliod et al. (1992) found indeed that only $\sim$30% of the G–K Pleiades binaries have separations smaller than 5 AU. Similarly, Delfosse et al. (2004) and Marchal et al. (2003) found that only $\sim$30% of the early M field binaries have separations smaller than 5 AU. These two values are much smaller than the above-mentioned 85%. Assuming that the properties of brown dwarf binaries in that range of masses are similar to that of field or Pleiades late-type stars is of course a strong assumption, although we showed in § 7.2 that the current results tend to confirm it.

The discrepancy between the photometric binary frequency and our visual binary frequency cannot be due to the companions we missed because of their small mass ratios, since the study of Pinfield et al. (2003) is sensitive to a similar range of mass ratio as our study. Moreover, Halbwachs et al. (2003) found that $\sim$60% of the F–G Pleiades spectroscopic binaries have a mass ratio larger than 0.5, and Delfosse et al. (2004) and Marchal et al. (2003) report that $\sim$75% of the field early M dwarfs have a mass ratio larger than 0.5. If once again we make the assumption that field and Pleiades late-type binaries have similar properties to Pleiades brown dwarf binaries, we should have missed 25%–40% of the multiple systems "only," leading to a corrected binary fraction of 15%–19%, still far from the 50% reported by Pinfield et al. (2003).

In addition to the spectroscopic binaries we miss, we suspect that the large discrepancy between the observations we report and the photometric binary frequency of Pinfield et al. (2003) could be due to a combination of the following effects:

1. Underestimations of the photometric uncertainties and of possible intrinsic photometric variability due, for example, to weather effects or magnetically driven surface features. Weather effects are known to be producing variability in the luminosity, up to 0.05 mag in *I* as observed by Bailer-Jones & Mundt (2001) and Martín et al. (2001), and magnetically driven surface feature modulation of up to 0.1 mag in *J* (for young Cha I brown dwarfs; Joergens et al. 2003).
2. Spread in the age of the objects. According to the DUSTY evolutionary models, a spread in the age between 80 and 125 Myr translates into differences of magnitude of up to 0.1 mag in *I*.
3. Contamination by field objects. Only 14 of 39 brown dwarfs of their sample have been confirmed as cluster members by proper motion and/or Li detection, while all the objects of our sample have been confirmed by one or both tests. The remaining 25 objects (64% of the sample) have been classified as brown dwarfs only on the basis of their photometric properties. From their photometric (I vs. $I - Z$) and proper-motion surveys, Moraux et al. (2001, 2003) estimated that the contamination by foreground M dwarfs in their sample of Pleiades brown dwarfs can be as high as 30%. From a three-color photometric study (*I*, *Z*, and *K*), they estimate the remaining contamination to be of the order of 10%. A similar nonnegligible level of contamination could be expected in the Pinfield et al. (2003) sample and explains some of the red objects identified as binaries. Since the contaminating objects would be foreground (i.e., closer) M dwarfs, most of them would indeed appear close to the Pleiades binary sequence. The binary CFHT-Pl-18 is an example of such contaminating objects (Martín et al. 2000).
4. Effect of rotation. Brown dwarfs are known to be fast rotators (Bailer-Jones 2004), and a correlation between the rotation and the luminosity, by up to 0.1 mag, could affect the colors of some objects, as measured by van Leeuwen & Alphenaar (1982). Deformation of the objects due to their fast rotation can produce variable light curves. A rapidly rotating brown dwarf seen pole-on may be reddened enough to perhaps be identified as a binary by the photometric technique.
5. Contamination by nonphysical pairs in unresolved blends.

The binary frequency we report here for brown dwarfs in the Pleiades is consistent with that observed for similar objects and similar separation and mass ratio ranges as in the field, as shown in Figure 7. It is comparable to that of slightly more massive field late M/early L dwarfs and close to the frequency observed for field T dwarfs, which have masses comparable to the brown dwarfs of our Pleiades sample.

Deep spectroscopic surveys on unbiased samples should provide answers to these questions and determine how many small mass ratio/small separation binaries we missed.

7.4. *Separations and Mass Ratios*

In his statistical analysis of the photometric binary properties in the Pleiades, Kähler (1999) shows that the distribution of mass ratios for late-type stars should be similar to that in the field. The distribution is expected to be bimodal, with a major peak at $q = 0.4$ and a minor one at $\sim$1. In a more recent observational study of unbiased samples of spectroscopic binaries of F to K dwarfs in the field and in the Pleiades cluster, Halbwachs et al. (2003) refine the results of Kähler (1999) in the range of periods shorter than 10 yr. They report a mass ratio distribution with a primary peak at $q = 1$, decreasing toward smaller mass ratios, with a broad secondary peak around $q = 0.4$. They observe no difference between the distributions of mass ratio of F–G and K stars and find that these are identical in the field and in the Pleiades.

If confirmed, the lack of multiple systems with small mass ratios would then imply a major difference between the distributions of mass ratios (and therefore the formation and evolution processes) of late-type stars and brown dwarfs. The current studies are inconclusive regarding that question since the observed lack might well be due to a combination of the following reasons:

1. The bias toward bright magnitudes in favor of binaries with large mass ratios (Opik 1924).
2. The current limit of sensitivity: $q > 0.4$ for separations larger than 30 AU and only $q > 0.7$ for separations larger than 10 AU (see Fig. 1).

Deep spectroscopic surveys on unbiased samples should allow us to answer these questions and see how many binaries of small mass ratios and small separations we missed.

8. CONCLUSIONS

Our new high angular resolution survey for brown dwarf binaries leads to a visual binary fraction in the Pleiades of $13.3^{+13.7}_{-4.3}$ % for separations larger than 7 AU, mass ratio in the range 0.45–0.9, and masses in the range 0.055–0.65 $M_{\odot}$. The preliminary results show that there might be a difference in the properties of multiplicity within the brown dwarf regime itself, with smaller separations at smaller masses. The binary frequency we report here is a lower limit of the overall binary frequency. It is much lower than the value reported by Pinfield et al. (2003) for photometric binaries over a slightly higher range of masses in the Pleiades, but a similar range of mass ratio. As suggested by the recent results of Maxted & Jeffries (2005), the difference could well be due to the spectroscopic binaries missed in our survey. While several surveys looking for visual binaries have already been successfully performed, spectroscopic surveys are only starting to provide results. The Maxted & Jeffries (2005) results, as well as the present study, show that there is a strong need for such systematic surveys looking for close companions, in the Pleiades but also in the field or in star-forming regions. The large difference between the results of the two above-mentioned independent and complementary studies and the remaining uncertainties on the overall binary frequency must remind us that any value of the multiplicity fraction must be very carefully used and always considered within its limits (separation range, mass ratio range, mass range) before a meaningful comparison with other binary frequencies or theoretical predictions can be done.

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