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H. Bouy

E. L. Martín
University of Central Florida

W. Brandner

J. Bouvier

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A POSSIBLE THIRD COMPONENT IN THE L DWARF BINARY SYSTEM DENIS-P J020529.0−115925 DISCOVERED WITH THE *HUBBLE SPACE TELESCOPE*

H. Bouy
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany;
and Laboratoire d'Astrophysique de l'Observatoire de Grenoble, 414 rue de la Piscine,
F-38400 Saint Martin d'Hère, France; hbouy@mpe.mpg.de

E. L. Martín
Instituto de Astrofísica de Canarias, E-38200 La Laguna, Spain; and Department of Physics, University of Central Florida,
P.O. Box 162385, Orlando, FL 32816-2385; ege@iac.es

W. Brandner
Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; brandner@mpia.de

and

J. Bouvier
Laboratoire d'Astrophysique, Observatoire de Grenoble, 414 rue de la Piscine, F-38400 Saint Martin d'Hère, France;
jerome.bouvier@obs.ujf-grenoble.fr
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ABSTRACT

We present results showing that the multiple system DENIS-P J020529.0−115925 is likely to be a triple system of very low mass stars and brown dwarfs. The secondary of this previously known binary system shows a clear elongation on six images obtained at six different epochs. Significant residuals remain after point-spread function (PSF) subtraction on these images, which is characteristic of multiplicity and indicates that the secondary is probably a double itself. Dual-PSF fitting shows that the shape of the secondary is consistent with that of a binary system. These measurements show that the probability that DENIS-P J020529.0−115925 is a triple system is very high. The photometric and spectroscopic properties of the system are consistent with the presence of three components, with spectral types L5, L8, and T0.

Key words: binaries: visual — stars: individual (DENIS-P J020529.0−115925) — stars: low-mass, brown dwarfs — techniques: high angular resolution

1. INTRODUCTION

Multiple systems are important tests for the models of formation and evolution of very low mass stars and brown dwarfs. The binary fraction reported recently by Bouy et al. (2003), Burgasser et al. (2003), Close et al. (2003), Gizis et al. (2003), and Martín et al. (2003) for very low mass stars and brown dwarfs (between 10% and ∼15%) cannot be well reproduced by the so-called "photoevaporation" and "embryo-ejection models," which predict a much lower binary frequency (<5%; see, e.g., Kroupa & Bouvier 2003 for a discussion on the different scenarios of formation mentioned here). On the other hand, the "starlike" model cannot explain the distribution of either the observed separation (all <20 AU, with a peak around 4 to ∼8 AU) or of the mass ratios (indicating a severe lack of multiple systems with large mass ratios). The overall process of formation of brown dwarfs is still not well understood. The existence itself of an old triple system made of brown dwarfs would put extremely important new constraints on these models since no such object has yet been observed.

In § 2, we present a summary of the known properties of DENIS-P J020529.0−115925. In § 3 we describe the observations. In § 4, we present the analysis of the data leading to the discovery of a possible third component, and in § 5 we discuss the triple system and its properties.

2. DENIS-P J020529.0−115925

DENIS-P J020529.0−115925 is a L5 field very low mass dwarf (Martín et al. 1999). From their photometry and spectroscopy, Geballe et al. (2002) classify the object as a L5.5 ± 2 dwarf. It is classified as L7 in the Kirkpatrick et al. (2000) scheme. We adopt a spectral class of L5. It was discovered by Delfosse et al. (1997) and first resolved as a binary by Koerner et al. (1999) using Keck images. This object has been well studied and observed, and it is reported in several surveys (DENIS; and the Two Micron All Sky Survey [2MASS], as 2MASSW J0205293−115930). Several authors (Delfosse et al. 1997; McLean et al. 2001; Burgasser et al. 2003) report methane absorption in their spectra, which implies a mass below the substellar limit and an effective temperature of less than 1800 K, as stated by Schweitzer et al. (2002). Tokunaga & Kobayashi (1999) report similar absorption features in their spectra but attribute it to H_2 rather than CH_4. Martín et al. (1997) reported a nondetection of lithium absorption from high-resolution optical spectra and inferred a lower limit on the mass of DENIS-P J020529.0−115925 A of $60 M_{\rm J}$. Its distance (19.76 ± 0.57 pc) and proper motion (437.8 ± 0.8 mas $\rm yr^{-1}$, with position angle [P.A.] = 82°.8 ± 0°.1) have been measured via trigonometric parallax (Dahn et al. 2002). Basri et al. (2000) also measured its rotational velocity (22 ± 5 km $\rm s^{-1}$), and from the Cs I and Rb I absorption they estimated its temperature to be $T_{\rm eff}$ = 1700 to ∼1800 K.

3. OBSERVATIONS

We observed DENIS-P J020529.0−115925 using the *Hubble Space Telescope* (*HST*) at six different epochs. The observations occurred between 2000 October and 2003 December

TABLE 1
OBSERVATION LOG

Filter	Exp. Time (s)	Date Obs. (UT)	Program
F814W..................	600	2000 Oct 18	GO8720
F675W..................	300	2000 Oct 28	GO8720
F814W..................	1700	2001 Jul 8	GO9157
F814W..................	1800	2002 Jan 21	GO9157
F814W..................	400	2002 Jul 14	GO9345
F606W..................	1600	2002 Jul 14	GO9345
F814W..................	400	2003 Jan 10	GO9345
F814W..................	800	2003 Dec 1	GO9968
F606W..................	1000	2003 Dec 1	GO9968

during *HST* Cycles 8, 9, 10, 11, and 12 (program GO8720; PI: W. Brandner, and programs GO9157, GO9345, and GO9968, PI: E. L. Martín). DENIS-P J020529.0−115925 was observed with the Planetary Camera (PC) of WFPC2 (Biretta et al. 2002) in the F675W and F814W filters (GO8720) and F606W and F814W filters (GO9157, GO9345, and GO9968). Table 1 gives a log of all the observations we used for this study. The target is very red, and the observations in the F814W filter were more sensitive than those in the F675W or F606W filters, despite the shorter exposure times and the lower quantum efficiency of WFPC2 at longer wavelengths. The possible third component does not appear clearly on the F675W and F606W images. For these reasons, the following analysis is based essentially on the F814W filter. The high angular resolution of the WFPC2-PC (0$''$.0455 pixel scale) allowed us to

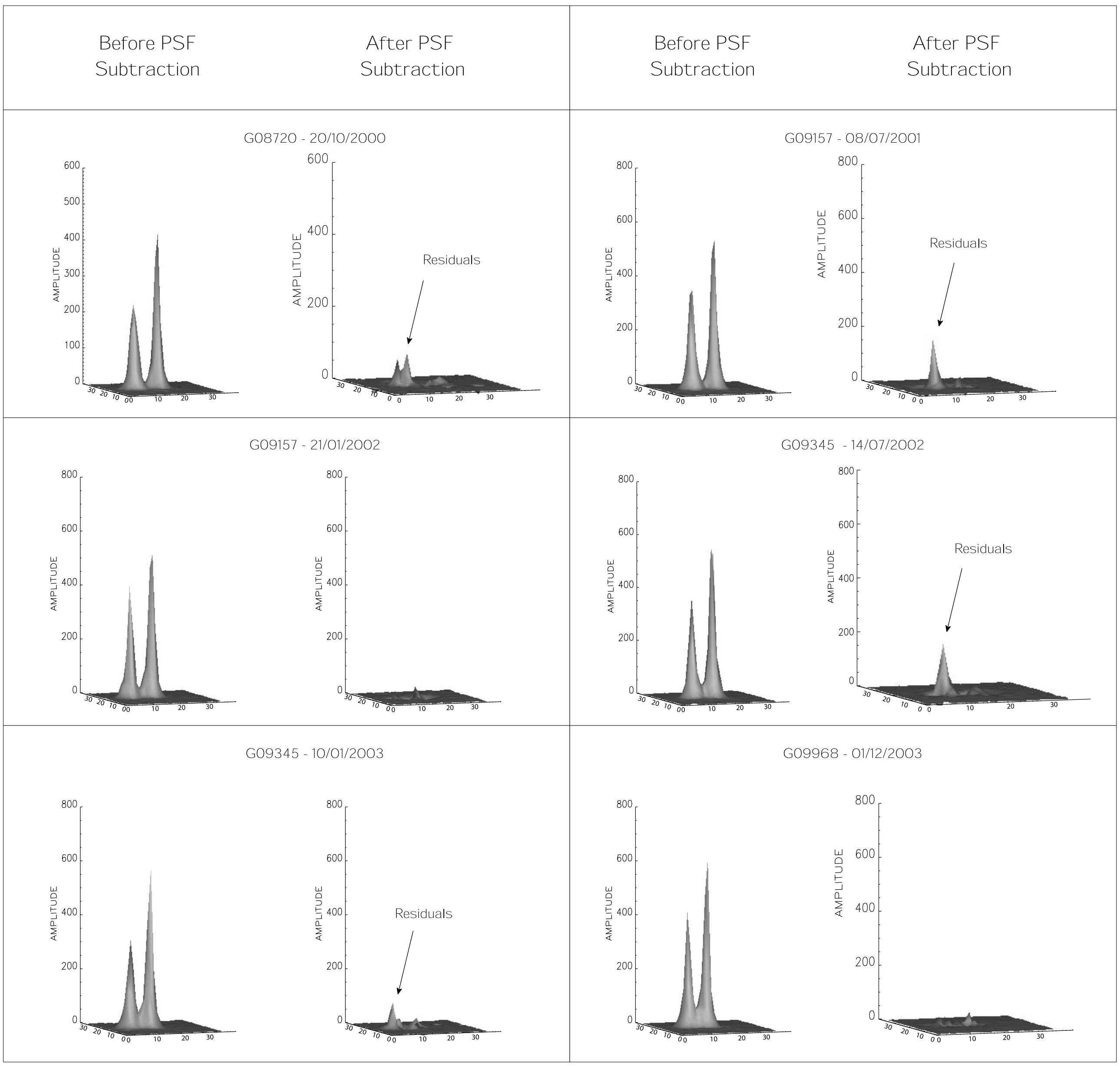

FIG. 1.—Results of the PSF subtraction at different epochs. This figure shows surface plots of the results of the PSF subtraction with one of the 10 reference PSFs used. The primary is well subtracted, whereas much stronger residuals remain for the secondary (clearly noticeable in four of the six epochs; *indicated by arrows*), indicating the presence of a third component. Similar results are obtained with the nine other reference PSF stars. The *X*- and *Y*-axes are in pixels, the *Z*-axis in counts.

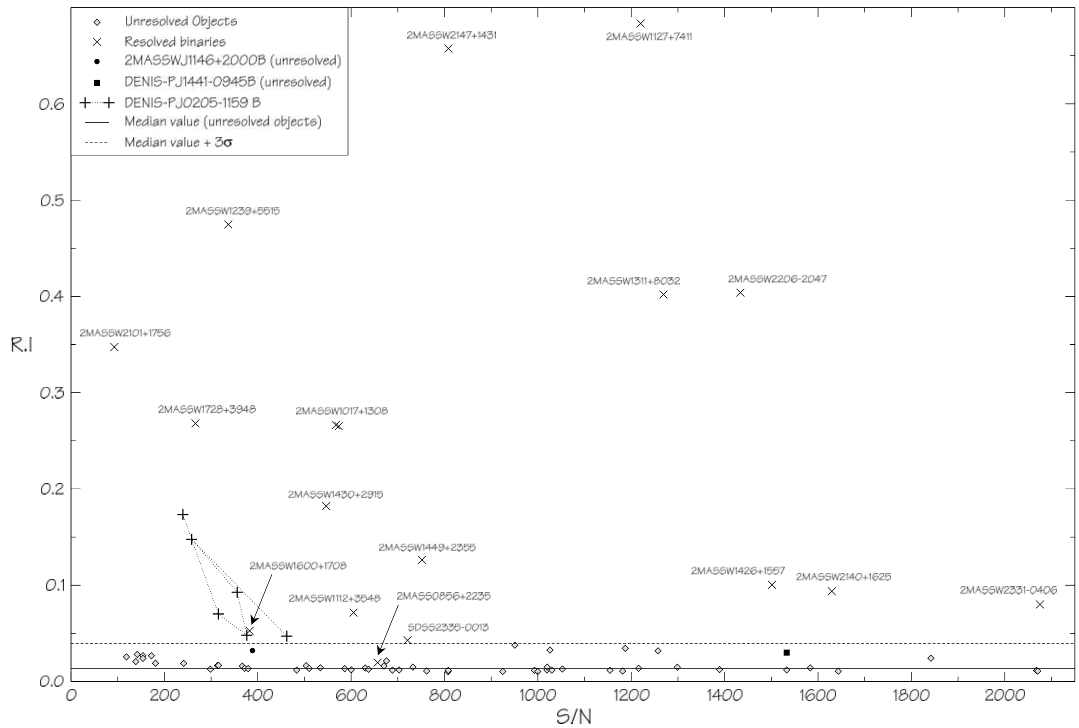

Fig. 2.—Residuals after PSF subtraction on *HST* WFPC2 images (F814W filter) of very low mass stars and brown dwarfs. This plot shows RI as a function of the S/N for the targets of program GO8581. The crosses represent the multiple systems. The plus signs represent the values obtained at six epochs for DENIS-P J020529.0−115925B. A filled square and a disk represent the results for two unresolved companions of known multiple systems, respectively 2MASSW J1146+2000B (program GO8146; PI: I. N. Reid) and DENIS-P J1441−0945B (program GO8720; PI: W. Brandner). The 3 σ above the median and the median values for the unresolved objects are represented. This figure shows that the intensity of the residuals after PSF subtraction appears to be a powerful indicator of multiplicity. DENIS-P J020529.0−115925B appears clearly different from the unresolved objects and from the unresolved companions of known multiple systems, while its residuals are comparable to that of known close multiple systems.

resolve easily the 0″3 secondary and to discover that it is elongated.

4. DATA ANALYSIS

We processed the data in two steps: (1) a point-spread function (PSF) subtraction on each component of the binary to look for residuals indicating the presence of a third companion and (2) a dual-PSF fitting of the secondary for confirmation.

4.1. *PSF Subtraction and Residuals*

Taking advantage of the extremely stable PSF of *HST* WFPC2, we performed a PSF subtraction on the six images of DENIS-P J020529.0−115925 using nine different unresolved objects from programs GO8720 (PI: W. Brandner; Bouy et al. 2003) and GO8581 (PI: I. N. Reid; Gizis et al. 2003) and one synthetic PSF obtained with Tiny Tim (Krist & Hook 2003) as reference PSF stars. Figure 1 shows that on four of the six images, the primary is extremely well subtracted, while strong residuals appear clearly after subtraction of the secondary, indicating the presence of a third component. The results with the nine other reference PSF stars are similar to those presented in Figure 1.

Using this technique, we tried to define a criterion that would allow us to determine quantitatively whether the secondary is a multiple system. We performed a detailed PSF analysis of all the WFPC2 images of programs GO8581 (PI: I. N. Reid; Gizis et al. 2003). This large sample has the advantage of being homogeneous (all targets were observed with the F814W filter of the WFPC2/PC), and all targets are very low mass stars and brown dwarfs with spectral properties (and therefore PSFs) similar to DENIS-P J020529.0−115925.

The relative intensity (RI) of the residuals, defined as the integrated intensity of the residuals after PSF subtraction divided by the integrated intensity of the object, as expressed in equation (1), appears to be a powerful criterion to identify binary candidates.

$$\mathrm{RI} = \frac{\sum_{i=1}^{n} F_R^2(i)}{\sum_{i=1}^{n} F_O^2(i)}, \tag{1}$$

where n is the number of pixels, $F_R(i)$ is the flux in pixel i after PSF subtraction, and $F_O(i)$ is the flux in pixel i before PSF subtraction.

Figure 2 shows that RI is very low and very stable for unresolved objects, while it is always more than $\sim$3 σ above the median value in the case of multiple systems. Using this technique we were able to find easily and automatically all the multiple systems present in the sample (see Bouy et al. 2003; Gizis et al. 2003), except one (2MASSW J0856479+223518). This latter multiple system is indeed a good example for illustrating the limitations of this technique. 2MASSW J0856479+223518 is a very close binary ($\delta = 0\farcs1$), with a relatively large magnitude difference (ΔMag $= 2.8$ mag; see Bouy et al. 2003). The relative intensity of the residuals after PSF subtraction of the primary, corresponding roughly to the ratio of the intensity of the secondary over that of the primary, is therefore on the order of only a few percent (ΔMag $= 2.8$ mag is equivalent to a flux ratio of $f_B/f_A \sim 0.07$). The relative intensity of the residuals after PSF subtraction is therefore a good method for finding multiple systems with moderate magnitude differences.

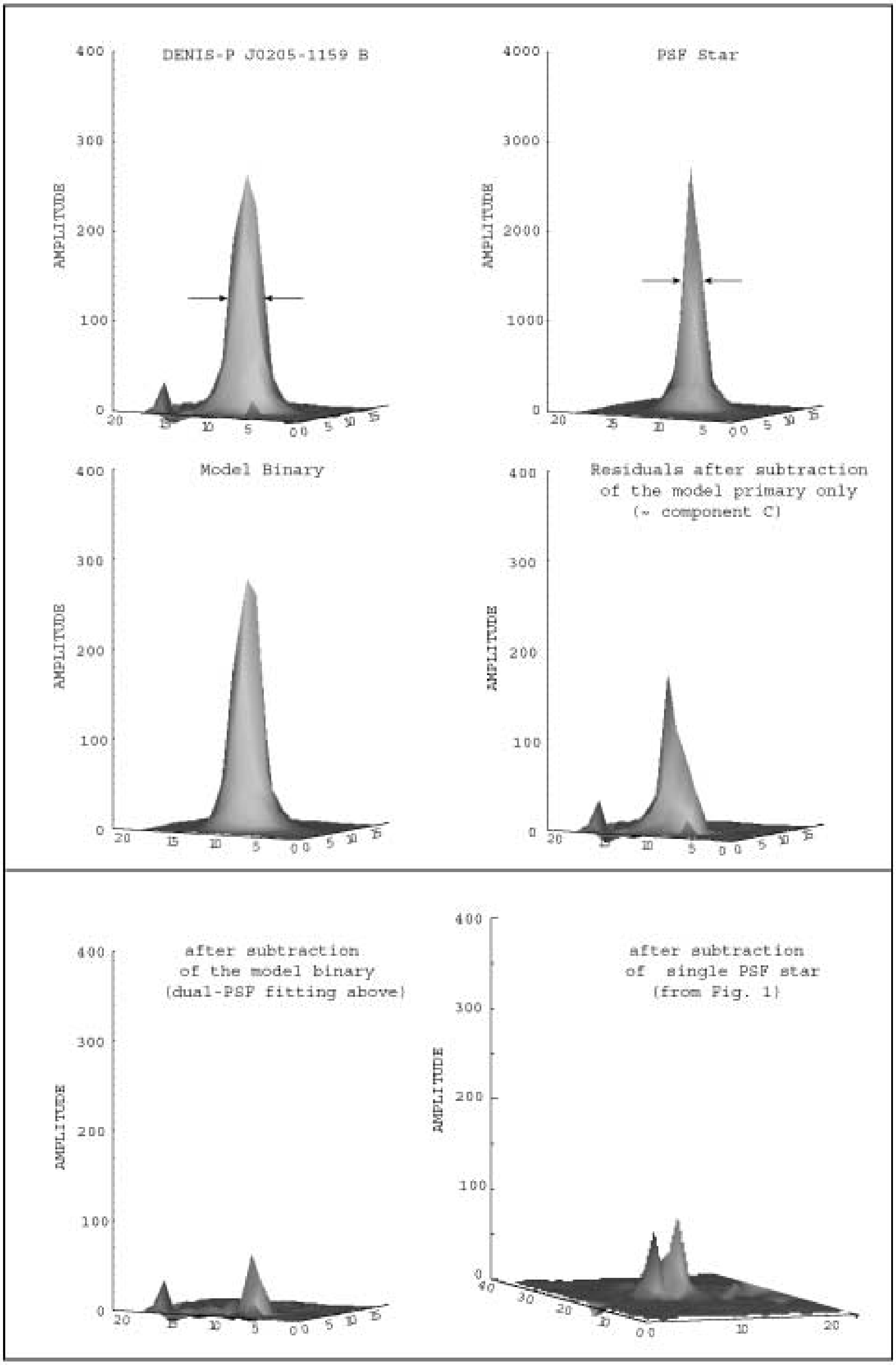

FIG. 3.—Results of the dual-PSF fitting on DENIS-P J020529.0−115925B for the GO8720 image. As shown with arrows, DENIS-P J020529.0−115925B has a FWHM much wider than the reference PSF star. The companion appears clearly after subtraction of the model primary. The residuals are small (*bottom left*), indicating that the quality of the fit is good. They are especially smaller than that obtained with a single PSF subtraction (*bottom right*). Similar results have been obtained with the nine other reference PSF stars, showing that the result of the fit is robust and reliable. The *X*- and *Y*-axes are in pixels, the *Z*-axis in counts.

TABLE 2

Flux Ratios and Magnitude Difference in the F814W Filter

Components	Flux Ratio	ΔMag
B/A	0.37	1.08
C/A	0.25	1.50
C/B	0.66	0.45

Notes.—Absolute Mag(A) = 17.3 mag. The measurements reported here have large uncertainties and should be considered with caution. The relative error from one image to the other is about 0.15 mag, but the real uncertainties can be higher. Measurements obtained from the GO8720 image.

Fortunately, this is the case with the possible third component of DENIS-P J020529.0−115925, as shown below.

Using this property, we compare the relative intensity of the residuals after PSF subtraction on the secondary of DENIS-P J020529.0−115925, using the same library of PSF stars. Figure 2 shows the results. The residuals at six different epochs are all higher than those of unresolved objects and unresolved companions of known binaries of the same sample, but they are very similar to those of other multiple systems. This figure shows clearly that DENIS-P J020529.0−115925B is itself very likely to be a binary system. Figure 2 also shows that even for the two images in which the residuals do not appear clearly by eye (see Fig. 1), the RI is slightly higher than in any unresolved object.

One should note that RI depends strongly on the signal-to-noise ratio (S/N). At low S/N, the value of RI must indeed increase because of the increased noise in the target. Figure 2 shows that all our images were obtained at sufficiently high S/N (always >100), so that RI provides a robust statistical test of multiplicity.

4.2. *PSF Fitting*

To confirm that these residuals are consistent with the presence of a third component, we performed a dual-PSF fitting on the secondary only, using a custom-made program described in Bouy et al. (2003). Briefly, and as presented in Figure 3, the PSF-fitting routine builds a model binary using each of the 10 different PSF stars mentioned above and then performs a nonlinear PSF fit of the observed image to determine the best-fit values for the three free parameters: separation, P.A., and flux ratio. The average of the 10 results gives the final values for the parameters. Figure 3 shows that the residuals after this dual fit are much better than after the single-PSF subtraction described in the previous section and in Figure 1. Moreover, the stability of the results for the 10 different PSF stars at each of the six epochs shows that the results are reliable and robust and that the third-component hypothesis is consistent with the shape of the elongated PSF and highly probable.

Table 2 gives the flux ratios among the three components of the multiple system estimated with this method, as well as the corresponding magnitude differences. According to the most recent DUSTY models of Chabrier et al. (2000), these magnitude differences indicate that the three components must have similar masses. A difference of 1.5 mag in the F814W filter corresponds indeed to a mass ratio of 75%, 85%, and 95% at, respectively, 0.5, 1.0, and 5 Gyr.

5. DISCUSSION

5.1. *Properties of the Triple System*

The present analysis of the high angular resolution images indicates that DENIS-P J020529.0−115925 is very likely to be

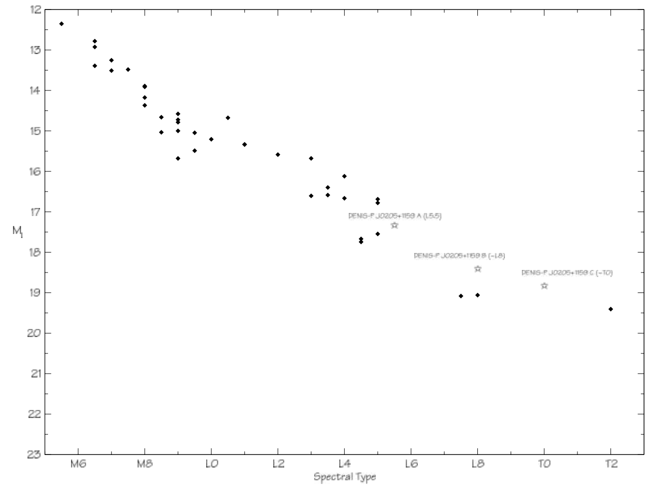

Fig. 4.—M_{I_C} vs. spectral-type relation. All measurements are from Dahn et al. (2002; see their Fig. 2, and Tables 1, 2, and 3), except for DENIS-P J020529.0−115925A, B, and C, evaluated as explained in the text. The absolute magnitudes of DENIS-P J020529.0−115925A, B, and C have been estimated using the magnitude differences reported in Table 2 and the DENIS I magnitude of the unresolved system.

a triple system. Figure 4 shows the M_{I_C} versus spectral type relation for all the objects reported by Dahn et al. (2002; see their Tables 1, 2, and 3). Assuming magnitude differences in I_C equal to those reported in Table 2 for the F814W filter (F814W filter is close to I_C; Biretta et al. 2002), and the DENIS I magnitude[1] of the unresolved objects, one can estimate the spectral types of the three components. DENIS-P J020529.0−115925 A is consistent with an L5.5 dwarf, in good agreement with the measurement reported by Martín et al. (1999) and Geballe et al. (2002), which shows that the primary would be dominating the optical spectrum. Components B and C would be consistent with ∼L8 and ∼T0 dwarfs, respectively, in the Geballe et al. (2002) classification scheme.

[1] The magnitude $I_{\rm DENIS}$ is very close to $I_{\rm Cousins}$ (Delfosse 1997).

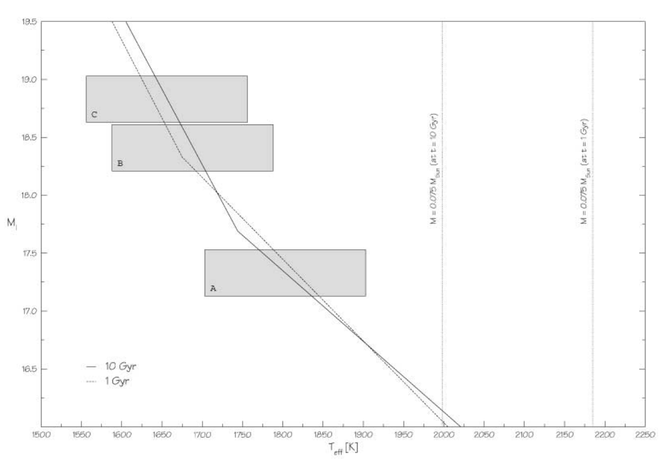

Fig. 5.—M_{I_C} vs. effective temperature. This figure shows the M_{I_C} as a function of the effective temperature, as given by the DUSTY models. Two isochrones (1 and 10 Gyr) are shown together with the corresponding limits for sustained hydrogen burning. The position of the three components is represented by gray boxes, assuming ±100 K uncertainty on the effective temperatures of the three components of DENIS-P J020529.0−115925 and including the uncertainty on the distance for the M_{I_C}. This figure shows that all three components must be substellar.

TABLE 3
Relative Astrometry of the Three Components

Date of Obs.	Separation (deg)	P.A. (deg)
Component B with respect to A:		
2003 Dec 1	0.287 ± 0.005	246 ± 1
2003 Oct 1	0.306 ± 0.005	249 ± 1
2002 Jul 14	0.330 ± 0.005	251 ± 1
2002 Jan 21	0.350 ± 0.005	253 ± 1
2001 Jul 8	0.370 ± 0.005	256 ± 1
2000 Oct 28	0.398 ± 0.005	259 ± 1
Component C with respect to B:		
2000 Oct 28	0.073 ± 0.005	86 ± 3
2001 Jul 8	0.050 ± 0.010	63 ± 5
2002 Jan 21[a]	...	...
2002 Jul 14	0.058 ± 0.010	109 ± 5
2003 Jan 10	0.063 ± 0.008	94 ± 5
2003 Dec 1[a]	...	...

Notes.—Component C is barely resolved. The measurements reported for component C and their uncertainties are close to the limit of resolution of *HST* WFPC2 and should be considered with caution.

[a] The secondary is elongated, and the residuals after PSF subtraction are strong, but the PSF fitting does not give good enough results for the astrometry.

Several authors report the detection of methane absorption in the infrared spectrum of DENIS-P J020529.0−115925 (Delfosse et al. 1997; McLean et al. 2001; Burgasser et al. 2003). Tokunaga & Kobayashi (1999) also observed this absorption feature in the spectrum, but they attribute it to H_2 rather than methane. Burgasser et al. (2002) note that this feature is weak and variable and conclude that it does not constitute a clear detection of methane. We note that, if real, this feature could be related to the presence of L8 and T0 companions, and its variability to some weather effects, as previously observed in other late L and T dwarfs by Enoch et al. (2003). Dahn et al. (2002) showed that the absolute *J*- and *K*-band magnitudes of early T dwarfs are similar to those of late L dwarfs, so that the contribution of B and C in the near-infrared can be larger than in the optical.

According to the DUSTY models (Chabrier et al. 2000) and assuming an age between 1 and 10 Gyr, Figure 5 shows that the absolute M_{I_C} magnitude of DENIS-P J020529.0−115925 A corresponds to an effective temperature of between 1700 and 1900 K, while B and C range between 1550 and 1800 K. These temperatures are consistent with the value reported by Basri et al. (2000) for the unresolved system (1700 to ∼1800 K) and show that all components appear to be clearly substellar. According to the DUSTY models, the stellar/substellar limit is indeed around 2000 K at 10 Gyr and 2180 K at 1 Gyr and is therefore warmer than any of the components of DENIS-P J020529.0−115925.

Finally, the proper motion of the object (∼438 mas yr^{-1}; Dahn et al. 2002) and the presence of these strong residuals at six different epochs spread over 3 yr allow us to rule out definitively the possibility of coincidence with some background object.

5.2. *Dynamical Properties*

The separation between the primary and the secondary changed from ∼0″.390 to 0″.270 between 2000 October and 2003 December, while the separation between the second and the third component is contained in $\sim 0''.075 \leq \delta_{BC} \leq 0''.055$ (see Table 3).

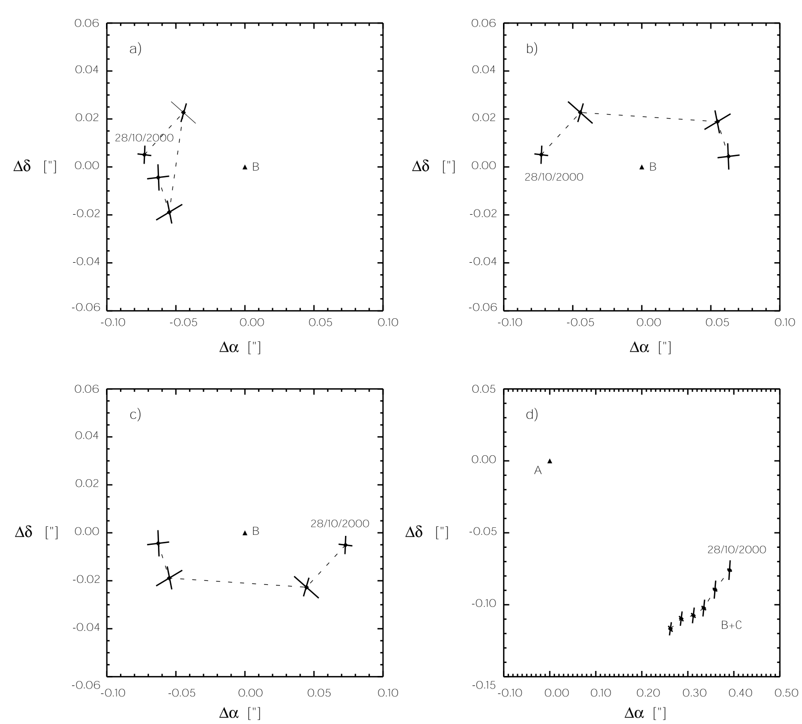

Fig. 6.—(*a*)–(*c*) Relative motion of C (*diamonds*) around B (*triangle*). (*d*) Relative motion of B+C (*diamonds*) around A (*triangle*). The 1 σ uncertainties are indicated, as well as the first epoch. Epochs are linked by a dotted line in chronological order. Because of the very short separation, there is an ambiguity of 180° in the P.A. of C around B. (*a*)–(*c*) Three possible configurations are (*a*) raw results of the PSF fitting; (*b*) epochs 1 and 2 from the raw results, but with 180° added to epochs 3 and 4; (*c*) epochs 3 and 4 from the raw results, but with 180° added to epochs 1 and 2. While case (*a*) cannot represent any Keplerian orbit, cases (*b*) and (*c*) could, with orbital periods comparable to the preliminary estimate we report here. Values are from Table 3.

As stated by Harrington (1968) and then Szebehely & Zare (1977) in their analytical study, triple systems with moderate eccentricity and equal-mass components are stable for ratios between the semimajor axes of the outer (a_2) and the inner orbits (a_1) greater than $a_2/a_1 \geq 3.2$. Assuming that the orbits of DENIS-P J020529.0−115925 components have moderate eccentricities and considering that the three components must have similar masses, as explained above, DENIS-P J020529.0−115925 would fit above the stability criterion, with a ratio of $3.6 \leq a_2/a_1 \leq 7.1$. The presence of a third component at the positions reported here is therefore dynamically possible.

The estimate of the separation corresponds to a semimajor axis of ∼1.2 AU (∼0.″075 at 19.7 pc). Corrected for a statistical factor of 1.26, as explained in Fischer & Marcy (1992), this leads to a "best-guess" semimajor axis of 1.9 AU. According to Kepler's third law (Kepler 1609) and assuming a total mass of ∼0.1 $M_{\odot}$, the corresponding period is ∼8 yr.

The dual-PSF fitting indicates that over the six epochs the separation between B and C is bounded between 0.″053 and 0.″074, while the P.A. is bounded between 63° and 109° (see Table 3). The raw results of the PSF-fitting give a motion of component C around B that cannot be orbital in nature (the P.A. does not vary monotonically, as shown in Fig. 6*a*), but at such very short separations the possible confusion between the primary and the secondary during the PSF-fitting yields to an ambiguity of ±180° in the measurements of the P.A. Figure 6 illustrates two cases for which two epochs have been switched by 180°, giving possibly Keplerian orbital motions. The corresponding period (about half of the orbit in about 3 yr) is in good agreement with that reported above (8 yr).

With large and hardly assessable uncertainties and with 180° ambiguity on the P.A., we regard the dual-PSF fitting as essentially a valuable sanity check showing that the elongation of the secondary is consistent with a binary. It gives a very rough and tentative estimate of the photometric and astrometric properties of the possible third component. New observations at higher angular resolution, using, for example, *HST* ACS, ground-based adaptive optics, or speckle imaging, should be performed to confirm the multiplicity and, if confirmed, to obtain more precise measurements of the motion of C around B.

6. CONCLUSIONS

We present here the results of high angular resolution observations with the *HST* WFPC2, which allow us to conclude that DENIS-P J020529.0−115925 is very likely a triple system of brown dwarfs. PSF subtraction on the secondary at six different epochs show unusual residuals in comparison with unresolved objects. Dual-PSF fitting shows that the shape of the secondary could be consistent with that of a binary and that the motion of the possible third component could be Keplerian in nature. The configuration is consistent with a dynamically stable multiple system.

Observations at higher angular resolution, using, for example, the *HST* ACS, ground-based adaptive optics, or speckle imaging, should make it possible to confirm whether DENIS-P J020529.0−115925 is a triple system or not.

This work is based on observations collected with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with programs GO8720, GO9157, GO9345, and GO9968. This publication makes use of data from the Deep Near Infrared Survey (DENIS). The DENIS project has been partly funded by the SCIENCE and the HCM plans of the European Commission under grants CT920791 and CT940627. It is supported by INSU, MEN, and CNRS in France, by the State of Baden-Württemberg in Germany, by DGICYT in Spain, by CNR in Italy, by FFwFBWF in Austria, by FAPESP in Brazil, by OTKA grants F-4239 and F-013990 in Hungary, and by the ESO C&EE grant A-04-046. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the National Science Foundation. This work made use of data from the Guide Star Catalogue II, which is a joint project of the STScI and the Osservatorio Astronomico di Torino. Facilities: *HST* (WFPC2).

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