A&A 428, 205–208 (2004)
DOI: 10.1051/0004-6361:20041912

Astronomy & Astrophysics

Research Note

Astrometric monitoring of the binary brown dwarf DENIS-P J1228.2-1547⋆

W. Brandner[1], E. L. Martín[2,3], H. Bouy[4], R. Köhler[1], X. Delfosse[5], G. Basri[6], and M. Andersen[1]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
e-mail: [brandner;koehler]@mpia.de; mortena@aip.de
[2] Instituto Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain
[3] University of Central Florida, Dept. of Physics, PO Box 162385, Orlando, FL 32816-2385, USA
e-mail: ege@iac.es
[4] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstr. 85748 Garching, Germany
e-mail: hbouy@mpe.mpg.de
[5] Laboratoire d'Astrophysique de Grenoble, Université Joseph Fourier, 38041 Grenoble Cedex 9, France
e-mail: delfosse@obs.ujf-grenoble.fr
[6] Astronomy Department, University of California, Berkeley, CA 94720, USA
e-mail: basri@soleil.berkeley.edu

Received 26 August 2004 / Accepted 21 September 2004

Abstract. We present astrometric monitoring data of the binary brown dwarf DENIS-P J1228.2-1547. The data have been obtained with the Hubble Space Telescope over a time span of 5.5 yr, and confirm that DENIS-P J1228.2-1547 is indeed a common proper motion, i.e., physical, binary. The data cover about 1/8th of the binary orbit, indicating an orbital period of ≈45 yr, and a semimajor axis of ≈6.4 AU. A plausible fit of the orbital parameters indicates that both components of the binary are substellar, which is in good agreement with previous mass estimates based on the presence of lithium in the combined spectra of both components. Since the next periastron passage of DENIS-P J1228.2-1547 is expected for the years 2030 to 2035, long-term astrometric monitoring is required to derive accurate mass estimates for the system and the individual components. The photometry obtained with HST/WFPC2 in the F814W band shows no indication for photometric variability with an amplitude larger than 0.05 mag over a time span of ≈1000 days.

Key words. astrometry – stars: binaries: visual – stars: low-mass, brown dwarfs – stars: fundamental parameters

1. Introduction

One of the ultimate goals of a theory of substellar objects is an accurate determination of the mass of an object based on spectroscopic characteristics and luminosity. Up to now, however, mass estimates for brown dwarfs are very much model dependent, in particular since theoretical models and evolutionary tracks have not yet been calibrated by observation. In particular, a brown dwarf with a given age and mass might have the same effective temperature and luminosity as a younger brown dwarf with a lower mass, or an older brown dwarf with a higher mass (e.g., Black 1980; Burrows et al. 1997). This degeneracy in the mass-luminosity relation for brown dwarfs makes it very hard to pin down physical properties of brown dwarfs, and to achieve the interaction between observation and theory, which is necessary in order to improve, adapt, and fine-tune models, and to gain a better understanding of the observations. A solution to by-pass these limitations is to search for binary brown dwarfs and to observe and compute their orbits. Once orbital elements and dynamical masses are known this can be used to feed-back theory.

In 1997, we started an extensive ground-based AO and HST program to search for substellar companions to post-T Tauri stars, ultra-cool dwarfs, and brown dwarfs themselves (Brandner et al. 1997, 2000; Martín et al. 2000; Close et al. 2002a,b; Neuhäuser et al. 2002; Potter et al. 2002; McCaughrean et al. 2004), which also led to the discovery of the first spatially resolved brown dwarf – brown dwarf binary DENIS-P J1228.2-1547 with HST/NICMOS (Martín et al. 1999a). No substellar companions could be found to

⋆ Based on observations made 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 NAS 5-26555. These observations are associated with programmes GO 7952, 8720, 9157, 9345, 9968.

Table 1. Observing log of imaging observations with the Hubble Space Telescope, and relative astrometry of the binary components as derived from the observations.

Date	MJD	Prog. ID GO	Instrument (filters)	sep [mas]	PA [deg]	Reference
2 Jun. 1998	50 966.3	7952	NIC1 (*F110M, F145M, F165M*)	275.0 ± 2.0	41.0 ± 0.2	Martín et al. (1999a)
24 Jun. 1998	50 988.6	7830	NIC3 (*F187N*)	–[a]	–[a]	Martín et al. (1999a)
4 Mar. 2001	51 972.6	8720	WFPC2 (*F675W, F814W*)	246.0 ± 20.0[b]	23.0 ± 2.0[b]	Bouy et al. (2003)
16 Jun. 2001	52 076.4	9157	WFPC2 (*F606W, F814W*)	255.4 ± 2.8	18.3 ± 0.3	Bouy et al. (2003)
3 Jan. 2002	52 277.8	9157	WFPC2 (*F606W, F814W*)	252.1 ± 2.8	13.7 ± 0.3	This paper
25 Apr. 2002	52 389.5	9157	STIS/CCD (*MIRVIS*)	250.0 ± 6.6	11.4 ± 0.8	This paper
8/9 Jun. 2002	52 433.9	9345	WFPC2 (*F606W, F814W*)	247.6 ± 2.8	9.8 ± 0.3	This paper
30 Dec. 2002	52 638.7	9345	WFPC2 (*F606W, F814W*)	243.6 ± 2.8	5.7 ± 0.3	This paper
29 Dec. 2003	53 002.7	9968	WFPC2 (*F606W, F814W*)	239.2 ± 2.8	356.7 ± 0.3	This paper

[a] NIC3 pixel scale of ≈200 mas/pixel is too coarse to derive meaningful relative astrometric measurements of the binary components.
[b] The binary was not centered on the detector, but located close to the bordering region between the PC-CCD and one of the WF-CCDs (edge of imaging pyramid), which resulted in larger uncertainties in the relative astrometry.

post-T Tauri stars at separations larger than 50 AU, and only two binary brown dwarfs in the Pleiades with separations larger than 7 AU were discovered (Martín et al. 2003; Bouy et al. 2004b). The search for companions to free-floating ultra-cool dwarfs and brown dwarfs in the solar neighbourhood, however, turned out to be rather successful (Bouy et al. 2003, and references therein).

DENIS-P J1228.2-1547 was only the second free-floating brown dwarf to be discovered in the solar neighbourhood (Deflosse et al. 1997; Martín et al. 1997; Tinney et al. 1997). The unresolved binary is of spectral type L5 to L6 (Martín et al. 1999b; Kirkpatrick et al. 1999; Geballe et al. 2001), exhibits high lithium abundance (Martín et al. 1997; Tinney et al. 1997), and has an absolute parallax $\varpi = 49.4 \pm 1.9$ mas, corresponding to a distance of 20.24 ± 0.08 pc (Dahn et al. 2002).

Based on observations with the Hubble Space Telescope, using NICMOS camera NIC1, Martín et al. (1999a) resolved DENIS-P J1228.2-1547 into two components separated by 275 mas and of almost equal brightness. The successful detection of the first spatially resolved binary brown dwarf marked the beginning of a multi-epoch monitoring of its orbital motion, with the aim to ultimately determine the orbital parameters and derive a dynamical mass estimate for the binary and its individual components.

In the present *research note*, we summarize the results of the first 5.5 years of astrometric monitoring of the orbital motion of the DENIS-P J1228.2-1547 binary.

2. Observations and data analysis

DENIS-P J1228.2-1547 was observed with HST/NICMOS camera 1 in June 1998 as part of a search for companions to nearby free-floating brown dwarfs. The discovery of the binary companion and its properties as derived from the NICMOS observations are presented in Martín et al. (1999a). After the discovery, we initiated follow-up observations, first to confirm that the two components form indeed a physical binary, and subsequently to monitor the orbital motion. Since NICMOS depleted its cryogenic supply in January 1999, all astrometric follow-up observations were carried out with WFPC2. Follow-up observations were obtained every 6 to 12 months with the aim to derive accurate parallax and proper motion measurements as well. Typically one or more 400 s exposures in *F814W* with DENIS-P J1228.2-1547 centered on the PC-CCD were obtained, supplemented by observations in *F606W* with DENIS-P J1228.2-1547 centered on one of the WF-CCDs. In addition, acquisition images for spectroscopic observations with NIC3 and STIS were obtained and analyzed as well (see Table 1).

Table 2. Brightness ratios Q and component magnitudes m_A and m_B.

Filter	Q	m_A [mag]	m_B [mag]
F814W	0.92 ± 0.04	18.15 ± 0.03	18.24 ± 0.03
F110M	0.83 ± 0.02	15.69 ± 0.03	15.89 ± 0.03
F145M	0.86 ± 0.02	14.96 ± 0.03	15.12 ± 0.03
F165M	0.87 ± 0.02	13.98 ± 0.03	14.13 ± 0.03

The subsequent data analysis was based on pipeline reduced frames as provided by the HST archive. Accurate positions and brightness ratios of the components were then derived by means of simultaneous PSF fitting, using the IDL procedure described and characterized in Bouy et al. (2003), and a set of observed PSF reference stars. The observations in *F606W* were obtained with the aim to derive absolute astrometric measurements. Here DENIS-P J1228.2-1547 was imaged on the one of the WF-CCDs, which have a coarser pixel sampling than the PC-CCD. Hence no relative astrometric or photometric measurements for the binary components were obtained in *F606W*. The relative astrometric measurements are summarized in Table 1, and the photometric measurements in Table 2.

A time series, depicting the *F814W*-band brightness variations of DENIS-P J1228.2-1547 over a time span of ≈1000 days is shown in Fig. 1. The photometric uncertainties are derived from the intrinsic scatter of the

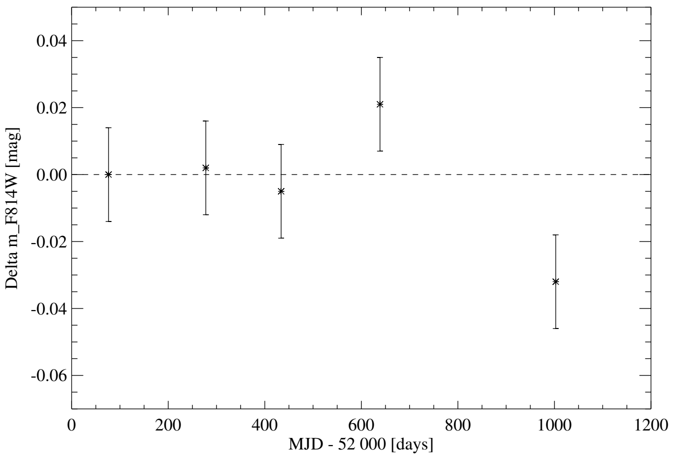

Fig. 1. Test for photometric variability of DENIS-P J1228.2-1547 over a time span of ≈1000 days. Within the measurement uncertainties, no significant variations in brightness are observed.

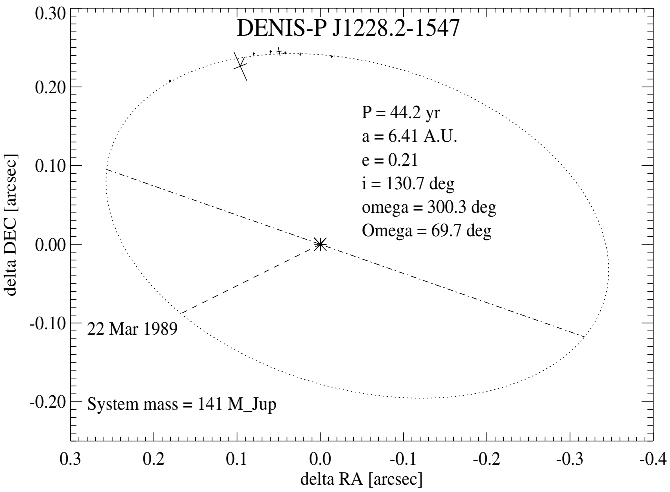

Fig. 2. The crosses and the star indicate the relative positions of the two binary components in the time span June 1998 to December 2003. The size of each cross corresponds to the measurement uncertainties. Overplotted is a possible orbital solution (dotted) for the astrometric data. The dash-dotted line is the line of nodes and the dashed line indicates the location of periastron. Fits omitting any one of the eight measurements indicate that the orbit depicted is only one possible solution in approximate agreement with the observations, but most likely not the final orbit.

four consecutive observations of DENIS-P J1228.2-1547 in *F814W* on Jun. 16, 2001. In general, the photometric accuracy is limited by faint cosmic ray events, and the lack of bright comparison stars within the PC field of view. As is evident from Fig. 1, within the measurement uncertainties DENIS-P J1228.2-1547 remains constant in brightness, i.e. there is no strong evidence for photometric variability with an amplitude of 0.05 mag or larger.

3. Discussion

The proper motion of DENIS-P J1228.2-1547 is of the order of $\mu \approx 260 \pm 40$ mas/yr (Scholz & Meusinger 2002; Dahn et al. 2002), i.e. of the same order as the separation between both binary components. The small changes in binary separation and position angle over a time span of 5.5 yr hence confirm that DENIS-P J1228.2-1547 is indeed a common proper motion pair (i.e. a physical binary).

Between June 1998 and December 2003, the position angle changed by about 45°. Since only 1/8th of the orbit has been covered thus far, a firm solution for the orbital parameters cannot be derived, yet. In the following, we therefore refrain from quoting (formal) uncertainties for the orbital parameters.

Figure 2 depicts one possible set of orbital parameters in approximate agreement with the multi-epoch astrometric observations obtained thus far. Fits omitting any one of the eight measurements indicate that the orbit depicted in Fig. 2 is only one possible solution in approximate agreement with the observations, but most likely not the final orbit. The fit is based on a three-dimensional grid search similar to the method described in Hartkopf et al. (1989). The possible orbit has an eccentricity of 0.21, and is inclined by ≈131°. The semi-major axis is 6.4 AU, and the orbital period is 44.2 yr, corresponding to a system mass of $\approx 141\ M_{\rm Jup}$. According to this fit, DENIS-P J1228.2-1547 passed periastron in 1989, hence we will have to wait till the years 2030 to 2035 for its next periastron passage. Long-term astrometric monitoring of the orbital motion of DENIS-P J1228.2-1547 over at least the next 20 to 25 yr is required, before a precise, dynamical estimate for the system mass (and the individual component masses) can be derived.

The photometric measurements summarized in Table 2 indicate that both components of the binary have about the same brightness. Based on the presence of lithium and the non-detection of Hα emission, Martín et al. (1997) and Tinney et al. (1997) derive an age in the range 100 Myr to 1 Gyr for DENIS-P J1228.2-1547. Since lower mass brown dwarfs cool (and hence dim) faster than higher mass brown dwarfs (e.g., Burrows et al. 1997), this in turn indicates that the mass ratio of the binary components must be close to unity. We note that the total system mass as derived from the preliminary orbit for DENIS-P J1228.2-1547, and a mass ratio close to unity indicates that both components are brown dwarfs. This is consistent with the mass estimate derived by Martín et al. (1997) based on the presence lithium, even though the lithium test indicates an even lower primary and secondary mass of less than 0.062 $M_\odot$ each.

4. Comparison to other results and conclusions

Periodic and non-periodic *I*-band brightness variations on time scales of several hours, attributed to clouds, and with an amplitude of 0.02 to 0.08 mag have been observed in a number of L dwarfs (e.g., Bailer-Jones & Mundt 2001; Koen 2003). For DENIS-P J1228.2-1547, individual integrations are too short (typically 400 s), and the sampling of the observations is too sparse (one observation every 6 months) to detect any periodic signal. The lack of bright local photometric reference stars on the PC frame, and the fact that DENIS-P J1228.2-1547 is composed of two equal brightness binary components further aggravate the detection of photometric variability in the integrated light. A dedicate photometric monitoring programme running for several consecutive HST orbits would be required to search for variabiltiy in either of the two binary components.

While the astrometric observations of DENIS-P J1228.2-1547 cover the longest epoch difference of any brown dwarf binary, robust orbital solutions for a couple of shorter period brown dwarf binaries have been derived in the meantime. Bouy et al. (2004a) recently derived a dynamical system mass of 153 $M_{\rm Jup}$ for the early L dwarf binary 2MASSW J0746425+2000321 by covering roughly 60% of its 10.5 yr orbit, including the periastron passage. While the primary of 2MASSW J0746425+2000321 is a very-low mass star, its secondary seems to be clearly substellar. Zapatero Osorio et al. (2004) refined the dynamical mass estimates for GJ 569 Bab, a young late-M brown dwarf binary with a system mass of 131 $M_{\rm Jup}$, and in orbit around the main sequence star GJ 569 A. Both Bouy et al. (2004a) and Zapatero Osorio et al. (2004) report good agreement between observations and theoretical evolutionary isochrones.

On the other hand, Close et al. (2004) derived a dynamical mass estimate of $\approx$87 $M_{\rm Jup}$ for a very-low mass stellar companion (spectral type M 8) to the young, nearby star AB Dor, and report that this companion appears to be sub-luminous by almost a factor of two compared to theoretical evolutionary tracks.

Hence further dynamical mass estimates are still required in order to calibrate and validate theoretical evolutionary tracks and isochrones. DENIS-P J1228.2-1547 with a system mass of 120 to 140 $M_{\rm Jup}$ and mid-L spectral type continues to be of interest as it is of later spectral type and also as it seems to be of even lower mass than the objects for which dynamical estimates have been derived thus far.

Acknowledgements. Support was provided by NASA through grants from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555, and by the Deutsches Zentrum für Luft- und Raumfahrt (DLR), Förderkennzeichen 50 OR 0401. We would like to thank the referee for the valuable comments, and the fast turn-around times.

References

Bailer-Jones, C. A. L., & Mundt, R. 2001, A&A, 367, 218
Black, D. C. 1980, Icarus, 43, 293
Bouy, H., Brandner, W., Martín, E. L., et al. 2003, AJ, 126, 1526
Bouy, H., Duchêne, G., Köhler, R., et al. 2004a, A&A, 423, 341
Bouy, H. et al. 2004b, in preparation
Brandner, W., Alcalá, J. M., Frink, S., & Kinkel, M. 1997, ESO – The Messenger, 89, 37
Brandner, W., Zinnecker, H., Alcalá, J. M., et al. 2000, AJ, 120, 950
Burrows, A., Marley, M., Hubbard, W. B., et al. 1997, ApJ, 491, 856
Close, L. M., Potter, D., Brandner, W., et al. 2002a, ApJ, 566, 1095
Close, L. M., Siegler, N., Potter, D., et al. 2002b, ApJ, 567, L53
Close, L. M., Lenzen, R., Guirado, J. C., et al. 2004, Nature, submitted
Dahn, C. C., Harris, H. C., Vrba, F. J., et al. 2002, AJ, 124, 1170
Delfosse, X., Tinney, C. G., Forveille, T., et al. 1997, A&A, 327, L25
Geballe, T. R., Knapp, G. R., Leggett, S. K., et al. 2001, ApJ, 564, 466
Hartkopf, W. I., McAlister, H. A., & Franz, O. G. 1989, AJ, 98, 1014
Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 1999, ApJ, 519, 802
Koen, C. 2003, MNRAS, 346, 473
Martín, E. L., Basri, G., Delfosse, X., & Forveille, T. 1997, A&A, 327, L29
Martín, E. L., Brandner, W., & Basri, G. 1999a, Science, 283, 1718
Martín, E. L., Delfosse, X., Basri, G., et al. 1999b, AJ, 118, 2466
Martín, E. L., Brandner, W., Bouvier, J., et al. 2000, ApJ, 543, 299
Martín, E. L., Barrado y Navascués, D., Baraffe, I., et al. 2003, ApJ, 594, 525
McCaughrean, M., Close, L. M., Scholz, R.-D., et al. 2004, A&A, 413, 1029
Neuhäuser, R., Brandner, W., Alves, J., et al. 2002, A&A, 384, 999
Potter, D., Martín, E. L., Cushing, M. C., et al. 2002, ApJ, 567, L133
Scholz, R.-D., & Meusinger, H. 2002, MNRAS, 336, L49
Tinney, C. G., Delfosse, X., & Forveille, T. 1997, ApJ, 490, L95
Zapatero Osorio, M. R., Lane, B. L., Pavlenko, Y., et al. 2004, ApJ, in press [arXiv:astro-ph/0407334]