DISCOVERY OF A 0.15 BINARY BROWN DWARF, 2MASS J1426316+155701, WITH GEMINI/HOKUPA’A
ADAPTIVE OPTICS

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ABSTRACT

Use of the highly sensitive Hokupa’a curvature wave front sensor has allowed for the first time direct adaptive optics (AO) guiding on brown dwarfs and very low mass stars (spectral type M7–L2). An initial survey of nine such objects discovered one 0.15 binary (2MASS J1426316+155701). The companion is about half as bright as the primary (ΔK = 0.61 ± 0.05, ΔH = 0.70 ± 0.05) and has even redder colors, H − K = 0.59 ± 0.14, than the primary. The blended spectrum of the binary has been previously determined to be M9.0. We modeled a blend of an M8.5 template and an L1−L3 template, reproducing a M9.0 spectrum in the case of ΔK = 0.61 ± 0.05, ΔH = 0.70 ± 0.05. These spectral types also match the observed H − K colors of each star. Based the previously observed low space motion and Hz activity, we assign an age of 0.8 ± 0.7 Gyr. Utilizing this age range and the latest DUSTY models of the Lyon group, we assign a photometric distance of 18.8 ± 1.4 pc and masses of M_A = 0.074 ± 0.013 M_☉ and M_B = 0.066 ± 0.015 M_☉. We therefore estimate a system separation of 2.92 ± 0.16 AU and a period of 13.3 ± 1.3 yr. Hence, 2MASS J1426316+155701 is among the smallest-separation brown dwarf binaries resolved to date.

Subject headings: binaries: general — instrumentation: adaptive optics — stars: evolution — stars: formation — stars: individual (2MASS J1426316+155701) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Since the discovery of Gl 229B by Nakajima et al. (1995), there has been intense interest in the direct detection of brown dwarfs. To fully understand this new population of substellar objects it is critical to characterize binary brown dwarfs (systems in which both components are likely substellar). Brown dwarf binary systems are of critical importance because they alone allow the masses and luminosities of brown dwarfs to be measured directly (Kenworthy et al. 2001; Lane et al. 2001). Without direct dynamical mass measurements, theoretical evolutionary models of brown dwarfs (Chabrier et al. 2001; Burrows et al. 2000) cannot be calibrated. Therefore, there is great interest in directly detecting close brown dwarf binaries.

Moreover, the binary frequency of brown dwarfs is interesting in its own right, because little is known about how common binary brown dwarf systems are. It is not clear currently if the brown dwarf binary distribution in mass ratio (q) and separation is similar to that of M stars; in fact, there is emerging evidence that double brown dwarfs (hereafter called binary brown dwarfs) tend to have mass ratios close to unity and small separations (Martin, Brandner, & Basri 1999). However, surveys also suggest that the binary frequency itself is similar to that of M stars (Reid et al. 2001b).

Despite the strong interest in binary brown dwarfs, very few systems have been detected to date. Before the Near-infrared Camera and Multiobject Spectrometer (NICMOS) on the Hubble Space Telescope (HST) ran out of cryogen, the first double L dwarf was detected (Martin et al. 1999). A young spectroscopic binary brown dwarf (PPL 15) was detected in the Pleiades (Basri & Martin 1999), but this spectroscopic system is too close to obtain separate luminosities for each companion. However, a large HST/NICMOS imaging survey by Martin et al. (2000a) of very low mass (VLM) dwarfs in the Pleiades failed to detect any brown dwarf binaries with separations greater than 0.2 (≥27 AU). Detections of closer binary systems were more successful. The nearby object Gl 569B was resolved into a 0.1 (1 AU) binary brown dwarf at Keck and the 6.5 m Multiple Mirror Telescope (Martin et al. 2000b; Kenworthy et al. 2001; Lane et al. 2001). Keck seeing-limited NIR imaging marginally resolved two more binary L stars (Koerner et al. 1999). A survey with WFPC2 detected four more (three newly discovered) close, equal-magnitude binaries out of a sample of 20 L dwarfs (Reid et al. 2001b). Then Potter et al. (2001) guided on HD 130948 with adaptive optics and discovered a binary brown dwarf companion. Hence, the total number of binary brown dwarfs known is just nine. In addition, of these, only eight have luminosities known for each component, because one is a spectroscopic binary.

In this paper, we present a newly discovered binary brown dwarf, 2MASS J1426316+155701 (hereafter 2M 1426), that is a significant addition to this list because it is the only example of an M8.5 primary with an L1−L3 secondary, a high mass ratio compared with that of other brown dwarf binaries. Its observed separation of 0.15 is the fourth-smallest of any resolved brown dwarf binary currently known, and so the 2M 1426 binary should play a significant role in the mass-luminosity calibration for brown dwarfs. Moreover, we show for the first time that it is possible to guide directly on a low-mass star/brown dwarf with adaptive optics on an 8 m telescope, opening up a new technique for diffraction-limited brown dwarf observations.

2. ADAPTIVE OPTICS IMAGING WITH GEMINI AND HOKUPA’A

Our approach to the detection of brown dwarf binaries is somewhat different from that tried before. We wished to
Figs. 1.—(a) 5 s exposure of the 2M 1426 binary at an $H$-band resolution of 0.131. (b) The system after being LUCY-restored to 0.080 resolution. Only astrometry was derived from the deconvolved images; photometry was derived from DAOPHOT PSF fitting of the undeconvolved data. The pixels are 0.0199 pixel$^{-1}$. Contours are linear at the 95, 75, 55, 35, and 15 percent levels.

utilize both diffraction-limited resolution and NIR (1–2.5 μm) imaging at the wavelengths where brown dwarf spectral energy distributions peak. To detect the closest binaries, we utilized the largest aperture possible ($D \approx 8$ m). Hence, ground-based NIR imaging with adaptive optics (AO) was a logical choice (see Close 2000 for a review on AO). However, because of the extreme optical faintness of these brown dwarfs ($V \approx 20$), most AO systems cannot lock onto such faint targets. The exceptions are curvature-based AO systems, which employ red-sensitive, photon-counting avalanche photodiodes (APDs) in their wave front sensors. Such a sensor can lock onto a target as faint as $V \approx 20$, as long as it is very red ($V-I = 4$). Because nearby VLM stars/brown dwarfs of spectral type M8–L1 have $V \approx 20$ and $V-I \approx 4$, we decided that such targets would be possible with a curvature AO system on an 8 m telescope.

Recently, the University of Hawaii curvature AO system Hokupa‘a (Graves et al. 1998; Close et al. 1998) was moved to the Gemini North Telescope and provided as a visitor instrument to the Gemini community. Although Hokupa‘a’s 36 elements were too few to obtain very high Strehl images on an 8 m telescope, it was well suited to locking onto nearby faint, red M8–L1 stars and producing 0.1 images (which is close to the 0.05 diffraction limit in the $H$ band). We decided to utilize this unique capability to survey the nearest extreme M and L stars, to characterize the nearby binary brown dwarf population.

Here we report the results of our first observing run, on 2001 June 20. We targeted VLM stars and brown dwarfs identified by Gizis et al. (2000). In total, nine brown dwarfs were observed over the first half of the night. Typically, we achieved 0.1–0.15 images of ~ 10 minutes total integration time in the $H$ (1.6 μm) band. Because the survey is ongoing, we will report in more detail about all the objects observed in a more comprehensive paper in the near future. In this paper we limit the discussion to the 2M 1426 binary observations.

One out of nine of our targets (2M 1426) was clearly a tight binary, with separation of 0.15. We observed the object, dithering over four different positions on the QUIRC NIR 1024 × 1024 detector with 0.0199 pixel$^{-1}$ (Hodapp et al. 1996). At each position we took three 5 s exposures and two 60 s exposures. In addition, we took a series of ten 10 s $K$ and $K'$ images, all in the same position.

3. REDUCTIONS

We have developed an AO data reduction pipeline in the IRAF language that maximizes sensitivity and image resolution. The pipeline cross-correlates each image, then rotates each image so that north is up and east is left, and then median-combines the data with an average sigma clip rejection at the $\pm 2.5 \sigma$ level. By use of a cubic spline interpolator the script preserves image resolution to the <0.02 pixel level. Next the script produces two final output images, one that combines all the images taken and another where only the sharpest 50% of the images are combined. The final images have a field of view of 30″ × 30″.

This pipeline produced a final deep 480 s $H$ image (8 × 60 s; FWHM = 0.197), a final unsaturated 60 s $H$ image (12 × 5 s; FWHM = 0.131; see Fig. 1), and unsaturated
50 s \(K\) (FWHM = 0\(^{\prime\prime}197\)) and \(K'\) (10 \times 10 s; FWHM = 0\(^{\prime\prime}197\)) images.

4. ANALYSIS

In Table 1 we present the analysis of the images of 2M 1426. The photometry was based on DAOPHOT (Stetson 1987) PSF-fitting photometry. The PSF (point-spread function) used was the 12 \times 5 s unsaturated data from the next brown dwarf observed after 2M 1426. This PSF “star” had a similar brightness (\(K = 12.5\)) and late M8.5 spectral type and was observed at a similar air mass. The flux ratio measured by DAOPHOT was normalized by the total flux of the binary in a 15\(^{\prime\prime}\) aperture. The resulting magnitudes are listed in Table 1.

The plate scale and orientation of QUIRC were determined from a short exposure of the Trapezium cluster in Orion and compared with published positions, as in Simon, Close, \\& Beck (1999). From these observations a plate scale of 0.0199 pixel \(^{-1}\) was determined.

The astrometry was based on lightly (100 iterations) LUCY-deconvolved data from the 12 \times 5 s unsaturated \(H\) image (see Fig. 1). For the deconvolution we used the same PSF as above. A good deconvolution result was obtained, with a restored resolution of FWHM = 0.080. This high resolution allowed for excellent astrometric accuracy to be achieved by centroiding on the well-separated stars. These astrometric measurements were also checked against the PSF-fitting photometry of DAOPHOT and were found to be in excellent agreement (DAOPHOT yielded separation of 0.158 and P.A. of 163\(^{\circ}\)).

5. DISCUSSION

5.1. Is the Companion Physically Related to the 2M 1426 System?

We believe there is a very high probability that the companion is physically associated with the 2M 1426 system. This is likely due to the small space density of very red (\(H - K = 0.59\)) background objects in the field. Furthermore, in the 9000 arcsec\(^2\) already surveyed we have not detected a similarly reddened background object in any of the fields. Therefore, we estimate that the probability of a chance projection of such a red object within 0\(^{\prime\prime}15\) of the primary is less than \(1 \times 10^{-5}\). We conclude that this very red, cool object is physically related to the 2M 1426 primary and hereafter refer to it as 2M 1426B.

5.2. What are the Spectral Types of the Components?

We do not have spatially resolved spectra of both components; consequently, we can only try to “blend” spectra of a hotter and cooler star while preserving the observed \(\Delta K = 0.61\) and \(\Delta H = 0.70\). In Kenworthy et al. (2001), it was found that an M8.5 spectrum and an L1–L3 spectrum could be blended together (with \(\Delta K = 0.61\)) to produce an M9 “blended” spectrum. Because Gizis et al. (2000) observed 2M 1426 to have a blended M9.0 spectrum, we can reasonably assume that the components may have spectral types of M8.5 and L1–L3. Hence, we estimate (until proper spatially resolved spectra are obtained of both components) that 2M 1426A is similar to an M8.5 and 2M 1426B is similar to an L1–L3 star. Furthermore, the \(H - K = 0.47\) color of the primary is consistent with an M8.5 spectral type. Similarly, the \(H - K = 0.59\) color of the companion is consistent with an L1–L3 spectral type (Reid et al. 2001a). So we will assume a spectral type of M8.5 for the primary and L1–L3 for the companion until proper spatially resolved spectra are obtained and the true spectral types determined. See Table 2 for a summary of the components’ properties.

5.3. What is the Distance to the 2M 1426 System?

Unfortunately, there is no published parallax to the 2M 1426 system. We can estimate, however, the distance based on the spectral types and a range of possible ages for the system. To do this, calibrated theoretical evolutionary tracks are required for objects in the temperature range 2300–1800 K. Recently, such a calibration has been performed by two groups using dynamical measurements of the Gl 569B brown dwarf binary. From the dynamical mass measurements of the Gl 569B binary brown dwarf (Kenworthy et al. 2001; Lane et al. 2001), it was found that the Chabrier et al. (2001) and Burrows et al. (2000) evolutionary models were in reasonably good agreement with observations. Based on the latest Chabrier et al. (2001) DUSTY models (see Fig. 2), we find that, even if the age of 2M 1426 was as old as 7.5 Gyr, the closest it could be is 17.8 pc, based on the observed \(K_a = 12.16\) and spectral type of M8.5. On the other hand, if 2M 1426 is as young as 0.5 Gyr it could be as far as 20.3 pc with \(K_a = 12.16\) and spectral type of M8.5. Because it is highly likely that the age of 2M 1426 is between 0.5 and 7.5 Gyr, we adopt a distance range of 17.8–20.3 pc.

5.4. What is the Age of the 2M 1426 System?

Estimating the age for the 2M 1426 system is difficult because there are no Li measurements yet made. The age could be anywhere from 0.5 to 7.5 Gyr. However, the low proper motion observed by Gizis et al. (2000) for the system \((\mu_{K,A} = 0.108 \text{ yr}^{-1}, \mu_{dec} = -0.056 \text{ yr}^{-1})\) yields \(V_{tan} = 12\)
and the first zero point to the theoretical tracks has been of great importance. The shortest-period resolved brown dwarfs required to calculate the dynamical mass, such objects are less than 25 yr. Because a good fraction of a period is currently known. This is of great importance, because only among the five shortest-period brown dwarf binaries currently known. This is of great importance, because only such crude estimates do allow us to see that 2M 1426 is among the five shortest-period brown dwarf binaries currently known. This is of great importance, because only systems with separations less than 4 AU will have periods less than 25 yr. Because a good fraction of a period is required to calculate the dynamical mass, such objects are of great importance. The shortest-period resolved brown dwarf binary (GI 569B) has already had its orbit calculated, and the first zero point to the theoretical tracks has been significant addition to the known brown dwarf binaries.

5.5. How Does 2M 1426 Compare with the Other Binary Dwarfs Known?

As was mentioned in §1, there are eight binary brown dwarfs (published at this time) with resolved (i.e., nonspectroscopic) components. A listing of these, in order of separation, can be seen in Table 3.

From Table 3 we see that, other than the very close (10 pc) system GI 569B, the next four systems all have estimated periods in the range 11–16 yr. These periods are crudely estimated by assuming face-on circular orbits. However, even such crude estimates do allow us to see that 2M 1426 is among the five shortest-period brown dwarf binaries currently known. This is of great importance, because only systems with separations less than 4 AU will have periods less than 25 yr. Because a good fraction of a period is required to calculate the dynamical mass, such objects are of great importance. The shortest-period resolved brown dwarf binary (GI 569B) has already had its orbit calculated, and the first zero point to the theoretical tracks has been

![Image](image_url)
paper were carried out with the Gemini North Telescope. The Hokupa’a AO observations were supported by the University of Hawaii AO group (D. Potter, O. Guyon, P. Badouz, and A. Stockton). Support for Hokupa’a comes from the National Science Foundation. Olivier Guyon kindly provided an algorithm for the rerotation of QUIRC images. We would also like to send a big mahalo nui to the Gemini operations staff (especially François Rigaut, Simon Chan, and John Hamilton) for a flawless night. Also, Steve Ridgway (NOAO) was a great help in acquiring the data at Gemini.

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