A SEARCH FOR SUBSTELLAR COMPANIONS TO THE TWO NEAREST BROWN DWARF SYSTEMS*

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ABSTRACT

WISE J104915.57–531906.1 A+B and WISE J085510.83–071442.5 were recently discovered as the third and fourth closest known systems to the Sun, respectively (2.0 and 2.3 pc). The former consists of a L8+T0.5 binary and the latter is a probable Y dwarf and is the coldest known brown dwarf (∼250 K). We present a search for common proper motion companions to these brown dwarfs using multi-epoch mid-infrared images from the Spitzer Space Telescope. We have also obtained near-infrared adaptive optics (AO) images of WISE J104915.57–531906.1 A+B with the Very Large Telescope to search for companions at smaller separations than reached by Spitzer. No new companions are detected in either system. At projected separations of 25″–420″ (50–840 AU) for WISE J104915.57–531906.1 A+B and 4″–420″ (9–970 AU) for WISE J085510.83–071442.5, the Spitzer images are sensitive to companions with $M_{\text{jup}} \gtrsim 21.6$ and 21.9, respectively, which correspond to masses of $\gtrsim 1 M_{\text{jup}}$ for ages of $\gtrsim 1$ Gyr and temperatures of $\gtrsim 150$ K. The detection limit in the AO images of WISE J104915.57–531906.1 A + B is $\Delta H \sim 10$ at 3″–15″ (6–30 AU), or $\gtrsim 7 M_{\text{jup}}$ for $\gtrsim 1$ Gyr.

Key words: brown dwarfs – infrared: stars – proper motions – solar neighborhood – stars: low-mass

1. INTRODUCTION

The all-sky mid-infrared (IR) images obtained by the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) have enabled the discovery of a large number of brown dwarfs in the solar neighborhood, particularly at very low temperatures (Cushing et al. 2011; Kirkpatrick et al. 2011). The closest of these newly found brown dwarfs are WISE J104915.57–531906.1 A and B (hereafter WISE 1049–5319 A and B, Luhman 2013) and WISE J085510.83–071442.5 (hereafter WISE 0855–0714, Luhman 2014a, 2014b), which are the third and fourth closest known systems to the Sun, respectively (2.0 and 2.3 pc). WISE 1049–5319 A and B have spectral types of L8 and T0.5, $\gtrsim$1 Jy at 250 K. The detection limit in the AO images of WISE J104915.57–531906.1 A+B with the Very Large Telescope (VLT) is $\Delta H \sim 10$ at 3″–15″ (6–30 AU), or $\gtrsim 7 M_{\text{jup}}$ for $\gtrsim 1$ Gyr.

2. OBSERVATIONS

2.1. Near-IR AO Images from VLT

Near-IR AO images were used to search for companions to WISE 1049–5319 A and B at small separations. These observations were performed on the Unit Telescope 4 of the VLT with the Nasmyth Adaptive Optics System (NAOS) and the High-resolution Near-IR Camera (CONICA), which together are known as NACO (Lenzen et al. 2003; Rousset et al. 2003). NACO was operated with the S27 camera, the N90C10 dichroic, and the H filter. The S27 camera contains a 1024 × 1024 array and has a plate scale of 0′′027 pixel$^{-1}$, corresponding to a field of view of 28″ × 28″. We selected individual exposure times of 4 and 120 s. The former provided unsaturated data for the binary components that could reveal companions at small separations, and the latter provided greater sensitivity to companions at large separations. We obtained 10 dithered short exposures and 17 dithered long exposures on the night of 2013 April 13. In these data, the point-spread functions (PSFs) of the binary components exhibited slight elongations in the direction of the axis connecting the pair, which was likely caused by the fact that both objects were present in the wavefront sensor sub-pupils. Because of these elongations, the observatory repeated the observations on the night of 2013 May 13, which produced similar results as on the first night. After performing dark subtraction and flat fielding, we registered and combined the images at a given exposure time from a given night. The final combined images from each of the two nights exhibit similar sensitivity and FWHM (∼0′′1). The combined image from the second night for the 120 s exposures is shown in Figure 1. In the long exposures, saturation occurs within the cores of the PSFs of the binary components (∼0′′1).

2.2. Mid-IR Images from Spitzer

To search for co-moving companions in wide orbits, we obtained multi-epoch images of fields surrounding WISE 1049–5319 and WISE 0855–0714 with the Infrared Array

* Based on data from the Spitzer Space Telescope and the ESO Telescopes at Paranal Observatory under program ID 290.C-5195.
Camera (IRAC; Fazio et al. 2004) on board the Spitzer Space Telescope. IRAC has a plate scale of 1.2′ and a field of view of 5.2′ × 5.2′. Two filters were available with IRAC, which were centered at 3.6 and 4.5 μm (denoted as [3.6] and [4.5]). Because the latter provides better sensitivity to cold brown dwarfs, only the maps in that band were centered on the targets. We did collect images at 3.6 μm in flanking fields during the 4.5 μm observations. WISE 1049–5319 was observed on 2013 May 3 and September 29 through Astronomical Observation Requests (AORs) 48641024 and 48640512, respectively. WISE 0855–0714 was observed on 2014 July 1 and 2015 January 29 through AORs 51040000 and 51040256, respectively. For each epoch and band for WISE 1049–5319, we obtained one short exposure and one long exposure at each of three dither positions near each of 18 locations in a 6 × 3 grid of pointings separated by 150″ and 260″, respectively. For WISE 0855–0714, nine dithered long exposures were collected near each of nine positions in a 3 × 3 grid of pointings separated by 260″ in each direction. For both targets, the long exposure times were 23.6 and 26.8 s at 3.6 and 4.5 μm respectively. A short exposure time of 0.8 s was used for WISE 1049–5319. The short exposures were included to provide images in which WISE 1049–5319 A and B were not saturated. These data were reduced in the manner described by Luhman et al. (2012). A combination of the reduced long exposures in both bands and epochs is shown in Figures 2 and 3 for WISE 1049–5319 and WISE 0855–0714, respectively. For each system, a field within 420″ was fully covered by both epochs at 4.5 μm corresponding to 840 and 970 AU, respectively, given their distances (Boffin et al. 2014; Luhman & Esplin 2014). The components of WISE 1049–5319 had a separation of 1.5″ in 2013 (Burgasser et al. 2013; Luhman 2013) and are only partially resolved in these data.

3. ANALYSIS

Because WISE 1049–5319 A and B have similar colors and magnitudes and appear near the same position in NACO’s field of view, we can use the PSF of one component for PSF subtraction of the other. The PSF-subtracted versions of the short and long exposures do not show any additional components at close separations. Outside of the PSFs of the

**Figure 1.** VLT NACO H-band image of WISE 1049–5319 A and B. To better show the positions of the binary components, we have reduced the counts near them by a factor of 30. The size of the image is 30″ × 30″.

**Figure 2.** Combination of IRAC images of WISE 1049–5319 from two bands (3.6 and 4.5 μm) and two epochs (“a” and “b”). We have searched for common proper motion companions to WISE 1049–5319 in the areas imaged at two epochs. The greatest sensitivity to substellar companions is achieved in the overlapping area between the two epochs at 4.5 μm which provides full coverage out to 420″ (840 AU) from WISE 1049–5319 (circle).

**Figure 3.** Same as Figure 2 for WISE 0855–0714.
components, several objects are detected, as shown in Figures 2 and 3. None of these sources exhibit a motion between the two epochs that is consistent with the motion of the binary. Most of these stars are also detected in $i$-band images from Luhman (2013), and a comparison of those images with the NACO data further indicates that they are not co-moving companions. WISE 1049–5319 moved $\sim 1''$ between the $i$ observations and the second epoch with NACO, but all of the sources detected in both images remained stationary to within $\sim 0''1$. To estimate the detection limit for companions in the NACO data, we measured the standard deviations within annuli across a range of radii from each component. The width of each annulus was four pixels, which is similar to the FWHM of the PSF. Because the PSFs of the components overlap, we ignored the data in the half of each annulus in the direction of the other component. In other words, the standard deviations were computed for the portions of the annuli from position angles of $45^\circ$–$225^\circ$ for A and $0^\circ$–$45^\circ$ and $225^\circ$–$360^\circ$ for B. The standard deviations as a function of separation are similar for the two stars, which is expected since they have similar $H$-band magnitudes. We have computed the average of the two curves of standard deviation versus separation. In the top panel of Figure 4, we show that average curve in terms of the $5\sigma$ magnitude contrast relative to the unresolved $H$-band magnitude for the binary system from the Point Source Catalog of the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006).

To search the IRAC images of WISE 1049–5319 and WISE 0855–0714 for companions, we began by measuring the positions for all point sources in each band and epoch with the task starfind within IRAF. The resulting positions were transformed to equatorial coordinates using the World Coordinate Systems in the image headers. We identified the closest matches between the two epochs for each combination of bands, namely 3.6a/3.6b, 3.6a/4.5b, 4.5a/3.6b, and 4.5a/4.5b where “a” and “b” refer to the two epochs (see Figures 2 and 3). The differences in coordinates for these matches are shown in Figure 5. The motions of WISE 1049–5319 and WISE 0855–0714 are large enough that the same motions for co-moving companions should be easily detected for the faintest sources in the images, but no such objects are present in Figure 5. As with the AO data, we estimated the detection limit at 4.5 $\mu$m as a function of separation from WISE 1049–5319 A and B based on the standard deviations within annuli over a range of radii, where the annuli were given widths of $1''.8$. The resulting values of $5\sigma$ are plotted relative to the combined 4.5 $\mu$m magnitude of WISE 1049–5319 A and B in the top panel of Figure 4. Because WISE 0855–0714 is much fainter than WISE 1049–5319, the sky background dominates the PSF down to rather small separations of $\sim 4''$. As a result, the detection limit does not vary beyond $4''$ for WISE 0855–0714, and hence it is not plotted as a function of separation in Figure 4. Within $4''$ from WISE 0855–0714, the detection limit in terms of $\Delta [4.5]$ is similar to that of WISE 1049–5319. At separations that are sufficiently large for the sky to dominate, $5\sigma$ occurs at $[4.5] = 18.1$ and 18.7 for WISE 1049–5319 and WISE 0855–0714, respectively, which correspond to $M_{4.5} = 21.6$ and 21.9.

We can use evolutionary and atmospheric models of brown dwarfs to convert the detection limits in $H$ and [4.5] to limits in mass. Because the ages of WISE 1049–5319 and WISE 0855–0714 are unknown, we perform this conversion with the fluxes predicted for ages of 1 and 10 Gyr, which encompass the ages of most stars in the solar neighborhood. We rely primarily on the fluxes from the models by Saumon & Marley (2008) and Saumon et al. (2012) that are cloudless and employ equilibrium chemistry. Other models that include clouds and non-equilibrium chemistry produce roughly similar fluxes in $H$ and [4.5] ($\Delta m \lesssim 0.2$) for the ranges of absolute magnitudes probed by our images (Morley et al. 2012, 2014; Saumon et al. 2012), and hence the derived mass limits do not depend significantly on the choice of models. The coldest brown dwarfs modeled by Saumon & Marley (2008) and Saumon et al. (2012) ($\sim 200$ K) have $M_{4.5} \sim 18$, whereas the IRAC

![Figure 4](image-url)
images approach \( M_{4.5} \sim 22 \) at the distances of our targets. To transform our limits at \( M_{4.5} > 18 \) to masses, we have adopted the absolute magnitudes from the models by Burrows et al. (2003) for 1 Gyr, which extend down to \( M_{4.5} = 20.65 \) (for 1 \( M_{\text{Jup}} \)). Those authors did not perform calculations for the other age of 10 Gyr that we consider. After combining the fluxes from the above sets of models with our measured limits in \( H \) and [4.5] for WISE 1049–5319, we arrive at the mass limits that are shown in the bottom panel of Figure 4. The NACO image provides greater sensitivity at smaller separations (e.g., 25 and 65 \( M_{\text{Jup}} \) at 0.4 AU for 1 and 10 Gyr, respectively). The mass limits for the NACO and IRAC images intersect at \( \sim 3\text{.}5 \) (~7 AU). At that separation, both images have limits near 7 and 20 \( M_{\text{Jup}} \) for 1 and 10 Gyr, respectively. Because none of the brown dwarf models that we have considered are as faint as the \( M_{4.5} \) limits reached at large separations, we are not able to estimate precise values for the lowest masses that are detectable in the IRAC images. However, an extrapolation of the mass limits in Figure 4 suggests that the IRAC images are able to detect companions at large separations from WISE 1049–5319 (and WISE 0855–0714) that are slightly below 1 \( M_{\text{Jup}} \) for 1 Gyr and \sim 4 \( M_{\text{Jup}} \) for 10 Gyr. Such objects would have temperatures of \sim 150 K according to the models.

4. DISCUSSION

Because WISE 1049–5319 and WISE 0855–0714 are nearby and intrinsically faint, direct imaging of these systems is sensitive to companions at low luminosities and small orbital distances. However, no companions have been detected in our NACO and IRAC data, which is not surprising given the low binary fractions exhibited by L and T dwarfs (~20%, Burgasser et al. 2007; Aberasturi et al. 2014, references therein). WISE 1049–5319 is a binary system (L8+T0.5), and triples composed entirely of cool dwarfs are especially rare in direct imaging surveys (Burgasser et al. 2012; Radigan et al. 2013). Most L and T dwarf binaries have small separations (<20 AU, Burgasser et al. 2007), and the same is true for the small number of known binaries among late-T and Y dwarfs (Gelino et al. 2011; Liu et al. 2011, 2012; Dupuy et al. 2015). As a result, it is unlikely that either WISE 1049–5319 or WISE 0855–0714 has cool companions beyond the boundaries of our images. Some brown dwarfs that are discovered in wide-field surveys and initially appear to be isolated objects are later found to be distant companions to stars (Burgasser et al. 2000; Scholz et al. 2003; Burningham et al. 2009; Faherty et al. 2010), but our two targets do not have co-moving stellar companions based on the WISE proper motion surveys by Luhman (2014a) and Kirkpatrick et al. (2014). Of course, WISE 1049–5319 and WISE 0855–0714 may have companions below our detection limits, especially at small separations. The components of WISE 1049–5319 are sufficiently bright for a search for close companions through radial velocity and astrometric measurements. Near-IR imaging with the Hubble Space Telescope is the only available option for improving the constraints on the presence of close companions to WISE 0855–0714 given that it is only barely detectable with ground-based telescopes (Faherty et al. 2014).

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REFERENCES

Aberasturi, M., Burgasser, A. J., Mora, A., et al. 2014, AJ, 148, 129
Boffin, H. M. J., Pourbaix, D., Mužič, K., et al. 2014, A&A, 561, L4
Burgasser, A. J., Kirkpatrick, J. D., Cutri, R. M., et al. 2000, ApJL, 531, L57
Burgasser, A. J., Luk, C., Dhital, S., et al. 2012, ApJ, 757, 110
Burgasser, A. J., Reid, I. N., Siegler, N., et al. 2007, in Protostars and Planets V, ed. V. B. Reipurth, D. Jewitt & K. Keil (Tucson: Univ. Arizona Press), 427
Burgasser, A. J., Sheppard, S. S., & Luhman, K. L. 2013, ApJ, 772, 129
Burningham, B., Pinfield, D. J., Leggett, S. K., et al. 2009, MNRAS, 395, 1237
Burrows, A., Sudarsky, D., & Lunine, J. I. 2003, ApJ, 596, 587
Cushing, M. C., Kirkpatrick, J. D., Gelino, C. R., et al. 2011, ApJ, 743, 50
Dupuy, T. J., Liu, M. C., & Leggett, S. K. 2015, ApJ, 803, 102
Faherty, J. K., Burgasser, A. J., West, A. A., et al. 2010, AJ, 139, 176
Faherty, J. K., Tinney, C. G., Skemer, A., & Monson, A. J. 2014, ApJL, 793, L16
Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Gelino, C. R., Kirkpatrick, J. D., Cushing, M. C., et al. 2011, AJ, 142, 57
Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2011, ApJS, 197, 19
Kirkpatrick, J. D., Schneider, A., Fajardo-Acosta, S., et al. 2014, ApJ, 783, 122
Lenzen, R., Hartung, M., Brandner, W., et al. 2003, Proc. SPIE, 4841, 944
Liu, M. C., Deacon, N. R., Magnier, E. A., et al. 2011, ApJ, 740, 108
Liu, M. C., Dupuy, T. J., Bowler, B. P., Leggett, S. K., & Best, W. M. J. 2012, ApJ, 758, 57
Luhman, K. L. 2013, ApJL, 767, L1
Luhman, K. L. 2014a, ApJL, 781, 4
Luhman, K. L. 2014b, ApJL, 786, L18
Luhman, K. L., Burgasser, A. J., Labbé, I., et al. 2012, ApJ, 744, 135
Luhman, K. L., & Esplin, T. L. 2014, ApJ, 796, 6
Morley, C. V., Fortney, J. J., Marley, M. S., et al. 2012, ApJ, 756, 172
Morley, C. V., Marley, M. S., Fortney, J. J., et al. 2014, ApJ, 787, 78
Radigan, J., Jayawardhana, R., Lafrenière, D., et al. 2013, ApJ, 778, 36
Rousset, G., Lacombe, F., Puget, P., et al. 2003, Proc. SPIE, 4839, 140
Saumon, D., & Marley, M. S. 2008, ApJ, 689, 1327
Saumon, D., Marley, M. S., Abel, M., Frommhold, L., & Freedman, R. S. 2012, ApJ, 750, 74
Scholz, R.-D., McCaughrean, M. J., Lodieu, N., & Kuhlbrodt, B. 2003, A&A, 398, L29
Skrutskie, M., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, ApJS, 154, 1
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Wright, E. L., Mainzer, A., Kirkpatrick, J. D., et al. 2014, AJ, 148, 82