DISCOVERY OF A TIGHT BROWN DWARF COMPANION TO THE LOW-MASS STAR LHS 2397a

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ABSTRACT

Using the adaptive optics system, Hokupa’a, at Gemini North, we have directly imaged a companion around the UKIRT faint standard M8 star LHS 2397a (FS 129) at a separation of 2.96 AU. Near-infrared photometry of the companion has shown it to be an L7.5 brown dwarf and confirmed the spectral type of the primary to be M8. We also derive a substellar mass of the companion of 0.068 $M_\odot$, although masses in the range 0.061–0.069 $M_\odot$ are possible, and the primary mass is 0.890 $M_\odot$ (0.089–0.094 $M_\odot$). Reanalysis of archival imaging from the Hubble Space Telescope has confirmed the secondary as a common proper motion object. This binary represents the first clear example of a brown dwarf companion within 4 AU of a low-mass star and should be one of the first late-L dwarfs to have a dynamical mass. As part of a larger survey of M8–L0 stars, this object may indicate that there is no “brown dwarf desert” around low-mass primaries.

Subject headings: binaries: general — instrumentation: adaptive optics — stars: evolution — stars: formation — stars: individual (LHS 2397a) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Radial velocity surveys have now probed on the order of 2000 nearby Sun-like FGKM main-sequence stars and found upward of 100 planetary companions (Marcy et al. 2003). However, there exists a distinct lack of brown dwarf companion detections at small separations to these stars (the “brown dwarf desert”) even though their larger reflex motion would be easier to detect than for planets. Marcy et al. (2003) estimate that 0.5% ± 0.2% of Sun-like stars have brown dwarf companions ($M > 10–80 M_J$) within 3 AU.

At the same time 13% ± 3% of G stars (Mazeh et al. 1992) and 8.1% of M stars (Fischer & Marcy 1992) have stellar companions within 3 AU. This dramatic dichotomy indicates that perhaps the formation of brown dwarf and stellar companions involves very different mechanisms.

Direct imaging surveys have also probed larger separation spaces ($\gtrsim 30$ AU) around Sun-like stars and found that a significant fraction may have very wide brown dwarf companions (e.g., Gizis et al. 2001), although a search of K0–M7 finds no companions ($\gtrsim 40 M_J$) at 100–1400 AU (Hinz et al. 2002). Aside from the recent brown dwarf companion imaged around a G1 V star at 14 AU (Liu et al. 2002), separations of 5–30 AU remain largely unexplored.

Does this same trend in brown dwarf companion frequency with separation extend to lower mass (later than M8) primary stars? Studies sensitive to large binary separations have come up empty-handed; a surprising 0% of low-mass stars and brown dwarfs appear to have brown dwarf companions at separations greater than $\sim 20$ AU (e.g., Martin et al. 2000; Oppenheimer et al. 2001).

Only with adaptive optics (AO) or space-based imaging can separations significantly less than $\sim 20$ AU around low-mass objects be successfully investigated. Several recent and ongoing studies have employed these methods, and each has found that the binary frequency of low-mass primaries (M8–M9/L/T) is $\sim 20\%$ for $a > 3$ AU (Reid et al. 2001; Close et al. 2002b; Burgasser et al. 2003). Furthermore, the companions tend to cluster around 4–5 AU, and no companions have been found at separations larger than 20 AU.

Here we present the discovery of a brown dwarf companion orbiting within 4 AU of the nearby UKIRT faint standard M8 star, LHS 2397a (FS 129) and discuss its implications. This is the first clear example of a brown dwarf companion to a low-mass star (later than M2) within 4 AU. Given the small separation of this system, dynamical masses can be determined in a relatively short period of time ($\sim 5$ yr), which will help calibrate mass-luminosity isochrone models and the bottom of the main sequence.

2. OBSERVATIONS

These observations were taken as part of a larger survey for companions to late-M stars (M8–L0). See Close et al. (2002a, 2002c) for a detailed discussion of this survey as well as the observing methods used. Taking advantage of the extremely sensitive curvature wave-front sensor on the now-retired AO system, Hokupa’a (Graves et al. 1998), at Gemini North, we were able to directly guide on our very faint primary targets in the visible. For LHS 2397a, with $V = 19.6$ (Martin, Rebolo, & Magazzù 1994), this meant resolutions of 0\arcsec13 at $K'$, 0\arcsec17 at $H$, and 0\arcsec22 at $J$. Using the Quick Infrared Camera (QUIRC) and its near-IR 1024 × 1024 detector with 0\arcsec0199 ± 0\arcsec0002 pixels (Hodapp et al. 1996), we obtained $J$, $H$, and $K'$ images of LHS 2397a on UT 2002 February 7, with a three-point dither pattern. For each dither position we obtained 5 s × 5 s exposures in the $J$ and $H$ bands for a total exposure time of 75 s and 5 s × 3 s exposures in the $K'$ band for a total exposure time of 45 s. The limiting magnitudes for wide separation

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1 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

2 Note that the “a” in LHS 2397a does not indicate that it is a binary, but simply that it lies between LHS 2397 and LHS 2398 in Luyten’s (1979) original catalog. It was considered a single star until this work.
companion in these images were \( J = 22.5, H = 22.8 \), and \( K' = 21.2 \) for a 5 \( \sigma \) result.

We also obtained two images of LHS 2397a from the Hubble Space Telescope (HST) public archival database, which were taken as part of a study by Kirkpatrick & Henry (1997). The images consist of a 2 s (unsaturated) and 300 s (saturated) exposure made with HST/WFPC2 on UT 1997 April 12 using the F814W (CWL = 0.82 \( \mu \)m) filter. These images have a resolution of \( \sim 0''1 \) with a plate scale of \( \sim 0''050 \) pixel\(^{-1}\).  

3. ASTROMETRY AND PHOTOMETRY

The AO data were reduced using a pipeline data reduction program as described in Close et al. (2002a) in detail. The program employs standard AO near-IR data reduction techniques to produce final images with a field of view of \( 30'' \times 30'' \) and north up (\( 00'0'0'' \)). Figure 1 shows images of LHS 2397a and its companion for each of the four observed bands. 

In order to determine the differential magnitudes (\( \Delta m \)) and astrometry of the components of LHS 2397a in each of our three observed bands, we employed the use of the DAOPHOT (Stetson 1987) package in IRAF. For the \( K' \) band, the point-spread function (PSF) fitting photometry package DAOPHOT successfully split the two components and determined an accurate \( \Delta K' \) as well as accurate positions for the two components. A single star (2MASSI J1024099+ 1815) observed the same night, with a similar air mass, spectral type, and visible magnitude, was used as the PSF star. Two different rotation angles of the PSF star were used to calculate the \( \Delta K' \) of the binary system. Since the rotator was on during the exposures, a rotation in the PSF may have occurred. Therefore, by using both a nonrotated and rotated version of the PSF, we could assign an error to the photometry. The average and difference of these values were taken as the best determination of \( \Delta K' \) and its error, respectively. The separation and position angle as determined from the nonrotated PSF were used along with the typical errors of these values for the entire survey.

For the \( J \) and \( H \) bands, where DAOPHOT could not separate the two components, the annulus photometry task \textit{phot} was used on the images with the low spatial frequencies removed. This technique gave reliable \( \Delta m \) and was verified on images with known magnitudes.

The standard STSDAS pipeline data products were used for the HST/WFPC2 F814W images. To obtain a deep, unsaturated image, the saturated pixels in the long (300 s) exposure were replaced with a scaled version of those unsaturated pixels in the short (2 s) exposure. DAOPHOT was then run on the final, deep image to obtain \( \Delta F814W \) and the positions of the two components. Short (2 s) images of other single stars (LHS 2243 and LP 412-31) taken from the same proposed data set were used as PSF stars. Values and errors for \( \Delta F814W \) and positions were taken as the mean and difference of results obtained for the two different PSF stars.

The values of \( \Delta m \) determined above were used in conjunction with the known integrated magnitudes of LHS 2397a (see Table 1) to solve for the individual magnitudes of the two components of the binary. In order to calculate the individual magnitudes, we assumed that \( \Delta I_c \sim \Delta F814W + 0.06 \) and \( \Delta K_s \sim \Delta K' \). The 0.06 correction was calculating by performing synthetic photometry on a sample of late-M and L dwarf spectra (Kirkpatrick et al. 1999a, 1999b; Gizis et al. 2000; Kirkpatrick et al. 2000, 2001; Reid et al. 2000; Wilson et al. 2001). It was assumed that the primary was an M8, as spectroscopically determined by several studies (e.g., Leggett et al. 2002), and the secondary was an M8–L9. The

![](image.png)

**Fig. 1.**—Images of LHS 2397a taken in four bandpasses. The low spatial frequencies have been removed in the \( JHK' \) images to highlight the companion. The position of the secondary is indicated with an arrow. The \( J \)-band image is from HST/WFPC2 archival data (Kirkpatrick & Henry 1997). Note how much clearer the companion is at \( K' \) compared to the earlier \( HST \) F814W images, where it was difficult to detect.
error in this correction was 0.09 and was incorporated into the error of $\Delta I_C$ appropriately. The latter assumption is correct to 0.02 mag, according to the Chabrier et al. (2000) DUSTY models of late-L and M stars. Absolute magnitudes were calculated using the trigonometric parallax of LHS 2397a ($\pi = 70.0 \pm 2.1$ mas yr$^{-1}$, $d = 14.3 \pm 0.4$ pc) as measured by van Altena, Lee, & Hoffleit (1995). See Table 2 for a summary of derived positions and photometry of the data.

4. SPECTRAL TYPE

To determine the spectral types of the two components, we compared our calculated absolute magnitudes, in all four bands, with the absolute magnitude versus spectral type relationships derived by Dahn et al. (2002) (see Fig. 2). However, in order to avoid the errors associated with converting from $K_s$ to $K$ magnitudes, we used the $K_s$ magnitudes, as determined by the second incremental 2MASS data release, along with the Dahn et al. (2002) parallaxes for as many of the stars as possible to derive a $M_{K_s}$ versus spectral type relationship. For every observed bandpass, we confirm that the primary is an M8 and the secondary is consistent with an L7.5. Spectral types later than L4.5 are predicted to consist entirely of substellar objects (Kirkpatrick et al. 2000). Therefore, we conclude that the companion is a brown dwarf.

5. SPACE AND ORBITAL MOTIONS

Our AO observations were taken nearly 5 yr after the HST images, which allows us to verify that the binary components have common proper motion as well as observe significant orbital motion.

Originally cataloged by Luyten (1979) in his high proper motion catalog, LHS 2397a has a large proper motion of $\mu_A = 513.4 \pm 7.8$ mas yr$^{-1}$ at a position angle of $\theta_A = 263^\circ 8 \pm 0^\circ 9$ (Tinney 1996). The observed proper motion of the secondary is $\mu_B = 555.1 \pm 8.2$ mas yr$^{-1}$ at $\theta_B = 259^\circ 6 \pm 0^\circ 9$. Taking into account the properties of the system as well as the known space density of L dwarfs (Gizis et al. No. 1, 2003 BROWN DWARF COMPANION TO LHS 2397a 455

\begin{table}[h]
\centering
\caption{New System Data}
\begin{tabular}{ll}
\hline
Parameter & LHS 2397a \\
\hline
Estimated age (Gyr) & 7.2 (2.0–12.0) \\
UT 1997 April 12 (HST): & \\
Separation (arcsec) & $0.27 \pm 0.01$ \\
Separation (AU) & $3.86 \pm 0.18$ \\
P.A. (deg) & $82.8 \pm 1.5$ \\
\hline
UT 2002 February 7 (AO): & \\
Separation (arcsec) & $0.207 \pm 0.007$ \\
Separation (AU) & $2.96 \pm 0.13$ \\
P.A. (deg) & $151.98 \pm 1.20$ \\
$P^a$ (yr) & 19–25 \\
$\Delta I$ (Cousins) & $4.42 \pm 0.17$ \\
$\Delta J$ & $3.83 \pm 0.60$ \\
$\Delta H$ & $3.15 \pm 0.30$ \\
$\Delta K$ & $2.77 \pm 0.10$ \\
\hline
\end{tabular}
\footnote{These numbers do not represent a robust determination of the period, simply an estimation given what information we have. See the text for more details.}
\end{table}

Fig. 2.—Absolute magnitudes vs. spectral type from Dahn et al. (2002) for all four bandpasses. For the $K_s$ plot, magnitudes were taken from the 2MASS database. The horizontal lines indicate our measured values (dotted lines show errors), while the vertical lines are our best-guess spectral types. Dark gray and light gray indicate the primary and secondary, respectively. We find a spectral type of M8 for the primary and L7.5 for the secondary to be consistent with all four observed filters.
2001), we find the probability that such an L dwarf would lie within 0°27 of the line of sight of LHS 2397a and have a similar proper motion is a negligible \(10^{-18}\).

As a result, taking into account orbital motion, these two objects form a common proper motion pair and are, therefore, physically associated. We denote the two components as LHS 2397aA and LHS 2397aB.

We can roughly estimate the period of the orbit to be 25 yr by assuming the fraction of the period observed is equal to the change in position angle of the secondary between the two observed dates. This period is not inconsistent with a substellar object orbiting LHS 2397aA. While two epochs of an orbit are insufficient to give a dynamical mass, we should be able to do so in another 5 yr. With such a short period, LHS 2397aB should be one of the first late-L dwarfs to have a dynamical mass. Note that the dynamical mass of the companion to 2MASSW J0920122+351742 (Reid et al. 2001) could be determined first.

6. AGE

Martín, Rebolo, & Magazzū (1994) have recorded a lithium nondetection of LHS 2397aA, giving \(\log N(\text{Li}) \lesssim 1.0\). Comparing this nondetection to the Chabrier et al. (2000) DUSTY models yields a minimum age of \(\sim 0.1\) Gyr. Unfortunately, the short-lived nature of Li gives little constraint on the age of the system. The fact that LHS 2397a is known to be a flare star (Bessell 1991) and has recorded Hα values between 15.3 and 47.3 Å (Tinney & Reid 1998; Gizis et al. 2000) suggests an older age for the system (given that it is a late-M star [Gizis et al. 2001]).

Since the total three-dimensional space velocity of LHS 2397a is known, we can determine a kinematic minimum age of the system. To do this we adopt Tinney & Reid (1998)'s heliocentric space motions for the system \((U_H, V_H, W_H) = (-30.0 \pm 2.1, -40.7 \pm 1.3, 8.6 \pm 1.4) \text{ km s}^{-1}\) and Dehnen & Binney’s (1998) solar velocity with respect to the local standard of rest (LSR) \((U_0, V_0, W_0) = (10.00 \pm 0.36, 5.25 \pm 0.62, 7.17 \pm 0.38) \text{ km s}^{-1}\). Therefore, our derived space velocity with respect to the LSR is \((U, V, W) = (-40.0 \pm 2.1, -46.0 \pm 1.4, 1.4 \pm 1.5) \text{ km s}^{-1}\). Using the method described by Lachaume et al. (1999), this translates into a statistical minimum age of 7.2 Gyr.

However, since the kinematic age is only statistical in nature (only true for 67% of stars), we conservatively choose the minimum age as 2 Gyr—that seen for stars in the solar neighborhood with similar space motions (Caloi et al. 1999). We denote the maximum age of the system as the maximum age of the solar neighborhood (12 Gyr; Binney, Dehnen, & Bertelli 2000). So our estimated age range for LHS 2397a is 2–12 Gyr, with a best-guess age of 7.2 Gyr.

7. MASS AND TEMPERATURE

Comparing the absolute \(K_s\) magnitudes of LHS 2397aA and LHS 2397aB to the Chabrier et al. (2000) DUSTY models, we can estimate the masses of the two components (see Fig. 3). We adopt a solar metallicity \((m/H) = 0\) as derived by Leggett, Allard, & Hauschildt (1998). The implied masses from these models are 0.090 \(M_\odot\) (0.089–0.094 \(M_\odot\)) for the primary and 0.068 \(M_\odot\) (0.061–0.069 \(M_\odot\)) for the secondary as summarized in Table 3. This gives a mass ratio for the system of \(q = 0.76\). We also find temperatures for the two components to be \(T_A = 2630 \text{ K}\) (2590–2660 K) and \(T_B = 1470 \text{ K}\) (1400–1500 K) for the primary and secondary, respectively. These temperatures are consistent with the independently derived relationships by Dahn et al. (2002). Note that the errors quoted for the mass and temperature only take into account observational errors and do not include virtually unquantifiable modeling errors.

Given these masses and assuming the semimajor axis of the orbit to be 3.86 AU, we derive a period of the system of 19 yr, which is consistent with the characteristic period calculated in § 5.

For the full range of \(M_{K_s}\) and age values, we find that the primary is a star and the secondary is unambiguously a brown dwarf.

8. IMPLICATIONS

LHS 2397aB appears to be the first clear example of a brown dwarf companion in a tight orbit around a low-mass star. As part of the same survey of 39 M8–L0 stars, two additional possible brown dwarf companions were both found at 3.9 AU from their respective primaries, and images

![Fig. 3.—Isochrones (0.1–12.6 by 0.5 Gyr) and isotherms (1400–2600 by 200 K) of the Chabrier et al. (2000) DUSTY \(K_s\) models with \([m/H] = 0\) are shown by solid and dashed lines, respectively. The polygons indicate the error boxes of each component, with black crosses marking the best-guess values.](image)

| Parameter | LHS 2397aA | LHS 2397aB |
|-----------|------------|------------|
| \(I\) (Cousins) | 15.07 ± 0.03 | 19.49 ± 0.17 |
| \(J\) | 11.86 ± 0.05 | 15.69 ± 0.60 |
| \(H\) | 11.32 ± 0.05 | 14.47 ± 0.30 |
| \(K_s\) | 10.80 ± 0.03 | 13.57 ± 0.10 |
| \(M_{K_s}\) (Cousins) | 14.29 ± 0.07 | 18.71 ± 0.18 |
| \(M_f\) | 11.09 ± 0.08 | 14.92 ± 0.61 |
| \(M_H\) | 10.54 ± 0.08 | 13.69 ± 0.31 |
| \(M_{K_s}\) | 10.03 ± 0.07 | 12.80 ± 0.12 |
| Spectral type\(a\) | M8 (±1) | L7.5 (±1) |
| Mass \((M_\odot)^b\) | 0.090 (0.089–0.094) | 0.068 (0.061–0.069) |
| Temp \((K)^b\) | 2630 (2590–2660) | 1470 (1400–1500) |

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\(a\) From the relationships of Dahn et al. 2002. See Fig. 2.

\(b\) From the models of Chabrier et al. 2000. See Fig. 3.
taken of the previously known binary 2MASSW J0746425+200032 (Reid et al. 2001) have determined the secondary to be a possible brown dwarf at 2.7 AU (Close et al. 2002b, 2002c). Therefore, taking into account the entire survey, this brings the brown dwarf companion frequency around low-mass stars up to 3%–10% at separations of 2–4 AU. This is 5–21 times the observed brown dwarf frequency around Sun-like stars within 3 AU (0.5%). It is important to note that we are insensitive to secondaries less than ~60 MJ at 2–4 AU and likely to all within 2 AU. Given the apparent fact that low-mass binaries tend to be tight, we may be missing a large number of brown dwarf companions. Therefore, this frequency estimate is only a lower limit to the true frequency.

The relatively high observed brown dwarf companion frequency (3%–10%) to low-mass stars as opposed to the very low frequency for Sun-like stars (0.5%) may hint that the “brown dwarf desert” does not apply to low-mass primaries. In addition, the dearth of brown dwarf companions to low-mass stars at large separations is possibly in contrast to what is observed for Sun-like stars.

Several groups have proposed theories explaining why the “brown dwarf desert” exists. Armitage & Bonnell (2002) propose that orbital migration due to a protoplanetary disk “dragging” low-mass objects into the primary could result in the so-called desert. Since the disk would be more massive at smaller separations, it would be in a better position to pull low-mass objects into the central star. The objects being “dragged” must be comparable to (or smaller than) the disk’s characteristic mass for the disk to have a migratory effect. The close separation of LHS 2397aB is consistent with this theory since lower mass primaries are expected to form with lower mass protoplanetary disks, which would not be massive enough to “drag” a brown dwarf. While this theory does explain the existence of companions at small separations well, it is difficult to envision how it could produce a lack of binaries at large separations around low-mass primaries if they are formed by a cloud fragmentation mechanism.

If the formation mechanism is disk fragmentation, the lack of wide-separation binaries could easily be attributed to a lack of material at large separations. However, this scenario tends to form lower mass ratio binaries than those observed. The maximum mass that can produce a stable disk around a star can be represented by the maximum solar nebula, which is given by $M_{\text{disk}} \approx 0.31 M_{\text{star}}$ (Shu et al. 1990). Assuming the extreme case that all the disk material is used, the highest mass ratio system that could be formed has $q = 0.31$. In contrast, the observed low-mass binary population produces components that are nearly equal mass ($q > 0.6$). Therefore, cloud fragmentation is generally the favored formation scenario for low-mass binaries. In this case, the separation of the companion from its primary is independent of the circumstellar disk size.

In another formation mechanism, Reipurth & Clarke (2001) postulate that brown dwarfs are simply ejected stellar embryos that could not accrete enough matter to become stars. Failing to compete with their larger counterparts, these “low-mass embryos” are kicked out of the system to become free-floating objects. In this scenario the existence of brown dwarfs close to large Sun-like stars is very unlikely; hence the “brown dwarf desert.” When a low-mass binary is ejected, brown dwarf companions at large separations from low-mass stars are stripped from the binary—so no wide low-mass binaries should be observed. Tight low-mass binaries should also be rare, but not impossible; a hydrodynamical star formation simulation by Bate, Bonnell, & Bromm (2002) finds a binary brown dwarf frequency of $\leq 5\%$. The binary frequency of brown dwarfs to M8–L0 stars we observe is consistent with this prediction. However, other observations including a larger range of primary and secondary masses find that $\sim 20\%$ of low-mass primaries have companions, which is larger than the theoretical predictions.

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REFERENCES

Armitage, P. J., & Bonnell, I. A. 2002, MNRAS, 330, L11
Bakos, G. A., Salu, K. C., & Németh, P. 2002, ApJS, 141, 187
Bate, M. R., Bonnell, I. A., & Bromm, V. 2002, MNRAS, 332, L65
Bessell, M. S. 1991, AJ, 101, 662
Binney, J., Dehnen, W., & Bertelli, G. 2000, MNRAS, 318, 658
Burgasser, A. J., Reid, I. N., Kirkpatrick, J. D., Brown, M. E., Miskey, C. L., & Gizis, J. E. 2003, ApJ, in press
Caloi, V., Cardini, D., D’Antona, F., Badioli, M., Emanuele, A., & Mazzitelli, I. 1999, A&A, 351, 925
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Close, L. M., Potter, D., Brander, W., Lloyd-Hart, M., Liebert, J., Burrows, A., & Siegler, N. 2002a, ApJ, 566, 1095
Close, L. M., Siegler, N., Freed, M., & Biller, B. 2002b, ApJ, submitted
Close, L. M., Siegler, N., Potter, D., Brander, W., & Liebert, J. 2002c, ApJ, 567, L53
Dahn, C. C., et al. 2002, AJ, 124, 1170
Dehnen, W., & Binney, J. 1998, MNRAS, 298, 387
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., Reid, I. N., Monet, D. G., Liebert, J., & Wilson, J. C. 2001, ApJ, 551, L163
Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000, AJ, 120, 1085
Graves, J. E., Northcott, M. J., Roddier, F. J., Roddier, C. A., & Close, L. M. 1998, Proc. SPIE, 3353, 34
Hinz, J. L., McCarthy, D. W., Simons, D. A., Henry, T. J., Kirkpatrick, J. O., & McGuire, P. C. 2002, AJ, 123, 2027
Hodapp, K.-W., et al. 1996, NewA, 1, 177
Kirkpatrick, J. D., Allard, F., Bida, T., Zucker, B., Becklin, E. E., Chabrier, G., & Baraffe, I. 1999a, ApJ, 519, 834
Kirkpatrick, J. D., Dahn, C. C., Monet, D. G., Reid, I. N., Gizis, J. E., Liebert, J., & Burgasser, A. J. 2001, AJ, 121, 3235
Kirkpatrick, J. D., & Henry, T. J. 1997, Hubble Space Telescope Proposal 6345
Kirkpatrick, J. D., et al. 1999b, ApJ, 519, 802
———. 2000, AJ, 120, 447
Lachaume, R., Dominik, C., Lanz, T., & Habing, H. J. 1999, A&A, 348, 897
Leggett, S. K., Allard, F., & Hauschildt, P. H. 1998, ApJ, 509, 836
Leggett, S. K., et al. 2002, ApJ, 564, 452
Liu, M. C., Fischer, D. A., Graham, J. R., Lloyd, J. P., Marcy, G. W., & Butler, R. P. 2002, ApJ, 571, 519
Luyten, W. J. 1979, LHS Catalog (2d ed.; Minneapolis: Univ. Minnesota)
Marcy, G., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2003, in ASP Conf. Ser., Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming, & S. Seager (San Francisco: ASP), in press
Martín, E. L., Brandt, W., Bouvier, J., Luhman, K. L., Stauffer, J., Basri, G., Zapatero Osorio, M. R., & Barrado y Navascués, D. 2000, ApJ, 543, 299
Martín, E. L., Rebolo, R., & Magazzù, A. 1994, ApJ, 436, 262
Mazeh, T., Goldberg, D., Duquennoy, A., & Mayor, M. 1992, ApJ, 401, 265
Oppenheimer, B. R., Golimowski, D. A., Kulkarni, S. R., Matthews, K., Nakajima, T., Creech-Eakman, M., & Durrance, S. T. 2001, AJ, 121, 2189
Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001, AJ, 121, 489
Reid, I. N., et al. 2000, AJ, 119, 369
Reipurth, B., & Clarke, C. 2001, AJ, 122, 432
Shu, F. H., Tremaine, S., Adams, F. C., & Ruden, S. P. 1990, ApJ, 358, 495
Stetson, P. B. 1987, PASP, 99, 191
Tinney, C. G. 1996, MNRAS, 281, 644
Tinney, C. G., & Reid, I. N. 1998, MNRAS, 301, 1031
van Altena, W. F., Lee, J. T., & Hoffleit, D. 1995, The General Catalog of Trigonometric Stellar Parallaxes (4th ed.; New Haven: Yale Univ. Obs.)
Wilson, J. C., Kirkpatrick, J. D., Gizis, J. E., Skrutskie, M. F., Monet, D. G., & Houck, J. R. 2001, AJ, 122, 1989