The Astronomical Journal, 132:2074–2081, 2006 November

RESOLVED SPECTROSCOPY OF M DWARF/L DWARF BINARIES. II. 2MASS J17072343−0558249AB

Michael W. McElwain[1]
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1562; mcelwain@astro.ucla.edu

and

Adam J. Burgasser[1]
Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue,
Building 37, Cambridge, MA 02139-4307; ajb@mit.edu
Received 2006 February 28; accepted 2006 July 31

ABSTRACT

We present Infrared Telescope Facility SpeX observations of the M/L binary system 2MASS J17072343−0558249. SpeX imaging resolves the system into a 1.″01 ± 0.″17 visual binary in which both components have red near-infrared colors. Resolved low-resolution ($R \sim 150$) 0.8–2.5 μm spectroscopy reveals strong H_2O, CO, and FeH bands and alkali lines in the spectra of both components, characteristic of late-type M and L dwarfs. A comparison to a sample of late-type field dwarf spectra indicates spectral types M9 and L3. Despite the small proper motion of the system (0.″100 ± 0.″009 yr^{-1}), imaging observations over 2.5 yr provide strong evidence that the two components share common proper motion. Physical association is also likely due to the small spatial volume occupied by the two components (based on spectrophotometric distance estimates of 15 ± 1 pc) as compared to the relatively low spatial density of low-mass field stars. The projected separation of the system is 15 ± 3 AU, similar to other late-type M and L binaries. Assuming a system age of 0.5–5 Gyr, we estimate the masses of the binary components to be 0.072–0.083 and 0.064–0.077 $M_\odot$, with an orbital period of roughly 150–300 yr. While this is nominally too long a baseline for astrometric mass measurements, the proximity and relatively wide angular separation of the 2MASS J1707−0558AB pair make it an ideal system for studying the M dwarf/L dwarf transition at a fixed age and metallicity.

Key words: binaries: visual — stars: individual (2MASS J17072343−0558249) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Wide-field photographic imaging and proper-motion surveys of the past were largely incapable of producing an accurate census of nearby very low mass (VLM; $M < 0.1\, M_\odot$) stars and brown dwarfs. Late-type dwarfs emit weakly at visual bands but are brighter at red optical and near-infrared wavelengths. Progress in optical and infrared detector technology has paved the way for the current generation of wide-field sky surveys, most notably the Deep Near-Infrared Survey of the Southern Sky (Epchtein et al. 1997), the Sloan Digital Sky Survey (York et al. 2000), and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). Searches for faint red sources in these catalogs (e.g., Delfosse et al. 1997; Kirkpatrick et al. 1999; Fan et al. 2000) have identified hundreds of VLM stars and brown dwarfs, greatly expanding our VLM census and revealing the new spectral classes L (Kirkpatrick et al. 1999; Martín et al. 1999) and T (Burgasser et al. 2002; Geballe et al. 2002).

The nascent field of VLM stars has been confronted with a number of fundamental questions regarding the properties of low-luminosity sources, including formation scenarios, thermal evolution, chemical compositions and dynamics of cool stellar/substellar atmospheres, and the initial mass function. Multiple star systems are important laboratories for understanding these physical properties. Binary systems are key in the determination of stellar masses, which can be used to calibrate theoretical evolutionary and structure models. Binary parameters probe the star formation process, and relative comparisons can be made between coeval components. Searches for cool dwarf binaries through high-resolution imaging have been conducted to explore the nature of VLM stars and brown dwarfs (e.g., Martín et al. 1999; Koerner et al. 1999; Reid et al. 2001; Close et al. 2002, 2003; Bouy et al. 2003; Burgasser et al. 2003a, 2006a; Gizis et al. 2003; Siegler et al. 2005; Law et al. 2006). The result of these efforts has been the discovery of roughly 75 VLM binary systems with varying mass ratios and projected separations (cf. Burgasser et al. 2006b).

The properties of the current sample of VLM stars and brown dwarfs suggest that both the multiplicity fraction and the peak of the semimajor axis distribution are directly related to the primary star mass. G to M binaries tend to peak at separations of 3–30 AU (Fischer & Marcy 1992; Henry & McCarthy 1993; Reid & Gizis 1997), with binary fractions $f_{\rm bin}$ ranging from ∼65% (Duquennoy & Mayor 1991) down to ∼30% (Fischer & Marcy 1992; Reid et al. 2004; Delfosse et al. 2004). In contrast, nearly all VLM binaries have separations $\rho \lesssim 20$ AU, with a binary fraction $f_{\rm bin} \approx 15\%$ (e.g., Close et al. 2003; however, see also Maxted & Jeffries 2005). The low frequency and preference of small separations for VLM binaries is a challenge for star formation theories, and a clear understanding of binary parameters as a function of mass, age, and metallicity provides empirical clues about VLM star and brown dwarf formation processes.

Studies of VLM binaries also reveal the detailed properties of cool star and brown dwarf atmospheres. Dust formation and evolution remains an outstanding problem across the spectral transition from M dwarfs to L dwarfs (hereafter the "M/L transition"), where lower temperatures and higher pressures enable some molecules to form solid condensates and descend from the photosphere, changing the overall morphology of the spectrum and the

[1] Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under cooperative agreement NCC 5-538 with the National Aeronautics and Space Administration, Office of Space Science, Planetary Astronomy Program.

TABLE 1
Observing Log

UT Date	Observation	t_{int} (s)	Air Mass	*J*-Band Seeing (arcsec)	Calibrator
2003 Mar 23	*JHK* imaging	60, 60, 60	1.17	0.5	None
	0.8−2.5 μm spectroscopy	480 (A), 720 (B)	1.16	0.5	HD 171149
2004 Aug 9	*JHK* imaging	80, 60, 48	1.17	0.9	USNO-A2.0 0825−10078125
2004 Aug 10	*JK* imaging	40, 40	1.15	0.9	USNO-A2.0 0825−10079794

atmospheric pressure/temperature profile (Lunine et al. 1989; Tsuji et al. 1996; Lodders 1999, 2002; Burrows & Sharp 1999; Ackerman & Marley 2001; Lodders & Fegley 2002). In particular, M dwarfs are characterized by their strong TiO and VO absorption bands; but as temperatures descend into the L dwarf regime, refractory elements such as Fe, Mg, Ti, V, Al, and Ca are removed from the gas in the photosphere by the condensation and sedimentation process. Theoretical models examining these processes are compared to the existing spectra of field dwarfs, which have a variety of metallicities, masses, and ages. M/L binaries, on the other hand, can help clarify the existence of atmospheric condensation by isolating parameters such as age and metallicity, assuming coevality.

A total of 14 binaries comprised of M and L dwarf components have been discovered to date (Gizis et al. 2000a, 2003; Bouy et al. 2003; Close et al. 2003; Freed et al. 2003; Martín et al. 2003; Siegler et al. 2003, 2005; Chauvin et al. 2004, 2005; Billères et al. 2005; Burgasser & McElwain 2006). This paper presents the discovery of a new M/L binary,[2] 2MASS J17072343−0558249AB (2MASS 1707−0558), identified via resolved near-infrared imaging and spectroscopy using the SpeX instrument (Rayner et al. 2003) mounted at the 3 m NASA Infrared Telescope Facility (IRTF). In § 2 we describe our observations and data reduction and present results. In § 3 we analyze these data, determining individual spectral types for the resolved components and the photometric properties of the system. We argue for physical association by common proper motion, similar spectrophotometric distances, and comparing the volume occupied by the M/L pair to the measured density of VLM dwarfs in the solar neighborhood. We also make preliminary estimates of the individual masses and orbital characteristics of the system. We discuss our results in § 4, placing the 2MASS 1707−0558 system in context with other VLM binaries. This work is summarized in § 5.

2. OBSERVATIONS

The unresolved source 2MASS 1707−0558 was discovered by Gizis (2002) in a search for late-type dwarfs in the direction of the TW Hydrae association using 2MASS. Optical spectroscopy of the composite system infers a spectral type of M9 on the Kirkpatrick et al. (1999) late-M and L dwarf scale and confirms this source as a normal field dwarf. Hα emission, common for late-type M dwarfs (Gizis et al. 2000b; West et al. 2004), was observed with an equivalent width of 0.4 Å. The signal-to-noise ratio (S/N) and resolution of the optical spectrum were not sufficient to detect the 6708 Å Li i line, so this source was suspected to be a nearby hydrogen-burning star or brown dwarf.

2.1. *Imaging*

The target 2MASS 1707−0558 was first observed on 2003 March 23 (UT) as a spectral comparison star for the 2MASS Wide-Field T Dwarf Search program (Burgasser et al. 2003b). Observing conditions were good, with 0.″5 seeing at the *J* band, and the SpeX imager/guider was used to sample a $60'' \times 60''$ field of view at 0.″12 pixel^{-1}. While acquiring 2MASS 1707−0558 with the imager, we resolved two sources at the given sky position. We subsequently obtained *J*, *H*, and *K*[3] images of the visual pair for color comparison. Integrations of 15 s were obtained in four dithered exposures on the chip. A second series of images was obtained on 2004 August 9, with slightly hazy conditions and 0.″9 seeing at *J*. Images were slightly out of focus during the second campaign. Integrations of 20, 15, and 12 s with four dithers were obtained in the *J*, *H*, and *K* band, respectively. We observed the single star USNO-A2.0 0825−10078125 (Monet et al. 1998) concurrently with the 2MASS 1707−0558 observations to serve as a point-spread function (PSF) calibrator. Finally, a third epoch of images was obtained on 2005 August 10, during poor conditions and 0.″9 seeing at *J*. Integrations of 10 s with four dithers were obtained in both the *J* and *K* band. In 2005 we observed the nearby star USNO-A2.0 0825−10079794 as a PSF calibrator. A log of our imaging observations is provided in Table 1.

All imaging data were reduced in a typical procedure for near-infrared imaging. Flat fields were constructed with sky frames, which were median-combined, subtracted by a median-combined dark frame of the same integration time, and normalized. An image mask was constructed to distinguish deviant pixels that were excessively bright in the dark frames and cold in the sky flats. The target and PSF images were pairwise subtracted, divided by the normalized flat, cleaned by linear interpolation over the bad pixels, and added together by integer pixel shifts to match the peak flux position of the brighter source.

Reduced *J*-, *H*-, and *K*-band images from the 2003 observations of 2MASS 1707−0558 are displayed in Figure 1. The two sources are clearly resolved in all three bands and separated by roughly 1″ on the sky. We discuss the relative fluxes and astrometry for the pair in § 3.1.

2.2. *Spectroscopy*

Near-infrared spectra of both components were acquired on 2003 May 23 (UT) with SpeX in prism mode, using the 0.″5 slit. This configuration yields a single-order, low-resolution ($R \sim 150$) 0.8−2.5 μm spectrum with a dispersion of 20−30 Å pixel^{-1} onto the Aladdin 3 1024×1024 InSb array. Conditions during the observations were good, with seeing of 0.″5 at the *J* band, and the target was observed at an air mass of 1.16. In order to obtain the spectrum of each component separately, we aligned the slit

[2] Reid et al. (2006) have concurrently resolved this system using the *Hubble Space Telescope* NICMOS instrument. Their photometric estimates of the spectral types and distance of the 2MASS 1707−0558AB system agree with our analysis.

[3] *JHK* filters for SpeX are based on the Mauna Kea Observatories near-infrared (MKO-NIR) system (Simons & Tokunaga 2002; Tokunaga et al. 2002).

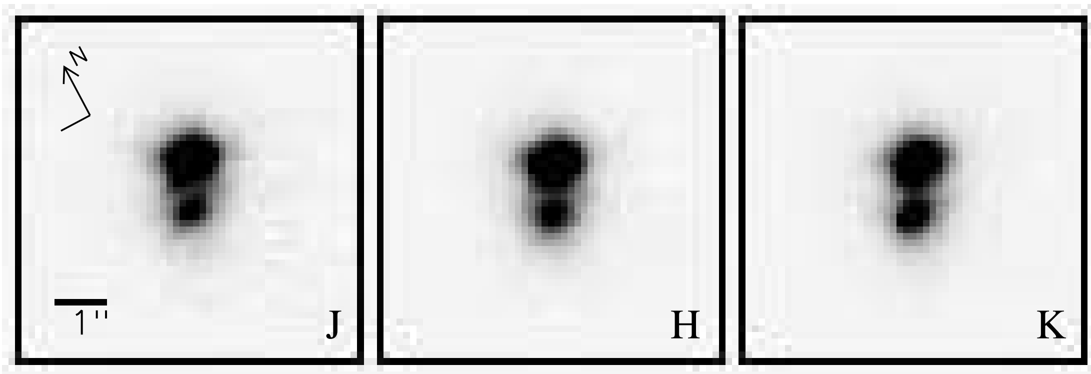

FIG. 1.—Reduced mosaic discovery images of 2MASS 1707−0558AB in the *J* (*left*), *H* (*middle*), and *K* bands (*right*) obtained on 2003 March 23. Images are 6″ on a side, with north (arrow) and east (line) indicated in the left panel.

perpendicular to the orientation of the two sources, guiding on one component while observing the other through the slit. Based on the slit width, component separation, and PSF full width at half-maximum, we estimate that only 4%–6% of the light from the guiding component contaminated the slit. Exposures of 120 and 180 s were taken as dithered pairs for the brighter and fainter components, respectively. The A0 star HD 171149 was observed immediately after the target exposures at a similar air mass (1.17), followed by internal flat-field and Ar arc lamps for pixel response and wavelength calibration.

Data were reduced using the Spextool package, version 3.2 (Cushing et al. 2004). The raw target data were processed by performing linearity corrections, pairwise subtraction, and division by a normalized flat field. The target spectra were then extracted using the Spextool default settings for point sources, and wavelength solutions were calculated using the Ar arc calibration frames. Extracted spectra from the same source were scaled to match the highest S/N spectrum of the set, and the scaled spectra were median-combined. The resulting spectrum was cleared of telluric features, intrinsic A0 V star lines, and instrumental response signatures following the procedures of Vacca et al. (2003). A Vega model spectrum was employed to produce a true telluric spectrum from the A0 standard. The model spectrum was shifted to match the radial velocity of the standard spectrum, and then the modified model spectrum was reddened and scaled to match the standard spectrum. Line shape kernels were constructed using unresolved arc lines from the wavelength calibration observations. These kernels were then used to broaden the model spectrum line widths and smooth the model spectrum to match the observed resolution. The model spectrum was completed by adjusting the H line strengths to reflect that of the observed A0 standard. The corrected telluric spectrum is constructed by dividing the model spectrum by the A0 spectrum. The corrected telluric spectrum is then multiplied by the target spectrum to produce the final flux-calibrated spectrum.

The reduced spectra of the two components are plotted in Figure 2. The spectrum of the bright component exhibits TiO absorption at 0.76, 0.82, and 0.84 μm; VO absorption at 1.05 μm; K I doublets at 1.17 and 1.25 μm; the onset of FeH absorption at 0.98, 1.19, and 1.58 μm; CO at 2.3 μm; and strong H_2O absorption at 1.4 and 1.9 μm. The spectrum of the faint component has diminished TiO and VO absorption features but still shows the CrH, K I doublet, FeH, CO, and H_2O absorption features. In addition, the peak flux of the spectral energy distribution for the faint component is also shifted redward to 1.28 μm. These spectral features suggest that the bright component is a late M dwarf, consistent with the optical spectral type of Gizis (2002), while the faint component shows features that are indicative of an early L dwarf. We discuss the classification of these sources in further detail in § 3.2.

3. ANALYSIS

3.1. *PSF Fitting*

The PSF wings of the two sources at the position of 2MASS 1707−0558 are slightly blended in the 0″.5, 0″.9, and 0″.9 seeing of the 2003, 2004, and 2005 image data, respectively. We therefore determined the relative fluxes and astrometry of the pair through a PSF-fitting algorithm similar to that employed by Burgasser & McElwain (2006). For the 2004 and 2005 images, we used a comparison star as the PSF model. For each filter, the components of the 2MASS 1707−0558 pair were first fitted to a two-dimensional Gaussian to determine the approximate flux center and a rough estimate of the peak amplitude. A synthetic image was created by shifting, scaling, and adding the corresponding

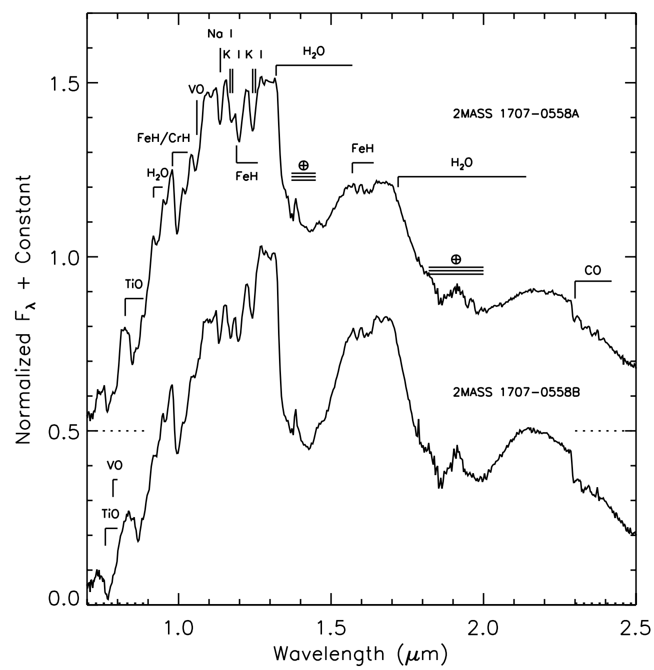

FIG. 2.—Near-infrared SpeX spectra of 2MASS 1707−0558A (*top*) and B (*bottom*), with the major absorption features of TiO, VO, H_2O, FeH, CrH, Na I, and K I indicated, as well as regions affected by telluric absorption (*circled plus signs*). All data are normalized at 1.27 μm and offset by a constant. The zero point of each spectrum is designated by a dotted line.

TABLE 2
2MASS 1707−0558 System Astrometry

	Measured Astrometry		Expected Astrometry if Background Source	
Date	Offset (arcsec)	P.A. (deg)	Offset (arcsec)	P.A. (deg)
2003 Mar 23	1.04 ± 0.04	145 ± 2	. . .	. . .
2004 Aug 9	0.99 ± 0.09	144 ± 3	0.97 ± 0.04	147 ± 2
2004 Aug 10	0.99 ± 0.14	142 ± 3	0.94 ± 0.04	152 ± 2

PSF star images to match each of the component positions and fluxes. This model image was subtracted from the original, and the standard deviation of the residual image was used to measure the quality of the fit. The model image was iteratively modified, changing the position of the primary, the position of the secondary, the peak flux of the primary, and the peak flux of the secondary, in that order, to improve the fit until a minimum in the standard deviation of the residual image was achieved. This routine was performed on every pairwise-subtracted image for each filter in order to estimate the experimental uncertainty of the fits. For the 2003 data, which did not include a PSF comparison star, we used the same algorithm with a fixed-width Gaussian profile to model the PSF. The astrometric results—measured separations (ρ) and position angle (ϕ)—are listed in Table 2. Relative magnitudes and aggregate astrometric measurements are given in Table 3. The uncertainties in all of these measurements correspond to the 1 σ scatter in the values computed from all image frames.

Relative magnitudes were measured using MKO-NIR filters, but composite systemic photometry is on the 2MASS system. In order to derive an apparent magnitude for each component, we converted the MKO-NIR relative magnitudes ($\Delta M^{\rm MKO}$) to the 2MASS system as follows:

$$\Delta M^{\rm 2MASS} = M_b^{\rm 2MASS} - M_a^{\rm 2MASS} \quad (1)$$

$$= M_b^{\rm MKO} - M_a^{\rm MKO} + \left(M_b^{\rm 2MASS} - M_b^{\rm MKO}\right) - \left(M_a^{\rm 2MASS} - M_a^{\rm MKO}\right) \quad (2)$$

$$= \Delta M^{\rm MKO} + \delta_b - \delta_a, \quad (3)$$

where $\delta \equiv M^{\rm 2MASS} - M^{\rm MKO}$ is the filter translation factor. These values were determined by calculating synthetic magnitudes from the spectra of the 2MASS 1707−0558 components, using MKO-NIR and 2MASS relative response curves [$R_M(\lambda)$ = filter M transmission function times optical response times telluric absorption at an air mass of 1] from S. Leggett (2004, private communication) and Cohen et al. (2003),[4] respectively:[5]

$$M = -2.5 \log_{10}\left[\frac{\int f_\lambda(\lambda) R_X(\lambda)\, d\lambda}{\int f_\lambda^{\rm Vega}(\lambda) R_M(\lambda)\, d\lambda}\right]. \quad (4)$$

[4] See Cutri et al. (2003) § IV.4.a, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4a.html#rsr.

[5] Note that we do not include an additional factor of λ/hc in eq. (4) for the MKO-NIR filters to compensate for the photon-counting properties of current detectors (this factor is already included in the response curves of Cohen et al. 2003). This omission only leads to an ~0.01 mag offset in the derived magnitudes for late-type dwarf spectra (Stephens & Leggett 2004). We thank our referee for pointing out this detail.

TABLE 3
2MASS 1707−0558AB System Properties

Parameter	Value	Notes[a]
α[b]	$17^{\rm h}07^{\rm m}23\overset{\rm s}{.}43$	1
δ[b]	−05°58′24″.9	1
μ	0″.100 ± 0″.008 yr^{-1}	2
θ	88° ± 10°	2
d[c]	15 ± 1 pc	3
ρ	1″.01 ± 0″.17	3
	15 ± 3 AU[d]	3
ϕ	145° ± 3°	3
J[e]	12.05 ± 0.02 mag	1
H[e]	11.26 ± 0.03 mag	1
K_s[e]	10.71 ± 0.02 mag	1
ΔJ	1.71 ± 0.15 mag	3
ΔH	1.14 ± 0.10 mag	3
ΔK_s	1.18 ± 0.12 mag	3
$M_{\rm tot}$[f]	0.136–0.160 $M_\odot$	3, 4
q[f]	0.88–0.92	3, 4
Period[f]	~150–300 yr	3, 4

[a] (1) 2MASS (Skrutskie et al. 2006); (2) SuperCosmos Sky Survey (Hambly et al. 2001a, 2001b, 2001c); (3) this paper; (4) Burrows et al. (1997).
[b] Equinox J2000.0 coordinates at epoch 1999 April 9 from 2MASS.
[c] Spectrophotometric distances derived using absolute magnitude/spectral type relations; see § 3.3.
[d] Physical separation derived from the angular separation and the spectrophotometric distance.
[e] 2MASS photometry of the unresolved system.
[f] Assuming an age of 0.5–5 Gyr.

Here $f_\lambda^{\rm Vega}$ is the observed spectrum of the A0 V star Vega from Hayes et al. (1985). The filter translation factors were measured to be $\delta_{J,b} - \delta_{J,a} = -0.026$, $\delta_{H,b} - \delta_{H,a} = 0.013$, and $\delta_{K,b} - \delta_{K,a} = 0.002$. Using these values, individual component magnitudes were computed from the composite 2MASS magnitudes for the 2004 and 2005 observations; mean values and their errors are listed in Table 3.

3.2. *Spectral Classification*

Spectral classification of stars is traditionally performed by comparison to a template of spectral standards observed with the same dispersion and S/N (Morgan et al. 1943). Unfortunately, a set of M and L dwarf spectral standards does not yet exist in the near-infrared, although methods of near-infrared classification have been considered by various groups (Tokunaga & Kobayashi 1999; Reid et al. 2001; Testi et al. 2001; Burgasser et al. 2002; Geballe et al. 2002; McLean et al. 2003). Here we simply compare the component spectra of 2MASS 1707−0558 to previously observed SpeX data for the optical late-M and L dwarf spectral standards (Burgasser et al. 2004; K. L. Cruz et al. 2007, in preparation). Figure 3 overlays the normalized 2MASS 1707−0558 component spectra with those of the comparison stars to demonstrate the best spectral type fit for each component. The northern component spectrum matches the M9 optical spectral standard LHS 2924 (Probst & Liebert 1983; Kirkpatrick et al. 1991) quite well, with equivalent depths of the TiO and VO bands, and maintains a similar shape over the entire spectrum. The southern component spectrum exhibits diminished TiO and VO features and increased H_2O absorption, matching that of the L3 field dwarf SDSS 2028+0052 (Hawley et al. 2002). Since we did not align the slit with the parallactic angle, we notice slight effects of differential atmospheric dispersion through the light lost in the K-band section of

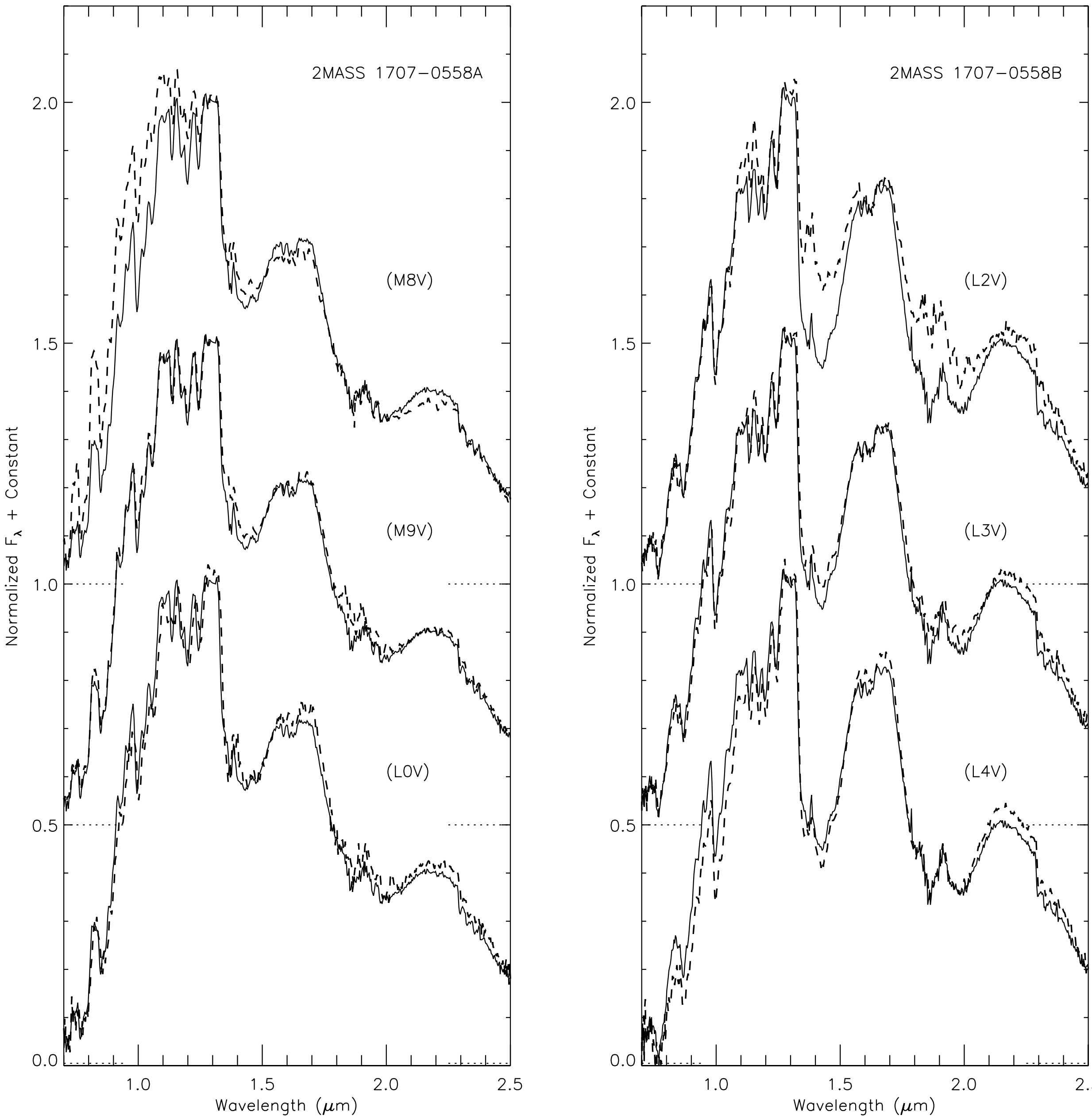

Fig. 3.—Comparison of 2MASS 1707−0558A and B spectra (*solid lines*) to optically defined spectral standards (*dashed lines*). *Left:* 2MASS 1707−0558A overlaid on the spectral standards VB 10 (M8; Probst & Liebert 1983; Kirkpatrick et al. 1991), LHS 2924 (M9; Probst & Liebert 1983; Kirkpatrick et al. 1991), and 2MASS 0345+2550 (L0; Kirkpatrick et al. 1997). *Right:* 2MASS 1707−0558B overlaid on 2MASS 0847−1532 (L2; Cruz et al. 2003), SDSS 2028+0052 (L3; Hawley et al. 2002), and 2MASS 1104+1959 (L4; Cruz et al. 2003). All data are normalized at 1.27 μm and offset by a constant.

the spectrum. While M and L spectral type classifications are generally defined at optical wavelengths, the excellent agreement between the 2MASS 1707−0558 near-infrared spectra and those of the spectral comparators suggests that our classifications are consistent with the optical types and accurate to within 0.5 subclasses.

An alternative method for near-infrared classification is the calculation of spectral indices of diagnostic regions of the spectrum that are correlated with spectral types. We measured the Reid et al. (2001) H_2O-A and H_2O-B indices, sampling the 1.3 and 1.5 μm steam bands, respectively, and the K1 index (Tokunaga & Kobayashi 1999), a probe of H_2O absorption at 2.0 μm. We then used the spectral type calibrations given in Reid et al. (2001) appropriate over optical spectral types M8 to L6 to derive classifications of M9 and L2 for the brighter and fainter components, respectively, with an uncertainty of two spectral types, as determined by the dispersions in each of the linear spectral type fits. Therefore, the spectral indices confirm the spectral types assigned by the spectral comparison method, but the large errors of this classification method prohibit a more precise estimate of the spectral types.

3.3. *Are the Components of 2MASS 1707−0558 Gravitationally Bound?*

The angular proximity of the 2MASS 1707−0558 components, as well as their similar brightnesses and spectral types, infer that the two components are gravitationally bound. One of the more conclusive tests of physical association is the detection of common space motion. We examined the astrometry of the system over three epochs spanning 2.47 yr to determine whether the pair shared common proper motion. Table 2 lists the astrometric

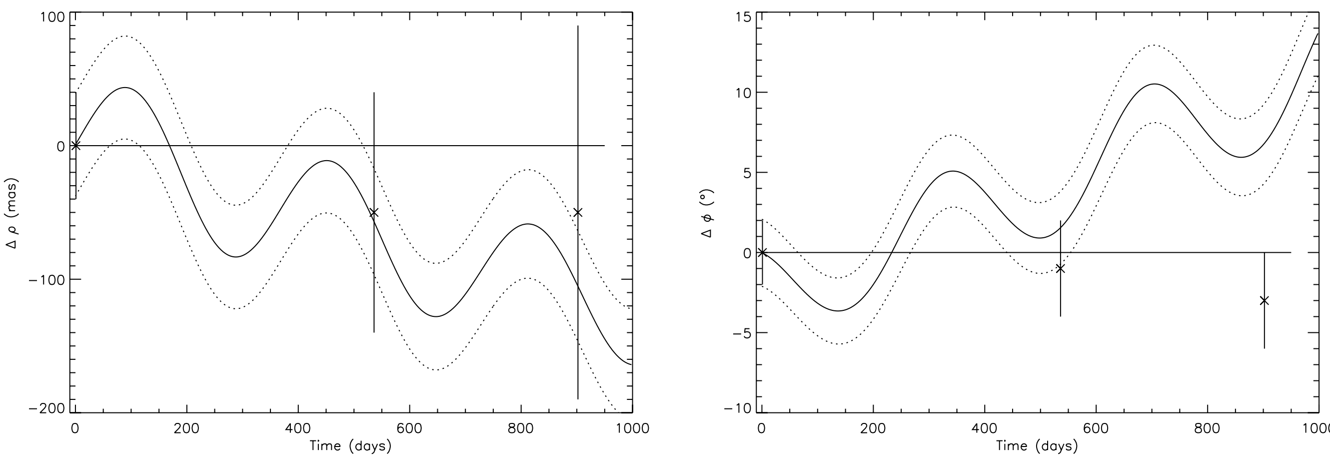

Fig. 4.—Astrometric motion of 2MASS 1707−0558B relative to A. Curves show the angular separation (*left*) and position angle (*right*) expected for an unmoving, unassociated background source, with dotted lines corresponding to the 1 σ errors in the estimated positions. The horizontal line marks the position of a companion sharing common proper motion with the primary. Data points are the mean values from the PSF-fitting algorithm, with the errors corresponding to the 1 σ uncertainty in these measurements. The periodicity of the relative background source position is due to the parallactic motion of the primary at its estimated spectrophotometric distance (15 ± 1 pc).

results from the PSF fitting, as well as the expected astrometric results if the secondary object were an unrelated, unmoving background source. Figure 4 displays the expected separation and position angle of the system over time if the system is not gravitationally bound, with overlying data points for the measurements from the PSF fitting. A constant separation and position angle over time confirms common proper motion. The proper motion of 2MASS 1707−0558, $\rho = 0\farcs100 \pm 0\farcs008$ at $88^\circ \pm 10^\circ$ (from the SuperCosmos Sky Survey; Hambly et al. 2001a, 2001b, 2001c), is small and implies angular motion of only $0\farcs25$ over our observational baseline, about 2 pixels at the SpeX plate scale. Our observations are not precise enough to establish common proper motion through the angular separation of the two components; however, our position angle measurements (accurate to 2°–3°) can rule out a stationary background source at the 2.9 σ (99.6%) confidence level.

We compare our spectral types and photometric relative magnitudes derived by PSF fitting to the predicted relative magnitudes for an M9 and L3 binary system. Cruz et al. (2003) produces a polynomial M_J/spectral type relation (based on 2MASS photometry) using a sample of ultracool dwarfs (M6–L8) identified in the 2MASS catalog with independent parallax measurements. Assuming that the stars are located at the same distance and are of spectral type M9 and L3, the empirical polynomial fit gives $\Delta M_J = 1.20 \pm 0.35$, consistent with our value of $\Delta M_J = 1.71 \pm 0.15$. There is no parallax measurement for 2MASS 1707−0558, but spectrophotometric distances can be estimated by comparing the apparent magnitudes of each component to the absolute magnitudes typical for M9 and L3 dwarfs, as calculated using low-mass absolute magnitude/spectral type relations (Dahn et al. 2002; Cruz et al. 2003; Vrba et al. 2004). The two observed sources in this system lie at a mean distance of 15 pc, with a 1 pc standard deviation in our measurements.

But what if these two sources are nearby but unaffiliated late-type dwarfs? We also find that the chance alignment of two similarly classified low-mass stars within 1″ of each other is highly improbable. Cruz et al. (2003) performed a wide-field search for VLM stars, discovering 30 M9–L3 stars over an area of 16,350 deg^2 at a depth of 20 pc, indicating a space density for these stars of $\rho \approx 0.002$ pc^{-3}. At a distance of 15 ± 1 pc and an angular separation of 1″, we estimate the volume of space occupied by the components of 2MASS 1707−0558 to be $V \approx 3.3 \times 10^{-8}$ pc^3. Assuming Poisson statistics, the probability (P) that one or more random low-mass stars would be located within this volume of space can be calculated as

$$P = 1 - e^{-\rho V}, \tag{5}$$

or 10^{-10}, ruling out chance alignment with high confidence. All the tests discussed in this section lead us to conclude that the components of 2MASS 1707−0558 comprise a gravitationally bound system.

4. DISCUSSION

4.1. *2MASS 1707−0558AB System Characteristics*

We calculate the projected physical separation of 2MASS 1707−0558AB to be 15 ± 3 AU, based on the astrometric measurements and derived spectrophotometric distance. Temperatures for the two components can be derived using the $T_{\rm eff}$/spectral type relation for low-mass stars from Golimowski et al. (2004), yielding $T_{\rm eff} = 2400 \pm 175$ K for 2MASS 1707−0558A and 1950 ± 190 K for 2MASS 1707−0558B. We calculate individual masses using the Burrows et al. (1997) models for ages of 0.5 and 5 Gyr, sampling the typical ages for field dwarfs (see below). The derived masses are 0.072–0.083 and 0.064–0.077 $M_\odot$ for the A and B components, respectively, with a total system mass of 0.136–0.160 $M_\odot$ and a mass ratio $q \equiv M_2/M_1 = 0.88$–0.92. This mass ratio is again consistent with the properties of VLM binaries, which are predominantly near-equal-mass systems. Combining the estimates of the physical separation and mass indicates an orbital period of roughly 150–300 yr, an unfortunately unreasonable timescale for dynamical mass measurements. A summary of the 2MASS 1707−0558AB system characteristics can be found in Table 4.

4.2. *Broader Implications for M and L Dwarfs*

This binary system is similar to other field binary systems, with a small separation and nearly equal mass components. Of known VLM binaries, 93% have separations less than 20 AU, like 2MASS 1707−0558, and 77% have $q \geq 0.8$ (Burgasser et al. 2006b). Therefore, this system further strengthens the case that VLM binaries have specific traits that may be related to their formation mechanism.

The M9/L3 binary 2MASS 1707−0558 is also a useful probe of the M/L transition, since the components have presumably

TABLE 4
2MASS 1707−0558AB Individual Properties

Parameter	2MASS 1707−0558A Value	2MASS 1707−0558B Value
Spectral type	M9[a]	L3[a]
$T_{\rm eff}$[b] (K)...........................	2400 ± 175	1950 ± 190
J[c].....................................	12.26 ± 0.11	13.96 ± 0.11
H[c].....................................	11.59 ± 0.07	12.72 ± 0.04
K_s[c].....................................	11.03 ± 0.08	12.20 ± 0.08
Estimated mass[d] ($M_\odot$)......	0.072−0.085	0.064−0.077

[a] Spectral type uncertainty of ±0.5 subclasses.
[b] Derived from the $T_{\rm eff}$/spectral type relation of Golimowski et al. (2004).
[c] Magnitude on the 2MASS photometric system.
[d] Estimated masses from 0.5 to 5 Gyr, based on the evolutionary models of Burrows et al. (1997).

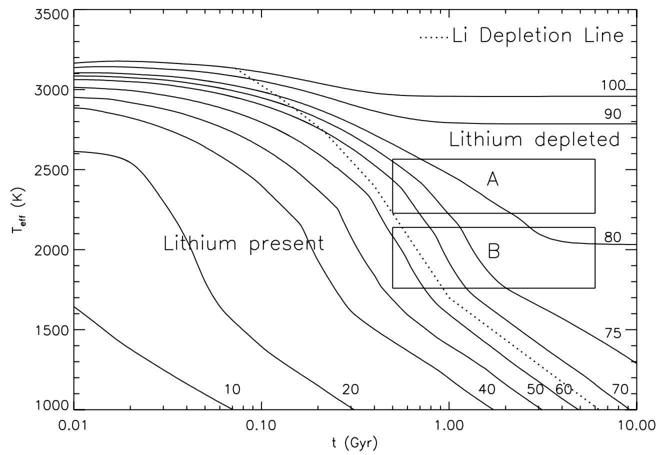

Fig. 5.— $T_{\rm eff}$ evolution as computed by Burrows et al. (1997, *solid lines*) for masses of 10$M_{\rm J}$, 20$M_{\rm J}$, 40$M_{\rm J}$, 50$M_{\rm J}$, 60$M_{\rm J}$, 70$M_{\rm J}$, 75$M_{\rm J}$, 80$M_{\rm J}$, 90$M_{\rm J}$, and 100$M_{\rm J}$ ($1M_{\rm J} \approx 0.001\ M_\odot$). The tracks are labeled from left to right and bottom to top. The mass-age loci of the 2MASS 1707−0558A and B components are indicated, based on $T_{\rm eff}$ values derived using the empirical $T_{\rm eff}$/spectral type relation of Golimowski et al. (2004) and an age estimate of 0.5−5 Gyr. The L3 (B) component is likely to be a brown dwarf, while the M9 (A) component is located near the hydrogen-burning minimum mass. The dotted line indicates the boundary where more than 90% of the primordial lithium abundance is depleted, according to the models of Burrows et al. (1997).

coevolved with a fixed age and metallicity. Resolved binaries with spectroscopy are ideal systems to study the complex atmospheric chemistry of low-mass stars, especially the thickening of dust, effects of condensation on the spectral energy distribution, and the relative heights of the cloud base. M dwarfs are characterized by their TiO and VO bands (Kirkpatrick et al. 1999), while the transition into the L dwarf regime is marked by the depletion of these molecules through condensation, leading to the expression of hydrides such as FeH and CrH (Lodders 2002). The atmospheric chemistry has been modeled for an assortment of field stars, yielding various masses, ages, and intrinsic metallicities. A study of resolved binary systems straddling the M/L boundary, such as 2MASS 1707−0558, will permit a fair comparison of low-mass atmospheres.

In addition, comparisons of the individual rotational velocities through atmospheric line broadening may constrain particular formation and evolution models. A direct measurement would determine whether the components have equivalent or varied rotation rates, clarifying a dependency on either the mass or the origin of the object. Chromospheric activity is not well understood in low-mass stars, but it is likely to be correlated to the spin rate of the star, possibly as a result of the magnetic fields induced by a turbulent dynamo mechanism (Durney et al. 1993; see also Chabrier & Kueker 2006). Field studies suggest that Hα activity increases from early-type to late-type M dwarfs and then diminishes through the early-type L dwarfs (Gizis et al. 2000b; Mohanty & Basri 2003; West et al. 2004). An unresolved optical spectrum of 2MASS 1707−0558 shows modest Hα emission (Gizis 2002), but the origins of this detection are unclear. Is this activity present in both components, and at what level does each component contribute to this detection? Furthermore, a measurement of the soft X-ray contributions of each component (resolvable with *Chandra*) will help further constrain the magnetic field mechanisms and their effects on coronal heating.

The substellar nature of brown dwarfs can be directly tested through measurements of the 6708 Å Li I line, but unfortunately the original optical spectrum was unable to resolve this line. The existence of primordial lithium is a conclusive determinant of substellar nature, as it is quickly destroyed when core temperatures reach $\sim 2 \times 10^6$ K, a prerequisite reached by VLM stars with masses greater than $\sim 0.06\ M_\odot$ (Rebolo et al. 1992; Magazzu et al. 1993). It should be noted that an object can lie below the hydrogen-burning minimum mass (i.e., substellar) and fail to exhibit Li I absorption. Depending on the age of the system, one or both of the components will show Li I in absorption, since they follow different evolutionary tracks. Hence, in the situation of a binary such as 2MASS 1707−0558 that may straddle the substellar boundary, the existence of the Li I line can also be used to trace the age of the system (cf. Liu & Leggett 2005). Three possible scenarios exist: 2MASS 1707−0558A and B could both be brown dwarfs and contain Li I undepleted from their atmospheres ($t \leq 0.5$ Gyr), 2MASS 1707−0558A could be a star or brown dwarf with mass greater than $\sim 0.06\ M_\odot$ and 2MASS 1707−0558B could be a Li-bearing brown dwarf with a mass less than $\sim 0.06\ M_\odot$ (0.5 Gyr $< t <$ 1 Gyr), or both components could be low-mass stars or brown dwarfs with masses greater than $\sim 0.06\ M_\odot$ ($t > 1$ Gyr). Therefore, 2MASS 1707−0558 is a rare VLM field system that can be assigned an accurate age through the Li I diagnostic.

An alternative age diagnostic, although less reliable, is a consideration of space kinematics and chromospheric activity. Stars are generally born with the space motion of their natal cloud, and over time they accumulate higher space velocities through interactions with the components of the Galactic disk (Wielen 1977). Gizis et al. (2000b) have found that a sample of field M and L dwarfs separate into two groups according to kinematics and chromospheric activity. An old population of M dwarfs has high tangential velocities ($v_{\rm tan} > 20$ km s^{-1}) and strong Hα emission, while a younger population exhibits low kinematics and low activity. Assuming our spectrophotometric distance and the proper motion as measured by the SuperCosmos Sky Survey, 2MASS 1707−0558 has a $v_{\rm tan}$ of 7 km s^{-1}. In comparison to the other late-M dwarfs identified in Gizis et al. (2000b), 2MASS 1707−0558 has one of the lowest tangential velocities and Hα measurements, suggesting that 2MASS 1707−0558 is associated with the young population. It is therefore likely to be closer to ~1 Gyr in age, but without additional constraints, we adopt a conservative age range of 0.5−5 Gyr. Figure 5 compares the properties of the 2MASS 1707−0558 components to evolutionary models from Burrows et al. (1997), clearly showing the secondary's possible location below the Li-burning mass limit.

5. SUMMARY

We have photometrically and spectroscopically resolved 2MASS 1707−0558 into an M9/L3 binary separated by 1."01 ± 0."17. Physical association is confirmed by common proper motion, angular proximity, similar distances, and the statistical likelihood of two low-mass stars occupying this small volume of space. System characteristics were derived by combining the imaging and spectral information obtained with the IRTF SpeX instrument and considering the current evolutionary models and empirical large-scale surveys. The derived *J*-, *H*-, and *K*-band relative magnitudes are consistent with assigned spectral classifications and imply a spectrophotometric distance of 15 ± 1 pc. The properties of 2MASS 1707−0558AB, including close separation and high mass ratio, are typical for late M/L binary systems. The angular separation of this system enables resolved spectroscopic measurements critical for the studies of low-mass star formation, atmospheric chemistry, and activity across the M/L transition.

We thank our telescope operators, Bill Golisch, Dave Griep, and Paul Sears, and instrument specialist John Rayner for their support during the IRTF observations. We would also like to thank James Larkin, Stan Metchev, and Peter Plavchan for many useful conversations regarding the science presented herein, Michael Cushing for discussions on synthetic photometry, and our anonymous referee for a careful review of the manuscript.

This publication makes use of data from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation. The 2MASS data were obtained from the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Electronic copies of the spectra presented here can be obtained directly from the primary author.

REFERENCES

Ackerman, A. S., & Marley, M. S. 2001, ApJ, 556, 872
Billères, M., Delfosse, X., Beuzit, J.-L., Forveille, T., Marchal, L., & Martín, E. L. 2005, A&A, 440, L55
Bouy, H., Brandner, W., Martín, E. L., Delfosse, X., Allard, F., & Basri, G. 2003, AJ, 126, 1526
Burgasser, A. J., Kirkpatrick, J. D., Cruz, K. L., Reid, I. N., Leggett, S. K., Liebert, J., Burrows, A., & Brown, M. E. 2006a, ApJS, 166, 585
Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., Brown, M. E., Miskey, C. L., & Gizis, J. E. 2003a, ApJ, 586, 512
Burgasser, A. J., & McElwain, M. W. 2006, AJ, 131, 1007
Burgasser, A. J., McElwain, M. W., & Kirkpatrick, J. D. 2003b, AJ, 126, 2487
Burgasser, A. J., McElwain, M. W., Kirkpatrick, J. D., Cruz, K. L., Tinney, C. G., & Reid, I. N. 2004, AJ, 127, 2856
Burgasser, A. J., Reid, I. N., Siegler, N., Close, L. M., Allen, P., Lowrance, P. J., & Gizis, J. E. 2006b, in Protostars and Planets V, ed. B. Reipurth (Tucson: LPI), in press (astro-ph/0602122)
Burgasser, A. J., et al. 2002, ApJ, 564, 421
Burrows, A., & Sharp, C. M. 1999, ApJ, 512, 843
Burrows, A., et al. 1997, ApJ, 491, 856
Chabrier, G., & Kueker, M. 2006, A&A, 446, 1027
Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckerman, B., Mouillet, D., Song, I., Beuzit, J.-L., & Lowrance, P. 2004, A&A, 425, L29
———. 2005, A&A, 438, L25
Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, ApJ, 587, 407
Close, L. M., Siegler, N., Potter, D., Brandner, W., & Liebert, J. 2002, ApJ, 567, L53
Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, AJ, 126, 1090
Cruz, K. L., Reid, I. N., Liebert, J., Kirkpatrick, J. D., & Lowrance, P. J. 2003, AJ, 126, 2421
Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2004, PASP, 116, 362
Cutri, R. M., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/explsup.html
Dahn, C. C., et al. 2002, AJ, 124, 1170
Delfosse, X., et al. 1997, A&A, 327, L25
———. 2004, in ASP Conf. Ser. 318, Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, ed. R. W. Hidlitch, H. Hensberge, & K. Pavlovski (San Francisco: ASP), 166
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Durney, B. R., De Young, D. S., & Roxburgh, I. W. 1993, Sol. Phys., 145, 207
Epchtein, N., et al. 1997, Messenger, 87, 27
Fan, X., et al. 2000, AJ, 119, 928
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Freed, M., Close, L. M., & Siegler, N. 2003, ApJ, 584, 453
Geballe, T. R., et al. 2002, ApJ, 564, 466
Gizis, J. E. 2002, ApJ, 575, 484
Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., & Burgasser, A. J. 2000a, MNRAS, 311, 385
Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000b, AJ, 120, 1085
Gizis, J. E., Reid, I. N., Knapp, G. R., Liebert, J., Kirkpatrick, J. D., Koerner, D. W., & Burgasser, A. J. 2003, AJ, 125, 3302
Golimowski, D. A., et al. 2004, AJ, 127, 3516
Hambly, N. C., Davenhall, A. C., Irwin, M. J., & MacGillivray, H. T. 2001a, MNRAS, 326, 1315
Hambly, N. C., Irwin, M. J., & MacGillivray, H. T. 2001b, MNRAS, 326, 1295
Hambly, N. C., et al. 2001c, MNRAS, 326, 1279
Hawley, S. L., et al. 2002, AJ, 123, 3409
Hayes, D. S., Pasinetti, L. E., & Philip, A. G. D., eds. 1985, IAU Symp. 111, Calibration of Fundamental Stellar Quantities (Dordrecht: Reidel)
Henry, T. J., & McCarthy, D. W., Jr. 1993, AJ, 106, 773
Kirkpatrick, J. D., Beichman, C. A., & Skrutskie, M. F. 1997, ApJ, 476, 311
Kirkpatrick, J. D., Henry, T. J., & McCarthy, D. W. 1991, ApJS, 77, 417
Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802
Koerner, D. W., Kirkpatrick, J. D., McElwain, M. W., & Bonaventura, N. R. 1999, ApJ, 526, L25
Law, N. M., Hodgkin, S. T., & Mackay, C. D. 2006, MNRAS, 368, 1917
Liu, M. C., & Leggett, S. K. 2005, ApJ, 634, 616
Lodders, K. 1999, ApJ, 519, 793
———. 2002, ApJ, 577, 974
Lodders, K., & Fegley, B. 2002, Icarus, 155, 393
Lunine, J. I., Hubbard, W. B., Burrows, A., Wang, Y.-P., & Garlow, K. 1989, ApJ, 338, 314
Magazzu, A., Martín, E. L., & Rebolo, R. 1993, ApJ, 404, L17
Martín, E. L., Barrado y Navascués, D., Baraffe, I., Bouy, H., & Dahm, S. 2003, ApJ, 594, 525
Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., & Zapatero Osorio, M. R. 1999, AJ, 118, 2466
Maxted, P. F. L., & Jeffries, R. D. 2005, MNRAS, 362, L45
McLean, I. S., McGovern, M. R., Burgasser, A. J., Kirkpatrick, J. D., Prato, L., & Kim, S. S. 2003, ApJ, 596, 561
Mohanty, S., & Basri, G. 2003, in The Future of Cool-Star Astrophysics, ed. A. Brown, G. M. Harper, & T. R. Ayres (Boulder: Univ. Colorado), 683
Monet, D. G., et al. 1998, USNO-A2.0 Catalog (Flagstaff: USNO)
Morgan, W. W., Keenan, P. C., & Kellman, E. 1943, An Atlas of Stellar Spectra, with an Outline of Spectral Classification (Chicago: Univ. Chicago Press)
Probst, R. G., & Liebert, J. 1983, ApJ, 274, 245
Rayner, J. T., Toomey, D. W., Onaka, P. M., Denault, A. J., Stahlberger, W. E., Vacca, W. D., Cushing, M. C., & Wang, S. 2003, PASP, 115, 362
Rebolo, R., Martin, E. L., & Magazzu, A. 1992, ApJ, 389, L83
Reid, I. N., & Gizis, J. E. 1997, AJ, 114, 1992
Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001, AJ, 121, 489
Reid, I. N., Lewitus, E., Allen, P. R., Cruz, K. L., & Burgasser, A. J. 2006, AJ, 132, 891
Reid, I. N., et al. 2004, AJ, 128, 463
Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L., & Reid, I. N. 2005, ApJ, 621, 1023
Siegler, N., Close, L. M., Mamajek, E. E., & Freed, M. 2003, ApJ, 598, 1265
Simons, D. A., & Tokunaga, A. T. 2002, PASP, 114, 169
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Stephens, D. C., & Leggett, S. K. 2004, PASP, 116, 9
Testi, L., et al. 2001, ApJ, 552, L147
Tokunaga, A. T., & Kobayashi, N. 1999, AJ, 117, 1010
Tokunaga, A. T., Simons, D. A., & Vacca, W. D. 2002, PASP, 114, 180
Tsuji, T., Ohnaka, K., Aoki, W., & Nakajima, T. 1996, A&A, 308, L29
Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, PASP, 115, 389
Vrba, F. J., et al. 2004, AJ, 127, 2948
West, A. A., et al. 2004, AJ, 128, 426
Wielen, R. 1977, A&A, 60, 263
York, D. G., et al. 2000, AJ, 120, 1579