

DISCOVERY OF A WIDE SUBSTELLAR COMPANION TO A NEARBY LOW-MASS STAR

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ABSTRACT

We report the discovery of a wide (135 ± 25 AU), unusually blue L5 companion, 2MASS J17114559+4028578, to the nearby M4.5 dwarf G203-50 as a result of a targeted search for common proper motion pairs in the Sloan Digital Sky Survey and the Two Micron All Sky Survey. Adaptive optics imaging with Subaru indicates that neither component is a nearly equal-mass binary with separation $>0.18''$ and places limits on the existence of additional faint companions. An examination of TiO and CaH features in the primary’s spectrum is consistent with solar metallicity and provides no evidence that G203-50 is metal-poor. We estimate an age for the primary of 1–5 Gyr based on activity. Assuming coevality of the companion, its age, gravity, and metallicity can be constrained from properties of the primary, making it a suitable benchmark object for the calibration of evolutionary models and for determining the atmospheric properties of peculiar blue L dwarfs. The low total mass ($M_{\text{tot}} = 0.21 \pm 0.03 M_{\odot}$), intermediate mass ratio ($q = 0.45 \pm 0.14$), and wide separation of this system demonstrate that the star formation process is capable of forming wide, weakly bound binary systems with low-mass and brown dwarf components. Based on the sensitivity of our search we find that no more than 2.2% of the early-to-mid-M dwarfs ($9.0 < M_V < 13.0$) have wide substellar companions with $m \geq 0.06 M_{\odot}$.

Subject headings: binaries: general — stars: formation — stars: individual (2MASS J17114559+4028578, G203-50) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Although star birth is a complex process, the observation of binary systems—frequencies, mass ratios, and separations—can provide insight into the formation process, as well as constraints for theoretical models. The formation of brown dwarfs (BDs) is particularly challenging, since their masses are an order of magnitude smaller than the typical Jeans mass in molecular clouds.

Whether BDs form similarly to their more massive stellar counterparts or require additional mechanisms is currently an open question. The answer may lie in the multiplicity properties of these substellar objects. Whereas free-floating BDs are observed in abundance, finding BDs as companions to stars has proved more difficult. A “brown dwarf desert” ($\leq 0.5\%$ companion fraction) is observed at close separations (<3 AU) to main-sequence stars, in comparison to a significant number of both planetary and stellar mass companions seen at similar separations (Marcy & Butler 2000). It has recently been determined that this desert does not extend out to larger separations for solar analogs (F, G, and K stars), $\sim 7\%$ of which are found to harbor substellar companions at separations greater than 30 AU (Metchev 2006). However, searches for substellar companions to M dwarfs at large separations (≥ 40 AU) have yielded mostly null results (e.g., Allen & Reid 2008; McCarthy & Zuckerman 2004; Hinz et al. 2002; Daemgen et al. 2007) or sparse results (e.g., Oppenheimer et al. 2001), and only a handful of such companions are currently known (e.g. TWA 5 b,c, Lowrance et al. 1999; G196-3B, Rebolo et al. 1998; GJ 1001B, Goldman et al. 1999; G1 229B, Nakajima et al. 1995; LP 261-75B, Burgasser et al. 2005, Reid & Walkowicz 2006; GJ 618.1B, Wilson et al. 2001).¹

In the very low mass (VLM) regime ($M_1 < 0.1 M_{\odot}$), surveys have found that no more than $\sim 1\%$ of stars have wide companions, including stellar ones (Burgasser et al. 2007; Caballero 2007). In addition, VLM binaries are found to be on average 10–20 times more tightly bound than their stellar counterparts, hinting that disruptive dynamical interactions may play an important role in their formation (Close et al. 2003). These observations have been cited as evidence in favor of the ejection hypothesis (Reipurth & Clarke 2001; Bate & Bonnell 2005), where BDs and VLM stars are thought to be stellar embryos formed by the fragmentation of a more massive prestellar core, then prematurely ejected from their birth environments. However, BD companions to more massive stars do not tend to form harder binaries than stellar systems of similar total mass (e.g., Reid et al. 2001b; Metchev 2006). While this is potentially evidence that BDs can form similarly to stars via turbulent fragmentation within molecular clouds (Padoan & Nordlund 2002), it is also consistent with simulations of disk instabilities (e.g., Stamatellos et al. 2007; Boss 2000), which are capable of producing substellar companions around more massive primaries.

While a significant fraction of solar mass stars may retain wide BD companions, this does not seem to hold true for lower mass stars. As a result, very few wide BD companions to low-mass stars are known. The discovery and characterization of these systems, especially in the intermediate range between the solar analog and VLM regimes, will help complete the emerging picture of BD multiplicity at wide separations. In addition, wide BD companions to stars make suitable “benchmark” objects, as their properties can be inferred from those of the primary (e.g., Pinfield et al. 2006). This is important for the calibration of BD evolutionary models, which requires independent age estimates.

¹ Included for thoroughness, the L2.5 companion GJ 618.1B is more likely stellar.

Here we present the discovery of a wide substellar companion to a nearby M4.5 star. The search, discovery, and follow-up observations are outlined in § 2, while the physical properties of the system and its components are given in § 3. In § 4 we discuss the companion’s unusual near-infrared (NIR) colors, possible formation scenarios, and the sensitivity of our search. Given a space density for M dwarfs, we make a crude estimate of how rare such systems may be. A brief summary and outlook are presented in § 5.

2. DISCOVERY AND OBSERVATIONS

The binary G203-50/2MASS J17114559+4028578 (G203-50AB) was found in a cross-match of the SDSS DR6 Photoprimary Catalog (Adelman-McCarthy et al. 2008) and the 2MASS Point Source Catalog (Skrutskie et al. 2006), in which we searched for common proper motion pairs containing at least one VLM or BD component. The cross-correlation of catalogs, calculation of proper motions, and identification of comoving stars was done in parallel for 4 deg² sections of the sky at a time, spanning the contiguous region of the SDSS Legacy survey in the northern Galactic cap. We made preliminary cuts to include only 2MASS sources with S/N > 5 in at least one band (*J*, *H*, or *K*) and not flagged as minor planets, as well as SDSS sources that were not classified as “sky pointings” or electronic ghosts. For every 2MASS source, the closest SDSS match was found and proper-motion vectors with uncertainties were computed. A cut was made in order to select only stars that had moved at the 3 σ level compared to all other stars within the area. Stars within 120'' of one another with proper-motion amplitudes agreeing within 2 σ and proper-motion components agreeing within 1 σ in either right ascension or declination were flagged as potential binaries. We applied a color cut of $z' - J > 2.5$ for at least one component to the proper-motion-selected sample in order to search for BD companions. Finally, all the candidates were examined visually to eliminate artifacts and spurious matches. Of all the candidate systems, G203-50AB stood out as harboring a very red companion with $z' - J \approx 2.9$. Although at first glance the companion passed our color cuts, the quoted z' error of ± 2 mag rendered this color meaningless. Fortunately, the primary was of known spectral type and absolute magnitude $M_J = 9.34 \pm 0.18$ (Reid et al. 2003), yielding $M_J = 13.3$ for the secondary, assuming it to be at the same distance as the primary. Average absolute magnitudes as a function of spectral type (Dahn et al. 2002) suggested that the companion was indeed a mid-L dwarf.

As a verification of the system’s physical association we have plotted the proper motions of G203-50AB, along with all other stars within 10' of the primary. Figure 1 clearly shows G203-50AB as a comoving pair.

In order to establish a spectral type for the companion we obtained an infrared spectrum ($R \sim 750$) of 2MASS J17114559+4028578 (2M1711+4028) on 2008 February 28 using the SpeX Medium-Resolution Spectrograph (Rayner et al. 2003) at NASA’s Infrared Telescope Facility (IRTF). Observations were made in short-wavelength (0.8–2.5 μm) cross-dispersed mode with the 0.8'' slit, and the seeing was 0.7''–0.9''. We obtained eight 180 s exposures arranged in two ABBA nod patterns with a nod step of 7'' along the slit. For telluric and instrumental transmission correction, the A0 star HD 165029 was observed immediately after the target at the same air mass. Flat-fielding, background subtraction, spectrum extraction, wavelength calibration, order merging, and telluric correction were done using Spextool (Cushing et al. 2004; Vacca et al. 2003). No scaling was applied to the cross-dispersed spectrum when merging the orders. The spectrum is presented and analyzed in § 3.2.

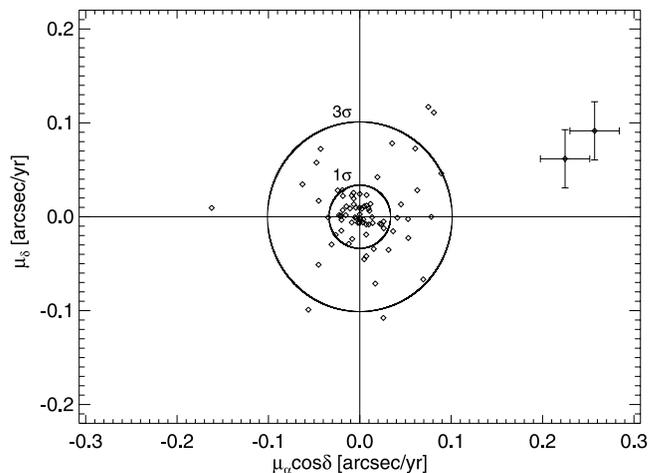


FIG. 1.— Proper motions of all sources within 10' of G203-50. Circles indicate the 1 σ and 3 σ dispersions. G203-50 and 2M1711+4028 are displayed with error bars based on the 1 σ dispersion along each axis, which dominates over the astrometric errors quoted by the individual catalogs. 2MASS and SDSS observations of this system are separated by a baseline of 6.0959 yr.

To constrain the possible binary nature of the primary and the companion, adaptive optics imaging observations of the system were obtained on 2008 July 8 at the Subaru Telescope (open use program S08A-074). The observations were made with the AO36 adaptive optics system (Takami et al. 2004) and the CIAO NIR camera (Murakawa et al. 2004). The primary star G203-50 was used for wave-front sensing. Five exposures of 7 s times three co-additions were obtained in K_s over five dither positions. The images were reduced in a standard manner. A sky frame was obtained as the median of the five images after masking the regions dominated by the signal from the target. After subtraction of this sky frame, the images were divided by a normalized dome flat image, and bad pixels were replaced by a median over their neighbors. All the images were finally coaligned, flux-normalized, and co-added. Owing to the faint *R*-band magnitude of the target star, the adaptive optics correction achieved is rather poor, with a PSF FWHM of 0.18''. Visual inspection of the adaptive optics images indicates that neither the primary nor the companion is a nearly equal-mass binary with a separation of $\sim 0.18''$ or larger. Subtraction of a properly shifted and scaled version of the primary star PSF from that of the companion confirms that conclusion, as this operation leaves no obvious residual. Our adaptive optics images also provide constraints on the existence of additional, fainter companions in the system. The detection limits achieved indicate that the primary has no other companion with $\Delta K_s < 4.3$, 7.0, or 7.8 mag at separations greater than 0.5'', 1'', or 2'', respectively. Similarly, the secondary has no companion with $\Delta K_s < 4.3$ above 0.5''.

3. PHYSICAL PROPERTIES

A summary of the observational and physical properties of the system is given in Tables 1 and 2. Proper motions for each component, in a reference frame defined by the median proper motion of all background stars within 10', were found and averaged to give a mean system proper motion of $242 \pm 15 \text{ mas yr}^{-1}$ in right ascension and $77 \pm 17 \text{ mas yr}^{-1}$ in declination. This is in good agreement with the proper motion tabulated for G203-50 of 250.5 ± 5.5 and $84.2 \pm 5.5 \text{ mas yr}^{-1}$ in the Revised NLTT Catalog (Salim & Gould 2003).

TABLE 1
PHYSICAL PROPERTIES OF THE COMPONENTS OF G203-50AB

Quantity	A	B
Designation	G203-50	2MASS J17114559+4028578
$\mu_\alpha \cos \delta$ (mas yr ⁻¹).....	229 ± 43	256 ± 36
μ_δ (mas yr ⁻¹).....	61 ± 49	92 ± 43
2MASS J (mag).....	11.074 ± 0.016	15.00 ± 0.06
2MASS M_J (mag).....	9.34 ± 0.44 ^a	13.5 ^{+0.7b} _{-0.5}
$J - K_s$	0.80	1.28 ^c
$J - H$	0.51	0.79 ^c
$H - K_s$	0.29	0.49 ^c
d	22.2 ± 4.5	20.0 ± 6.3
Spectral type.....	M4.5 ^d	L5 ⁺² _{-1.5}
T_{eff} (K).....	3114 ± 125	1700 ⁺²¹⁰ ₋₂₅₀
Mass (M_\odot).....	0.146 ± 0.031	0.066 ^{+0.008} _{-0.015}
H α EW (Å).....	3.8 ± 0.5	...
TiO5 ^d	0.34	...
CaOH ^d	0.32	...
CaH2 ^d	0.35	...
CaH3 ^d	0.60	...

^a Based on TiO5, CaOH, and CaH2 spectral indices (Reid et al. 2003).

^b Based on average absolute magnitudes by spectral type; see Dahn et al. (2002).

^c Synthetic colors computed from the spectrum of 2M1711+4028 using relative spectral response curves and zero-magnitude fluxes given in Cohen et al. (2003).

^d Spectral type and indices from Reid et al. (2003).

3.1. The Primary: G203-50

G203-50 has been assigned a spectral type of M4.5 and an absolute magnitude of $M_J = 9.34 \pm 0.18^2$ by Reid et al. (2003). The spectral type is assigned based on the TiO5 spectral index (Cruz & Reid 2002), while the absolute J magnitude is derived from polynomial fits to the TiO5, CaOH, and CaH2 spectral indices as a function of absolute J magnitude for M dwarfs with trigonometric parallaxes (Cruz & Reid 2002). We have verified the spectral type by comparison of G203-50's spectrum (courtesy of N. Reid) with reference spectra from Kirkpatrick et al. (1991) using standard spectra made available online by K. Cruz,³ as well as Pickles (1998). The spectrum of G203-50 is shown alongside the M4.5 spectral standard G1 83.1 in Figure 2.

Since the absolute J magnitude is derived from spectral indices which may vary continuously between spectral types, it is in principle more precise than a magnitude derived based on the average value for all members of a given subtype. However, the absolute J magnitude provided by Reid et al. (2003) seems to have unrealistically low errors, given the large spread in absolute magnitude for mid-M spectral types (e.g., see Fig. 4 of Cruz & Reid 2002). As a sanity check we conducted a SIMBAD search yielding 45 M4.5 dwarfs with measured parallaxes and J -band fluxes. The distribution of absolute J magnitudes has a median value of 9.0 and a standard deviation of 0.44. Therefore, we choose to adopt a more conservative error estimate of 0.44 mag.

Using $M_J = 9.34 \pm 0.44$, the corresponding photometric distance is 22.2 ± 4.5 pc. Assuming an age >500 Myr, we derived a mass of $0.146 \pm 0.031 M_\odot$ using the empirical mass-luminosity relationship of Delfosse et al. (2000), also in agreement with the models of Baraffe et al. (1998).

The spectrum of G203-50 shows moderate H α emission. We measured the H α equivalent width (EW) to be $3.8 \pm 0.5 \text{ \AA}$ with

² Errors were not provided with the online data, but we have inferred them from the quoted error in photometric distance.

³ See http://www.astro.caltech.edu/~kelle/M_standards/.

TABLE 2
SYSTEM PROPERTIES OF G203-50AB

Quantity	Value
Distance (pc) ^a	21.2 ± 3.9
Angular separation (arcsec).....	6.40 ± 0.02
Physical separation (AU).....	135 ± 25
$\mu_\alpha \cos \delta$ (mas yr ⁻¹) ^a	242 ± 15
μ_δ (mas yr ⁻¹) ^a	77 ± 17
Total mass (M_\odot).....	0.212 ± 0.032
Mass ratio.....	0.45 ± 0.14
Binding energy (10^{41} erg).....	12.6 ± 3.8

^a Mean quantities of the components.

errors stemming from a high sensitivity to the regions chosen to fit the pseudocontinuum on either side of the line. We used a cubic polynomial to fit the pseudocontinuum regions from 6544.3 to 6551.9 Å and from 6576.6 to 6582.3 Å. The relationship between H α activity and age becomes degenerate for low-mass dwarfs (Zuckerman & Song 2004), making it difficult to draw firm conclusions about the age of G203-50. However, the activity lifetime of M stars in terms of H α emission has recently been constrained using a sample of 38,000 M dwarfs from SDSS Data Release 5 (West et al. 2008). The activity lifetime for M4 and M5 stars is found to be 4.5 and 7 Gyr, respectively. Considering that G203-50 is more active than the majority of M dwarfs of similar spectral type (e.g., Reid et al. 2003; see online data), it is reasonable to infer that it is not near the end of its active phase. Nor does G203-50 display signs of extreme youth, as it has no associated X-ray source in *ROSAT*. Therefore, we tentatively estimate the age of G203-50 to be between 1 and 5 Gyr.

Based on the metallicity scale of Gizis (1997), the TiO5 and CaH2 indices of G203-50 are consistent with solar metallicity, indicating $[M/H] > -1.0$. We measured the metallicity index of Lépine et al. (2007) to be $\zeta_{\text{TiO/CaH}} = 0.95$, where solar metallicity is represented by $\zeta_{\text{TiO/CaH}} = 1$ and metal-poor stars have $\zeta_{\text{TiO/CaH}} < 0.825$. Our own fits of model spectra in the 6200–7300 Å region verify these results. We fit the NextGen99 model atmospheres (Hauschildt et al. 1999) to G203-50's spectrum in the region of the TiO and CaH bands of 6200–7300 Å. We used a grid of models with $3000 \text{ K} < T_{\text{eff}} < 3300 \text{ K}$ in steps of 100 K, $4.5 < \log g < 5.5$ in steps of 0.5 dex, and $-2.0 < [M/H] < 0.0$ in steps of 0.5 dex. These parameter ranges were chosen based on values of

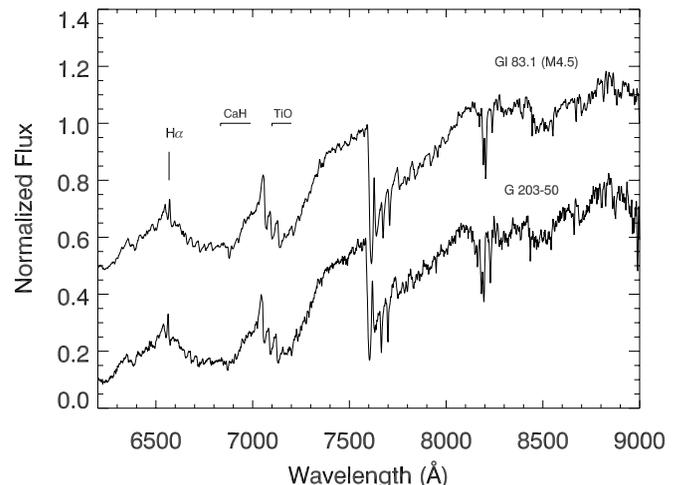


FIG. 2.— Spectrum of G203-50 (Reid et al. 2003), plotted with the M4.5 spectral standard G1 83.1 for comparison.

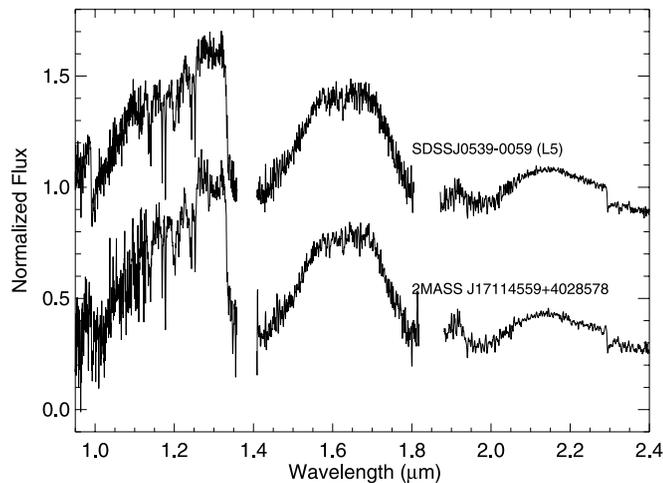


FIG. 3.— Spectrum of 2M1711+4028 obtained at IRTF using the SpeX Medium-Resolution Spectrograph. The spectrum is plotted alongside a reference spectrum of the L5 dwarf SDSS J0539199–0059020 from the IRTF Spectral Library (Cushing et al. 2005). Both spectra are normalized in 1.27–1.33 μm and offset for clarity.

$T_{\text{eff}} = 3114 \pm 125$ and $\log g = 5.14 \pm 0.05$ computed from the evolutionary models of Baraffe et al. (1998) using the 1–5 Gyr isochrones. In each case the templates were convolved with a Gaussian with a FWHM equal to the instrumental resolution ($\sim 5.5 \text{ \AA}$) of G203-50’s spectrum and then interpolated onto the data. As noted by Lépine et al. (2007), none of the model spectra were good fits, with the CaH band consistently appearing too strong relative to TiO. However, as expected, the best-fitting model spectra were those with solar metallicity, with the fit becoming progressively worse for decreasing $[M/H]$. Therefore, we find no evidence to suggest that G203-50 is metal-poor. A higher resolution spectrum is required to determine the metallicity more precisely (e.g., using the method of Bean et al. [2006], accurate to ~ 0.1 dex).

3.2. The Companion: 2MASS J17114559+4028578

Using reference spectra from the IRTF⁴ (maintained by J. Rayner), SpeX Prism (maintained by A. Burgasser), CGS4 (Leggett et al. 2001), and NIRSPEC BDSS (McLean et al. 2003) spectral libraries, we determined the best-fitting spectral type for the companion to be L5 (see Fig. 3). However, other reasonable matches were found from L3.5 to L6.5. We also measured spectral indices defined by Geballe et al. (2002), Tokunaga & Kobayashi (1999), Reid et al. (2001a), and McLean et al. (2003). The indices are presented in Table 3, yielding spectral types from L4.5 to L8. We calculated synthetic 2MASS colors of $J - K_s = 1.28$, $J - H = 0.79$, and $H - K_s = 0.49$ from the spectrum⁵ of 2M1711+4028 using the relative spectral response curves and zero-magnitude fluxes given in Cohen et al. (2003). These NIR colors make 2M1711+4028 unusually blue for a mid-to-late-L dwarf (Cushing et al. 2008). The large range in spectral type implied by the spectral indices and the unusually blue NIR colors of 2M1711+4028 likely have a common origin. Several instances of anomalously blue L dwarfs have been previously noted (e.g., Knapp et al. 2004; Burgasser et al. 2008), where the optical spectra appear normal, but the NIR colors are much bluer than average. These blue L dwarfs are characterized by enhanced H₂O absorption bands and diminished CO, giving the appearance of a later spectral type in the NIR, while

⁴ Available at <http://irtfweb.ifa.hawaii.edu/~spex/spexlibrary/IRTFlibrary.html>.

⁵ The quoted 2MASS J , H , and K_s magnitudes are flagged as being biased by the nearby primary; however, our derived colors agree with the former to within 0.1 mag.

TABLE 3
SPECTRAL INDICES MEASURED FOR 2M1711+2048

Index	Value	Spectral Type	Reference
H ₂ O 1.5 μm	1.73	L8	1
CH4 2.2 μm	1.09	L7	1
K1	0.33	L4.5	2
H ₂ O ^A	0.49	L7.5	3
H ₂ O ^B	0.60	L6	3
H ₂ O A	0.45	L7	4
H ₂ O B	0.76	L5.5	4
J -FeH	0.81	<L6	4
z -FeH	0.46	<L6	4

REFERENCES.— (1) Geballe et al. 2002; (2) Tokunaga & Kobayashi 1999; (3) Reid et al. 2001b; (4) McLean et al. 2003.

J - and K -band features such as FeH are more consistent with an earlier optical classification (see § 4.1 for further discussion). Similarly for 2M1711+4028, the strong H₂O indices predict spectral types from L6.5 to L8, while z -FeH and J -FeH indices predict types <L6, and the K1 (not to be confused with K₁) index predicts a spectral type of L4.5. This is consistent with the two best-matching reference spectra, the relatively blue L dwarfs SDSS J0539199–0059020 (Fan et al. 2000) and 2MASS J15074769–1627386 (Reid et al. 2000), both of which have optical spectral types of L5, and the latter of which is an optical spectral standard. Considering all of our measurements, we have assigned a NIR spectral type of L5⁺²_{-1.5} to 2M1711+4028, with our choice being most strongly influenced by the best-fitting reference spectra. The error bars span the entire range of reasonable spectral types based on template fitting and spectral indices, excluding the H₂O indices.

Using the absolute magnitude–spectral type relationship provided by Dahn et al. (2002), an absolute magnitude of $13.5^{+0.7}_{-0.5}$ is found for the secondary, corresponding to a distance of 20.0 ± 6.3 pc. This is consistent with the distance of 22.2 ± 4.5 pc derived for the primary. The average distance for the system is 21.2 ± 3.9 pc. We find an effective temperature of 1700^{+210}_{-250} K based on the spectral type–effective temperature relationship of Golimowski et al. (2004). Using the DUSTY model isochrones for 1 and 5 Gyr (Chabrier et al. 2000), we derive a mass of $0.066^{+0.008}_{-0.015} M_{\odot}$. The quoted uncertainty takes into account the 1σ uncertainty in T_{eff} , as well as the age interval. While our upper limit of $0.074 M_{\odot}$ straddles the stellar-substellar boundary, this is the most conservative estimate, allowing for a very broad range in spectral types. We conclude that 2M1711+4028 is most likely substellar, an issue which can be resolved in the future by obtaining an optical spectrum in order to further constrain its spectral type.

Based on 2MASS and SDSS astrometry, 2M1711+4028 is separated from G203-50 by a mean angular separation of $6.47'' \pm 0.14''$, in agreement with the angular separation measured from the adaptive optics images of $6.40'' \pm 0.02''$ at $234.1^{\circ} \pm 0.2^{\circ}$. This corresponds to a projected separation of 135 ± 25 AU at the average system distance.

4. DISCUSSION

4.1. The Blue NIR Colors of 2M1711+4028

The NIR colors of mid-to-late-L dwarfs vary significantly within a single spectral type. For L5 dwarfs there is a spread of ~ 0.7 mag in $J - K_s$ (Kirkpatrick 2008; Cushing et al. 2008). Although surface gravity and metallicity play a role, comparison of atmospheric models to actual spectra (e.g., Knapp et al. 2004; Cushing et al. 2008; Burgasser et al. 2008) suggests that large variations in the NIR colors of L dwarfs are primarily related to

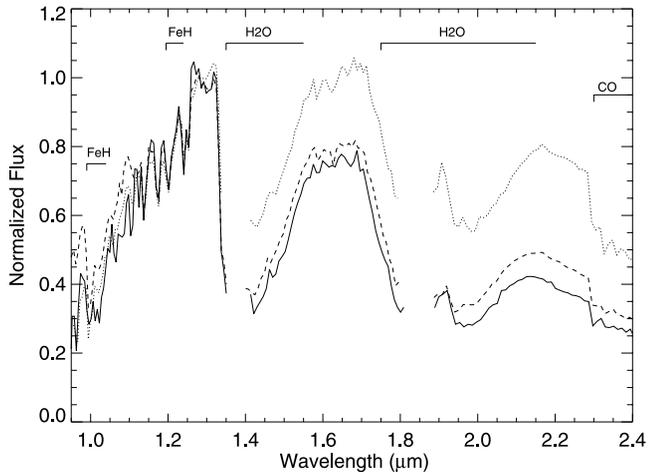


FIG. 4.— Spectrum of the blue ($J - K_s = 1.28$) L dwarf 2M1711+4028 (solid line) overplotted with the spectrum of the relatively red ($J - K_s = 2.05$) L4.5 dwarf 2MASS J22244381-0158521 (dotted line) and the relatively blue ($J - K_s = 1.52$) L5 optical standard 2MASS J15074769-1627386 (dashed line). Both comparison spectra are from the IRTF Spectral Library (Cushing et al. 2005). All spectra are normalized in 1.27–1.29 μm . They have been rebinned to a lower resolution for clarity.

the properties of condensate clouds in their atmospheres, with unusually red SEDs arising from thick clouds and blue ones from thin or large-grained clouds. Common to the known peculiar blue L dwarfs is exaggerated H_2O absorption and diminished CO, as seen in the spectrum of 2M1711+4028. As discussed in § 3.2, the discrepancy between the late-type H_2O indices and the earlier type FeH and K1 indices, along with its unusually blue NIR colors, are indications that 2M1711+4028 falls into this category. For comparison we overplot 2M1711+4028’s spectrum with the spectra of the very red L4.5 dwarf 2MASS J22244381-0158521 (Kirkpatrick et al. 2000) and the relatively blue L5 optical standard 2MASS J15074769-1627386 (see Fig. 4). All spectra agree reasonably well in the J band but diverge significantly at H and K , which may indicate differing properties of condensate clouds in their atmospheres. As a member of a wide binary system, the surface gravity and metallicity of 2M1711+4028 can be constrained from properties of the primary, yielding an excellent laboratory for studying BD atmospheres. The estimated age of 1–5 Gyr for the G203-50 primary implies a relatively high surface gravity for the companion, possibly contributing to its blue NIR colors. However, surface gravity alone does not seem to be sufficient to explain the NIR colors of peculiar blue L dwarfs (Burgasser et al. 2008). In addition, the primary shows no signs of being metal-poor, lending support to the hypothesis that unusually blue NIR colors can be primarily attributed to cloud properties. Higher resolution spectroscopy of the primary and a more precise determination of the metallicity are required in order to confirm this conclusion.

Another potential cause of unusually blue NIR colors is unresolved binarity. This may explain the slight onset of CH_4 absorption at 2.2 μm in the spectrum of 2M1711+4028. At least one of the known peculiar blue L dwarfs, 2MASS J08053189+4812330 (Burgasser 2007), is thought to be an unresolved binary with L4.5 and T5 components. However, this system exhibits a pronounced dip in the 1.6 μm CH_4 feature due to the peaked shape of the T dwarf’s SED, whereas the spectrum of 2M1711+4028 is relatively flat in that region. Furthermore, the SED and colors of our companion are very similar to those of another blue L4.5 dwarf, 2MASS J11263991-5003550 (2M1126-5003), discussed at length by Burgasser et al. (2008). By constructing composite spectra using published L and T dwarf spectra from the SpeX prism library, Burgasser et al. (2008) determined that no rea-

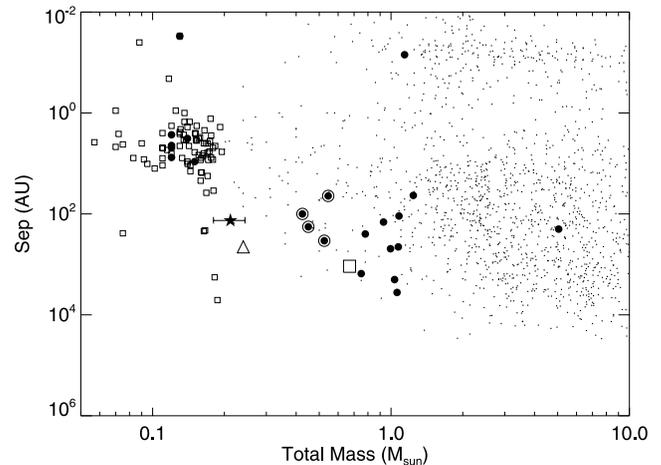


FIG. 5.— Separation vs. total system mass for known binary systems. Stellar binaries (dots) are from Tokovinin (1997), Fischer & Marcy (1992), Reid & Gizis (1997), and Close et al. (1990); VLM binaries (squares) are from the VLM binary archive, maintained by N. Siegler; and BD-stellar binaries (circles) are from Reid et al. (2001b) and Metchev (2006). G203-50AB (star) falls between the VLM and solar analog regimes and appears to be more loosely bound than most systems of similar mass. BD-stellar systems with M-dwarf primaries from Reid et al. (2001b) are circled. The large triangle and square represent BD-M dwarf systems from Wilson et al. (2001) and Reid & Walkowicz (2006).

sonable composite spectrum could be found that matched that of 2M1126-5003 in both the optical and NIR. Without an optical spectrum for 2M1711+4028 we are limited in the conclusions we can draw, but its similarities to 2M1126-5003 may suggest that 2M1711+4028 is a single BD. Our adaptive optics images support this conclusion, indicating that the BD is not a near-equal-mass binary with separation $>0.18''$.

4.2. Formation of G203-50AB

With a total mass of $\sim 0.21 M_\odot$, G203-50AB is slightly more massive than the rare wide VLM binaries but much less massive than the solar analogs around which BDs are routinely found at wide separations (see § 1 and Fig. 5). It is therefore of interest to consider how G203-50AB may have formed. Could the secondary have formed through gravitational instability in a disk around the primary? Given the mass ratio of $q = 0.45$, that would imply $M_{\text{disk}} > 0.45 M_*$, whereas typical disks around low-mass stars contain a few percent M_* at ~ 1 Myr (Scholz et al. 2006). Since it is unlikely that the entire disk would end up in the companion, the total disk mass, even in a conservative estimate, would have to be larger than the primary’s own mass to start with. Thus, we conclude that formation of 2M1711+4028 in a protostellar disk around G203-50 is implausible.

On the other hand, gravitational fragmentation of prestellar cores appears to be capable of forming a wide variety of binary systems, depending on the size, mass, and angular momentum of the core (e.g., Bate 2000). However, simulations usually have some difficulty producing binary stars with low component masses and wide separations (e.g., Bate et al. 2003; Goodwin et al. 2004). Some theoretical models invoke ejection from the parent cloud to halt further accretion that would otherwise lead to higher masses. Given its projected separation of 135 ± 25 AU, the G203-50AB binary has a binding energy of $(12.6 \pm 3.8) \times 10^{41}$ erg, placing it below the empirical “minimum” noted by Close et al. (2003) and Burgasser et al. (2007). Thus, it is unlikely to have survived such an ejection. We suggest that G203-50AB most likely formed via fragmentation of an isolated core and did not suffer strong dynamical interactions during the birth process or subsequently.

4.3. Search Sensitivity

In order to assess the sensitivity of our search, we simulated proper-motion distributions of M dwarfs scattered uniformly in a spherical volume out to 25 pc, with tangential space velocities drawn from the distribution of Schmidt et al. (2007). To be sensitive to a particular M dwarf primary, its displacement between the 2MASS and SDSS surveys had to be greater than the 3σ dispersion of all other stars in the 4 deg^2 section of the sky in which it was found. For each such section of the sky, the time baseline between the surveys was computed and used to determine the minimum proper motion required for a detection. We assumed that the population of M dwarfs within 25 pc was uniformly distributed and assigned equal weight to each 4 deg^2 area of the sky. Using the simulated proper-motion distributions, the fraction of M dwarfs whose proper motions we could have measured was determined for each section of the sky, giving an average fraction of 0.58. Adopting an M dwarf space density ($9.0 < M_V < 13.0$ or roughly M0.5–M5.5) of $283.37 \times 10^{-4}\text{ pc}^{-3}$ (Reid et al. 2002) and given a search area of 7668 deg^2 of the sky, we should have been sensitive to approximately 201 ± 12 early-to-mid-M dwarfs within 25 pc.

Although in some cases we were able to recover binary systems with separations $< 4''$, we conservatively put a lower limit of $6''$ on our sensitivity, ensuring that components were well separated. The upper limit for separation was set by our search radius, which extended to $120''$. These limits correspond to projected separations of 30–600 AU at 5 pc and 150–3000 AU at 25 pc. Our sensitivity to companions around each star was dictated by the mean 2MASS *J*-band limiting magnitude ($S/N = 10$) of ~ 16.5 , corresponding to a minimum mass of $\sim 0.06 M_\odot$ at 25 pc, assuming an age of 1–5 Gyr. Other factors preventing us from finding companions included poor astrometry due to saturation of the primary and a low S/N of the secondary. To estimate the number of binaries missed we used SIMBAD and DwarfArchives⁶ to compile a list of 31 M dwarfs and 38 BDs with previously measured proper motions large enough to pass our cuts, and we tested whether we could measure the same proper motions using SDSS and 2MASS astrometry. We found that 91% of the time for M dwarfs and 79% of the time for BDs our measured proper motions agreed with the previously measured ones, using the same criteria as our matching algorithm described in § 2. Therefore, we should have been capable of identifying approximately 72% of binaries with sufficiently high proper motions. Correspondingly, we adjusted our sensitivity to $\sim 145 \pm 9$ M dwarfs. Adopting Poisson uncertainties on a 1σ confidence interval for our single detection, we roughly estimated that $0.7\%_{-0.6\%}^{+1.5\%}$ of early-to-mid-M dwarfs have substellar companions with masses greater than $\sim 0.06 M_\odot$ at separations above ~ 120 AU.

5. SUMMARY AND OUTLOOK

We have outlined our discovery of a wide, unusually blue, L5 companion to the nearby M4.5 dwarf G203-50. Since BDs cool with time, it is not possible to infer their masses from observed luminosities. In order to break this degeneracy, the age (or an age indicator such as gravity) of the BD must be known. Even so, determining the mass of a BD requires accurate evolutionary models. In order to constrain these models we must rely on a handful of BDs for which independent age estimates can be obtained. Our companion, 2M1711+4028, falls into this category, as its age can be constrained from the age of the primary. With an angular separation of over $6''$, the components of G203-50AB are well

separated, allowing the primary and secondary to be studied independently. At a distance of only ~ 21 pc, the parallax can be measured relatively easily, providing a more precise determination of distance and luminosity. Assuming an age of 1–5 Gyr, 2M1711+4028 is older than most BDs with independent age estimates (e.g., those found in star-forming regions) and can therefore provide an anchor point in a poorly constrained mass-age regime. Furthermore, as an unusually blue L dwarf in the NIR, 2M1711+4028 provides a unique opportunity for studying the relative importance of gravity, metallicity, and cloud properties in determining the NIR colors of L dwarfs.

With a total mass falling between the solar mass and VLM regimes, G203-50AB is also important in star formation theory. Based on the large mass ratio between the system components, we rule out formation of the companion in the disk of the primary. Instead, we suggest that this weakly bound binary formed via the fragmentation of an isolated core and did not suffer disruptive dynamical interactions. Statistically, we put an upper limit of 2.2% on the wide companion fraction for BD companions with $m > 0.06 M_\odot$ around early-to-mid-M dwarfs.

In order to better constrain the properties of this unique system we recommend that future observations of G203-50AB include a parallax measurement to resolve uncertainties over the distance and absolute magnitude of G203-50, a high-resolution spectrum of G203-50 to determine the metallicity more precisely, an optical spectrum for 2M1711+4028 to determine an optical spectral type, and time series spectra to check for spectroscopic binarity.

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⁶ Available at <http://DwarfArchives.org>.

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