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SDSS J080531.84+481233.0: AN UNRESOLVED L DWARF/T DWARF BINARY

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ABSTRACT

SDSS J080531.84+481233.0 is a peculiar L-type dwarf that exhibits unusually blue near-infrared and mid-infrared colors and divergent optical (L4) and near-infrared (L9.5) spectral classifications. These peculiar spectral traits have been variously attributed to condensate cloud effects or subsolar metallicity. Here I present an improved near-infrared spectrum of this source which further demonstrates the presence of weak CH_4 absorption at 1.6 μm but no corresponding band at 2.2 μm. It is shown that these features can be collectively reproduced by the combined light spectrum of a binary with L4.5 and T5 components, as deduced by spectral template matching. Thus, SDSS J080531.84+481233.0 appears to be a new low-mass binary straddling the L dwarf/T dwarf transition, an evolutionary phase for brown dwarfs that remains poorly understood by current theoretical models. The case of SDSS J080531.84+481233.0 further illustrates how a select range of L dwarf/T dwarf binaries could be identified and characterized without the need for high angular resolution imaging or radial velocity monitoring, potentially alleviating some of the detection biases and limitations inherent to such techniques.

Key words: binaries: general — stars: fundamental parameters —
stars: individual (SDSS J080531.84+481233.0) — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION

Coeval systems, from binaries to dense clusters, are invaluable resources for stellar studies. By significantly reducing uncertainties in distance, age, and composition, multiple systems enable comparative analyses of atmospheric properties, circumstellar environments, magnetic activity trends, and angular momentum evolution. Close binary systems also facilitate dynamical mass measurements, as well as radius measurements for eclipsing systems. The multiplicity characteristics of a coeval population provide critical constraints for theories exploring stellar genesis, as well as the distribution of stellar and substellar masses and the incidence of planetary systems throughout the Galaxy.

Multiple systems are of particular importance in studies of the lowest-mass stars incapable of sustained core hydrogen fusion, the so-called brown dwarfs. The apparently low resolved binary fraction of field brown dwarfs (~10%–15%; see Burgasser et al. 2007b and references therein) has been cited as evidence of mass-dependent multiple formation (e.g., Bouy et al. 2006), as predicted by some brown dwarf formation models (e.g., Sterzik & Durisen 2003). However, resolved imaging studies provide only a lower limit to the true binary fraction, and evidence from radial velocity studies (e.g., Maxted & Jeffries 2005) and overluminous cluster members (Pinfield et al. 2003; Chappelle et al. 2005; Bouy et al. 2006) suggests a much higher total binary fraction, perhaps 25% or more (Basri & Reiners 2006; Reid et al. 2006). This may prove to be a significant challenge for some brown dwarf formation theories (e.g., Bate et al. 2002).

Unresolved multiples also play an important role in understanding the transition between the two lowest luminosity classes of known brown dwarfs, the L dwarfs and T dwarfs (Kirkpatrick 2005 and references therein). This transition occurs when photospheric condensates, a dominant source of opacity in L dwarf atmospheres, disappear, resulting in near-infrared spectral energy distributions that are blue and dominated by molecular gas absorption, including CH_4 (Tsuji et al. 1996, 1999; Burrows & Sharp 1999; Chabrier et al. 2000; Allard et al. 2001). While condensate cloud models provide a physical basis for this transition (Ackerman & Marley 2001; Cooper et al. 2003; Burrows et al. 2006), they fail to explain its apparent rapidity, as deduced by the small effective temperature ($T_{\rm eff}$) differential (Kirkpatrick et al. 2000; Golimowski et al. 2004; Vrba et al. 2004) and apparent brightening at 1 μm (Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004) between late-type L dwarfs and midtype T dwarfs. Multiplicity effects may be partly responsible for these trends, particularly as the resolved binary fraction of L/T transition objects is nearly twice that of other spectral types (Burgasser et al. 2006), and can result in overestimated temperatures and surface fluxes (Golimowski et al. 2004; Liu et al. 2006). As the total binary fraction of L/T transition objects may be higher still (perhaps as high as 65%; Burgasser 2007), interpretations of absolute brightness, color, and $T_{\rm eff}$ trends across this important evolutionary phase for nearly all brown dwarfs may be skewed.

Empirical constraints on the L/T transition can be made through the identification and characterization of binaries with components that span this transition (Cruz et al. 2004; Burgasser et al. 2005, 2006; Liu et al. 2006; Reid et al. 2006). One such system that may have been overlooked is the peculiar L dwarf SDSS J080531.84+481233.0 (hereafter SDSS J0805+4812; Hawley et al. 2002; Knapp et al. 2004), identified in the Sloan Digital Sky Survey (hereafter SDSS; York et al. 2000). This source has widely discrepant optical (L4; Hawley et al. 2002) and near-infrared (L9.5 ± 1.5; Knapp et al. 2004; Chiu et al. 2006) spectral types, and unusually blue near-infrared colors ($J-K = 1.10 \pm 0.04$; Knapp et al. 2004) compared to either L4 ($\langle J-K\rangle = 1.52$) or L8–T0.5 dwarfs ($\langle J-K\rangle = 1.58$–$1.74$; Vrba et al. 2004). Its mid-infrared colors are also peculiar (Golimowski et al. 2004; Knapp et al. 2004; Leggett et al. 2007). These characteristics

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have been interpreted as resulting from a metal-poor photosphere or one with unusually thin photospheric condensate clouds (Knapp et al. 2004; Golimowski et al. 2004; Leggett et al. 2007; Folkes et al. 2007). However, unresolved multiplicity may provide a better explanation for the peculiar properties of this source. In this article I present and analyze new low-resolution near-infrared spectral data for SDSS J0805+4812 that support this hypothesis, and demonstrate that this source is likely to be a binary with components straddling the L/T transition. Spectral observations are described in § 2, including a detailed discussion of the unusual features observed in these data. Analysis of these data in regard to the source's possible binary nature is described in § 3, and the properties of the components inferred from this analysis are discussed in § 4. Finally, the implications of this study, including application of the technique used here to identify and characterize brown dwarf binaries independent of angular resolution limitations, are briefly discussed in § 5.

2. OBSERVATIONS

2.1. *Data Acquisition and Reduction*

Low-resolution near-infrared spectral data for SDSS J0805+4812 were obtained on 2006 December 24 (UT) using the SpeX spectrograph (Rayner et al. 2003) mounted on the 3 m NASA Infrared Telescope Facility (IRTF). The conditions were clear with good seeing (0.8″ at *J* band). The 0.5″ slit was employed, providing 0.75–2.5 μm spectroscopy with a resolution of $\lambda/\Delta\lambda \approx$ 120 and dispersion across the chip of 20–30 Å pixel^{-1}. To mitigate the effects of differential refraction, the slit was aligned to the parallactic angle. Six exposures of 120 s each were obtained in an ABBA dither pattern along the slit. The A0 V star HD 71906 was observed immediately afterward at a similar air mass ($z = 1.18$) for flux calibration. Internal flat field and argon arc lamps were also observed for pixel response and wavelength calibration.

Data were reduced using the Spextool package, version 3.4 (Cushing et al. 2004), using standard settings. Raw science images were first corrected for linearity, pairwise subtracted, and divided by the corresponding median-combined flat-field image. Spectra were optimally extracted using the default settings for aperture and background source regions, and wavelength calibration was determined from arc lamp and sky emission lines. The multiple spectral observations were then median-combined after scaling individual spectra to match the highest signal-to-noise ratio observation. Telluric and instrumental response corrections for the science data were determined using the method outlined in Vacca et al. (2003), with line-shape kernels derived from the arc lines. Adjustments were made to the telluric spectra to compensate for differing H I line strengths in the observed A0 V spectrum and pseudovelocity shifts. Final calibration was made by multiplying the spectrum of SDSS J0805+4812 by the telluric correction spectrum, which includes instrumental response correction through the ratio of the observed A0 V spectrum to a scaled, shifted, and deconvolved Kurucz[2] model spectrum of Vega.

2.2. *The Spectrum of SDSS J0805+4812*

The reduced spectrum of SDSS J0805+4812 is shown in Figure 1 and compared to equivalent SpeX prism data for the optically classified L4 2MASS J11040127+1959217 (hereafter 2MASS J1104+1959; Cruz et al. 2003), and 2MASS J03105986+1648155 (hereafter 2MASS J0310+1648; Kirkpatrick et al. 2000), which is classified as L8 in the optical and L9 in the near-infrared (Geballe et al. 2002). The spectrum of SDSS J0805+4812 is most similar to that of 2MASS J1104+1959 based on their overall spectral energy distributions, strong FeH absorption at 0.99 μm, and prominent Na I and K I lines in the 1.1–1.25 μm range. However, the 1.15 and 1.3 μm H_2O bands are clearly much stronger in the spectrum of SDSS J0805+4812 but similar in strength to those in the spectrum of 2MASS J0310+1648. Other spectral characteristics of SDSS J0805+4812 are inconsistent with either of the comparison sources, such as the suppressed *K*-band flux peak and weak CO absorption at 2.3 μm.

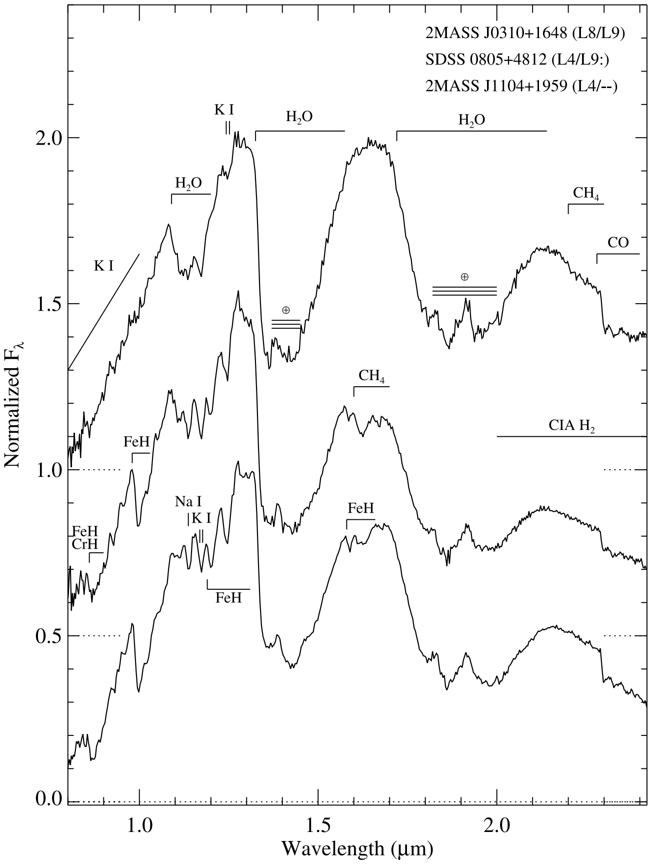

FIG. 1.—Reduced SpeX prism spectrum for SDSS J0805+4812 (*middle*) compared to equivalent data for the optically classified L4 2MASS J1104+1959 (*bottom*) and the L8/L9 (optical/near-infrared type) 2MASS J0310+1648 (*top*). All three spectra are normalized at their 1.25 μm flux peaks and offset by constants (*dotted lines*). Prominent features resolved by these spectra are indicated. Note in particular the weak band of CH_4 at 1.6 μm in the spectrum of SDSS J0805+4812.

The most unusual feature observed in the spectrum of this source, however, is the distinct absorption band at 1.6 μm, which is offset from 1.55–1.6 μm FeH absorption seen in the spectra of 2MASS J1104+1959 (Fig. 1) and other midtype L dwarfs (Cushing et al. 2003). The 1.6 μm feature is instead coincident with the *Q*-branch of the $2\nu_3$ CH_4 band, a defining feature for the T dwarf spectral class. It should be noted that this feature appears to be weakly present but overlooked in spectral data from Knapp et al. (2004), and no mention is made of it by Chiu et al. (2006), who also obtained SpeX prism data for SDSS J0805+4812. Interestingly, there is no indication of the 2.2 μm CH_4 band, which is commonly seen in the spectra of the latest-type L dwarfs (this band is weakly present in the spectrum of L8/L9 2MASS J0310+1648; Fig. 1).

Several of the peculiar spectral characteristics of SDSS J0805+4812 are similar to those shared by a subclass of so-called blue L dwarfs (Cruz et al. 2003, 2007; Knapp et al. 2004; Burgasser et al. 2007a), including the blue spectral energy distribution, strong H_2O absorption, and weak CO bands. These properties can be explained

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[2] See http://kurucz.harvard.edu/stars.html.

by the presence of thinner photospheric condensate clouds (Burgasser et al. 2007a), which enhances the relative opacity of atomic and molecular species around 1 μm and produces bluer $J-K$ and mid-infrared colors (Marley et al. 2002; Knapp et al. 2004; Leggett et al. 2007). However, Golimowski et al. (2004) have found that the thin cloud interpretation fails to explain the unusually blue $K-L'$ colors of SDSS J0805+4812, nor does it explain the presence of CH_4 absorption at 1.6 μm but not at 2.2 μm. Subsolar metallicity has also been cited as an explanation for the peculiar nature of SDSS J0805+4812 (Golimowski et al. 2004; Knapp et al. 2004), although this source does not show the extreme peculiarities observed in the spectra of L subdwarfs (Burgasser et al. 2003b), nor does subsolar metallicity explain the presence of CH_4 absorption.

A potential clue to the nature of SDSS J0805+4812 can be found by noting that only two other late-type dwarfs have CH_4 absorption at 1.6 μm but not at 2.2 μm: 2MASS J05185995−2828372 (hereafter 2MASS J0518−2828; Cruz et al. 2004) and SDSS J141530.05+572428.7 (Chiu et al. 2006). The latter source has not been studied in detail, but in the case of 2MASS J0518−2828 Cruz et al. (2004) have found that the combined light spectrum of an L6 plus T4 binary provides a reasonable match to the near-infrared spectrum of this source, including its weak CH_4 band. Subsequent high-resolution imaging has resolved this source into two point-source components and apparently confirms this hypothesis (Burgasser et al. 2006). The similarity in the spectral peculiarities between 2MASS J0518−2828 and SDSS J0805+4812 suggests that the latter may be a similar but as yet unrecognized pair.

3. BINARY TEMPLATE MATCHING

To explore the binary hypothesis for SDSS J0805+4812, the technique of binary spectral template matching was employed.[3] A large set of binary spectral templates was constructed from a sample of 50 L and T dwarf SpeX prism spectra, including sources that are unresolved in high angular resolution imaging,[4] and are not reported as spectrally peculiar. The individual spectra were flux-calibrated using the M_K−spectral type relation of Burgasser (2007) based on published optical and near-infrared spectral types for L dwarfs and T dwarfs, respectively, and synthetic MKO[5] magnitudes determined directly from the spectra. Binaries were then constructed by combining spectral pairs with types differing by 0.5 subclasses or more, resulting in 1164 unique templates. Then χ^2 deviations[6] were computed between the spectra of the synthesized binaries and SDSS J0805+4812 over the 1.0–1.35, 1.45–1.8, and 2.0–2.35 μm regions (i.e., avoiding regions of strong telluric absorption) after normalizing at 1.25 μm. The single L and T dwarf spectra were also compared to that of SDSS J0805+4812 in a similar manner.

The best-match binary template for SDSS J0805+4812 is shown in Figure 2, composed of the L5 2MASS J15074769−1627386 (hereafter 2MASS J1507−1627; Reid et al. 2000) and the T5.5 2MASS J15462718−3325111 (hereafter 2MASS J1546−3325; Burgasser et al. 2002). The combined spectrum is an excellent match to that of SDSS J0805+4812 ($\chi^2 = 0.10$), reproducing the latter's blue spectral energy distribution, enhanced 1.15 and 1.3 μm H_2O absorption bands, weak 2.3 μm CO absorption, and most notably the presence of weak CH_4 absorption at 1.6 μm. Several combinations of midtype L dwarf and midtype T dwarf components produced similar excellent fits; in contrast, the single spectral templates were all poor matches ($\chi^2 > 1$). A mean of all binary spectral templates with $\chi^2 < 0.5$ (33 pairs) weighted by their inverse deviations yielded mean component types of L4.6 ± 0.7 and T4.9 ± 0.6. The inferred primary type is notably consistent with the optical classification of SDSS J0805+4812. This is an encouraging result, since L dwarfs are significantly brighter than T dwarfs at optical wavelengths and should thus dominate the combined light flux. The inferred secondary spectral type is significantly later, explaining both the presence (strong absorption) and weakness (lower relative flux) of the CH_4 feature at 1.6 μm in the composite spectrum of SDSS J0805+4812. Spectral types of L4.5 and T5 are hereafter adopted for the binary components of this system.

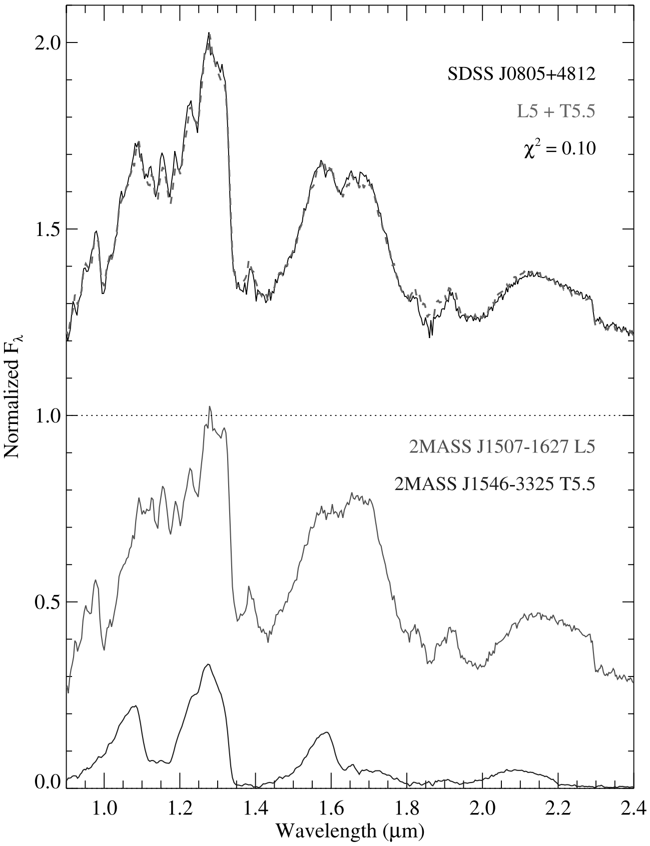

Fig. 2.—Best-match binary spectral template for SDSS J0805+4812, a combination of the L5 2MASS J1507−1627 and the T5.5 2MASS J1546−3325, shown in the bottom panel (*gray and black lines, respectively*). The combined spectrum (*top*, *dashed line*) is an excellent match to that of SDSS J0805+4812 (*top*, *solid line*). All spectra are normalized at their 1.25 μm flux peaks, with the spectrum of 2MASS J1546−3325 scaled to match its relative flux compared to 2MASS J1507−1627 according to the M_K−spectral type relation of Burgasser (2007). [*See the electronic edition of the Journal for a color version of this figure.*]

4. THE COMPONENTS OF SDSS J0805+4812

4.1. *Estimated Physical Properties*

Based on the excellent match of the spectrum of SDSS J0805+4812 to empirical binary templates composed of normal, single sources, it is compelling to conclude that unresolved binarity

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[3] For other examples of this technique, see the analyses of Burgasser et al. (2006, 2007a), Liu et al. (2006), Reid et al. (2006), Burgasser (2007), and Looper et al. (2007).

[4] For an up-to-date list of known L and T dwarf binaries, see the VLM Binaries Archive maintained by N. Siegler at http://paperclip.as.arizona.edu/∼nsiegler/VLM_binaries

[5] Mauna Kea Observatory (MKO) photometric system (Simons & Tokunaga 2002; Tokunaga et al. 2002).

[6] Here, $\chi^2 \equiv \sum_{\{\lambda\}}[f_\lambda(0805) - f_\lambda(SB)]^2/f_\lambda(0805)$, where $f_\lambda(0805)$ is the spectrum of SDSS J0805+4812 and $f_\lambda(SB)$ is the spectrum of the synthesized binary over the set of wavelengths $\{\lambda\}$ as specified in the text.

TABLE 1

Predicted Component Parameters for SDSS J0805+4812AB

Parameter	SDSS J0805+4812A	SDSS J0805+4812B	Difference
Spectral type	L4.5 ± 0.7	T5 ± 0.6	...
J [a]	14.25 ± 0.04	15.75 ± 0.08	1.50 ± 0.09
H [a]	13.62 ± 0.03	16.01 ± 0.14	2.39 ± 0.15
K [a]	12.37 ± 0.03	15.40 ± 0.16	3.03 ± 0.16
$\log L_{\rm bol}/L_{\odot}$ [b]	−4.15 ± 0.13	−4.93 ± 0.13	0.88 ± 0.16
Mass ($M_{\odot}$) at 1 Gyr [c]	0.066	0.036	0.55 [d]
Mass ($M_{\odot}$) at 5 Gyr [c]	0.078	0.069	0.88 [d]
$T_{\rm eff}$ (K) at 1 Gyr [c]	1830 ± 90	1200 ± 70	...
$T_{\rm eff}$ (K) at 5 Gyr [c]	1780 ± 100	1100 ± 70	...
Estimated d (pc)	14.5 ± 2.1	14.8 ± 2.5	−0.3 ± 0.5

[a] Synthetic magnitudes in the MKO system.
[b] Luminosities based on the $M_{\rm bol}$–spectral type relation of Burgasser (2007).
[c] Based on the evolutionary models of Burrows et al. (2001) and the estimated luminosities.
[d] Mass ratio (M_2/M_1).

provides the simplest explanation for the peculiarities of this source. Assuming this to be the case, it is possible to characterize the components of SDSS J0805+4812 in some detail. Component *JHK* magnitudes in the MKO system were determined from reported photometry of the source (Knapp et al. 2004) and integrating MKO filter profiles over the flux-calibrated binary template spectra. The best values, again using a weighted mean for all matches with $\chi^2 < 0.5$, are listed in Table 1. Comparison of the component magnitudes to absolute magnitude–spectral type relations from Burgasser (2007) yields distance estimates of 14.5 ± 2.1 and 14.8 ± 2.5 pc for the primary and secondary, respectively, where the uncertainties of the spectral types of the components and photometric magnitudes are explicitly included. It is of no surprise that these distance estimates are consistent, since the binary templates from which the component types are inferred are flux-calibrated using the same absolute magnitude scales. A mean distance of 14.6 ± 2.2 pc is estimated for this system.

The secondary is considerably fainter than the primary, particularly at K band, where $\Delta K = 3.03 \pm 0.16$ is deduced. This suggests a low system mass ratio ($q \equiv M_2/M_1$). Using the relative K-band flux and K-band bolometric corrections from Golimowski et al. (2004) and assuming $q \approx 10^{-0.15\Delta M_{\rm bol}}$ (Burrows et al. 2001), $q = 0.48$ is inferred. This value is indeed smaller than the mass ratios of most very low mass binaries, 77% of which have $q \geq 0.8$ (Burgasser et al. 2007b). However, the approximation used here assumes that both components are brown dwarfs. The primary is of sufficiently early type that it may be an older hydrogen-burning low-mass star or massive brown dwarf. Using the evolutionary models of Burrows et al. (2001) and assuming component luminosities calculated from the $M_{\rm bol}$–spectral type relation of Burgasser (2007),[7] the estimated component masses and $T_{\rm eff}$ values for ages of 1 and 5 Gyr were computed and are listed in Table 1. If SDSS J0805+4812 is an older system, the mass ratio of the system increases toward unity. This is because the slightly less massive substellar secondary has had a much longer time to cool to T dwarf temperatures, while the primary has settled onto the main sequence. The strong age dependence on mass ratio estimates for low-mass stellar/substellar binaries is an important bias that is frequently overlooked.

4.2. Li I *Detection and Age/Mass Constraints*

From the previous discussion, it is clear that a robust characterization of the SDSS J0805+4812 components requires an age determination for the system, which is generally difficult for individual field sources. Age constraints may be feasible in this case, however, as the inferred luminosities of its components straddle the Li I depletion line (Rebolo et al. 1992; Magazzú et al. 1993), as illustrated in Figure 3. The so-called binary lithium test pointed out by Liu & Leggett (2005) states that if lithium is present in the atmosphere of both components of the system, a maximum age may be inferred. Conversely, if lithium is absent, a minimum age may be inferred. The most interesting case is the absence of lithium in the primary spectrum but its presence in the secondary spectrum, which restricts the age of the system to a finite range.

The presence of lithium in the primary may be inferred from the 6708 Å Li I line in the system's composite spectrum. Optical data from Hawley et al. (2002) show no obvious feature at this wavelength, indicating lithium depletion in the primary and a

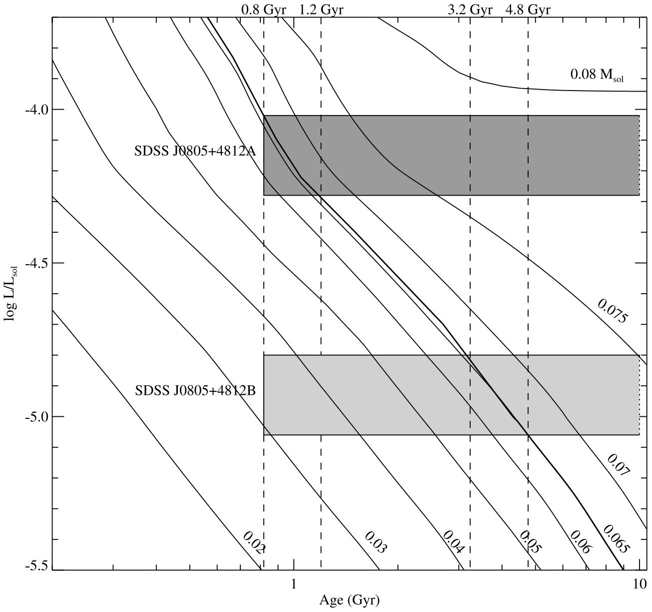

FIG. 3.—Limits on the masses and ages of the SDSS J0805+4812 components based on their estimated luminosities (*gray regions*) and evolutionary models from Burrows et al. (2001). Lines trace the evolutionary tracks for masses of 0.02–0.08 $M_{\odot}$. The lithium depletion boundary is indicated by the thickened line. Lower age limits assuming the absence of lithium in the atmospheres of the primary and secondary, and upper age limits assuming its presence, are indicated. The shaded regions are defined based on the absence of the 6708 Å Li I line in the combined light optical spectrum of SDSS J0805+4812 from Hawley et al. (2002).

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[7] Based on data from Golimowski et al. (2004).