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SPECTROSCOPIC CONFIRMATION OF THE LEAST MASSIVE KNOWN BROWN DWARF IN CHAMAELEON[1]

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ABSTRACT

We present spectroscopy of two candidate substellar members of the Chamaeleon I star-forming region. The candidates, which were identified photometrically by Oasa, Tamura, & Sugitani, have been observed at 1–2.5 μm during commissioning of the Gemini Near-Infrared Spectrograph. The late-type nature of one of the candidates, OTS 44, is confirmed through the detection of strong steam absorption bands. The other object, OTS 7, exhibits no late-type features and is likely a background star or galaxy. The gravity-sensitive shape of the H and K band continua demonstrate that OTS 44 is a young, pre–main-sequence object rather than a field dwarf. We measure a spectral type of M9.5 for OTS 44 based on a comparison of its spectrum to data for optically classified young late-type objects. Because OTS 44 is the coolest and faintest object with confirmed membership in Cha I, it is very likely the least massive known member of the cluster. By comparing the position of OTS 44 on the H-R diagram to the evolutionary models of Chabrier & Baraffe, we infer a mass of $\sim$0.015 $M_\odot$. Although this estimate is uncertain by at least a factor of 2, OTS 44 is nevertheless one of the least massive free-floating brown dwarfs confirmed spectroscopically to date.

Subject headings: infrared: stars — stars: evolution — stars: formation — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

Because brown dwarfs are relatively bright soon after birth and fade precipitously thereafter, star-forming clusters are the most promising sites in which to search for the least massive brown dwarfs. At a distance of 160–170 pc (Whittet et al. 1997; Wichmann et al. 1998; Bertout et al. 1999), the Chamaeleon I cloud complex is one of the nearest major star formation regions, and therefore is a particularly attractive hunting ground. A variety of methods have been used to identify candidate low-mass stars and brown dwarfs in Cha I, including objective prism spectroscopy at Hα (Comerón et al. 1999, 2000, 2004; Neuhäuser & Comerón 1999), photometric variability (Carpenter et al. 2002), X-ray emission (Comerón et al. 2000; Feigelson & Lawson 2004), and optical and infrared (IR) photometry (Cambrésy et al. 1998; Oasa et al. 1999; Persi et al. 2000, 2001; Gómez & Kenyon 2001; López Martí et al. 2004; Comerón & Claes 2004). All spectroscopic observations of candidates from these surveys have been compiled and evaluated by Luhman (2004a), with the exception of the recent spectroscopy provided by Comerón et al. (2004). To date, the coolest confirmed members of Cha I have spectral types of $\sim$M8, corresponding to masses of $\sim$0.03 $M_\odot$.

From the previous surveys of Chamaeleon, there remain several promising candidate brown dwarfs that lack spectroscopy and that should have masses as low as 0.01 $M_\odot$ if they are indeed late-type members of the star-forming region. During the recent commissioning of the Gemini Near-Infrared Spectrograph (GNIRS), we obtained near-IR spectroscopy of the two faintest objects from the compilation of candidates in Luhman (2004a), sources 7 and 44 from Oasa et al. (1999) (hereafter OTS 7 and OTS 44). In this article, we describe these observations (§ 2), assess the membership of the candidates in Cha I and measure the spectral type for the one confirmed member (§ 3.1), estimate the extinction, effective temperature, and bolometric luminosity of that source (§ 3.2), and infer its mass from theoretical evolutionary models (§ 3.3).

2. OBSERVATIONS

Near-IR spectroscopy was performed on the brown dwarf candidates OTS 44 and OTS 7 during queue observations with GNIRS at Gemini South Observatory on the nights of 2004 March 9 and 10, respectively. To facilitate the spectral classification of these objects, we also observed an optically classified late-type member of Cha I, source 17173 from Carpenter et al. (2002) (hereafter CHSM 17173). The spectrograph was operated in the cross-dispersed mode with the 31.7 lines mm^{-1} grating and a $0\farcs3 \times 6''$ slit, producing full coverage from 1 to 2.5 μm, with a spectral resolution that varied between $R = \lambda/\Delta\lambda = 1800$ and 2200, depending on wavelength. Each object was dithered between two positions along the slit separated by 3″. The numbers of exposures and the integration times were 8×60, 8×100, and 20×100 s for CHSM 17173, OTS 44, and OTS 7, respectively. A nearby A0 V star (HD 98671) was also observed for the correction of telluric absorption. After dark subtraction and flat-fielding, adjacent images along

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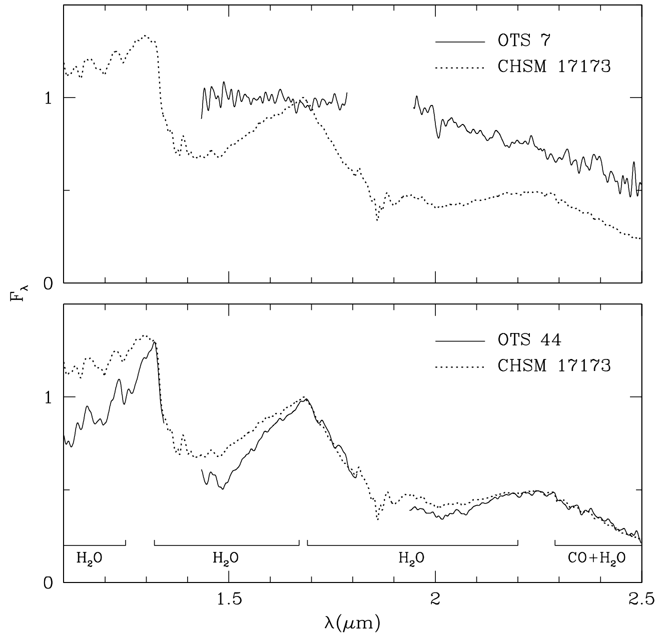

Fig. 1.—GNIRS near-IR spectra of two candidate substellar members of the Cha I star-forming region identified by Oasa et al. (1999; OTS 7 and OTS 44). The previously known late-type member CHSM 17173 (M8) is included for comparison. The steam absorption bands in the spectrum of OTS 44 confirm that it is a cool object and indicate a spectral type later than that of CHSM 17173. The other candidate, OTS 7, is probably a field star or extragalactic source, given the absence of steam absorption or other late-type features. The spectra are displayed at a resolution of $R = 200$ and are normalized at 1.68 μm.

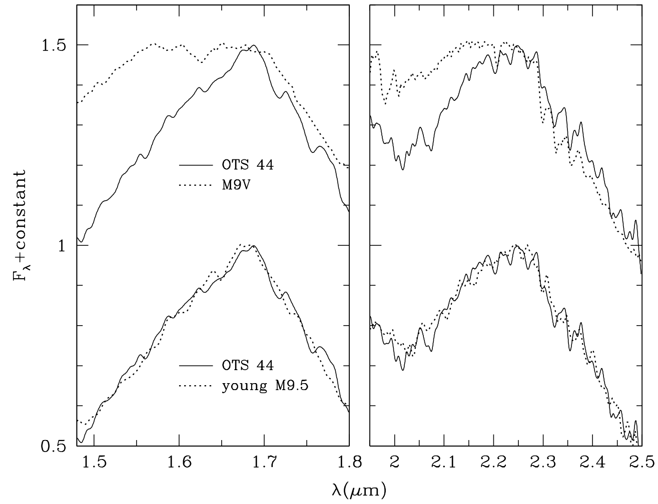

Fig. 2.—GNIRS H and K band spectra of the candidate brown dwarf OTS 44 compared to IRTF SpeX data for the field dwarf LHS 2065 (M9 V) and the young Taurus member KPNO-Tau 4 (M9.5). OTS 44 exhibits the triangular continua that are indicative of young late-type objects rather than the broad plateaus found in field dwarfs (Lucas et al. 2001), confirming its youth and membership in the Cha I star-forming region. A spectral type of M9.5 is assigned to OTS 44 based on the close match to KPNO-Tau 4. The spectra are displayed at a resolution of $R = 200$ and are normalized at 1.68 and 2.25 μm.

the slit were subtracted from each other to remove sky emission. The sky-subtracted images were aligned and combined. A spectrum was extracted from each of the five orders in the cross-dispersed format. The detectable hydrogen absorption lines in the spectrum of the telluric standard were removed manually through interpolation. The intrinsic spectral slope of the standard was removed with an artificial blackbody spectrum of $T_{\rm eff} = 10000$ K. At a given order, this modified spectrum was then divided into the extracted spectra of the three targets. Wavelength calibration was performed with OH airglow lines. For each object, the spectra from the five orders were scaled multiplicatively to align the overlapping regions between adjacent orders to the same flux level.

During the spectral classification of the GNIRS targets in § 3.1, we use spectra of standards obtained with the near-IR spectrometer SpeX (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF). The field dwarf LHS 2065 (M9 V) and the young Taurus member KPNO-Tau 4 (M9.5; Briceño et al. 2002) were observed with SpeX on the nights of 2003 December 21 and 23, respectively. The instrument was operated in the prism mode with a 0$''$.5 slit, producing a wavelength coverage of 0.8–2.5 μm and a resolution of $R \sim 200$. The spectra were reduced with the Spextool package (Cushing et al. 2004), which included the same basic steps described for the GNIRS data reduction. We corrected for telluric absorption with the method described by Vacca et al. (2003).

3. ANALYSIS

3.1. *Membership and Spectral Classification*

The GNIRS spectra of the brown dwarf candidates OTS 7 and OTS 44 and the known late-type Chamaeleon member CHSM 17173 are shown in Figure 1. The spectrum of OTS 44 closely resembles that of CHSM 17173, most notably in terms of the strong steam absorption bands. In this section, we assess the membership of this object in Cha I and measure its spectral type. Meanwhile, the steam absorption expected from a cool photosphere is absent from the spectrum of OTS 7. This object is probably an early-type field star or a background galaxy and is discussed no further.

OTS 44 could be a field dwarf, a field giant, or a young, pre–main-sequence member of Cha I. These distinct luminosity classes can be differentiated with spectral features that are sensitive to surface gravity, a variety of which have been identified for cool objects at both optical (Martín et al. 1996; Luhman 1999; McGovern et al. 2004) and near-IR (Luhman et al. 1998; Gorlova et al. 2003; McGovern et al. 2004) wavelengths. In this work, we do not consider the gravity-sensitive atomic transitions, such as K I at J and Na I at K, because of insufficient signal-to-noise ratio and spectral resolution in the GNIRS spectrum of OTS 44 and the SpeX data, respectively. Instead, we use the steam absorption bands to determine if OTS 44 is a young member of Cha I. The shape of the continuum induced by steam absorption varies noticeably with surface gravity. The broad plateaus in the H and K spectra of late M and L dwarfs (Reid et al. 2001; Leggett et al. 2001) are absent in young objects, resulting in sharply peaked, triangular continua (Lucas et al. 2001). This gravity diagnostic is easily detectable at the signal-to-noise ratio and resolution of our data, as illustrated with the spectra of the young late-type object KPNO-Tau 4 and the field dwarf LHS 2065 in Figure 2. OTS 44 is compared to these two objects in Figure 2, in which we find that it clearly exhibits the triangular continua that are indicative of youth rather than the broad plateaus expected for a field dwarf. Meanwhile, the strength of the CO band heads in OTS 44 is comparable to that of the comparison dwarf and young object and much less than that of an M giant (e.g., Luhman & Rieke 1999). Based on the behavior of these spectral features, we conclude that OTS 44 is not a field dwarf or giant and is instead a member of the Cha I star-forming region.

TABLE 1
Data for OTS 44 and KPNO-Tau 4

ID	α (J2000.0)	δ (J2000.0)	Spectral Type	$T_{\rm eff}$ (K)	A_J	$L_{\rm bol}$	$J-H$	$H-K_s$	K_s
OTS 44	11 10 09.33[a]	−76 32 18.1[a]	M9.5 ± 1	2300[b]	0.3	0.0013	1.01[c]	0.79[c]	14.61[c]
KPNO-Tau 4[d]	04 27 28.01	26 12 05.3	$M9.5^{+0.5}_{-0.25}$	2300	0.0	0.0023	0.97	0.74	13.28

[a] Measured in *I* band images from K. Luhman (in preparation).
[b] Temperature for M9.5 from Briceño et al. 2002.
[c] Oasa et al. 1999.
[d] Data for KPNO-Tau 4 from Briceño et al. (2002), updated with the values of JHK_s from the 2MASS Point Source Catalog.

In addition to surface gravity, the IR steam bands are also sensitive to temperature and thus can be used to measure spectral types (Wilking et al. 1999; Cushing et al. 2000; Reid et al. 2001; Leggett et al. 2001; Testi et al. 2001). At a given optical spectral type, these bands are stronger in young objects than in field dwarfs (Luhman & Rieke 1999; Lucas et al. 2001; McGovern et al. 2004), as shown with KPNO-Tau 4 and LHS 2065 in Figure 2. As a result, if a young source is classified by comparing the strength of its steam absorption to that of field dwarfs, the derived spectral type will be systematically too late. To arrive at accurate spectral types, optically classified young objects, rather than dwarfs, should be used as the standards (Luhman & Rieke 1999; Luhman et al. 2003), which is the approach we adopt for classifying OTS 44. In Figure 2, we find that the depths of the steam bands in OTS 44 closely match those in KPNO-Tau 4, which has an optical type of M9.5. Because few IR spectra of young, optically classified late-type objects are available, we cannot compare OTS 44 to a finely sampled sequence of standards and determine the precise range of types that would match the steam depths for OTS 44. This source is clearly later than CHSM 17173 (M8; Luhman 2004a) according to the relative strengths of their steam bands, as shown in Figure 1. Meanwhile, we have no constraints on the latest possible type for this object. For the purposes of this work, we assign an uncertainty of ±1 subclass to the M9.5 classification of OTS 44. The latest spectral types for previously confirmed members of Cha I are M8 for CHSM 17173 (Luhman 2004a), M8.25 for 2MASS J11011926−7732383B (Luhman 2004b), and M8.5 for source 554 from Comerón et al. (2004).[5] At a type of M9.5, OTS 44 is now the latest confirmed member of Cha I.

3.2. *Extinction, Temperature, and Luminosity*

We can estimate the extinction of OTS 44 from its near-IR spectrum and colors. The comparison of the 1–2.5 μm spectra of OTS 44 and CHSM 17173 in Figure 1 and the relative $J-H$ and $H-K_s$ colors of OTS 44 and KPNO-Tau 4 imply that OTS 44 is slightly redder ($A_J \sim 0.3$) than both of these objects. Both CHSM 17173 and KPNO-Tau 4 lack noticeable reddening in their optical spectra. Therefore, for OTS 44 we estimate an extinction $A_J = 0.3 \pm 0.3$. For the M9.5 spectral type of OTS 44, we adopt the temperature of 2300 K used by Briceño et al. (2002) for KPNO-Tau 4. The bolometric luminosity is estimated by combining the *H* band measurement from Oasa et al. (1999), a distance of 168 pc (Whittet et al. 1997; Wichmann et al. 1998; Bertout et al. 1999), and a bolometric correction for M9.5 from Reid et al. (2001). The combined uncertainties in A_H, H, BC_H, and the distance modulus ($\sigma \sim 0.2$, 0.05, 0.2, 0.13) correspond to an error of ±0.12 in $\log L_{\rm bol}$. The extinction, effective temperature, and bolometric luminosity for OTS 44 are listed in Table 1. For comparison, we also include the same parameters for KPNO-Tau 4 as estimated by Briceño et al. (2002).

3.3. *Mass*

The temperature and luminosity for OTS 44 from the previous section can be used to estimate its mass via theoretical evolutionary models. We select the models of Baraffe et al. (1998) and Chabrier et al. (2000) because they provide the best agreement with observational constraints (Luhman et al. 2003). OTS 44 and previously known late-type members of Cha I (Luhman 2004a, 2004b) are plotted on the Hertzsprung-Russell (H-R) diagram in Figure 3 with these evolutionary models, which imply a mass of $\sim$0.015 $M_\odot$ for OTS 44. The uncertainty in the spectral type of OTS 44 corresponds to roughly a factor of 2 in mass. The conversion of spectral type to temperature and the models themselves contribute additional errors

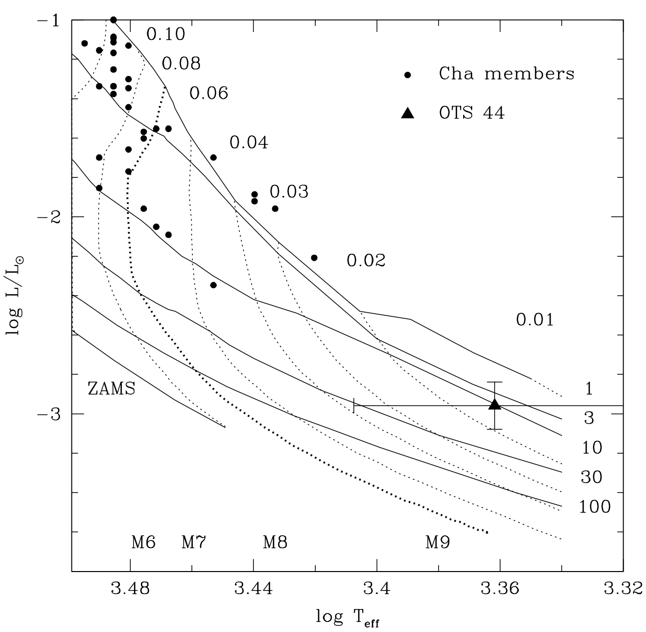

Fig. 3.—H-R diagram for previously known late-type members of Cha I (Luhman 2004a, 2004b) and the new member OTS 44 shown with the theoretical evolutionary models of Baraffe et al. (1998; $M/M_\odot > 0.1$) and Chabrier et al. (2000; $M/M_\odot \leq 0.1$), where the mass tracks (*dotted lines*) and isochrones (*solid lines*) are labeled in units of $M_\odot$ and Myr, respectively. These models imply a mass of $\sim$0.015 $M_\odot$ for OTS 44.

[5] The spectral types from Comerón et al. (2004) are systematically later than those in Luhman (2004a) by an average of 0.5 subclass, which suggests that 554 is probably M8 in our spectral type system.

to this mass estimate that cannot be quantified. Nevertheless, because OTS 44 has the lowest luminosity and temperature of any confirmed member of Cha I, it very likely has the lowest mass. This brown dwarf is one of the nearest and least massive free-floating objects discovered to date.

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