PROPERTIES OF THE T8.5 DWARF WOLF 940 B

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1. INTRODUCTION

The study of brown dwarfs, stellar-like objects with a mass below that required for the onset of hydrogen fusion (e.g., Burrows et al. 2001) has advanced dramatically in the last decade. Primarily, this has been due to the discovery of a significant population of brown dwarfs by far-red and near-infrared surveys: the Sloan Digital Sky Survey (York et al. 2000), the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the UK Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), and the Canada France Hawaii Telescope’s Brown Dwarf Survey (CFBDS; Delorme et al. 2008b). The latest spectral type and coolest dwarfs currently known are classified as T dwarfs. At the time of writing, there are eight objects known with type later than T0 (e.g., Delorme et al. 2009). These objects have very low effective temperatures (Teff) of 500–600 K (e.g., Leggett et al. 2010), approaching the temperature where water clouds are expected to form in the atmosphere (e.g., Burrows et al. 2003).

The T dwarfs that have stellar companions are of particular interest as the primary can provide distance, metallicity, and age constraints for the brown dwarf. There are ten known examples of such systems at this time. In order of increasing T dwarf sub-class, they are: Gl 337 CD (T0; T0 + K4V + G9V; Wilson et al. 2001; Burgasser et al. 2005), Epsilon Indi B (T1; T6 + K5V; Scholz et al. 2003; McCaughrean et al. 2004), HD 163296 (T2.5 + G0V; Liu et al. 2007; Delorme et al. 2008a), SCR 1446-6142 (T3 + M8; Bailer et al. 2007; Kasper et al. 2007), Gl 229 B (T7p + M1V; Nakajima et al. 1995; Leggett et al. 2002), HD 3651 B (T7.5 + K0V; Mugrauer et al. 2006; Burgasser et al. 2007; Liu et al. 2007; Luhman et al. 2007), Gl 570 D (T7.5 + M3V + M1.5V + K4V; Burgasser et al. 2000; Saumon et al. 2006; Geballe et al. 2009), Wolf 940 B (T8.5 + M4V, B09), and Ross 458 C (T8.5 + M7V + M0.5; Goldman et al. 2010). The degree of accuracy that can be obtained in the fundamental parameters of such T dwarfs is illustrated by the Geballe et al. (2009) study of the T7.5 dwarf Gl 570D. The Gl 570 system has a well-determined distance and metallicity, and the K4V primary constrains the age to be between 2 and 5 Gyr (Geballe et al. 2001). Comparison of the observed luminosity and spectral properties of the T dwarf to atmospheric and evolutionary models constrains Teff to be 800–820 K and the gravity to be log g = 5.09–5.23. These values constrain the age further to 3–5 Gyr, and the mass of the T dwarf to be between 38 and 47 MJup.

This paper presents an analysis of the spectral energy distribution (SED) of the T8.5 dwarf Wolf 940 B. The dwarf was discovered in the Large Area Survey component of the UKIDSS, and identified as a companion to the M4V star Wolf 940 (also known as LHS 3708 and GJ 1263), by B09. B09 present...
near-infrared spectroscopy and photometry, as well as L’ photometry, for the T dwarf. They use these data to derive the luminosity of the dwarf and hence $T_{\text{eff}}$ and surface gravity. Leggett et al. (2010) give Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004) [3.6], [4.5], [5.8], and [8.0] photometry for the T dwarf and use the infrared colors to support and further constrain the atmospheric properties determined by B09. Here, we report new mid-infrared spectroscopy for Wolf 940 B, obtained with the Spitzer Infrared Spectrograph (IRS; Houck et al. 2004). The improved accuracy of the luminosity we derive, and the additional spectroscopy, enables us to refine the B09 results. Wolf 940 B is currently the coolest companion to a star with both near- and mid-infrared photometric and spectroscopic data. A more complete energy distribution for such a cool object, which has other basic data provided by its companion (distance, age, and metallicity), provides a good test of the model atmospheres for these almost-planetary objects.

In Section 2, we describe the Wolf 940 system. The IRS data are presented in Section 3. In Section 4, we use atmospheric and evolutionary models to calculate an accurate luminosity for Wolf 940 B and constrain its fundamental properties. Our conclusions are given in Section 5.

2. THE WOLF 940 SYSTEM

The Wolf 940 binary consists of a widely separated M4 and T8.5 dwarf pair (Reid et al. 1995; B09). Table 1 lists the astrometric and photometric properties of the system. The primary is a high proper-motion M4 dwarf, identified in historic proper motion surveys as Wolf 940 (and LHS 3708, GJ 1263, among other identifiers).

B09 use the colors of the primary and the $M_K$: $V-K$ relationships presented by Bonfils et al. (2005) to derive a metallicity [$m/H$] = −0.06 ± 0.20 for the system. However, Leggett et al. (2010) show that the $H - K$ and $H - [4.5]$ colors of the secondary imply that the system has solar or slightly super-solar metallicity. Here, we use the Johnson & Apps (2008) significant revision of the Bonfils et al. calibration, together with the parallax, V and $K$ values given in Table 1, to derive a metallicity of [$m/H$] = $+0.24 \pm 0.09$ for the system. We discuss metallicity further in Section 4.6.

The measured radial velocity, combined with the parallax and proper motion, gives $UVW$ space motions of $35, -49,$ and $-26$ km s$^{-1}$ (B09, and references therein), typical of old disk objects. B09 match the combination of the kinematics and the Bonfils et al. metallicity value to the 3–5 Gyr-old disk population in the Galaxy population synthesis model by Robin et al. (2003).

In this paper, we constrain the age of the system using the Geneva–Copenhagen survey of age, kinematics, and metallicity of a large number of stars in the solar neighborhood (Holmberg et al. 2009). Based on this work, the $UVW$ velocities and revised metallicity of the Wolf 940 system imply an age of between 3 Gyr and 10 Gyr. We adopt this age range, taking a more conservative approach than B09.

Wolf 940 A shows the H$\alpha$ line in absorption, with an equivalent width of $-0.26$ Å, typical for an M4 dwarf (Gizis et al. 2002, their Figure 6). The evolution of chromospheric activity in low mass stars is a complex process, and its relationship to the strength of the H$\alpha$ line is not well understood (e.g., Gizis et al. 2002; West et al. 2008; Walkowicz & Hawley 2009). While it is clear that H$\alpha$ in emission implies a highly active and therefore young star, stars with H$\alpha$ in absorption may have “no” to moderate activity. Given that Wolf 940 A shows the line in absorption with a very typical strength for its type, we assume that it is no longer active and is therefore older than 3 Gyr, which is the lower limit on the activity lifetime for an M4 dwarf (West et al. 2008, their Figure 10). Again, we take a more conservative approach than B09 and do not assume that the presence of H$\alpha$ absorption implies that the star is still somewhat active, and so we do not put an upper limit on the age of the system based on chromospheric activity arguments.

In summary, the kinematic and H$\alpha$ properties of Wolf 940 A imply that the system is between 3 and 10 Gyr old. A rotational velocity for Wolf 940 A would be useful as it would allow a gyrochronology age to be determined. The metallicity of the system is approximately solar.

3. OBSERVATIONS

We obtained Spitzer IRS spectra of Wolf 940 B via the Director’s Discretionary Time program 527. The Short-Low module was used in first order which provides a spectrum covering the 7.5–14.5 $\mu$m range, with a resolution of $R \approx 120$. A nearby star was used in the blue peak-up array to acquire the target in the 3.7 slit. Standard staring mode was used with a ramp duration of 60s and 84 cycles, for an observation of duration 3.6 hr; two such observations were obtained. Each cycle places the target at two slit positions, about one-third and two-thirds of the way along the slit. Thus, the total on-source exposure was 5.6 hr. Both observations were carried out on 2008 December 16.

We used the Basic Calibrated Data (BCD) produced by the Spitzer pipeline version S18.7.0. This produces a two-dimensional long-slit spectrum at each of the nod positions, so for each of our two observations there are 84 files for each nod position. The BCD files have been processed by the pipeline, which includes ramp fitting, dark subtraction, droop correction.
linearity correction, flat fielding, and wavelength calibration (see Section 5.1 of the IRS Instrument Handbook\(^6\)).

We treated the two observations as independent data sets. We used the IRAF data reduction tool (Tody 1993) to subtract each nod pair and combined the 84 subtracted images using sigma-clipping in the `imcombine` routine. Some structure remained in the background of the combined images; we removed this by subtracting a smoothed version of the image, using an 11 × 11 box. This residual-structure subtracted image was then fed into the Spitzer IRS data reduction package SPICE.\(^7\) The source signal was low, and there were a large number of bad and hot pixels.

SPICE takes as input: the image file, a bad pixel mask, and an uncertainty image. We used the sigma image produced by the `imcombine` routine as the uncertainty mask and a bad pixel mask included with the BCD files. SPICE traces the appropriate module’s slit profile over the input image, allowing the user to set the location and the width of the extraction window. We extracted the positive and negative spectrum using a relatively small window of 2 pixels in order to avoid adding noise. The final step in the SPICE application converts the signal to a flux density.

We combined the two negative and two positive extracted spectra manually. The signal-to-noise ratio (≈4–10) is quite low, and we visually identified bad data points by comparison of the four spectra. Figure 1 shows the final spectrum, with the noise spectrum which is based on the deviation between the four individual spectra. We checked the flux calibration by synthesizing the IRAC [8.0] photometry from the spectrum, after extending it to the short end of the filter bandpass (≈6.3 μm) using as a template the IRS second order spectrum of a bright T8 dwarf (this extension contributed 17% of the total flux through the filter). This check indicated that the flux calibration is good to 5%.

4. ANALYSIS

Our analysis is based on a method we developed that uses synthetic spectra to determine a bolometric correction that is consistent with the luminosity obtained from evolution models. Because the effective temperatures and gravities obtained in this fashion are obtained from the integrated observed flux and not by fitting the observed spectrum, it is quite robust and is not sensitive to the known (and unknown) systematic biases that arise when fitting model spectra to the observed spectrum.

The solution for the \(T_{\text{eff}}\) and gravity is further refined by direct comparison of the corresponding synthetic spectra with the spectroscopic and photometric data, as well as age constraints. In this section, we first obtain \(T_{\text{eff}}\) and the gravity using solar metallicity models. The mid-infrared photometry and spectrum allow an exploration of non-equilibrium chemistry driven by vertical transport, and we estimate the mixing time scale. Finally, we perform the analysis again with non-solar metallicity models and by considering the uncertainty in \(L_{\text{bol}}\).

4.1. Effective Temperature and Gravity

Our analysis of Wolf 940 B is based on the atmospheric models and non-equilibrium chemistry scheme described in Saumon et al. (2006, 2007) and the evolution sequences of Saumon & Marley (2008). We use cloudless atmospheres and evolution as appropriate for a late T dwarf and initially assume solar metallicity. The observed 1.05–2.43 μm spectrum (B09) and 7.5–14.2 μm spectrum (this work) are integrated to give an observed flux at Earth of \((9.22 ± 0.24) \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\). The IRS spectrum contributes 39% of this value. Following the method described in Geballe et al. (2001) and Saumon et al. (2006, 2007) we derive a family of \((T_{\text{eff}}, g)\) values that provide \(L_{\text{bol}}\) values that are consistent with the bolometric correction from the model spectra and the evolution. That is, the \((T_{\text{eff}}, g)\) of the spectral model used to calculate the correction from observed to total flux must be consistent with the \((T_{\text{eff}}, g)\) implied by the evolutionary models for that total luminosity. These \((T_{\text{eff}}, g)\) solutions are shown in Figure 2 and Table 2 and correspond approximately to a constant \(L_{\text{bol}}\) curve in the \((T_{\text{eff}}, g)\) plane. The bolometric correction amounts to \(\sim 53%\) of the luminosity, and the derived luminosity is \(\log L_{\text{bol}}/L_{\odot} = -6.009\) for \(T_{\text{eff}} = 600\) K (see below and Table 2). Combining the uncertainty in the flux calibration of the spectrum (using a Monte Carlo sampling of a Gaussian distribution of the calibration uncertainty for each

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\(^6\) http://ssc.spitzer.caltech.edu/irs/irsinstrumenthandbook/49/

\(^7\) http://ssc.spitzer.caltech.edu/dataanalysistools/tools/spice/spiceusersguide/1/
segment of the spectrum) and in the distance, the uncertainty in $L_{\text{bol}}$ is $\pm 0.047 \text{dex}$.

Figure 2 shows evolutionary sequences in a $T_{\text{eff}}$ against log $g$ plot; the allowed set of values for Wolf 940 B obtained with the method outlined above is indicated by the sequence of solid dots. The $T_{\text{eff}}$ is thus constrained to be in the range of 500 to 640 K. This range can be narrowed from a knowledge of the age of the system or by comparison of the data to model spectra. The $(T_{\text{eff}}, g)$ of the models used to generate the synthetic spectra for such a data comparison must fall between the dashed red lines of Figure 2, which corresponds to log $L_{\text{bol}}/L_\odot = -6.099 \pm 0.047$. Figure 2 also demonstrates how each $(T_{\text{eff}}, \log g)$ pair determines the dwarf’s mass and age. Table 2 gives the set of allowed parameters $(T_{\text{eff}}, \log g, \log L_{\text{bol}}/L_\odot, \text{mass}, \text{radius, and age})$ in steps of $\Delta T_{\text{eff}} = 25 \text{ K}$ for ages ranging from 0.4 to 10 Gyr and for solar metallicity. The impact of varying metallicity is discussed below in Section 4.6.

4.2. Comparison with the Near-infrared Spectrum

Having constrained the allowed $(T_{\text{eff}}, \log g)$ parameter range, we compare the corresponding synthetic spectra with the data. Figure 3 shows such a comparison for the solutions with ages of 1, 5.5, and 10 Gyr, i.e., the $(T_{\text{eff}}, \log g)$ solutions (575, 4.722), (600, 4.989), and (625, 5.221) (see Table 2). Note that the scaling of the model fluxes to the data is not adjustable; it is fixed by the measured distance to the Wolf 940 system and the radius given in Table 2, determined by evolutionary models from the values of $(T_{\text{eff}}, \log g)$. Here, we have assumed solar metallicity and an eddy diffusion coefficient $K_{zz} = 10^8 \text{ cm}^2 \text{ s}^{-1}$. The eddy diffusion coefficient parameterizes the time scale of vertical mixing in the upper radiative region of the atmosphere, which drives the chemistry of carbon and nitrogen out of equilibrium (Saumon et al. 2006; Hubeny & Burrows 2007). In this analysis, we have considered $K_{zz} = 0$ (chemical equilibrium), $10^4$, $10^5$, and $10^6 \text{ cm}^2 \text{ s}^{-1}$. T dwarfs typically have values of $K_{zz}$ between $10^4$ and $10^6 \text{ cm}^2 \text{ s}^{-1}$ (e.g., Saumon et al. 2007; Leggett et al. 2009; Stephens et al. 2009); the effect of varying $K_{zz}$ is discussed further below. In the deeper convection zone, the mixing time scale is determined from the mixing length formulation of convection.

As shown in Figure 3 and as we have found for other late T dwarfs, the near-infrared spectra of models constrained with our method are very nearly identical (Saumon et al. 2007; Geballe et al. 2009). Since these models have very nearly the same $L_{\text{bol}}$, it is a fairly accurate statement that the near-infrared spectra of low-$T_{\text{eff}}$ models are independent of gravity at fixed $L_{\text{bol}}$, for a given metallicity. This is because the effect of increasing the gravity is partially canceled by the accompanying increase in effective temperature. Also note that the effect of vertical mixing is not significant in the near-infrared at these $T_{\text{eff}}$ (e.g., Saumon et al. 2006 and Section 4.4 below).

The match to the near-infrared spectrum is poor, with the modeled J and H peaks high and the K low (Figure 3, top panel). This has been noticed before and is likely due to the known incompleteness of the molecular opacity line lists in this region (e.g., Saumon & Marley 2008).

4.3. Comparison with the Mid-infrared Spectrum

In contrast to the near-infrared region, differences are seen between the mid-infrared synthetic spectra generated by the approximately constant-luminosity models (Figure 3, lower panel). Calculation of the reduced $\chi^2$ between the models and the observed mid-infrared spectrum shows that the best match is the $T_{\text{eff}} = 600 \text{ K}$ model ($\chi^2 = 3.64$), which is better than the 575 K ($\chi^2 = 4.93$) and 625 K ($\chi^2 = 4.29$) solutions. The $T_{\text{eff}} = 550 \text{ K}$ solution is clearly excluded with $\chi^2 = 10.7$.

Vertical transport in the convection zone drives the chemistry of nitrogen away from equilibrium and results in a typical depletion of NH$_3$ of a factor of 8–10 (e.g., Saumon et al. 2006). This increases the overall flux level in the 9–15 $\mu$m region where absorption by NH$_3$ dominates. A comparison of the observed spectrum and synthetic spectra computed with equilibrium chemistry gives large $\chi^2$ values—from 6.9 (550 K solution) to 11.7 (625 K solution). Those higher $\chi^2$ values arise from the inability of the equilibrium models to match the overall flux level of the IRS spectra for $\lambda > 9 \mu$m (Saumon et al. 2006; see also further discussion below). We can conclude that there is convincing evidence for a depleted abundance of NH$_3$ in the atmosphere of Wolf 940 B, which is consistent with findings from all of the other IRS spectra of late T dwarfs (Saumon et al. 2006, 2007; Burgasser et al. 2008; Leggett et al. 2009).

4.4. Comparison with 3–9 $\mu$m Photometry

Synthetic fluxes in the L' and IRAC bandpasses were obtained by integrating the model spectra over the filter bandpasses, and

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Table 2

| $T_{\text{eff}}$ (K) | $\log g$ (cm s$^{-2}$) | $\log L/L_\odot$ | Mass ($M_\odot$) | Radius ($R_\odot$) | Age (Gyr) |
|---------------------|----------------------|-----------------|-----------------|-----------------|----------|
| 550                 | 4.395                | -5.994          | 12              | 0.1107          | 0.4      |
| 575                 | 4.722                | -6.004          | 20              | 0.1004          | 1.0      |
| 600                 | 4.989                | -6.009          | 31              | 0.0915          | 5.5      |
| 625                 | 5.221                | -6.012          | 45              | 0.0839          | 10       |

Note. * Assuming [m/H] = 0.
these are shown in Figure 3. The IRAC [3.6] photometry is not well matched by any of the models. This is a known model deficiency; Leggett et al. (2009, 2010) show that the calculated [3.6] fluxes are systematically low by 20\%–50\%. It is not clear if this is related to missing opacities in the near-infrared (which may lead to too high near-infrared fluxes and too low mid-infrared fluxes), or if it is due to distortions of the pressure-temperature structure of our non-equilibrium models.

The reduced $\chi^2$ between the synthetic and measured photometry in these five bands strongly favors the highest $T_{\text{eff}}$ model at 625 K as well as a value of the eddy diffusion coefficient of $\log K_{zz} \approx 6$. However, the $\chi^2$ is dominated by a large contribution from the IRAC [3.6] bandpass (Figure 3). If we ignore this flux measurement, then all three models with $T_{\text{eff}} \geq 575$ K and $\log K_{zz} = 6$ match equally well and are far better than all other parameter combinations. For all four models from Table 2, the spectrum computed in chemical equilibrium ($K_{zz} = 0$) is by far the worst. Thus, the photometry strongly favors models that depart from chemical equilibrium.

For a fixed metallicity, the IRAC [4.5] flux is a sensitive probe of non-equilibrium carbon chemistry as the filter bandpass covers the fundamental band of CO centered at 4.65 $\mu$m. More vigorous vertical transport (i.e., larger $K_{zz}$) leads to an over-abundance of CO in the upper atmosphere and a strong band where none should be detectable at such low $T_{\text{eff}}$ (Noll et al. 1997; Golimowski et al. 2004; Patten et al. 2006; Geballe et al. 2009). A low [4.5] flux is thus a hallmark of excess CO and of a non-equilibrium CO abundance. The observed [4.5] flux for Wolf 940 B is well below what would be expected from chemical equilibrium and only non-equilibrium models can match its value. We find that $\log K_{zz} = 5.5$ gives an excellent match and Figure 4 shows our best-fitting non-equilibrium model spectrum, along with the corresponding equilibrium spectrum ($K_{zz} = 0$). A diffusion coefficient of $K_{zz} = 10^{3.5} \text{ cm}^2 \text{s}^{-1}$ corresponds to a vertical mixing time scale of $\sim 4$ hr. Note in Figure 4 the large difference between the non-equilibrium and equilibrium models in [4.5] flux and in the flux level in the 9–15 $\mu$m region where absorption by NH$_3$ dominates. Finally, we note that fitting $K_{zz}$ independently from $T_{\text{eff}}$, gravity, and $L_{\text{bol}}$ affects $L_{\text{bol}}$ by less than 0.016 dex, which is small compared to the contributions from the distance and flux calibration uncertainties of 0.047 dex.

### 4.5. Optimal Parameters for Solar Metallicity

Based on our solar metallicity model atmospheres, spectra, and evolution, we conclude that Wolf 940 B is best fitted with $T_{\text{eff}} = 575–625$ K, $\log g = 4.72–5.22$, and $\log K_{zz} \approx 5.5$. If we apply the age constraint of 3–10 Gyr determined by the primary, then the parameter range is further restricted to $T_{\text{eff}} = 585–625$ K and $\log g = 4.83–5.22$. The derived parameters $T_{\text{eff}}$, $\log g$, $K_{zz}$, mass, radius, and age are summarized in Table 3. As shown in Figure 2, the values of $T_{\text{eff}}$ and $\log g$ are correlated, thus Wolf 940 B cannot be both low-$T_{\text{eff}}$ and high gravity. These ranges do not reflect the effect of the uncertainty in the determination of $L_{\text{bol}}$, which translates to $\pm 16$ K in $T_{\text{eff}}$ (for a fixed gravity) and $\pm 0.16$ dex in gravity (for a fixed $T_{\text{eff}}$).

### 4.6. The Effects of Varying Distance and Metallicity

While we have been able to obtain a reasonably good fit of all the data available (parallax, spectra, and photometry), systematic differences between the models and the near-infrared spectrum linger. In particular, we find that the models are much bluer in $J-K$ than the data (Figures 3 and 4). The $K$-band modeled flux is about half of what is observed. A blue $J-K$ color in a late T dwarf is an indicator of a high-gravity or low-metallicity object (e.g., Knapp et al. 2004). Given all the constraints applied in our method of analysis, we cannot change the gravity independently of $T_{\text{eff}}$ (except within the error bars) and we have seen that this has no effect on the $K$-band flux (Figure 3). We can, however, consider variations in metallicity and of the distance, within the range allowed by the parallax uncertainty.

We have redone the complete analysis by assuming that the luminosity is increased by 1 $\sigma$ to $L_{\text{bol}}/L_\odot = -5.939$ (see Figure 2) and keeping $[m/H] = 0$. For consistency, this new luminosity implies that the distance is increased by $1.4\sigma$ to 13.58 pc. This moves our best-fitting model of $T_{\text{eff}} = 600$ K and $\log g = 4.989$ to $T_{\text{eff}} = 625$ K and $\log g = 5.0$. This worsens the fit slightly but is well within the uncertainties and thus not significant.

### Table 3

| $T_{\text{eff}}$ (K) | $\log g$ | $[m/H]$ | $K_{zz}$ (cm$^2$ s$^{-1}$) | Mass ($M_{\text{Jupiter}}$) | Radius ($R_\odot$) | Age (Gyr) |
|----------------------|----------|---------|---------------------------|--------------------------|------------------|-----------|
| 585–625              | 4.83–5.22| 0.24 ± 0.09| 10$^4$–10$^6$        | 24–45                   | 0.097–0.084      | 3–10      |

Notes. Temperature, gravity, mass, and radius are correlated and are listed in order of increasing age. Metallicity has been determined by application of the Johnson & Apps (2008) $V-K$ relationship to Wolf 940 A. Age is constrained by the kinematic and H$\alpha$ properties of Wolf 940 A.
using the Johnson & Apps (2008) mid-infrared, we can reasonably conclude that Wolf 940 B has a metallicity within \([m/H] = -0.3\) to +0.3 are shown in Figure 5. The optimal value of \(K_{zz}\) depends on \([m/H]\). To better show the role of \([m/H]\) in shaping the spectrum, we keep \(K_{zz}\) fixed at \(10^4\) cm\(^2\) s\(^{-1}\) for the non-solar metallicity models. As expected, increasing the metallicity raises the modeled \(K_{zz}\) and a very good agreement is obtained for \([m/H] = +0.3\), but this comes at the cost of a significant increase in the modeled flux in the \(Y\), \(J\), and \(H\) bands. On the other hand, the spectrum with \([m/H] = -0.3\) is an excellent match to the observed \(Y/J/H\) peaks but increases the discrepancy at \(K\). Calculation of the reduced \(\chi^2\) confirms the qualitative visual impression from the top panel of Figure 5 that the \([m/H] = -0.3\) spectrum is a better fit to the near-infrared spectrum of Wolf 940 B. The lower panel shows the opposite situation at mid-infrared wavelengths; the fit of the spectrum improves steadily as the metallicity increases from -0.3 to +0.3. The mid-infrared photometry also favors higher metallicity if we neglect the poorly fit 3–4 \(\mu\)m region (where there is little flux). Hence, varying the metallicity from \([m/H] = -0.3\) to +0.3 has a seesaw effect on the shape of the spectrum compared to the data and provides no real improvement over the solar metallicity fit. Since the extremes of that range lead to notably poor fits in the near-infrared or the mid-infrared, we can reasonably conclude that Wolf 940 B has a metallicity within \(-0.2\) dex of solar, which is consistent with the value of \([m/H] = +0.24 \pm 0.09\) derived for the primary star using the Johnson & Apps (2008) \(M_K\): \(V - K\) relationship (see Section 2).

Figure 5 (lower panel) shows that the [4.5] flux is not only sensitive to \(K_{zz}\), it is also sensitive to \([m/H]\). The best solar metallicity solution gives log \(K_{zz} \approx 5.5\) using this data point, as described above in Section 4.4. If \([m/H] = +0.3\) then log \(K_{zz} \approx 4\) reproduces the observed [4.5] flux, and similarly if \([m/H] = -0.3\) then log \(K_{zz} > 7\). Values of log \(K_{zz} = 4, 6, \) and 7 correspond to mixing time scales of 2.8 days, 1.6 hr, and 14 minutes, respectively. The convective mixing time scale is 0.6 minute for comparison, meaning that log \(K_{zz} > 7\) implies that mixing is almost as vigorous as convection which may not be realistic. A metallicity as low as \([m/H] = -0.3\) appears unlikely based on the very high value of \(K_{zz}\) required, again consistent with the solar or slightly metal-rich solution found for the primary.

5. CONCLUSIONS

We have presented a 7.5–14.2 \(\mu\)m low-resolution spectrum of the T8.5 dwarf Wolf 940 B, which is a companion to an M4 dwarf with a projected separation of 400 AU. This spectrum complements the near-infrared spectrum and \(L^*\) photometry presented by B09 and the IRAC photometry presented by Leggett et al. (2010). Combining all these data allows a rigorous analysis of the dwarf’s SED. Assuming an age range of 3–10 Gyr as indicated by the primary, evolutionary and atmospheric models show that for the T dwarf secondary \(T_{eff} = 585–625\) K and log \(g = 4.83–5.22\). Gravity and temperature are correlated such that the lower gravity corresponds to the lower \(T_{eff}\) and younger age for the system and the higher value to the higher \(T_{eff}\) and older age. The mass of the T dwarf is 24 \(M_{Jupiter}\) for the younger to older age limits. An age younger than 1 Gyr is excluded by the analysis of the T dwarf spectrum alone.

These temperatures and gravities are slightly higher than those derived in B09. Our luminosity, which benefits from the inclusion of the IRS spectrum, is slightly (but not significantly) higher than determined by B09. Our higher temperature and gravity range principally arises from our more conservative approach to the age of the primary, for which we adopt 3–10 Gyr as opposed to B09’s 3–5 Gyr.

The IRS spectrum demonstrates that vertical mixing is important in the radiative zone of the atmosphere of Wolf 940 B, as is the case for many, if not all, T dwarfs. The [4.5] photometric data point constrains log \(K_{zz}\) to 5.5 for solar metallicity. If the metallicity is higher then \(K_{zz}\) is lower, and vice versa. Comparison of the synthetic SED to the observational data shows that Wolf 940 B has a metallicity within \(-0.2\) dex of solar. More extreme values give poor fits to the data—lower metallicity produces a poor fit at \(\lambda > 2\) \(\mu\)m while higher metallicity produces a poor fit at \(\lambda < 2\) \(\mu\)m. This is consistent with the value of \([m/H] = +0.24 \pm 0.09\) derived here for the primary star using the Johnson & Apps (2008) \(M_K\): \(V - K\) relationship.

It is very useful to find T dwarf companions to main-sequence stars, given that the brown dwarfs are cooling and hence mass is difficult to constrain without knowing age. We look forward to more examples like Wolf 940 B (B09) and Ross 458 C (Goldman et al. 2010) being found, as the UKIDSS sky area increases.

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