SPECTROSCOPIC DETECTION OF CARBON MONOXIDE IN TWO LATE-TYPE T DWARFS

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ABSTRACT

M-band spectra of two late-type T dwarfs, 2MASS J09373487+2931409, and Gliese 570D, confirm evidence from photometry that photospheric carbon monoxide (CO) is present at abundance levels far in excess of those predicted from chemical equilibrium. These new and unambiguous detections of CO, together with an earlier spectroscopic detection of CO in Gliese 229B and existing M-band photometry of a large selection of T dwarfs, suggest that vertical mixing in the photosphere drives the CO abundance out of chemical equilibrium and is a common, and likely universal feature of mid-to-late-type T dwarfs. The M-band spectra allow determinations of the timescale of vertical mixing in the radiative region of the atmosphere of each object, the first such measurements of this important parameter in late T dwarfs. A detailed analysis of the spectral energy distribution of 2MASS J09373487+2931409 results in the following values for metallicity, temperature, surface gravity, and luminosity: [M/H] = −0.3, $T_{\text{eff}} = 925–975$ K, log g = 5.20–5.47, and log $L/L_\odot = −5.308 ± 0.027$. The age is 3–10 Gyr and the mass is in the range 45–69 $M_{\text{Jup}}$.

Key words: infrared: general – stars: individual (Gliese 570D, 2MASS J09373487+2931409) – stars: low-mass, brown dwarfs

Online-only material: color figures

1. INTRODUCTION

In the 1500–4000 K photospheres of late-type stars and early-to-mid-type L brown dwarfs carbon is predominantly locked up in carbon monoxide (CO), due to the much higher binding energy of CO than that of any other carbon-bearing molecule. By spectral-type L5 ($T_{\text{eff}} \sim 1500$ K, Golimowski et al. 2004), the $\nu_3$ methane (CH$_4$) band appears in the spectrum (Noll et al. 2000) and as a brown dwarf cools below this temperature, the main carbon-bearing species shifts from CO to CH$_4$ (Fegley & Lodders 1994, 1996; Lodders & Fegley 2002). Recently, the M-band fluxes of numerous late T dwarfs have been measured to be as much as one magnitude fainter than predictions based on their brightnesses in other wavebands and the assumption of equilibrium chemistry (Saumon et al. 2003; Golimowski et al. 2004; Patten et al. 2006). This strongly indicates that the CO phenomenon seen in Gl 229B is common to most if not all late T dwarfs. Here we describe spectroscopic observations of two late-type T dwarfs, 2MASS 09373487+2931409 (hereafter, 2MASS 0937) and Gliese 570D, whose physical properties differ significantly from Gl 229B, in order to test this hypothesis spectroscopically.

2MASS 0937 and Gl 229B have nearly the same spectral classifications, T6p and T7p, respectively (Burgasser et al. 2006b). However, the K-band flux of 2MASS 0937 is significantly depressed relative to Gl 229B and other T6–T7 dwarfs; e.g., its $J$–$K$ color is 0.8 mag bluer (Burgasser et al. 2002; Knapp et al. 2004). This is believed to be due to the effect of greatly enhanced collision-induced absorption by H$_2$ and implies that 2MASS 0937 is considerably more massive than other T6–T7 dwarfs and/or that it has unusually low metallicity (Burgasser et al. 2002, 2003, 2006a; Burrows et al. 2002; Knapp et al. 2004). The L–M color of 2MASS 0937 (Golimowski et al. 2004) is close to that of Gl 229B, suggesting that its photosphere contains an enhanced abundance of CO, but a spectroscopic observation is needed to verify that this is indeed the cause.

GI 570D (Burgasser et al. 2000) is part of a quadruple system whose other members are low-mass main-sequence stars. Saumon et al. (2006) determined an age for it of 3–5 Gyr and a mass of 38–47 $M_{\text{Jup}}$ by comparing evolutionary models of brown dwarfs and 1–2.5 $\mu$m synthetic spectra of Gl 570D to the known luminosity and the observed spectrum. Comparison of
Spitzer 3.5–7.9 μm photometry and models strongly suggest that the abundance of CO is enhanced by vertical mixing (Patten et al. 2006; Leggett et al. 2007a). The Spitzer 5–15 μm spectrum of Gl 570D provides strong evidence for mixing also being responsible for the depletion of NH3 (Saumon et al. 2006). In late T dwarfs the nitrogen chemistry is insensitive to the timescale of mixing in the radiative zone because it is quenched deep in the atmosphere where the mixing timescale is the convective timescale. On the other hand the carbon chemistry, and thus the abundance of CO, is very sensitive to the mixing timescale in the radiative zone. Since Gl 570D is significantly cooler than Gl 229B and 2MASS 0937, observations of the 4.7 μm band of CO provide an opportunity to determine the mixing timescale in the radiative zone for a different set of atmospheric parameters.

This paper is structured as follows. Section 2 discusses the properties of the fundamental CO band, Section 3 presents the \( M \)-band spectroscopic observations and data reduction, and Section 4 covers the modeling and analyses of Gl 570D and 2MASS 0937. The final section summarizes and compares the results for the two objects.

2. THE SPECTRAL APPEARANCE OF THE FUNDAMENTAL BAND OF CO

In the photospheres of cool stars and “warm” brown dwarfs the fundamental (\( \Delta \nu = 1 \)) vibration-rotation band of CO, as viewed at low or medium resolution, is a broad and more or less structureless absorption stretching across the entire \( M \) band. This is the consequence of (1) several vibrational levels \( \nu \) being populated, (2) each \( \Delta \nu = 1 \) (i.e., 1–0, 2–1, 3–2, ...) band being successively shifted by \( \sim 0.06 \mu \text{m} \) (\( \sim 25 \text{ cm}^{-1} \)) to longer wavelength, and (3) the spacing of vibration-rotation lines in each \( \Delta \nu = 1 \) band being slightly different. If the rotational levels of only the ground vibrational state are populated, however, the absorption spectrum of CO observed at low or medium spectral resolution will exhibit a bump (due to minimum absorption) around the center of the \( v = 1–0 \) band at 4.666 μm separating the P and R branches. As excited vibrational levels become more populated at higher temperatures, this bump is filled in and gradually disappears.

The absorption gap in the spectrum is predicted to become noticeable at photospheric temperatures below 1500 K; that is, at about the same temperature at which equilibrium CO abundances are dropping rapidly in the photosphere of a cooling brown dwarf. Thus, for a mid-late type (\( T \lesssim 1000 \text{ K} \)) T dwarf photosphere in chemical equilibrium, CO absorption lines will be very weak and no gap will be evident. If, however, the abundance of CO is considerably enhanced, then a broad absorption with a gap at the band center should be relatively prominent and detectable at moderate spectral resolution. The effect is illustrated in early nonequilibrium model spectra of cool dwarfs of Saumon et al. (2003).

\( \text{H}_2\text{O} \) also is an important absorber in the \( M \) band, but its lines, which are irregularly spaced, tend to be spread across the \( M \) band (although generally increasing in strength toward longer wavelengths). The \( \text{H}_2\text{O} \) lines may partially mask the CO absorption gap at band center, but if the gap is prominent they should not entirely conceal it.

3. OBSERVATIONS AND DATA REDUCTION

\( M \)-band spectra of 2MASS 0937 and Gliese 570D were accumulated over several nights during 2004–2005, at the Frederick C. Gillett Gemini North telescope, using the facility near-infrared imager/spectrograph, (NIRI; Hodapp et al. 2003), which contains grisms for low-resolution spectroscopy. The instrument was configured with a 0.75 slit, which when used with the \( M \)-band grism provides a resolving power of 460 (corresponding to \( \Delta \lambda = 0.010 \mu\text{m} \)).

An observing log is given in Table 1. The total exposure times were 6.1 hr for 2MASS 0937 and 6.5 hr for Gl 570D. Observations were made in the standard stare-nod mode so that spectra were obtained alternately at two locations along the array, separated by 3″. Co-addition of subtracted pairs of frames then result in a final sky-subtracted image containing both a positive and a negative spectrum of the brown dwarf. Positioning of the target in the slit was checked using \( J \)-band imaging and was adjusted if necessary every 45–60 minutes. Typical adjustments were 0.1; thus each brown dwarf probably was centered well within the slit at all times during most integrations. A telluric standard (a mid F dwarf) was observed just before or just after the brown dwarf, and at an air mass that closely matched that of the brown dwarf. The seeing, as judged from the intensity profiles along the slit of bright calibration stars, ranged from 0.5 to 0.7.

To our knowledge, at \( M \sim 12.3 \) (as determined here) Gl 570D is the faintest astronomical object to have its \( M \)-band spectrum successfully observed from the ground. Data reduction of \( M \)-band spectra of faint sources such as Gl 570D and 2MASS 0937 is difficult, because not only is the residual background in the sky-subtracted coadded spectral image considerably brighter than the brown dwarf, but also the gradient in the residual background along the slit is steep compared to the signal produced by the spectrum of the faint source, even after \( \sim 1 \text{ hr} \) of integration. For these data it was necessary to extract sky rows adjacent on either side of each of the positive and negative spectra, in order to remove this gradient, prior to combining the positive and negative spectra.

Wavelength calibrations of the spectra were obtained from the host of strong telluric lines evident in the spectra of telluric standards observed just before and/or after the spectra of the brown dwarfs. The accuracies of the calibrations were better than 0.001 \( \mu\text{m} \) (3σ). Flux calibrations utilized the 2MASS \( K_s \) magnitudes of the telluric standards and the very small color corrections to derive their \( M \) magnitudes. It was assumed that the spectra of the standards and the brown dwarfs suffered identical slit losses due to seeing and guiding. That assumption might be suspect, both because the brighter stars can be more accurately centered in the slit of the spectrograph and because during the longer integration times on the brown dwarfs it is more likely that guiding “drifts” occur and result in higher signal losses. Nevertheless, the average flux density in the 4.55–4.80 μm spectrum of 2MASS 0937 in Figure 1, (5.0 ±0.1) \( \times \)
10^{-16} \text{ W m}^{-2} \mu\text{m}^{-1}, agrees to within several percent with the \( M' \) (4.55–4.79 \( \mu\text{m} \)) magnitude of 11.74 ± 0.10 reported by Golimowski et al. (2004). No \( M' \) photometry is available for Gl 570D. From Figure 1 we estimate \( M' = 12.3 \pm 0.3 \text{ mag} \), where the uncertainty is largely that of calibration. This value is consistent with the Patten et al. (2006) IRAC [4.5] photometry and values of \([4.5]−M'\) for late T dwarfs as given by Leggett et al. (2007b, see their Figure 2); the uncertainty in the color is several tenths of a magnitude.

In Figure 1 the co-added, ratioed, and flux-calibrated spectra are binned into 0.01 \( \mu\text{m} \) intervals. The spectra are qualitatively similar to the published spectra of Gl 229B (Noll et al. 1997; Oppenheimer et al. 1998), but have higher signal-to-noise ratios. Both hint at a broad maximum flux density in the 4.65–4.70 \( \mu\text{m} \) region, as expected if photospheric CO depresses the spectrum everywhere except near the 1–0 band center. The wavelengths of the 1–0 CO lines are shown in the upper panel. In the middle panel the opacity spectrum of all CO lines, smoothed to \( R = 460 \), is shown at 1 bar and 800 K, which is roughly the region where the observed spectrum is formed. Lines of the CO 2–1 band also make a significant contribution to the opacity spectrum, altering it from the similarity of a pure 1–0 opacity spectrum. In addition, lines of \( \text{H}_2\text{O} \), the only other significant source of opacity in this spectral region, may contribute spectral features. The model spectra (see below) show that the strongest \( \text{H}_2\text{O} \) absorption feature in this region is at 4.68 \( \mu\text{m} \), not far from the CO band center, and indeed the spectrum of each brown dwarf shows a pronounced dip at that wavelength, which is not seen in the CO opacity spectrum. Thus the overall shapes of the spectra suggest detections of CO in both 2MASS 0937 and Gl 570D. The effect of the band center appears more pronounced in the spectrum of Gl 570D than in 2MASS 0937.

4. MODELING AND ANALYSIS

We analyze the \( M \)-band spectra with the goals of establishing the presence of CO on a quantitative basis and determining the timescale of vertical mixing in the atmosphere. The parallaxes of both objects are known and red, near-infrared, and mid-infrared \textit{Spitzer Space Telescope} spectra are available, together sampling about 70% of the total flux emitted. The distance and spectra effectively constrain the luminosity, \( L \), effective temperature, \( T_{\text{eff}} \), gravity, \( g \), and metallicity. The \textit{Spitzer} Infrared Spectrograph (IRS, Houck et al. 2004) spectra of T dwarfs later than ∼T1 show \textit{NH}_3 features (Cushing et al. 2006) whose strengths are influenced by nonequilibrium nitrogen chemistry and thus by vertical mixing. Given a chemical timescale \( \tau_{\text{chem}} \) for the conversion of \textit{N}_2 to \textit{NH}_3 and a vertical mixing timescale \( \tau_{\text{mix}} \), the \textit{NH}_3/\textit{N}_2 abundance ratio becomes frozen (“quenched”) at its value where \( \tau_{\text{mix}} = \tau_{\text{chem}} \) for the region where \( \tau_{\text{mix}} < \tau_{\text{chem}} \) and thus departs from its local chemical equilibrium value. The mid-infrared features of \textit{NH}_3 are not helpful in determining the timescale of mixing in the radiative zone of the atmosphere, however. There are two reasons for this: (1) the nitrogen chemistry is quenched in the deep convective part of the atmosphere where \( \tau_{\text{mix}} \) is given by the convective turnover time, and (2) the nitrogen chemistry deep in the atmospheres of late T dwarfs is nearly independent of depth (Saumon et al. 2006; Hubeny & Burrows 2007). However, once the other parameters have been constrained, the strength of the CO 4.7 \( \mu\text{m} \) band can be used to find \( \tau_{\text{mix}} \) in the radiative zone. As in our previous work (Geballe et al. 2001; Saumon et al. 2006), we parametrize the vertical mixing timescale in the radiative zone by the eddy diffusion coefficient \( K_{zz} = H^2/\tau_{\text{mix}} \), where \( H \) is the mixing scale length, generally assumed to be equal to the local pressure scale height, \( H_p \) (Griffith & Yelle 1999). The convective mixing timescale is given by the mixing length theory with a mixing length parameter chosen to be \( l = H_p \).

Our analysis is based on the models and methods described in Saumon et al. (2006, 2007) and the evolution sequences of Saumon & Marley (2008) and has used the elemental abundances of Lodders (2003). The details of the model chemical equilibrium calculation are given in Freedman et al. (2008), Lodders & Fegley (2002) and references therein. Since both GI 570D and 2MASS 0937 are late T dwarfs, we assume that their atmospheres are cloudless, which is amply supported by their \( JHK \) photometry and the detailed analysis of the T7p dwarf Gl 229B (Saumon et al. 2000), Gl 570D (Saumon et al. 2006), and the T8 dwarf 2MASS J0415195−093506 (Saumon et al. 2007). The evolutionary sequences were computed with consistent surface boundary conditions provided by a grid of cloudless atmospheric models with the appropriate metallicities (Saumon & Marley 2008). We use the quenching scheme of Smith (1998) which defines an effective mixing scale length \( H_{\text{eff}} \) that reproduces detailed calculations of nonequilibrium abundances caused by diffusion in a stratified atmosphere. Additional details regarding the calculation of the nonequilibrium chemistry can be found in Saumon et al. (2003, 2006) and Saumon et al. (2007).

The values of \( K_{zz} \) and of \( \tau_{\text{mix}} \) we derive below depend directly on the choice of reaction pathway for the kinetics of the carbon chemistry and on the choice of quenching scheme. Traditionally, the quenching level is defined by \( \tau_{\text{mix}} = \tau_{\text{chem}} \), which is a
reasonable and simple prescription (Fegley & Lodders 1994; Hubeny & Burrows 2007). Using the reaction pathway proposed by Prinn & Bashary (1977) for the conversion of CO into CH₄ and its associated “slow” reaction rate, the excess CO abundance observed in Jupiter can be explained by vertical mixing (Prinn & Bashary 1977; Noll et al. 1988; Fegley & Lodders 1994; Lodders & Fegley 2002). On the other hand, the quenching scheme of Smith (1998) is physically and computationally more realistic than the simple $t_{\text{mix}} = t_{\text{therm}}$ scheme. Its application to modeling the excess CO in Jupiter’s troposphere then requires the fast reaction rate of Yung et al. (1988) to reproduce the spectroscopic data (Bézard et al. 2002). We use the latter quenching scheme and the “fast” kinetics for the carbon chemistry here, as we have done in the past, so that the present determinations of $K_{zz}$ and our previous estimates are consistent with each other. Using the “slow” kinetic scheme of Prinn & Bashary (1977) would result in significantly lower values of $K_{zz}$ and longer mixing timescales for a given quenched CO mole fraction.

4.1. Gliese 570D

Because it is a companion to a well studied main sequence star, Gl 570D has precisely determined physical parameters. The K4 V primary provides an accurate distance and metallicity and a tight age constraint on the system. We obtain the basic parameters from the bolometric luminosity $L$ derived using the method developed by Geballe et al. (2001). Briefly, we use the well sampled spectral energy distribution (SED) and a combination of synthetic spectra and evolutionary sequences to obtain $L$. Given $L$, the evolutionary sequences provide a range of possible effective temperatures $T_{\text{eff}}(g)$ that is consistent with the age. Detailed comparisons of synthetic spectra with the observed spectrum then further limit the possible range of solutions. This is a robust method to determine $L$, $T_{\text{eff}}$, and $g$ for T dwarfs, as the results depend only weakly on the metallicity assumed for the models, the details of the synthetic spectra, and the degree of sampling of the SED. The method involves no assumption other than some confidence in the models, which have been validated by comparisons with observational data (Saumon et al. 2006, 2007).

For Gl 570D, Saumon et al. (2006) found $T_{\text{eff}} = 800$–820 K, log $g$ (cm s$^{-2}$) = 5.09–5.23, and log $L/L_\odot = -5.525$ to $-5.528$. The above ranges of values are not due to random uncertainties because the parameters are correlated; e.g., for $T_{\text{eff}} = 800$ K, log $g = 5.09$, and log $L/L_\odot = -5.525$. Fits of the spectrum favor the high-$T_{\text{eff}}$, high-$g$ limit of this range. The metallicity of the system is [Fe/H] = 0.09 ± 0.04 (an average of several determinations; Thorén & Feltzing 2000; Santos et al. 2005; Valenti & Fisher 2005). Saumon et al. (2006) used solar metallicity models to obtain the above parameters and we do likewise in the following analysis of the M-band spectrum.

The 5–15 μm Spitzer spectrum shows strong ammonia features that can be accurately modeled using an NH₃ abundance reduced by a factor of ~10 compared to that in chemical equilibrium, as expected for nonequilibrium chemistry driven by vertical mixing in the atmosphere (Lodders & Fegley 2002; Saumon et al. 2006). We therefore expect that the M-band spectrum will show a nonequilibrium abundance of CO. We have performed the analysis using a baseline model computed with the most likely values determined by Saumon et al. (2006), which correspond to their Model C: $T_{\text{eff}} = 820$ K, log $g = 5.23$, and an age of 5 Gyr (solar metallicity). The only free parameter left to fit the M-band spectrum is the eddy diffusion coefficient $K_{zz}$, which determines the surface abundance of CO.

4.1.1. Fits of the M-band Spectrum

There are two approaches to fitting the spectrum shown in Figure 1 with a set of synthetic spectra. The first method fits only the shape of the spectrum, i.e. the synthetic spectra are scaled by a constant multiplicative factor that is adjusted to minimize $\chi^2$ with the data. In this approach, the uncertainty in the fitting parameter ($K_{zz}$) is determined by the random noise in each data point of the observed spectrum. This is estimated at $\sigma = 5.0 \times 10^{-17}$ W m$^{-2}$ m$^{-1}$ (Figure 1). The second approach uses evolutionary sequences to obtain the radius of the brown dwarf and computes absolute model fluxes that are directly compared to the observed fluxes. This method simultaneously fits the shape of the spectrum and its overall flux level and is subject to the additional uncertainty in the flux calibration of the data, which is estimated at ±30%. We compute $K_{zz}$ and its uncertainty using both methods. With perfectly calibrated data and perfect models, both methods would give the same value of $K_{zz}$. We find that the flux calibration uncertainty dominates the noise when fitting the absolute fluxes. The final source of uncertainty in the determination of $K_{zz}$ arises from the possible range of model parameters for the brown dwarf. For Gl 570D, where $T_{\text{eff}}$ is narrowly constrained, this last contribution is negligible. Uncertainties in the models are difficult to quantify and are not included in the error budget.

To account for the influence of noise on the interpretation of the spectrum, we generated 1000 simulated observed spectra by adding random Gaussian noise with the above dispersion to the observed flux in each data point. Each of the simulated observed spectra was fitted with a synthetic spectrum computed with the baseline model parameters and log $K_{zz}$ (cm$^2$ s$^{-1}$) ranging between 2 and 8.5. The high-resolution ($\lambda/\Delta \lambda \sim 16000$) synthetic flux densities were converted to the resolution of the spectrum in Figure 1 by integration over 0.01 μm wide bins. The best value of log $K_{zz}$ is obtained by minimizing

$$\chi^2 = \frac{1}{N-3} \sum_{i=1}^{N} \left[ a f_{i}^{\text{obs}} - b f_{i}^{\text{mod}}(K_{zz}) \right]^2 \sigma$$

(1)

where $N$ is the number of points in the M-band spectrum, $f^\text{obs}_i$, $f^\text{mod}_i$, and $\sigma$ are the observed flux, the absolute model flux, and the random noise in pixel $i$, respectively. The flux calibration uncertainty of ±30% enters as $a$ ($a = 0.7, 1, 1.3$) and $\beta$ is the model flux renormalization. For the absolute flux fitting procedure $\beta$ was set to unity. When fitting the shape of the spectrum only, $\beta$ was adjusted to minimize $\chi^2$ for each value of $K_{zz}$. The resulting distribution of 1000 values of $K_{zz}$ gives an average value and its dispersion. The procedure was repeated for all three values of $a$ (with $\beta = 1$) to quantify the effect of the uncertainty of the flux calibration.

The general behavior of the $\chi^2$ for these different assumptions is shown in Figure 2. For a given value of $K_{zz}$, the best fit, indicated by the lowest $\chi^2$ value, occurs when the model fluxes are scaled to the data, i.e. when only the shape of the observed spectrum is fitted (dotted curve). This curve has a broad minimum and our statistical sampling finds the minimum at log $K_{zz}$(cm$^2$ s$^{-1}$) = 6.21 ± 0.73. Equilibrium chemistry ($K_{zz} = 0$), which Saumon et al. (2006) found is strongly excluded on the basis of the NH₃ depletion revealed by the Spitzer spectrum, is also excluded by the shape of the M-band spectrum. The equilibrium model has $\chi^2 = 5.70$, which is 4.4σ above the value for the best fitting nonequilibrium model ($\chi^2 = 2.39$). Thus, the 4.5–4.9 μm spectrum of
The curves are model spectra plotted at $R$ (A color version of this figure is available in the online journal.)

Figure 3 which compares the equilibrium model spectrum, with Gl 570D contains a solid detection of CO. This can be seen in Figure 3.

Figure 2. Goodness of fit to the $M$-band spectrum as a function of the eddy diffusion coefficient $K_{zz}$ for the nominal parameters of Gl 570D ($T_{\text{eff}} = 820$ K, $\log g = 5.23$, [M/H] = 0). $\chi^2$ is defined in Equation (1) (see the text). The dotted curve is obtained when the model spectra are scaled to minimize $\chi^2$; i.e., only the shape of the observed spectrum is fitted. The equilibrium model ($K_{zz} = 0$) has $\chi^2 = 5.7$. The discontinuity in $\chi^2$ near $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 7.2$ occurs when the quenching of the carbon chemistry goes through the radiative/convective boundary in the atmosphere model. The solid curves are obtained when three absolute fluxes, corresponding to the nominal calibration (heavy line) and two calibrations that differ by $\pm 30\%$.

Figure 3. Fits to the $M$-band spectrum of Gl 570D. The data are the black histogram and the typical pixel noise level ($\pm 1\sigma$) is shown at lower right. The curves are model spectra plotted at $R = 500$ with $T_{\text{eff}} = 820$ K, $\log g = 5.23$, and [M/H] = 0 that have been fit to the data with scaling factors adjusted to minimize the residuals. The red curve is the equilibrium model ($K_{zz} = 0$), the blue curve is the nonequilibrium model shown in Figure 4 ($\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 4.5$) and the green curve is the best-fitting model ($\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 6.2$).

(A color version of this figure is available in the online journal.)

GI 570D contains a solid detection of CO. This can be seen in Figure 3 which compares the equilibrium model spectrum, with no detectable CO, with the best-fitting nonequilibrium model spectrum. Furthermore, by increasing the statistical sampling by one order of magnitude to 10,000 simulated observed spectra, we found only three simulated spectra giving $\log K_{zz} < 4$ and none below 3.8. This illustrates the negligible likelihood that the model using chemical equilibrium is consistent with the data. If we fit the data, including the absolute flux calibration, we find narrower distributions of $\chi^2$ (solid curves on Figure 2) that depend sensitively on the flux calibration of the data. For the nominal calibration, we get $\log K_{zz} = 3.98 \pm 0.12$. Decreasing the absolute flux level by the estimated uncertainty of 30% we find $\log K_{zz} = 5.23 \pm 0.13$. The systematic uncertainty in $\log K_{zz}$ due to flux calibration is $\sim 8$ times larger than that due to random noise in the spectrum. Consistent solutions between the two fitting methods can be obtained if the calibrated flux density is reduced by a factor of 0.65 to 0.5, corresponding to a $-1.1\sigma$ to $-1.7\sigma$ correction, which is just plausible.

4.1.2. Photometry

Photometric measurements of Gl 570D in the MKO $L'$ (Golimowski et al. 2004) and the Spitzer IRAC [3.6] and [4.5] bands (Patten et al. 2006) provide additional information. We generated synthetic fluxes by integrating the model spectra over the bandpasses, multiplying by $R(D)^2$, where $R(T_{\text{eff}}, g)$ is the radius obtained from our cloudless [M/H] = 0 evolution sequences and $D$ is the distance (Perryman et al. 1997). The observed magnitudes were converted to fluxes by computing zero magnitude fluxes in each bandpass with a spectrum of Vega or from the flux calibration of the IRAC instrument. A least squares fit of the three photometric points gives $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 4.49 \pm 0.24$ for our nominal model ($T_{\text{eff}} = 820$ K, $\log g = 5.23$ and [M/H] = 0). This best-fitting synthetic spectrum, its corresponding equilibrium spectrum and the photometry are shown in Figure 4 along with the $M$-band spectrum. The $M$-band spectrum in the figure is scaled by a factor of 0.83 relative to the flux-calibrated spectrum in order to minimize the residuals with the model spectrum. This is a shift of about half of the calibration uncertainty of the spectrum. The figure clearly shows the strong and broad CO band, centered at 4.7 $\mu$m complete with the bump at band center, that appears when vertical transport drives the carbon chemistry far out of equilibrium. The spectrum outside of the 4.4–5.0 $\mu$m region is barely affected, however.

4.1.3. Summary: Optimal Model

Figure 4 shows that a cloudless model with $T_{\text{eff}} = 820$ K, $\log g = 5.23$, [M/H] = 0 and $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 4.5$ agrees...
with (1) the optical, near-infrared, and the 5–15 μm Spitzer IRS spectrum (Saumon et al. 2006), (2) the MKO L′ and Spitzer IRAC [4.5] photometry, and (3) the flux level of the M-band spectrum within its uncertainties. The IRAC [3.6] flux is too low, however. In addition log $K_{zz} = 6.21 \pm 0.73$ provides a better fit to the shape of the spectrum. This latter value also fits all of the data except for the photometry. Within the various sources of uncertainty, these two results for log $K_{zz}$ are barely compatible. For instance, the (non-Gaussian) statistical distribution that led to the determination log $K_{zz} = 6.21 \pm 0.73$ has only 1.6% of the sample falling within the range 4.5 ± 0.24.

We believe that fitting the shape of the M-band spectrum only is the more reliable way to determine the value of $K_{zz}$. This method depends primarily on the CO/H$_2$O abundance ratio in the photosphere and much less on modeling details. While the flux level in the Spitzer 4.5 μm band is indicative of CO absorption, it does not specifically point to CO as the absorber and the filter is not well matched to the CO band. In addition, there is no photometric data point outside of and just to longer wavelength of the CO band, where absorption by H$_2$O, which also occurs within the CO band, should dominate.

The photometric measurements are much more precise than the M-band spectrum calibration, however. They measure the spectral energy distribution in the vicinity of the 4–5 μm peak, which is strongly affected by the $\nu_3$ band of CH$_4$ centered at 3.3 μm extending to ~4 μm, and by the $\nu_2$ band of H$_2$O on the long wavelength side of the peak. The disagreement of the IRAC [3.6] flux with the model spectra suggests that the models are inaccurate in that wavelength region. The CH$_4$ line list is known to be incomplete at the temperatures of brown dwarf atmospheres. The attempts and modest success in fitting the 3–4 μm spectra of T dwarfs (Stephens et al. 2008) suggests that the inconsistency between the two solutions could be resolved in favor of the higher value of $K_{zz}$ by invoking a higher CH$_4$ opacity. Indeed the incompleteness of the CH$_4$ line list implies that the CH$_4$ opacity in our model is a lower limit to the actual opacity. Increasing the opacity in the red wing of the $\nu_3$ band of CH$_4$ would nudge all three broad band fluxes in a direction that would increase the value of the best fitting $K_{zz}$. The flux removed due to the increased CH$_4$ absorption in the near-infrared will reemerge primarily in low-opacity windows. It is very likely that the shape of the 4–5 μm peak will be altered by the flux redistribution caused by an increase in the CH$_4$ opacity. Such a change could in turn significantly change the value of $K_{zz}$ necessary to fit the photometry.

Thus, we adopt log $K_{zz}$ (cm$^2$ s$^{-1}$) = 6.2 ± 0.7 as the most likely value for Gl 570D, based on the favored nominal model parameters (Model C of Saumon et al. 2006). Repeating the above analysis with the less favored but still possible values of Model B of Saumon et al. (2006; $T_{\text{eff}} = 800$ K, log $g = 5.09$), gives log $K_{zz}$ (cm$^2$ s$^{-1}$) = 6.0 ± 0.7 which is almost identical within the uncertainty. The complete infrared synthetic spectrum of our optimal model for Gl 570D is not shown because it is within the uncertainty. The complete infrared synthetic spectrum is shown in Figure 5. The chemistry of nitrogen is quenched in the convection zone where $r_{\text{mix}}$ becomes shorter than $r_{\text{N}_2}$, the timescale for conversion of N$_2$ to NH$_3$. This occurs at log $T \sim 3.8$. In the upper atmosphere, the NH$_3$ abundance is nearly a factor of 10 lower than the equilibrium value. Because the eddy diffusion coefficient $K_{zz}$ determines the mixing timescale in the radiative zone, the quenching level of the nitrogen chemistry is unaffected by the choice of $K_{zz}$; rather it is determined by the convective mixing timescale. On the other hand, the carbon chemistry is quenched in the radiative zone around log $T = 3.17$ and the abundances of CO and CH$_4$ depend sensitively on $K_{zz}$ because the equilibrium mole fraction of CO has a steep dependence on depth in low-$T_{\text{eff}}$ atmosphere models. In the upper part of the atmosphere the CO mole fraction is log $X_{\text{CO}} = -4.10 \pm 0.18$. The conservation of the elemental abundance of carbon and oxygen requires that the nonequilibrium abundances of CH$_4$ and H$_2$O be reduced. This effect is modest in Gl 570D as both decrease by less than 0.1 dex.

Figure 5 shows different mixing timescales in the radiative zone for the carbon and nitrogen chemistry. This is a consequence of using the quenching scheme of Smith (1998) whose effective mixing length depends on $r_{\text{chem}}$, among other factors. Since by definition, $r_{\text{mix}} = H_Z^2 / K_{zz}$, the mixing timescale will vary with the chemical timescale for a given $K_{zz}$.

Finally, the atmosphere model and synthetic spectrum uniquely specify the level of formation of spectral features in the atmosphere. In brown dwarfs, the depth of the “photosphere” is a strong function of wavelength, due to the huge variations of molecular opacities between bands and the absence of a continuum level of emission. In Gl 570D, we find that the 4.7 μm band
of CO and the 10–11 μm feature of NH₃ probe the same level of the atmosphere, because the lines in both spectral regions are formed at log T ∼ 2.75–2.9.

4.2. 2MASS 0937

4.2.1. Determination of T_eff, Gravity, and Metallicity

Due to its very blue J − K color, 2MASS 0937 has long been recognized as having low metallicity and/or high gravity (Burgasser et al. 2002, 2003; Burrows et al. 2002; Knapp et al. 2004; Burgasser et al. 2006a). Previous estimates give T_eff = 725–1000 K (Golimowski et al. 2004) and 700–850 K (Vrba et al. 2004), and log g ∼ 5.5 (Knapp et al. 2004). More recently Burgasser et al. (2006a), using a calibrated set of spectral indices, found that 2MASS 0937 is metal poor with [M/H] between −0.4 and −0.1. For [M/H] = −0.2, they obtain T_eff = 780–840 K and log g = 5.3–5.5. With the wealth of information provided by the wide spectral coverage now available, we can determine these parameters more accurately. The observed spectrum covers the intervals 0.63–1.01 μm, 1.03–1.345 μm, 1.40–2.53 μm and 5.13–15.35 μm. The integrated observed flux is 2.97 × 10^{-12} erg s^{-1} cm^{-2}, which represents about 70% of the total flux. The flux calibration uncertainties are ±3% in the red, ±5% in the near-infrared, and ±3.7% for the Spitzer IRS spectrum. The distance is 6.14 ± 0.146 pc (Vrba et al. 2004). The resulting uncertainty in the bolometric luminosity is ±6.4%, or 0.027 dex, where we have combined the various flux calibration uncertainties rather than treating them as statistically independent variations.

We first applied our suite of solar-metallicity models and found, as expected, that the model overestimate the K band flux by about 60%, even at the highest possible gravity of log g = 5.43. A better match of the near-infrared spectrum, and the K-band flux in particular, thus requires a subsolar metallicity. Applying our grid of model atmospheres, spectra, and evolution for [M/H] = −0.3 to the method described in Geballe et al. (2001) and Saumon et al. (2006), we obtain the parameters shown in Figure 6 and given in Table 2 for four different ages in the range 1–10 Gyr. We will see below that models corresponding to ages of 1 Gyr and less do not fit the data satisfactorily. We find that log L/L_⊙ ∼ −5.30, they obtain T_eff = 5–15 K lower than the solar metallicity models, which includes the random uncertainty in the flux of each pixel.

The goodness of fit of a particular model is measured by χ², which includes the random uncertainty in the flux of each pixel. The ensemble of χ² for these models reveals a clear picture.

Figure 6. T_eff and gravity for 2MASS 0937. Heavy black lines labeled with the mass in M⊙ are cloudless brown dwarf evolution tracks for [M/H] = −0.3. Isochrones (blue dotted lines) are labeled in Gyr. The nearly vertical lines (solid and dashed, red) are the locus of (T_eff, g) points with log L/L_⊙ = −5.308 ± 0.027. The solid dots show the four models of Table 2. The range of parameters for GI 570D (M/H = 0) is shown by the small box centered at 800 K (Saumon et al. 2006).

(A color version of this figure is available in the online journal.)

Table 2 Range of Physical Parameters for 2MASS J09373487+2931409ab

| Model | T_eff (K) | log g (cm/s²) | log L/L_⊙ | Mass (M_⊙) | Radius (R_⊙) | Age (Gyr) | log K_2 (cm²/s⁻¹) |
|-------|----------|---------------|-----------|------------|--------------|-----------|------------------|
| A     | 865      | 4.86          | −5.296    | 27         | 0.0984       | 1.0       | ···              |
| B     | 923      | 5.20          | −5.304    | 45         | 0.0870       | 3.0       | 3.2 ± 0.10       |
| C     | 950      | 5.35          | −5.308    | 57         | 0.0818       | 5.0       | 3.0 ± 0.11       |
| D     | 974      | 5.47          | −5.312    | 69         | 0.0778       | 10.0      | 2.7 ± 0.14       |

Notes.

a [M/H] = −0.3.

b The 1σ uncertainty in the luminosity is Δ log L/L_⊙ = 0.027, corresponding to ΔT_eff = 15 K and ΔR/R_⊙ = 0.001 at constant gravity.

c For the nominal flux calibration of the M-band spectrum.

The goodness of fit of a particular model is measured by χ², which includes the random uncertainty in the flux of each pixel. The ensemble of χ² for these models reveals a clear picture.
In every case, the best of the equilibrium models (A–D) is a much worse fit than the best nonequilibrium model, at more than an 8σ level of significance. The IRS spectrum thus rules out equilibrium chemistry for nitrogen in 2MASS 0937. For the nonequilibrium case, Models A through D fit the shape of the spectrum equally well. If absolute fluxes are considered, for all choices of calibration (within ±3.7%) the lowest gravity model (A) is ruled out at >22σ. Models B through D can provide equally good fits depending on the choice of absolute calibration. For the nominal calibration, the best fit is obtained with Model C. We conclude that the parameters of 2MASS 0937 fall within the range between Models B and D in Table 2 and with Model C. We conclude that the parameters of 2MASS 0937 we find that $M_{\text{eff}} = -0.3$, do not include vertical mixing, and are plotted at $R = 500$. The main molecular absorbers are indicated. (A color version of this figure is available in the online journal.)

Figure 7. Comparison of near-infrared synthetic spectra corresponding to Models A (red) and D (blue) in Table 2 to the observed spectrum of 2MASS 0937 (thick black). Data are from Burgasser et al. (2006a). The models have a $[\text{M/H}] = -0.3$, do not include vertical mixing, and are plotted at $R = 500$. The main molecular absorbers are indicated. (A color version of this figure is available in the online journal.)

In every case, the best of the equilibrium models (A–D) is a much worse fit than the best nonequilibrium model, at more than an 8σ level of significance. The IRS spectrum thus rules out equilibrium chemistry for nitrogen in 2MASS 0937. For the nonequilibrium case, Models A through D fit the shape of the spectrum equally well. If absolute fluxes are considered, for all choices of calibration (within ±3.7%) the lowest gravity model (A) is ruled out at >22σ. Models B through D can provide equally good fits depending on the choice of absolute calibration. For the nominal calibration, the best fit is obtained with Model C. We conclude that the parameters of 2MASS 0937 fall within the range between Models B and D in Table 2 and that vertical transport occurs in its atmosphere, resulting in a depletion of NH$_3$. The synthetic spectrum for nonequilibrium vertical transport occurs in its atmosphere, resulting in a depletion within the range between Models B and D in Table 2 and with Model C. We conclude that the parameters of 2MASS 0937 we find that $M_{\text{eff}} = -0.3$ are and are plotted at $R = 120$. The main molecular absorbers are indicated.

Figure 8. Comparison of Spitzer IRS spectrum of 2MASS 0937 (Cushing et al. 2006; black histogram), best fitting model with equilibrium chemistry (Model A, Table 2; red), and best fitting nonequilibrium model (Model C, Table 2 with $K_{zz} = 10^3$ cm$^2$ s$^{-1}$; in blue). The lower histogram is the noise spectrum. Flux calibration of the data is uncertain to ±3.7%. Model spectra are not renormalized to the data. The models have $[\text{M/H}] = -0.3$ and are plotted at $R = 120$. The main molecular absorbers are indicated. (A color version of this figure is available in the online journal.)

We attempted to fit the MKO $L'$ and $M'$ magnitudes (Golimowski et al. 2004) and the Spitzer IRAC [3.6] and [4.5] fluxes (Patten et al. 2006) as in Section 4.1.2. In this case however, it was not possible to closely match the shape of the 3.5–5 μm peak with any of our models, not even with discarded Model A (Table 2), for any value of $K_{zz}$. In all cases, the modeled 3.3 μm band of CH$_4$ is too deep, and the resultant $L'$ and [3.6] fluxes are too low (Figure 10). Values of $K_{zz}$ that fit the [4.5] or the $M'$ fluxes can be found but are different from each other. Using the Model C parameters, we find $K_{zz} = 3.3 \pm 2.2$, but both the fit and $\chi^2$ are very poor, with the [3.6] flux falling several standard deviations below the IRAC measurement. The 3.3 μm band of CH$_4$ can be weakened by further decreasing the metallicity or increasing $K_{zz}$ to a value that is incompatible with the shape of the $M'$-band spectrum. Both of these possibilities appear unlikely, given the good agreement that we find with the spectroscopic data. A more complete line list for the CH$_4$ band would increase the opacity and thus go in the wrong direction. The discrepancy

4.2.2. Fits of the $M$-band Spectrum

We fit the $M$-band spectrum of 2MASS 0937 to determine the value of the eddy diffusion coefficient $K_{zz}$ using the procedure described in Section 4.1.1. In this case, the random noise in each pixel of the observed spectrum is estimated at $\sigma = 4.2 \times 10^{-17}$ W m$^{-2}$ μm$^{-1}$ and the systematic uncertainty in the flux calibration is estimated at ±30% although the agreement with previous $M'$ photometry is much better than this. We consider the three Models B though D in this analysis. By fitting the shape of the $M$-band spectrum only, we find that log $K_{zz}$ (cm$^2$ s$^{-1}$) = 4.3 ± 0.3 for Model C. The value increases slowly with log $g$ among the suite of models but the differences

with the above result remain well within the uncertainty. All three models give equally good fits to the shape of the $M$-band spectrum. An example of such a fit is shown in Figure 9 where the nonequilibrium spectrum corresponding to Model C with log $K_{zz}$ (cm$^2$ s$^{-1}$) = 4.3 is in better agreement with the shape of the $M$-band spectrum than the same model in equilibrium. The latter fails to produce the 4.665 μm bump seen in the data that indicates the presence of CO. Based on the $\chi^2$ distribution of our simulated spectra, the best nonequilibrium model gives a fit that is 3.2σ better than the equilibrium model.

By fitting absolute model fluxes to the data we obtain lower values of log $K_{zz}$ (Table 2). If we rescale the observed fluxes by factors of 0.8–0.75 (less than the nominal calibration uncertainty), then Models B through D can all be made to give log $K_{zz}$ (cm$^2$ s$^{-1}$) = 4.3 ± 0.3, and a consistent solution is found between fitting the shape of the $M$-band spectrum and its flux level. This value of the eddy diffusion coefficient gives a CO mole fraction of log $X_{\text{CO}} = -5.10 \pm 0.13$. 4.2.3. Photometry

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between our best fitting model and the [3.6] and $L'$ photometry might be attributable to the secondary effect of increasing the CH$_4$ opacity and redistributing flux in the low-opacity windows at wavelengths less than 1.7 $\mu$m into the 4–5 $\mu$m region.

4.2.4. Summary: Optimal Model

In view of the difficulty in fitting the 3–5 $\mu$m photometry and the likelihood that the model spectra are impacted by an incomplete CH$_4$ line list, we again rely on the shape of the $M$-band spectrum to determine the most likely value of $K_{zz}$, and thus conclude that $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 4.3 \pm 0.3$. With the data in hand, we are unable to distinguish between Models B, C, and D, as they give essentially equally good—or in the case of the photometry, equally poor—fits to the ensemble of data. Model C ($T_{\text{eff}} = 950$ K, $\log g = 5.35$, $[\text{M/H}] = -0.3$) with $\log K_{zz} = 4.3$ as an example, provides an excellent fit to the red and near-infrared spectra and to the Spitzer IRS spectrum as well (Figure 11). It also gives a good fit to the shape of the $M$-band spectrum (Figure 9, although it underestimates the $M'$ flux by 1.4$\sigma$ (Figure 10). This model also substantially underestimates the [3.6], [4.5], and $L'$ fluxes, however.

The chemical composition of the atmosphere as a function of depth is shown in Figure 12. In the region of formation of the 4.7 $\mu$m band of CO ($\log T = 2.9 - 2.98$), vertical transport increases the CO abundance by about 2 orders of magnitude. The NH$_3$ abundance decreases by $\sim 0.8$ dex which accounts for the large effect seen in Figure 8. The H$_2$O and CH$_4$ mole fractions are barely affected by vertical transport in this model. As was found for Gl 570D, the nitrogen chemistry is quenched deep in the convection zone of the atmosphere (at $\log T = 3.38$) and thus is unaffected by the value of $K_{zz}$. On the other hand, the carbon chemistry is quenched much higher in the atmosphere, at $\log T = 3.12$.

5. DISCUSSION AND CONCLUSIONS

Low-resolution $M$-band spectra of Gl 570D and 2MASS 0937 reveal the presence of photospheric CO via the CO absorption minimum between the P and R branches of the $v = 1 - 0$ band. These are 4.4$\sigma$ and 3.2$\sigma$ detections, respectively, based on fits of the spectra with models, both in chemical equilibrium (no detectable CO) and with CO abundances increased by vertical transport. In addition to these spectroscopic detections, we have derived the first set of well constrained physical parameters for 2MASS 0937 based on the analysis of its observed spectral energy distribution. We firmly established that this T6p dwarf has a subsolar metallicity and a moderately high gravity, as has long been suggested.

The detections of CO in these two late T dwarfs are the first since the original discovery in the T7p dwarf Gliese 229B.
The $M$-band spectra are well reproduced by model spectra with surface CO mole fractions of $X_{\text{CO}} = -4.10 \pm 0.18$ and $-5.10 \pm 0.13$, corresponding to quenching temperatures of $T = 3.17$ and 3.12, respectively. In both cases, the region of the atmosphere probed by 4.7 $\mu$m band of CO is well above the quenching level.

The model spectra that include vertical mixing reproduce the entire observed SEDs of both dwarfs very well, with the exception of the photometry of the 4–5 $\mu$m peak in 2MASS 0937. Similar difficulties have been encountered with 2MASS photometry. The deviations of the NH$_3$/N$_2$ and the CO/CH$_4$ ratios from chemical equilibrium in both objects can be explained consistently with one parameter model including vertical mixing in the radiative and convective regions of the atmosphere and the kinetics of carbon and nitrogen chemistry. The present work firmly establishes this process in cool T dwarfs.

Presently, the most direct way to determine the vertical mixing timescale $\tau_{\text{mix}}$ in the radiative zone of the atmosphere is from the CO abundance derived by fitting models to the shape of the $M$-band spectrum. The timescale is parametrized by the eddy diffusion coefficient, $K_{zz} = H^2/\tau_{\text{mix}}$, for which we find $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 6.2 \pm 0.7$ for Gl 570D, corresponding to a mixing timescale of 0.1 to 3 hr. While the uncertainty in $\tau_{\text{mix}}$ remains large, it is crudely comparable to the measured rotation period of $P = 3.6$ sin $i$ hr, where $i$ is the inclination of the axis of rotation to the line of sight (Zapatero Osorio et al. 2006). For 2MASS 0937, $\log K_{zz} = 4.3 \pm 0.3$, implying a much longer mixing timescale of $\tau_{\text{mix}} = 5$ to 25 hours, which is also comparable to the $\sim 2–10$ hr rotation periods of T dwarfs (Zapatero Osorio et al. 2006). Comparable mixing and rotation timescales suggest that the rotation couples with the vertical mixing process in the radiative zone.

The eddy diffusion coefficients of these two dwarfs differ by nearly two orders of magnitude, which seems a rather large difference for two T dwarfs whose physical properties are much more similar: $\Delta \log g < 0.25$, and $\Delta \log T < 0.22$, effective temperature, which differs by 100–150 K and metallicity, where $\Delta[M/H] = 0.3$ to 0.4. In the absence of a physical model for vertical mixing in brown dwarf atmospheres, it is difficult to appreciate the significance of this large difference between Gl 570D and 2MASS 0937. In this context, a measure of the rotational velocity of 2MASS 0937 would be of interest.

The physical parameters and the eddy diffusion coefficients that we have derived for several late T dwarfs are compiled in Table 3. In most cases, these determinations are based on the same method and models but the data sets are not fully homogeneous. Details are given in the individual references for each object. So far, all the brown dwarfs with suitable data that have been analyzed show evidence for nonequilibrium chemistry of carbon, nitrogen, or both. The parameter controlling the mixing timescale in the radiative zone generally falls in the range $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 4$ to 6. There is no apparent trend of $K_{zz}$ with $T_{\text{eff}}$, gravity, or metallicity in this small sample. More accurate values of $K_{zz}$ could be obtained with models that could simultaneously fit the $M$-band spectroscopy and the 3.5–5 $\mu$m photometry.

Eddy diffusion coefficients (or bounds on their values) have been derived for the atmospheres of all of the solar system giants, often by comparing models with measurements of the vertical profiles of various photochemical products. Other methods have been used as well. As reviewed by Moses et al. (2004), estimates for Jupiter’s upper stratosphere cluster around $\log K_{zz} (\text{cm}^2 \text{s}^{-1}) = 6$, comparable to or larger than the values we derive here for T dwarfs, despite Jupiter’s 4 orders of magnitude smaller heat flow and nearly 2 orders of magnitude lower gravity. Constraints have even been placed on eddy mixing in the atmosphere of Neptune, where similar values of $\log K_{zz}$ are inferred (Bishop et al. 1995). Such mixing in the radiatively stable solar system stratospheres is often attributed to the propagation and/or breaking of atmospheric waves. Bishop et al. review the literature in some detail and point out that $K_{zz}$ likely varies vertically through an atmosphere, increasing with falling density. Such a shortening of the mixing timescale with height would leave the quenching level and the resulting chemistry unchanged (Figures 5 and 12). As such, the $K_{zz}$ values we...
derived from the observations are local values at the quenching level of the atmosphere, which is at both higher pressure and higher density than the regions typically probed in giant planet atmospheres. The relatively similar mixing coefficients in such a great diversity of atmospheres is striking, even though the derived values apply to different atmospheric regions. Further investigation of the underlying mechanisms responsible for mixing in giant planet and brown dwarf atmospheres would be of interest and may also find applicability to the study of extrasolar giant planet stratospheres.

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Table 3

Physical Parameters and Eddy Diffusion Coefficients of Brown Dwarfs

| Object          | Sp. Type | $T_{\text{eff}}$ (K) | log $g$ (cm s$^{-2}$) | [$\text{M}/\text{H}$] | log $K_{\text{v},b}$ (cm$^2$ s$^{-1}$) | NH$_3$$^a$ | CO$^a$ | Source$^a$ |
|-----------------|----------|----------------------|------------------------|----------------------|---------------------------------------|------------|--------|------------|
| 2MASS J04151954–0935066 | T8       | 725–775              | 5.00–5.37              | 0                    | −4                                    | yes        | yes    | 4          |
| Gliese 570D     | T7.5     | 800–820              | 5.09–5.23              | 0                    | 6.2 ± 0.7                             | yes        | yes    | 3, 5       |
| Gliese 229B     | T7p      | 870–1030             | 4.5–5.5                | −0.1 to −0.5          | 4–5                                   | –          | yes    | 1, 2       |
| 2MASS J09373487+2931409 | T6p      | 925–975              | 5.20–5.47              | −0.3                 | 4.3 ± 0.3                             | yes        | yes    | 5          |

Notes.

$^a$ Infrared spectral types from Burgasser et al. (2006b).

$^b$ Spectroscopic evidence of depleted NH$_3$ in the 9–14 μm region.

$^c$ Spectroscopic evidence of excess CO in the 4.66–6.7 μm band.

$^d$ Parameters taken from (1) Saumon et al. (2000), (2) Saumon et al. (2003), (3) Saumon et al. (2006), (4) Saumon et al. (2007), (5) This work.