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AN IMPROVED RED SPECTRUM OF THE METHANE OR T-DWARF SDSS 1624+0029: ROLE OF THE ALKALI METALS

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ABSTRACT

A Keck II low resolution spectrum shortward of one micron is presented for SDSS 1624+0029, the first field methane or T dwarf discovered in the Sloan Digital Sky Survey. Significant flux is detected down to the spectrum's short wavelength limit of 6200Å. The spectrum exhibits a broad absorption feature centered at 7700Å, which we interpret as the K I 7665/7699 resonance doublet. The observed flux declines shortward of 7000Å, due most likely to the red wing of the Na I doublet. Both Cs I doublet lines are detected more strongly than in an earlier red spectrum. Neither Li I absorption nor Hα emission are detected.

An exploratory model fit to the spectrum suggests that the shape of the red spectrum can be primarily accounted for by the broad wings of the K I and Na I doublets. This behavior is consistent with the argument proffered by Burrows, Marley and Sharp that strong alkali absorption is principally responsible for depressing T dwarf spectra shortward of 1μm. In particular, there seems no compelling reason at this time to introduce dust or an additional opacity source in the atmosphere of the SDSS object. The width of the K I and strengths of the Cs I lines also indicate that the Sloan object is warmer than Gl 229B.

Subject headings: stars: individual (SDSS1624+0029 – stars: brown dwarfs – stars: atmospheres

1. INTRODUCTION

Methane or T dwarfs are substellar objects cooler than L and M dwarfs, and have near-infrared (1-2μm) spectra dominated by molecular absorption due to water, methane, and pressure-induced molecular hydrogen. Methane is expected to remain an important atmospheric constituent down to the temperature of Jupiter ($\sim$125 K), where it also is prominent in the infrared spectrum. The prototype of the class is the companion to the nearby M dwarf star Gl 229 (Nakajima et al. 1995, Oppenheimer et al. 1995). Model atmosphere analyses fitting synthetic spectra to detailed spectrophotometric and photometric observations indicate a temperature for this object near or slightly below 1,000 K (Marley et al. 1996, Allard et al. 1996). This past year has seen the discovery of several, similar field T dwarfs, found first in the Sloan Digital Sky Survey (Strauss et al. 1999, S99; Tsvetanov et al. 2000), shortly thereafter in the Two Micron All Sky Survey (Burgasser et al. 1999) data sets, and also in an ESO survey (Cuby et al. 1999).

All of the new objects also have 1–2μm spectra characterized by the very strong molecular absorbers listed above. Unfortunately, at least at low spectral resolution, the differences among their spectra appear somewhat subtle. The current field surveys by SDSS and 2MASS are magnitude limited, and therefore likely to identify the warmest (highest luminosity) T dwarfs. Still, the known parallax for Gl 570D shows that this object must be substantially cooler than the prototype, yet its infrared spectrum is similar to the others (Burgasser et al. 2000). The relative strengths of the molecular bands are not strongly dependent on the effective temperature. The molecular absorbers also are effective in hiding the weaker atomic line transitions which might be useful discriminants of temperature. At least initially, it is proving difficult to establish spectral types and a temperature sequence for the T dwarfs at the wavelengths where they are easiest to observe.

It is possible to observe the brightest of the new T dwarfs at wavelengths significantly shortward of 1μm, where the atmospheres may prove to be more transparent. Model calculations indicate that there may be few molecular and atomic opacity sources, and those that are present may be more sensitive to temperature. In particular, the behavior of the alkali resonance doublet features which reside generally in this red part of the spectrum (0.5-0.9μm) could be particularly useful in diagnosing the temperature and testing for the formation of dust grains (Burrows and Sharp 1999; Lodders 1999; Tsuji, Ohnaka & Aoki 1999; Burrows, Marley & Sharp 2000; hereafter, BMS). These papers generally predict that different alkalis should precipitate out as sulfides, salts or other condensates over a range of $T_{\rm eff}$ below about 1,500 K, in the order (with decreasing $T_{\rm eff}$) according to BMS of Li first, then Cs, K and Na. Indeed, the latter two alkali features are the most prominent features in the red spectra of the somewhat-warmer late L dwarfs (Kirkpatrick et al. 1999, Martín et al. 1999, Reid

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et al. 2000).

The red spectra of field T dwarfs can be relevant to another controversy regarding the spectrum of Gl 229B: The companion object shows too little red flux relative to the model predictions of Marley et al. (1996) and Allard et al. (1996). These authors concluded that an additional opacity source exists shortward of 1μm. Golimowski et al. (1998) suggested as the solution that TiO returned to gaseous form (it precipitates out in M-L dwarfs above 2,000 K) in Gl 229B. However, this hypothesis predicts TiO band absorption at the wavelengths seen in M dwarfs, but these are seen neither in late L dwarfs nor in Gl 229B. Griffith et al. (1998) turned to solar system physics for an intriguing answer: they hypothesized a population of small photochemical haze particles analogous to the red Titan Tholins (Khare and Sagan 1984), heated by ultraviolet radiation from the primary M dwarf to temperatures at least 50% higher than the T_{eff}. Dust is invoked in two other proposed solutions to the Gl 229B spectral slope: Tsuji, Ohnaka & Aoki (1999) describe a hybrid atmospheric model with a warm dust layer that effectively blocks short-wavelength flux. Pavlenko, Zapaterio Osorio & Rebolo (2000) attempt to fit the red spectrum with a scattering dust opacity which increases sharply to shorter wavelengths. Finally, BMS suggest that the alkali opacity alone – in particular the broad wings of K and Na – is the agent which depresses the emergent flux out to 1μm. Provided K and Na still exist in atomic form at the relevant temperature, they argued that there is no need to invoke dust or some additional absorber at short wavelengths.

SDSS 1624+0029 (hereafter, SDSS 1624), the first field T dwarf, was found in preliminary Sloan Digital Sky Survey data (S99). The discovery paper includes a red spectrum with the Apache Point 3.5-m telescope, with detected flux down to 8000Å. The accessible Cs I features at 8521Å and 8943Å appeared weak or absent, while both are distinct features in the Gl 229B red spectrum (Oppenheimer et al. 1998). The apparent weakness of the Cs I features and shallower red spectral slope of SDSS 1624 led BMS to the preferred conclusion that this object "is tied to a lower core entropy," which would normally imply a lower T_{eff} than that of Gl 229B. In contrast, the Sloan source showed somewhat shallower methane absorption in the infrared spectrum, suggesting to Nakajima et al. (2000) that it is warmer than the prototype. The red spectrum also shows that a field object can show a similar excess below 1μm as the companion object Gl 229B, thus demonstrating that the excess does not depend upon the presence of a nearby source of potential ultraviolet photons (ie., to produce the "Titan Tholins").

We discuss here a red spectrum of SDSS 1624 obtained with the Keck II LRIS spectrograph that extends the detection of flux down to 6200Å, and has improved signal-to-noise ratio at longer red wavelengths. We believe this observation allows us to test the roles of the alkali metals and the need for dust and/or an additional short-wavelength absorber.

2. THE SPECTRUM AND ITS FEATURES

Two consecutive spectra of SDSS 1624 were obtained on 1999 July 16 with the Keck II telescope and LRIS using the configuration described for most observations in Kirkpatrick et al. (1999). Each had an exposure time of 1800 seconds. Reduction was done with standard IRAF tools. The averaged spectrum spanning the entire wavelength interval of 6,300–10,100Å at 9Å resolution is shown in Fig. 1. Significant flux is detected over this entire range, as shown in an inset, which details the 6,300–8,200Å spectrum on an appropriate vertical scale. The variance spectrum from the standard IRAF task is also shown in the short wavelength inset where the signal-to-noise ratio (SNR) is smallest. Longward of 8200Å the variance spectrum (not shown) rises slowly to about 4×10^{-18} near one micron, except for the noisier intervals affected by the strongest atmospheric OH bands. Some significant conclusions may be drawn just from inspection of these figures.

(1) The spectrum at the shorter wavelengths, not accessible in previous observations, shows a strong, broad dip to zero flux centered precisely on the 7700Å blended doublet (see upper inset). Note that the variance plot remains flat over this interval, a strong indication that the feature is not due to any change in the noise. A "pseudo"-EW (pEW) of 390Å for the line cores was measured over the interval 7300-8100Å. This was estimated from the IRAF "splot" routine which simply fits a linear continuum across the stated interval. It is recognized that the flux levels at the interval boundaries are not the true continuum. Moreover, the procedure ignores the the considerable absorption in the extended wings of this doublet. Nonetheless, the pEW estimate may serve as a useful benchmark of the K I strength for quick comparison with any similar spectra obtained for other objects. The strength of the feature confirms the suggestion of Tsuji et al. (1999) and BMS that the red wing of this feature is a substantial absorber shortward of one micron in this T dwarf; presumably the same feature contributes to the flux deficiency in Gl 229B. Indeed, it was already recognized that this feature increases in strength with later types among the L dwarfs (Kirkpatrick et al. 1999; Martín et al. 1999).

(2) The detected flux rises shortward of 7700Å, revealing the blue wing of the K I feature. A broad maximum of the flux level may be reached near 7000Å, but significant flux is detected down to 6200Å, after moderate decline in the flux level shortward from 7000Å. This last decline is likely due to the red wing of the Na I resonance doublet centered near 5892Å. Na is normally the most abundant of the five alkalis in a Popuation I mix. Both Na and K are expected to survive to lower temperatures than Li, Cs and Rb, so their presence here is not surprising. Indeed, subordinate lines of K I were reported in the S99 (see also Nakajima et al. 2000) infrared spectrum. The SNR dips below unity at the last few hundred Å, but the conclusions about the shape of the continuum are robust. No significant absorption features are claimed.

(3) Significant Cs I absorption lines, both members of the well-separated doublet, are easily detected. The pEWs of 6.5Å and 6.1Å, for the respective 8521Å and 8943Å transitions, were measured over full width intervals of 25Å each. The Cs lines appear much stronger than was apparent in the Arc 3.5-m spectrum of S99. We note that the apparent strength of the 8943Å line could be enhanced by contribution from an overlapping weak CH_4 band. For the same intervals, pEWs of 6.5Å and 5.4Å were measured for the web-posted Oppenheimer et al. (1998) spectrum of Gl 229B. While detailed modeling of the alkali line pro-

files and red spectrum needs to be done, the conclusion of BMS that SDSS 1624 may have a lower temperature than Gl 229B needs to be reconsidered. It is also possible, however, that the Cs line strength varies with time and/or location on the surface.

(4) No significant Hα emission or Li I absorption is detected, to limits we estimate as pEWs of 15Å very approximately, since the SNR is near unity.

(5) The ~9300Å H_2O band reported by S99 is strong in this spectrum. A possible absorption which appears to be strongest near 9955Å, could be due at least in part to FeH, if the wavelength calibration is poor near the edge of the spectrum. A possible absorption feature near 8343Å may be H_2O; one near 8624Å (see lower inset of Fig. 1) coincides with both CH_4 and CrH bands, more likely the former.

3. AN EXPLORATORY MODEL FIT AND POSSIBLE IMPLICATIONS

Several authors have explored quantitative fits to the alkali resonance lines as a tool for estimating $T_{\rm eff}$ values for L and T dwarfs. Unfortunately, the detailed treatment of the line broadening poses a complicated problem – see BMS Section 3. Only a few key points are mentioned here. Available empirical data (cf. Nefedov, Sinel'shchikov, and Usachev 1999) provide valuable clues to what might be the best functional form for the profile. However, broadening parameters remain uncertain. In any case, simple treatments (ie. Lorentzian profiles) used previously in the literature appear inappropriate.

The detailed spectral fit depends upon several parameters, including the $T_{\rm eff}$, gravity, and abundances, but also the line profile shapes, and the degree of rainout (Burrows and Sharp 1999; BMS). We emphasize that the physical treatment of these last two remain uncertain. A detailed exploration of these many parameters would be required, at minimum, to achieve quantitative estimates of the $T_{\rm eff}$, surface gravity and abundances. It is questionable whether a satisfactory, unique solution will be found until a trigonometric parallax can help fix the luminosity and radius. What is shown below is an exploratory fit which we argue nonetheless yields useful qualitative conclusions. The techniques employed are described more generally in BMS.

Figure 2 shows a comparison between a representative model spectrum (dashed line) and a smoothed version of the SDSS 1624 spectrum (solid). Superposed is the Leggett et al. Gliese 229B spectrum of Oppenheimer et al. (1998). However, the observed flux has been transformed to an absolute flux for an assumed distance to the Sloan dwarf of 10 parsecs (S99), and is in milliJanskys, while the wavelength is in microns.

It may be seen clearly that the K I and Na I doublets and their broad wings dominate the spectrum. For this illustrative model fit, we assumed $T_{\rm eff}$ = 1100 K, gravity = 10^5 cm s^{-2}, abundances of one half solar, alkali line wing cutoff parameters defined in BMS of 0.2 (Na I) and 0.5 (K I), and an intermediate degree of rainout for the alkalis (BMS). The SDSS 1624 data were smoothed with a 10-Å boxcar function, which, among other things, muted the depth of the Cs lines relative to the model, but are of similar strength. No strong Li I absorption is predicted.

To obtain a reasonable fit, it is not clear to us that a dust component or additional source of red opacity is required. Tsuji's need for additional red opacity may be explainable by (1) underestimation of the alkali wing opacity due to the assumption of a Lorentzian, and (2) the I-band broad band flux was plotted at the wrong mean wavelength (see BMS). Although the presence of dust in the atmosphere certainly cannot be precluded, the alkalis appear to be the dominant cause of the unique shape of the red energy distribution. The detection of flux to the blue boundary of the spectrum also has consequences. In particular, a Rayleigh scattering dust opacity, as suggested by Pavlenko et al (2000), would have more than double the opacity at 7000Å than at 8400Å. Finally, the observed narrowness of the 7700Å feature (relative to our models at the Gl 229B temperature near 950 K) and the presence of strong cesium features together argue that the effective temperature of SDSS 1624 is above that of Gliese 229B (BMS), in concurrence with Nakajima et al. (2000).

We emphasize that no concerted attempt was made to find a rigorous fit, that other combinations of parameters are still viable, and that, given the SNR of the data at the shorter wavelengths, there are indeed parameter degeneracies.

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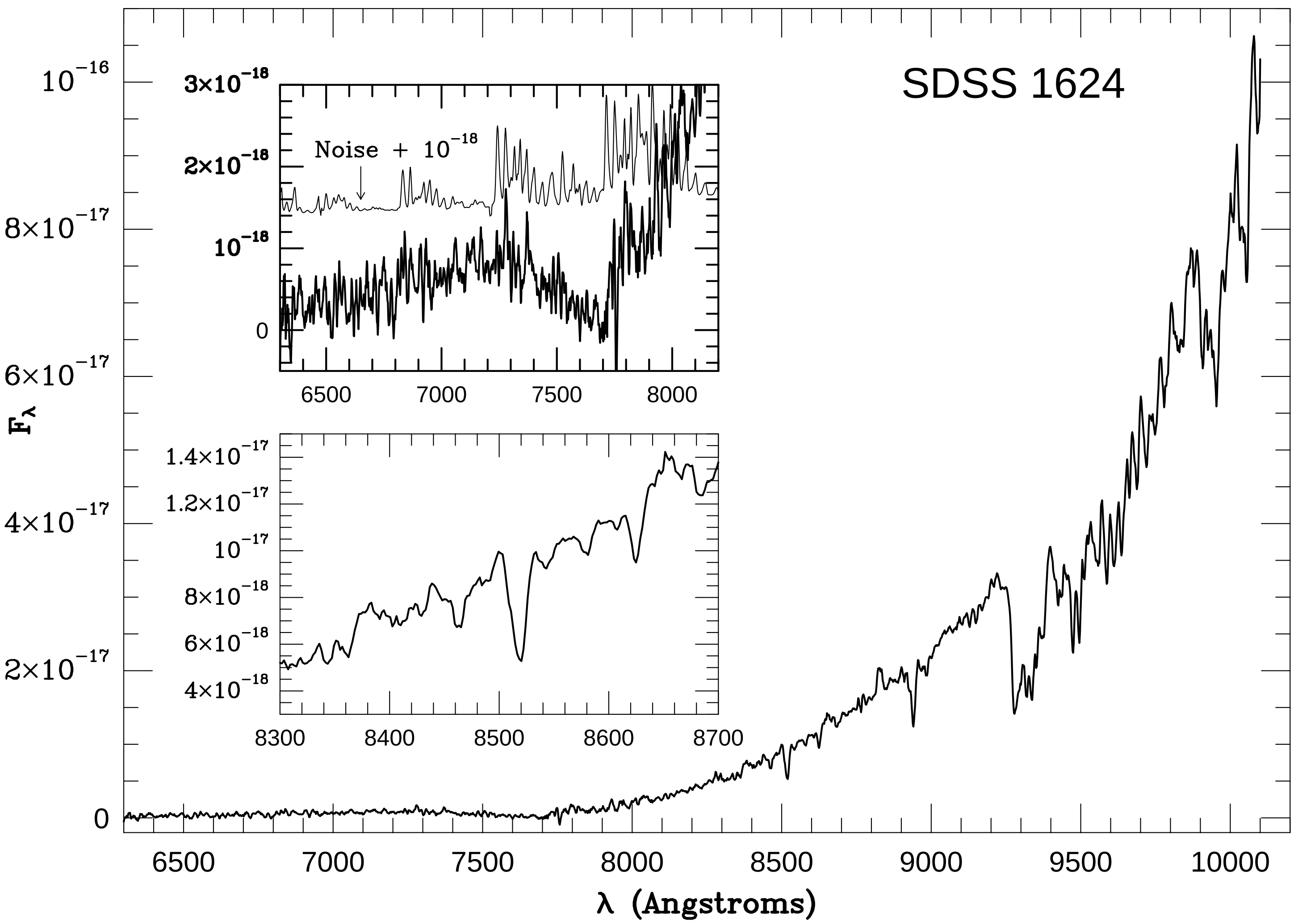

FIG. 1.— The Keck II spectrum of 2M1624+0029, F_λ vs. λ(Å), boxcar-smoothed by 5 pixels (10Å). Two inset boxes are discussed in the text. The noise (variance) spectrum is shown in the top inset (shifted upward by 10^{-18}) and is flat over this interval.

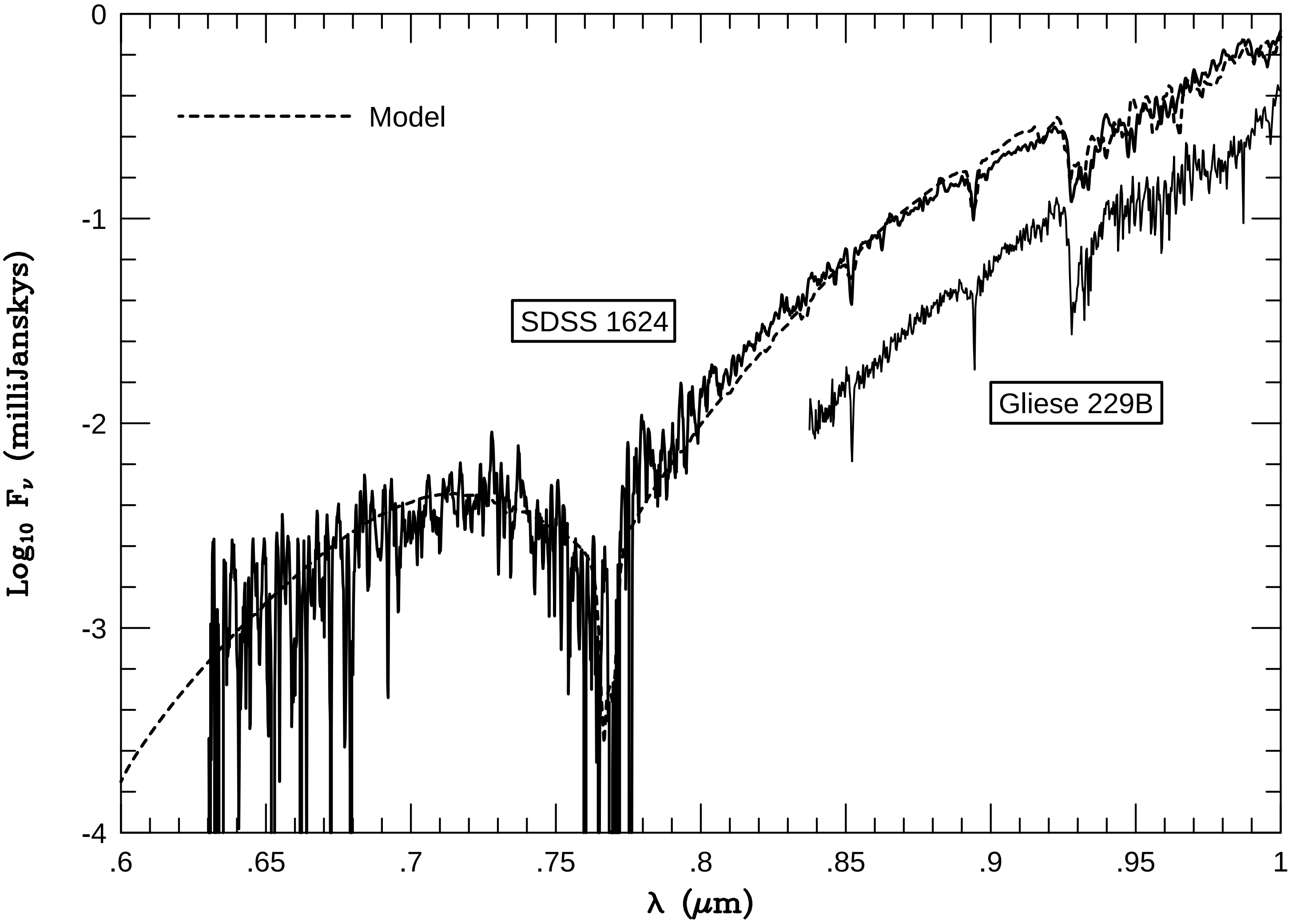

FIG. 2.— Comparison between a representative model spectrum (dashed) and a smoothed version of the SDSS1624 spectrum (solid), along with the published spectrum of Gl 229B (see text for details). The flux is in milliJanskys, and the wavelength in microns. The normalizations of the observations are based on an arbitrary distance assumed for SDSS1624 and the trigonometric parallax of Gl 229B.