THE NEAR-INFRARED AND OPTICAL SPECTRA OF METHANE DWARFS AND BROWN DWARFS

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ABSTRACT

We identify the pressure-broadened red wings of the saturated potassium resonance lines at 7700 Å as the source of anomalous absorption seen in the near-infrared spectra of Gliese 229B and, by extension, of methane dwarfs in general. In broad outline, this conclusion is supported by the 1999 work of Tsuji et al. The WFPC2 I-band measurement of Gliese 229B is also consistent with this hypothesis. Furthermore, a combination of the blue wings of this K I resonance doublet, the red wings of the Na D lines at 5890 Å, and, perhaps, the Li I line at 6708 Å can explain in a natural way the observed WFPC2 R-band flux of Gliese 229B. Hence, we conclude that the neutral alkali metals play a central role in the near-infrared and optical spectra of methane dwarfs and that their lines have the potential to provide crucial diagnostics of brown dwarf properties. We speculate on the systematics of the near-infrared and optical spectra of methane dwarfs, for a given mass and composition, that stems from the progressive burial with decreasing $T_{\text{eff}}$ of the alkali metal atoms to larger pressures and depths. Moreover, we surmise that those extrasolar giant planets (EGPs) that achieve $T_{\text{eff}}$ values in the 800–1300 K range because of stellar isolation will show signatures of the neutral alkali metals in their albedo and reflection spectra. We estimate that, predominantly because of absorption by Na D lines, the geometric albedo of the EGP τ Boo b at $\lambda = 0.48$ μm is less than 0.1, which is consistent with the new (and low) upper limit of 0.3 recently obtained by Charbonneau et al. in 1999.

Subject headings: planetary systems — stars: atmospheres — stars: individual (Gliese 229B, SDSS 1624+00) — stars: low mass, brown dwarfs

1. INTRODUCTION

The discovery of Gliese 229B in 1995 was a milestone in the study of brown dwarfs, providing the first bona fide object with an effective temperature ($T_{\text{eff}} \sim 950$ K) that was unambiguously substellar (Nakajima et al. 1995; Oppenheimer et al. 1995). It also validated in dramatic fashion the allied theoretical and observational efforts of the many groups around the world that were engaged in brown dwarf research, which started a race to discover and understand brown dwarfs that shows no sign of abating. Indeed, seven similar substellar mass objects, the so-called T or methane dwarfs, have since been discovered in the field by the Sloan Digital Sky Survey (Strauss et al. 1999; Ts Peytonov et al. 2000), by the 2MASS survey (Burgasser et al. 1999), and by the NTT/VLT (Cuby et al. 1999). Superficially, these all seem to be clones of Gl 229B, but there are subtle spectral differences that no doubt reflect true differences in mass, metallicity, and effective temperature. In addition to this flurry of brown dwarf discoveries, the first new stellar spectral class in almost 100 years, the “L type,” has been defined, with ~100 members having been found to date by 2MASS (Kirkpatrick et al. 1999) and DENIS (Delosse et al. 1997; Tinney et al. 1998). These objects are characterized by the clear onset of refractory heavy metal depletion, in particular that of titanium and vanadium, and by the growth in strength of the alkali metal lines of cesium, potassium, rubidium, and sodium in their optical and near-infrared spectra. L dwarfs also show distinct bands of FeH and CrH. Such transitions in chemical makeup with decreasing $T_{\text{eff}}$ are in keeping with theoretical predictions of the molecular constituents of substellar atmospheres (Burrows & Sharp 1999; Fegley & Lodders 1996) that can serve to anchor and define the sequence of L dwarf spectral subtypes (Kirkpatrick et al. 1999). The L dwarfs have $T_{\text{eff}}$ ranges from ~1500 to ~2000 K and constitute the spectroscopic link between M dwarfs and Gl 229B-like objects (Kirkpatrick et al. 1999). Many L dwarfs are also brown dwarfs (with masses below the stellar boundary at $\sim 0.075 M_\odot$), but some will turn out to be stars very near the stellar edge. The current ambiguity reflects the newness of this subject.

In this paper, we address T (methane) dwarf spectra in the optical and near infrared, focusing predominantly on Gl 229B as the prototype. Marley et al. (1996) and Allard et al. (1996) analyzed the full spectrum of Gl 229B (Oppenheimer et al. 1995; Geballe et al. 1996; Oppenheimer et al. 1998; Schultz et al. 1998) and obtained reasonable fits from the J band (~1.2 μm) through the N band (~10 μm). They concluded that its $T_{\text{eff}}$ was ~900–1000 K and that its gravity ($g$) was ~3 × 10^4–10^5 cm s^{-2}. The gravity error bars were large and translated into a factor of ~2–3 uncertainty in its inferred mass and age. They also concluded that the atmosphere of Gl 229B is indeed depleted in the refractory heavy elements, such as Al, Si, Ca, Fe, and Mg, just as the theory of condensate formation and rainout in cool molecular atmospheres would suggest, and that its spectrum longward of ~1 μm can be fit, in the main, by a simple mixture of H_2O, CH_4, and H_2. (Noll, Geballe, & Marley 1997 have detected CO at 4.67 μm in Gl 229B as well.) However, neither Marley et al. (1996) nor Allard et al. (1996) were able to fit the near-infrared observations between 0.8 and 1.0 μm and the theoretical excesses in flux ranged from 10 to 100. The line marked “Clear” in Figure 1 demonstrates the typical discrepancy between theory, that otherwise fits rather well at longer wavelengths, and the observed spectrum of Gl 229B (Leggett et al. 1999). Clearly, some
ingredient is absorbing in the blue, creating a very steep spectrum with a deep red (infrared) cast.

Attempts to fit this problematic spectral interval were made by Golimowski et al. (1998), who invoked a Tsuji et al. (1996) spectrum that retained TiO in the atmosphere to take full advantage of TiO's strong absorption in the blue, and Griffith, Yelle, & Marley (1998), who hypothesized that a population of small photochemical haze particles analogous to the red Titan Tholins (Khare & Sagan 1984) resided between ~1400 and ~1800 K in Gl 229B's atmosphere. Indeed, TiO does give roughly the correct continuum slope, but it imposes the characteristic TiO bands on the spectrum that are not seen in either late L or T dwarfs. Furthermore, chemical abundance studies show that Ti and V are depleted (rained out) from the atmosphere to depths below the silicate clouds and to temperatures near 2000 K, far below the Gl 229B's visible atmosphere. As to the suggestion by Griffith et al., the dependence on wavelength between 0.85 and 0.93 μm of the imaginary index of refraction of the hazes inferred by construction was ~5 times steeper than the corresponding published Tholin or polycetylene values. Moreover, though Gl 229B has in its primary, Gliese 229A, a nearby source of UV photons needed to generate a haze, the late L dwarfs and the new field methane dwarfs do not have such a source, yet they demonstrate similar profound absorption in the blue.

2. THE PIVOTAL ROLE OF THE K I RESONANCE DOUBLET AT ~7700 Å

What motivated Griffith et al. to posit the presence of a photochemical haze was the need for a continuum absorber to suppress the “blue” flux and to act shortward of ~1.0 μm down to at least 0.8 μm (Fig. 1). Small Mie scattering particles might quite naturally have fit the bill. However, there is another, ready-made, source of continuum opacity, the red wings of the K I resonance lines at 7665 and 7699 Å, that are in just the right place, shortward of the Gl 229B data, with what appear to be just the right strength and opacity slope, to fully explain the anomalous data. The K I resonance doublet, caused by the 4s²S₁/₂ - 4p²P₁/₂,3/₂ transitions, comes into its own only if other sources of opacity that dominate in M dwarfs, such as TiO and VO, are absent. The formation of refractories and their subsequent rainout accomplishes just that.

The concept of “rainout” warrants further explanation. When condensates form, there are two possible general categories for their ultimate distribution within an atmosphere. The condensate (solid grain or liquid drop) can remain well mixed with the atmosphere above the condensation level, or the condensate can rain out of the atmosphere. In the latter case, the exact vertical profile of the condensate depends on poorly understood microphysical processes. However, guided by experience with planetary atmospheres, we expect the condensate to form a cloud layer of some finite thickness. Both the condensable gas and its condensate are thus depleted above the cloud top. We refer to this process as “rainout.” In the other, well-mixed case, the condensate can continue to react with the gas; we refer to this case as complete thermochemical equilibrium. Based on the Gl 229B data, on experience with the planets of our solar system, and on general physical grounds, some form of rainout seems to occur.

As shown by Burrows & Sharp (1999), Fogley & Lodders (1996), and Lodders (1999), the alkali metals are less refractory than Ti, V, Ca, Al, Fe, and Mg and survive in abundance as neutral atoms in substellar atmospheres to temperatures of 1000–1500 K. This is below the 1500–2500 K temperature range in which the silicates, iron, the titanates, corundum, and spinel, etc. condense. Hence, in the depleted atmospheres of cool brown dwarfs, alkali metals quite naturally come into their own. Figures 2 and 3 show some representative abundance profiles for the alkali metals Li, Cs, K, and Na, with and without rainout. A Tiₐ = 950 K and g = 10⁵ cm s⁻² Gl 229B atmosphere model from Burrows et al. (1997) and Burrows & Sharp (1999) was used. As demonstrated in Figures 2 and 3, with or without rainout, elemental potassium and sodium persist to low temperatures to near the top of the T dwarf atmosphere. However, the distributions of the atomic alkalis are not the same, with Li and Cs being deeper than Na and K. At lower temperatures in an atmosphere, the atomic forms give way to the chlorides and hydroxides (e.g., LiOH). With rainout (Fig. 2), below ~1000 K both sodium and potassium exist as sulfides (Na₂S and K₂S) (Lodders 1999). Without rainout (Fig. 3), a situation we deem unlikely, complete chemical equilibrium at low temperatures requires that sodium and potassium reside in the feldspars, high albite, and sandine. If such compounds formed and persisted at altitude, then the nascent alkali metals would be less visible, particularly in T dwarfs. For either case, as Figures 2 and 3 demonstrate, all the elemental alkalis reside in the lower pressure/lower temperature reaches of cool, substellar atmospheres.

Lines of Cs I at 8521 and 8943 Å, Rb I at 7800 and 7948 Å, Li I at 6708 Å, and Na I at 8183 and 8195 Å have already been identified in L dwarf spectra. In addition, as Figure 4 and Kirkpatrick et al. (1999) demonstrate, the K I doublet is clearly dominant in the spectra of such late L dwarfs as 2MASS-1228, 2MASS-0850, DENIS-0205, and 2MASS-1632. Therefore, it is quite natural to explain the steep red slope of the new T dwarfs as being caused by the red wing of a saturated and pressure-broadened K I feature. This is the thesis of our paper. Moreover, Gl 229B's I-band flux (M_I ~ 20.76), as measured using WFPC2 on HST (Golimowski et al. 1998), can be explained by the same K I resonance feature, and the Gl 229B R-band flux (M_R ~ 24.0), also...
measured by Golimowski et al. (1998), can be explained by a mix of the sodium D lines at 5890 Å, the lithium line at 6708 Å, and the blue tail of the K I resonance doublet. Note that the 1.25 µm lines of excited K I have also been identified in T dwarfs (Strauss et al. 1999; Tsvetanov et al. 2000), so that the presence of potassium, at least at the higher temperatures in their atmospheres, is in no doubt. The alkali metal lines may well prove to be the key to probing the atmospheric structure of the methane dwarfs, since their distributions and relative depths (cf. Fig. 2) will be reflected in the systematic dependence of T and L dwarf spectra with $T_{\text{eff}}$ and $g$.

3. PROFILES OF THE ALKALI METAL RESONANCE LINES

Before we proceed with a discussion of our synthetic Gl 229B spectra between 0.3 and 1.5 µm, we discuss our algorithm for handling the pressure broadening of the alkali metal lines by molecular hydrogen. The line lists containing the wavelength of the transition, the lower excitation energy, the log (gf) value, and the quantum numbers of the participating states were obtained from the Vienna Atomic Line Data Base (Piskunov et al. 1995). The major transitions of immediate relevance are those that correspond to the Na D lines at 5890 Å and the K I resonance lines at 7700 Å. Given the high H$_2$ densities in brown dwarf atmospheres, the natural widths (for Na D, ~0.12 mÅ) and Doppler widths of these lines are completely overwhelmed by collisional broadening. However, in general, the line shapes are determined by the radial dependence of the difference of the perturber/atom potentials for the lower and upper atomic states (Griem 1964; Breene 1957, 1981, p. 344) and these are rarely known. The line cores are determined by distant encounters and are frequently handled by assuming a van der Waals interaction potential with an adiabatic impact theory (Weisskopf 1933; Ch'en and Takeo 1957; Dimitrijević & Peach 1990), and the line wings are determined by close encounters and are frequently handled with a statistical theory (Holtzmark 1925; Holstein 1950). The transition between the two regimes is near the frequency shift ($\Delta v$), or detuning, associated with the perturbation at the so-called Weisskopf radius ($\rho_w$), from which the collision cross section employed in the impact theory is derived (Spitzer 1940; Anderson 1950). In the simple impact theory, the line core is Lorentzian, with a half-width determined by the effective collision frequency, itself the product of the perturber density, the average relative velocity of the atom and the perturber ($v$), and the collision cross section ($\pi \rho_w^2$). If the frequency shift ($\Delta v$) caused by a single perturber is given...
Fig. 3.—Fractional abundances of different chemical species involving the alkali elements Li, Na, K, and Cs for a Gl 229B model, assuming complete (true) chemical equilibrium and no rainout (disfavored). The temperature/pressure profile for a $T_{\text{eff}} = 950$ K and $g = 10^3$ cm s$^{-2}$ model, taken from Burrows et al. 1997, was used. Each curve shows the fraction of the alkali element in the indicated form out of all species containing that element, e.g., in the case of sodium, the curves labeled as Na, NaCl, NaH and are the fractions of that element in the form of the monatomic gas and three of its compounds: NaAlSi$_3$O$_8$.

All species are in the gas phase except for the condensates, which are in braces [ ]. The solid curves indicate the monatomic gaseous species Li, Na, K, and Cs and the two condensates NaAlSi$_3$O$_8$ and KAlSi$_3$O$_8$, i.e., high albite and sanidine, respectively; the dashed curves indicate the chlorides; the dot-dashed curves indicate the hydrides and the triple-dot-dashed curve indicates LiOH.

by $C_n/r^n$, where $r$ is the interparticle distance, then $\rho_w$ is determined from the condition that the adiabatic phase shift, $\int_{-\infty}^{\infty} 2\pi n\Delta \tilde{v} dt$, along a classical straight-line trajectory, with an impact parameter $\rho_w$, is of order unity. This yields $\rho_w \propto (C_n/v)^{1/(n-1)}$. For a van der Waals force, $n = 6$. In the statistical theory, the line shape is a power law that goes like $1/\Delta v^{(n+3)/3}$, and this is truncated (cut off) by an exponential Boltzmann factor, $e^{-V_0(r)/kT}$, where $V_0(r)$ is the ground-state perturbation at the given detuning. The detuning at the transition between the impact and statistical regimes is proportional to $(v^6/C_n)^{0.2}$ (Holstein 1950).

All this would be academic, were it not that for the Na/H$_2$ pair the simple theory in the core and on the red wing is a good approximation (Nefedov, Sinel'shchikov, & Usachev 1999). We use this theory here. For the Na D lines perturbed by H$_2$, we obtain from Nefedov et al. (1999) a $C_6$ of $2.05 \times 10^{-32}$ cgs and a transition detuning, in inverse centimeters, of $30 \text{ cm}^{-1}(T/500 \text{ K})^{0.6}$, where $T$ is the temperature. For the K I resonance lines, we scale from the Na D line data, using a $C_6$ of $1.16 \times 10^{-31}$ cgs, itself obtained from the theory of Unsöld (1955, p. 305). This procedure yields a transition detuning for the $7700 \text{ Å}$ doublet of 20 cm$^{-1}(T/500 \text{ K})^{0.6}$. From Nefedov et al. (1999), we see that for a variety of perturbing gases the exponential cutoff for the Na D lines can be (for temperatures of 1000–2000 K) a few times $10^3$ cm$^{-1}$. The difference between 5890 and 7700 in inverse wavenumbers, is $\sim 4000$ cm$^{-1}$ and that between 7700 Å and 1.0 μm is only 3000 cm$^{-1}$. Hence, it is reasonable to expect that the detunings at which the line profiles are cut off can be much larger than the Lorentzian widths or the impact/statistical transition detunings of tens of cm$^{-1}$. Since we as yet have no good formula for the
exponential cutoff term, we assume that it is of the form $e^{-q k T}$, where $q$ is an unknown parameter. Comparing with the examples in Nefedov et al. (1999), $q$ may be of order 0.3–1.0 for the Na/H$_2$ pair. Without further information or guidance, we assume that it is similar for the K/H$_2$ pair. We stress that this algorithm is merely an ansatz and that a more comprehensive theory based on the true perturber potentials is sorely needed. Nevertheless, whatever the detailed line shape, as we will show, the basic conclusion that the K I resonance doublet is the “mystery” absorber in the near-infrared spectra of T dwarfs seems robust.

Figure 5 depicts our opacity spectrum versus wavelength for the K I doublet at $T = 2000$ K and 1 bar pressure for three different parameterizations. Included are other, non-resonant, potassium lines excited by the high temperature. The solid line is the Lorentzian theory without corrections in the broad wings at large detunings. The short-dashed and long-dashed lines are for the corrected theory, with $q$ values of 0.5 and 1.0, respectively. The crucial fact is the useful slope between 0.8 and 1.0 µm.

4. MODEL SPECTRA FOR GLEISE 229B

Gliese 229B has been well studied from the red to $\sim 10$ µm and has a well-measured distance (5.8 pc). Hence, with moderate resolution spectra in hand and absolute fluxes, it is natural to use Gl 229B to demonstrate our basic thesis about the near-infrared and optical spectra of the entire T dwarf class. On Figure 1, in addition to depicting the “Clear” atmosphere fluxes from 0.5 to $\sim 1.45$ µm, we give the synthetic spectra for four different models of Gl 229B that include the lines of the alkali metal atoms, in particular the K I doublet at 7700 Å, employing the formalism of § 3. The Gl 229B data are taken from Leggett et al. (1999). Rainout abundance profiles of the alkali metals were used (cf. Fig. 2). As Figure 1 demonstrates, the fit between 0.85 and 1.0 µm is quite good and does not seem to require a layer of red particulates. We were guided in our choices of $T_{\text{eff}}$ values, gravities, and metallicities for these models by the work of Marley et al. (1996), Allard et al. (1996), and Griffith et al. (1998). Three of the models, those with higher fluxes around 0.7 µm and lower fluxes near 1.0 µm used a $q$ of 0.4 and assumed alkali metal abundances of 0.3 times solar (Anders & Grevesse 1989). They had $T_{\text{eff}} / g$ pairs of [900 K/10$^5$ (cgs)], [950 K/10$^5$ (cgs)], and [800 K/3 × 10$^4$ (cgs)]. From Burrows et al. (1997), the ages and masses for these models are 1.46 Gyr/34.9 $M_J$, 1.26 Gyr/35.3 $M_J$, and 0.44 Gyr/14.8 $M_J$, respectively. The fourth model, that with the lowest fluxes near 0.7 µm and the highest fluxes near 1.0 µm, employed a $q$ of 1.0, had a $T_{\text{eff}} / g$ pair of [950 K/10$^5$ (cgs)], and assumed that the alkali metal abundances were solar. Note that values for $q$ of 0.4 and 1.0 are merely possibilities and that we do not necessarily advocate either one. As stressed in §3, the far wings of the neutral alkali metal lines, perturbed by molecular hydrogen, have not been properly calculated. In fact, to our knowledge there is no other environment in which the neutral alkali line strengths at 1000–3000 Å detunings have ever before been needed.

Figure 6 depicts the behavior of the theoretical spectra as a function of $q$, from 0 to 1, for the [950 K/10$^5$ (cgs)] model (with 0.3 times solar alkali metal abundances). Also included is the predicted spectrum for the uncorrected Lorentzian K I line profile (dotted line). Though Figure 6 depicts a range of near-infrared and optical spectra, the character of these spectra is similar. However, as a consequence of the current ambiguity in the proper shape of the 7700 Å profile, which we have parameterized with $q$, we cannot yet tie down the alkali metal abundances to better than perhaps a factor of 3. Nevertheless, the good fits indicated in Figure 1 are quite compelling. Rather stunningly, both the measured WFPC2 I-band flux near 0.814 µm and the WFPC2 R flux near 0.675 µm (Golimowski et al. 1998) fit as well. Hence, we
conclude that the I-band flux is determined by the red wing of the K 1 resonance doublet and that the R band is a consequence of the red wings of the Na D lines (\( \sim 5890 \) Å), the blue wings of the K 1 doublet, and, perhaps, the lithium line at 6708 Å. The broad width of the I-band filter extends it to beyond the saturated center of the doublet at 7700 Å. Our theoretical models have absolute I-band magnitudes from 21.0 to 21.3, compared with the measured value of \( \sim 20.76 \). Given the calibration problems when an underlying spectral slope is so steep and so unlike that of the standard stars, we conclude that the fit is indeed good. As Figure 1 demonstrates, our R-band predictions bracket the R-band measurement.

We emphasize that one should be very careful about interpreting band magnitudes as fluxes. There are two points to make in this regard: (1) bands are spread over a sometimes broad range of wavelengths and, (2) magnitudes are calibrated on stars with certain underlying spectra that may not be similar to the spectrum of the object under study. If these spectra are very different, large errors can be made in assigning magnitudes, as well as in assigning fluxes at a given wavelength in the band. A quick look at the spectrum of Gl 229B from 0.8 to 1.0 \( \mu m \) will show why this should be of concern; the calibration stars cannot have such steep slopes, and the errors in the measured magnitudes might be very large, many tenths of magnitudes. This, and extravagant bandwidth, are particularly relevant for the Gunn r and i band measurements of Matthews et al. (1996). Given this, we compare with just the WFPC2 R- and I-band data of Golimowski et al. as a set from a single group and depict the breadth of these bands on our figures.

We note in passing that the discrepancy between the depth of the predicted and measured flux trough between the \( Z (\sim 1.05 \) \( \mu m \)) and the J (\( \sim 1.25 \) \( \mu m \)) bands may be resolved with a lower abundance of water and, hence, oxygen (Griffith et al. 1998) and that the shape of the J band cannot be fit without the methane bands at \( \sim 1.15-1.2 \) \( \mu m \) and \( \sim 1.3 \) \( \mu m \) to sculpt it. Hence, the shape of the J band in T dwarfs is not just a consequence of bracketing by H\_2O absorption features but requires methane and is another signature of methane in their atmospheres. However, this point, as well as the inferred elemental abundances, are not the subject of the current paper and we defer a fuller discussion to a later work.

The variety of models that fit the Gl 229B data, given the current state of the theory and observations, was noted in Marley et al. (1996) and Allard et al. (1996) and reflects the fact that different models with different \( T_{\text{eff}} / g \) pairs can have similar atmospheric temperature-pressure profiles and luminosities. The atmospheres of substellar objects are convective at depth and radiative on the periphery. For a given composition, brown dwarfs and extrasolar giant planets (EGPs; Burrows et al. 1995) are a two-parameter family; given two independent quantities, such as \( T_{\text{eff}} \), luminosity, radius, gravity, or age, one can derive, with theory, any of the others. In particular, as discussed in Hubbard (1977) and Saumon et al. (1996), in an approximate sense, the entropy (S) at depth is a function of \( T_{\text{eff}} \) and \( g \), and this entropy determines the temperature/pressure profile. (This is not to say that the atmospheres are adiabatic, merely that the \( T/P \) profile of the outer radiative zone can be calculated from S, \( T_{\text{eff}} \), and \( g \)). Hubbard (1977) showed that S is approximately a function of the combination \( T_{\text{eff}}^{0.95} / g^{1.6} \). From Marley et al. (1996), we obtain rough power-law relations for mass (M), radius (R), and age (t), as a function of \( g \) and \( T_{\text{eff}} \):

\[
M = 35 M_J \left( \frac{g}{10^5} \right)^{0.64} \left( \frac{T_{\text{eff}}}{10^4} \right)^{0.23}
\]

\[
R = 6.7 \times 10^4 \text{ km} \left( \frac{10^5}{g} \right)^{0.18} \left( \frac{T_{\text{eff}}}{10^3} \right)^{0.11}
\]

\[
t = 1.1 \text{ Gyr} \left( \frac{g}{10^5} \right)^{1.7} \left( \frac{T_{\text{eff}}}{10^4} \right)^{2.8},
\]

where \( g \) is in cm s\(^{-2}\). From these equations, and the dependence of S on \( T_{\text{eff}} \) and \( g \) cited above, we derive, approximately, that, for a given core entropy and, hence, for a given \( T/P \) profile, \( M \sim t^{0.55} \). Using the same set of power laws, we can derive that, for a given luminosity, \( M \sim t^{0.43} \).

Hence, since these two power-law relations are similar, fits to Gl 229B roughly define a trajectory in \( M-t \) space with a \( \sim 0.5 \) power. This is why low-mass/short-age models and high-mass/long-age models both fit Gl 229B, at least for the low-resolution comparisons attempted thus far. In principle, this degeneracy can be broken once the theory and the observations are better constrained. Figure 7 shows temperature/pressure profiles for a few models from Burrows et al. (1997). The higher curves are for higher \( T_{\text{eff}} \) values and lower gravities. Note that the lower \( T_{\text{eff}} \), lower \( g \) model [\( 800 \text{ K}/3 \times 10^4 \) (cgs)] is in the same vicinity as the higher \( T_{\text{eff}} \), higher \( g \) model [\( 900 \text{ K}/10^3 \) (cgs)], both of which are good fits to Gl 229B (Fig. 1). Note also that the [\( 1100 \text{ K}/5 \times 10^4 \) (cgs)], [\( 400 \text{ K}/5 \times 10^4 \) (cgs)], and [\( 800 \text{ K}/10^5 \) (cgs)].
5. THE SLOAN DWARF: SDSS 1624 +00

The models and data depicted in Figure 1 capture the Cs lines at 8521 and 8943 Å, indicating that cesium is in Gl 229B's atmosphere in modest abundance between 1200 and 1400 K. The depths to which cesium can be found are shown in detail for a specific model in Figures 2 and 3 and approximately for the variety of models by the position of the intercept in Figure 7 of the "Cs/CsCl = 1" line with a given $T/P$ profile. Similarly, the depths of atomic K, Na, Rb, and Li can be found. Shown on Figure 7 along with the Cs/CsCl = 1 line is a corresponding complete equilibrium (no rainout) "K/KCl = 1" trajectory. As Figure 2 demonstrates, with rainout (a more realistic situation), atomic potassium persists to much lower temperatures, perhaps shifting the K/KCl = 1 line on Figure 7 down by 200-300 K. Nevertheless, qualitatively and importantly, the lower the $T/P$ profile in Figure 7, the deeper are the atomic cesium and potassium. Depth and higher pressure imply a higher column density of and and, hence, a higher optical depth of these competing absorbers. Therefore, for a given composition, at lower $T_{\text{eff}}$ and higher $g$, both potassium and cesium are more deeply buried than at higher $T_{\text{eff}}$ and lower $g$. The expected upshot is the gradual diminution with decreasing core entropy of the strengths of the cesium and potassium features. A decrease in the effect of the $K$ I resonance doublet at 7700 Å would result in an increase in the influence below 1.0 μm of the H2O, CH4, and H2 features that are not as steep as the red wing of the doublet. As a result, the spectrum shortward of ~0.95 μm would be shallow and the 7700 Å region of the spectrum would fill in. The Rb lines at 7800 and 7948 Å may make an appearance in the K I trough, but they will still be rather weak. Note that, for a given $T_{\text{eff}}/g$ pair, lowering the abundances of the alkali metals would raise the flux in the 0.7-0.95 μm region, but it might also make the $Z - J$ color bluer than observed for the current crop of T dwarfs. Furthermore, the presence of the potassium line at 1.25 μm both in Gl 229B and in the two Sloan dwarfs makes this explanation suboptimal. Nevertheless, potential variations in abundances and metallicity from object to object do complicate the analysis.

The shallowing of the spectrum shortward of 0.9 μm and the weakening of the cesium features at 8521 and 8943 Å are indeed seen in the preliminary spectrum of SDSS 1624 +00 (Strauss et al. 1999). Strauss et al. note that the spectra of Gl 229B and SDSS 1624 +00 seem uncannily similar and conclude that they must have similar mass, age, and $T_{\text{eff}}$. Given the lower apparent flux of SDSS 1624 +00, they put this object further away than Gl 229B, at ~10 pc. However, theory implies the $J - H$ and $J - K$ colors do not change hugely in the 600-1200 K range (Burrows et al. 1997). As a consequence, for a given gravity or mass, a decrease in $T_{\text{eff}}$ merely, though approximately, translates the absolute spectrum down to lower fluxes. Hence, there is a need for more subtle diagnostics of a substellar object's properties. Such diagnostics may be the strengths of the alkali metal lines in the optical and near infrared. Figure 8 compares the observed SDSS 1624 +00 spectrum with a theoretical model spectrum, as well as with the observed Gl 229B spectrum. The model (dotted line) has an atmosphere with $T_{\text{eff}} = 700$ K and $g = 3 \times 10^4$ cm s$^{-2}$. Its core entropy is below those of the Gl 229B models. We theorize that the shallower near-infrared spectrum of SDSS 1624 +00, with respect to Gl 229B, as well as the weakness of the Cs lines, are both consequences of a lower core entropy $T/P$ profile. This could mean a lower $T_{\text{eff}}$, a higher $g$ or mass, or some suitable combination that buries the tops of the potassium and cesium distributions at higher pressure and, hence, larger H2O optical depths than found in Gl 229B. However, given the remaining theoretical ambiguities, we cannot rule out completely the possibility that lower K and Cs abundances are the explanation. Note that it is still possible that the $T_{\text{eff}}$ for SDSS 1624 +00 is much larger than 700 K. However, given its provisional cesium line strengths, we would then require its gravity, and presumably its mass, to be correspondingly higher to achieve the lower core entropy we suggest can explain its spectrum. Importantly, if improved spectra were to show that Cs is much stronger in SDSS 1624 +00 than its preliminary, low-resolution spectrum now indicates, a higher $T_{\text{eff}}$, perhaps higher than that of Gl 229B, would be indicated. This emphasizes the importance of the alkali metal lines as diagnostics of the T dwarfs and the need to obtain better spectra. Note that with the [700 K/$3 \times 10^4$ (cgs)] model, the absolute $Z$- and $J$-band fluxes of the SDSS 1624 +00 are below those for Gl 229B and match only near $\lambda = 0.85$ μm. If the $T_{\text{eff}}$ of SDSS 1624 +00 is indeed lower than that of Gl 229B, SDSS 1624 +00 could be closer than the 5.8 pc of Gl 229B. A smaller distance would increase the inferred number density of objects like SDSS 1624 +00, perhaps beyond what is credible. Hence, obtaining a parallax for this new T dwarf will be a crucial prerequisite for future substantial improvements in characterizing it.

Of importance, any $T_{\text{eff}}$ estimate for SDSS 1624 +00 must be confirmed by a comparison of models and observations at longer wavelengths, similar to that performed for Gl 229B (Marley et al. 1996; Allard et al. 1996). As with Gl 229B, simultaneously achieving a satisfactory fit to the optical flux, the near-infrared windows, and absorption features will be challenging. In particular, if SDS 1624 +00 has
a lower \( T_{\text{eff}} \) than Gl 229B, the water and methane band depths will likely be deeper. Yet the methane opacity database at 1.7 \( \mu \text{m} \) is too poor to permit detailed comparisons and the 2.3 \( \mu \text{m} \) band is also influenced by \( \text{H}_2 \) opacity, the relative strength of which depends upon the metallicity. L-band spectra, which probe the methane fundamental band at 3.3 \( \mu \text{m} \) where there are no competing absorptions and the opacity database is better understood, may provide the best point of comparison.

However, for a given mass and composition, the “history” of the alkali metal lines in L and T dwarfs may follow the following sequence. At higher \( T_{\text{eff}} \) values (in the L dwarf range), the depletion of the refractory elements allows the strengths of the alkali metal lines to wax. The cesium lines peak before reaching the \( T_{\text{eff}} \) of Gl 229B, though they are still prevalent in such atmospheres, and potassium determines the character of the spectrum from 0.7 through 1.0 \( \mu \text{m} \). As \( T_{\text{eff}} \) decreases further, the alkali metals are buried progressively more deeply and begin to wax in strength. Because of this burial of potassium, the slope of the spectrum from 0.8 to 1.0 \( \mu \text{m} \) decreases. Since the abundance distribution of the atomic form of each alkali metal is different (Figs. 2 and 3), the \( T_{\text{eff}} \) values at which the lines of a given alkali start to wax will be different, with the effects of Li, Cs, Rb, K, and Na waning in approximately that order with decreasing \( T_{\text{eff}} \) (at a given mass and metallicity). The specific numbers will depend on the actual effects of rainout on the alkali metal profiles, but the systematics should not.

Eventually, perhaps below \( T_{\text{eff}} \) values of 500–600 K, the effects of the neutral alkali metals are eclipsed, with clouds of \( \text{H}_2\text{O} \) eventually effecting the next important change in the character of brown dwarf atmospheres. Given this systematics, whatever the true \( T_{\text{eff}} \) of SDSS 1624+00, we would predict that both above Gl 229B’s \( T_{\text{eff}} \), near the \( T_{\text{eff}} \) juncture between the L dwarfs and the T dwarfs, and below a \( T_{\text{eff}} \) of \( \sim 800 \) K, the troughs around the K I resonance doublet at 7700 \( \AA \) would be partially filled and the slope of the “optical” spectra between 0.8 and 1.0 \( \AA \) would be shallow.

6. SUMMARY

We conclude that the anomalous absorption seen in the near-infrared and optical spectra of all the T dwarfs discovered to date is caused by the red wings of the saturated K I resonance lines at 7700 \( \AA \). This theory also explains the WFPC2 I and R flux measurements made of Gl 229B, with the Na D lines at 5890 \( \AA \) helping to determine the strength of the R band. There are still ambiguities in the \( T_{\text{eff}} \) values, gravities, and compositions of Gl 229B, in particular, and of T dwarfs, in general, but a sequence from Gl 229B to SDSS 1624+00 of decreasing core entropy is seen to be consistent with the expected systematics of the temperature/pressure and alkali-metal abundance profiles. (However, lower K and Cs abundances for the Sloan dwarf or a reassessment of its cesium line strengths once higher resolution spectra become available cannot yet be ruled out.) Silicate grains are expected at depths of 1500–2500 K. Their formation is inferred in the late M dwarfs (Jones & Tsuji 1997), and their eventual burial is seen in the appearance at lower \( T_{\text{eff}} \) values of the new L spectral class (Kirkpatrick et al. 1999). Complete refractory element depletion ushers in a phase of neutral alkali metal dominance at short wavelengths, which persists until the tops of the alkali metal distributions are buried at higher pressures and higher \( \text{H}_2\text{O} \), \( \text{CH}_4 \), and \( \text{H}_2 \) optical depths. This occurs in low-entropy atmospheres, though low alkali metal abundances can mimic the same effect somewhat. We note that if the Lorentzian theory for the line shapes of the Na D lines were used, because of the high relative abundance of sodium, their influence would stretch 7000 cm\(^{-1} \) to 1.0 \( \mu \text{m} \) and would flatten the top of the Z band, contrary to observation. This is indirect evidence for the action of an “exponential cutoff” on the Na D line shape. Even with such a cutoff, the K I resonance line dominates the spectra of Gl 229B and its ilk from 0.7 to 1.0 \( \mu \text{m} \). For Gl 229B, we predict the presence of a saturated absorption line around 7700 \( \AA \), with higher fluxes on either side. We also expect a deep, broad trough around the Na D lines at 5890 \( \AA \) (see Fig. 1).

At the time of this writing, we became aware of a paper by Tsuji, Ohnaka, & Aoki (1999) that also has concluded that the K I feature is the major, “mystery” absorber at short wavelengths. We wholeheartedly concur with this conclusion. However, contrary to Tsuji et al., we determine that dust may not be required to achieve a good fit short-ward of 1.0 \( \mu \text{m} \). Moreover, we believe that the Gl 229B I-band flux is well fit by the red wing of the K I doublet alone. In addition, if the Na D lines are included in a natural way, an acceptable fit to the WFPC2 R-band flux is achieved as a by-product. However, filling in the troughs between the Z and J bands and between the H and K bands may still require some combination of grains, as Tsuji et al. suggest, and subsolar metallicity, though subsolar metallicity and improvements in the molecular opacity databases alone may be sufficient. If silicate dust is important, it could be because of upwelling from below, a very nonequilibrium process that is not easily modeled. In addition, optical constants, particle shapes, and particle sizes would need to be known. There is no credible guidance concerning the particle size; the guessed average particle radius could be off by 1 or 2 orders of magnitude. This ambiguity translates into a correspondingly large ambiguity in the dust opacity. As Griffith et al. (1998) demonstrate, a sufficiently arbitrary dust model can be found to fit the Gl 229B spectrum. Nevertheless, a possible model might be one in which a small population of dust from minor species at low pressures warms the atmosphere near the 1 bar, thus decreasing the depths of the water and methane absorption bands that originate near this pressure, yet providing little opacity elsewhere. However, we reiterate that, given the new-found importance of the K I feature, there is much less reason to evoke a population of dust or grains to fit methane dwarf spectra.

Note that in this paper we have considered only objects in isolation. However, we expect that those EGPs that achieve \( T_{\text{eff}} \) values in the 800–1300 K range because of stellar insolation will also show signatures of the neutral alkali metals. Recently, Charbonneau et al. (1999) have put an upper limit of 0.3 to the geometric albedo at \( \lambda = 0.48 \mu \text{m} \) of the planet orbiting \( \tau \) Boo. This is below some published predictions (Marley et al. 1998), though not others (Seager & Sasselov 1998), and may indicate the presence in its atmosphere of sodium and absorption by the Na D lines (Sudarsky, Burrows, & Pinto 1999). Our preliminary estimate of the geometric albedo at \( \lambda = 0.48 \mu \text{m} \) of such a planet, because of the influence of the neutral alkali metals, is less than 0.1. Since stellar insolation is bound to create hazes (Marley 1998), such as absorb in the blue and UV in
Jupiter, detailed reflection spectra of τ Boo and similar “close-in” EGPs will be needed to disentangle the relative contribution of the alkali metals to EGP albedos.

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