SPECTRAL CLASSIFICATION AND EFFECTIVE TEMPERATURES OF L AND T DWARFS BASED ON NEAR-INFRARED SPECTRA

TADASHI NAKAJIMA
National Astronomical Observatory, 2-21-1, Osawa, Mitaka 181-8588, Japan; tadashi.nakajima@nao.ac.jp

TAKASHI TSUJI
Institute of Astronomy, University of Tokyo, 2-21-1, Osawa, Mitaka 181-0015, Japan; tsuji@ioa.s.u-tokyo.ac.jp

AND

KENSHI YANAGISAWA
Okayama Astrophysical Observatory, Kamogata, Okayama 719-0231, Japan; yanagi@oao.nao.ac.jp

Received 2003 November 4; accepted 2004 February 3

ABSTRACT

We have obtained near-infrared spectra of L dwarfs, L/T transition objects, and T dwarfs using the Subaru telescope. The resulting spectra are examined in detail to study their dependence on spectral types. One question is where the methane feature appears: we suggest that it appears at L8 and marginally at L6.5. The water bands at 1.1 and 1.4 μm do not necessarily show steady increase toward later L types but may show inversion at late L types. This does not necessarily imply that the spectral types do not represent a temperature sequence, but rather can be interpreted as the increasing water abundance being offset by the heavier dust extinction in the later L types. We confirm that the FeH 0.99 μm bands appear not only in the late L dwarfs but also in the early T dwarfs. We suggest that FeH could be dredged up by the surface convective zone induced by the steep temperature gradient as a result of the large opacity of the dust cloud itself, and replenished constantly by convection. We have obtained bolometric luminosities of the objects with known parallaxes in our sample, first by integrating the spectra between 0.87 and 2.5 μm, and second by the K-band bolometric correction. Apart from an L3 dwarf, the bolometric luminosities obtained by both methods agree well, and this implies that the K-band bolometric correction, which is obtained using the unified cloudy models, can be applied to obtain the bolometric luminosities and effective temperatures of the L and T dwarfs with known parallaxes from the literature. The relation between the effective temperature and spectral type derived from the K-band bolometric correction shows monotonic behavior throughout the L–T sequence.

Subject headings: infrared: stars — stars: late-type — stars: low-mass, brown dwarfs

1. INTRODUCTION

The very coolest stars and the warmer brown dwarfs require a new spectral class, known as “L” (Martín et al. 1997; Kirkpatrick et al. 1999). The L dwarf sequence is characterized by the disappearance of the red TiO and VO bands from the optical (0.6–1.0 μm) spectrum, the increasing dominance at these wavelengths by broad absorption resonance lines of Na i and K i, and strong H₂O absorption bands and persistent CO overtone bands in the 1–2.5 μm region (Martin et al. 1999; Kirkpatrick et al. 1999, 2000; Leggett et al. 2000; Reid et al. 2001a). In terms of broadband colors, L dwarfs are characterized by very red infrared colors (e.g., J−K > 1.3). Even cooler brown dwarfs require the additional class, “T” (Kirkpatrick et al. 1999). In T dwarfs, the CO bands are replaced by stronger and more extensive absorptions of CH₄ in the H and K bands, and there is further strengthening of water bands (Oppenheimer et al. 1995; Geballe et al. 1996; Strauss et al. 1999; Burgasser et al. 1999). T dwarfs are characterized by blue infrared colors (e.g., J−K ≈ 0).

Spectral classification of L and T dwarfs, including L/T transition objects, has been made by Geballe et al. (2002) and Burgasser et al. (2002a). L dwarfs are now classified from L0 to L9 and T dwarfs from T0 to T8. The classification scheme is purely observational and uses indices in the 1–2.5 μm region related to H₂O, CO, CH₄, and near-infrared colors. We reexamine the spectral classification using the spectra obtained at Subaru. We pay special attention to the behavior of FeH and the features related to H₂O and CH₄.

Once the classification scheme is established, the next step is to find the correspondence between effective temperatures and spectral type and elucidate the physical meaning of the spectral classification. Some authors have derived relations between the effective temperatures and spectral type for L dwarfs (Leggett et al. 2002; Dahn et al. 2002) and for L and T dwarfs (Burgasser 2001); however, there has not been a study in which the relation was obtained from effective temperatures based on a bolometric correction derived from photospheric models that is applicable throughout the L–T sequence.

Some of the objects in our sample have known parallaxes. We obtain bolometric luminosities and effective temperatures for these objects by integrating the observed spectra between 0.87 and 2.5 μm and by the K-band bolometric correction using the unified cloudy models (UCMs; Tsuji 2002; Tsuji & Nakajima 2003). The comparison of the two methods implies that the K-band bolometric correction leads to reasonable effective temperatures, except for early L type. Encouraged by this analysis, we apply the K-band bolometric correction to the objects whose parallaxes are known from the literature.
The paper is organized as follows. In § 2, observations, data reduction, and the sample for the analysis are described. Spectral classification is discussed, and identification of spectral features is reexamined in § 3. We confirm the validity of the $K$-band bolometric correction derived by UCMs with the integrated fluxes as noted above. We then obtain bolometric luminosities of the objects with known parallaxes and the relation between the effective temperature and spectral type in § 4. A summary of the paper is given in § 5.

2. OBSERVED SPECTRA

2.1. Observations

Observations were made on 2002 June 3 UT at the Subaru telescope using imaging and grism modes of CISCO (Motohara et al. 2002). We obtained the spectra of six objects (Table 1), for four of which $JHK^\prime$ photometry was also obtained (Table 2). The six objects were selected to sample the L–T sequence widely from the objects in Geballe et al. (2002) and Burgasser et al. (2002a).

The sky was clear and the seeing was less than 0.5 arcsec through the night. CISCO employs the Mauna Kea Observatories Near-Infrared (MKO-NIR) filters (Simons & Tokunaga 2002; Tokunaga, Simons, & Vacca 2002). Photometric observations were made when the objects were near transit, and the air masses were less than 1.2. For photometric calibration, UKIRT faint standards (Hawarden et al. 2001) were used.

In the case of spectroscopy, the slit width of 0.5 arcsec was sampled at 0.105 pixel$^{-1}$, and the resolutions of $zJ$ (0.882–1.400 μm), $JH$ (1.056–1.816 μm), and wide-$K$ (1.850–2.512 μm) grisms were 550, 400, and 600, respectively. The targets were nodded along the slit and observations taken in “ABBA” sequence, where A and B stand for the first and second positions on the slit. Integration time is summarized in Table 1. SDSS 2249+00 was observed at the end of the night, and only a $JH$ spectrum was obtained for it. Spectra of a nearby F/G star were obtained before or after the observations of each object.

2.2. Data Reduction

For photometric data reduction, aperture photometry was made using the APPHOT package in IRAF. Photon statistics gave uncertainties much less than 0.05 mag. However, we estimated that air-mass differences between the targets and standards and the difference between the UKIRT and MKO-NIR systems introduced uncertainties of about 0.05 mag.

Spectral data were reduced using IRAF. The effect of the terrestrial atmosphere was removed by dividing by the spectra of nearby F/G stars after removing hydrogen recombination lines seen in their spectra. Spectral segments were individually flux-calibrated using the photometric data given in Table 2.

### Table 1

**Spectroscopy**

| Object                | Grism | Integration Time(s) | Reference Star |
|-----------------------|-------|---------------------|----------------|
| 2MASS 1217–03........... | $zJ$  | 200 × 4             | SAO 138672 (G0) |
|                       | JH    | 200 × 4             |                |
|                       | wK    | 200 × 4             |                |
| SDSS 1254–01........... | $zJ$  | 100 × 4             | SAO 139015 (G0) |
|                       | JH    | 50 × 4              |                |
|                       | wK    | 50 × 4              |                |
| 2MASS 1523+30.......... | $zJ$  | 200 × 4             | SAO 64641 (GO)  |
|                       | JH    | 100 × 4             |                |
|                       | wK    | 100 × 4             |                |
| 2MASS 1711+22.......... | $zJ$  | 400 × 4             | SAO 84938 (F8)  |
|                       | JH    | 100 × 8             |                |
|                       | wK    | 100 × 4             |                |
| SDSS 1750+17........... | $zJ$  | 200 × 4             | SAO 85439 (G0)  |
|                       | JH    | 100 × 8             |                |
|                       | wK    | 200 × 4             |                |
| SDSS 2249+00..........  | JH    | 200 × 4             | SAO 127766 (F8) |

### Table 2

**Photometry**

| Object    | R.A.   | Decl. | J   | H   | K'  | K   | Source |
|-----------|--------|-------|-----|-----|-----|-----|--------|
| 2MASS 1217–03........... | 12 17 11.9 | –03 11 13 | 15.41 | 15.96 | 15.62 | 1     |
| SDSS 1254–01........... | 12 54 53.9  | –01 22 47 | 14.54 | 14.03 | 13.82 | 1     |
| 2MASS 1523+30.......... | 15 23 22.6  | +30 14 56 | 15.93 | 15.04 | 14.44 | 1     |
| 2MASS 1711+22.......... | 17 11 45.7  | +22 32 04 | 16.57 | 15.86 | 15.20 | 1     |
| SDSS 1750+17........... | 17 50 33.0  | +17 59 04 | 16.14 | 15.94 | 16.02 | 2     |
| SDSS 2249+00..........  | 22 49 53.5  | +00 44 04 | 16.46 | 15.42 | 14.43 | 2     |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Photometric uncertainties are 0.05 mag.

**References.**—(1) This work. (2) Leggett et al. 2002.
Each segment and spectral data of Vega (Bergeron, Wesemael, & Beaulchamp 1995) were integrated over the appropriate filter profile. Vega was assumed to be zero magnitude at all wavelengths, and the target flux was scaled to match the broadband photometry.

2.3. Sample for Analysis

In addition to the six objects for which spectra were obtained in 2002 June, we added three objects whose spectra were obtained previously by the Infrared Camera and Spectograph (IRCS; Kobayashi et al. 2000) on Subaru, 2MASS 1146+22, 2MASS 0920+35, and 2MASS 1507−16 from a previously published paper (Nakajima, Tsuji, & Yanagisawa 2001), and GI229B from the literature (Geballe et al. 1996; Leggett et al. 2000; Geballe et al. 1996; Leggett et al. 1999; Nakajima et al. 1995; Burgasser et al. 1999).

| Object | Spectral Type | Source | Discovery |
|--------|---------------|--------|-----------|
| 2MASS 1146+22AB............. | L3 | 1 | 2 |
| 2MASS 1507−16............. | L5 | 1 | 3 |
| 2MASS 1711+22............. | L6.5 | 4 | 5 |
| 2MASS 0920+35............. | L6.5 | 1 | 3 |
| 2MASS 1523+30............. | L8 | 4 | 3 |
| SDSS 1254−01............. | T2* | 4 | 6 |
| SDSS 1505+17............. | T3* | 4 | 5 |
| GI 229B............. | T6* | 7, 8 | 9 |
| 2MASS 1217−03............. | T7.5 | 4 | 10 |

a Infrared classification by Geballe et al. 2002.
b Infrared classification by Burgasser et al. 2002a.

3. NEAR-INFRARED SPECTRA AND SPECTRAL CLASSIFICATION

We examine our spectra that cover a representative sample of L and T types in some detail. It turns out that some of the prominent spectral features remain unidentified, and the interpretation of the identified features is by no means clear yet. In this section, we apply the predicted spectral line intensities based on the UCMs discussed in a separate paper (Tsuji, Nakajima, & Yanagisawa 2004) as a guide to interpret the observed spectra.

3.1. The K-Band Region

The spectra of eight objects in the K-band region are shown on the log fν scale in Figure 1. The prominent features are CO first-overtone bands at 2.3 μm in L dwarfs and can be traced up to T2 or T3.5 dwarfs in our sample. The methane bands at 2.2 μm are quite strong in T dwarfs; one question is whether they are already seen in late L dwarfs. A very weak bandhead feature may be seen at 2.2 μm in the L6.5 dwarf 2MASS 0920+35, as already noted previously (Nakajima et al. 2001). The spectrum of another L6.5 dwarf 2MASS 1711+22 is a bit noisy, and it is difficult to identify the methane 2.2 μm bands. In L8 dwarf 2MASS 1523+30, the presence of the methane 2.2 μm bands was previously suggested by McLean et al. (2001). The signal-to-noise ratio (S/N) of our spectrum of 2MASS 1523+30 may be somewhat better than that of McLean et al., and the methane 2.2 μm bands can be clearly seen in Figure 1. Thus, the methane 2.2 μm bands can be detected as detected at L8. This better S/N is probably due to the lower spectral resolution and higher throughput of CISCO on Subaru than NIRSPEC on Keck.

3.2. The H-Band Region

In the H-band region, absorption features are clearly seen at 1.58, 1.59, 1.61, and 1.625 μm in L3 and L5 dwarfs, as shown by the filled triangles in Figure 2.

Of these features, those at 1.58, 1.613, and 1.627 μm were noted in L dwarfs by Reid et al. (2001a). On the other hand, the features at 1.583, 1.591, and 1.625 μm were identified as due to the FeH E′II−A′II system in the spectra of sunspot as well as M−L dwarfs by Wallace & Hinkle (2001), who also remarked that the feature at 1.611 μm had a confused appearance. More recently, the analysis of the FeH bands in M and L dwarfs has been extended by Cushing et al. (2003), who showed that the 1.625 μm feature is the strongest among the four features prominent in the H-band region. Thus, all four features (1.583, 1.591, 1.611, and 1.625 μm) in our spectra of L3−L5 dwarfs can be identified with FeH.

One question is whether the same identification can be applied to the L6.5 and L8 dwarfs in our sample. Another possibility is that the 1.63 as well as 1.67 μm feature in the L6.5 and L8 dwarfs are due to methane bands. We have already attributed these features to methane in the L6.5 dwarf 2MASS 0920+35 (Nakajima et al. 2001), but the possible presence of the FeH bands was not known at that time. The 1.63 μm feature can also be seen in all the L dwarfs, while the 1.67 μm feature is not clear in the L3−L5 dwarfs and appears first in L6.5. Also, the 1.583 and 1.591 μm features are rather weak in the L6.5 dwarfs. These observations may support the appearance of methane at L6.5, and it is at least possible that FeH and CH4 both contribute to the 1.63 and 1.67 μm features in L6.5 dwarfs. To settle this problem, higher resolution studies are needed. As for 2MASS 1523+30, the absence of the 1.61 μm feature suggests that the 1.63 μm feature may be due to CH4 rather than FeH. The methane features at 1.63 and 1.67 μm are clearly seen in the T2 dwarf and strengthen rapidly toward the later T dwarfs. Where methane bands appear is a critical issue in the spectral classification of brown dwarfs, since methane is a sensitive indicator of temperature. Although the methane bands depend on gravity as well as on temperature, the increased abundance of methane at the higher gravity is compensated for to some extent by the increased H2 CIA, which also increases with gravity (Tsuji et al. 2004).
We note that the $H$-band region is by no means a good continuum window but is contaminated by molecular bands of unknown origin in addition to FeH, especially in L dwarfs. Also, we note a large difference in the spectra of the same spectral type, namely, between the L dwarfs 2MASS 1507–16 and SDSS 2249+00: The $H$ band spectrum of 2MASS 1507–16 is rather flat, as are those of the other L dwarfs, while that of SDSS 2249+00 shows a prominent peaking centered at about 1.7 $\mu$m. The reason for this difference is unknown at present.

### 3.3. The Region between $J$ and $H$ Bands

In Figure 3, we show the region between the $J$ and $H$ bands. We note that water bands at 1.4 $\mu$m can be well measured in the five spectra observed by CISCO, despite the water bands in the Earth’s atmosphere. Unfortunately, only the edge of the 1.4 $\mu$m bands, arising in hotter environments of these cool dwarfs than the Earth’s atmosphere, can be measured in the three objects observed by IRCS. One interesting result is that the $H_2O$ 1.4 $\mu$m band does not appear stronger in the L8 dwarf 2MASS 1523+30 than in the L6.5 dwarfs 2MASS 1711+22 and 2MASS 0920+35. Furthermore, in the 1.1 $\mu$m bands of water, the absorption is clearly weaker in the L8 dwarf 2M1523 than in L6.5 dwarf 2M1711, as shown in Figure 4. The spectral types are based on Kirkpatrick et al. (2000), and those by Geballe et al. (2002) also show the similar types. This result is somewhat surprising, since the 1.1 and 1.4 $\mu$m water bands were used as classification criteria by Geballe et al. (2002). The water band strengths, however, do not necessarily increase linearly with the L types, and some water bands show little change in their strengths between L3 and L8 (Reid et al. 2001a; Testi et al. 2001).

Although there appears to be a plateau in the $T_{\text{eff}}$ scale between L6 and L8 (§ 4.2), we think that the spectral types basically correspond to a temperature sequence, since the present spectral types are determined by the several temperature-sensitive spectral features in the optical region on a purely

---

2 The depression of the edge near 1.32 $\mu$m is comparable between 2M1711 and 2M1523, but the overall depression between 1.31 and 1.60 $\mu$m may be slightly larger in 2M1711 than in 2M1523.
empirical basis (Kirkpatrick et al. 1999), and they are consistent mostly with the infrared spectral indices, including methane bands (Burgasser et al. 2002a; Geballe et al. 2002). Thus, it is possible that water bands are weaker in the cooler L dwarfs than in the warmer objects, while the methane feature at 2.2 μm is stronger in the L8 dwarf than in the L6.5 dwarfs, as shown in Figure 1. We interpret this result as follows. The water abundance should be larger in cooler objects, but extinction by dust clouds, still located in the optically thin region in L dwarfs, should be larger in cooler objects as well. Then the increasing water abundance and the increasing dust extinction may cancel out in L dwarfs. For this reason, water band strengths do not show a large increase in L dwarfs (Tsuji 2002), and it is no wonder that they show an inversion somewhere in L types. The methane feature at 2.2 μm does not necessarily suffer the same effect, either because the dust extinction is already less important in the 2.2 μm region than the 1.4 μm region, as can also be seen in the cloud models by Ackerman & Marley (2001), or else because of the more rapid increase of the methane band strength with the decreasing effective temperature than in the case of the water bands. We have confirmed these results by a detailed computation of the spectral line intensities based on the UCMs by considering the effect not only of $T_{\text{eff}}$ and $\log g$ but also of the change of the background opacities due to atoms, ions, dust grains, and quasi-continuous sources such as H$_2$ CIA (Tsuji et al. 2004).

Fig. 2.—$H$-band spectra. Spectra of eight objects are shown. Filled triangles are the bandheads of FeH, and open triangles are locations of CH$_4$. Note that the ordinate scales of the left and right panels differ by factor of 2.
3.4. The J-Band Region

The spectra between 0.95 and 1.3 μm are shown in Figure 4. First, we confirm that FeH $^4\Delta - ^4\Delta$ 0.99 μm bands can be clearly seen not only in L dwarfs but also in T dwarfs, as noted by Burgasser et al. (2002b). The 0.99 μm FeH bands gradually weaken from L6.5 to L8 and further to T2, but they strengthen again at T3.5. The weakening of the 0.99 μm FeH bands from L6.5 to L8 is consistent with the weakening of the 1.61 and 1.63 μm features in the same objects; this lends support for the contribution of FeH to these features. However, the observed strengths of FeH 0.99 μm bands, not only of T dwarfs but also of L dwarfs, are difficult to interpret directly by our UCMs, as well as by other models now available. In this connection, Burgasser et al. (2002b) suggested that the dust cloud breaks in the early T dwarfs and FeH formed deep in the photosphere can be seen through the holes of the cloud. The idea of a cloud-clearing model was motivated by the difficulty of the cloudy models by Marley et al. (2002) in explaining the observed color-magnitude diagram, but we have shown that the color-magnitude diagram can be accounted for by our UCM without introducing such a hypothesis as break-up of the cloud (Tsuji & Nakajima 2003).

As an alternative interpretation, we would like to call attention to the possible formation of the second convective zone near the surface of the late L and early T dwarfs. This second convective zone is predicted by the UCMs of $T_{\text{eff}} \approx 1200$–1600 K and is formed by the steep temperature gradient as a result of the large opacity of the dust cloud itself (Tsuji 2002). The lower boundary of this convective zone is facing the region free of dust, but FeH can be abundant there. Then these FeH molecules are dredged up by the convection to the upper cooler region, and some FeH molecules remain supersaturated until they are eventually transformed to the condensates. In fact, the second convective zone is rather thin, and some FeH molecules survive at the upper boundary of the convective zone. These FeH molecules are constantly replenished by the convection and can be observed so long as the second convective zone reaches the region to give observable effect. Such a possibility of vertical transport of FeH was also noted by Burgasser et al. (2002b), who remarked, however, that the fragility of the FeH bond (dissociation energy of only 1.67 eV) precludes such a possibility, even if such a vertical mixing accounts for the unexpectedly strong CO fundamental bands observed in the T dwarf Gl 229B (Noll, Geballe, & Marley 1997; Oppenheimer et al. 1998). Certainly, more detailed quantitative analysis will be required before we reach a definite conclusion.

The other prominent features are K $^1$ doublets at 1.1690/1.1773 and at 1.2432/1.2522 μm. The K $^1$ lines are rather strong in the early and middle L dwarfs, but they weaken in the late L dwarfs. After passing the minimum at L8, they are again...
reinforced in the early and middle T dwarfs until masked by the strong 1.1 μm water bands in the late T dwarfs. These results are quite consistent with those reported by Burgasser et al. (2002a). The diminishing $K_i$ lines toward later L dwarfs can be interpreted as due to the effect of extinction by dust, which is located in the optically thin photosphere in L dwarfs and shows the maximum at late L dwarfs. For this reason, $K_i$ lines show the minimum at late L as the water bands at 1.1 and 1.4 μm.

After the cloud is buried below the observable photosphere, $K_i$ lines strengthen again despite the unfavorable excitation at lower temperatures until being masked by rapidly strengthened water bands.

The feature near 1.14 μm is identified as due to the Na $i$ doublet 1.1404/1.138 μm with log $gf = -0.186/-0.487$ (Wiese, Smith, & Miles 1969). However, the observed feature near 1.14 μm shows asymmetry with the stronger absorption at the short wavelength side, contradicting the expectation from the $gf$-values. Thus, there should be some other contributions, such as of $H_2O$ and CH$_4$ to the 1.14 μm feature, which shows a pattern similar to that of the $K_i$ lines.

The 1.1 μm bands of water cannot be seen in the L5 dwarf, SDSS 2249+90, and this is unusually weak for L5, compared with the published results for other L5 dwarfs (e.g., Geballe et al. 2002; Reid et al. 2001a). The $K_i$ lines discussed above are also unusually weak for L5 in SDSS 2249+90. Remembering the unique spectrum around 1.7 μm as noted in § 3.2, this object may be peculiar for an L5 dwarf. The 1.1 μm bands of water are stronger in the L6.5 dwarf, 2MASS 1711+22, than in the L8 dwarf, 2MASS 1523+30, as already noted.

4. BOLOMETRIC LUMINOSITIES AND EFFECTIVE TEMPERATURES

Since the observed infrared spectrum covers the major part of the total flux, it can be a useful measure of the bolometric luminosity if combined with a parallax measurement. Since the number of objects with known parallaxes is modest in our sample, we also apply $K$-band bolometric correction (BC$_K$) to the photometric data of the objects with known parallaxes in the literature. We then estimate effective temperatures based on the bolometric luminosities and the radius that can be nearly constant at the Jupiter radius.

4.1. Objects with Known Parallaxes in Our Sample

A direct measurement of the bolometric flux is difficult for brown dwarfs at present. However, a large part of the luminosity is found in the near-infrared region we have observed, namely, between 0.87 and 2.5 μm. This is predicted using SEDs based on UCMs (Tsuji 2002), and the fraction of the integrated flux between 0.87 and 2.5 μm over the total flux is shown in Figure 5a. In Figure 5a, three curves are given for $log g = 4.5$, 5.0, and 5.5 ($T_{eff} = 1800$ K). Since they are not very different, we use the one for log $g = 5.0$. It turns out that the near-infrared flux is about 50% of the total flux at

Fig. 4.—$J$-band spectra. Spectra of nine objects are shown. Filled triangles indicate FeH (0.99 μm), $H_2O$ (0.925 and 1.1 μm), Na $i$ (1.14 μm), and $K_i$ (1.169/1.177 and 1.243/1.252 μm).
$T_{\text{eff}} \approx 700$ K, but nearly 70% at $T_{\text{eff}} \approx 2000$ K. The inversion around $T_{\text{eff}} \approx 1600$ K is due to the dust extinction, which is the largest around that temperature. We integrate our observed spectra of the objects with known parallaxes, which are flux-calibrated as noted in § 2, and then the bolometric fluxes are estimated by applying the ratio of the integrated infrared flux to the bolometric flux using the model prediction shown in Figure 5a. To obtain $T_{\text{eff}}$, we assume the range of the brown dwarf radius $R$ to be from $1.0R_J$ (relatively young object; Burrows et al. 1997). 2MASS 1146+22AB is assumed to be an equal binary composed of two L3 dwarfs, since the magnitude difference at $I$ is small (Reid et al. 2001b). The resulting bolometric luminosities and effective temperatures are given in Table 4.

An alternative approach to obtaining bolometric luminosities is to apply bolometric correction to the absolute magnitudes. The bolometric correction $BC_K$ for $K$-magnitude is given by

$$BC_K = M_{\text{bol}} - M_K,$$

and this $BC_K$ has been evaluated using UCMs in the CIT photometric system. The bolometric correction given as a function of $T_{\text{eff}}$ is shown in Figure 5b, where three curves for $\log g = 4.5$, 5.0, and 5.5 are drawn. Again the gravity dependence is weak, and we use the curve for $\log g = 5.0$. In order to estimate $T_{\text{eff}}$ of an object whose $M_K$ is given, the following iterative procedure is required. First, a tentative $T_{\text{eff}}$ is assumed and corresponding $BC_K$ is evaluated from Figure 5b. From $BC_K$, $M_{\text{bol}}$ is derived, and by assuming the radius of the object, $T_{\text{eff}}$ is obtained. The initial and resulting $T_{\text{eff}}$ are compared. If they agree with each other, the procedure is stopped.

![Figure 5](image_url)  
Fig. 5.—(a) Fraction of integrated flux between 0.87 and 2.5 $\mu$m over total flux given as a function of $T_{\text{eff}}$ estimated by the UCMs ($T_{\text{cr}} = 1800$ K). Three curves are drawn for $\log g = 4.5$ (dotted curve), 5.0 (solid curve), and 5.5 (dashed curve). The gravity dependence is weak, and we adopt the one for $\log g = 5.0$. (b) $K$-band bolometric correction given as a function of $T_{\text{eff}}$. Three curves are drawn for $\log g = 4.5$ (dotted curve), 5.0 (solid curve), and 5.5 (dashed curve). The gravity dependence is weak, and we adopt the one for $\log g = 5.0$.

### Table 4

| Object            | Spectral Type | $L_{\text{bol}}$(integrated flux) ($L_\odot$) | $T_{\text{eff}}$(integrated flux) (K) | $L_{\text{bol}}$ (BC$_K$) ($L_\odot$) | $T_{\text{eff}}$ (BC$_K$) (K) |
|-------------------|---------------|---------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------|
| 2MASS 1146+22A    | L3            | $6.06 \times 10^{-4}$                       | $1612$–$1748$                        | $1.73 \times 10^{-4}$                | $2098$–$2276$                   |
| 2MASS 1507–16     | L5            | $3.17 \times 10^{-5}$                       | $1371$–$1487$                        | $5.51 \times 10^{-5}$                | $1544$–$1675$                   |
| 2MASS 1523+30     | L8            | $2.46 \times 10^{-5}$                       | $1287$–$1395$                        | $3.63 \times 10^{-5}$                | $1418$–$1538$                   |
| SDSS 1254–01      | T2            | $2.20 \times 10^{-5}$                       | $1252$–$1358$                        | $2.46 \times 10^{-5}$                | $1286$–$1395$                   |
| SDSS 1254–01      | T2            | $2.96 \times 10^{-5}$                       | $1348$–$1462$                        | $2.91 \times 10^{-5}$                | $1342$–$1456$                   |
| GJ229B             | T6.5          | $6.02 \times 10^{-4}$                       | $905$–$981$                          | $6.67 \times 10^{-6}$                | $928$–$1007$                    |
| 2MASS 1217–03     | T7.5          | $5.50 \times 10^{-4}$                       | $885$–$960$                          | $5.22 \times 10^{-6}$                | $873$–$947$                     |

*a Parallax data from Dahn et al. 2002.

*b Parallax data from Tinney et al. 2003.
If they do not, the resulting $T_{\text{eff}}$ is used as the initial value and the procedure is repeated. Normally, $T_{\text{eff}}$ converges after a few iterations. Again we assume the range of the radius to be from 1.0$R_J$ to 0.85$R_J$. The bolometric luminosities and effective temperatures obtained this way are given in Table 4.

In Table 4, $L_{\text{bol}}$(integrated flux) and $L_{\text{bol}}$(BC$_K$) show reasonable agreement except for 2MASS 1146+22A for which the difference is by a factor of 2.9. As we find later, effective temperature estimates for early L dwarfs obtained by the $K$-band bolometric correction using UCMs tend to be higher than the estimates by other methods. The agreement of the two methods for objects with spectral types L5 and later is encouraging in that the $K$-band bolometric correction may be applied to all objects with known parallaxes to derive the relation between the effective temperature and spectral type for a larger sample.

4.2. $T_{\text{eff}}$ versus Spectral Type

Parallaxes and photometry of L and T dwarfs have been obtained, compiled, and published in the literature (Burgasser 2001; Dahn et al. 2002; Tinney et al. 2003, and references therein). Some authors have derived relations between $T_{\text{eff}}$ and spectral type for L dwarfs (Leggett et al. 2002; Dahn et al. 2002) and for L and T dwarfs (Burgasser 2001), but there has not been a work in which the relation that was obtained based on bolometric correction derived from photospheric models was applicable throughout the L–T sequence. In this subsection, we apply the bolometric correction derived at $K$ band from UCMs to obtain the relation between $T_{\text{eff}}$ and spectral type.

We use 39 parallax measurements of 36 objects from Burgasser (2001 and references therein), Dahn et al. (2002), and Tinney et al. (2003). For SDSS 1254–01 and SDSS 1624+00, different values of the parallaxes have been obtained by Dahn et al. and Tinney et al. For a binary, Tinney et al. (2003 and references therein) estimate the contribution to broadband photometry and spectral type of each component. We adopt the estimate of the $K$ magnitude and spectral type of the primary component from Tinney et al., but we do not include the secondary component. Since the spectral type of the secondary component was not determined by spectroscopy, but by the magnitude difference, it is not logical to use it to derive the relation between $T_{\text{eff}}$ and spectral type. 2MASS 0559–14 appears exceedingly overluminous, and the range of $T_{\text{eff}}$ is obtained also for the case of an equal binary (Burgasser 2001). Burgasser et al. (2003) obtained a Hubble Space Telescope image of this object and did not resolve it into a binary with a resolution of 0.5 AU. The resulting effective temperatures are given in Table 5.

The relation between $T_{\text{eff}}$ and the spectral type is plotted in Figure 6. Apart from the two overluminous objects, Kelu1 and Gl417B, $T_{\text{eff}}$ monotonically decreases toward later spectral types. Values of $T_{\text{eff}}$ appear too high for early L, but reasonable otherwise. This problem may have some bearing on the fact that a significant fraction of early L dwarfs are main-sequence stars. Another possibility is that the simplest assumption we adopted that the cloud properties do not change throughout the entire L–T sequence may not be valid.

4.3. Some Representative Objects

In this subsection, we discuss three representative objects in comparison with works by others.

Gl229B.—The first T dwarf, Gl229B (Nakajima et al. 1995), is also the most extensively observed brown dwarf so far. Matthews et al. (1996) used broadband photometry from 0.8 to 10.5 $\mu$m to derive the observed luminosity in the atmospheric windows, and a dust-free model (Tsuji et al. 1996) to derive the bolometric luminosity, $6.4 \times 10^{-6} L_\odot$. Assuming the radius of Gl229B to be $R_J$, they gave the best estimate of the effective temperature, $T_{\text{eff}} = 900$ K. Leggett et al. (1999) used $JHK$ spectra, $L$-band photometry, and a model (Allard et al. 2001) to estimate the bolometric luminosity, $6.6 \times 10^{-6} L_\odot$. From a comparison with the evolutionary model by Burrows et al. (1997), they also gave an estimate of $T_{\text{eff}} = 900$ K. In this paper, we obtained the luminosity $L_{\text{bol}}$(integrated flux) = $6.02 \times 10^{-6} L_\odot$ and the effective temperature, $T_{\text{eff}}$(integrated flux) = $905$ K for $R = R_J$. Since UCMs become indistinguishable from dust-free models for the late T dwarfs, this result is as expected, and $T_{\text{eff}}$ for the late T dwarfs are determined well.

SDSS 1254–01.—This is one of the first L/T transition objects discovered by Sloan Digital Sky Survey (Leggett et al. 2000). Determination of its effective temperature directly leads to that of the L/T transition temperature. Burgasser (2001) estimated the effective temperature of this object by linear interpolation of the relation between effective temperature and spectral type obtained empirically to be $T_{\text{eff}} = 1270 \pm 120$ K. Dahn et al. (2002) and Tinney et al. (2003) obtained significantly different values for the parallax, and we calculated $L_{\text{bol}}$(integrated flux) = $2.20 \times 10^{-5} L_\odot$ for the parallax measurement by Dahn et al. and $L_{\text{bol}}$(integrated flux) = $2.96 \times 10^{-5} L_\odot$ for that by Tinney et al. Corresponding effective temperatures are $T_{\text{eff}} = 1252$ K (parallax from Dahn et al. 2002) and $T_{\text{eff}} = 1348$ K (parallax from Tinney et al. 2003) for $R = R_J$. In a separate paper (Tsuji et al. 2004), we show that the observed spectrum of SDSS 1254–01 is fitted well by the UCM model spectrum for $T_{\text{eff}} = 1300$ K. The agreement of the $T_{\text{eff}}$ obtained by the different methods indicates that the L/T transition temperature is well constrained to about 1300 K.

2MASS 1523+30.—This is one of the latest L dwarfs discovered by Two Micron All Sky Survey (2MASS; Kirkpatrick et al. 2000) and is also known as Gl 584C Kirkpatrick et al. (2001), a companion to a G star. Kirkpatrick et al. (2000), Burgasser (2001), and Dahn et al. (2002) used empirical bolometric correction to estimate $T_{\text{eff}} \approx 1300$ K, $T_{\text{eff}} = 1240 \pm 80$ K, and $T_{\text{eff}} = 1376 \pm 58$ K, respectively. Leggett et al. (2002) obtained the bolometric luminosity of this object by using the integrated flux from the red to $K$, $L'$ photometry, and assuming a Rayleigh-Jeans curve longward of $L'$ to be $2.69 \times 10^{-5} L_\odot$. They used the evolutionary models of Chabrier et al. (2000) to estimate the range of effective temperature, $T_{\text{eff}} = 1250$–1500 K. We obtained the bolometric luminosity, $2.46 \times 10^{-5} L_\odot$, which is consistent with the one by Leggett et al. (2002). We gave the range of effective temperature to be $T_{\text{eff}} = 1252$–1358 K. So $T_{\text{eff}}$ of this object is not significantly different from that of SDSS 1254–01. From an analysis of effective temperatures obtained by empirical bolometric correction, Burgasser (2001) noted that there is essentially no change in effective temperatures between types L8 V and T5 V. Here we confirm his observation for the range between L8 and T2. The relation between the effective temperature and spectral type derived by the $K$-band bolometric correction obtained above further indicates that
effective temperatures do not change significantly between L7 and T5.

4.4. $T_{\text{eff}}$—Spectral Type Relations Obtained by Others

Stephens et al. (2001) obtained the trends observed in the $(K-L^*)$ and $(K-L)$ colors as a function of L and T dwarf spectral classes. They compared these colors with theoretical models (Marley et al. 2002) and derived a relationship between $T_{\text{eff}}$ and the L spectral class:

$$T_{\text{eff}} = 2200 - 100 L_K,$$

where $L_K$ is the spectral class from Kirkpatrick et al. (1999), which ranges from 0 to 8. They noted that the equation was presented for its heuristic value as an indicator of the $T_{\text{eff}}$ range of L dwarfs and not as a definite analysis. In the narrow range between L3 and L8, this linear relation appears consistent with the relation we obtained in the previous section.

Leggett et al. (2002) determined the luminosities of 2M0036+18 (L4), 2M0825+21 (L6), 2M1523 (L8), and 2M1632+19 (L7.5), by summing their energy distributions from the red to the $K$ band, interpolating the flux between the $K$ band and the effective $L'$ flux computed from their photometry, and assuming Rayleigh-Jeans curves longward of $L'$. A correction to this simple approach was determined for Gl 229B by Leggett et al. (1999) using model atmospheres. Leggett et al. (1999) also used models to show that no correction is needed for dwarfs as late as mid-L type. Leggett et al. (2002) adopted a correction for the 2MASS L7.5 and L8 dwarfs that is half that computed for Gl 229B. They compiled the bolometric luminosities of 18 dwarfs and used the models of Chabrier et al. (2000) to compute $T_{\text{eff}}$ for the L dwarfs, for which they obtained the bolometric luminosities. Their compilation of $T_{\text{eff}}$ for L dwarfs is consistent with the
Fig. 6.—Effective temperature vs. spectral type. The higher and lower estimates of $T_{\text{eff}}$ obtained by the $K$-band bolometric correction are plotted as a function of spectral type.

our result between L3 and L8 within given error estimates. For early L dwarfs, our temperature estimates are somewhat higher. Their sample does not include early T dwarfs; however, they estimated that the effective temperature range for the L dwarfs in their sample was approximately 2200–1300 K and for the T dwarfs 1300–800 K. Their estimate of the L/T transition temperature, 1300 K, is in agreement with our result.

Dahn et al. (2002) and Burgasser (2001) used the empirical bolometric corrections of Leggett et al. (2002) and Reid et al. (2001a) to derive $T_{\text{eff}}$, and Burgasser (2001) obtained $T_{\text{eff}}$ for T dwarfs by linear approximation. The values of $T_{\text{eff}}$ of L dwarfs obtained by Dahn et al. (2002) are mostly consistent with our estimates. Burgasser (2001) linearly fitted the compiled data of L dwarfs to obtain the relation

$$T_{\text{eff}} = (2380 \pm 40) - (138 \pm 8) \text{SpT},$$

where SpT ranges from L0 to L8. This relation shows somewhat better agreement with our data than that of Stephens et al. (2001) between L0 and L8.

Burgasser et al. (2002b) adopt a completely different approach in estimating the effective temperatures of L/T transition objects. They think that a cloudy model alone cannot explain the L/T transition process because of the failure of the cloudy model by Marley et al. (2002) to reproduce the color-magnitude diagram. In their cloud-clearing model, they assume that the location of the L/T transition object in the color-magnitude diagram is determined by the fraction of the clear region on the surface of the brown dwarf, and this is compared with the predicted color-magnitude using the mixture of the cloudy model and the cloud-free model. Their estimate of the L/T transition temperature is 1200 K, which is about 100 K cooler than ours. Here we briefly examine the cloud-clearing model. First, one underlying assumption is that the model by Marley et al. (2002) is correct as a cloudy model, about which we have some doubt. UCMs (Tsuji & Nakajima 2003) reproduced the basic features of the color-magnitude diagram of L and T dwarfs, although the basic assumptions regarding the clouds are simpler. Second, the cloud-clearing model has not passed the test of comparing the spectra of L/T transition objects with model spectra. Third, Enoch, Brown, & Burgasser (2003) observed variabilities of L and T dwarfs and did not find significant correlations between variability amplitude and spectral type or $J-K$ color. This result does not support the cloud-clearing model positively. Burgasser et al. (2002b) claim that the plateau of the effective temperature near the L/T transition, which we also see in Figure 6, is naturally explained by the cloud-clearing model, but there is a 100 K difference in the transition temperature.

In summary, UCM estimates of L dwarf temperatures are consistent with others, except for early L, for which the UCMs give somewhat higher temperatures. The estimate of the L/T transition temperature, 1300 K, is in agreement with that of Leggett et al. (2002) but somewhat higher than that of Burgasser et al. (2002b).

5. SUMMARY AND CONCLUDING REMARKS

We have obtained near-infrared spectra of L dwarfs, L/T transition objects, and T dwarfs using the Subaru telescope. The resulting spectra are examined in detail to study their dependence on the spectral types. As for methane, we have found that it appears at L8 and marginally at L6.5. The water bands at 1.1 and 1.4 $\mu$m do not necessarily show steady increase toward later L types but may show inversion at late L types. This does not necessarily imply that the spectral types do not represent a temperature sequence but can be interpreted as being due to the increasing water abundance being offset by the dust extinction in the later L types. We confirm that the FeH 0.99 $\mu$m bands appear not only in late L dwarfs but also in the early T dwarfs, as was first noted by Burgasser et al. (2002b). We suggest that FeH could be dredged up by the surface convective zone induced by the steep temperature gradient as a result of the large opacity of the dust cloud itself and will be replenished constantly by the convection.

We have obtained bolometric luminosities of the objects with known parallaxes in our sample by integrating the spectra between 0.87 and 2.5 $\mu$m and by the $K$-band bolometric correction. Apart from the L3 dwarf, 2MASS 1146+22A, the bolometric luminosities obtained by the two methods agree well, and this implies that the $K$-band bolometric correction obtained by UCMs can be used to obtain the bolometric luminosities and effective temperatures of the L and T dwarfs with known parallaxes from the literature. The relation between the effective temperature and spectral type derived from the $K$-band bolometric correction shows monotonic behavior throughout the L-T sequence.

There is another method for estimating the effective temperature of a brown dwarf, which is to compare the observed spectrum and model spectra. Such an analysis is also vital as a test of model photospheres. For these purposes, we analyze the observed spectra discussed in this paper with the model spectra obtained by an extended grid of UCMs in the separate paper (Tsuji et al. 2004).

We thank the support astronomer K. Aoki and the staff of the Subaru Observatory for excellent support of the observations. We also thank the referee, A. Burgasser, for his careful reading of the manuscript. This work was supported by the grants-in-aid of JSPS grants 14520232 (T. N.) and 11640227 (T. T.).
REFERENCES

Ackerman, A. S., & Marley, M. S. 2001, ApJ, 556, 872
Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A., 2001, ApJ, 556, 357
Burgasser, A. J. 2001, Ph.D. thesis, Caltech
Burgasser, A. J., et al. 1999, ApJ, 522, L65
—. 2002a, ApJ, 564, 421
—. 2002b, ApJ, 571, L151
—. 2003, ApJ, 586, 512
Burrows, A., et al. 1997, ApJ, 491, 856
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, ApJ, 542, 464
Cushing, M. C., Rayner, J. T., Davis, S. P., & Vacca, W. D. 2003, ApJ, 582, 1066
Dahn, C. C., et al. 2002, AJ, 124, 1170
Enoch, M. L., Brown, M. E., & Burgasser, A. J. 2003, AJ, 126, 1006
Geballe, T. R., Kulkarni, S. R., Woodward, C. E., & Sloan, G. C. 1996, ApJ, 467, L101
Geballe, T. R., Saumon, D., Leggett, S. K., Knapp, G. R., Marley, M. S., & Lodders, K. 2001, ApJ, 556, 373
Geballe, T. R., et al. 2002, ApJ, 564, 466
Gizis, J. E., Kirkpatrick, J. D., & Wilson, J. C. 2001, AJ, 121, 2185
Hawarden, T. G., Leggett, S. K., Letawski, M. B., Ballantyne, D. R., & Casali, M. M. 2001, MNRAS, 325, 563
Kirkpatrick, J. D., Dahn, C. C., Monet, D. G., Reid, I. N., Gizis, J. E., Liebert, J., & Burgasser, A. J., 2001, AJ, 121, 3235
Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802
—. 2000, AJ, 120, 447
Kobayashi, N., et al. 2000, Proc. SPIE, 4008, 1056
Leggett, S. K., Toomey, D. W., Geballe, T. R., & Brown, R. 1999, ApJ, 517, L139
Leggett, S. K., et al. 2000, ApJ, 536, L35
—. 2002, ApJ, 564, 452
Marley, M. S., Seager, S., Saumon, D., Lodders, K., Ackerman, A. S., Freedman, R. S., & Fan, X. 2002, ApJ, 568, 335
Martin, E. L., Barst, G., Delfosse, X., & Forveille, T. 1997, A&A, 327, L29
Martin, E. L., Delfosse, X., Barst, G., Goldman, B., Forveille, T., & Zapatero-Osorio, M. R. 1999, AJ, 118, 2466
Matthews, K., Nakajima, T., Kulkarni, S. R., & Oppenheimer, B. R. 1996, AJ, 112, 1678
McLean, I. S., Prato, L., Kim, S. S., Wilcox, M. K., Kirkpatrick, J. D., & Burgasser, A. 2001, ApJ, 561, L115
Motohara, K., et al. 2002, PASJ, 54, 315
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Nakajima, T., Tsuji, T., & Yanagisawa, K. 2001, ApJ, 561, L119
Noll, K. S., Geballe, T. R., & Marley, M. S. 1997, ApJ, 489, L87
Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & Nakajima, T. 1995, Science, 270, 1478
Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & van Kerkwijk, M. H. 1998, ApJ, 502, 332
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Reid, I. N., Burgasser, A. J., Cruz, K. L., Kirkpatrick, J. D., & Gizis, J. E. 2001a, AJ, 121, 1710
Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001b, AJ, 121, 489
Simons, D. A., & Tokunaga, A. 2002, PASP, 114, 169
Stephens, D. C., Marley, M. S., Noll, K. S., & Chanover, N. 2001, ApJ, 556, L97
Strauss, M. A., et al. 1999, ApJ, 522, L61
Testi, L., et al. 2001, ApJ, 552, L147
Tinney, C. G., Burgasser, A. J., & Kirkpatrick, J. D. 2003, AJ, 126, 975
Tokunaga, A. T., Simons, D. A., & Vacca, W. D. 2002, PASP, 114, 180
Tsuji, T. 2002, ApJ, 575, 264
Tsuji, T., & Nakajima, T. 2003, ApJ, 585, L151
Tsuji, T., Nakajima, T., & Yanagisawa, K. 2004, ApJ, 607, 511
Tsuji, T., Ohnaka, K., Aoki, W., & Nakajima, T. 1996, A&A, 308, L29
van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The General Catalog of Trigonometric Stellar Parallaxes (4th ed.; New Haven: Yale Univ. Obs.)
Wallace, L., & Hinkley, K. 2001, ApJ, 559, 424
Wiese, W. L., Smith, M. W., & Miles, B. M. 1969, Atomic Transition Probabilities, Vol. 2: Sodium through Calcium. A Critical Data Compilation (Washington, DC: DOC)
Wilson, J. C., Kirkpatrick, J. D., Gizis, J. E., Skrutskie, M. F., Monet, D. G., & Houck, J. R. 2001, AJ, 122, 1989