AKARI OBSERVATIONS OF BROWN DWARFS. I. CO AND CO2 BANDS IN THE NEAR-INFRARED SPECTRA

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ABSTRACT

Near-infrared medium-resolution spectra of seven bright brown dwarfs are presented. The spectra were obtained with the Infrared Camera on board the infrared astronomical satellite AKARI, covering 2.5–5.0 μm with a spectral resolution of approximately 120. The spectral types of the objects range from L5 to T8 and enable us to study the spectral evolution of brown dwarfs. The observed spectra are in general consistent with predictions from previous observations and photospheric models; spectra of L-type dwarfs are characterized by continuum opacity from dust clouds in the photosphere, while very strong molecular absorption bands dominate the spectra in T-type dwarfs. We find that the CO fundamental band around 4.6 μm is clearly seen even in the T8 dwarf 2MASS J041519−0935, confirming the presence of a non-equilibrium chemical state in the atmosphere. We also identify the CO2 fundamental stretching-mode band at 4.2 μm for the first time in the spectra of late-L- and T-type brown dwarfs. As a preliminary step towards interpretation of the data obtained by AKARI, we analyze the observed spectra by comparing with those predicted by the unified cloudy model (UCM). Although overall spectral energy distributions can be reasonably fitted with the UCM, observed CO and CO2 bands in late-L and T dwarfs are unexpectedly stronger than the model predictions assuming local thermodynamical equilibrium. We examine the vertical mixing model and find that this model explains the CO band at least partly in the T dwarfs 2MASS J041519−0935 and 2MASS J055919−1404. The CO fundamental band also shows excess absorption against the predicted one in the L9 dwarf SDSS J083008+4828. Since CO is already highly abundant in the upper photospheres of late-L dwarfs, the extra CO due to vertical mixing has little effect on the CO band strengths, and the vertical mixing model cannot be applied to this L dwarf. A more serious problem is that the significant enhancement of the CO2 4.2 μm band in both the late-L and T dwarfs cannot be explained at all by the vertical mixing model. The cause of this enhancement of the CO2 band remains to be explained.

Key words: brown dwarfs – molecular processes – stars: atmospheres – stars: late-type – stars: low-mass

1. INTRODUCTION

Brown dwarfs are defined as objects that were born as isolated objects but were not massive enough to ignite hydrogen nuclear burning (Burrows et al. 2001). They are particularly of interest for their extremely low temperature atmospheres in relation to giant planets. Observational studies of brown dwarfs have been extensively carried out since the first definitive identification of a genuine brown dwarf Gl 229B (of the class now known as T dwarfs) by Nakajima et al. (1995). The first L-type brown dwarf GD 165B was reported by Becklin & Zuckerman (1988) although it was debated for some time whether it was a star or a brown dwarf. This very red object is important in that the presence of a dust layer in the photosphere was inferred, while very strong molecular absorption bands dominate the spectra in T-type dwarfs. This very red object is important in that the presence of a dust layer in the photosphere was inferred, while very strong molecular absorption bands dominate the spectra in T-type dwarfs. As a preliminary step towards interpretation of the data obtained by AKARI, we analyze the observed spectra by comparing with those predicted by the unified cloudy model (UCM). Although overall spectral energy distributions can be reasonably fitted with the UCM, observed CO and CO2 bands in late-L and T dwarfs are unexpectedly stronger than the model predictions assuming local thermodynamical equilibrium. We examine the vertical mixing model and find that this model explains the CO band at least partly in the T dwarfs 2MASS J041519−0935 and 2MASS J055919−1404. The CO fundamental band also shows excess absorption against the predicted one in the L9 dwarf SDSS J083008+4828. Since CO is already highly abundant in the upper photospheres of late-L dwarfs, the extra CO due to vertical mixing has little effect on the CO band strengths, and the vertical mixing model cannot be applied to this L dwarf. A more serious problem is that the significant enhancement of the CO2 4.2 μm band in both the late-L and T dwarfs cannot be explained at all by the vertical mixing model. The cause of this enhancement of the CO2 band remains to be explained.

Carbon monoxide (CO) plays a decisive role in determining the major characteristics of cool stars because of its very large dissociation energy (Russell 1934). In brown dwarfs, the CO first overtone band at 2.3 μm is observed until early-T-type sources (see, e.g., Geballe et al. 2002 and Burgasser et al. 2006b). The role of CO, however, changes in very cool dwarfs: carbon resides mostly in CH4 rather than in CO in a very cool (e.g., T ≈ 1000 K) and high-density (e.g., log Pg ≈ 6.0) environment (Tsuji 1964), and CO no longer plays any critical role under such circumstances. Although no celestial object outside our solar system having this physical condition was previously known, it was found that such a case is actually realized in the brown dwarf Gl 229B showing strong CH4 bands (Oppenheimer et al. 1995). However, nature is not so straightforward as predicted by a simple theory of thermochemistry. In fact, it was not long before an unexpected detection of the CO fundamental band at 4.6 μm in Gl 229B, classified as T6, was reported by Noll et al. (1997) and Oppenheimer et al. (1998). These pioneering observations highlighted the roles of non-equilibrium chemical processes. The idea of vertical mixing was suggested by Griffith & Yelle (1999) and Saumon et al. (2000). Because of the extreme stability of CO, the chemical timescale is much longer than the mixing timescale and CO is dredged up by vertical mixing from the inner part of the atmosphere, where CO is still abundant, to the surface layers, where CH4 dominates instead of CO. Recently two more late-T dwarfs were found to show the CO band by Geballe et al. (2009), confirming that the presence of CO is a general characteristic of late-T dwarfs.

It is to be remembered that the observations so far are limited to late-T dwarfs. Observations of the CO fundamental band in early-T- and L-type dwarfs are needed for a unified understanding of the physical and chemical processes related to CO in the atmospheres of brown dwarfs. Spectroscopic observations of the CH4 and of the CO transitions in L and M bands are always difficult from the ground. Severe atmospheric absorption and limited wavelength coverage make precise analysis difficult. Thus, there is a strong motivation to carry out near-infrared spectroscopy of brown dwarfs from space, especially
in the region of 2.5–5.0 μm which remains the least explored so far.

The infrared astronomical satellite AKARI (Murakami et al. 2007) was launched in 2006 February. Scientific observations under cryogenic condition were carried out from 2006 May to 2007 August and ended with the liquid helium boil-off. The satellite is equipped with a 68.5 cm cooled telescope and two scientific instruments covering the wavelength range of 1.8–180 μm. One of them, the Infrared Camera (IRC; Onaka et al. 2007) carried out imaging and spectroscopic observations in the near- to mid-infrared wavelength regions. The IRC provided a unique opportunity to take spectra of brown dwarfs in the range between 2.5 and 5.0 μm without interference of telluric absorption from the atmosphere. In the framework of the AKARI Mission Programme (coordinated observations by the project team members), we have carried out a series of near-infrared spectroscopic observations of ultracool dwarfs. This programme, NIRLT (PI: I.Yamamura), aims to obtain a set of legacy data for studies of the evolution of physical and chemical structure of L and T dwarfs. In this paper, we present the initial results from this programme.

As a basis of interpretation of the spectra observed with AKARI, we determine basic physical parameters of six well-observed objects. For this purpose, we apply model photospheres as in the analyses of ordinary stars. However, the model photospheres of ultracool dwarfs including brown dwarfs are by no means well established. It has been discussed that dust grains in the atmosphere play an important role in the formation of spectra of ultracool dwarfs: in particular, spectra of L-type dwarfs (T_{eff} = 2200–1400 K) are strongly influenced by the continuous opacity of dust, while spectra of even cooler T-type dwarfs are dominated by deep molecular absorption bands (Tsuji et al. 1996). In particular, we have no definite guideline for treating dust formation in the photosphere. Some attempts to model the photospheres of brown dwarfs with dust clouds have been carried out by several groups and these are discussed in detail by Helling et al. (2008). It was shown that all models agree on the global structure of the dusty photospheres, but predicted features such as the emergent spectra differ considerably, depending on the opacity data and reflecting the extreme complexity of such objects.

We apply the unified cloudy model (UCM; Tsuji 2002, 2005) as an example of such dusty model photospheres to the analysis of our objects. We assume solar metallicity throughout, and estimate T_{eff}, T_{cr} (critical temperature that defines the upper boundary of the dust cloud; see Section 4.1 for details), and log g from the relative spectral energy distributions (SEDs, i.e., shapes of the spectra). We then fit the observed and predicted spectra on an absolute scale and estimate the radii of individual objects with the use of known parallaxes. Based on the final fits of the model spectra to the observed ones, we try to interpret the new features in the spectral region between 2.5 and 5.0 μm observed with AKARI for the first time.

2. OBSERVATIONS AND DATA REDUCTION

The AKARI/IRC covered its wavelength range with three independent cameras operated simultaneously, namely the NIR (near-infrared), MIR-S (mid-infrared short), and MIR-L (mid-infrared long) channels. Our observations were all carried out in the Astronomical Observation Template (AOT) IRC04 with parameters of “b:Np” (Lorente et al. 2008). In this mode a grism was used to achieve the highest available spectral resolution; the dispersion was 0.0097 μm pixel^{-1} or \( R = \lambda / \Delta \lambda = 120 \) at 3.6 μm (Ohyama et al. 2007). Targets were placed in the 1° × 1° point source aperture mask to minimize the contamination from nearby stars and background sky. The aperture mask was only available for the NIR channel, and the spectra obtained in this programme were limited to the near-infrared wavelength range of 2.5–5.0 μm.

Our target list consisted of 30 brown dwarfs selected by their expected fluxes (to be bright enough for the AKARI/IRC instrument to provide high-quality spectra within a reasonable number of pointings) and their spectral types (to sample various types from L to T). A pointed observation by AKARI allowed about 10 minutes of exposure. At least two observations were requested per target to obtain data redundancy. Due to the severe visibility constraint of the satellite, not all requested observations were carried out. There were 18 pointing opportunities for 11 objects in the cryogenic mission phase. A summary of the observed targets is given in Table 1, and the observation record is presented in Table 2. The tables include targets and observations which were not successful, for completeness.

The standard software toolkit IRCSPEC_RED (Ohyama et al. 2007) was used for the data reduction. The processing was

Table 1

| Object Name | R.A. (J2000) | Decl. (J2000) | Sp. Type | J   | H   | K   | L'   | Ref. |
|-------------|-------------|--------------|----------|-----|-----|-----|------|------|
| 2MASS J04151954−0935066 | 04:15:19.54 | −09:35:06.6 | T8     | 15.32 | 15.70 | 15.83 | 13.28 | 1,3 |
| SDSS J053951.99−005902.0 | 05:39:52.00 | −00:59:01.9 | L5     | 13.85 | 13.04 | 12.40 | 11.32 | 1,3 |
| 2MASS J05591914−1404488 | 05:59:19.14 | −14:04:48.8 | T4.5   | 13.57 | 13.64 | 13.73 | 12.14 | 1,3 |
| 2MASS J083008.12+482847.4 | 08:30:08.25 | +48:28:48.2 | T1.9   | 15.22 | 14.40 | 13.68 | 11.98 | 1,3 |
| 2MASS J11217110−0311314 | 12:17:11.10 | −03:11:13.1 | T7.5   | 15.56 | 15.98 | 15.92 | 13.96 | 1,3 |
| GD 165B | 14:24:39.09 | +09:17:10.4 | L3     | 15.64 | 14.75 | 14.09 | 12.93 | 1,3 |
| SDSS J144600.60+002452.0 | 14:46:00.61 | +00:24:51.9 | L5     | 15.56 | 14.59 | 13.80 | 12.54B | 1,3 |
| 2MASS J15232263+3014562 | 15:23:22.63 | +30:14:56.2 | L8     | 15.95 | 15.05 | 14.35 | 12.86 | 1,3 |
| 2MASS J17114573+2232044 | 17:11:45.73 | +22:32:04.4 | L6.5   | 17.09 | 15.80 | 14.73 | N/A | 2   |
| SDSS J175032.96+175903.9 | 17:50:32.96 | +17:59:03.9 | T3.5   | 16.14 | 15.94 | 16.02 | 14.95b | 1,4 |
| e Ind Ba+Bb | 22:04:10.52 | −56:46:57.7 | T1+T6 | 11.91 | 11.31 | 11.21 | 9.97b | 1,4 |

Notes.
- a Estimated magnitude.
- b Spitzer/IRAC 3.5 μm band magnitude.

References. J, H, K: (1) Knapp et al. 2004; (2) 2MASS Point Source Catalog; (3) Golimowski et al. 2004; (4) Patten et al. 2006; (5) Leggett et al. 2002.
performed in 2008 January with the pre-released version of the toolkit, which should be equivalent to the public version “20080528.” We followed the standard reduction recipe. Fine tuning of the on-source/off-source mask on the spectral images was adopted to obtain the maximum signal and minimum contamination. Corrections of instrumental effects and wavelength calibration were all done automatically in the toolkit, and we did not observe any calibration sources by ourselves. Since our observations were in principle slitless spectroscopy, the major source of wavelength error was the determination of the reference point. The typical error was 0.5 pixel of the detector or ∼0.005 μm (Ohyama et al. 2007), but could be larger on some occasions. We applied a small correction (−0.008 μm) to 2MASS J152322+3014 by comparing the position of the CH4 Q-branch feature with other objects and with the synthesized spectrum. The overall flux calibration error was 10% in the middle of the wavelength range and 20% at the short/long edges. See Ohyama et al. (2007) for more details about data reduction and calibration.

3. NEAR-INFRARED SPECTRA OF BROWN DWARFS

Figure 1 shows the observed AKARI spectra of brown dwarfs in the sequence of their spectral types from L (bottom) to T (top). When an object was observed twice, the two data sets were processed independently and are plotted in different colors. In general, the two spectra are consistent with each other, demonstrating the high quality and reliability of the data.

The overall SEDs of the observed spectra agree well with the predictions from the previous photometry and theoretical works. The spectra of L-type dwarfs are rather smooth and featureless, gently peaking at 3.8 μm as a result of broad absorption bands of H2O at shorter wavelengths and CO at longer wavelengths. On the other hand, spectra of T-type dwarfs are dominated by deep molecular absorption features. As expected, we detect CH4 and H2O molecular bands. The bands deepen as the spectral type evolves. The band shapes are heavily distorted due to saturation in the latest object, 2MASS J041519−0935 (T8).

The most remarkable finding in the current AKARI spectra is a detection of the CO2 fundamental stretching-mode band at 4.2 μm in the late-L and T-type dwarfs. The identification of this band is demonstrated in Figure 2, in which the spectrum of 2MASS J055919−1404 is compared with synthesized spectra of CO2. Spectra of CO and PH3 are also presented for reference. The shape of the band profile, especially a sharp edge around 4.2 μm, confirms the identification of the feature as CO2.

This is the first detection of CO2 in brown dwarfs, since the wavelength is inaccessible from the ground or even from airborne observations due to huge opacity of the molecule itself in the telluric atmosphere. The band is most apparent in the L9 dwarf SDSS J083008+4828 and very marginally in the L8 dwarf 2MASS J152322+3014. We suspect that the formation of the molecule takes place in a relatively low temperature environment.

Another important result from our observations is that we see the CO fundamental band in the 4.4−5.0 μm region in all of our samples including the coolest T8 dwarf, 2MASS J041519−0935, but could be larger on some occasions. We applied a small correction (−0.008 μm) to 2MASS J152322+3014 by comparing the position of the CH4 Q-branch feature with other objects and with the synthesized spectrum. The overall flux calibration error was 10% in the middle of the wavelength range and 20% at the short/long edges. See Ohyama et al. (2007) for more details about data reduction and calibration.

Table 2

| Object Name       | Date       | ObsID:   | Remarks         |
|-------------------|------------|----------|-----------------|
| 2MASS J041519−0935 | 2007 Feb 18| 1720005-001| Ghosting        |
| 2MASS J041519−0935 | 2007 Feb 18| 1720005-002| Ghosting        |
| 2MASS J041519−0935 | 2007 Aug 23| 5125081-001| Re-observation  |
| 2MASS J041519−0935 | 2007 Aug 24| 5125081-001| Re-observation  |
| SDSS J053951−0059  | 2006 Sep 17| 1720009-001|                |
| 2MASS J055919−1404 | 2006 Sep 22| 1720006-001|                |
| 2MASS J055919−1404 | 2006 Sep 22| 1720008-001|                |
| SDSS J083008+4828  | 2006 Oct 20| 1720007-001|                |
| SDSS J083008+4828  | 2006 Oct 21| 1720007-002|                |
| 2MASS J121711−0311 | 2007 Jun 26| 1720068-001| Too faint       |
| GD165B            | 2007 Jul 24| 1720074-001| Data lost       |
| SDSS J144600+0024  | 2007 Aug 2 | 1720072-001|                |
| ϵ Ind Ba+Bb       | 2006 Nov 2 | 1720003-001|                |
| ϵ Ind Ba+Bb       | 2006 Nov 2 | 1720004-001|                |
| 2MASS J152322+3014 | 2007 Jan 26| 1720002-001|                |
| 2MASS J171145+2322 | 2007 Mar 5 | 1720001-001| Too faint       |
| SDSS J175032+1759 | 2007 Mar 17| 1720050-001| Confusion       |
| SDSS J175032+1759 | 2007 Mar 17| 1720050-002| Confusion       |

Figure 1. NIR spectra of brown dwarfs obtained by the AKARI/IRC. The spectra are ordered in the sequence of their spectral types from bottom (L5) to top (T8). When two observations were made for an object, the data were processed independently and the second spectrum is indicated in blue. The difference between the two observations represents the practical errors. Positions of major molecular bands are indicated.
J041519−0935. The detection of the CO molecule in a late-T dwarf was first reported by Noll et al. (1997) and Oppenheimer et al. (1998) in the T6 dwarf Gl 229B. Two more objects have been added recently by Geballe et al. (2009); 2MASS J09373487+2931409 (T6) and Gl 570D (T7.5). The presence of CO band is also suggested from the Spitzer 3.5–7.9 μm photometry (Patten et al. 2006; Leggett et al. 2007). Our AKARI spectra provide direct and indubitable evidence of the molecule and strongly support the idea that the presence of the CO band is a common feature in the late-T dwarfs.

We also detect the CH4 molecule in SDSS J053951−0059 (L5), confirming the previous report by Noll et al. (2000) that the molecule is already present in the atmosphere of L5 dwarfs. The feature is not clear in another L5 source SDSS J144600+0024, partly because of its relatively low signal-to-noise ratio (S/N). The band develops in the L8 dwarf, 2MASS J152322+3014, and starts showing the P- and R-branches.

Because of moderate spectral resolution it is difficult to identify any more molecules in the spectra.

3.1. Comments on Individual Objects

3.1.1. SDSS J053951−0059

Fan et al. (2000) selected this object as a high-z quasar candidate from the SDSS commissioning image and found it to be an L5 dwarf through follow-up spectroscopy. Due to its relatively high flux level (~8 mJy at 3.8 μm) the quality of the obtained spectrum is good. We can clearly recognize the presence of CH4 Q-branch absorption at 3.3 μm on the otherwise rather smooth spectrum.

3.1.2. SDSS J144600+0024

This L5 object was nominated as a brown dwarf by Geballe et al. (2002). Because of relatively low S/N compared to another L5 object SDSS J053951−0059 above, we do not recognize the CH4 Q-branch dip in the spectrum of this source, while the overall SEDs are consistent with each other.

3.1.3. 2MASS J152322+3014

McLean et al. (2000) found that this source is of the latest L-type and assigned it as L8/L9. It was confirmed as L8 by Geballe et al. (2002). This source, together with SDSS J144600+0024, is one of the faintest objects among our current data set, and the quality of the spectrum is not excellent. However, we clearly see a more developed CH4 band than in the L5 sources. The CO2 band is marginally detected.

3.1.4. SDSS J083008+4928

Geballe et al. (2002) classified this object as L8–T0, or L9 as an average. It is on the border of L/T spectral types and is a good example to investigate the transition from L to T. There are rather remarkable changes in the spectral features between this source from the previous L8 source 2MASS J152322+3014. We see that H2O and CO absorption bands become more prominent than earlier L-type sources. The CH4 Q-branch is very clear, but P- and R-branches are less obvious. The CO2 band is clearly seen.

3.1.5. ϵ Ind Ba+Bb

This object was identified by Scholz et al. (2003) as a companion to the K5V star, ϵ Ind A. Because of its proximity to the Sun (3.6 pc), it is the brightest among our observed targets. We observed the object twice within a day but found that one observation (OBSID=1720003-1) was significantly degraded by charged particle hits before and during the exposure. The other spectrum (OBSID=1720004-1) shown in Figure 1 clearly exhibits the four major molecular bands: CH4, H2O, CO and CO2. This object is in fact a binary system of T1 and T6 dwarfs, with K-band magnitudes of 14 and 16, respectively (McCaughrean et al. 2004; King et al. 2010). AKARI’s spectrum is a mixture of the two spectral types and we will not use it for quantitative analysis.

3.1.6. 2MASS J055919−1404

The object was identified as a “warm” T dwarf by Burgasser et al. (2000). From a near-infrared spectrum in 0.9–2.3 μm they concluded that the source was near the L/T transition border. Burgasser et al. (2006b) classified the object as T4.5. The AKARI spectra of this dwarf show very deep CO and CO2 absorptions beyond 4.0 μm, together with CH4 and H2O bands below 3.8 μm. As a result the spectra show a peak at 4 μm. A sharp peak, probably the CO band center, appears very clearly between the R- and P-branches. Our observations are consistent with the photometry by Leggett et al. (2002) that the M’ band flux of this source is fainter by a factor of 3 than that expected if CO/CH4 abundance follows thermal equilibrium. Our spectra confirm that CO is the major source of opacity in the wavelength region.

3.1.7. 2MASS J041519−0935

This object was first identified as a T-type brown dwarf by Burgasser et al. (2002) based on near-infrared spectroscopy. The
object has been designated a “standard” T8 source by Burgasser et al. (2006b). It is one of the latest spectral-type brown dwarfs, and is the coolest object in our sample. The first observations of this target with AKARI were carried out in 2007 February. However, the data were considerably contaminated by ghosting from a nearby bright star. We reobserved the object a half year later in 2007 August and obtained a clean spectrum.

The spectra exhibit deep H2O and CH4 absorption bands, which are almost completely saturated at the wavelengths below 3.5 μm. On the other hand, the object has sufficient flux in the longer wavelength range, where we clearly identify the CO and CO2 bands. Two independent observations show almost identical shape in this wavelength range, strengthening the reality of the detections.

4. COMPARISONS OF THE OBSERVED AND MODEL SPECTRA

In this section, we examine to what extent the newly observed spectra of the 2.5–5.0 μm region can be explained with the model spectra and what remains unexplained with the present models of the photospheres of cool dwarfs. For this purpose, we apply our unified cloudy model (UCM), a brief description of which is given in Section 4.1. We assume local thermodynamical equilibrium (LTE) throughout this section. Then we outline our method of analysis with some examples in Section 4.2 and the results of our analysis in Section 4.3. The physical parameters estimated by our analysis are summarized in Section 4.4. Finally, we examine the errors and limitation of our analysis based on the UCM in Section 4.5.

4.1. Predicted Spectra of Dusty Dwarfs

Generally, stellar spectra can be interpreted in terms of $T_{\text{eff}}$, log $g$, chemical composition, and micro-turbulent velocity. However, a new feature in the spectra of brown dwarfs, compared with usual stellar spectra, is the effect of dust clouds formed in the photosphere. If the properties of dust clouds can be defined uniquely from the four basic parameters considered above, the spectra of brown dwarfs could eventually be interpreted in terms of these four parameters, namely $T_{\text{eff}}$, log $g$, chemical composition, and micro-turbulent velocity. At present, the dependence of the dust cloud properties on the four basic parameters is unknown, because the formation and disappearance of dust clouds in the photospheres of brown dwarfs is not yet well understood.

On the other hand, some observations indicate that the properties of the dust clouds do not necessarily depend uniquely on such a basic parameter as $T_{\text{eff}}$. For example, infrared colors such as $J-K$ plotted against $T_{\text{eff}}$ show a large variation at a fixed $T_{\text{eff}}$ (e.g., Marley et al. 2005; Tsuji 2005). Since these infrared colors depend directly on the properties of the dust clouds, this fact implies that the properties of the dust clouds should be different even for the same $T_{\text{eff}}$. Also, one important observational result is that $T_{\text{eff}}$ shows slight change over the spectral types between about L5 and T5 (e.g., Golimowski et al. 2004; Nakajima et al. 2004). In other words, the characteristics of the spectra used as signatures of the spectral types are quite different even for the same $T_{\text{eff}}$ and hence they are not necessarily determined by $T_{\text{eff}}$. This result implies that the basic features of the spectra of brown dwarfs should be determined by some additional parameter(s) other than $T_{\text{eff}}$. Again dust should play a major role in this respect as in the case of the infrared colors noted above.

Thus, a major problem is how to consider the effect of dust in the interpretation and analysis of the spectra of brown dwarfs. For this purpose, we apply our UCM in which the dust forms at a layer where temperature is equal to the condensation temperature, $T_{\text{cond}}$, but disappears at somewhat lower temperature which we refer to as the critical temperature, $T_{\text{cr}}$. At this temperature, the radius of the dust grain $r_{\text{gr}}$ reaches the critical radius $r_{\text{cr}}$, where the Gibbs energy of condensation is maximum. Then, at this point, dust starts to grow larger and larger and will precipitate from the gaseous mixture. For this reason, dust disappears in the layers with $T < T_{\text{cr}}$ and will exist only in the layers of $T_{\text{cr}} < T < T_{\text{cond}}$. Thus dust is present in the layers whose photospheric temperatures are within the above range, and this means that a thin dust cloud forms in the photosphere of brown dwarfs, as discussed in more detail elsewhere (Tsuji 2001, 2002). It is to be noted that $T_{\text{cond}}$ is defined by the thermodynamical data and is hence fully controlled by $T_{\text{eff}}$ and log $g$ (see, e.g., Figure 3 in Tsuji 2002). On the other hand, $T_{\text{cr}}$ is not predictable by any physical theory at present. Instead, $T_{\text{cr}}$ is introduced as a free parameter in our UCM, and it serves as a measure of the thickness of the dust cloud (the dust cloud is thicker if the deviation of $T_{\text{cr}}$ from $T_{\text{cond}}$ is larger).

With the introduction of $T_{\text{cr}}$, the UCM is characterized by the five parameters including $T_{\text{cr}}$ in addition to the usual four parameters, $T_{\text{eff}}$, log $g$, chemical composition, and micro-turbulent velocity. From observations, we showed that at least one additional parameter is needed to describe the observed characteristics of brown dwarfs, and we now propose to identify $T_{\text{cr}}$ as the additional parameter required from observations.

A new feature in the AKARI observations discussed in Section 3 is the detection of the CO2 band at 4.2 μm. Although CO2 is included in the construction of the UCM as well as in our evaluation of the spectra with the use of the band model opacity (see the Appendix of Tsuji 2002), we recompute the spectra with the CO2 line list from the HITEMP database (Rothman et al. 1997) in view of the detection of the CO2 band in several objects. As an example, a predicted spectrum including CO2 based on the line list (solid line) is compared with the case without CO2 lines (dashed line) in Figure 3 for a UCM with $T_{\text{eff}} = 1300$ K, $T_{\text{cr}} = 1800$ K,
log g = 4.5, micro-turbulent velocity = 1 km s$^{-1}$, and solar abundance. For comparison, the result based on the band model opacity is shown by the dotted line. We use the band model opacity during the iterations of model construction but apply the line list in all computations of the spectra. So far, CO$_2$ has been largely neglected in spectroscopy and model photospheres of cool dwarfs, but the result shown in Figure 3 reveals that the effect of CO$_2$ absorption is significant even within the framework of the LTE analysis. Since carbon atoms are mostly consumed in CO and/or CH$_4$ in cool dwarfs, CO$_2$ cannot be very abundant, but rather large $f$-values of CO$_2$ transitions make the molecule an important absorber in the spectra of cool dwarfs.

The major spectral feature in the 2.5–5.0 μm region is the CH$_4$ fundamental band at 3.3 μm, for which we apply the line list by R. S. Freedman (2005, private communication) discussed in detail by Freedman et al. (2008). Certainly the CH$_4$ line lists including the high excitation lines are not yet satisfactory as discussed before (Tsuji 2005), but we believe that Freedman’s list is the best one currently available for the fundamental band. Other line lists included are H$_2$O (Partridge & Schwenke 1997), CO (Guelachivili et al. 1983; Chackerian & Tipping 1983), OH (Jacquinet-Husson et al. 1999), CN (Cerny et al. 1978; Bauschlicher et al. 1988), and SiO (Lavas et al. 1981; Tipping & Chackerian 1981). Also, NH$_3$, PH$_3$, and H$_2$S are considered on the basis of the band models. With these spectroscopic data, the spectra between 2.5 and 5.0 μm for our UCMs are evaluated at a resolution of 0.01 cm$^{-1}$ and convolved with a slit function of FWHM = 3000 km s$^{-1}$, which is about the resolving power of the AKARI spectrometer. Note that the observed spectra shown in Figures 4–7, 9, 11 are smoothed with $R = 100$ and that the error-weighted average is taken if two valid spectra are available.

4.2. Method of Analysis and Some Examples

We restrict our analysis to the spectral region between 2.5 and 5.0 μm, which we have observed completely for the first time. Although analyses of different spectral regions do not necessarily provide the same answer as to what are the best parameters of the photosphere, as shown in detail by Cushing et al. (2008), we restrict our analysis to the 2.5–5.0 μm region for this very reason. In fact, for our purpose stated at the beginning of this section, it is meaningless to find a solution that provides a good fit to other regions but not to the 2.5–5.0 μm region. We return to this problem in Section 4.5.

We assume that the objects we have observed are all of solar metallicity (Anders & Grevesse 1989; Allende Prieto et al. 2002) and that the micro-turbulent velocity is near solar (1 km s$^{-1}$) throughout. Then, major parameters that define the characteristics of a spectrum are $T_{\text{eff}}, \log g$, and $T_{\text{ex}}$. In fitting the observed spectrum with the predicted one, we refer to the empirical data summarized in Table 3. We start with the parallaxes by Vrba et al. (2004) which cover our full sample.
We note that their values agree quite well with other results in general. We choose $T_{\text{eff}}$ to be $T_{\text{eff}}^0$ close to the so-called empirical $T_{\text{eff}}$ suggested by Vrba et al. (2004) (Table 3) and examine the cases of $T_{\text{eff}} = T_{\text{eff}}^0$ and $T_{\text{eff}}^0 \pm 100$ K. As a result, we examine three values of $T_{\text{eff}}$ near the empirical $T_{\text{eff}}$. But this choice of trial $T_{\text{eff}}$ is not necessarily successful as described below (e.g., a case of 2MASS J055919−1404 to be discussed in Section 4.2). This fact suggests that the so-called empirical $T_{\text{eff}}$ cannot be fully realistic as will be discussed in Section 4.4.1. We also consider three cases of $T_{\text{eff}} = 1700, 1800, \text{and } 1900$ K and three values of log $g = 4.5, 5.0, 5.5$. Thus, we consider $3 \times 3 \times 3 = 27$ combinations of these parameters ($T_{\text{eff}}, T_{\text{cr}}, \text{and } \log g$), and select the case that shows a best fit to the overall shape of the 2.5–5.0 $\mu$m SED.

We discuss the procedure outlined above for the case of SDSS J083008+4828 as an example. The empirical $T_{\text{eff}}$ of this L9 dwarf is 1327 K (Table 3), but the CH$_4$ 3.3 $\mu$m band is too weak for such a low value of $T_{\text{eff}}$. Therefore, we start our trials with $T_{\text{eff}} = 1300$ K and extend them to higher $T_{\text{eff}}$, rather than to examine the cases of $T_{\text{eff}} = 1300 \pm 100$ K. It is rather difficult to find a good fit in this object, but one possible solution is obtained for ($T_{\text{eff}}, T_{\text{cr}}, \log g$) = (1500, 1700, 4.5) from our 27 trial models. The effect of $T_{\text{eff}}$ along with the possible best case is shown in Figure 4(a): only the case of $T_{\text{eff}} = 1500$ K provides a reasonable fit to the $P$- and $R$-branches of CH$_4$ fundamentals, although the predicted $Q$-branch is somewhat stronger than that in the observed spectrum.

The effect of $T_{\text{cr}}$ at fixed values of $T_{\text{eff}} = 1500$ K and log $g = 4.5$ is illustrated in Figure 4(b). Although the fit to the observed CO$_2$ 4.2 $\mu$m feature can be improved by higher values of $T_{\text{cr}}$ (i.e., with thinner dust cloud), the fit to the CH$_4$ 3.3 $\mu$m feature appears to be worse. The effect of log $g$ is modest as shown in Figure 4(c), but the lowest gravity of log $g = 4.5$ provides better fits both to the CH$_4$ 3.3 $\mu$m and CO$_2$ 4.2 $\mu$m bands than the higher values. The final fit we find, however, is not so good around 2.7, 4.2, and 4.5 $\mu$m and we will discuss these wavelength regions in Section 4.3.

Another example is the case of 2MASS J055919−1404. The empirical $T_{\text{eff}}$ of this T4.5 dwarf is 1469 K (Table 3), and we, at first, examined the cases of $T_{\text{eff}} = 1400 \pm 100$ K. It was difficult to find a good fit, but we found that the case of $T_{\text{eff}} = 1300$ K provides a relatively close fit to some features. However, an anonymous referee called our attention to a recent result by Cushing et al. (2008) who obtained $T_{\text{eff}} = 1200$ K for this object, and suggested that we examine this case. Although this differs by a large value ($\sim 300$ K!) from the empirical value, we now include $T_{\text{eff}} = 1200$ K in our trial and find that this actually provides a better fit as shown in Figure 5(a). For example, the relatively strong CH$_4$ fundamental band can be better explained by $T_{\text{eff}} = 1200$ K than by $T_{\text{eff}} = 1300$ K. However, the CO$_2$ 4.2 $\mu$m feature as well as the strong absorption at the positions of CO fundamentals cannot be fitted at all. We will return to this problem in Section 5.2.

If we assume values of $T_{\text{cr}}$ lower than 1900 K, the fits to the CH$_4$ 3.3 $\mu$m band tend to become worse while those to the CO$_2$ and possible CO bands show little change as seen in Figure 5(b). The $J − K$ color near zero (Table 3) also suggests that the dust cloud is rather thin, consistent with the high value of $T_{\text{cr}}$. The effect of log $g$ is examined for the fixed values of $T_{\text{eff}} = 1200$ K and $T_{\text{cr}} = 1900$ K. It is found that the spectrum shows little change for the change of log $g$, but the 2.8–3.0 $\mu$m feature tends to fit better for the lower values of log $g$ (Figure 5(c)). We conclude that the case of ($T_{\text{eff}}, T_{\text{cr}}, \log g$) = (1200, 1900, 4.5) is the best compromise for this object.

### 4.3. Results

We now extend the procedure outlined in Section 4.2 to the other objects except for ι Ind Ba+Bb because of the composite nature of its spectrum due to its binarity. The observed and predicted spectra can be fitted rather well in the remaining four objects (see Figure 6), and thus they are more or less easier to analyze compared to the cases discussed in Section 4.2. For this reason, we only give the resulting best fits for them. The parameters that give the best fits for all six objects are summarized in Table 4. After we find the possible best model for each object, we measure the vertical shift in logarithmic scale between the observed spectrum and the predicted one based on the best model we found. The emergent flux from the unit surface area of the object, $F_{\nu}$ (in units of erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$), is written as

$$
\log F_{\nu} = \log f_{\nu} − 2 \log(R/d) − 23.497,
$$

where $f_{\nu}$ (in units of Jy) is the observed flux, $d$ is the distance to the object based on the measured parallax, and $R$ is the radius of the object. The vertical shift provides $R/d$. With the known

---

**Figure 5.** Observed spectrum of 2MASS J055919−1404 (T4.5) compared with predicted spectra based on the UCM. The best fit is obtained for ($T_{\text{eff}}, T_{\text{cr}}, \log g$) = (1200, 1900, 4.5). See the caption of Figure 4 as for other details. (a) Effect of $T_{\text{eff}}$ under the fixed values of $T_{\text{cr}} = 1900$ K and log $g = 4.5$. (b) Effect of $T_{\text{cr}}$ under the fixed values of $T_{\text{eff}} = 1200$ K and log $g = 4.5$. (c) Effect of log $g$ under the fixed value of $T_{\text{cr}} = 1900$ K and $T_{\text{eff}} = 1200$ K.
distance, we can estimate the radius $R$ and the result is also given in Table 4. The resulting fits in absolute scale are given in Figure 6.

4.3.1. SDSS J053951−0059

The empirical $T_{\text{eff}}$ of this L5 dwarf is 1690 K (Table 3), and we find that the case of $(T_{\text{eff}}, T_c, \log g) = (1800, 1800, 5.5)$ shows the best fit for this object. In fact, the overall shape of the SED as well as the strengths of the CH$_4$ $Q$-branch at 3.3 $\mu$m and the CO fundamental at 4.6 $\mu$m is reasonably fit for this case as shown in Figure 6(a). It is to be noted that the effect of $T_c$ is of comparable importance to that of $T_{\text{eff}}$. In fact, the column densities of both dust and molecules generally increase at the lower $T_{\text{eff}}$ (at fixed $T_c$) and also at the lower $T_c$ (at fixed $T_{\text{eff}}$).

For this reason, the effects of $T_{\text{eff}}$ and $T_c$ on the spectra are often difficult to distinguish. We have considered the effects of both $T_{\text{eff}}$ and $T_c$ from the beginning, and looked for the best solution. The effect of $\log g$ on the spectrum is rather minor.

![Figure 6. Observed and predicted spectra based on the UCMs compared on an absolute scale: (a) SDSS J053952−0059 (L5); (b) SDSS J144600+0024 (L5); (c) 2MASS J152322+3014 (L8); (d) SDSS J083008+4828 (L9); (e) 2MASS J055919−1404 (T4.5); and (f) 2MASS J041519−0935 (T8).](image)

Table 4

| No. | Object            | $T_{\text{eff}}$ (K) | $T_c$ (K) | $\log g$ | $R/R_J$ | $\Delta T_{\text{eff}}$ (K) |
|-----|-------------------|----------------------|-----------|----------|---------|-----------------------------|
| 1   | SDSS J053952−0059 | 1800                 | 1800      | 5.5      | 0.804   | −110                        |
| 2   | SDSS J144600+0024 | 1700                 | 1700      | 4.5      | 0.716   | −108                        |
| 3   | 2MASS J152322+3014| 1500                 | 1700      | 4.5      | 0.684   | −170                        |
| 4   | SDSS J083008+4828 | 1500                 | 1700      | 4.5      | 0.700   | −173                        |
| 5   | 2MASS J055919−1404| 1200                 | 1900      | 4.5      | 1.175   | −269                        |
| 6   | 2MASS J041519−0935| 800                  | $T_{\text{cond}}$ | 4.5       | 0.767   | −36                         |

Notes.

$^a$ Radius $R$ relative to Jupiter’s radius $R_J$ (see Section 4.3).

$^b$ $\Delta T_{\text{eff}} = T_{\text{eff}}$ (Table 3 by empirical method) − $T_{\text{eff}}$ (Table 4 by our model fitting).
compared with the other parameters, but the lower gravities may reasonably be excluded from the overall poor fits.

The resulting fit in absolute scale (Figure 6(a)) shows that the spectrum observed by AKARI can reasonably be accounted for by our model.

### 4.3.2. SDSS J144600+0024

Although the empirical $T_{\text{eff}}$ of this L5 dwarf is near 1600 K (Table 3), we find it very difficult to assume $T_{\text{eff}} < 1600$ K since the observed CH$_4$ feature at 3.3 $\mu$m is very weak if present. Again by the procedure outlined in Section 4.2, we find that a case of $(T_{\text{eff}}, T_{\text{cr}}, \log g) = (1700, 1700, 4.5)$ shows the best fit for this object. For example, we see that not only the strength of the CH$_4$ 3.3 $\mu$m band but also the overall shape of SED are best fitted with $T_{\text{eff}} = 1700$ K. The effect of $T_{\text{cr}}$ is rather large and we can easily exclude such high values of $T_{\text{cr}}$ as 1800 and 1900 K. Also, the very red $J - K$ color (Table 3) suggests that the dust cloud is considerably thick and $T_{\text{cr}}$ cannot be as high as 1900 K. It is found that the overall SED is again not sensitive to $\log g$, but the strengths of both the CH$_4$ Q-branch at 3.3 $\mu$m and CO fundamental band could discriminate the best log $g$ of 4.5 from the higher values of $\log g = 5.0$ and 5.5.

The resulting fit in absolute scale in Figure 6(b) shows that the observed spectrum of the 2.5–5.0 $\mu$m region, which possesses almost no distinct features, can reasonably be accounted for by our model.

### 4.3.3. 2MASS J152322+3014

The empirical $T_{\text{eff}}$ of this L8 dwarf is 1330 K (Table 3), but we found that the best fit is found for $(T_{\text{eff}}, T_{\text{cr}}, \log g) = (1500, 1700, 4.5)$. In fact, the modest strength of the CH$_4$ 3.3 $\mu$m band suggests that $T_{\text{eff}}$ cannot be below 1300 K, and it is only the case of $T_{\text{eff}} = 1500$ K that provides a reasonable fit not only to the Q- but also to the P- and R-branches of the CH$_4$ fundamental band. We confirm that such a fit as shown for $T_{\text{cr}} = 1700$ K can no longer be found for $T_{\text{cr}}$ as high as 1800–1900 K. This result is consistent with the red $J - K$ color of 1.60 (Table 3), which implies that the dust cloud of this L8 dwarf is rather thick. The strength of the CO fundamental band is almost independent of $\log g$, but the P- and R-branches of the CH$_4$ fundamentals depend on $\log g$ and can only be explained with the low gravity of $\log g = 4.5$. The effect of $\log g$ on the infrared spectrum is again modest and accurate determination of $\log g$ is difficult.

A detection of CO$_2$ at 4.2 $\mu$m suggested in Section 3 can be well supported by our model prediction that shows a depression at the expected position of the CO$_2$ 4.2 $\mu$m band and even shows a reasonable fit quantitatively (see Figure 6(c)). The fit in the region of the CO fundamental band appears to be poor and the deep absorption features near 4.5 and 4.9 $\mu$m remain unexplained. We suspect, however, that the CO fundamental band provides the major contribution as in later type dwarfs, to be discussed in Section 4.3.4.

Thus the spectrum observed by AKARI now shows some dissonances with the predicted spectrum in this late-L dwarf as shown in Figure 6(c).

### 4.3.4. SDSS J083008+4828

As already discussed in some detail in Section 4.2, we find $(T_{\text{eff}}, T_{\text{cr}}, \log g) = (1500, 1700, 4.5)$ for this object. The final fit is shown in Figure 6(d). We note that the resulting parameters are the same as that for 2MASS J152322+3014 discussed in Section 4.3.3. This result is also consistent with the similarity of the empirical $T_{\text{eff}}$ and of the $J - K$ color between these two late-L dwarfs (see Table 3). Nevertheless, the observed spectra of the two objects differ significantly. For example, the observed feature near the 2.7–2.9 $\mu$m region (largely due to H$_2$O 1$
u_1$, 1$
u_3$, and 2$
u_3$ bands) shows a large difference between these two objects of the same physical parameters. Since this feature is well reproduced by our models in other objects except for SDSS J083008+4828 (see Figure 6), this should not be due to any systematic effects in our models.

A more interesting result is that the observed CO$_2$ 4.2 $\mu$m feature in this object is very strong as noted already (Section 3), and that it is too strong compared with the prediction in marked contrast to the case of 2MASS J152322+3014. It appears that the CO$_2$ 4.2 $\mu$m feature cannot be explained by any combination of $T_{\text{eff}}, T_{\text{cr}}$, and $\log g$ with our UCM essentially based on the LTE assumption, while those of 2MASS J152322+3014 may be more consistent with the LTE prediction. Such a large difference in CO$_2$ band in the two objects of similar physical parameters cannot be explained by differences in dust cloud properties if, as we find, $T_{\text{cr}}$ is nearly the same around 1700 K in both objects. The deep absorption at 4.5 $\mu$m can be identified with the R-branch of the CO fundamental, but cannot be explained within the framework of the LTE assumption as well.

Thus, there are serious difficulties in understanding the spectrum observed by AKARI in that the region between 4 and 5 $\mu$m cannot be fitted at all by the LTE prediction based on our UCM.

### 4.3.5. 2MASS J055919–1404

Details of the model fitting of this object were described in Section 4.2, and our final fit on an absolute scale is shown in Figure 6(e). We are shocked to see that the discrepancy between the observed and predicted spectra is so large in the region beyond 4.1 $\mu$m. The region of the CO R-branch is too deep to be explained by our LTE model and the CO P-branch also appears to be appreciable. Thus we confirm that the CO bands are actually enhanced not only in late-T dwarfs but also in mid-T dwarfs, as anticipated by photometric observations (e.g., Leggett et al. 2007).

In this object, a more important result is that the new spectrum observed by AKARI provides definite evidence for the presence of the strong CO$_2$ band in brown dwarfs for the first time. The depression at 4.2 $\mu$m is too large to be accounted for by the predicted CO$_2$ band and the discrepancy between the observed and predicted spectra is quite serious. All these new features due to CO and CO$_2$ cannot be accounted for by the present LTE model such as our UCM. In contrast to these serious disagreements in the region beyond 4 $\mu$m, the observed and predicted spectra agree quite well in the region between 2.5 and 4.1 $\mu$m.

Recent analysis of the SED of this object by Cushing et al. (2008) concluded that $T_{\text{eff}} = 1200$ K, $\log g = 5.5$, and $f_{\text{sed}} = 4$, where $f_{\text{sed}}$ is the cloud sedimentation efficiency parameter and a larger value implies greater sedimentation efficiency resulting in a thinner cloud (Ackerman & Marley 2001). Thus $f_{\text{sed}}$ is a parameter that may have a similar role as our $T_{\text{cr}}$, with larger $f_{\text{sed}}$ corresponding to higher $T_{\text{cr}}$. Thus their result showing a relatively large value of $f_{\text{sed}} = 4$ is consistent with our relatively high value of $T_{\text{cr}} = 1900$ K, and we agree with them on the properties of the dust cloud in this T4.5 dwarf. We also agree that $T_{\text{eff}} = 1200$ K for this object. Thus our results for the cloud properties as well as for $T_{\text{eff}}$ show good agreement with those of Cushing et al. (2008), despite the fact that different spectral
regions are analyzed with different models. Unfortunately, the results for gravity differ considerably. However, SEDs are not very sensitive to gravity and this is the parameter most difficult to determine from the model fittings (as will further be discussed in Section 4.4.2).

In summary, some dissonances between the observed and predicted spectra, seen in the late-L dwarfs, appear to be quite distinct in this mid-T dwarf.

4.3.6. 2MASS J041519−0935

The empirical \( T_{\text{eff}} \) of this T8 dwarf is 764 K (Table 3) and, if a dust cloud forms, it is situated below the layer of the optical depth unity in such a very cool dwarf. For this reason, the spectrum no longer depends on \( T_{\text{eff}} \), as we have actually confirmed. Accordingly, we apply the dust-free models in which dust grains have all precipitated just after they are formed (this means \( T_{\text{cr}} = T_{\text{cond}} \)), and we find the best possible fit for \( (T_{\text{eff}}, T_{\text{cr}}, \log g) = (800, T_{\text{cond}}, 4.5) \).

Determination of the physical properties of the coolest brown dwarfs including 2MASS J041519−0935 has been discussed by Burgasser et al. (2006a), who calibrated the strengths of H2O bands and relative fluxes in terms of \( T_{\text{eff}} \) and \( \log g \). As a result, they suggested \( T_{\text{eff}} = 740–760 \) K and \( \log g = 4.9–5.0 \) for this object. Also, Saumon et al. (2007) suggested a similar result of \( T_{\text{eff}} = 725–775 \) K and \( \log g = 5.00–5.37 \) based on the analysis of a spectrum including new data obtained with Spitzer Space Telescope. Our result is reasonably consistent with these results, although the values of \( \log g \) differ from each other. Thus analyses of the different spectral regions by the different models show more or less consistent results in this object at least for \( T_{\text{eff}} \).

The overall fit of the predicted spectrum of the possible best model is not so bad (see Figure 6(f)), but we confirm that the region of the CO bands cannot be fitted at all. Such a possible large discrepancy in the predicted and observed CO bands in late-T dwarfs was previously suggested based on the ground-based observation of Gl 229B (Noll et al. 1997; Oppenheimer et al. 1998), and more recently for two other late-T dwarfs by Geballe et al. (2009). We confirm these previous results and add a new case of largely enhanced CO fundamentals in late-T dwarfs. We also note that the \( R \)-branch is much stronger compared with the \( P \)-branch.

A more interesting result is that the CO2 band at 4.2 \( \mu \)m appears quite distinctly in this late-T dwarf too. It is impossible to explain both the CO and also the CO2 bands by the LTE models, and we will discuss such cases in Section 5.

In conclusion, the new spectral region explored by AKARI for the first time reveals: first, the enhancement of the CO fundamental bands is a general feature and, second, the CO2 band at 4.2 \( \mu \)m appears to be an important absorber, in late-L and T dwarfs.

4.4. Basic Physical Parameters of Six Brown Dwarfs

We now discuss briefly the resulting \( T_{\text{eff}} \), \( T_{\text{cr}} \), \( \log g \), and \( R/R_J \) values summarized in Table 4. Also, we discuss briefly the effects of other basic parameters, namely chemical composition (in Section 4.4.4) and micro-turbulent velocity (in Section 4.4.5), which we assumed to be solar. If we try to determine these two parameters by the same way as we have done in Sections 4.2 and 4.3 for the three basic parameters, we must consider at least \( 3 \times 3 \times 3 \times 3 \times 3 = 243 \) models instead of 27 models for each object, but this is clearly impractical. Moreover, we do not think that the chemical abundances and micro-turbulent velocity can be determined from such low-resolution spectra as those we have at hand.

4.4.1. Effective Temperature and Radius

We note first that our \( T_{\text{eff}} \) values do not agree with the so-called empirical effective temperatures obtained from the observed luminosities and a constant radius such as \( R = 0.9 R_J \) (Vrba et al. 2004) (see the 7th column of Table 4). In fact, we already notice through Sections 4.3.1 and 4.3.6 that the observed SEDs cannot be fitted well with the predicted ones assuming the empirical \( T_{\text{eff}} \) by Vrba et al. (2004). The reliability of the empirical \( T_{\text{eff}} \) largely depends on the accuracy of the values of the radius. The constant radius of \( R = 0.9 R_J \) was based on a statistical analysis by Burgasser (2001) of the evolutionary models of cool dwarfs by Burrows et al. (1997), but it is unknown if it is appropriate to apply such a value to all the objects.

It is known that the radii of cool substellar objects are independent of mass to within 30% for a broad range of masses from 0.3 to 70 \( M_J \) (Burrows et al. 2001). The resulting radii of all our six objects (Table 4) appear to be consistent with the prediction of the evolutionary models and confirm that the radii of ultracool dwarfs are within approximately 30% of Jupiter’s radius. The mean radius for our six objects is 0.81 \( R_J \), and thus we agree with Burgasser (2001) in that the radii of ultracool dwarfs are statistically smaller than Jupiter’s radius. However, the variation of radii among brown dwarfs appears to be appreciable (Table 4) and may not be represented by a single mean value. For this reason, the so-called empirical effective temperature cannot be completely reliable. Although we use it as a guideline in our analysis (Sections 4.2 and 4.3), it may even be misleading as we showed in the case of 2MASS J055919−1404 (Section 4.2).

Also, because of such variations of the radii in real ultracool dwarfs, an attempt to analyze the observed spectra on an absolute scale based on an assumed radius of \( R = R_J \) (Tsuji 2005) does not necessarily work well. For example, we showed before that the near-infrared spectrum of 2MASS J152322+3014 observed with Subaru, reduced to an absolute scale with the known parallax and with the assumption of \( R = R_J \), agreed with the predicted spectrum of \( T_{\text{eff}} = 1300 \) K. For this reason, we suggested \( T_{\text{eff}} \) of this object to be \( \approx 1300 \) K (Tsuji 2005). However, we find that the shape of the AKARI spectrum can be best explained by \( T_{\text{eff}} = 1500 \) K (Section 4.3.3), and that a consistency with the SED on an absolute scale can be achieved if we abandon the ad hoc assumption of \( R = R_J \) (see Figure 6(c)).

In conclusion, we believe that the observed spectrum (or relative SED) can provide a more direct and realistic estimation of the effective temperature of an individual object. Further, an empirical estimation of the radius can be possible if the SED can be reduced to an absolute scale with the known parallax. With this conclusion, we now think it inappropriate to analyze the observed spectrum in absolute scale based on an ad hoc assumption of \( R = R_J \), as we proposed before (Tsuji 2005).

4.4.2. Gravity

The determination of \( \log g \) is more difficult since the low-resolution infrared spectra depend little on \( \log g \), as can be seen in our Figures 4 and 5. Also, this difficulty is clearly shown by a goodness-of-fit statistic \( G_k \) defined by Equation (1) in Cushing et al. (2008) and shown in their Figure 5, in which \( G_k \) only
shows minor changes for different $\log g$ (except possibly for no cloud case).

Inspection of Table 4 reveals that our result appears to be biased toward low gravity, namely $\log g = 4.5$ for 5 out of 6 objects. This may be due to the difficulty of gravity determination noted above, at least partly, or may be simply because our sample mostly consists of low gravity objects by chance. We examine if this may be due to any systematic effects in our UCMs. Our gravity determination is essentially based on the gravity dependence of the gas and dust opacities, but we are using more or less standard methods in treating molecular and dust opacities. Also, a comparative study of different modeling approaches did not reveal any systematic effect in our models (Helling et al. 2008). Thus we cannot identify any systematic effect. We hope to examine this problem further with a larger sample in future.

Cushing et al. (2008) used ultracool dwarf evolution models to transfer their ($T_{\text{eff}}, R$) values to ($T_{\text{eff}}, g$) values, from which they obtained $\log g = 4.7$ for 2MASS J055919−1404. This result differs from their result based on their spectral fitting referred to in Section 4.2 ($\log g = 5.5$), but agrees rather well with our value given in Table 4 ($\log g = 4.5$). Thus this result is supporting evidence for our $\log g$, despite some difficulties noted above. However, the results based on the evolutionary sequences may suffer more or less similar difficulty to the spectral fitting method, since it depends critically on the physical parameters such as $T_{\text{eff}}$, which cannot be very accurate if they are based on the spectral fitting in the limited spectral region (as will be detailed in Section 4.5).

Given the radius and $\log g$, it is in principle possible to estimate the mass. However, SEDs are not so sensitive to $\log g$ and the accuracy of the estimation is rather low. For this reason, we believe it impossible to obtain a reasonable mass estimate from our spectra.

4.4.3. Critical Temperature

Inspection of Table 4 reveals that the resulting $T_{\text{cr}}$ show a variety of values in our limited sample, and this result implies that the dust cloud properties differ significantly among different objects. In modeling dusty dwarfs, it is still difficult to determine the dust cloud properties from the basic physics, and we had to introduce such an empirical parameter as $T_{\text{cr}}$ to represent the dust cloud properties, at least partly. Other models of dusty dwarfs also have a more or less similar feature. For example, Ackerman & Marley (2001) introduced the cloud sedimentation efficiency $f_{\text{sed}}$ in their models and, as discussed in Section 4.3.5, their $f_{\text{sed}}$ and our $T_{\text{cr}}$ consistently showed that the dust cloud in 2MASS J055919−1404 is rather thin. We hope that a larger sample will be analyzed to clarify the nature of dust clouds and that the result will serve as a guide toward a more physical theory of cloud formation in dusty dwarfs.

4.4.4. Chemical Composition

We assumed that the chemical composition in such unevolved objects as brown dwarfs should be the same as the solar composition. However, the solar composition itself is by no means well established. For example, we adopted $\log A_{C} = 8.60$ and $\log A_{O} = 8.92$ (on the scale of $\log A_{H} = 12.0$) in our initial version of UCM based on the latest results known at that time (Tsujii 2002). However, these values were revised to be $\log A_{C} = 8.39$ and $\log A_{O} = 8.69$ based on the three-dimensional (3D) time-dependent hydrodynamical model of the solar photosphere (Allende Prieto et al. 2002) and our present version of UCM is based on these revised values as noted previously (Tsujii et al. 2004). These values are close to the more recent values of $\log A_{C} = 8.43$ and $\log A_{O} = 8.69$ (Asplund et al. 2009). Since a direct determination of abundances in brown dwarfs cannot be expected in the near future, we think it best for now to use the most reliable solar composition.

Unlike the cases of evolved stars in which the surface chemical composition may suffer drastic variations due to convective dredge-up of the products of nuclear processing in the interior, large variations of the surface chemical composition may not be expected in brown dwarfs, but a possibility of small variations may not be excluded. As an example, we examine the effect of carbon abundance on CO and CO$_{2}$ features in J083008+4828 and J055919−1404, since CO and CO$_{2}$ features in these objects could not be reproduced well with the composition we have assumed. For this purpose, we compute two spectra with $\log A_{C}$ changed by $\pm 0.15$ dex compared to the standard composition we have assumed, namely, $\log A_{C} = 8.39$.

The results for J083008+4828 are shown in the upper diagram of Figure 7. The effect of increasing $\log A_{C}$ by 0.15 dex results in a considerable strengthening of the methane band, but the overall fitting tends to be worse (compare (c) with (a) in the figure). The
CO$_2$ and CO bands at 4.2 and 4.6$\mu$m, respectively, however, do not show any strengthening. The effect of decreasing log A$_C$ by 0.15 dex is rather modest (see (d) in the figure). The results for J055919$-$1404 are shown in the lower diagram of Figure 7. The effect of changing log A$_C$ by $\pm$0.15 dex can be noticed on the CH$_4$ band, but CO$_2$ and CO bands remain almost unchanged. We conclude that the large discrepancies between the observed and predicted CO and CO$_2$ bands in J083008+4828 and J055919$-$1404 cannot be the cause of the problem of the carbon abundance.

### 4.4.5. Micro-turbulent Velocity

We have assumed the micro-turbulent velocity to be the solar value of 1 km s$^{-1}$ throughout. To see the effect of the micro-turbulent velocity, we increased it to 2 km s$^{-1}$ and the resulting spectra are compared with those for the case of 1 km s$^{-1}$ for J083008+4828 and J055919$-$1404 in the upper and lower diagrams, respectively, of Figure 7. Clearly, dependence on the micro-turbulent velocity is quite small (compare (a) and (b) in Figure 7) as expected for such high-density photospheres dominated by the pressure broadening.

### 4.5. Errors and Limitations of the Present Analysis Based on the UCMs

Since we examine the effect of T$_{\text{eff}}$ by steps of 100 K, our T$_{\text{eff}}$ cannot be more accurate than $\pm$50 K. Further, combined with the similar uncertainty in T$_{\text{gr}}$, the final uncertainty in our estimation of T$_{\text{eff}}$ may be $\pm$100 K. But we should note that the parameters we have found are simply those that explain the AKARI spectra in the 2.5$-$5.0$\mu$m region. We tried more or less similar analysis of the 1.0$-$2.5$\mu$m region of our objects and found some differences in the resulting parameters, although the differences are mostly within the errors outlined above. In other words, the solution obtained by fitting other spectral regions may not in general explain the 2.5$-$5.0$\mu$m spectra. As summarized in Figure 6, we are trying to reach a unified understanding of the series of new spectra observed for the first time by AKARI covering from mid-L to late-T dwarfs. For this purpose, we believe it best to apply the parameters obtained from the AKARI spectra themselves and analyze all our sample consistently.

As shown by Cushing et al. (2008), the effective temperatures obtained by fitting a limited spectral region differ from those obtained by fitting the full SED (0.95$-$14.5$\mu$m) by typically $\sim$200 K and by as large as 700 K in the worst case. As noted above, we confirm essentially the same difficulty with our UCM. The reason for this difficulty may be because the present models are far from perfect. For example, we do not know the exact form of the dust opacities which suffer from many unknown effects (e.g., composition, size, shape, impurity, etc.) and of the molecular opacities based on imperfect line lists. Moreover, we do not yet know the exact nature of the dust clouds formed in the photosphere of cool dwarfs. For these reasons, we think it difficult to expect such rigorous numerical accuracy for brown dwarfs as realized in model photospheres of ordinary stars. We intended from the beginning that our models can at least be of some help as a guide in interpretation and analysis of the observed data of ultracool dwarfs (e.g., Tsuji 2001).

A better model would allow us to more safely analyze a wider spectral region. However, current models of brown dwarf atmospheres are far from perfection. Fitting of a wider spectral region may sample more regions of uncertain opacities at the same time, and is by no means easier to have better results. Thus we must allow for additional uncertainties beyond those found by fitting one spectral region. We fully agree with Cushing et al. (2008) who concluded that the accurate determination of the physical parameters is still an elusive goal, even though the SED fitting method shows reasonable success in general.

For now, we must be satisfied in that our SED fitting analysis based on our UCM has also been done fairly consistently for the new spectral region observed by AKARI. The UCM is a semi-empirical model in which the property of the dust clouds is represented by a single parameter T$_{\text{cr}}$ and, for this very reason, our UCM is free from yet unknown details of the cloud formation processes. Thus, our UCM can be flexible enough to interpret the major characteristics of the observed spectra in terms of a few basic physical parameters. The UCM, however, assumes LTE throughout and hence cannot be applied directly to the observed features showing possible deviations from LTE. We will discuss such a case in the next section.

### 5. SPECTRAL FEATURES UNEXPLAINED BY LTE MODELS

In the previous section, we showed that the overall SEDs can be understood reasonably well with the UCM based on LTE, but the observed features of CO and CO$_2$ in T dwarfs (and possibly late-L dwarfs) cannot be fitted at all with the spectra predicted by the model. For CO, this was known for late-T dwarfs (e.g., Noll et al. 1997; Oppenheimer et al. 1998; Geballe et al. 2009), and we confirm this fact by the better quality data for T dwarf 2MASS J041519$-$0935 (Figure 6(f)). But we also find that CO band is enhanced significantly in the mid-T dwarf 2MASS J055919$-$1404 (Figure 6(e)) as well as in the late-L dwarf SDSS J083008+4828 (Figure 6(d)). A new and more difficult problem is that the CO$_2$ band at 4.2$\mu$m is enhanced enormously in all the cool dwarfs later than L9.

#### 5.1. Late-T Dwarf

The unexpected detection of CO in the late-T dwarf Gl 229B has been interpreted as due to vertical mixing of CO from the warm layers, where CO is still abundant, to the cooler layers, where CO is mostly transformed to CH$_4$ under LTE. This is possible since CO is so stable that the timescale $\tau_{\text{chem}}$ of the reaction

$$CO + 3H_2 = CH_4 + H_2O$$

is very slow compared to the mixing timescale $\tau_{\text{mix}}$ (Griffith & Yelle 1999; Saumon et al. 2000), and a detailed computation including such a non-equilibrium effect has been carried out (e.g., Saumon et al. 2007; Hubeny & Burrows 2007).

We try to explain our observations by a simple computation as follows: we show the LTE molecular abundances of CO, H$_2$O, CH$_4$, and CO$_2$ in the photosphere of 2MASS J041519$-$0935, using the UCM of $(T_{\text{eff}}, T_{\text{cr}}, \log g) = (800, T_{\text{cont}}, 4.5)$, by the solid lines in Figure 8. We assume that the timescale of CO destruction $\tau_{\text{chem}}$ is equal to the timescale of mixing $\tau_{\text{mix}}$ at a depth point P in Figure 8 and CO/CH$_4$ abundance ratio is fixed at the value b of that point. We examine several values of b. The case of b = 0.10 is shown in Figure 8 as an example. The resulting non-equilibrium abundance of CO is indicated by the dashed line. If H$_2$O and CO$_2$ abundances relative to CO are fixed at the values at P as are CH$_4$, H$_2$O as well as CH$_4$ abundances in the upper layers should be decreased and the results are also shown by the dashed lines. The decreases, however, are small and difficult to see in the figure. On the other hand, CO$_2$ abundance shows a large increase as seen by the dashed line in Figure 8.
Figure 8. Molecular abundances, presented as partial pressure vs. total pressure (pressure in units of dyn cm$^{-2}$), in LTE (solid lines) and in non-equilibrium modified by vertical mixing for the case of $b = 0.1$ (dashed lines) in the photosphere of the T8 dwarf 2MASS J041519$-$0935 (model: ($T_{\text{eff}}$, $T_{\text{cr}}$, log $g$) = (800, $T_{\text{cond}}$, 4.5)). The arrow indicates the onset of convection.

Figure 9. Effect of vertical mixing on the CO spectrum in 2MASS J041519$-$0935 (T8): the cases of LTE, $b = 0.03$, and $b = 0.10$ are compared with the observed spectrum.

Figure 10. Molecular abundances in LTE (solid lines) and in non-equilibrium by vertical mixing for the case of $b = 0.5$ (dashed lines) in the photosphere of T4.5 dwarf 2MASS J055919$-$1404 (model: ($T_{\text{eff}}$, $T_{\text{cr}}$, log $g$) = (1200, 1900, 4.5)). The arrow indicates the onset of convection.

Figure 11. Predicted spectra in LTE and in non-equilibrium by vertical mixing ($b = 0.10$ and 0.50) compared with the observed one of T4.5 dwarf 2MASS J055919$-$1404.

We compute the spectra based on the non-equilibrium abundances for $b = 0.03$ and $b = 0.1$ together with that of the full LTE, and the results are compared with the observed spectrum of 2MASS J041519$-$0935 in Figure 9. Inspection of the figure reveals that the observed CO spectrum of 2MASS J041519$-$0935 can roughly be accounted for with $b = 0.1$. However, the predicted CO$_2$ band is still too weak compared with the observation even for $b = 0.1$. Of course, there is no reason why the CO$_2$/CH$_4$ ratio can be fixed at the value at point P, since chemical reaction timescale of CO$_2$ cannot be the same as for CO. Further, there is little possibility that more CO$_2$ can be dredged-up, since CO$_2$ abundance in the deeper layers is not so large, as shown in Figure 8.

On the other hand, it is possible that CO$_2$ abundance will change to the equilibrium value of the local physical condition if the chemical timescale related to CO$_2$ formation is not as slow as in the case of CO. However, if CO$_2$ attains its equilibrium value with the abundant CO resulting from vertical mixing, CO$_2$ abundance will be too large. In fact, CO$_2$ is more abundant than CO at log $P_{\log g} < 4.0$ in LTE as can be inferred from the solid lines in Figure 8. For this reason, we cannot assume simply that CO$_2$ can be in equilibrium with CO. We cannot predict the precise value of CO$_2$ abundance without more detailed non-equilibrium analysis, but we can expect from the above consideration that...
the CO$_2$ abundance can be somewhat larger than those shown by the dashed line in Figure 8 in the surface layers of 2MASS J041519−0935 and hence the CO$_2$ band could then be stronger than those suggested in Figure 9.

5.2. Mid-T Dwarf

A new result of the AKARI observation is that the mid-T dwarf 2MASS J055919−1404 also shows much stronger CO and CO$_2$ bands than those predicted with the use of the UCM based on LTE. We show the LTE molecular abundances in the photosphere of 2MASS J055919−1404, using the UCM of (T$_{\text{eff}}$, T$_{\text{cr}}$, log g) = (1200, 1900, 4.5), by the solid lines in Figure 10.

We first try the vertical mixing model used for the late-T dwarf 2MASS J041519−0935. We again assume that the timescale of CO destruction $t_{\text{chem}}$ is equal to the timescale of mixing $t_{\text{mix}}$ at a point P in Figure 10 and the CO/CH$_4$ abundance ratio is fixed to a value $b$ at this point. We again test a few values of $b$. A case of $b = 0.50$ is shown in Figure 10. The resulting non-equilibrium abundance of CO is indicated by the dashed line. Also, H$_2$O and CO$_2$ abundances relative to CO are fixed at the values at P and shown by the dashed lines in Figure 10.

We compute the spectra based on the non-equilibrium abundances for $b = 0.1$ and $b = 0.5$ together with those based on the LTE values, and the results are compared with the observed spectrum of 2MASS J055919−1404 in Figure 11. The predicted spectra for non-equilibrium CO and CO$_2$ abundances show additional depression in the region of CO R+P-branches but little change in the 4.2 $\mu$m region, compared to the predicted one for the LTE case. This result indicates that the observed CO band can be explained at least partly by the vertical mixing model, but the observed CO$_2$ remains completely unexplained. The observed CO feature is still too deep compared with the predicted one, but this may be due to the effect of the deep CO$_2$ feature whose origin is still unknown.

We conclude that the very strong CO band observed in 2MASS J055919−1404 by AKARI can be at least partly explained by the vertical mixing model but the CO$_2$ feature cannot be at all.

5.3. Late-L Dwarf

We detected a deep absorption around 4.5 $\mu$m in the late-L dwarf SDSS J083008+4828 and it can be identified with the CO R-branch. The R-branch tends to be deeper than P-branch in CO because of narrower line separation. We notice such a structure of the CO fundamental consisting of the deep R-branch and weak P-branch in 2MASS J055919−1404, and this similarity lends support in identifying the 4.5 $\mu$m feature in SDSS J083008+4828 as due to the R-branch of CO in the relatively low quality spectrum of this source (see also Figure 1), even though the presence of such a deep CO feature is quite unexpected in L dwarfs. We also see that the 4.2 $\mu$m feature is very strong.

In SDSS J083008+4828, the observed CO band is quite strong while the CH$_4$ band is fairly weak. These observed features imply that CO is quite abundant, and we confirm this possibility in Figure 12 where LTE abundances of CO, CO$_2$, CH$_4$, and H$_2$O are shown based on the UCM of (T$_{\text{eff}}$, T$_{\text{cr}}$, log g) = (1500, 1700, 4.5). Inspection of Figure 12 reveals that the CO abundance under LTE is already at its maximum possible value (i.e., almost all the carbon is in CO). Then, vertical mixing, if present, cannot supply additional CO to the upper photosphere and has little effect on the CO band strengths. Thus, without any computation of the spectrum, it is clear that the vertical mixing model cannot be applied to this late-L dwarf. Given that an increase of the CO abundance in the photosphere can no longer be possible (Figure 12), not only by vertical mixing but also by any other method, some changes in the structures of the photosphere and/or in the atmosphere are required to produce the unusually deep CO band observed.

The large strengthening of the CO$_2$ band cannot be due to vertical mixing either, since CO$_2$ abundance relative to other molecules is smaller in the deeper layers (Figure 12) and hence vertical mixing will reduce rather than enhance the CO$_2$ abundance in the upper layers. This result suggests that a non-equilibrium process other than vertical mixing is needed to explain the large enhancement of the CO$_2$ band.

5.4. Vertical Mixing and/or Other Possibilities

Our analysis confirms that the vertical mixing model can be applied to T dwarfs at least for CO. This result certainly shows that the vertical mixing model provides one possible way to explain the CO anomaly, but this fact may not necessarily imply that it is a unique solution for this phenomenon. In fact, our analysis cannot prove the applicability of the vertical mixing model to the late-L dwarfs.

One problem is that the convective zone is actually situated rather deep in the photosphere of cool dwarfs (e.g., Tsuji 2002), although it is said that cool dwarfs are fully convective. For example, the upper boundary of the convective zone is indicated by the arrow in Figures 8 and 10, and the layers where vertical mixing is expected are well above the convective zone. Hence vertical mixing cannot be due to convective mixing. Then, the problem is the unknown mechanism of efficient mixing in the photosphere of T dwarfs.

A more difficult problem is how to understand the enhancement of CO$_2$ bands at 4.2 $\mu$m in late-L and T dwarfs throughout. We confirm that this phenomenon cannot be explained by the vertical mixing model at all. So the question is whether the enhancements of CO and CO$_2$ bands in late-L and T dwarfs are due to the same mechanism. It is still possible that an unknown process resulting in the enhancement of CO$_2$ will also result in
the CO anomaly. In any case, the vertical mixing model cannot have general applicability, and we must look for a more unified model that can be applied to CO and CO$_2$ in L and T dwarfs. Currently, we have no solution as to the reason why CO$_2$ (and also CO at least partly) is so strong in these objects. If non-equilibrium processes play major roles, we wonder why the departure from LTE can be so significant in the brown dwarf photosphere, where local density is so high that the LTE condition can be naturally satisfied.

More recently, Stephens et al. (2009) analyzed the 0.8–14.5 μm region spectra of many L–T dwarfs and determined not only effective temperature, surface gravity, and grain sedimentation efficiency but also vertical gas transport efficiency, based on the models of Saumon & Marley (2008). They showed that vertical mixing improves the fits and the observed spectra were fitted well in general. It will be interesting to check whether their models can explain the enhanced CO bands in late-L dwarfs.

6. DISCUSSION AND CONCLUDING REMARKS

**AKARI** provides the first and unique opportunity to take brown dwarf spectra in the important wavelength range 2.5–5.0 μm continuously without interference of telluric atmosphere. In particular, molecular bands of CO, CH$_4$, and CO$_2$ altogether in one spectrum present a great advantage for investigating chemical processes in the atmospheres of ultracool dwarfs through quantitative analysis of their carbon budgets. **AKARI** reveals many remarkable features of ultracool dwarfs. Our observations confirm the presence of CO molecules in the brown dwarf atmospheres of all spectral types from L to very late T-type objects. The fact that all observations ever made for the late-T dwarfs have detected CO molecules implies that the non-equilibrium chemical composition is a common property of the late-T dwarfs.

It has been discussed that this non-equilibrium abundance is due to vertical mixing in the upper photosphere. The CO fundamental band in the T8 dwarf 2MASS J041519−0935 and the T4.5 dwarf 2MASS J055191−1404 can be accounted for by the vertical mixing model (Sections 5.1 and 5.2). The idea is also supported by Saumon et al. (2006) and by Mainzer et al. (2007) based on the analysis of the mid-infrared spectrum of T7.5 dwarf GI 5707D taken by Spitzer/IRS. They found that the abundance of the NH$_3$ molecule in the object is almost one order of magnitude smaller than that expected under equilibrium conditions. It is considered that fresh N$_2$ molecules are continuously provided from inside. Also, the vertical mixing model is shown to be consistent with the photometry of a larger sample of brown dwarfs obtained with Spitzer/IRAC (Patten et al. 2006; Leggett et al. 2007).

However, our observations reveal that the CO fundamental band is stronger than predicted by the LTE models in the late-L dwarf (SDSS J083008+4828). Since, unlike in T dwarfs, CO is already highly abundant in the upper photosphere of these objects, no appreciable increase of CO abundance and hence of the CO band strength can be expected by additional CO from the deeper warm layers. For this reason, some mechanism(s) other than vertical mixing should be looked for in late-L dwarfs. This quest is further strengthened by the detection of CO$_2$ by **AKARI** as discussed below.

A new piece of information provided by **AKARI** is the detection of CO$_2$ molecules. The CO$_2$ band is never observable from the ground, and its 4.2 μm band is just outside of Spitzer/IRS coverage. Gas phase CO$_2$ in stellar atmospheres was first detected in late-type giants by ISO/SWS observations. It was rather unexpected that in addition to the stretching-mode absorption band at 4.2 μm, the bending mode ro-vibrational bands in the 15 μm region are often seen in these stars, sometimes in emission (Ryde et al. 1998; Justtanont et al. 1998). The CO$_2$ band is generally stronger than those expected from the LTE models, implying that some kinds of non-equilibrium processes, either formation of the molecule or radiative excitation, might play a role in the atmospheres of such stars. The situation is of course quite different in brown dwarfs, with lower temperature and much higher surface density than in red giants. Some amount of the CO$_2$ molecule is expected under LTE conditions in brown dwarf atmospheres. Though the relative abundance with respect to that of H$_2$O and CH$_4$ is small (Figures 8, 10, and 12), the high $f$-value of this molecule helps to form a rather strong absorption band at 4.2 μm region as shown in Section 4.1 (see Figure 3). However, a simple comparison with the model tells us that observed absorption is much stronger than expected.

We estimate the temperatures and column densities of the extra CO$_2$ and CO absorption components in 2MASS J055919−1404 and SDSS J083008+4828. The observed spectra are divided by the best-fit UCM spectra shown in Figure 6, and the residual spectra are fitted by a two-layer plane-parallel model with given excitation temperature $T_{\text{ex}}$ (K) and column density $N$ (cm$^{-2}$) for each molecule. In this simple model, we adopt a Gaussian line width of FWHM = 30 km s$^{-1}$ based upon measurements of H$_2$O lines by high-resolution spectroscopy in the J band (McLean et al. 2007). Because of the simplicity of the model, the fitting results are suitable mainly for order of magnitude discussions. The excitation temperature is only mildly constrained by the band shape. Nevertheless, we obtain ($T_{\text{ex}}$, $N_{\text{CO}}$) = (800, 5 × 10$^{17}$) and ($T_{\text{ex}}$, $N_{\text{CO}}$) = (1000, 2 × 10$^{20}$) for 2MASS J055919−1404, and ($T_{\text{ex}}$, $N_{\text{CO}}$) = (800, 2.5 × 10$^{17}$) and ($T_{\text{ex}}$, $N_{\text{CO}}$) = (1000, 1.5 × 10$^{19}$) for SDSS J083008+4828, respectively. The results for 2MASS J055919−1404 are presented in Figure 13 as an example. Considering that CO molecules with higher excitation temperature may located in a slightly interior portion of the photosphere, the ratio of the column densities $N_{\text{CO}}$/$N_{\text{CO}}$ = 2 × 10$^{-2}$ to 3 × 10$^{-3}$ indicates lower limits of the abundance ratio of the two molecules. It is found that CO$_2$ is obviously overabundant compared to CO than predicted by the UCM (Figures 10 and 12). This implies that non-equilibrium processes other than vertical mixing may play a role in determining the molecular abundances especially for CO$_2$.

Another possibility is the presence of extended atmosphere beyond the hydrostatic photospheres, similarly in the case of red giants. It is interesting that Spitzer/IRS observation did not detect any clear CO$_2$ bands in the 15 μm region in any brown dwarfs (Roellig et al. 2004; Cushing et al. 2006; Saumon et al. 2006; Mainzer et al. 2007). If the CO$_2$ molecular layer is extended, emission beyond the photosphere could compensate for the absorption and the observed band strength would be weakened. This effect is usually more effective at longer wavelengths. Of course, there is a more conventional explanation: that the heavy opacity of H$_2$O veils the wavelength region completely. The H$_2$O opacity reaches a minimum around 4 μm and makes the 4.2 μm band visible. If this is the case, the CO$_2$ molecules would be located in the same layer, or in layers internal to the H$_2$O. This may be a constraint on constructing chemical models of the brown dwarf atmospheres. High dispersion spectroscopy in the 4 and 15 μm region from space is an ideal tool for investigating this problem.
Although non-equilibrium conditions for the CO/CH$_4$ and NH$_3$/N$_2$ ratios appeared to be explained by the vertical mixing model at least in late-T dwarfs, the unexpected detection of CO$_2$ by AKARI casts doubt as to whether the vertical mixing model alone could explain the carbon chemistry even in late-T dwarfs. In fact, there is no reason why we expect excess CO$_2$ by the vertical mixing model (Section 5.1) and there should be some other mechanism to produce excess CO$_2$. A yet unknown mechanism may affect not only CO$_2$, but also CO. In fact, such a new mechanism could also be what we need to explain the enhancement of CO in late-L to mid-T dwarfs for which the vertical mixing model failed.

We are continuing the AKARI brown dwarf programme with the near-infrared channel of the IRC in the “post-helium” phase (Phase 3). More targets are being observed to cover the spectral ranges from M, L, to T. With the enhanced data set we hope to revise the analysis of Section 4.2. We are grateful to Dr. Gandhi Poshak for his careful checking of the manuscript and constructive comments that especially helped to revise the analysis of Section 4.2. We are grateful to Dr. Tadashi Nakajima for his careful checking of the manuscript and many suggestions to improve the text. Dr. Tadashi Nakajima is appreciated for helpful discussions at an initial phase in making this observing programme. Satoko Sorahana gave us useful comments. This research is based on observations with AKARI, a JAXA project with the participation of ESA. We acknowledge JSPS/KAKENHI(C) No.22540260 (PI: I. Yamamura) and No. 17540213 (PI: T. Tsuji). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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**Figure 13.** AKARI spectrum of 2MASS J055919–1404 divided by the best-fit UCM model and shown in black. Blue line indicates the fitted model spectrum by a plane-parallel configuration with the excitation temperature and the column density of $(T_{ex}, N_{CO}) = (800, 5 \times 10^{17})$ and $(T_{ex}, N_{CO}) = (1000, 2 \times 10^{20})$, respectively.
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