AKARI OBSERVATIONS OF BROWN DWARFS. III. CO, CO2, AND CH4 FUNDAMENTAL BANDS AND PHYSICAL PARAMETERS

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Abstract

We investigate variations in the strengths of three molecular bands, CH4 at 3.3 μm, CO at 4.6 μm, and CO2 at 4.2 μm, in 16 brown dwarf spectra obtained by AKARI. Spectral features are examined along the sequence of source classes from L1 to T8. We find that the CH4 3.3 μm band is present in the spectra of brown dwarfs later than L5, and the CO 4.6 μm band appears in all spectral types. The CO2 absorption band at 4.2 μm is detected in late-L and T-type dwarfs. To better understand brown dwarf atmospheres, we analyze the observed spectra using the Unified Cloudy Model. The physical parameters of the AKARI sample, i.e., atmospheric effective temperature Teff, surface gravity log g, and critical temperature Tcr, are derived. We also model IRTF/SpEX and UKIRT/CGS4 spectra in addition to the AKARI data in order to derive the most probable physical parameters. Correlations between the spectral type and the modeled parameters are examined. We confirm that the spectral-type sequence of late-L dwarfs is not related to Teff, but instead originates as a result of the effect of dust.

Key words: brown dwarfs – stars: atmospheres – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

Brown dwarfs are objects that are too light to sustain hydrogen fusion in their cores. Their effective temperatures are very low, ranging over 2200–600 K. They are classified into L and T spectral types. The discovery of the first genuine brown dwarf, Gl 229B, by Nakajima et al. (1995) triggered active study of these sources. With their intermediate masses and temperatures, brown dwarfs are expected to have the blended properties of stars and planets, bridging the gap between them. However, their properties (for example, their dusty atmospheres) make them unique enough to be classed separately, and it is not straightforward to understand their internal physical and chemical processes from our knowledge of stars and planets. Studies of brown dwarf atmospheres will lead us to a more comprehensive understanding of the nature of “atmospheres” of various objects from stars to planets.

The photospheres of brown dwarfs are cool and dense (log Pp ~ 6.0 dyn cm−2, where Pp is the total gas pressure), and are thus dominated by molecules and dust. The chemistry of the photosphere and the resultant molecular abundances govern the presence of spectral features. Hydrogen is predominantly in the form of H2. The dominant equilibrium forms of carbon are CO and CH4, oxygen is in H2O, and nitrogen is in N2 and NH3. Silicates, TiO, and VO are found in objects with temperatures Teff above 1600–2000 K (Burrows et al. 2001). Neutral alkali metals are found at Teff of ~ 1000 K (Fegley & Lodders 1996). These values are derived by solving for thermochemical equilibrium.

Condensation of dust under a thermochemical equilibrium photosphere was discussed as early as the 1960s (e.g., Lord 1965; Larimer 1967; Larimer & Anders 1967). The major elements that construct dust grains are Fe, Mg, Si, O, Ca, Ti, and Al. When temperature decreases below a certain threshold (~2000 K), condensation starts in the photosphere. For L dwarfs dust exists in the upper photosphere and contributes to its spectral features. Dust in the photosphere contributes to the spectra directly by filling in the molecular absorption bands and by extinction. Dust also contributes indirectly by changing the thermal structure of the photosphere. On the other hand, for T dwarfs with lower Teff, dust disappears from the photosphere and does not play any role in the spectral features.

Since almost all carbon atoms are in CH4 rather than CO in the photospheres of T dwarfs with Teff less than about 1300 K under thermochemical equilibrium, we expected the CO absorption band not to be present in the spectra of these coldest dwarfs. As we describe below, observations have shown us that this is not the case. Several observations from the ground have detected the CO absorption band at 4.6 μm in late-T dwarfs against theoretical expectation based on the local thermodynamical equilibrium (LTE). The band was observed in the T6 dwarf Gl 229B (Oppenheimer et al. 1998; Noll et al. 1997) and in the T8 dwarf Gl 570D (Geballe et al. 2009). Another example of deviation from the thermal equilibrium chemistry was found in the nitrogen-containing molecules observed by the Spitzer Space Telescope. The NH3 absorption band at 10.5 μm was much weaker than that expected from the atmospheric model (Saumon et al. 2006). Although we do not know how common these phenomena are, these discrepancies between observed and model spectra have been critical problems in the study of brown dwarf atmospheres. To interpret the non-LTE abundances of these molecules, Griffith & Yelle (1999) suggested that “vertical mixing” plays a role, in which CO molecules are dredged up from inner warm areas to outer cooler regions in the photosphere. However, the paucity of data to date did not allow us to assess the relevance of this suggestion, and more spectroscopic data are required to investigate the above discrepancies.

Spectroscopic observations in the infrared regime are the most powerful tools used to obtain physical and chemical information about brown dwarf photospheres, since brown dwarfs emit the majority of their radiative energy over this regime, and
various molecular and dust features can be found therein. In the wavelength range of 2.5–5.0 μm, there are several prominent molecular absorption bands: the CH$_4$ ν$_3$ fundamental band at 3.3 μm, the CO$_2$ ν$_3$ fundamental band at 4.2 μm, the CO fundamental band at 4.6 μm, and the H$_2$O ν$_1$ and ν$_3$ absorption bands around 2.7 μm. The CO, CH$_4$, and H$_2$O absorption bands are also present in the shorter wavelength range (≤ 2.5 μm), and spectra of these bands have been used in previous studies of brown dwarf atmospheres. However, it is difficult to analyze these molecular bands independently because they are blended in the observed spectra. In addition, almost all absorption bands present at wavelengths shorter than 2.5 μm, for example, CO at 2.3 μm and CH$_4$ at 1.6 and 2.2 μm, are overtone bands, and are about 10–100 times weaker than the fundamental bands in 2.5–5.0 μm. These fundamental bands are mostly non-blended and suitable for detailed analysis in the moderate-resolution spectra. However, observations in this wavelength range from the ground are always challenging. Severe absorption due to Earth’s atmosphere and limited wavelength coverage make precise analysis difficult.

The Japanese infrared astronomical satellite AKARI (Murakami et al. 2007) was launched in 2006 February. The InfraRed Camera (IRC; Onaka et al. 2007) onboard AKARI is capable of yielding moderate-resolution (R ~ 120) spectra in this important wavelength range devoid of any degradation by telluric features. We have conducted an observing program using the IRC to obtain continuous spectra of brown dwarfs in 2.5–5.0 μm wavelengths with the aim of carrying out systematic studies of physical and chemical processes in their atmospheres. Continuous spectra of brown dwarfs in 2.5–5.0 μm were obtained by AKARI for the first time, and provided new insight into the brown dwarf atmosphere.

The initial results based on the AKARI spectra of six brown dwarfs taken in the liquid-He cooled phase (Phase 2; see Section 2.1) are reported in Yamamura et al. (2010) and Tsuji et al. (2011). Yamamura et al. (2010) found that the observed CO band strength at 4.6 μm in late-L to late-T dwarfs is not consistent with predictions and attempted to explain the discrepancy of the CO band strength in late-L to late-T dwarfs by vertical mixing effects. They argue that the CO band in late-T dwarfs could be reproduced by this effect, but earlier brown dwarfs between late-L and mid-T dwarfs are not. The CO$_2$ absorption band at 4.2 μm in one L dwarf and two T dwarfs was also stronger than expected. They find that the excess of CO$_2$ abundance cannot be explained by vertical mixing either. Tsuji et al. (2011) suggested that a possible reason of the 4.2 μm CO$_2$ absorption feature in the late-L and T-type spectra is higher than solar C and O elemental abundances used in the previous studies.

In this paper, we summarize the observation and data reduction of AKARI brown dwarf spectra in 2.5–5.0 μm and present the results of systematic analysis of 16 brown dwarf spectra covering a wide range of spectral types from L to T including those taken in the warm phase (Phase 3; see Section 2.1).

2. OBSERVATIONS AND DATA REDUCTION

2.1. AKARI

AKARI is equipped with an infrared telescope with an aperture of 68.5 cm. It was sensitive over the wavelength range from 1.7 to 180 μm with two scientific instruments; the Far-Infrared Surveyor (Kawada et al. 2007) and the IRC. AKARI’s primary mission was to carry out an all-sky survey in six bands, with a better sensitivity and spatial resolution than the previous survey by the IRAS mission (Neugebauer et al. 1984). Thousands of pointed observations were also carried out. The liquid-He cool holding period of observations (Phase 1, 2) lasted from 2006 May until 2007 August. After the boil-off of liquid-He, observations were continued with cryocooler only with the near-infrared camera of the IRC (Phase 3).

2.2. The InfraRed Camera (IRC)

The IRC onboard AKARI covers the wavelength range of 1.8–26.5 μm with three independent cameras operating simultaneously, namely, the NIR (near-infrared), MIR-S (mid-infrared short), and MIR-L (mid-infrared long) channels. Our observations were carried out in the Astronomical Observation Template IRC04 for Phase 2 and IRCZ4 for Phase 3, with the observation parameter of “b:Np” (Lorente et al. 2008). In this mode, the entire 2.5–5.0 μm wavelength range is covered with a grism with a dispersion of 0.0097 μm pixel$^{-1}$ or an effective spectral resolution of $R = \lambda / \Delta \lambda \approx 120$ at 3.6 μm for point sources (Ohyama et al. 2007). The source was placed in the 1 × 1 arcmin$^2$ aperture, referred to as “Np,” prepared for spectroscopy of point sources, preventing contamination of the spectra from nearby sources. A pointed observation by AKARI allowed about 10 minute exposure.

2.3. The Mission Program NIRLT

AKARI observation programs are classified into three categories, Large-Area Surveys organized by the project, Mission Programs (MP) by the project members, and Open-Time programs. We have conducted an MP titled “Near-InfraRed spectroscopy of L and T dwarfs” (NIRLT; P.I. I. Yamamura) to obtain full NIR band spectra of brown dwarfs using the IRC. The program aimed at constructing a set of legacy data for studies of the physical and chemical structure of brown dwarfs over a wide range of spectral types from L to T.

Our target list included 40 objects selected by their expected fluxes (to be bright enough for the AKARI/IRC instrument to provide high-quality spectra within a reasonable amount of exposure time) and their spectral types (to sample various types from M to T). 9 M dwarfs, 17 L dwarfs, and 14 T dwarfs were included in the target list.

2.4. Observations

Thirty-five dwarfs (15 L, 11 T, and 9 M) were observed, and thirty-three objects (14 L dwarfs, 10 T dwarfs, and 9 M dwarfs) were detected. In addition, data for the L dwarf GJ 1001B were also obtained as part of the observation of its primary star, the M dwarf GJ 1001A. We list the 27 observed L and T dwarfs in Table 1. Table 2 summarizes all NIRLT observation records. We observed 10 brown dwarfs in Phase 2, and 17 sources in Phase 3.

2.5. Data Reduction

The standard software toolkit IRC_SPEC_TOOLKIT (Ohyama et al. 2007) was used for data reduction. We used the toolkit version 20110301, released in 2011 March. Wavelength and flux calibrations were all done automatically in the toolkit. Spectral data are extracted from two-dimensional spectral images. The two axes of the images correspond to spatial and wavelength directions, respectively. Along the spatial direction, the signal is extended by the point-spread function (PSF), and along the wavelength direction the signal extension is determined by
the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or

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**Table 1**

| Object Name | Object Name in This Paper |
|-------------|---------------------------|
| 2MASS J14392837+1929150 | 2MASS J1439+1929 |
| GD 165B | GD 165B |
| Kulu-1 | Kulu-1 |
| 2MASS J00361617+1821104 | 2MASS J0036+1821 |
| 2MASS J2224381−0158521 | 2MASS J2224−0158 |
| 2MASS J05959200−0059019 | 2MASS J0595−0059 |
| SDSS J144600.60+002452.0 | SDSS J1446+0024 |
| 2MASS J15074769−1627386 | 2MASS J1507−1627 |
| GI 1001B | GI 1001B |
| 2MASS J08251968+2115521 | 2MASS J0825+2115 |
| 2MASS J11711457+2320444 | 2MASS J1171+2320 |
| 2MASS J16322911+1904407 | 2MASS J1632+1904 |
| 2MASS J15232263+3014562 | 2MASS J1523+3014 |
| SDSS J083008.12+482647.4 | SDSS J0830+4826 |
| 2MASS J03105986+1648155 | 2MASS J0310+1648 |
| 2MASS J03284265+482357.9 | 2MASS J0328+4823 |
| SDSS J042438.57−014034.3 | SDSS J0424−0140 |
| SDSS J125453.90−012247.4 | SDSS J1254−0122 |
| SIMP J013656.5+003347.3 | SIMP J0136+0033 |
| SDSS J175032.96+175039.3 | SDSS J1750+1750 |
| 2MASS J05591914−1404488 | 2MASS J0559−1404 |
| GI 229B | GI 229B |
| 2MASS J15530228+1532369 | 2MASS J1553+1532 |
| 2MASS J12171100−031131 | 2MASS J1217−0311 |
| GI 57OD | GI 57OD |
| 2MASS J04151954−0935066 | 2MASS J0415−0935 |

Notes. Reference of spectral type (1) Kirkpatrick et al. 2000; (2) Geballe et al. 2002; (3) Burgasser et al. 2006. Distances are estimated based on trigonometric parallaxes. The parallaxes are referred from (a) Dahn et al. 2002; (b) Vrba et al. 2004; (c) Stumpf et al. 2010; (d) Artigau et al. 2006; (e) Jameson et al. 2008; (f) Burgasser et al. 2000; (g) King et al. 2010.

This process was partially applied to GJ 1001B. GJ 1001 is a low-mass binary system, with GJ 1001B being the companion of the M dwarf, GJ 1001A. The difference in the magnitude is about 3 mag at the L′ band, e.g., GJ 1001A is about 16 times brighter than GJ 1001B. Since the separation between GJ 1001B and GJ 1001A is only 13 arcsec (11 pixels on the detector), the spectrum of GJ 1001B was contaminated by a shoulder of intense signal from GJ 1001A, as the PSF of the IRC/NIR channel has an FWHM ~ 3.2 pixels. To measure the signal of GJ 1001B accurately, we took into account the extended signal of GJ 1001A.

Since brown dwarfs are generally very faint (a few mJy < \(F_\nu\) < 25 mJy), one pointed observation is not always sufficient to obtain good quality data. This is especially true for the Phase 3 observations, where the noise level is about a factor of 2.5 higher than that of Phase 2. Six to eight spectral frames were taken per pointing (Lorente et al. 2008). The toolkit stacks all available exposure frames within a pointing. We observed each object at least twice, unless the observations failed for some reason. The toolkit does not stack the frames over multiple pointings. For this, we used additional customized programs; IRC\_SPEC\_TOOLKIT\_w\_STACKMULTI version 20100918 (T. Shimonishi 2010, private communication). The fourth and fifth columns in Table 3 show the number of pointings and the total number of frames used in the data reduction, respectively. The stacked data are better than single pointing data. When an object was observed both in Phase 2 and Phase 3, we used only Phase 2 data.

2.5.3. Subtraction of Signal from a Nearby Object

We modified the IRC\_SPEC\_TOOLKIT program to improve the sky subtraction. The original program subtracts the sky derived from same pixel width with the on source signal. Since the Phase 3 data are noisier than those in the Phase 2, the sky level derived from only a few pixels (3–5 pixels) is not sufficiently flat. The revised program derives the sky level using a larger area (~10 pixels).

2.5.2. Stacking of Multiple Observations

Since brown dwarfs are generally very faint (a few mJy < \(F_\nu\) < 25 mJy), one pointed observation is not always sufficient to obtain good quality data. This is especially true for the Phase 3 observations, where the noise level is about a factor of 2.5 higher than that of Phase 2. Six to eight spectral frames were taken per pointing (Lorente et al. 2008). The toolkit

the spectral resolution and the PSF. The typical wavelength calibration error is 0.5 pixel of the detector or

\[0.005 \mu \text{m}\] (Ohyama et al. 2007), but could be larger in some cases (see Table 3). We applied small corrections (0.01–0.03 \(\mu \text{m}\)) to the data of several sources by comparing the position of the CH\(_4\) Q-branch feature with other objects. The overall flux calibration error is 10% in the middle of the wavelength range, and 20% at the short/long wavelength edges.

We carried out the following three additional processing steps in order to improve the final data quality: (1) derivation of appropriate sky background, (2) stacking of multiple observations, and (3) correction of contaminating light from nearby objects.

### 2.5.1. Derivation of Probable Sky Background

We modified the IRC\_SPEC\_TOOLKIT program to improve the sky subtraction. The original program subtracts the sky derived from same pixel width with the on source signal. Since the Phase 3 data are noisier than those in the Phase 2, the sky level derived from only a few pixels (3–5 pixels) is not sufficiently flat. The revised program derives the sky level using a larger area (~10 pixels).

### 2.5.2. Stacking of Multiple Observations

Since brown dwarfs are generally very faint (a few mJy < \(F_\nu\) < 25 mJy), one pointed observation is not always sufficient to obtain good quality data. This is especially true for the Phase 3 observations, where the noise level is about a factor of 2.5 higher than that of Phase 2. Six to eight spectral frames were taken per pointing (Lorente et al. 2008). The toolkit...
### Table 2

Summary of the Observations in the NIRLT Program

| Object Name | Sp. Type | Date          | ObsID             | Remarks         |
|-------------|----------|---------------|-------------------|-----------------|
| 2MASS J14392+1929 | L1       | 2008 Jul 22   | 1770009-001       | Wrong coordinate |
| 2MASS J14392+1929 | L1       | 2008 Jul 22   | 1770009-002       | Wrong coordinate |
| 2MASS J14392+1929 | L1       | 2010 Jan 19   | 1771009-001       |                 |
| GD 165B      | L3       | 2007 Jul 24   | 1720074-001       |                 |
| GD 165B      | L3       | 2008 Jul 22   | 1770010-001       |                 |
| GD 165B      | L3       | 2010 Jan 20   | 1771010-001       | Too faint       |
| GD 165B      | L3       | 2010 Jan 20   | 1771010-002       | Too faint       |
| GD 165B      | L3       | 2010 Jan 20   | 1771010-003       | Too faint       |
| GD 165B      | L3       | 2010 Jan 20   | 1771010-004       | Too faint       |
| Kelu–1       | L3       | 2008 Jul 16   | 1770018-001       | Wrong coordinates |
| Kelu–1       | L3       | 2008 Jul 16   | 1770018-002       | Wrong coordinates |
| 2MASS J0036+1821 | L4       | 2008 Jul 6    | 1770024-001       |                 |
| 2MASS J0036+1821 | L4       | 2008 Jul 6    | 1770024-002       |                 |
| 2MASS J0036+1821 | L4       | 2010 Jan 5    | 1771024-001       |                 |
| 2MASS J2224–0158 | L4.5     | 2009 May 29   | 1770019-001       |                 |
| SDSS J0539+0456 | L5       | 2006 Sep 17   | 1720009-001       |                 |
| SDSS J0539+0456 | L5       | 2009 Sep 16   | 1770007-001       |                 |
| SDSS J1446+0024 | L5       | 2007 Aug 2    | 1720072-001       |                 |
| 2MASS J1507–1627 | L5       | 2008 Aug 12   | 1770020-001       |                 |
| 2MASS J1507–1627 | L5       | 2009 Feb 7    | 1770120-001       |                 |
| 2MASS J0825+2115 | L6       | 2008 Oct 26   | 1770016-001       |                 |
| 2MASS J0825+2115 | L6       | 2009 Apr 23   | 1770016-002       |                 |
| 2MASS J0825+2115 | L6       | 2009 Oct 26   | 1771016-001       |                 |
| 2MASS J1711+2232 | L6.5     | 2007 Mar 5    | 1720001-001       |                 |
| 2MASS J1711+2232 | L6.5     | 2008 Sep 5    | 1770001-001       | Data lost       |
| 2MASS J1711+2232 | L6.5     | 2008 Sep 5    | 1770001-002       | Data lost       |
| 2MASS J1632+1904 | L7.5     | 2009 Feb 21   | 1770025-001       | Too faint       |
| 2MASS J1632+1904 | L7.5     | 2009 Feb 21   | 1770025-002       | Too faint       |
| SDSS J1523+3014 | L8       | 2007 Jan 26   | 1770002-001       |                 |
| SDSS J1523+3014 | L8       | 2008 Jul 30   | 1770002-002       |                 |
| SDSS J0830+4828 | L9       | 2006 Oct 20   | 1720007-001       |                 |
| SDSS J0830+4828 | L9       | 2006 Oct 21   | 1720007-002       |                 |
| SDSS J0830+4828 | L9       | 2009 Apr 17   | 1770006-001       |                 |
| 2MASS J0310+1648 | L9       | 2008 Aug 12   | 1770011-001       |                 |
| 2MASS J0310+1648 | L9       | 2008 Aug 13   | 1770011-002       |                 |
| 2MASS J0328+2302 | L9.5     | 2009 Aug 19   | 1770027-001       | Too faint       |
| 2MASS J0328+2302 | L9.5     | 2010 Feb 14   | 1771027-001       | Too faint       |
| 2MASS J0328+2302 | L9.5     | 2010 Feb 14   | 1771027-002       | Too faint       |
| SDSS J0423–0414 | T0       | 2008 Aug 25   | 1770015-001       |                 |
| SDSS J0423–0414 | T0       | 2008 Aug 25   | 1770015-002       |                 |
| SDSS J1125–0122 | T2       | 2008 Jul 3    | 1770012-001       | Wrong coordinates |
| SDSS J1125–0122 | T2       | 2008 Jul 4    | 1770012-002       | Wrong coordinates |
| SIMP J0136+0933 | T2.5     | 2008 Jul 17   | 1770031-001       |                 |
| SIMP J0136+0933 | T2.5     | 2008 Jul 17   | 1770031-002       |                 |
| SIMP J0136+0933 | T2.5     | 2010 Jan 16   | 1771031-001       |                 |
| SIMP J0136+0933 | T2.5     | 2010 Jan 16   | 1771031-002       |                 |
| SDSS J1750+1759 | T3.5     | 2007 Mar 17   | 1720050-001       | Too faint       |
| SDSS J1750+1759 | T3.5     | 2007 Mar 17   | 1720050-002       | Too faint       |
| 2MASS J0559–14044 | T4.5    | 2006 Sep 22   | 1720006-001       |                 |
| 2MASS J0559–14044 | T4.5    | 2006 Sep 22   | 1720008-001       |                 |
| 2MASS J0559–14044 | T4.5    | 2008 Sep 22   | 1770005-001       |                 |
| 2MASS J0559–14044 | T4.5    | 2008 Sep 22   | 1770005-002       |                 |
| GI 229B      | T6       | 2008 Sep 25   | 1770013-001       | Contaminated    |
| GI 229B      | T6       | 2008 Sep 25   | 1770013-002       | Contaminated    |
| 2MASS J1553+1532 | T7       | 2008 Aug 15   | 1770022-001       |                 |
| 2MASS J1553+1532 | T7       | 2008 Aug 15   | 1770022-002       |                 |
| 2MASS J1553+1532 | T7       | 2008 Aug 15   | 1770022-003       |                 |
Table 2 (Continued)

| Object Name         | Sp. Type | Date      | ObsID          | Remarks     |
|---------------------|----------|-----------|----------------|-------------|
| 2MASS J1553+1532    | T7       | 2009 Feb 9| 1770022-004    |             |
| 2MASS J1553+1532    | T7       | 2009 Feb 9| 1771022-001    | Too faint   |
| 2MASS J1553+1532    | T7       | 2009 Feb 9| 1771022-002    | Too faint   |
| 2MASS J1217−0311    | T7.5     | 2007 Jun 26| 1720068-001    | Too faint   |
| Gl 570D             | T8       | 2009 Aug 10| 1770023-001    |             |
| Gl 570D             | T8       | 2009 Aug 10| 1770023-002    |             |
| Gl 570D             | T8       | 2009 Aug 10| 1770023-003    |             |
| 2MASS J0415−0935    | T8       | 2007 Feb 18| 1720005-001    | Ghosting    |
| 2MASS J0415−0935    | T8       | 2007 Feb 18| 1720005-002    | Ghosting    |
| 2MASS J0415−0935    | T8       | 2007 Aug 24| 5125080-001    | DT          |
| 2MASS J0415−0935    | T8       | 2008 Aug 21| 1770004-001    | Too faint   |
| 2MASS J0415−0935    | T8       | 2008 Aug 21| 1770004-002    | Too faint   |
| 2MASS J0415−0935    | T8       | 2008 Aug 21| 1770004-003    | Too faint   |
| 2MASS J0415−0935    | T8       | 2008 Aug 21| 1770004-004    | Too faint   |
| ϵ Ind Ba+Bb         | T1+T6    | 2006 Nov 2| 1720003-001    |             |
| ϵ Ind Ba+Bb         | T1+T6    | 2006 Nov 2| 1720004-001    |             |
| ϵ Ind Ba+Bb         | T1+T6    | 2008 Nov 1| 1770003-001    |             |
| ϵ Ind Ba+Bb         | T1+T6    | 2008 Nov 1| 1770003-002    |             |

Notes. Wrong coordinates: observed with wrong coordinates. Data lost: data downlink failed due to troubles in the ground system. Too faint: the object was too faint. Contaminated: not able to extract the source spectrum due to heavy contamination from the nearby bright star. Ghosting: the data were not obtained due to instrumental ghosting. DT: observed as part of Director’s Time.

Table 3

| Object Name         | Sp. Type | x Shift (μm) | Number of Pointings | Total Number of Flames | Remarks     |
|---------------------|----------|--------------|---------------------|------------------------|-------------|
| 2MASS J1439+1929    | L1       | 0.00         | 2                   | 14                     |             |
| GD 165B             | L3       | 0.00         | ...                 | ...                    | Too faint   |
| Kelu−1              | L3       | ...          | ...                 | ...                    | Not detected|
| 2MASS J0036+1821    | L4       | 0.015        | 2                   | 15                     |             |
| 2MASS J2224−0158    | L4.5     | −0.010       | 2                   | 16                     |             |
| SDSS J0539−0059     | L5       | 0.00         | 1                   | 9                      |             |
| SDSS J1446+0024     | L5       | 0.00         | 1                   | 9                      |             |
| 2MASS J1507−1627    | L5       | −0.020       | 1                   | 7                      |             |
| GJ 1001B            | L5       | 0.00         | 1                   | 9                      |             |
| 2MASS J0825+2115    | L6       | 0.00         | 4                   | 31                     |             |
| 2MASS J1711+2232    | L6.5     | 0.00         | 1                   | 9                      | Too faint   |
| 2MASS J1632+1904    | L7.5     | 0.00         | 2                   | 15                     |             |
| 2MASS J1523+3014    | L8       | −0.030       | 1                   | 9                      |             |
| SDSS J0830+4828     | L9       | 0.00         | 1                   | 9                      |             |
| 2MASS J0310+1648    | L9       | 0.00         | 2                   | 12                     | Binary      |
| 2MASS J0328+2302    | L9.5     | ...          | ...                 | ...                    | Too faint   |
| SDSS J0423−0414     | T0       | 0.00         | 1                   | 9                      | Binary      |
| SDSS J1254−0122     | T2       | 0.00         | 1                   | 9                      |             |
| SIMP J0136+0933     | T2.5     | 0.010        | 4                   | 31                     | Too faint   |
| SDSS J1750+1759     | T3.5     | ...          | ...                 | ...                    | Too faint   |
| 2MASS J0559−14044   | T4.5     | 0.00         | 1                   | 9                      |             |
| Gl 229B             | T6       | ...          | ...                 | ...                    | Contamination|
| 2MASS J1553+1532    | T7       | −0.010       | 4                   | 24                     | Binary      |
| 2MASS J1217−0311    | T7.5     | ...          | ...                 | ...                    | Too faint   |
| Gl 570D             | T8       | 0.00         | 4                   | 28                     |             |
| 2MASS J0415−0935    | T8       | −0.020       | 1                   | 9                      |             |
| Ind Ba+Bb           | T1+T6    | 0.00         | 1                   | 9                      | Binary      |

2.6. Validation of Absolute Flux Calibration

Among the observed 25 brown dwarfs (15 L dwarfs and 10 T dwarfs) by AKARI, 16 sources (11 L dwarfs and 5 T dwarfs) present high-quality spectra whose averaged signal-to-noise ratio (S/N) is higher than about 3.0. The corresponding flux level is about 1 mJy for the Phase 2 data and 2.5 mJy for the Phase 3 data. The highest S/N and mean S/N are about 18 and 8, respectively. Four known binary brown dwarfs, ϵ Ind Ba+Bb (T1+T6), SDSS J0423−3014 (T0), 2MASS J0310+1648 (L9),
and 2MASS J1553+1532 (T7), are excluded. The data set is summarized in Table 4. 6 objects taken in Phase 2 and 10 objects in Phase 3 are used for the analysis in this paper.

We checked AKARI’s absolute flux calibration by comparing the $L'$ band fluxes with past photometry from Leggett et al. (2002a, 2002b) and Golimowski et al. (2004; Table 4). We derive the $L'$ fluxes from AKARI spectra by applying the Mauna Kea Observatory (M KO) $L'$ filter used by Leggett et al. (2002a, 2002b) and Golimowski et al. (2004). The 50% cutoff wavelength of the filter is $3.43\, \mu m$ and $4.11\, \mu m$. No previous $L'$ photometry data are available for SIMP J0136+0933. Figure 1 shows the comparison of the $L'$ flux from AKARI (hereafter $L'_{A}$) and past $L'$ photometry values. We see that the $L'_{A}$ are consistent with the past $L'$ photometry to within 10%.

3. THE 2.5–5.0 $\mu m$ SPECTRAL DATA SET OF BROWN DWARFS

Figure 2 shows the spectra of the brown dwarfs in the sequence of their spectral types from L (left bottom) to T (right top).

### Table 4

Infrared Magnitudes and Colors of the Analyzed Brown Dwarfs

| Object Name | Sp. Type | $L'$ | $L'_{A}$ | [3.3]–$L'_{A}$ | $J$–$L'_{A}$ | $J$–$K$ | $J$ |
|-------------|----------|------|----------|-------------|-------------|--------|------|
| 2MASS J1439+1929 | L1 | 10.80$^1$ | 10.87(0.003) | 0.47 | 1.79 | 1.20 | 12.66$^4$ |
| 2MASS J0036+1821 | L4 | 10.08$^1$ | 10.11(0.002) | 0.46 | 2.20 | 1.36 | 12.31$^1$ |
| 2MASS J2224–0158 | L4.5 | 10.90$^1$ | 10.87(0.002) | 0.45 | 3.02 | 1.97 | 13.89$^5$ |
| GI 1001B | L5 | 10.41$^2$ | 10.38(0.004) | 0.47 | 2.68 | 1.68 | 13.06$^6$ |
| SDSS J1446+0024 | L5 | 12.54$^3$ | 12.67(0.004) | 0.94 | 2.89 | 1.81 | 15.56$^1$ |
| SDSS J0539–0059 | L5 | 11.32$^1$ | 11.29(0.001) | 0.57 | 2.56 | 1.37 | 13.85$^2$ |
| 2MASS J1157–1627 | L5 | 9.98$^1$ | 10.10(0.002) | 0.58 | 2.60 | 1.45 | 12.70$^1$ |
| 2MASS J0825+2115 | L6 | 11.53$^1$ | 11.52(0.004) | 0.80 | 3.37 | 1.94 | 14.89$^1$ |
| 2MASS J1632+1904 | L7.5 | 12.54$^1$ | 12.45(0.009) | 0.96 | 3.32 | 1.81 | 15.77$^1$ |
| 2MASS J1523+3014 | L8 | 12.86$^1$ | 12.84(0.004) | 0.90 | 3.11 | 1.82 | 15.95$^1$ |
| SDSS J0830+4828 | L9 | 11.98$^1$ | 12.08(0.003) | 1.11 | 3.14 | 1.61 | 15.22$^1$ |
| 2MASS J1507+0432 | L8 | 12.25$^1$ | 12.35(0.010) | 1.48 | 2.31 | 0.93 | 14.66$^1$ |
| SDSS J1404+0024 | L9 | 10.41$^2$ | 10.38(0.004) | 0.47 | 2.68 | 1.68 | 13.06$^6$ |
| 2MASS J0415–0935 | L5 | 11.32$^1$ | 11.29(0.001) | 0.57 | 2.56 | 1.37 | 13.85$^2$ |

**Notes.** The error in $L'$ and $J$ is typically 5%. SIMP J0136+0933 is calibrated with 2MASS photometric data. $L'$ and $J$ magnitudes are from $^1$Leggett et al. (2002a), $^2$Leggett et al. (2002b), $^3$Golimowski et al. (2004), $^4$No data, $^5$Knapp et al. (2004), and $^6$Skrutskie et al. (2006) $J$–$K$ colors are derived from IRTF/SpEx and UKIRT/CGS4 data (see Section 4.2.1 and 4.2.2 with the M KO $J$ and $K$ filters).

The following molecular absorption bands are clearly recognized in the AKARI data: $H_2O$ (broad absorption bands around $2.7\, \mu m$ and at longer than $4.0\, \mu m$), $CO$ ($4.6\, \mu m$), $C_2H_6$ ($4.2\, \mu m$), and $CH_4$ ($3.3\, \mu m$). Figure 2 shows identification of these bands in the AKARI spectra. The AKARI spectra of L-type dwarfs generally peak at $3.8\, \mu m$ and are rather smooth and featureless with the current resolution throughout $2.5–5.0\, \mu m$, except for the positions of $H_2O$ and $CO$. $CH_4$ at $3.3\, \mu m$ exists in the dwarfs later than L5. On the other hand, the spectra of T-type dwarfs exhibit deep molecular absorption features further to the broad $H_2O$ bands and $CO$ band.

### 3.1. CO Absorption Band at 4.6 $\mu m$

Under the assumption of LTE, CO is expected to disappear from the spectra of the late-T-type dwarfs because carbon resides mostly in $CH_4$ rather than in $CO$ in a very cool and high-density ($T \sim 1000$ K, log $P_g \sim 6.0$ dyn cm$^{-2}$) environment (Tsuji 1964). Only a few brown dwarf spectra have been obtained in the $M$-band wavelength range (Noll et al. 1997; Oppenheimer et al. 1998; Geballe et al. 2009). They all showed the detections of the CO absorption band in the spectra of mid- to late-T dwarfs. These results raised a very important problem regarding the physics and chemistry of brown dwarf atmospheres. However, due to disturbance caused by Earth’s atmosphere, the quality of these data was not sufficient and the wavelength coverage was limited. Thus, detailed analysis of these bands was not easy.

We have obtained much better spectra covering a broader range including the CO band with AKARI. The AKARI data show that CO appears in all observed brown dwarf spectra from early-L to late-T type. We confirm that the spectra of our T-type brown dwarfs clearly exhibit the CO absorption band, supporting the previous ground-based studies. It is now clear that the presence of CO in the late-T dwarfs is a common characteristic. It has been argued that CO in the photosphere of late-T dwarfs is maintained by vertical mixing (Griffith & Yelle 1999; Saumon et al. 2000; Yamamura et al. 2010). The vertical mixing transfers CO molecules from the inner regions, where CO is still abundant, to outer cooler regions in the photosphere.
Figure 2. AKARI spectra of 11 L dwarfs and 5 T dwarfs. Data taken in Phase 2 are shown as the blue line and that in Phase 3 are drawn in red. The Phase 2 data are generally of better quality than the Phase 3 data. The CO 4.6 µm band appears in the spectra of all spectral types. The CH$_4$ 3.3 µm fundamental band appears in the spectra later than L5. The band is seen in SDSS J0539−0059 and 2MASS J1507−1627, but not in the other two L5 sources, GJ 1001B and SDSS J1446+0024. The CO$_2$ absorption band at 4.2 µm presents in the spectra of late-L and T-type dwarfs. The band appears clearly in the spectra of 2MASS J0825+2115 (L6) and SDSS J0830+4828 (L9), but not in the spectrum of 2MASS J1523+3014 (L8).

(A color version of this figure is available in the online journal.)
3.2. CO$_2$ Absorption Band at 4.2 $\mu$m

AKARI detected CO$_2$ absorption band at 4.2 $\mu$m in the spectra of brown dwarfs. The band is recognized in all T dwarfs and some late-L dwarfs. We see the band in the spectra of 2MASS J0825+2115 (L6) and SDSS J0830+4828 (L9) clearly, but not in the spectra of late-L to early-T dwarfs. However, we see the band in only two sources out of four L5 dwarfs in our AKARI sample. The band is seen in SDSS J0539−0059 and 2MASS J1507−1627, but not in the other two L5 sources, SDSS J1446+0024 and GJ 1001B (Figure 2).

3.3. CH$_4$ Absorption Band at 3.3 $\mu$m

It is known that the CH$_4$ $\nu_3$ absorption band at 3.3 $\mu$m already appears in the spectra of a mid-L dwarf (Noll et al. 2000), but the CH$_4$ $\nu_2 + \nu_3$ absorption band at 2.2 $\mu$m which is used for the classification of T-type dwarfs was not detected in the spectra of the same L dwarf (Nakajima et al. 2004). The AKARI data including the 3.3 $\mu$m region should enhance our understanding of the CH$_4$ molecule in the photospheres of L dwarfs. We find that the CH$_4$ 3.3 $\mu$m fundamental band appears in the spectra of brown dwarfs later than L5. Interestingly, we see the band in only two sources out of four L5 dwarfs in our AKARI sample. The band is seen in SDSS J0539−0059 and 2MASS J1507−1627, but not in the other two L5 sources, SDSS J1446+0024 and GJ 1001B (Figure 2).

3.3.1. Equivalent Width of the CH$_4$ Absorption Band

We examine the appearance of the CH$_4$ band quantitatively in the AKARI spectra from L1 to L9 dwarfs to confirm this result in detail. In L dwarfs, the CH$_4$ band is still weak and only the Q-branch feature is prominent. We derive the equivalent width of the 3.3 $\mu$m CH$_4$ Q-branch feature in each spectrum, and calculated the ratio between the equivalent width and its uncertainty derived from the standard deviation of the data in the nearby off-feature wavelengths. We evaluate the “CH$_4$ index” $B_{\text{CH}_4}$ as

$$B_{\text{CH}_4} = \frac{\text{EW}}{\left(\frac{\sigma}{F_{\text{center}}}\right) \times d\lambda \times \sqrt{N - 1}},$$

where EW is the equivalent width, $\sigma$ is the standard deviation in the off-band wavelengths, $F_{\text{center}}$ is the estimated flux at the wavelength of the band center derived by linear interpolation from the off-feature region fluxes, $d\lambda$ is the wavelength grid interval, and $N$ ($\sim 20$) is the number of data points within the defined region. We show the results in Table 5 and Figure 4. We regard the detection to be significant when $B_{\text{CH}_4}$ is larger than 5. This threshold is chosen because of the following reasons: the $B_{\text{CH}_4}$ of the L7.5 dwarfs where the CH$_4$ band is confirmed by eye is 5.25. For L1 and L4 dwarfs where the band is not confirmed, $B_{\text{CH}_4}$ is 4.12 and 4.24, respectively. We find that the CH$_4$ 3.3 $\mu$m fundamental band is seen at L5 type, and the band appears in only two of the L5 dwarfs, SDSS J0539−0059 and 2MASS J1507−1627. The detection of the...
CH$_4$ absorption band in the spectra of 2MASS J1507$-$1627 is consistent with the past result reported by Noll et al. (2000).

3.3.2. Color Index [3.3]$-\lambda_A$

$B_{CH_4}$ used in the previous section is only applicable for L-type dwarfs. The CH$_4$ absorption band in T-type spectra becomes broader and deeper, and P- and R-branches are not negligible any more. In order to follow the variation of the CH$_4$ 3.3 $\mu$m absorption in the spectra of brown dwarfs including T-type, we define a photometry band [3.3], which is measured by simply averaging the flux between 3.27 and 3.36 $\mu$m. [3.3]$-\lambda_A$ are listed in Table 4 and plotted against the spectral types in Figure 5. The large error of the color for late-T-type sources is caused by the lack of valid data points around 3.3 $\mu$m. The [3.3]$-\lambda_A$ increases monotonically along L to T sequence, indicating that the CH$_4$ $\nu_3$ absorption develops simply toward the later spectral types.

3.3.3. $J-K$ Color

Next, the effects of dust on the observed CH$_4$ band strength are evaluated. The $J$-band flux is most sensitive to dust extinction. Thus, the $J-K$ color would give information on the conditions of dust in the L dwarf photospheres. $J-K$ colors are derived from IRTF/Spex and UKIRT/CGS4 data (see Section 4.2.1 and 4.2.2) with the MKO $J$ and $K$ filters. $J-K$ colors are shown in Table 4 and Figure 6. We see a trend of redder colors from L1 to L6. Thereafter, $J-K$ colors become bluer later than L6. The red color of early- to mid-L dwarfs is thought to be due to increasing dust extinction at the $J$ band. We find that the $J-K$ colors of two L5 dwarfs showing the CH$_4$ $\nu_3$ absorption band, 2MASS J1507$-$1627 and SDSS J0539$-$0059, are bluer than that of other L5 objects without the band, SDSS J1446+0024 and GJ 1001B. This indicates that the difference in L5 dwarfs with or without the CH$_4$ $\nu_3$ absorption band is caused by dust reddening.

4. INTERPRETATION WITH THE UCM

4.1. The Unified Cloudy Model

To understand the atmospheres of brown dwarfs better, we analyze the AKARI spectra using the Unified Cloudy Model (UCM, Tsuji 2002, 2005). The atmospheres of cool stars are dominated by molecules. The UCM calculates molecular abundance by assuming LTE. Generally, stellar spectra can be interpreted in terms of effective temperature $T_{\text{eff}}$, surface gravity log $g$, chemical composition, and micro-turbulent velocity. Dust is an essential component in the atmospheres of brown dwarfs. We assume metallic iron, enstatite (MgSiO$_3$), and corundum (Al$_2$O$_3$) in the UCM as the dust species. Under the LTE, dust forms at a layer where temperature drops down to the condensation temperature, $T_{\text{cond}}$. Although we do not know the exact physics behind the behavior of dust layers, comparison with observations tells us that it is difficult to explain the spectra with only these four basic parameters. The UCM assumes that the dust disappears at somewhat lower temperatures given as an additional parameter, namely, the critical temperature $T_{\text{crit}}$. Thus, the dust would exist only in the layer with $T_{\text{crit}} < T < T_{\text{cond}}$. $T_{\text{crit}}$ is not predictable by any physical theory at present and is required to be determined from observations empirically. The UCM applies the CH$_4$ line list by Freedman et al. (2008), which is based on the Spherical Top Data System model of Wenger & Champion (1998) and believed to be the best one currently available for this band. Other line lists are CO (Guelachivili et al. 1983; Chackerian & Tipping 1983), CO$_2$ (HITEMP database; Rothman 1997), and H$_2$O (Partridge & Schwenke 1997). See Tsuji (2002, 2005) for details of the model. We assume that the objects have solar metallicity (here, we take the values...
the shorter wavelength spectra firstly. Then, we explain the problem of model fitting and the fitting strategy to overcome the problem.

4.2.1. IRTF/Spex Data

The NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, is a 3.0 m telescope optimized for infrared observations. Spex is a medium-resolution spectrograph covering 0.8–5.4 μm onboard IRTF. Spex is superior due to its capability to provide maximum simultaneous wavelength coverage. A high throughput prism mode that uses single order long slit (60 arcsec) provides the spectral resolution $\lambda/\Delta \lambda = R \sim 100$ for 0.8–2.5 μm. Using prism cross-dispersers (for 15 arcsec long slits), $R$ becomes 1000–2000 across 0.8–2.4 μm, 2.0–4.1 μm, and 2.3–5.5 μm.

Almost all brown dwarfs in our samples have been observed by Burgasser et al. (2004, 2006, 2008, 2010), Burgasser (2007), and Cushing (2004) with SpeX. Nine data sets have been obtained using its low-resolution prism-dispersed mode with resolutions of 75–200 depending on the used slit width. For these nine objects, we retrieve the data from The SpeX Prism Spectral Libraries built by Adam Burgasser. Only SDSS J0539–0059 was unpublished and the data were obtained from M. Cushing (2010, private communication). Six other sources have been observed by SpeX using its short wavelength cross-dispersed mode with resolutions of 1200–2000, depending on the used slit width. We obtained these data from the IRTF Spectral Library maintained by Michael Cushing.

4.2.2. UKIRT/CGS4 Data

SDSS J1446+0024 has not been observed with SpeX. A spectrum in 1.0–2.5 μm was obtained with UKIRT/CGS4 (Geballe et al. 2002). CGS4 is a 1.0–5.0 μm multi-purpose grating spectrometer which was mounted on the 3.8 m United Kingdom Infrared Telescope (UKIRT), which is located on Mauna Kea, Hawaii. CGS4 has four gratings. The data of SDSS J1446+0024 were obtained using 40 line mm$^{-1}$ grating that provided the resolution of 300–2000, which are defined by 400 × λ. The wavelength coverage of this observation is 1.03–1.34 μm and 1.43–2.53 μm. We obtained the spectral data of SDSS J1446+0024 from D.Looper (2010, private communication).

4.2.3. Absolute Flux Calibration of Short Wavelength Spectral Data

Since nine SpeX data of AKARI samples are normalized at 1.25 μm, we calibrate their absolute fluxes using the J-band photometric data (hereafter $I_p$) given by Leggett et al. (2002a) and Knapp et al. (2004) listed in Table 4. These $I_p$ were taken with the MKO filter. SIMP J0136+0933 was not observed with the MKO filter, and we use Two Micron All Sky Survey (2MASS) J-band photometric data (Cutri et al. 2003) for the flux calibration of this object. The 2MASS J-band magnitude is also listed in the eighth column of Table 4. We estimate the J-band flux from SpeX data ($J_{\text{SpeX}}$) with the MKO or 2MASS J-band filter transmission function $7' \text{by calculating}$

$$J_{\text{SpeX}} = \frac{\sum F_i \Delta v}{\sum T(v) \Delta v}. \tag{2}$$

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5 URL: http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library/

4 These data are now included in The SpeX Prism Spectral Libraries.

5 URL: http://pono.ucsd.edu/~adam/browndwarfs/spexprism/
After that, we scale the absolute flux of SpeX spectral data with the ratio of \( J_p / J_{\text{SpeX}} \).

The absolute flux levels of six objects observed by SpeX and one object observed by the UKIRT/CGS4 were calibrated with the 2MASS \( J \)-band photometry data by Cushing et al. (2004) and Geballe et al. (2002), respectively. We derive the \( J \)-band flux from the calibrated spectra to compare with \( J_p \) from Leggett et al. (2002) and Knapp et al. (2004). They are confirmed to be consistent within 10\%. Figure 8 shows the results.

The spectra of three objects, 2MASS J1439+1929, 2MASS J0036+1821, and 2MASS J1507−1627, were observed by SpeX in 0.81–4.11 \( \mu \)m simultaneously with a gap over 2.53–2.85 \( \mu \)m. They are calibrated by Cushing et al. (2004). In Figure 9, their AKARI spectra and SpeX spectra are plotted in red and black lines, respectively. Both the AKARI and SpeX data of each object are calibrated independently and scaled by the same factor on the plot. We find that two spectra are consistent within 10\%, which is the uncertainty level of the AKARI spectra.

4.2.4. Step 1—Fitting the AKARI Spectra

Our model fitting consists of two processes. As the first step, we compare the models with observed AKARI spectra between 2.5 and 4.15 \( \mu \)m. We use the data only over 2.5–4.15 \( \mu \)m for fitting, not up to 5.0 \( \mu \)m, because we know that the current model does not explain the observed spectra beyond 4.15 \( \mu \)m, where the absorption bands of CO2 at 4.2 \( \mu \)m and CO at 4.6 \( \mu \)m are present (Yamamura et al. 2010; Tsuji et al. 2011). We follow Cushing et al. (2008) and evaluate the goodness of the model fitting by the statistic \( G_k \), defined as

\[
G_k = \frac{1}{n-m} \sum_{i=1}^{n} \omega_i \left( \frac{f_i - C_k F_{k,i}}{\sigma_i} \right)^2, \tag{3}
\]

where \( n \) is the number of data points; \( m \) is the degree of freedom (this case \( m = 3 \)); \( \omega_i \) is the weight for the \( i \)th wavelength points (we give the weight as \( \omega_i = 1 \) for all data points because of no bias within each observed spectrum); \( f_i \) and \( F_{k,i} \) are the flux densities of the observed data and \( k \)th model, respectively; \( \sigma_i \) are the errors in the observed flux densities; and \( C_k \) is the scaling factor given by

\[
C_k = \frac{\sum \omega_i f_i F_{k,i}/\sigma_i^2}{\sum \omega_i F_{k,i}^2/\sigma_i^2}. \tag{4}
\]

\( G_k \) is equivalent to reduced \( \chi^2 \), since we adopt \( \omega_i = 1 \) in our analysis.

It is difficult to determine a unique best-fit model for each AKARI object because of the large error associated with the AKARI spectral data. In general, when the reduced \( \chi^2 \) \((= G_k)\) is 1–2, the model is regarded to fit the observed data well. However, in our case, \( G_k \) easily falls below unity and we have too many “good fit” models. This degeneracy is demonstrated in Figure 10 for the AKARI spectra of 2MASS J1507−1627 (L5). We see that many models have small \((<1.04)\) \( G_k \) between 1700 and 2000 K of \( T_{\text{eff}} \). The minimum \( G_k \) is 0.94, and the second minimum is 0.97. The differences of \( G_k \) between the models near the minimum are too small to determine the best-fit model.

Therefore, at this step, we select candidates of the best model with the following condition:

\[
G_{\text{min}} \leq G_k < G_{\text{min}} + 1, \tag{5}
\]

where \( G_{\text{min}} \) is the minimum \( G_k \) value. \( G_{\text{min}} \) is different for every object and is not always near unity, due to the difference in the error of the AKARI observed spectra. We apply \( G_{\text{min}} + 1 \) as an upper limit. This criterion reasonably selects 5–20 model candidates for almost all the observed data.

4.2.5. Step 2—Constraining Models with the Short Wavelength Data

To constrain the models from the candidates, we additionally use the spectra in the shorter wavelength range (1.0–2.5 \( \mu \)m) taken by IRTF/SpeX and UKIRT/CGS4. It is only possible to constrain the model parameter uniquely with the help of the short wavelength range spectra along with the AKARI data. The wavelength region of the AKARI data gives us information about molecules (= gas) in brown dwarf photospheres. On the other hand, data covering shorter wavelengths are the most sensitive to the presence of dust.
We calculate $G_k$ for the IRTF/SpeX or UKIRT/CGS4 (hereafter SpeX/CGS4) spectral data for the candidate models derived in Step 1. Since we have validated the absolute flux of the spectra to be accurate to better than 10% (see Section 2.6), we apply $C_k$ values derived in Step 1 (from the AKARI data) to Step 2. Figure 10 shows that the degeneracy that appeared in the AKARI wavelengths is resolved in the shorter wavelengths. Results of the model fitting through these processes are shown in Table 6.

We do not fit the AKARI data and the SpeX/CGS4 data simultaneously. This is because the errors of two data sets are very different. The average relative error of the AKARI spectra is about 10% (Ohyama et al. 2007), while that of the SpeX and CGS4 data is below 0.05% (Rayner et al. 2009). This difference would give much higher weight to the SpeX/CGS4 data in the fitting evaluation in Equation (3). Actually, while the reduced $\chi^2$ ($= G_k$) values of the AKARI data are between 0.1 and 100, those of the SpeX/CGS4 data are between 100 and 5000. Therefore, we decided to use the AKARI spectra first and use the SpeX and CGS4 spectra in the second step.

### 4.3. Uncertainty of the Model Fitting

Here, we discuss the uncertainty of the best-fit model parameters. The models we use for the current analysis are calculated on the 100 K (for $T_{\text{eff}}$ and $T_{\text{cr}}$) and 0.5 dex (for log $g$) grid, and the uncertainty should be no better than the grid spacing. To estimate the uncertainty we change one of $T_{\text{eff}}$, log $g$, and $T_{\text{cr}}$ by one grid from the best-fit value, and search for the “restricted best” model by changing other two parameters following the same manner through Steps 1 and 2. If we do not find any models satisfying $G_{\min} \leq G_k < G_{\min} + 1$ (here, $G_{\min}$ is taken from all parameter space in Step 1), then the uncertainty of the parameter should be smaller than the grid spacing. When the best parameter is already on the edge of the parameter space, i.e., $T_{\text{eff}} = 700$ or 2200 K, log $g = 4.5$ or 5.5, and $T_{\text{cr}} = 1700$ K or $T_{\text{cond}}$, we only run the test on the available side of the parameter grid.

We show a detailed example for 2MASS J2224−0158 (L4.5), whose best model is ($T_{\text{eff}}$, log $g$, $T_{\text{cr}}$) = (1700 K/5.5/1800 K), in Figure 11. We see large differences in $J$ and $H$ bands in some “restricted best” model spectra. We derive a factor to further scale the “restricted best” model from that given by $C_k$ to adjust the observed spectra in the $J$- and $H$-band region ($1.01$–$1.81 \mu m$) using Equation (4) (hereafter $C_{J,H}$). We exclude the “restricted best” models if the factor, $C_{J,H}$, is more than 1.10 or less than 0.90, regarding the uncertainty of the SpeX/CGS4 absolute flux. For example, $C_{J,H}$ for the “restricted best” models for $T_{\text{eff}}$ (+100 K and $-100$ K), log $g$ (<0.5) of 2MASS J2224−0158 (L4.5) are 0.74, 1.12, 0.65, 0.88, respectively. Thus, any “restricted best” model is invalid for 2MASS J2224−0158 (L4.5), i.e., the uncertainty is smaller than one grid.

We find that the “restricted best” models for the case of changing $T_{\text{eff}}$ by $\pm 100$ K and $T_{\text{cr}}$ by $+100$ K exhibit a noticeable change from the real best models. On the other hand, the case of changing $T_{\text{cr}}$ by $-100$ K and log $g$ only results in minor differences. We further continue the test of changing each parameter by two grids from the real best-fit model. Almost all the “restricted best” models do not stay between 0.90 and 1.10 any longer, except for the case of changing the two grids.
5. BROWN DWARF ATMOSPHERES ALONG WITH THE SPECTRAL TYPES

5.1. Comparison of the Observed and the Best-fit Model Spectra

The spectra of observed and best-fit models are compared in Figure 12. The model spectra generally explain the observed spectral features well, except for some objects noted below. We see that the fit in the entire AKARI region is fairly good, except for the wavelength region longer than 4.15 $\mu$m in mid-to late-T dwarfs, which we do not take into account in the fitting evaluation. We were aware that the CO and CO$_2$ bands are not reproduced by the current UCM. Actually, the model fit including this wavelength range makes the fit of the overall AKARI range even worse.

A noticeable deviation is seen in the late-T dwarfs around 3.0 $\mu$m, where the H$_2$O and CH$_4$ absorption features overlap. The flux density around the 3.0 $\mu$m region in the model spectra of three late-T dwarfs is too low in comparison to that in the observed spectra. The CH$_4$ absorption at 1.6 $\mu$m in the model spectra of these late-T dwarfs is always significantly weaker than that in the observed spectra. For other brown dwarfs, model spectra sometimes do not explain the strength of the CH$_4$ $v_3$ absorption band around 3.3 $\mu$m. We also find that the CO$_2$ absorption band in the model of late-L to T dwarfs is sometimes too deep and sometimes too shallow compared to the observations. The fit in the SpeX/CGS4 region is good in an overall sense, except for five late-L and two early-T dwarfs. The $H$- and $K$-band flux densities in the model spectra of these five dwarfs are higher than that in the observed spectra.

The high flux level around the 3.0 $\mu$m region in the observed spectra indicates that the actual photospheric temperature is higher than that of the models. On the other hand, the stronger CH$_4$ absorption band at 1.6 $\mu$m in the observed spectra of late-T dwarfs indicates that the temperature in the photosphere of these dwarfs should be lower than observed. This contradiction implies that the thermal structure of the objects derived by the model is not perfect. The deviation of the 3.3 $\mu$m CH$_4$ for mid- to late-L dwarfs may also indicate the incompleteness of the thermal structure in the model. We have to consider the mechanism used to improve the thermal structure to reproduce the observation data. The second possible reason for a discrepancy between the model and observations is the incompleteness of the line lists. It is known that the line lists of polyatomic molecules, such as H$_2$O, CH$_4$, or CO$_2$, are still not perfect. The effects of the line list should be investigated; however, it is not likely that these discrepancies are caused only by the incomplete line lists. A third option would be the elemental abundance. The discrepancy of CO$_2$ absorption in the observed spectra may indicate that the elemental abundances in the photospheres of these objects are different from the assumptions in the model. Excess CO$_2$ absorption for SDSS J0830+4828 (L9), 2MASS...
J0559−1404 (T4.5), and 2MASS J0415−0935 (T8) was discussed by Tsuji et al. (2011) in terms of enhanced C and O elemental abundances. Recently, Madhusudhan et al. (2011) reported an anomaly in the H2O and CH4 abundances as compared to the solar abundance chemical equilibrium model prediction in the atmosphere of the hot-Jupiter WASP-12b. They suggested that the abundance of these molecules can be explained if the carbon-to-oxygen ratio [C]/[O] in this planet’s atmosphere is much greater than the solar value ([C]/[O] = 0.54), i.e., [C]/[O] > 1. Although the structure of the atmosphere may be different in planets and brown dwarfs, these results are consistent with our conclusion; the elemental abundance is an essential parameter of the brown dwarf/planet atmosphere and should be carefully considered in future studies. We extend the study of possible elemental abundance variations among brown dwarfs using model atmospheres and the AKARI data in a forthcoming paper (S. Sorahana et al. in preparation).

The H- and K-band flux densities in the model spectra of late-L and early-T dwarfs are always higher than those in the observed spectra. Since the wavelength range of SpeX/CGS4 is the most sensitive to the dust extinction, we can evaluate the dust amount from the spectra of this wavelength region. The effect of dust extinction turned out to be small in the late-L to early-T dwarfs. Less of a warming up effect by the dust is expected. This argument indicates that an increase of the dust and the inner temperature are overestimated in the models as compared to actual photospheres. Since dust opacity relies on the composition, grain size distribution, and amount, we shall confirm the effects of these quantities in the UCM. We also propose that a self-consistent, more realistic theory of
condensation and sedimentation in the atmospheres is essential in future brown dwarf atmosphere models.

5.2. Model Parameters and Spectral Type

Parameters of the best-fit models are shown in Table 6, and the parameters are plotted in Figure 13 with respect to the spectral types. We see that spectral type is in the sequence of $T_{\text{eff}}$ except for the late-L dwarfs. $\log g$ decreases toward the late spectral types. $T_{\text{cr}}$ is minimum for mid- to late-L types.

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

Figure 13. Best-fit model parameters vs. spectral type. (a) $T_{\text{eff}}$, (b) $\log g$, and (c) $T_{\text{cr}}$. Objects with the same spectral type may overlap when they have the same parameters. We see that spectral type is in the sequence of $T_{\text{eff}}$ except for the late-L dwarfs. $\log g$ decreases toward the late spectral types. $T_{\text{cr}}$ is minimum for mid- to late-L types.

5.3. Advantage of AKARI Spectra to the Model Fitting

In previous studies, physical parameters of brown dwarfs have been derived mainly from near-infrared ($1.0–2.5 \mu m$) spectra. Tsuji et al. (2004) attempted to interpret the near-infrared spectra ($0.882–1.400 \mu m$, $1.056–1.816 \mu m$, and $1.850–2.512 \mu m$) obtained with the Subaru Telescope with the UCM. They reported that the overall spectral energy distributions and the strengths of the major spectral features are reasonably, but not perfectly, reproduced by the UCM. In their fitting, dust extinction effects (most effectively contributing to $J$ and $H$ bands) and molecular band strengths were the key features in determining the physical parameters from model candidates, but it is hardly realized that these features are all consistent with an observation. They commented that it was difficult to derive reliable physical parameters for each object by the UCM, even though their fitting to the near-infrared spectra (only) can constrain the physical parameters in a certain range.

The spectra in $2.5–5.0 \mu m$ obtained by AKARI should provide additional information on brown dwarf atmospheres, as the fundamental bands of major molecules, $\text{H}_2\text{O}$, $\text{CO}$, $\text{CO}_2$, and $\text{CH}_4$, are located in this region with less effects of dust opacity. These molecular bands may sample a different part of the photosphere. By including the AKARI spectra into the model analysis, we expect to improve the model fitting to reflect more global characteristics of the objects. Cushing et al. (2008) also mentioned that the model fitting to the broader wavelength range results in more reliable physical parameters, even though the fits to the narrower wavelength region can be better.

To demonstrate the benefit of the AKARI spectra, we compare the observed spectra of two brown dwarfs, 2MASS J1523 + 3014 (L8) and SDSS J1525–0122 (T2), with the models derived by the current study and by Tsuji et al. (2004) in Figure 14. We see that both model spectra reasonably reproduce the near-infrared part of the observed spectra. However, the AKARI spectra can only be explained with our models.

This result indicates that the parameters derived only from near-infrared spectra might have large uncertainties, and the broader wavelength data including AKARI spectra are essential to understand the nature of brown dwarf atmospheres. We find that $T_{\text{eff}}$ derived by our model fitting is generally $\sim 100 \text{ K}$ higher than that of Tsuji et al. (2004) for the same spectral type objects. It is probably because of the fact that molecular bands in the AKARI wavelength range help to distinguish between the effects of $T_{\text{eff}}$ and $T_{\text{cr}}$. 

\[ T_{\text{eff}} \]
need improvements and the AKARI spectra should be analyzed in further detail.

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REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2002, ApJ, 573, L137
Artigau, E., Doyon, R., Lafrenière, D., et al. 2006, ApJ, 651, L57
Burgasser, A. J. 2007, ApJ, 659, 655
Burgasser, A. J., Cruz, K. L., Cushing, M., et al. 2010, ApJ, 710, 1142
Burgasser, A. J., Geballe, T. R., Leggett, S. K., Kirkpatrick, J. D., & Golimowski, D. A. 2006, ApJ, 637, 1067
Burgasser, A. J., Liu, M. C., Ireland, M. J., Cruz, K. L., & Dupuy, T. J. 2008, ApJ, 681, 579
Burgasser, A. J., McElwain, M. W., Kirkpatrick, J. D., et al. 2004, AJ, 127, 2856
Burgasser, A. J., Wilson, J. C., Kirkpatrick, J. D., et al. 2000, AJ, 120, 1100
Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Rev. Mod. Phys., 73, 719
Chackerian, C. J., & Tipping, R. H. 1983, J. Mol. Spectrosc., 99, 431
Cushing, M. C. 2004, PhD thesis, Univ. Hawaii
Cushing, M. C., Marley, M. S., & Leggett, S. K. 2004, ApJ, 617, 579
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR On-line Data Catalog, 2246, 0
Dahn, C. C., Harris, H. C., Vrba, F. J., et al. 2002, AJ, 124, 1170
Fegley, B., Jr., & Lodders, K. 1996, ApJ, 472, L37
Freedman, R. S., Marley, M. S., & Lodders, K. 2008, ApJS, 174, 504
Geballe, T. R., Knapp, G. R., Leggett, S. K., et al. 2002, ApJ, 564, 466
Geballe, T. R., Saumon, D., & Podolak, D. A., et al. 2009, ApJ, 695, 844
Golimowski, D. A., Leggett, S. K., Marley, M. S., et al. 2004, AJ, 127, 3516
Griffith, C. A., & Yelle, R. V. 1999, ApJ, 519, L85
Guedel, H., De Villeneuve, D., Farihi, J., Urban, W., & Verges, J. 1983, J. Mol. Spectrosc., 98, 64
Jameson, R. F., Casewell, S. L., Bannister, N. P., et al. 2008, MNRAS, 384, 1399
Kawada, M., Baba, H., Barthel, P. D., et al. 2007, PASJ, 59, S389
King, R. R., McCaughrean, M. J., Homeier, D., et al. 2010, A&A, 510, 99
Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 2000, AJ, 120, 447
Knapp, G. R., Leggett, S. K., Fan, X., et al. 2004, AJ, 127, 3553
Larimer, J. W. 1967, Geochim. Cosmochim. Acta, 31, 1215
Larimer, J. W., & Anders, E. 1967, Geochim. Cosmochim. Acta, 31, 1239
Leggett, S. K., Allard, F., Geballe, T. R., Hauschildt, P. H., & Schweitzer, A. 2001, ApJ, 548, 908
Leggett, S. K., Geballe, T. R., Fan, X., et al. 2000, ApJ, 536, L35
Leggett, S. K., Golimowski, D. A., Fan, X., et al. 2002, ApJ, 564, 452
Leggett, S. K., Hauschildt, P. H., Allard, F., Geballe, T. R., & Baron, E. 2002b, MNRAS, 332, 78
Lord, H. C., III 1965, Icarus, 4, 279
Lorente, R., Onaka, T., Ita, Y., et al. 2008, AKARI IRC Data User Manual, Version 1.4, http://www.ir.isas.jaxa.jp/AKARI/Observation/
Madau, D. A., & Franceschini, A. 2011, Nature, 469, 64
Murakami, H., Baba, H., Barthel, P. D., et al. 2007, PASJ, 59, S369
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, Nature, 378, 463
Nakajima, T., Tsuji, T., & Yanagisawa, K. 2004, ApJ, 607, 499
Neugebauer, G., Soifer, B. T., Miley, G., et al. 1984, ApJ, 278, L83
Noll, K. S., Geballe, T. R., Leggett, S. K., & Marley, M. S. 2000, ApJ, 541, L75
Ohyama, Y., Onaka, T., Matsuhara, H., et al. 2007, PASJ, 59, S411

Figure 14. Best-fit model spectrum in the current study (red) and that from
Tsuji et al. (2004) (blue) are compared with the AKARI-SpeX observed spectra
(black) of two brown dwarfs, 2MASS J1523+3014 and SDSS J1254−0122. It is
seen that the near-infrared part (≤ 2.5 μm) is reasonably well reproduced by
both the models, but AKARI spectra at longer wavelength are much better
explained by the current model, showing that the AKARI spectra give further
constraint to the model parameters.

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

6. CONCLUSION

We study the presence of the 4.6 μm CO, 4.2 μm CO₂, and
3.3 μm CH₄ bands in 16 AKARI brown dwarf spectra over
the wide range of spectral types. We confirm that the CH₄ band
appears in the sources as early as L5 and find that the band is seen
in only two of four L5 dwarfs in our sample. Their J − K color
indicates that the appearance of the CH₄ band in two L5 dwarfs
is related to the dust abundance. The CO 4.6 μm band appears
in the spectra of all spectral types until late-T dwarfs. The fact
that CO generally exists in all brown dwarf atmospheres is very
important, since it is confirmed that the deviation of molecular
abundance in brown dwarf atmospheres from the LTE prediction
is a common feature. We need to consider this problem further
in future works. We detect the CO₂ absorption band at 4.2 μm
in the spectra of late-L and T-type dwarfs. These detections
indicate that the CO₂ molecule is generally in the atmospheres
of these dwarfs.

We analyze the AKARI spectra using the UCM. We derive the
three physical parameters, effective temperature $T_{\text{eff}}$, critical
temperature $T_c$, and surface gravity log $g$, of 16 sources by
systematic model fitting. We investigate how the spectral type
correlates with the parameters. We find that the spectral type
follows a sequence of $T_{\text{eff}}$, except for the late-L dwarfs, for
which the spectral type is a sequence of $T_c$, the parameter
related to the effects of dust. This result confirms expectations
from past studies. AKARI gives us these new insights into brown
dwarf atmospheres in the new spectral range, 2.5−5.0 μm. We
also find important problems, which are not explained with the
current brown dwarf atmosphere model. Therefore, the models
Onaka, T., Matsuhara, H., Wada, T., et al. 2007, PASJ, 59, S401
Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & van Kerkwijk, M. H. 1998, ApJ, 502, 932
Partridge, H., & Schwenke, D. W. 1997, J. Chem. Phys., 106, 4618
Rayner, J. T., Cushing, M. C., & Vacca, W. D. 2009, ApJS, 185, 289
Rothman, L. S. 1997, High-temperature Molecular Spectroscopic Database (Andover (CD-ROM): ONTAR Co.)
Saumon, D., Geballe, T. R., Leggett, S. K., et al. 2000, ApJ, 541, 374
Saumon, D., Marley, M. S., Cushing, M. C., et al. 2006, ApJ, 647, 552
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stumf, M. B., Brandner, W., Joergens, V., et al. 2010, ApJ, 724, 1

Tsuji, T. 1964, Molecular Abundance in Stellar Atmospheres (2nd edn; Mitaka, Tokyo: Annals of the Tokyo Astronomical Observatory)
Tsuji, T. 2002, ApJ, 575, 264
Tsuji, T. 2005, ApJ, 621, 1033
Tsuji, T., & Nakajima, T. 2003, ApJ, 585, L151
Tsuji, T., Nakajima, T., & Yanagisawa, K. 2004, ApJ, 607, 511
Tsuji, T., Yamamura, I., & Sorahana, S. 2011, ApJ, 734, 73
Vrba, F. J., Henden, A. A., Laginbuhl, C. B., et al. 2004, AJ, 127, 2948
Wenger, C., & Champion, J. P. 1998, J. Quant. Spectrosc. Radiat. Transfer, 59, 471
Yamamura, I., Tsuji, T., & Tanabé, T. 2010, ApJ, 722, 682