AKARI OBSERVATIONS OF BROWN DWARFS. II. CO2 AS PROBE OF CARBON AND OXYGEN ABUNDANCES IN BROWN DWARFS

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ABSTRACT

Recent observations with the infrared astronomical satellite AKARI have shown that the CO2 bands at 4.2 μm in three brown dwarfs are much stronger than expected from the unified cloudy model (UCM) based on recent solar C & O abundances. This result has been a puzzle, but we now find it is simply due to the effect of C & O abundances. We show that these strong CO2 bands can be explained with the UCMs based on the classical C & O abundances (log AC and log AO), which are about 0.2 dex larger compared to the recent values. Since three other brown dwarfs could be interpreted fairly well with the recent solar C & O abundances, we require at least two model sequences based on the different chemical compositions to interpret all the AKARI spectra. The reason is that the CO2 band is especially sensitive to C & O abundances, since the CO2 abundance depends approximately on $A_C A_O^2$—the cube of C & O abundances. For this reason, even low-resolution spectra of very cool dwarfs, especially of CO2, cannot be understood unless a model with proper abundances is applied. For the same reason, CO2 is an excellent indicator of C & O abundances, and we can now estimate C & O abundances of brown dwarfs as follows: Three of the six brown dwarfs observed with AKARI should have high C & O abundances similar to the classical solar values (e.g., log AC = 8.60 and log AO = 8.92), but the other three may have low C & O abundances similar to the recent solar values (e.g., log AC = 8.39 and log AO = 8.69). This result implies that three of the six brown dwarfs are highly metal-rich relative to the Sun, if the recent solar C & O abundances are correct.

Key words: brown dwarfs – infrared: stars – stars: abundances – stars: atmospheres – stars: individual

1. INTRODUCTION

In our recent work, the CO2 molecule was identified for the first time in the spectra of brown dwarfs observed with the infrared astronomical satellite AKARI (Yamamura et al. 2010, hereafter referred to as Paper I). We tried to interpret the observed behavior of the CO2 band using the model photosphere of brown dwarfs, referred to as the unified cloudy model (UCM; Tsuji 2002, 2005). In modeling the photospheres of brown dwarfs, the problem lies in considering the chemical composition, since no direct abundance analysis is known for brown dwarfs. We thought it reasonable to assume a typical composition for the disk stellar population, such as the Sun. However, the solar composition has experienced drastic changes over the past decades and the true chemical composition of the Sun is still by no means well established. Nevertheless, we thought it appropriate to use the latest version of solar abundances as possible proxies for chemical abundances in brown dwarfs.

In our earlier version of UCMs (Tsuji 2002), we assumed the solar abundances to be largely based on the classical LTE analysis using one-dimensional (1D) hydrostatic model photospheres and, in particular, C & O abundances log AC = 8.60 and log AO = 8.92 on the log $A_H = 12.0$ scale (e.g., Anders & Grevesse 1989; Grevesse et al. 1991). While we were computing our first version of UCMs, a new result for the solar C & O abundances based on a three-dimensional (3D) time-dependent hydrodynamical model of the solar photosphere was published (Allende Prieto et al. 2002). Since the classical 1D model may be too simplified for the real solar photosphere, this new approach appeared to be useful for solar abundance analysis. The current version of UCMs (Tsuji 2005) is thus based on this new result (log AC = 8.39 and log AO = 8.69) by Allende Prieto et al. (2002), as noted elsewhere (Tsuji et al. 2004). The new C & O abundances are about 0.2 dex smaller compared to the classical values mentioned above.

We applied the current version of UCMs to the brown dwarfs observed with AKARI in Paper I, and we could almost perfectly explain about half of our sample of spectra. For the remaining targets, we could explain the overall spectral energy distributions (SEDs) by this version of UCMs, but not their strong CO2 bands. This may be due to an unknown process related to CO2, since anomalously strong CO band depths have also been explained by a special process now known as vertical mixing (e.g., Noll et al. 1997; Oppenheimer et al. 1998; Griffith & Yelle 1999; Saumon et al. 2000; Leggett et al. 2007b).

However, we tried the old version of UCMs based on the classical C & O abundances and found that the CO2 band appeared to be much stronger in the spectra based on the old models than on the present models. At the first glance, this is rather surprising because C & O abundances in the old models are only about 0.2 dex larger than those in the present models. However, we realized immediately that the CO2 abundance is extremely sensitive to both C & O abundances because the CO2 abundance depends on the cube of C & O abundances ($A_{CO} \propto A_C A_O^2$). The strong dependence of the CO2 abundance on metallicity, $[\text{Fe}/\text{H}]$,4 was previously known by other authors

4 Differential iron abundance of a star relative to the Sun, defined by $[\text{Fe}/\text{H}] = \log(A_{\text{Fe}}/A_{\text{H}})_{\odot} - \log(A_{\text{Fe}}/A_{\text{H}})_{\odot}$. 


based on a detailed thermodynamical analysis of the C-, N-, and O-bearing gaseous molecules (Lodders & Fegley 2002).

The above result demonstrates that at least two different series of model photospheres are needed for the analysis of the CO2 band observed with AKARI. For this purpose, we reconsider the old version of UCMs based on the classical C & O abundances to represent a case of fairly high C & O abundances. Compared with the old version of the UCMs, the current version based on the new C & O abundances is representative of reduced C & O abundances. An important implication of this result is that the metallicity (C & O abundances) in brown dwarfs has various values.

The interpretation and analysis of the spectra of cool dwarfs have a rather long history (e.g. Kirkpatrick 2005; Burgasser et al. 2006b; Leggett et al. 2007a; Cushing et al. 2008; Stephens et al. 2009; Yamamura et al. 2010), and the effect of metallicity has been discussed by some authors. For example, Burgasser et al. (2006b) measured the strengths of the major H2O and CH4 bands in the 1.0-2.5 μm region in a large sample of T dwarfs and found that the resultant spectral indices plotted against spectral type revealed a considerable scatter. Several causes for this result, including the effects of dust, gravity, and metallicity, have been considered. However, it appeared difficult to separate the effect of metallicity from the remaining parameters. Leggett et al. (2009) showed that the effect of metallicity on the SEDs of T dwarfs should be significant, but noted that other parameters such as gravity can similarly affect SEDs. This result again showed the difficulty in determining metallicity uniquely from SEDs. Also, the so-called blue L dwarfs classified as L subdwarfs have been interpreted to have low metallicity with [Fe/H] from −1.5 to −1.0 (e.g., Burgasser et al. 2009), but those L dwarfs of unusually blue near-infrared colors can also be explained by a patchy cloud model (Folkes et al. 2007; Marley et al. 2010).

The brief review presented above reveals that the problem of metallicity in brown dwarfs is still unresolved. In this paper, we will for the first time show clear evidence of metallicity variations in brown dwarfs. In fact, the most important significance of the discovery of CO2 with AKARI is that it demonstrated the variations of the C & O abundances by at least 50% in brown dwarfs and that it enabled estimation of the C & O abundances in very cool dwarfs.

In Paper I, we analyzed the AKARI spectra and discussed the basic physical parameters of the objects in detail. We applied the conventional method based on a direct comparison of the observed and predicted spectra. In this paper, we examine the results of Paper I via a more detailed numerical method in Section 4.1 and confirm that the physical parameters determined in Paper I largely agree with those based on the reduced-χ2 minimization method within the estimated errors. A problem, however, is that an adequate application of such a rigorous numerical method requires input data of sufficient accuracy. Unfortunately, the input data—our present models of brown dwarfs—are not precise enough for this purpose, as discussed in Section 4.5 of Paper I. Therefore, the numerical method does not necessarily provide the best answer. The traditional fitting method “by eye” can still be useful for some cases. For these reasons, we use the physical parameters determined in Paper I and adopt the same approach as in Paper I, eye-fitting, throughout this paper.

### 2. ROLE OF THE CARBON AND OXYGEN ABUNDANCES IN THE UCM

Our two series of UCMs are referred to as UCM-a and UCM-c, which differ only in C & O abundances as summarized in Table 1. The UCM-a series is based on the classical C & O abundances, for simplicity referred to as 1D solar abundances, and the UCM-c series on the new abundances, referred to as 3D solar abundances.

We first examine the effects of C & O abundances on the thermal structure of the photosphere. For this purpose, models of the UCM-c series are taken from our database.5 Since our code to compute UCMs has been modified to some extent over

### Table 1

| Series   | log Ac | log Ao | Note on Chemical Composition |
|----------|--------|--------|-----------------------------|
| UCM-a    | 8.60   | 8.92   | 1D solar abundances (e.g., Anders & Grevesse 1989) |
| UCM-c    | 8.39   | 8.69   | 3D solar abundances (e.g., Allende Prieto et al. 2002) |

**Notes.**

a The logarithmic abundance on the scale of log Ac = 12.0.

b We have applied a slightly updated version as given in Table 1 of Tsuji (2002).

c A complete list of the abundances is given in http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucm/tables/table1.dat.

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![Figure 1. Effects of C & O abundances on the thermal structure of cool dwarfs.](http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucmLM/ and http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucm/)

Figure 1. Effects of C & O abundances on the thermal structure of cool dwarfs. The solid and dashed lines show the thermal structures based on the 3D and 1D solar abundances (see Table 1), respectively, (a) $T_{\text{eff}} = 1500$ K, $T_{\text{crit}} = 1700$ K, and log $g = 4.5$; (b) $T_{\text{eff}} = 1200$ K, $T_{\text{crit}} = 1900$ K, and log $g = 4.5$; (c) $T_{\text{eff}} = 900$ K, $T_{\text{crit}} = 1900$ K, and log $g = 4.5$. 

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5 Numerical details of this version (UCM-c series) are available from http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucmLM/ and http://www.mtk.ioa.s.u-tokyo.ac.jp/~tsuji/export/ucm/
Table 2

Basic Parameters from the Model Fittings by Using UCMs

| Number | Object                  | UCM Series | $T_{\text{eff}}$ (K) | $T_{\text{cr}}$ (K) | $\log g$ | $R / R_J$ | $\Delta T_{\text{eff}}$ (K) |
|--------|-------------------------|------------|----------------------|----------------------|---------|-----------|-----------------------------|
| 1      | SDSS J053952−0059       | UCM-c      | 1800                 | 1800                 | 5.5     | 0.804     | −110                        |
| 2      | SDSS J144600+0024       | UCM-c      | 1700                 | 1700                 | 4.5     | 0.716     | −108                        |
| 3      | 2MASS J152322+3014      | UCM-c      | 1500                 | 1700                 | 4.5     | 0.684     | −170                        |
| 4      | SDSS J083008+4828       | UCM-a      | 1500                 | 1700                 | 4.5     | 0.610     | −173                        |
| 5      | 2MASS J055919−1404      | UCM-a      | 1200                 | 1900                 | 4.5     | 1.122     | −269                        |
| 6      | 2MASS J041519−0935      | UCM-a      | 900                  | $T_{\text{cond}}$    | 4.5     | 0.676     | −136                        |

Notes.

a The UCM series applied and indicates approximate C & O abundances (see Table 1).
b Radius $R$ relative to the Jupiter’s radius $R_J$.
c $\Delta T_{\text{eff}} = T_{\text{eff}}$ (empirical values by Vrba et al. (2004)) − $T_{\text{eff}}$ (Column 4 in this Table).

The last 10 yr, we recompute all the models of the UCM-a series used in the present paper. Therefore, the models of the UCM-a and UCM-c series are now computed exactly by the same code, except for the Rosseland and Planck mean opacities, which of course differ according to the chemical composition adopted.

In Figure 1, we show a simple comparison of the photospheric structures of the UCM-a and UCM-c series for the cases of $T_{\text{eff}} = 900, 1200$, and 1500 K. Other parameters such as $T_{\text{cr}}$ and $\log g$ were chosen to match those found for our objects (see Table 2). Inspection of Figure 1 reveals that the models of the UCM-a series (shown by dashed lines) are generally warmer by up to about 100 K as compared to those of the UCM-c series (shown by solid lines). Since the major opacity sources such as CO and H$_2$O are more abundant in the UCM-a than in the UCM-c series, the blanketing effect due to molecular bands should be more effective; hence, the models of the UCM-a series are warmer than those of the UCM-c series.

Next, we examine the effects of C & O abundances on CO$_2$ and other molecular abundances. We present the abundances of H$_2$O, CO, CO$_2$, and CH$_4$ for the case of $T_{\text{eff}} = 1500$ K, $T_{\text{cr}} = 1700$ K, and $\log g = 4.5$ for the models of the UCM-c (applied to 2MASS J152322+3014 in Section 3) and UCM-a (applied to SDSS J083008+4828) series in Figure 2, shown by solid and dashed lines, respectively. As expected, the increased C & O abundances result in increases of CO, CO$_2$, and H$_2$O abundances. The increase of the CO$_2$ abundance in the UCM-a series is quite significant for the previously noted reason. In contrast, the CH$_4$ abundance shows a decrease in the UCM-a series; this unexpected result may occur because the direct effect of the increased carbon abundance on the CH$_4$ abundance is superseded by the dissociation of CH$_4$ due to the elevated temperatures in the model of the UCM-a series (Figure 1).

As another example, we show the case of $T_{\text{eff}} = 1200$ K, $T_{\text{cr}} = 1900$ K, and $\log g = 4.5$ in Figure 3. The results are again shown for the UCM-c and UCM-a series by solid and dashed lines, respectively. In this case, the effects of the abundance changes are more pronounced, especially for CO$_2$. We will see in Section 3 that the case of the UCM-a series is approximately realized in 2MASS J055919−1404, in which the CO$_2$ band appears to be very strong.
Figure 4. Comparison of spectra observed using AKARI with the predicted spectra based on the models of the UCM-c (curve 1, blue) and UCM-a (curve 2, green) series. The UCM-a series is based on the classical solar C & O abundances (1D abundances, see Table 1) and the UCM-c series on the more recent solar C & O abundances (3D abundances, see Table 1). Note that the brown dwarfs shown in (a), (b), and (c) are relatively well fitted by the models of the UCM-c series, while those in (d), (e), and (f) are better described by the models of the UCM-a series.

3. EFFECTS OF THE CARBON AND OXYGEN ABUNDANCES ON THE SPECTRA OF BROWN DWARFS

We compare the observed spectra of six brown dwarfs with the predicted spectra based on the models of the UCM-a and UCM-c series in Figures 4(a)–(f). The effect of C & O abundances on the spectra of brown dwarfs can be most clearly seen in the comparison of 2MASS J152322+3014 and SDSS J083008+4828 shown in Figures 4(c) and (d), respectively. These two brown dwarfs were found to have nearly the same physical parameters ($T_{\text{eff}} = 1500$ K, $T_{\text{cr}} = 1700$ K, and log $g = 4.5$) but the spectra appeared to be quite different (Paper I). In particular, the CO$_2$ band at 4.2 $\mu$m appeared to be much stronger in SDSS J083008+4828 than in 2MASS J152322+3014. In 2MASS J152322+3014, the observed spectrum could be accounted for by the model of the UCM-c series, as confirmed by curve 1 in Figure 4(c). The regions of the H$_2$O 2.7 $\mu$m and the CO$_2$ 4.2 $\mu$m bands as well as the $Q$-branch of the CH$_4$ band appeared to be explained fairly well by the model of the UCM-c series. On the other hand, the predicted spectrum based on the model of the UCM-a series shown by curve 2 cannot explain those features.

In SDSS J083008+4828 shown in Figure 4(d), the observed spectrum could not be accounted for by the model of the UCM-c series (Paper I), as confirmed by curve 1. On the other hand, the strong CO$_2$ band at 4.2 $\mu$m can now be explained reasonably well by the model of the UCM-a series, as shown by curve 2 in Figure 4(d). Thus, the large depression due to the CO$_2$ band turns out to be due to the high C & O abundances in an LTE model. Note that this result is due to the simultaneous increase of both C & O abundances. In fact, a change in the C abundance alone, for example, produced only a minor change in CO$_2$ band strength (Paper I). The large depression over the 2.7 $\mu$m region mostly due to H$_2$O can also be better explained with the model of the UCM-a series. The $Q$-branch of the CH$_4$ band appears to be weaker with the model of the UCM-a than with that of the UCM-c series, consistent with the decrease of the CH$_4$ in the UCM-a compared to the UCM-c series (Figure 2). Also, the observed CH$_4$ $Q$-branch indeed agrees better with the predicted
one based on the model of UCM-a. Thus, we conclude that the UCM-a series rather than the UCM-c series should be applied to SDSS J083008+4828.

In Figure 4(a), we compare the observed spectrum of SDSS J053952–0059 with the predicted spectra based on the models of the UCM-a and UCM-c series. As is already known, this spectrum is well explained by a model of the UCM-c series in Paper I (curve 1). On the other hand, the observed spectrum cannot be explained by a model of the UCM-a series of the same parameters (curve 2). We obtain a more or less similar result for SDSS J144600+0024, namely the observed spectrum of this object can be well explained by the model of the UCM-c, as shown in curve 1 in Figure 4(b), but not with that of the UCM-a series (curve 2).

In Figure 4(e), we examine 2MASS J055919–1404, in which the observed CO2 band is very strong. We could not explain the CO2 and CO bands in this object with our UCM-c series, as shown in Figure 5(a), the observed spectrum can be explained by the model of a higher effective temperature of $T_{\text{eff}} = 900 \text{ K}$ with the model of the UCM-a series. Also, we find that the case of log g = 4.5 provides the best fit, as shown in Figure 5(b). Thus, we conclude that ($T_{\text{eff}}$, $T_{\text{cr}}$, log g) = (900, $T_{\text{cond}}$, 4.5) for 2MASS J041519–0935 for the models of the UCM-a series. In curves 1 and 2 of Figure 4(f), we show the best possible predicted spectra based on the models of the UCM-c and UCM-a series with $T_{\text{eff}} = 800 \text{ K}$ and $T_{\text{eff}} = 900 \text{ K}$, respectively. We observe that the model of the UCM-a series appears to match better with the observed spectrum than the model of the UCM-c series.

Finally, we summarize the basic parameters of the six brown dwarfs in Table 2. The major change from Table 4 of Paper I is the introduction of abundance classes in Column 3 indicated by the UCM series applied: In UCM-a and UCM-c, C & O abundances should be close to those of the 1D and 3D solar abundances, respectively. The physical parameters are re-examined with the models of the UCM-a series in the same manner as in Paper I. A major change in the physical parameters is $T_{\text{eff}}$ for 2MASS J041519–0935, which is changed from 800 K to 900 K, as shown in Figure 5(a). For the other five objects, the physical parameters for the models of the UCM-a series remain the same as for the UCM-c series. We confirm that the overall SEDs based on the models of the UCM-a and UCM-c series of the same physical parameters agree well (see Figure 4) even though some local features due to the CO2 and H2O bands differ somewhat. Thus, it is natural that the physical parameters derived mainly from the fits of the overall SEDs remain the same for both the UCM-a and UCM-c series. The $R/R_{J}$ values for SDSS J083008+4828, 2MASS J055919–1404, and 2MASS J041519–0935 are changed slightly, reflecting the changes of models from the UCM-c to the UCM-a series.

4. DISCUSSION

4.1. Validity of Our “Best-fit” Models

Fitting of the model spectra to the observed spectra is carried out by “eye” throughout in this paper and in Paper I. The reader might wonder whether the eye-fitting can find reliable “best” models for various objects. In this subsection, we assess our eye-fitting by comparing it with the numerical fitting results.

We evaluate the goodness of fit by the reduced-chi-square (hereafter $R$) defined as

$$R = \sum_{i=1}^{N} \left( \frac{f_{i} - C F_{i}}{\sigma_{i}} \right)^{2} / (N - m),$$

where $f_{i}$ and $F_{i}$ are fluxes of the observed and model spectra at i-th wavelength grid, respectively. The uncertainty of the observed flux is indicated by $\sigma_{i}$ and $m$ is the degree of freedom. Here $C$ is the scaling factor that minimizes $R$ and is given by

$$C = \frac{\sum f_{i} F_{i} / \sigma_{i}^{2}}{\sum F_{i}^{2} / \sigma_{i}^{2}}.$$

These definitions are in principle equivalent to goodness-of-fit statistics $G$ by Cushing et al. (2008) for the equal weight case.

As demonstrated in Paper I, the current UCM cannot fit the observations beyond 4 $\mu$m at least in some objects. Therefore, we limit the wavelength range for calculating $R$ to 2.64–4.15 $\mu$m (cf. model spectra are available from 2.64 $\mu$m and CO2 band starts from 4.17 $\mu$m).
Table 3
The Best Three Models According to the Numerical Fitting

| No. | \( T_{\text{eff}} \) (K) | \( \log g \) | \( T_{\text{cr}} \) (K) | \( C \) \((\times 10^6)\) | \( R \) |
|-----|----------------|---------|----------------|-------------|-----|
| 1   | SDSS J053951−0059 (L5) | 1800 | 5.5 | 1800 | 6.32 | 1.127 |
| 2   | 1900 | 5.5 | 1800 | 5.82 | 1.206 |
| 3   | 1900 | 5.0 | 1800 | 6.37 | 1.288 |
| 1   | SDSS J144600+0024 (L5) | 2000 | 4.5 | 1700 | 1.53 | 0.496 |
| 2   | 1900 | 4.5 | 1700 | 1.61 | 0.513 |
| 3   | 1800 | 4.5 | 1700 | 1.69 | 0.553 |
| 10  | 1700 | 4.5 | 1700 | 1.79 | 0.695 |
| 2   | 2MASS J152322+3014 (L8) | 1600 | 5.5 | 1700 | 1.89 | 0.675 |
| 3   | 1600 | 5.0 | 1700 | 1.91 | 0.733 |
| 3   | 1700 | 5.5 | 1800 | 1.69 | 0.740 |
| 4   | 1500 | 4.5 | 1700 | 2.45 | 0.793 |
| 1   | SDSS J083008+4828 (L9) | 1600 | 4.5 | 1800 | 3.78 | 0.679 |
| 3   | 1700 | 4.5 | 1800 | 3.52 | 0.711 |
| 3   | 1800 | 5.0 | 1900 | 3.44 | 0.746 |
| 9   | 1500 | 4.5 | 1700 | 4.54 | 0.841 |
| 1   | 2MASS J055919−1404 (T4.5) | 1200 | 4.5 | 1900 | 21.8 | 0.389 |
| 2   | 1200 | 4.5 | 1900 | 20.3 | 0.418 |
| 3   | 1100 | 4.5 | 1700 | 25.3 | 0.482 |
| 1   | 2MASS J041519−0935 (T8) | 800 | 4.5 | 1900 | 29.1 | 0.170 |
| 2   | 900 | 4.5 | 1900 | 20.6 | 0.173 |
| 3   | 900 | 5.0 | 1900 | 17.2 | 0.195 |

Notes. Models of the UCM-c series are adopted throughout as in Paper I. The eye-fitting results quoted from Paper I are indicated by bold face.

In Table 3, we list the three best models based on the \( R \) value and the model quoted in Paper I (by eye-fitting) for each object in our sample. The eye-fitting results are indicated by bold face. The models selected by the eye-fitting achieve minimum \( R \) for SDSS J053951−0059 (L5) and 2MASS J041519−0935 (T8; for this particular object, we search for the best model with \( T_{\text{eff}} = T_{\text{cond}} \) for the reason given in Section 4.3.6 of Paper I) and the second minimum \( R \) for 2MASS J055919−1404 (T4.5). The difference in \( R \) between the first and second models for the last case is tiny, and the model parameters are within the uncertainty stated in Paper I (±100 K for \( T_{\text{eff}} \) and \( T_{\text{cr}} \), and ±0.5 dex for \( \log g \)).

For two late-L objects, 2MASS J152322+3014 (L8) and SDSS J083008+4828 (L9), the differences in the model parameters are mostly within the uncertainty of eye-fitting, although the models used in Paper I are not included in the best three according to numerical fitting for these dwarfs. Although log \( g \) of 2MASS J152322+3014 differs by 1.0 dex, the eye-selected model is at the fourth position in the list, which we consider to be in the accepted range.

A significant difference between the two methods is found in the L5 dwarf SDSS J144600+0024. The numerical fitting suggests \( T_{\text{eff}} = 2000 \) K, which is 300 K higher than that selected by eye-fitting. The second and third best models are those of \( T_{\text{eff}} \) = 1900 and 1800 K. Note that \( \log g \) and \( T_{\text{cr}} \) are the same in all four models. In fact, we regarded such high \( T_{\text{eff}} \) values to be unrealistic for an L5 dwarf and did not consider them in the eye-fitting. The empirical \( T_{\text{eff}} \) of this object, derived by Vrba et al. (2004), is even lower as 1592 K. A key feature is the CH\(_{4}\) 3.3 \( \mu \)m band, which appears only in the \( T_{\text{eff}} \) = 1700 K model. The observed spectrum of this source is rather noisy, and the detection of this band is marginal. If the tiny dip seen near 3.3 \( \mu \)m in the observed spectrum is actually the CH\(_{4}\) band, the eye-fitting results, even if they are not perfect, are justified.

The nature of mid-L to early-T type dwarfs is still under debate and their effective temperatures might actually spread to higher values. Incomplete atmosphere modeling is another possible reason for large deviation in \( T_{\text{eff}} \) between eye-fitting and numerical fitting. As discussed in Paper I, current atmosphere models for brown dwarfs are still being explored: the UCM is one such model. Many physical and chemical processes in brown dwarfs are not yet understood. These problems, which are beyond the scope of this paper, shall be tackled and eventually incorporated into future model atmospheres. In addition, some of our AKARI spectra have a relatively low signal-to-noise ratio (S/N). Under such circumstances, numerical fitting may not always provide a unique and physically reasonable solution. On the other hand, the eye-fitting would focus on some key features and consider balance over the wavelength range. Our goal in this paper is to highlight the effects of chemical abundance in the brown dwarf atmosphere. The comparisons described above demonstrate that, though it is not perfect, the eye-fitting is useful to find reasonable models for our purpose. Therefore, we apply the model parameters derived from our eye-fitting to the six objects, including J144600+0024, in the analysis throughout this paper.

Note that the differences between the models appear more prominently over the shorter wavelength range, especially in the J band, even if the spectra in the AKARI wavelength range are similar to each other. Consideration of near-infrared data such as Two Micron All Sky Survey (2MASS) photometry or ground-based spectroscopy will enable better constraint of the model parameters (S. Sorahana et al., preparation). Such improvements in the spectral range will also help the evaluation of the goodness of fit of wavelengths beyond 4 \( \mu \)m.

4.2. C & O Abundances in Brown Dwarfs

The unexpectedly strong CO\(_{2}\) feature observed with AKARI in some brown dwarfs has been a puzzle (Paper I), but we find it is simply due to the effect of C & O abundances. Generally, a small change in the chemical composition does not have a large effect on either the predicted spectra at low resolution or on the thermal structure of the photosphere in hotter stars. In fact, this is the reason why one-dimensional spectral classification (e.g., Harvard system) is possible for such stars. However, in the case of cool stars, a small change in the chemical composition is amplified in molecular abundances. An apt example is the spectral branching of cool giant stars into M, S, and C types, depending on whether the C/O ratio is smaller or larger than unity. In cool dwarfs, because of the large molecular opacities, the change in C & O abundances also has a significant effect on the strengths of molecular bands as well as on the photospheric structures.

The results given in Section 3 reveal that half of the brown dwarf spectra observed with AKARI (i.e., SDSS J053952−0059, SDSS J144600+0024, and 2MASS J152322+3014) can be fitted by the predicted spectra based on the models of the UCM-c series (Paper I). Although the fits are by no means perfect, the fits with the predicted spectra based on the UCM-c series are better than those based on the UMC-a series. For this reason, C & O abundances in these three brown dwarfs should be closer to the recent 3D solar abundances rather than to the classical 1D solar abundances. On the other hand, the remaining brown...
The problem of solar C & O abundances is still under intensive discussion (e.g., Ayres et al. 2006; Caffau et al. 2008; Asplund et al. 2009). Although our problem here is not the solar composition, it is of interest to know which of the proposed solar compositions proves most realistic for the Sun. If the recent 3D result is most realistic for the Sun, our sample may have compositions similar to the Sun and the remaining three may be about 0.2 dex more metal-rich. This means that the proportion of metal-rich objects with the highest [Fe/H] of about +0.2 is quite high in our present sample of brown dwarfs.

4.3. Effects of C & O Abundances on the 0.9–2.5 μm Spectra

Having shown that C & O abundances have significant effects on the 2.5–5.0 μm spectra of brown dwarfs, we now examine their effect on the 0.9–2.5 μm spectra. As examples, we compare the predicted 0.9–2.5 μm spectra of the models of the UCM-a and UCM-c series for the case of $T_{\text{eff}} = 1700$ K, $T_{\text{eff}} = 1500$ K, and log $g = 4.5$. The 0.9–2.5 μm spectrum is convolved with the slit function of FWHM = 500 km s$^{-1}$ (a typical resolution of observed spectra in this region) and the 2.5–5.0 μm spectrum with that of FWHM = 3000 km s$^{-1}$ (resolution of the AKARI spectra).

Thus, H$_2$O band strengths depend sensitively on oxygen abundance, and we may determine oxygen abundance from the H$_2$O bands. However, note that the H$_2$O band strengths also depend on other parameters such as $T_{\text{eff}}$, $T_{\text{eff}}$, and log $g$, and we should consider the same difficulty due to a degeneracy of these parameters as noted earlier by other authors (e.g., Burgasser et al. 2006b; Leggett et al. 2009). This fact reconfirms the unique role of CO$_2$ as a metallicity (C & O abundances) indicator in brown dwarfs.

5. CONCLUDING REMARKS

Thanks to the AKARI spectra, we are for the first time able to demonstrate that the metallicity, more specifically C & O abundances, is an important parameter for understanding brown dwarf atmospheres. Until now, we had assumed that it was sufficient to use one sequence of model photospheres based on the representative chemical composition analyzing the low-resolution spectra of cool dwarfs. We must now admit that such an assumption is inappropriate, and we should consider abundance effects, especially of C & O, more carefully in our future analysis of cool dwarfs. Also, we cannot use any solar composition for cool dwarfs unless this substitution can be justified by a direct analysis of the spectra of cool dwarfs.

Although a detailed abundance analysis of brown dwarfs is especially difficult with low-resolution spectra, well-defined molecular bands, even at low resolution, can be potential abundance indicators. We know that CO$_2$ is a fine indicator of C & O abundances. Unfortunately, however, CO$_2$ is accessible only from space telescopes and, moreover, spectroscopic observations in the near-infrared have largely been neglected by the recent space infrared missions. From the viewpoint of the study on cool dwarfs (and other cool stars), the importance of observing the near-infrared spectra (especially between 2.5 and 5.0 μm) from space cannot be emphasized too much.

Although the spectra of brown dwarfs appear to be complicated, we are now convinced that the spectra of brown dwarfs can be basically understood on the basis of the LTE model photospheres, but only if the chemical composition is properly considered. This is a reasonable result for such high-density photospheres as those of brown dwarfs in which frequent collisions easily maintain thermal equilibrium. Thus, chemical composition is the most important ingredient in the interpretation and analysis of even low-resolution spectra. Now, with better observed data, including those from space, an analysis of the spectra and abundance determination for brown dwarfs can be done iteratively as for ordinary stars.

Finally, we point out that a major difficulty in the analysis of the spectra of brown dwarfs is that we have no model of comparable accuracy as for ordinary stars yet. For this reason, even an accurate numerical method such as that outlined in Section 4.1 cannot be infallible. In fact, we have no model reproducing all the observable features correctly, and the model found by the numerical method, as well as that found by the eye-fitting method, may prove incorrect even if they are relatively satisfactory among the models currently available. Within this limitation, we hope that our main results on the differential effects of C & O abundances are relatively free of present brown dwarf model uncertainties.

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