AKARI OBSERVATIONS OF BROWN DWARFS. IV. EFFECT OF ELEMENTAL ABUNDANCES ON NEAR-INFRARED SPECTRA BETWEEN 1.0 AND 5.0 $\mu$m

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ABSTRACT

The detection of the CO$_2$ absorption band at 4.2 $\mu$m in brown dwarf spectra by AKARI has made it possible to discuss CO$_2$ molecular abundance in brown dwarf atmospheres. In our previous studies, we found an excess in the 4.2 $\mu$m CO$_2$ absorption band of three brown dwarf spectra, and suggested that these deviations were caused by high C and O elemental abundances in their atmospheres. To validate this hypothesis, we have constructed a set of models of brown dwarf atmospheres with various elemental abundance patterns, and we investigate the variations of the molecular composition and the thermal structure, and how they affect the near-infrared spectra between 1.0 and 5.0 $\mu$m. The 4.2 $\mu$m CO$_2$ absorption band in some late-L and T dwarfs taken by AKARI is stronger or weaker than predicted by corresponding models with solar abundance. By comparing the CO$_2$ band in the model spectra to the observed near-infrared spectra, we confirm possible elemental abundance variations among brown dwarfs. We find that the band strength is especially sensitive to O abundance, but C is also needed to reproduce the entire near-infrared spectra. This result indicates that both the C and O abundances should increase and decrease simultaneously for brown dwarfs. We find that a weaker CO$_2$ absorption band in a spectrum can also be explained by a model with lower “C and O” abundances.

Key words: brown dwarfs – stars: abundances – stars: atmospheres – stars: late-type – stars: low-mass
Online-only material: color figures

1. INTRODUCTION

Elemental abundances of low-temperature objects such as brown dwarfs and extra-solar giant planets have been studied extensively, for example, by Tsuji et al. (2011), Madhusudhan et al. (2011), Barman et al. (2011), Fortney (2012), Konopacky et al. (2013), and Moses et al. (2013). In particular, they focused on the abundances of C and O. Some researchers, including Madhusudhan et al. (2011), Fortney (2012), and Moses et al. (2013), especially discussed the C/O ratio in exoplanet atmospheres. The C/O ratio is an important parameter that governs atmospheric composition, such as the abundances of CO, H$_2$O, and CH$_4$ molecules. The C/O ratio can provide information about the origin and evolution of the object, and thus could be an indicator for the classification of planets. For example, Madhusudhan et al. (2011) reported that the hot Jupiter WASP–12b has a carbon-rich atmosphere (i.e., C/O > 1). This indicates substantial depletion of oxygen in the disk during its evolution.

Swain et al. (2009) used NASA’s Hubble Space Telescope to obtain the first detection of CO$_2$ in the spectrum of a transiting extrasolar planet, HD 209458b. The presence of CO$_2$ absorption at 4.2 $\mu$m in brown dwarf spectra was first reported by Yamamura et al. (2010) from spectra taken with the Japanese infrared astronomical satellite AKARI (Murakami et al. 2007). They found that the CO$_2$ absorption band at 4.2 $\mu$m in three out of six AKARI brown dwarfs was deeper than predicted by the Unified Cloudy Model (UCM; Tsuji 2002, 2005), a brown dwarf atmosphere model. Sorahana & Yamamura (2012) investigated the spectral features of 16 AKARI objects and confirmed that the CO$_2$ molecule is always present in the atmosphere of T dwarfs. They also pointed out that the observed CO$_2$ absorption band in some late-L to T dwarfs is sometimes stronger or weaker than the predictions by the UCM. This problem seems to be related to CO$_2$ abundance and is not solved by adjusting the three model parameters in the UCM: effective temperature $T_{\text{eff}}$, surface gravity $\log g$, and critical temperature $T_c$ (this is an additional parameter in UCM that controls the thickness of the dust cloud in the photosphere; see Section 2 for details).

Yamamura et al. (2010) attempted to explain these deviations through vertical mixing following Griffith & Yelle (1999) and Saumon et al. (2000), and concluded that the CO$_2$ feature could not be reproduced by such a mechanism. Solar elemental abundances (Allende Prieto et al. 2002) have been assumed in UCM, as they were believed to be sufficient for analyzing the low-resolution spectra of cool dwarfs. However, Tsuji et al. (2011) proposed that the excess of the CO$_2$ absorption band in the observed spectra found by Yamamura et al. (2010) could be reproduced by increasing both the C and O abundances. In fact, the CO$_2$ band excess in the three brown dwarfs appeared to be reproduced due to the C and O abundances of the old solar values ($\log A_C = 8.60$ and $\log A_O = 8.92$; Anders & Grevesse 1989; Grevesse et al. 1991) being larger by about +0.2 dex than the revised solar values ($\log A_C = 8.39$ and $\log A_O = 8.69$; Allende Prieto et al. 2002). This result raised other questions: (1) whether abundance variation in brown dwarfs is a general phenomenon, (2) whether there are objects that have lower C and O abundances, (3) whether only the C and O abundances change, and (4) how widely do elemental abundances in brown dwarfs range.

To confirm the validity of the result of Tsuji et al. (2011) and answer the above questions, we construct a set of brown dwarf atmosphere models using UCM with various elemental abundances that differ from the standard solar abundance (Allende Prieto et al. 2002), and investigate the effects on atmospheric structure and infrared spectra from 1.0 to 5.0 $\mu$m.
We also discuss how the excess or deficiency in the observed CO\(_2\) absorption band in some late-L and T dwarfs can be explained.

2. BROWN DWARF ATMOSPHERE WITH VARIOUS METALLICITIES

In order to test how the atmospheric structure and the resultant infrared spectra vary with elemental abundance, we take a model of (\(T_d/\log g/T_{\text{eff}}\)) = (1800 K/5.5/1800 K) as an example L dwarf atmosphere and a model of (\(T_d/\log g/T_{\text{eff}}\)) = (1900 K/4.5/1200 K) as an example T dwarf. The physical parameters of these two types of brown dwarfs, \(T_{\text{eff}}, \log g, \) and \(T_d\), were obtained by model fitting to the observed spectra of actual objects, SDSS J0539−0059 (L5) and 2MASS J0559−1404 (T4.5) (Sorahana & Yamamura 2012).

UCM accounts for dust formation and sublimation/sedimentation. \(T_d\) cannot currently be predicted by any physical theory and is an empirical parameter. We assume that dust (with a typical size of \(\sim 0.01 \mu m\)) balances with gas and is not growing. Therefore, the dust would exist in a layer of \(T_d < T < T_{\text{cond}}\) (see also Tsuji 2002, 2005 for details). UCM applies the line lists of CO\(_2\) (HITEMP database; Rothman 1997), CH\(_4\) (Freedman et al. 2008 based on the Spherical Top Data System model of Wenger & Champion 1998), CO (Guelachivili et al. 1983; Chackerian & Tipping 1983), and H\(_2\)O (Partridge & Schwenke 1997).

We adjust the elemental abundances from the solar value by ±0.2 dex. The elemental abundances [X/H] of a solar neighborhood star are distributed between −1.0 and +1.0 dex (Bodaghee et al. 2003), and thus variations of −0.2 and +0.2 dex are reasonably within the common abundance range. We investigate cases where the following parameters are varied:

1. All metal abundances.
2. Only carbon abundance.
3. Only oxygen abundance.
4. Only Fe abundance.
5. C and O abundances.
6. C, O, and Fe abundances.

Table 1 shows the elemental abundances applied in this study. For each case, we increase (+0.2 dex) or decrease (−0.2 dex) the abundance, and therefore we have 12 total test cases.

“All metal abundances” means all elemental abundances except for hydrogen and helium. Carbon and oxygen are the main components of the major molecules in brown dwarf atmospheres along with hydrogen. Dust components treated in UCM are Fe, MgSiO\(_3\), and Al\(_2\)O\(_3\) (Tsuji 2002). The most important dust component among these is Fe, because it has the highest number density at the low temperatures encountered in brown dwarf atmospheres.

In the wavelength range 1.0−5.0 \(\mu m\), there are fundamental and overtone bands of major molecules: H\(_2\)O at 1.4, 1.8, and 2.7 \(\mu m\); CO at 2.3 and 4.6 \(\mu m\); CO\(_2\) at 4.2 \(\mu m\); and CH\(_4\) at 2.2 and 3.3 \(\mu m\). We expect that their abundances are affected by those of C and O. The J-, H-, and K-band fluxes are affected mainly by the Fe dust abundance and continuum source intensity. In evaluating the calculated models, we focus on the following three points: (1) changes in H\(_2\)O, CO, CO\(_2\), and CH\(_4\) abundances in the photosphere; (2) variation of the temperature structure; and (3) molecular band profiles and flux levels in the J, H, and K bands. We show the result of each calculation in Sections 2.1−2.6.

2.1. Models in Which All Metal Abundances are Varied

First, we show the results for the cases of increased and decreased abundances of all metal elements (except for H and He) for typical L (Figure 1) and T dwarfs (Figure 2). We show the abundance, i.e., the partial pressure of each molecule, \(log P_{\text{partial}}\) [y dyn cm\(^{-2}\)], divided by total gas pressure, \(log P_g\) [y dyn cm\(^{-2}\)], (top left panel); the temperature [K] against total gas pressure, \(log P_g\) [y dyn cm\(^{-2}\)], (top right panel); and the emergent spectrum between 1.0 and 5.0 \(\mu m\) (bottom panel). Partial pressure profiles for the solar abundance (dashed line), increased abundance (solid line), and decreased abundance (dotted line) models are drawn for each molecule in the top left panel. We also show the positions at which the Rosseland & Planck mean opacity becomes unity for each model. The temperature structures of the modified abundance models (red for increased and blue for decreased models) are also shown as deviations from the temperature of the solar abundance model (black). In the bottom panel, the continuum of each abundance model is also shown.

Figure 1 shows the L dwarf case. For the case of increased elemental abundances, we see that the abundances of all of the major molecules increase, except for CH\(_4\) in deep layers (\(log P_g \geq 5\)). CH\(_4\) decreases in deep layers by \(\sim 0.3 \text{ dex}\) according to the increased temperature caused by increasing H\(_2\)O;
Figure 1. Chemical structures, temperature structures, and spectra of the L dwarf model ($T_{\text{eff}}/\log g/T_{\text{eff}} = (1800 \, \text{K}/5.5/1800 \, \text{K})$ for the cases of increased (solid line for (a) and red lines for (b) and (c)) and decreased (dotted line for (a) and blue lines for (b) and (c)) all metal abundances compared with the solar abundance model. (a) Partial pressures of H$_2$ ($\sim$total gas pressure $P_g$), CO, H$_2$O, CH$_4$, and CO$_2$ molecules normalized by the total gas pressure are plotted against total gas pressure, log $P_g$. The abundances of dust are represented by the pressures of the nuclei of the refractive elements locked in the dust grains (i.e., Fe and Al for iron and corundum, respectively). The position where the Rosseland and Planck mean opacity becomes unity is also shown: a plus represents the solar abundance model, an open triangle represents the increased abundance case, and a filled triangle represents the decreased abundance case. Note that two triangles overlap with each other in this figure because the optical depth for the increased and decreased cases are the same. (b) Left: the temperature structure of each abundance model. Right: deviations of the temperature in the models of modified abundance from that of the solar abundance model. (c) The spectra of the models. The continuum levels of the solar abundance and modified models are also shown. (A color version of this figure is available in the online journal.)

The molecule holds energy from the inner, warmer region due to high opacity (greenhouse effect). On the other hand, surface CH$_4$ abundance increases because of enhanced carbon. The gas temperature becomes lower toward the surface because of more efficient radiative cooling following the increase of molecular abundances in the optically thin region. All of the absorption bands, except for that of CH$_4$, become deeper by 5%–7% because of the enhanced abundances. The flux level around the 3.3 $\mu$m CH$_4$ band is a result of radiation from the background continuum source traveling through the atmosphere with varying molecular number density and temperature. The entire flux level along the $J$, $H$, and $K$ bands basically reflects the continuum level, which depends on the inner region ($\tau_R \sim 1$) temperature and dust opacity, as shown in Figure 1 of
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Figure 2. T dwarf model \((T_{\text{cr}}/\log g/T_{\text{eff}}) = (1900 \text{ K}/4.5/1200 \text{ K})\) with all metal abundances increased. The notation is the same as in Figure 1.

(Tsui 2002). In this case, the dust abundance increases but the inner temperature also increases. Thus, the flux of the \(J\) band, which is most affected by the dust, does not change, and the \(H\)- and \(K\)-band fluxes increase. For the case of decreased elemental abundances, the change in molecular abundances, temperature structure, and spectral features are generally opposite to the case of increased elemental abundances. Almost all of the molecular abundances decrease, except for the \(\text{CH}_4\) abundance in the inner region \((\log P_g \gtrsim 5)\). The temperature of the inner region decreases by 150 K due to the \(\text{H}_2\text{O}\) abundance decreasing by \(\sim 0.2\) dex. Consequently, the \(\text{CH}_4\) abundance in this region increases by \(\sim 0.3\) dex. The surface temperature becomes higher by about 20 K. This is caused by the suppressed cooling effect due to the decrease of molecules, contrary to the increased elemental abundance case. Although the \(\text{H}_2\text{O}\), \(\text{CO}_2\), and \(\text{CO}\) abundances decrease by about 0.2–0.5 dex in the optically thin surface area, the absorption bands of these molecules barely change. The \(H\)- and \(K\)-band fluxes drop because of the decreasing continuum level due to the lower temperature of the inner optically thick region. On the other hand, the \(J\)-band flux rises because of the rising continuum flux level due to the decreasing amount of dust.
In the corresponding T dwarf model shown in Figure 2, the abundances of all the molecules increase almost proportionally to the increased elemental abundances, except for CH$_4$ in the inner layers, as observed in the L dwarf model. The temperature rises throughout the entire atmosphere. The absorption bands of CO and CO$_2$ become deeper, as observed in the case of the L dwarf model. The change in the CO$_2$ band at 4.2$\mu$m is particularly significant, as much as 20%. On the other hand, the flux levels in the 2.4–3.8$\mu$m region (including H$_2$O and CH$_4$ bands) become higher, contrary to the case of the L dwarf model. This is because of the rise in the continuum flux level due to the higher photosphere temperature, rather than changes of the H$_2$O and CH$_4$ abundances. The changes of the J-, H-, and K-band fluxes are due to the continuum level. For the decreased elemental abundance case, the entire temperature drops due to decreasing H$_2$O. The effect of radiative cooling in the optically thin region is reduced, as observed in the L dwarf model. The changes in the spectral features are contrary to those observed in the increased elemental abundance case, but not completely. For example, the flux level from 3.0 to 4.0$\mu$m changes only slightly. This is the result of a competition between the decreasing continuum flux level caused by the lower temperature and the weaker absorption bands caused by less abundant H$_2$O and CH$_4$. The J-, H-, and K-band fluxes depend mainly on the continuum level.

2.2. Models in Which Only the Carbon Abundance is Varied

We show the results for the case in which only the C abundance is varied for L (Figure 3) and T dwarfs (Figure 4), respectively. In the increased elemental abundance cases, the abundances of CO and CH$_4$ molecules increase. Oxygen atoms are captured in CO molecules, and thus the abundance of H$_2$O decreases. The molecular abundances of the decreased C abundance case are opposite to the increased C abundance case. The residual oxygen atoms, which cannot obtain carbon atoms, exist as H$_2$O.

The L dwarf model with increased C abundance is shown in Figure 3. The CO and CH$_4$ abundances increase by about 0.2 and 1.0 dex, respectively. The H$_2$O abundance deep inside the photosphere (log $P_g > 6$) decreases by 0.5 dex and the temperature in this region also becomes lower by more than 140 K. The increase of the surface temperature (∼60 K) correlates with the decrease of H$_2$O (∼1.0 dex) and CO$_2$ (∼1.0 dex) molecules as cooling by these molecules becomes less effective. We see that the H$_2$O and CO$_2$ absorption bands become shallower by 50% and 15%, respectively. On the other hand, the CH$_4$ band becomes deeper. The flux level around the CO band seems mostly unchanged because of the balances between changes in the CO abundance, continuum level, and surface temperature. Since the inner region temperature goes down, the entire continuum level becomes lower and the J-, H-, and K-band fluxes are reduced by about 20%. The trends in the decreased C abundance case are generally contrary to those of the increased C abundance case, even though the variations in molecular abundances, photosphere temperature, and spectral features are less significant than those in the increased C case. Both CO and CH$_4$ decrease by about 0.2 and 0.4 dex, respectively, while the H$_2$O abundance increases by about 0.2 dex. Although the CO$_2$ abundance changes very little, the flux level around 4.2$\mu$m near the CO$_2$ absorption band becomes fainter because of the effect of increasing H$_2$O abundance. The decrease of the surface temperature is caused by the larger cooling effect due to the increased H$_2$O abundance.

The temperature deep inside increases by about 50 K due to the increase in H$_2$O molecules (greenhouse effect). Because of this increased inner region temperature, the continuum flux rises and the fluxes in the $J$ and $H$ bands increase by ∼5%–10%. A slight increase of the continuum level and abundant H$_2$O changes the $K$-band flux a little.

In the T dwarf model shown in Figure 4, the change of the molecular abundance is not similar to the L dwarf model, especially for H$_2$O and CO$_2$. For both the increased and decreased abundance cases, the change in the H$_2$O abundance is less significant than those in the L dwarf model, especially in the surface region. As noted at the beginning of this subsection, the variation of the H$_2$O abundance relates to that of CO. Since the carbon atoms are transferred from CO to CH$_4$ as the spectral type changes from L to T and the temperature decreases, the abundance of CO in the T dwarf photospheres is generally smaller than that in the L dwarf photospheres following the result of chemical equilibrium calculation. Thus, the variation of CO in the varied C abundance model is small, and therefore the change of H$_2$O is also less in the T dwarf atmosphere. Consequently, the flux levels of the H$_2$O bands at 1.4, 1.8, and 2.7$\mu$m do not change as much as in the L dwarf model. The CO$_2$ abundance increases opposite to the L dwarf model. This indicates that CO$_2$ can be created more easily in the T dwarf atmosphere than in the L dwarf atmosphere. However, because of the little change in the CO$_2$ abundance and the little absolute amount, the CO$_2$ band also does not change for either the increased or decreased C abundance cases. The CH$_4$ absorption band around 3.3$\mu$m becomes deeper by ∼5% corresponding to the increasing CH$_4$ abundance. The flux level around the CO band also becomes lower, not only with increasing CO but also lower continuum level. For the decreased abundance case, the flux level of the 3.0–4.0$\mu$m region becomes higher, in contrast to the flux level of the same wavelength range in the L dwarf model spectrum being lower than in the solar abundance model. This is explained as follows. In the L dwarf photosphere, the increase of the H$_2$O abundance lowers the flux level. In T dwarfs, the CH$_4$ abundance decreases. This effect weakens the absorption band at 3.0–4.0$\mu$m by 5%–20%. The J-, H-, and K-band fluxes do not change for either the increased or decreased abundance models, because the H$_2$O abundance near the surface does not change; also, there is little change in the continuum level as the dust temperature changes little.

2.3. Models in Which Only Oxygen Abundance is Varied

The results for the case in which only the O abundance is varied in L and T dwarfs are shown in Figures 5 and 6, respectively. In the L dwarf model, the change in the H$_2$O abundance and temperature structure in the increased/decreased only O abundance model are in principle similar to the case of the decreased/increased only C abundance (Section 2.2; Figure 3). Thus, the H$_2$O absorption band shape of the increased/decreased only O abundance case looks similar to that of the decreased/increased only C abundance case. In the increased abundance model, the H$_2$O and CO$_2$ abundances increase by about 0.5 dex and the temperature of the inner region (log $P_g \geq 6.0$) increases by 150 K. These variations are larger than those of the decreasing C abundance only model, reflecting the fact that the absolute number of extra O atoms is about double in the case of increasing O abundance. At the surface region (log $P_g \leq 5.0$), the temperature decreases by about 50 K due to enhanced cooling by abundant molecules such as H$_2$O and CO$_2$. The abundance of CH$_4$ reflects the temperature structure. The effects of the in-
increased H$_2$O and CO$_2$ abundances appear in the model spectra as deeper absorption bands. Although the CO abundance changes only a little, the flux level around the 4.6 $\mu$m CO band becomes lower due to decreased surface temperature. Because of the rising inner region temperature and decreasing iron grains, the fluxes in the J, H, and K bands increase by 2%–30%. For the decreased O abundance model, the results are generally in the opposite direction of the case of increased O abundance. H$_2$O and CO$_2$ are significantly reduced, and the spectral features of such molecular bands dramatically change.

For the T dwarf case shown in Figure 6, the change of H$_2$O and CH$_4$ at the surface region in the increased/decreased O abundance model is different from that of the decreased/increased C abundance model (Section 2.2; Figure 4), in contrast to the L dwarf case. In the C only abundance varied model, the carbon abundance contributes to the CO and CH$_4$ abundances, and the CO abundance affects the H$_2$O abundance. On the other hand, in the O only abundance varied model, the oxygen abundance directly affects the H$_2$O abundance, and the CH$_4$ abundance reflects the temperature structure which depends on the H$_2$O abundance. The flux level around the 3.3 $\mu$m CH$_4$ absorption band in both the increased/decreased only O abundance is similar to the decreased/increased only C abundance model. Since the CH$_4$ abundance at the surface...
region does not change in the model of varied O abundance only, we recognize that the 3.3 μm CH₄ absorption band reflects the abundance of CH₄ not only in the surface region but also the inner region. The variations of the CO and CO₂ abundances of the varied O only abundance case are larger than those of the varied C only abundance model, even though the directions of the changes are the same as each other. This indicates that both the CO and CO₂ abundances directly reflect the abundances of both carbon and oxygen, but more strongly for the O abundance. These variations appear in the spectrum of the varied O elemental abundance model. Specifically, the spectral feature of CO₂ band significantly changes. The temperature increases and decreases in almost the entire region for the increased and decreased abundance cases, respectively. Because of this, the flux in 2.5–3.0 μm stays at the same level even though the H₂O abundance increases/decreases, unlike the case of the L dwarf model.

2.4. Models in Which Only the Fe Abundance is Varied

The results of only varied Fe abundance for L and T dwarfs are shown in Figures 7 and 8, respectively. In the L dwarf model with increased Fe abundance, the temperature inside the dust layer (log \( P_\delta \sim 6.5 \)) increases by about 50 K, in agreement with...
the increase of the amount of Fe dust by 0.5 dex. Subsequently, the abundance of CH$_4$ decreases slightly in the dust layers. The fluxes in the $J$ and $H$ bands decrease 5%–13% due to larger dust extinction, while the flux level in 2.0–4.0 $\mu$m increases by about 5%, reflecting the rising continuum level and lower CH$_4$ abundance. The case of decreased Fe shows an almost opposite trend to the case of increased Fe.

On the other hand, the partial pressure of each molecule, and the temperature of the T dwarf model shown in Figure 8 change only a little, and the spectrum remains identical to the solar abundance model. This is expected, as the dust in a T dwarf photosphere precipitates deep inside and does not affect the spectrum.

### 2.5. Models in Which the C and O Abundances are Varied

The result of the varied C and O abundances of the L dwarf model is shown in Figure 9. In the increased C and O abundance model, the spectral features are generally the same as that of the model with only increased O abundance (Section 2.3; Figure 5), even though the variation of spectral features is generally smaller than that of the model with only an increased O abundance. We can understand this as competition between the increasing C and increasing O. The abundances of H$_2$O, CO, and CO$_2$ increase by 0.3, 0.2, and 0.7 dex, respectively. These changes make the temperature in the inner photosphere higher by about 80 K, and the surface temperature lower by...
A gradual decrease of temperature toward the surface (log P_g ∼ 3) is caused by the same reason as for the case in which only the O abundance is increased, i.e., the energy from the inner region is transferred outside more efficiently by the more abundant molecules. Following the change of the thermal structure, the abundance of CH_4 in the inner region of the photosphere decreases by 0.2 dex, but increases by 0.5 dex near the surface. The flux level between 2.3 and 5.0 μm is diminished by 2%–30% because of increased H_2O, CO, CO_2, and surface CH_4 abundances. The CO_2 abundance increases significantly throughout the entire photosphere, and the CO_2 absorption band becomes deeper by about 20%. The flux in the J and H bands increase by 15%–20% because of the rising continuum flux level. The K-band flux also slightly increases due to the higher temperature in the inner photosphere. The decreased abundance case is generally opposite to the increased case. The variation of spectral features is generally smaller than that of the model with only decreased O. The abundances of H_2O, CO, and CO_2 decrease by 0.5, 0.2, and 0.8 dex, respectively. The temperature of the inner photosphere becomes lower by 80 K and the CH_4 abundance increases by 0.2 dex. The higher surface temperature is caused by the decreased H_2O and CO_2 as in the case of
Figure 7. L dwarf model with only the Fe abundance increased/decreased. The notation is the same as in Figure 1.
(A color version of this figure is available in the online journal.)

decreased only O abundance. Due to the lower inner region temperature, the flux values in the $J$, $H$, and $K$ bands decrease by 5%–15%.

The T dwarf models are shown in Figure 10. In general, the trend of the model atmosphere for the increased C and O abundances case is similar to that of the increased only O abundance case (Section 2.3; Figure 6), except for the surface CH$_4$ abundance. However, the variation of the spectral features is smaller than in the L dwarf case. Since CH$_4$ increases at the surface in the model of the varied C and O abundances, the flux level around the CH$_4$ absorption band becomes lower than that in the spectrum of the increased only O abundance model. The change in the CO$_2$ band is significant compared to the variations of other features. This indicates that changes in the C and O abundances in the T dwarf model mostly appear in the CO$_2$ absorption band in the spectrum. These results confirm the suggestion by Tsuji et al. (2011) that CO$_2$ can be an index of the C and O abundances of brown dwarfs, especially for T dwarfs. The temperature of the photosphere of the decreased C and O abundance model drops by about 80 K, but the spectrum does not change much, except for the shallower 4.2 $\mu$m CO$_2$, 4.6 $\mu$m CO bands and smaller $K$-band fluxes. The CO$_2$ and CO band strengths are affected by the changes in their abundances. The $K$-band flux level reflects the decreasing continuum...
Figure 8. T dwarf model with only the Fe abundance increased/decreased. The notation is the same as in Figure 1. (A color version of this figure is available in the online journal.)

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2.6. Models in Which the C, O, and Fe Abundances are Varied

The results of cases in which the C, O, and Fe abundances are varied in L and T dwarfs are shown in Figures 11 and 12, respectively. In the cases of both increased and decreased C, O, and Fe in the L dwarf model, the changes of the abundances of H$_2$O, CO, and CO$_2$ are almost the same as those of the models in which the C and O abundance are varied. On the other hand, CH$_4$ abundance, temperature structure, and spectral features are different from those of the models in which the C and O abundance are varied (Section 2.5; Figure 9). For the increased case, more abundant Fe enhances dust formation, and the temperature, especially around the dust layer (log $P_g$ $\sim$ 6.2), increases by more than 100 K. The higher temperature raises the continuous flux level and smaller CH$_4$ abundance. The higher continuum level compensates for the deepened H$_2$O absorption. Consequently, the variation of the entire flux level seems to be smaller than that of the case in which the C and O abundances are varied. The fluxes in the $J$ and $H$
bands are affected by the dust amount along with the effects of the inner temperature, as discussed in the model spectrum with the varied C and O abundances. In the decreased abundance case, the variations in molecular abundance and temperature structure are also similar to the case of decreased C and O abundances, but the decrease in temperature around the dust layer in the current model is larger than that in the case of decreased C and O abundances, as is the case of increased abundance. Thus, the variation of the continuum flux level in the current model is also large. Accordingly, the decrease of the flux level over the entire wavelength range is moderate compared to the case of decreased C and O abundances, except for the CH₄ absorption band. Since CH₄ abundance increases above the dust layer due to the lower temperature, the depth of this absorption band becomes deeper by about 30%. The K-band flux reflects the lower continuum level due to the decreased inner region temperature.

The changes in the molecular abundances except for Fe, temperature, and the spectrum of the T dwarf model (Figure 12) with increased C and O and Fe abundances are almost identical to the case of increased C and O abundances (Section 2.5; Figure 10). This can be understood by the fact that the dust has little effect on the T dwarf model. The change in the CO₂ absorption band is particularly large as observed in the varied C...
Figure 10. T dwarf model with the C and O abundances increased/decreased. The notation is the same as in Figure 1.

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

and O abundance model. For the case of decreased abundances, we do not see any noticeable differences from the case of decreased C and O abundances. This result, and that of the case in which only the Fe abundance is varied, indicate that the spectrum of the T dwarf is not affected by Fe dust.

3. FITTING THE CO$_2$ 4.2 μm ABSORPTION BAND WITH MODELS OF DIFFERENT ELEMENTAL ABUNDANCES

In order to see the effects of elemental abundances on the infrared spectra of brown dwarfs more clearly, we calculate models of various elemental abundances for the best-fit model parameter set determined by Sorahana & Yamamura (2012) for AKARI + IRTF/SpEx$^3$ and spectra. Then we compare the result with the observed data and the solar abundance models. In this section, we mainly discuss how the CO$_2$ band behaves under different elemental abundances. The six cases of modified elemental abundances examined in Section 2 are

$^3$ We obtained the SpeX data from the SpeX Prism Spectral Libraries built by Dr. Adam Burgasser and Dr. Sandy Leggett (http://pono.ucsd.edu/~adam/browndwarfs/spexprism/html/all.html) and the IRTF Spectral Library maintained by Dr. Michael Cushing (http://irtfweb.ipac.caltech.edu/~spex/IRTF_Spectral_Library/).
considered. We show a comparison of the observed spectrum and these six model spectra in Figure 13. We choose 2MASS J0559−1404 (T4.5) as an example, because the object shows the CO$_2$ absorption band clearly in its high signal-to-noise ratio spectrum. The CO$_2$ 4.2 $\mu$m absorption band in the observed spectrum of this object is deeper than that of the best-fit model of the solar abundance. The CO$_2$ absorption band in the model spectra of varied C only abundance and Fe only abundance show minor changes in the CO$_2$ band region. For the case of only increasing O abundance, we see that the CO$_2$ 4.2 $\mu$m feature in the model spectra is significantly deepened, but as a side effect other features in the model spectra, for example, H$_2$O around 1.4, 1.8, and 2.7 $\mu$m and CH$_4$ at 3.0−4.0 $\mu$m, deviate from the observation. The CO$_2$ 4.2 $\mu$m band in the model spectra of increased “C and O” abundances fits the observation reasonably well without changing other features. We find that the O abundance plays the largest role in the photosphere of brown dwarfs, and the C abundance controls the extra chemical effects caused by the O abundance. This result indicates that the ratio of C−O in this brown dwarf atmosphere is similar to that of the sun. The model in which “C and O and Fe” are varied behaves similarly to the cases in which both “C and O” are varied in the case of a T4.5 dwarf. The behavior of spectral features for the case of increased all

Figure 11. L dwarf model with the C, O, and Fe abundances increased/decreased. The notation is the same as in Figure 1.

(A color version of this figure is available in the online journal.)
metal abundances is also similar to the case in which the “C and O (and Fe)” abundances are varied. This indicates that the most effective elements for reproducing the near-infrared spectral features of brown dwarfs are C and O, even though other elements such as Fe also contribute to suppressing the variation caused by C and O abundances, as discussed in Section 2.6. To constrain the other elemental abundances, we should investigate other band and line features, such as CO, CH₄, NH₃, Kᵢ, and FeH, with high-resolution and high-sensitivity spectroscopy in the future.

Next, we calculate models in which the “C and O” abundances are varied for other middle- to late-L and T dwarfs and we check the behavior of the CO₂ 4.2 μm fundamental absorption band. Since the effect of Fe on the spectral features is relatively minor compared to that of C and O, we only consider the models in which the “C and O” abundances are varied following Tsuji et al. (2011). The results are shown in Figure 14. We find that the CO₂ 4.2 μm absorption band does not change at all by changing the elemental abundance for late-T dwarfs ($T_{\text{eff}} \sim 700$ K). In the models of late-T dwarfs, the CO₂ abundance is already very low and small changes of the abundance will not change the spectrum. The presence of the CO₂ band in these sources should be explained by another mechanism. We find that the CO₂ band in the spectra of the models with
increased “C and O” abundances fits the spectra of 2MASS J0559–1404 and 2MASS J0830+4828 better than the solar abundance models, as concluded by Tsuji et al. (2011). The model with increased “C and O” abundances also fits the spectra of SDSS J1254–0122 better than the solar abundance model, although the error of the observed spectrum is large. On the other hand, the model of decreased “C and O” provides better fits for 2MASS J1523+3014 than the original model. 2MASS J1523+3014 being metal-poor is consistent with the statement by Kirkpatrick et al. (2001). This object is a companion of a well-known G-type star. Thus, they suggested that the metallicity of 2MASS J1523+3014 (called GJ 584C in their paper) is −0.2 dex, assigned from that of the primary star. For the first time, we confirm the elemental abundances of this brown dwarf directly and also confirm that the C and O abundances of the companion are almost the same as those of the primary star. We also confirm that the model of decreased all metal abundances does not give a better fit for the CO2 band because the variation is suppressed by other elements, except for C and O. Our results imply that 2MASS J0559–1404, SDSS J0830+4828, and SDSS
J1254–0122 are C- and O-rich relative to the Sun, and 2MASS J1523+3014 is a C- and O-poor object.

4. SUMMARY

We attempt to improve brown dwarf atmosphere models by varying the elemental abundances. We calculate the model atmospheres of typical L and T dwarfs varied with (1) all metal abundances (elements except for H and He), (2) C abundance only, (3) O abundance only, (4) Fe abundance only, (5) C and O abundances, and (6) C, O, and Fe abundances. We investigate the variation of CO, CO₂, CH₄, and H₂O abundances and temperature in the photospheres. We also examine flux levels at several wavelengths in the spectra, namely, the J, H, and K bands, the centers of the CO bands at 4.6 μm, the CO₂ band at 4.2 μm, the CH₄ band at 3.3 μm, and the H₂O bands at 1.4, 1.8, and 2.7 μm.

We now summarize the variation of molecular abundances. In the case of only increasing the C abundance, the CO and CH₄ abundances increase. Since more O atoms are captured in CO, the H₂O and CO₂ abundances decrease. However, the variations of the H₂O and CO₂ abundances in T dwarf photospheres are smaller than those in L dwarfs. This is because of a small variation of the CO abundance in T dwarf photospheres. In all cases of increasing O abundance, the abundances of H₂O and CO₂ in the photosphere increase. All decreasing cases behave contrary to the increasing case.

Temperature generally correlates tightly with H₂O and CO₂ abundances. When the H₂O and/or CO₂ abundances increase in the optically thick region of the photosphere, they play the role of holding the energy from the inner photosphere and the temperature in the region rises (greenhouse effect). On the other hand, when the H₂O and/or CO₂ abundances in the optically thin region increase, the temperature in the region decreases through radiative cooling. The temperature around the dust layers depends on the amount of dust, especially of iron grains. Fe has the largest extinction effect relative to other dust components, Al₂O₃ and MgSiO₃, included in UCM. When Fe increases, the temperature around the layers increases because of the greenhouse effect. The CH₄ abundance tends to be affected by the variations of the photosphere temperature in addition to the C abundance.

In general, the flux level of each molecular band reflects its abundance and temperature profile along the line of sight. The three T dwarf models where the following parameters are varied: (1) all metal abundances, (2) C and O abundances, and (3) C, O, and Fe abundances, show spectra similar to each other, and only the CO₂ absorption band changes noticeably. The flux levels of the J, H, and K bands reflect primarily the temperature of the inner photosphere where Rossland and Planck mean optical depth τR ≈ 1, and secondly H₂O abundance. The J and H bands are also sensitive to the dust abundance.

Sorahana & Yamamura (2012) have found that the observed CO₂ absorption bands in some objects are stronger or weaker than the prediction by the solar abundance models. We construct a set of model atmospheres with various elemental abundances for the same model parameters determined by Norahana & Yamamura (2012), and compare the model spectra with the observed spectra. First, we compare the observed spectrum of 2MASS J0559–1404(T4.5) with six model spectra with various elemental abundances. As a result, the CO₂ band in the model spectrum with increased “C and O (and Fe)” abundances and increased all metal abundances fit the observed spectra better than that of the solar abundance models and any other abundance pattern models. This indicates that C and O are the most effective elements to reproduce the near-infrared spectral features of brown dwarfs. Next, we attempt to investigate whether the CO₂ absorption band in the spectrum of late-L to T dwarfs are explained by the model in which only the C and O abundances are varied. We find that the excess of CO₂ abundance in the observed spectra of three objects can be reproduced by the increased abundance model, and there is one object for which the model in which C and O abundances are decreased better explains the band in the observed spectrum. This indicates that there are C- and O-poor brown dwarfs. We also confirm that the model with all metal abundances decreased does not fit better, at least for 2MASS J1523+3014, because the variation of the CO₂ band strength is suppressed by other elements except for C and O. This may suggests that C and O abundances vary independently of other elements. The result of poor C and O abundances in 2MASS J1523+3014 is consistent with the statement of Kirkpatrick et al. (2001). The remaining three objects are best fit by the solar abundance model. These results indicate that both the C and O abundances should increase and decrease simultaneously.

Recently, Madhusudhan et al. (2011) reported an anomaly in the H₂O and CH₄ abundances compared to the solar abundance chemical equilibrium model prediction for the atmosphere of the hot-Jupiter WASP-12b. They suggested that the abundances 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), C/O > 1 at 3σ significance. From our result, however, we suggest that the ratio of C to O in our AKARI/brown dwarf sample should be closer to the solar value. This difference between brown dwarfs and exoplanets is potentially caused by their formation. While almost all isolated brown dwarfs are born in the interstellar medium like stars, planets are born in protoplanetary disks. There are several mechanisms for planet formation, e.g., core accretion (CA) and gravitational instability (GI). In the CA model, giant gas planets have a lot of H₂O in their core because the core first forms from an H₂O-rich disk. After the core forms, they capture a lot of gas from the surrounding disk with lack of H₂O, i.e., O. Thus the giant gas planets formed by the CA may have an O-poor atmosphere. On the other hand, the giant gas planets in the GI model form directly in mixed gas and dust, and thus their atmospheres are considered to have no lack of O. WASP-12b is possibly formed by the CA. If most planets are formed by CA, then the C/O ratio will be an index to distinguish between brown dwarf and planet.

The range of elemental abundances (from −0.2 to +0.2 dex) is within the range of metallicity variation among solar neighborhood stars (i.e., [X/H] distributed between −1.0 and 1.0 dex). Our analysis also reveals the possibility that a remarkable fraction of brown dwarfs seem to be C- and O-rich. On the other hand, none of the revised models can explain the CO₂ absorption band strength in the latest T dwarfs yet. To understand the deviation of the CO₂ abundance in these T dwarf photospheres, we need to consider other mechanisms.

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