A Comprehensive Study of Brown Dwarf and Exoplanet Atmospheres

Satoko Sorahana[1]

[1]*Department of Physics, Nagoya University, Japan:*

ABSTRACT

We present an analysis of brown dwarf spectra taken by *AKARI*, a Japanese infrared astronomical satellite. We observed 27 brown dwarfs, and for the first time obtained good continuous spectra between 2.5 and 5.0 μm for 16 sources. We investigate the appearance of the CH_4 (3.3 μm), CO_2 (4.2 μm) and CO (4.6 μm) molecular absorption bands in this new wavelength range along their spectral types, and attempt to interpret these results with the Unified Cloudy Model (UCM), a theoretical brown dwarf atmosphere model.

We find that the physical and chemical structures in the brown dwarf atmospheres deviate from theoretical predictions for local thermodynamic equilibrium (LTE) with solar metallicity. As our first trial for improving UCM, we focus on “elemental abundances". We find that the CO_2 band is better reproduced by a model with revised C & O abundances than the solar elemental abundance model, except for very late-T dwarfs.

There are two types of brown dwarfs: isolated objects, the targets of our current study, and objects orbiting around a primary star (extra gas planets). We are also interested in the atmospheres of such extra gas planets, especially, those having relatively longer orbital radii and masses and temperatures similar to those of brown dwarfs. To understand their atmospheres, we should compare these two types of objects through the analysis of infrared spectra. This study may also inform us about the origin of gas planet formation. We will observe such extra gas planets with *SPICA*/SCI, and gain a comprehensive understanding of atmospheres from brown dwarfs to gas planets.

1. INTRODUCTION

Brown dwarfs are objects with mass intermediate between stars and planets. Heavier brown dwarfs maintain deuterium burning when they are young (10^6 yr) instead of hydrogen fusion in their core. Hence, they simply cool after deuterium burning ends (Burrows et al. 2001). Their effective temperatures are very low (2200–600 K). They are classified into spectral types L and T (Geballe et al. 2002); L dwarfs are warmer than T dwarfs. Since they are very faint, the first observation was only made in 1995 (Nakajima et al. 1995).

The atmospheres of brown dwarfs are dominated by molecules and dust. Infrared spectra of brown dwarfs are the most important tools for understanding their physical and chemical structures, because there are many molecular absorption bands. The effects of dust are observed in the near-infrared spectra of L dwarfs (Tsuji et al. 2004), particularly in the *J*- and *H*-bands, whereas the spectra of T dwarfs show little sign of dust (Tsuji & Nakajima 2003). Current brown dwarf atmosphere models include dust effects empirically through a model parameter (Tsuji 2002, 2005; Allard et al. 2001, 2003; Ackerman & Marley 2001; Woitke & Helling 2003; Helling et al. 2008). For example, the Unified Cloudy Model (UCM), a brown dwarf atmosphere model constructed by Tsuji (2002, 2005), considers dust formation and sublimation/sedimentation. This model can explain the observed SEDs more or less satisfactorily, however the models still have problems explaining some molecular absorption band strengths, for example, the 4.6 μm CO band (Geballe et al. 2009).

2. SPECTRA OF 16 *AKARI* OBJECTS

We observed 27 brown dwarfs with *AKARI*, a Japanese infrared astronomical satellite launched in February 2006 (Murakami et al. 2007). The InfraRed Camera (IRC) on-board *AKARI* is capable of obtaining moderate-resolution ($R\sim120$) spectra devoid of any degradation due to telluric features (Onaka et al. 2007). We use the IRC to obtain continuous spectra of brown dwarfs in the wavelength range 2.5–5.0 μm. We obtained 16 good quality spectra (11 L dwarfs and 5 T dwarfs) with a signal-to-noise ratio (S/N) averaged over the spectra higher than or about 3.0. Known binaries are excluded. Figure 1 shows the spectra of the brown dwarfs as a sequence of their spectral types from L1 (bottom) to T8 (top). We investigate the appearance of three molecular absorption bands (CH_4 at 3.3 μm, CO_2 at 4.2 μm and CO at 4.6 μm) in the brown dwarf spectra along their spectral types (Sorahana & Yamamura 2012).

2.1. CO Fundamental Absorption Band at 4.6 μm

The CO 4.6 μm band appears in all spectral types including late-T dwarfs. This result confirms that CO generally exists in the atmospheres of all spectral types, contrary to the prediction by UCM. However, we have not yet succeeded in understanding these phenomena and will investigate these CO excesses in future work.

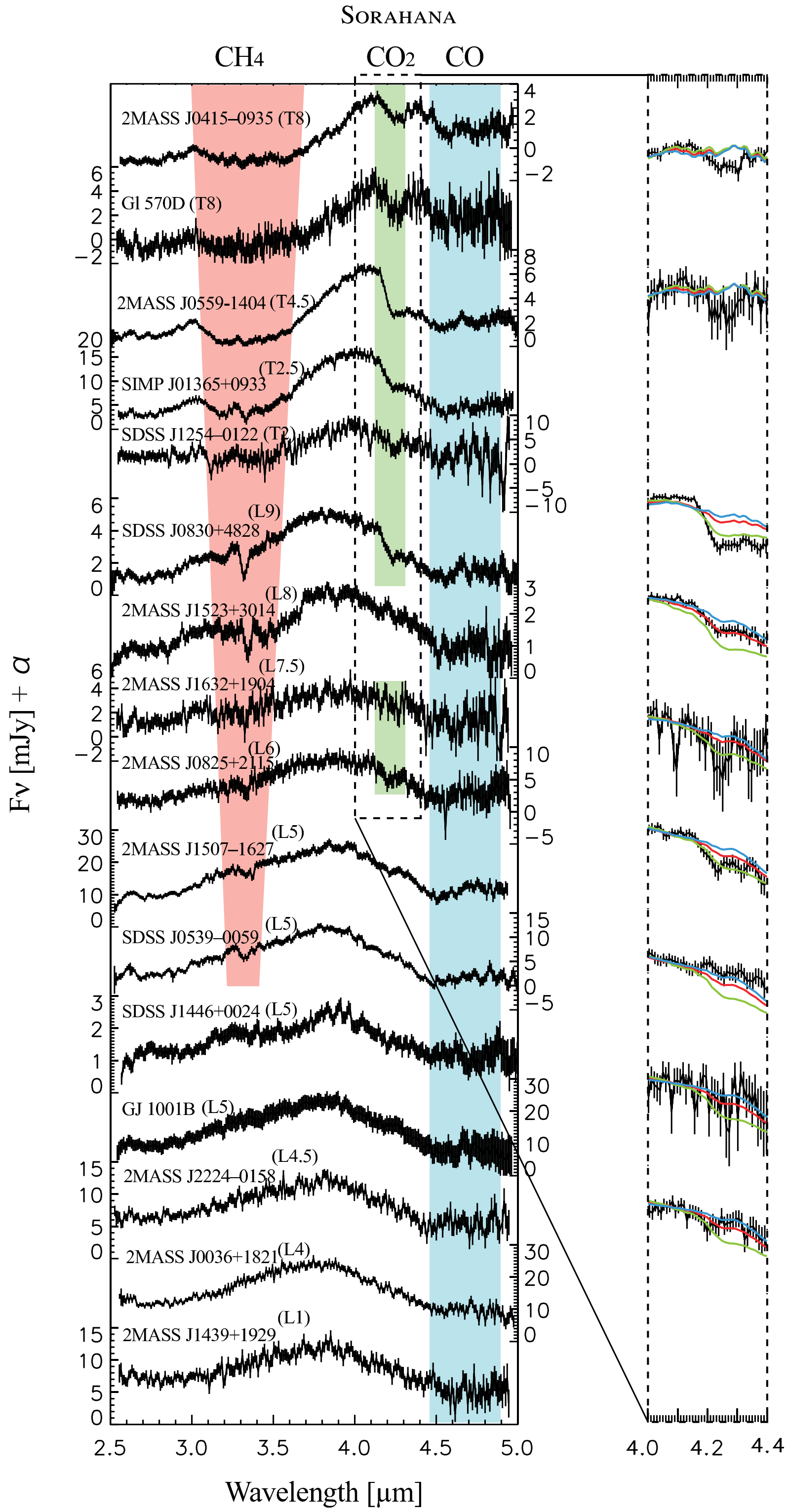

Figure 1. *AKARI* spectra of brown dwarfs with errors shown in black. Eleven L dwarfs and 5 T dwarfs are successfully observed. The 3.3 μm CH_4, 4.2 μm CO_2 and 4.6 μm CO absorption bands are shown in red, green and blue, respectively in the left panel. We also enlarge the CO_2 absorption band region and show a comparison between the observations and models with varying elemental abundances. We pick up 9 sources of our sample. They show the 4.2 μm CO_2 band, except for 2MASS J1523+3014. Three objects are better explained by the model with increased C and O elemental abundances (green), one object is well reproduced by the model with decreased abundances (blue), and the spectra of the other three sources are best explained by the solar abundance model (red). We are not yet able to explain the other two T8 sources.

2.2. CH_4 Fundamental Absorption Band at 3.3 μm

The CH_4 3.3 μm band appears in spectra later than L5. This result indicates that CH_4 already exists and plays a role in the photosphere of mid-L dwarfs. The band is seen in only two of our four L5 dwarfs. We confirm that the appearance of the CH_4 band in two L5 dwarfs is associated with the presence of dust by model fitting with UCM.

2.3. CO_2 Absorption Band at 4.2 μm

We have made the first detection of the CO_2 4.2 μm absorption band in the spectra of late-L and T type dwarfs. We find that the CO_2 molecule is generally observed in the atmosphere of T dwarfs. We also find that the observed CO_2 bands in some spectra are stronger or weaker than the prediction of UCM.

3. ELEMENTAL ABUNDANCES OF BROWN DWARFS

We discuss possible elemental abundance variations among brown dwarfs using model atmospheres and *AKARI* data to explain the deviations. We construct a set of models with various elemental abundances as a first trial, and investigate the variation of the molecular composition and atmospheric structure. From the results, we suggest that a possible reason for the CO_2 4.2 μm absorption feature in the late-L and T type spectra is the C and O elemental abundances being higher or lower than the solar values used in previous studies (Figure 1; see also Tsuji et al. 2011, Sorahana et al. 2013, in preparation).

4. FROM BROWN DWARFS TO EXOPLANETS WITH *SPICA*

We now understand that the physical and chemical structures of brown dwarf atmospheres are complicated, and do not simply follow a radiative equilibrium state under LTE. We are also interested in whether the atmospheric structures of extra gas planets can also not be explained by a simple radiative equilibrium model. To test this, we extend our analysis of brown dwarfs to extra gas planets, especially those having relatively longer orbital radii and masses and temperatures similar to those of brown dwarfs. We derive their atmospheric structure by model fitting and compare the atmospheres of the two types of objects. Since we can derive the elemental abundances of extra gas planets, we will also gain insight into the origin of gas planet formation. We will observe such extra gas planets with *SPICA*/SCI (Nakagawa et al. 2011), and gain a comprehensive understanding of the atmospheres from brown dwarfs to gas planets.

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