論文の内容の要旨

Brown Dwarf Atmospheres Revealed with *AKARI* Near-Infrared Spectra

（「あかり」近赤外線分光観測データを用いた褐色矮星の大気構造の研究　）

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This thesis present new results on the nature of brown dwarf atmospheres revealed by the analysis based on the spectra taken by the infrared astronomical satellite *AKARI* and a brown dwarf atmosphere model. The main results of this thesis are summarized as follows. (1) We construct a spectral data set of brown dwarfs that continuously covers a new wavelength range, 2.5–5.0 μm, (2) we verify a generality of the molecular abundances deviating from a thermo-chemical equilibrium state for T dwarfs, (3) we show that L5 dwarfs with or without the CH_4 3.3 μm band in their spectra differ in dust presence and mass (surface gravity) in addition to $T_{\rm eff}$, (4) we verify the theoretical prediction of radius inversion observationally for the first time, (5) we argue that the dust contribution to the atmospheric structure is larger than that in the current models, and (6) we suggest a possibility that relative C and O elemental abundances with respect to H are different in every objects.

Brown dwarfs are objects that are too light to maintain the hydrogen fusion in their cores. Their effective temperatures are very low as 2200–600 K. They are classified into newly introduced spectral types L and T. L dwarfs are warmer than T dwarfs. The study of brown dwarfs has been actively carried out since 1995, when the first genuine brown dwarf, Gl 229B, was discovered by Nakajima et al. Brown dwarfs are important as a bridge between stars and planets. With intermediate masses and temperatures, brown dwarfs are expected to have the blended properties of star and planet. However, their properties are actually quite unique, for example dusty photosphere, and it is not straightforward to understand their internal physical and chemical processes from our knowledges of stars and planets. Studies of brown dwarf atmosphere will lead us to understand the comprehensive nature of "atmospheres" of various objects from stars to planets.

Atmospheres of brown dwarfs are so cool and are dominated by molecules. When temperature decreases below the condensation temperature, dust forms in the photosphere. Dust affects the spectra of brown dwarfs by changing the photospheric structure and by extinction. The effects of dust are observed most apparently in the near-infrared spectra of L dwarfs. On the other hand, the spectra of T dwarfs show little sign of dust. This indicates that the dust in the photosphere disappears somewhere between L and T types. Since the mechanism of dust disappearance is not yet clear, current brown dwarf photosphere models implement dust segregation effect empirically through a model parameter. Such models can explain the observed SED more or less satisfactory. On the other hand, the models still have problems to explain some molecular absorption bands especially in the spectra of late-L to T dwarfs. It is not clear whether the deviation of molecular abundance from theoretical prediction is general characteristics or not. This inconsistency is one of the essential problems in the study of brown dwarf atmospheres.

Spectroscopic observations in the infrared regime are the most powerful tools to obtain physical and chemical information of brown dwarf atmospheres through various molecular bands. So far, brown dwarf spectra shorter than 2.5 μm have been obtained by ground-based observations. The brown dwarf atmospheres have been investigated with the data, but it is difficult to discuss molecular abundances in detail and systematically because of weak and blended molecular overtone absorption bands. The wavelength range between 2.5 and 5.0 μm is the most suitable for this purpose as it contains features of major molecular spices, including the CH_4 ν_3 fundamental band at 3.3 μm, CO_2 ν_3 fundamental band at 4.2 μm, CO fundamental band at 4.6 μm and H_2O ν_1 and ν_3 absorption bands around 2.7 μm. Since these fundamental bands of important molecules are non-blended each other, we can investigate these molecular bands in detail. However, observations in the wavelength range from the ground is always challenging. Severe absorption due to the Earth's atmosphere and limited wavelength coverage make the precise analysis difficult.

The Japanese infrared astronomical satellite *AKARI* was launched in February 2006. The InfraRed Camera (IRC) on-board *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 aiming to carry out systematic studies of physical and chemical processes in their atmospheres.

Twenty seven brown dwarfs, sixteen L dwarfs and eleven T dwarfs, were successfully observed by *AKARI*. The standard software toolkit IRC SPEC TOOLKIT was used for the data reduction. Wavelength and flux calibrations were all done in the toolkit. Spectral data are derived from two dimensional spectral image. We applied the following three additional processing to obtain better quality data; (1) derivation of appropriate sky background, (2) stacking of multiple observation data, and (3) correction of contaminated light from nearby objects. As a result, we obtain 18 continuous spectra of brown dwarfs from 2.5 to 5.0 μm for the first time (Figure1). We validate the absolute flux calibration of the obtained *AKARI* spectra by comparing the integrated flux measured in the spectra with (i) the *AKARI* photometry data obtained simultaneously during the observation, and (ii) past photometry data in literatures. We find that absolute flux of the spectra is consistent with the both *AKARI* photometry and past photometry data within 15% and 10%, respectively.

As a first step, we investigate the behavior of various non-blended molecular fundamental bands in brown dwarf spectra, the CH_4 at 3.3 μm, CO at 4.6 μm and CO_2 at 4.2 μm, relative to their spectral types systematically with the 18 *AKARI* observed spectra. Carbon resides mostly in CH_4 rather than in CO in very cool (e.g. $T < 1000K$) and high density environment. The temperature of brown dwarf atmospheres is just around the boundary that CH_4 molecule starts appearing. The behavior of the CH_4 3.3 μm fundamental band has not been investigated in detail because of fragmented and small number of data samples. It is also difficult to observe the CO 4.6 μm fundamental band. In the past study, one observed data of T8 dwarf shows that the CO absorption band strength is stronger than theoretical prediction, but its generality has not been ensured. We find that the CH_4 3.3 μm fundamental band appears in the spectra of dwarfs later than L5 and CO 4.6 μm band appears in the spectra of all spectral types until late-T dwarfs (Figure1). Investigation of the CO_2 absorption band is the first attempt for the brown dwarf atmosphere. We detected CO_2 absorption band at 4.2 μm in the spectra of late-L and T type dwarfs. The result for the non-blended CO molecular band is very important because of the fact that CO generally exists in all brown dwarf atmospheres, which is against theoretical predictions. We also find that the CO_2 molecule is generally in the atmosphere of T dwarfs.

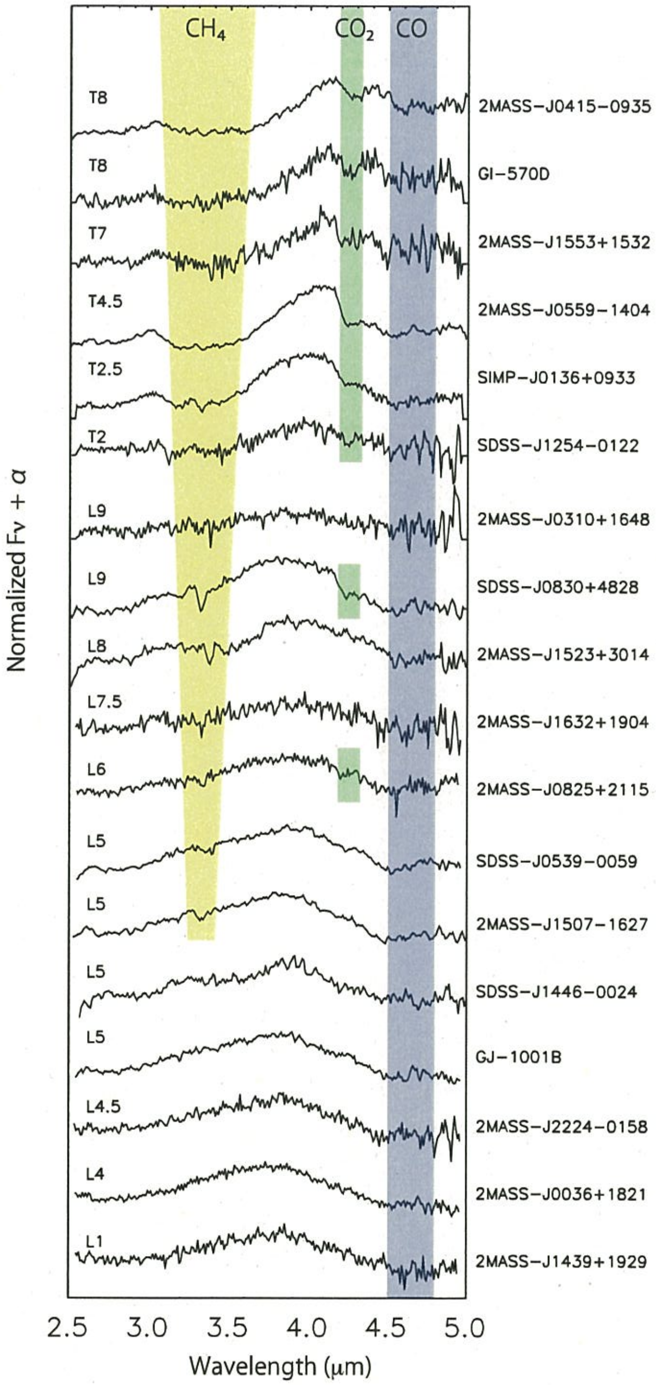

Figure1 *AKARI* spectral data of 19 brown dwarfs observed for the first time. The position of CH_4, CO_2 and CO fundamental bands are shown in yellow, green and blue respectively.

To understand the atmospheres of brown dwarfs better, we analyze the *AKARI* spectra using the Unified Cloudy Model (UCM) developed by Tsuji et al., which is one of the brown dwarf atmosphere models. We derive the physical parameters, effective temperature T_{eff}, surface gravity $\log g$ and critical temperature T_{cr}, of *AKARI* samples by model fitting. We investigate how the parameters correlate with the spectral type. We confirm that the spectral types of late-L dwarfs are not a sequence of T_{eff}, but a sequence of the decreasing of dust effect.

We investigate the property of the objects in which the CH_4 3.3 μm band starts to appear. We find that the band is seen in two of four L5 dwarfs. We evaluate the physical condition of the photosphere of the objects by applying the UCM. We find that the model parameters of the sources with and without the CH_4 3.3 μm band are systematically different, except for the effective temperature. Surface gravity and critical temperature, which is an additional parameter to determine the upper limit of the dust layer, of the objects with the CH_4 3.3 μm band are higher than those of the objects without the band. Our model fitting analysis confirms that the appearance of the CH_4 absorption band at 3.3 μm in L5 type spectra depends on not only their effective temperatures but also dust presences and surface gravities. We suggest that the two groups are different in their masses.

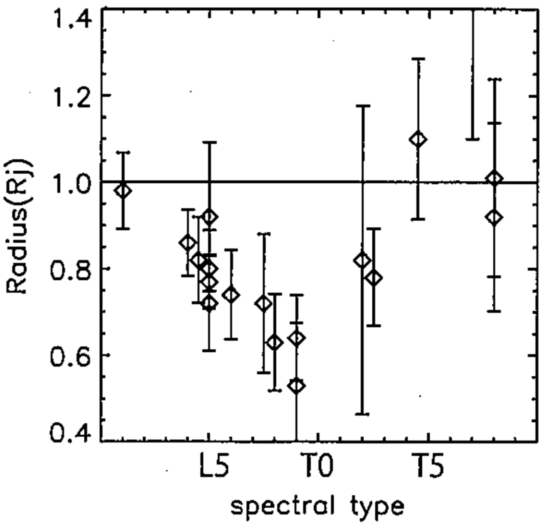

Figure 2 Radius of *AKARI* observed brown dwarfs. The decreasing radius between early- to late-L dwarfs and the increasing radius to late-T dwarfs may indicate that radius inversion predicted by theories is detected by current analysis.

Theoretical models of brown dwarf evolution predict that the radius of a young object follows a monotonically increasing function of mass and a decreasing function of age. On the other hand, for old object (≥10^8 yrs) the dependency of radius on mass inverts, i.e. the radii of less massive objects become larger because the less massive objects reach the terminal radii early. We derive the radii of the 18 *AKARI* objects using their parallaxes and the ratio of observed to model fluxes, and observationally verify this radius changes for the first time (Figure 2).

In this thesis we use the archived near-infrared spectra (IRTF/SpeX and UKIRT/CGS4, hereafter SpeX/CGS4) covering the shorter wavelength range (1.0–2.5 μm) along with *AKARI* to derive the physical parameters of the *AKARI* objects. With the additional short wavelength data we can constraint the model fitting better. However, a concern is that we could not determine a unique model that explains the entire wavelength range perfectly, and there are always some deviation. This has been pointed out in previous studies. In order to investigate this problem further, we fit the *AKARI* and SpeX/CGS4 spectra separately. We find that the *AKARI* spectra is more sensitive to the effective temperature, while the dust presence is better determined by the SpeX/CGS4 data. When the SpeX/CGS4 spectra show the presence of large amount of dust, the effective temperatures derived only from *AKARI* spectra show a higher value than those determined using the *AKARI* +SpeX/CGS4 data. The *AKARI* spectra also show higher effective temperatures when the SpeX/ CGS4 spectra show a small amount of dust. These results imply that the warming up effect due to the dust in the photosphere is always underestimated in the model than that in the actual photosphere. Dust opacity is sensitive to the grain size distribution, their amount and composition. We propose that a self-consistent, more realistic theory of condensation and sedimentation in the atmospheres is the most essential in the future brown dwarf atmosphere models.

The observed CO_2 absorption band in some objects is stronger or weaker than the prediction by the model. We discuss possible metallicity variation among brown dwarfs using the model atmosphere and the *AKARI* data. We construct a set of models with various elemental abundances as a first trial. We investigate the variation of the molecular composition and atmospheric structure. From the results, we suggest a possible reason of CO_2 4.2 μm absorption feature in the late-L and T type spectra is the higher or lower C and O elemental abundances than the solar values used in the previous studies.