論文の内容の要旨

Studies of exoplanets with high resolution spectroscopy

（高分散分光による系外惑星の観測的研究）

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High resolution spectroscopy is one of the powerful techniques to probe the atmospheres of exoplanets. Since the radial velocity of the planet changes rapidly during the observations due to the planet's orbital motion, it is possible to distinguish the planetary signal from other signals such as stellar spectrum or telluric absorption. The cross-correlation technique enables us to sum up all weak signals of the planetary atmospheres effectively and leads to robust detection of chemical species. Chemical species in the planetary atmospheres are important information to understand formation processes and atmospheric structure of exoplanets. Fortunately, the line lists of various species have been constantly improved till now. Therefore, now is the good timing to employ high resolution spectroscopy to study exoplanetary atmospheres.

The aim of this thesis is to characterize atmospheres of hot-Jupiters. Hot-Jupiters are a class of exoplanets which do not exist in our solar system. Owing to the high temperature and inflated atmospheres, hot-Jupiters are suitable for studies of planetary atmospheres. Particularly, hotter hot-Jupiters (called Ultra Hot-Jupiters, UHJs) are promising targets because their extremely high temperatures hinder cloud formation. The formation processes and atmospheric structure of hot-Jupiters are still not understood well. Thus hot-Jupiters are important targets to understand planetary formation and atmospheric structure of exoplanets. Transmission spectrum is not sensitive to the temperature strucuture of planetary atmospheres, therefore transmission spectroscopy is an appropriate method to investigate the chemical composition of planetary atmospheres.

In this thesis, we present results of high resolution transmission spectroscopy for UHJs in two systems at visible wavelengths. The targets

are HD149026b and WASP-33b. We remove the systematic components in the transmission spectra to search for weak planetary signals. We also make the model transmission spectra of several neutral metals and molecular species and calculate the cross-correlation of the residual and model spectra to search for chemical species. We have detected a signal of neutral titanium and a marginal signal of neutral iron in the atmosphere of HD149026b. Assuming chemical equilibrium, titanium tends to form titanium oxide (TiO) at the expected atmospheric temperature of HD149026b. The non-detection of TiO implies a supersolar C/O ratio, which suggests that HD149026b was formed outside the H_2O snowline and migrated to the current orbit.
On the other hand, we have detected TiO in the atmosphere of WASP-33b. Due to the variable line profile of the central star, it is difficult to search for metals in the atmosphere of WASP-33b. This is because there are also absorption lines of metals in the spectrum of the central star. Thus, we focus on TiO for WASP-33b. Since there has been a problem of line list accuracy for TiO, we use three kinds of TiO line lists and check the accuracy of them with an M-dwarf spectrum. Two line lists provided by Plez (1998) and McKemmish et al. (2019) are confirmed to be accurate at visible wavelengths, and we detect TiO with the two line lists. Our results strongly support the previous detection of TiO by Nugroho et al. (2017), which reported the detection of TiO in the dayside thermal emission spectrum of WASP-33b. Since transmission spectroscopy probes the terminator region atmosphere, TiO is likely to be widely distributed in the atmosphere of WASP-33b combined with the previous detection by Nugroho et al. (2017). TiO has been considered as a key molecule for thermal inversion in the atmosphere of hot-Jupiters, though there are only a few examples of detection. Considering the detection of emission lines of TiO by Nugroho et al. (2017), our robust detection of TiO by transmission spectroscopy shows that TiO really exists in planetary atmospheres and cause thermal inversion.

Our results show the rich diversity of atmospheres of hot-Jupiters combined with previous studies of hot-Jupiters, especially recent high resolution spectroscopy of UHJs. Our results also prove the capability of high resolution spectroscopy to characterize exoplanetary atmospheres. Investigation of metal and their compounds is a promising approach to study exoplanetary atmospheres, because their abundance reflects atmospheric environments such as temperature or C/O ratio. Future extremely large telescopes and/or improvement of the accuracy of molecular line lists will enable us to observe fainter hot Jupiters and more various lines and thus to understand exoplanetary atmospheres more comprehensively.