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# 論 文 要 旨

THESIS SUMMARY

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要旨（和文 2000 字程度）
Thesis Summary（approx.2000 Japanese Characters ）


The Kepler mission have revealed the prevalence of super-Earths, exoplanets whose sizes fall between Earth and Neptune, and revolutionized our understanding of exoplanet population. This finding poses a fundamental question: how were they formed? One of the valuable clues to infer the past formation process is the planetary composition. Since the composition presumably reflects the physical and chemical properties of planetary building blocks, it potentially diagnoses where and how the planet was formed. The observation of transmission spectra of exoplanetary atmospheres open a new window to derive the information on the composition. Atmospheric composition likely reflects not only the information on interior composition but also on the past formation process. However, recent observational efforts have suggested that exoplanets are prone to be covered by clouds at high altitude that make it difficult to observe the atmosphere directly. This cloud problem is serious for super-Earths since most of them exhibit featureless atmospheric spectra, suggesting the presence of clouds.

Despite its importance, cloud formation processes on super-Earths have been highly uncertain since most of previous studies prescribed the clouds as a fitting parameter. Because many observed exoplanets are orbiting close to central stars, hot exoplanetary atmospheres likely produce solid mineral clouds. The intense stellar insolation also drives vigorous atmospheric circulation that result in distinct cloud structures compared to terrestrial clouds. Since the cloud formation process is associated to the atmospheric composition, understanding it may help to explore the atmospheric composition of cloudy super-Earths. In this thesis, we aim to figure out mineral cloud formation on super-Earths and what we can learn from the cloudy atmospheres.

We first develop a cloud microphysical model that solves vertical transport and growth of cloud particles in a self-consistent manner. Then, we apply the examine the formation process of KCl clouds in super-Earth atmospheres. We find that the particle is mainly determined by the competition between particle growth and eddy transport near the cloud base. We also find that the cloud particle always grows into a size larger than a threshold determined by collision growth. The minimum size sets the upper limit of the cloud vertical extent if clouds are made of compact spheres.

Conventionally, cloud models have commonly assumed that the cloud particles are compact spheres. However, because the exoplanetary clouds are made of solid minerals, cloud particles potentially grow into non-spherical porous aggregates. We investigate how the porosity of cloud particles evolve in planetary atmospheres during the cloud formation. Using the porosity evolution model developed in planet formation community, we show that the density of cloud particles can be smaller than the material density by ~ 2–3 orders of magnitude. The cloud particle aggregates are compressed by gas drag once the size exceeds a threshold, which is approximately 30 μm. Using our cloud microphysical model, we find that the cloud particle aggregate rarely grow into the size so large that the compression sets in. As a result, the aggregate clouds can ascend to altitude much higher than that for compact-sphere clouds.

We calculate synthetic transmission spectra to examine the composition of cloudy atmospheres from the observations. In particular, we investigate how the aggregate clouds affect the observations of the transmission spectra for the first time. The aggregate clouds obscure the spectral feature substantially. Moreover, at long wavelength, the aggregate clouds produce the spectral slope originated by the scattering properties of an aggregate. We apply the cloud and spectrum models to super-Earths GJ1214b, GJ436b, GJ3470b, HD97658b, and HAT-P-11b to constrain their atmospheric metallicity. We find that the models of high-metallicity atmospheres (≥ 100× solar abundance) better explain the transmission spectra of GJ1214b, GJ436b, and HD97658b, while the models of low-metallicity atmospheres (≤ 10×solar) better explain the observations of GJ3470b and HAT-P-11b. Our results potentially indicate the presence of dichotomy of super-Earths in terms of the atmospheric metallicity. We also simulate the expected observational noise of the upcoming James Webb Space Telescope and suggest that it would be possible to distinguish between the aggregate and the compact sphere clouds from mid-infrared observations. This would help to further figure out the cloud formation on super-Earths and verify our cloud model.

We also investigate the interior structure of the super-Earths. Although the interior structure is sensitive to the upper boundary condition set by an atmosphere, our investigation on the transmission spectra enables us to use the reasonable atmospheric properties in the interior structure calculations. We find that the super-Earths studied in this thesis have planetary masses of 1–30% in their atmospheres, depending on ice mass fraction of planetary core. We also find that the GJ1214b, GJ436b, and HD97658b would have atmospheres too massive to explain the current atmospheric mass if in-situ formation is assumed. This potentially indicates that these super-Earths were formed at outer parts of protoplanetary disks followed by inward migration.