論文の内容の要旨

Theoretical modeling of transmission spectra of exoplanet atmospheres with hydrocarbon haze and applications to multi-wavelength transit observations
（炭化水素ヘイズを持つ系外惑星大気の透過スペクトルの理論モデリングと多波長トランジット観測への応用）

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Since the first discovery of an exoplanet in 1995, detection of more than 3000 exoplanets has been reported. The atmospheric composition of planets provides a valuable clue to understanding the bulk composition and origin of exoplanets. A promising method for atmospheric characterization is multi-wavelength transit observation, which measures an apparent decrease in stellar brightness during planetary transit in front of its host star (called transit depth). Sets of transit depths so far measured at different wavelengths (called transmission spectra) are somewhat diverse: Some show steep spectral slope features in the visible, some contain featureless spectra in the near-infrared, some show distinct features from radiative absorption by gaseous species. These facts infer the existence of haze in the atmospheres.

Previous studies that addressed theoretical modeling of transmission spectra of hydrogen-dominated atmospheres with haze used some assumed distribution and size of haze particles and did not access the viability of those assumed haze properties sufficiently from a physical point of view. In addition, although the previous studies found that various haze parameters being chosen, one can generate the observed variation in transmission spectra, it remains to be clarified what yields such a variety of haze properties.

In this doctoral thesis, we focus on photochemically-produced hydrocarbon aerosols as a possible candidate for the haze. Most transiting exoplanets, which orbit very close to their host stars, are constantly exposed to strong stellar UV radiation. Also, many of the transiting small exoplanets detect so far have relatively large radii, which means that they likely have hydrogen-rich atmospheres. Such atmospheres would contain precursor molecules such as CH_4 and HCN for hydrocarbon. Furthermore, current and near-future target stars for exoplanet search are low-mass, low-temperature main-sequence stars, which are called M dwarfs. Observation shows that M dwarfs are diverse in UV emission intensity. Since hazes are formed through photochemical reactions triggered by photo-dissociation of CH_4, the transmission spectrum of an exoplanet atmosphere with such haze should depend on the UV intensity of its host star. Thus, the diversity in UV intensity of M dwarfs can be considered to bring about the diversity of transmission spectra, which no previous theoretical studies have explored.

The purpose of this doctoral thesis is to explore what diversity of transmission spectra of exoplanets are brought from different production rates and distributions of the monomers of haze particles, which are related to the variety in UV intensities of M dwarfs. To do so, we develop a new numerical code from scratch for simulating transmission spectra of transiting exoplanet atmospheres, which include calculations of thermo- and photo-chemistry, particle growth, opacities of gases and particles, and wavelength-dependent atmospheric absorption of stellar radiation. Then, we model the haze formation processes, assuming hydrogen-dominated atmospheres of close-in warm ($\lesssim$ 1000 K) exoplanets, derive the realistic distribution of the size and number density of haze particles, and explore its impacts on transmission spectra, which were not investigated previously. Then, we explore the production rate of haze monomers and resultant transmission spectra of the atmospheres of currently observable warm exoplanets including GJ 1214b, GJ 3470b, and GJ 436b.

First, we have found that the haze particles tend to distribute more broadly in the atmosphere than previously assumed and consist of various sizes. We have also found that the difference in the production rate of haze monomers with ten orders of magnitude, which relates to the UV irradiation intensity from the host star, yields the diversity of transmission spectra observationally suggested: Completely flat spectra, spectra with only extinction features of hazes (i.e., spectral slope due to Rayleigh scattering and absorption features of hazes), spectra with slope due to Rayleigh scattering and some molecular absorption features, and spectra with only molecular absorption features.

In addition, we have explored the dependences of the vertical distribution of haze particles and the gaseous species, and the transmission spectrum on the other model parameters such as eddy diffusion coefficient, C/O ratio, atmospheric temperature structure, and monomer size. We have found that efficient eddy diffusion yields a steeper Rayleigh-scattering slope in the visible and that the differences in C/O ratio and monomer size have little effect on the vertical distribution of haze particles and the gaseous species, and the transmission spectrum.

Moreover, by applying a simplified grain-growth model, we have examined the validity of characteristic size approximation in particle growth calculation. We have quantified the precisions of observed transit depths beyond which the characteristic approximation suffices to be used for comparison with observation.

Finally, applying our developed models to GJ 1214b, GJ 3470b, and GJ 436b, we have found the followings: For the atmosphere of GJ 1214b, the high production rate of haze monomers can explain the observed flatness of the transmission spectra in the near-infrared and it is likely that large amount of hazes is present in the atmosphere. For the atmosphere of GJ 3470b, the relatively low rate of monomer production matches the observed spectrum; a steep spectral slope in the visible and relatively featureless in the near-infrared. For the atmosphere of GJ 436b, the values of modest to high rate of monomer production can explain the observed relatively featureless spectrum in the near-infrared. To further constrain the monomer production rate, the transit observations in the visible are crucially important, where transit depth strongly varies depending on the monomer production rate. The existence of hazes in these three planets are inferred from our detailed theoretical modeling of haze particles in addition to the observations so far.

At present, the number of exoplanets suitable for atmospheric characterization is still small due to lack of bright targets and sufficient observational precision. Fortunately, all-sky survey projects such as Transiting Exoplanet Survey Satellite (TESS) launched in June 2018 and PLAnetary Transits and Oscillations of stars (PLATO) launched in the mid-2020s will detect a great number of transiting exoplanets around nearby stars that are bright enough for atmospheric characterization. Also, James Webb Space Telescope (JWST) scheduled for launch in late spring of 2019 and Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) planned for launch in the mid-2020s will perform high-precision spectroscopy of transiting exoplanets in the infrared. In addition, World Space Observatory-UltraViolet (WSO-UV) planned for launch in the mid-2020s will perform exoplanet transit observation in the UV. In this thesis, we have predicted the diversity in transmission spectra of warm exoplanets exposed to stellar UV, which will be the primary targets of such near-future atmospheric characterization missions. In particular, simultaneous observations in the UV, visible, and infrared are quite interesting for verifying our predictions in this thesis. In any case, the transmission spectrum models developed in this thesis will be able to make a great contribution to the near-future atmospheric characterization of exoplanets.