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Clouds of Fluffy Aggregates in Exoplanetary Atmospheres

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Abstract

Recent observational efforts have suggested the ubiquity of mineral clouds in exoplanetary atmospheres. Previous models approximated the cloud particles with compact spheres, but this approximation is not necessarily good for aggregates of solid particles. Here, we investigate how the porosity of cloud particle aggregates varies in exoplanetary atmospheres and influence the cloud vertical profiles and observed transmission spectra. Our newly developed porosity model shows that the interior density of cloud particle aggregates can be much lower than the material density. This results in the cloud vertical extent much larger than that for classically assumed clouds of compact spheres. We find that the fluffy-aggregate clouds significantly obscure molecular signatures in transmission spectra and produce a spectral slope originating from the scattering properties of the aggregates. We also demonstrate that the fluffy-aggregate clouds can produce flat spectra as observed in several super-Earths. Our results indicate the importance of the microstructure of cloud particles for interpreting current and future observations.

1. Introduction

Transmission spectroscopy is a powerful approach to probe the compositions of exoplanetary atmospheres. Recent surveys of transmission spectra have revealed that clouds are commonly present in exoplanetary atmospheres [2,8]. A remarkable feature of the exoplanetary clouds is that they are present at extremely high altitude. For example, the super-Earth GJ1214b are suggested to have an opaque cloud deck at an altitude as high as ~ 0.01 mbar [5]. Cloud formation is controlled by atmospheric composition via atmospheric circulation and cloud microphysics. Thus, understanding how the high-altitude clouds form may enable us to infer what composition the atmosphere beneath the clouds would have, which in turn might tell us how the planets formed.

Theoretically, it is sometimes challenging to explain the high-altitude cloud formation. The high-altitude clouds can be formed if the settling velocity of cloud particles are much slower than the atmospheric vertical velocity [1, 6]. However, studies with cloud microphysical models have shown that an efficient particle growth yields large cloud particles with large settling velocity, which inhibits the high-altitude cloud formation unless extremely strong vertical mixing is assumed [3, 7]. One of the promising way to solve the puzzle is to consider the microstructure of cloud particles. Previous studies assumed that the cloud particle is a compact sphere; however, this is not always true for solid condensate particles. If the cloud particles grow into fluffy aggregates, it might explain the high-altitude cloud formation.

2. Method

We have constructed for the first time a porosity evolution model of cloud particles in exoplanetary atmospheres. Following the model used for dust aggregates in protoplanetary disks [4], our model calculates the equilibrium aggregate porosity taking into account the fractal aggregation of cloud particles and the aggregate compression caused by gas drag and high-energy collision. We have combined the porosity model with the cloud microphysical model developed in our previous studies [7] to predict how the porosity evolution affects the cloud vertical profiles. The model calculates steady state vertical distributions of the cloud mass density, characteristic aggregate size, and the equilibrium porosity. Using the obtained cloud profiles, we have also calculated synthetic transmission spectra and discussed how the fluffy-aggregate clouds affect observed spectra. In this study, we have assumed KCl clouds and PT profiles of GJ1214b. The eddy diffusion coefficient is taken from the study of tracer transport in a GJ1214b's atmosphere with a 3D general circulation model with passive tracers [1].

3. Results and Summary

Our porosity model shows that the cloud particle aggregates experience the fractal growth until the size exceeds the threshold that depends on the size of monomers, particles constituting the aggregate. The gas-drag compression occurs once the size becomes larger than ~30 μm. The example is shown in Figure 1. Using the cloud microphysical model, we have found that the cloud particle aggregates hardly grow into so large size that the compression takes place. The aggregate density can be lower than the material density by 2–3 orders of magnitude. The low density yields the low settling velocity, which in turn leads to the cloud vertical extent much larger than that for the classically assumed compact-sphere clouds.

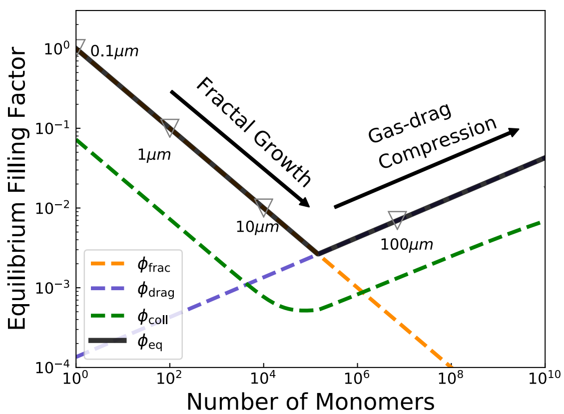

Figure 1: Equilibrium filling factor of a cloud particle aggregate as a function of a number of monomers. The filling factor is the aggregate density normalized by the material density. The yellow, blue, and green lines show the filling factor determined by the fractal growth, gas-drag, and collisional compression, respectively.

In the synthetic transmission spectrum, we have found that the fluffy-aggregate clouds significantly obscure the molecular signature in visible to near-infrared wavelength, as shown in Figure 2. The fluffy-aggregate clouds produce the spectral slope originating from the scattering properties of the aggregate. This potentially helps to identify the aggregate clouds from the observations. We have also found that the aggregate clouds can produce flat spectra observed in several super-Earths if the atmospheric metallicity is sufficiently high. Although the aggregate clouds largely mask molecular signatures, they will be optically thin in mid-infrared wavelength. Thus, future observations with JWST and ARIEL may detect the molecular signatures even if the near-infrared spectrum seems featureless. In the meeting, we will also present what atmospheric composition enables the fluffy-aggregate clouds to explain the flat transmission spectrum of GJ1214b.

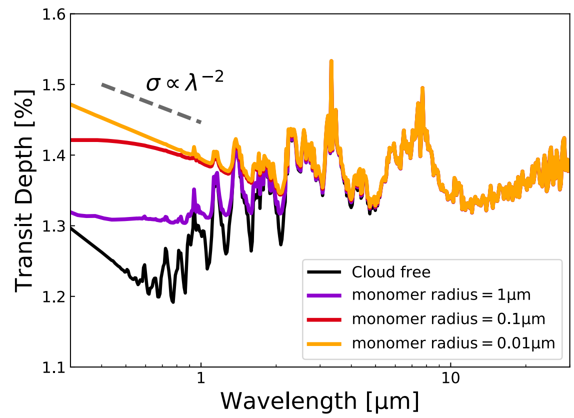

Figure 2: Transmission spectra of atmospheres with the fluffy-aggregate clouds. The atmospheres are assumed to be solar composition. Different colored lines show the spectra for different monomer size.

Acknowledgements

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