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Cloud Atlas: Unraveling the Vertical Cloud Structure in Ultracool Atmospheres with Self-consistent Heterogeneous Cloud Models

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Abstract

Clouds are commonly distributed non-uniformly in planetary atmospheres. The cloud heterogeneity is a result of the coupling between cloud microphysics and atmospheric dynamics. Under the HST Cloud Atlas program, we have utilized 112 HST orbits for monitoring ultracool atmospheres at a superior precision over $1.1 - 1.7\ \mu m$. These precise spectral variability observations provide a unique opportunity to characterize the three-dimensional cloud structure. In light of the observed spectral variability in ultracool atmospheres, we have developed a heterogeneous cloud model that is self-consistent with the T-P profile. With this heterogeneous cloud model, we can explain *both* the time-averaged spectra and the spectral variability of WISEP J0047, a moderately-young late-L dwarf that shares an almost identical spectrum with HR8799e. In addition to the modeling result, our semi-analytical analysis also limits the pressure of cloud heterogeneity to 5mbar or deeper. Lastly, we show that disequilibrium chemistry is important at the near-IR optically-thick level for brown dwarfs and exoplanets. Our modeling result demonstrates that high-precision time-resolved spectroscopy is a powerful tool for constraining the vertical cloud structure.

1. Modeling Approach and Results

Model Assumption: There are two types of clouds in the heterogeneous cloud model – thick and thin clouds. We assume that the spatial scale of the heterogeneous clouds is much smaller than the planetary radius. Therefore, both clouds share the same temperature-pressure profile, as well as the same interior entropy. The thin-cloud column is "cleared out" above an altitude threshold, otherwise shares the same cloud opacity as the thick cloud column. (Figure 2)

Model Parameters: In addition to the three main free parameters for the homogeneous cloud model [1] ($T_{\rm eff}$, f_{sed}, log(g)), there are two additional free parameters for the heterogeneous cloud model: global cloud coverage h and truncation temperature T_{trc} , which describes the temperature threshold at which the thin-cloud column is cleared out.

Key Results on WISEP J0047:

1. We find that the best-fit parameters of $T_{\rm eff}$ = 1200K , f_{sed} =1, and log(g) = 4.0 through fitting a grid of homogeneous cloud models. This best-fit cloud model serves as the baseline model for heterogeneous cloud model.
2. Given a global thin-cloud coverage of 50%, we change the T_{trc} and find that the cloud need to be perturbed down to $T_{trc} = 1350K$, or P∼0.3bar to match the HST wavelength-dependent spectral variability (bottom panel of Figure 1). This result can also be shown to be consistent with a semi-analytical analysis based on the in- and out-of-water band variability.
3. We find that disequilibrium chemistry is required to explain the time-averaged spectra (Figure 1). However, our cloud model overestimates the non-contemporaneously observed photometric variability in the Spitzer 3.6-μm band. This may be caused by large-scale atmospheric waves or incomplete physics in our cloud model.

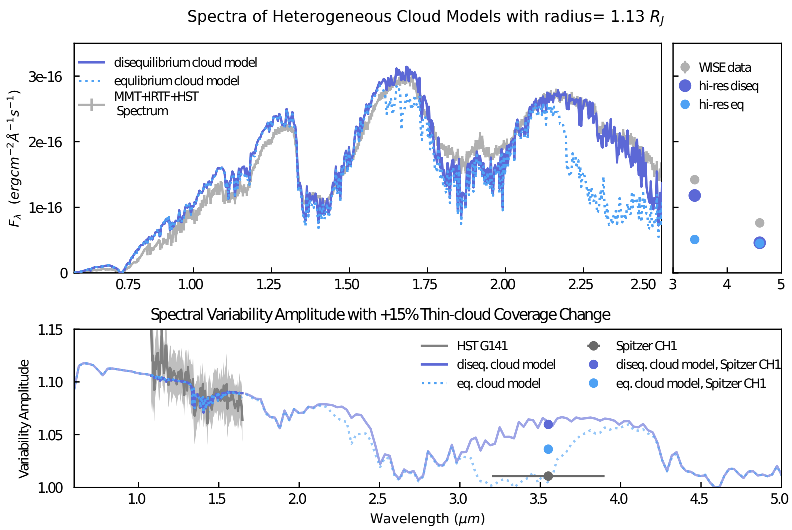

Figure 1: With a 15% increase of thin-cloud coverage, the heterogeneous cloud model can explain both the time-averaged spectra (Upper panel) and the HST spectral variability (bottom panel). [Lew et. al. in prep]

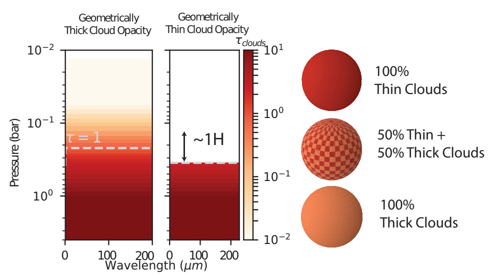

Figure 2: Left two columns: The thick and thin cloud column opacity. Right: Cartoon images for different global cloud coverage. By assuming that the thick and thin clouds share the same T-P profile, we imply that the spatial scale of cloud patchiness is much smaller than the planetary radius (see also [4]). [Lew et al. in prep]

2. Conclusions and Implications

We have built a toy model of heterogeneous clouds to study the impact of cloud heterogeneity toward the emission spectrum and spectral variability. We benchmark our self-consistent heterogeneous cloud model with both the high-quality time-averaged and time-domain spectra (Figure 1) of WISEP J0047 [2, 3]. From this modeling practice, we find that heterogeneous clouds and disequilibrium chemistry dominate the low-gravity ultracool atmospheres. In my talk, I will also show that both low- and high-gravity ultracool photospheres at near-IR wavelength are likely affected by disequilibrium chemistry. Understanding the pressure level of cloud heterogeneity and the vertical structure will be useful for distinguishing clouds and high-altitude haze in planetary atmospheres in the era of JWST.

Acknowledgements

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