Coupling haze and cloud microphysics in hot-Jupiter atmospheres

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Haze and clouds are expected in many exoplanet atmospheres, demonstrating various composition, and have been the subject of many works. However, most studies on cloud microphysics in hot-Jupiter atmospheres consider the heterogeneous nucleation of the condensing material over TiO_2 particles formed through homogeneous nucleation. However, TiO_2 is a high temperature condensate and is not expected to form in sufficient abundances the atmospheres we are studying, as HD-209458b or WASP-39b (Carone et al., 2023). In this work, we propose that photochemical haze particles, already expected in such atmospheres, can serve as nucleation sites, as they settle through the atmosphere. We use a cloud and haze microphysics model to compute the size distributions of hazes and condensates (as Na_2S, $MgSiO_3$ or MnS), coupled to a disequilibrium chemistry model, thus allowing to study the effect of cloud formation on the chemical composition.

We first focus on the hot-Jupiter WASP-39b, which has been observed with the JWST (Ahrer et al., 2023a,b; Alderson et al., 2023; Feinstein et al., 2023; Rustamkulov et al., 2023). These transit observations provide further constrains on this planet's properties, especially its metallicity and C/O ratio, and demonstrate that cloud opacities are expected to partially mute the water band. The 10×solar metallicity retrieved from the JWST observations is larger than the solar values typically assumed for hot-Jupiters (e.g. Arfaux & Lavvas, 2022) and has major ramifications for the haze and cloud properties. Indeed, while the presence of haze in WASP-39b's atmosphere was considered unnecessary for reproducing the UV-Visible transit spectrum for a solar metallicity assumption, higher metallicity results in a weaker UV transit depth, therefore requires a high altitude absorber. Preliminary results on the inclusion of clouds indicate that both haze and clouds are required to fit the JWST data (Arfaux & Lavvas, 2023). We run individual simulations for the morning and evening terminators, using temperature profiles from Tsai et al. (2023). We find that Na_2S, MnS and $MgSiO_3$ clouds form in the morning terminator, while the relatively higher temperature of the evening terminator allows only for $MgSiO_3$ and MnS cloud formation. We additionally test for the effect of changing the strength of the eddy diffusion and the mass flux of haze particles. The combined gas, haze & cloud composition of the two terminators provide a good fit to the JWST observations through out the spectrum, demonstrating the need for both clouds and hazes (Arfaux & Lavvas, 2024). Moreover, the depletion of Na on the morning terminator due to the Na_2S cloud formation is instrumental for understanding the Na line observations.

We also conduct calculations for HD-209458b atmosphere and explore the effects of cloud formation on the thermal profile of this planet. Cloud opacities result in a local heating of the atmosphere and cool the atmosphere below the cloud layer while the latent heat exchange between the condensed and gas phase during cloud sublimation and condensation processes may further affect the temperature structure. These modifications of the temperature profile may have further ramifications on the atmospheric composition and on the transit spectrum.

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