How Heterogeneous Cloud Particles Affect Transmission Spectra

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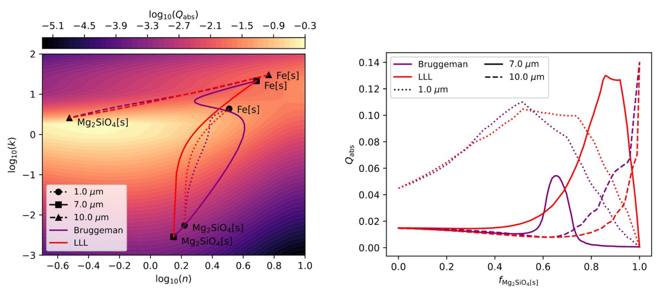
Opacity of Well-Mixed Particles

There are two different ways to calculate the optical properties of well-mixed particles:

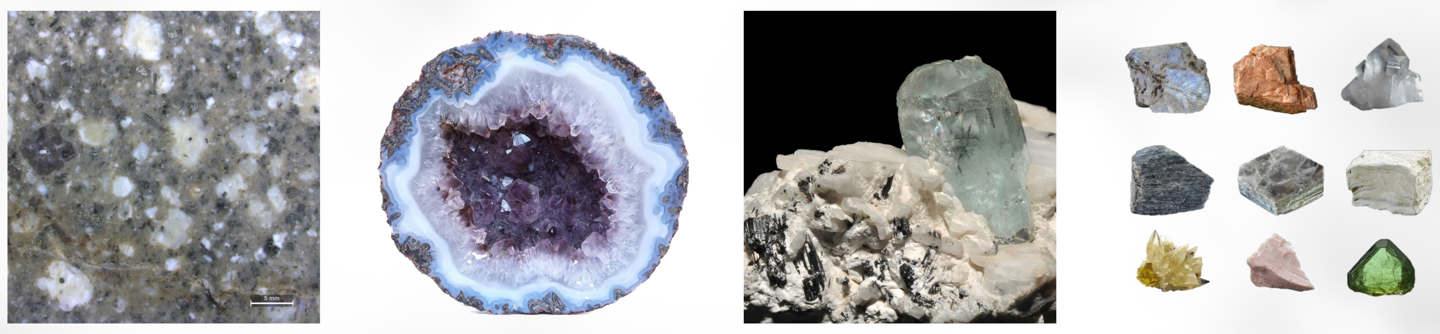
Bruggeman: $$\sum_i f_i \frac{\epsilon_i - \epsilon_{\rm eff}}{\epsilon_i + 2\epsilon_{\rm eff}} = 0$$

Landau-Lifshitz-Looyenga: $$\epsilon_{\rm eff} = \left(\sum_i f_i \sqrt[3]{\epsilon_i} \right)^3$$

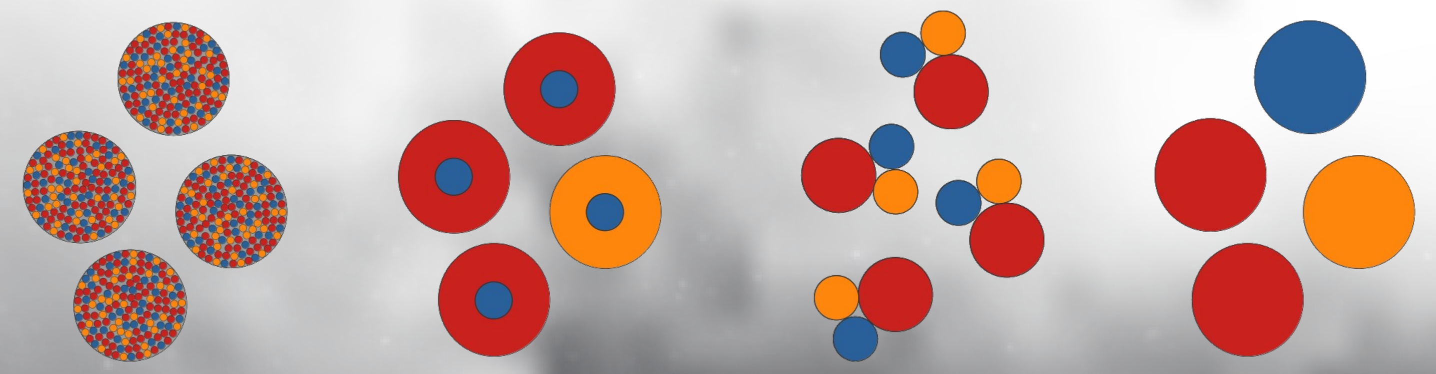
The different assumptions in the derivation of Bruggeman and LLL lead to different absorption coefficients (Q_{abs}). For example, the refractive index change at 7 µm from pure Mg_2SiO_4 to pure Fe illustrates how Bruggeman 'avoids' high Q_{abs} values. The figures also shows how Si-O features are affected (10 µm) and how mixed particles can be more opaque then their pure components (1 µm).



How cloud materials mix



Well-mixed | Core-shell | Islands (BAS) | Homogeneous (SSA)



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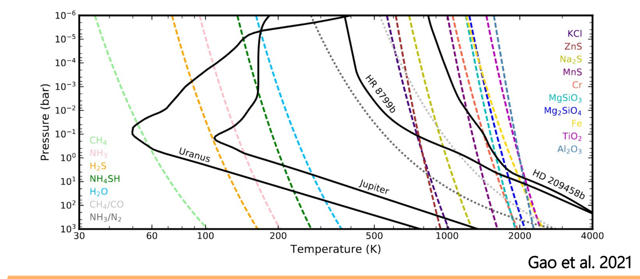
Origin of Heterogeneous Cloud Particles

On Earth only water can form clouds, but in hotter exoplanets materials like SiO, Mg_2SiO_4, TiO_2, Fe_2O_3, KCl, and NaCl can form.



Gao et al. 2021

The morphology of the cloud particles depends on their formation history:

- If all materials quickly condense and evaporate together, particles become well-mixed.
- If one material forms first, later materials can coat it, creating core-shell particles.
- If each material prefers to condense onto its own kind, a single particle contains separate "islands" of different materials (also called BAS).
- If each material forms its own cloud particles, the particles are homogeneous (also called SSA).

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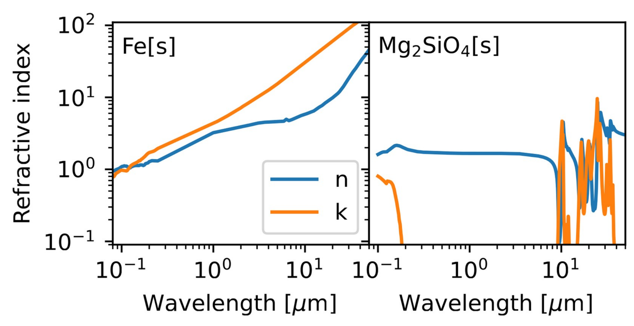
Iron can Dominate the Optical Properties

The real part of the refractive index n describes the ratio of the speed of light and the phase velocity of light in the medium. The imaginary part k describes the attenuation of the electromagnetic wave traveling through the medium. Typically, materials with large k values absorb more light.



Fe-bearing species and carbon have much higher k values than other materials. Because of the non-linear behavior of LLL and Bruggeman, even small inclusions (<1%) of Fe or C can dominate the optical properties of mixed clouds. Accurate modeling of these materials is essential to model the optical properties of heterogeneous particles.

The morphology of cloud particles affects the transmission spectrum

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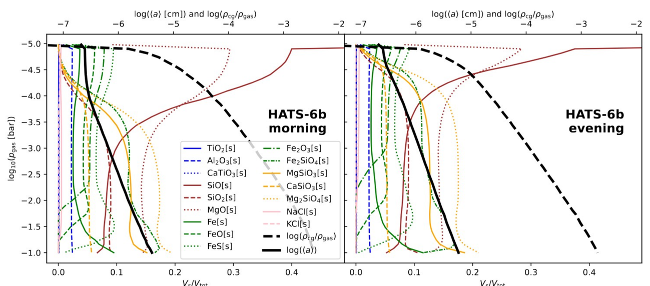
The Cloud Structure of HATS-6b

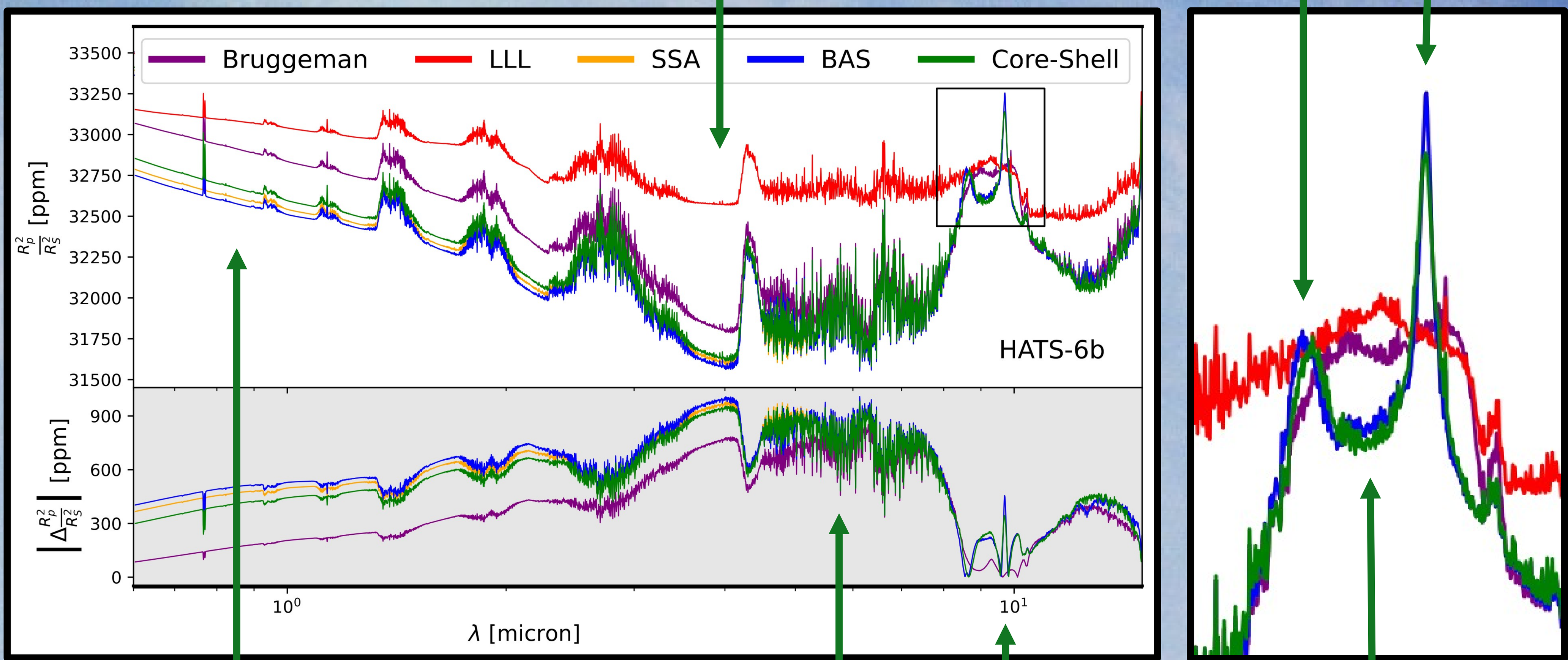
HATS-6b is a warm Saturn with a radius of 0.998 R_J, a mass of 0.319 M_J, and an equilibrium temperature of ≈700 K. It has one of the deepest transit depths known today (3.23%) making it an ideal target for transmission spectroscopy.



We model the cloud structure of HATS-6b for both evening and morning terminator separately. Both terminators show significant cloud coverage. Our model predicts that 13 materials can form simultaneously with Si-, Mg-, and Fe-bearing cloud materials being predominant. A more in-depth study of the global cloud structure of HATS-6b can be found in Kiefer et al. (2024c).

LLL leads to a stronger muting of molecular features

BAS, SSA, and core-shell retain the spectral features of components



Different inclinations of the Rayleigh slope

Differences between morphologies are > 300 ppm

Well-mixed particles have broad spectral features

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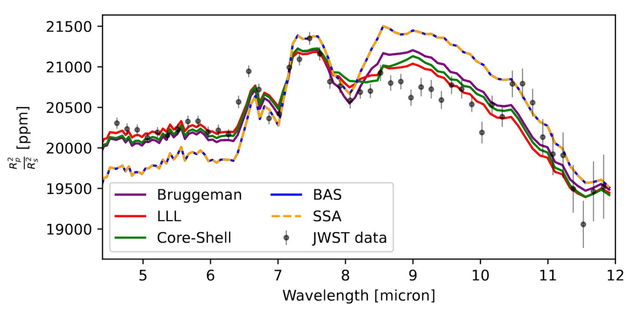
Importance for Retrieval Models

We investigate how cloud particle morphology impacts retrievals by reproducing the WASP-107b transmission spectra from Dyrek et al. (2024) under different morphology assumptions.



The strength of the silicate feature depends on the assumed morphology of the cloud particles. There is a difference between the core-shell and BAS/SSA assumption because the nucleating species which forms the core (SiO) is also the dominant material. The assumption about the morphology will affect the predicted cloud mass fraction and potentially impacts the retrieved cloud particle radius and the location of the cloud within the atmosphere.

Take Home Message

- ➔ Non-mixed particles retain the features of their components
- ➔ Well-mixed particles have broad spectral features
- ➔ Iron can dominate the opacity of well-mixed particles

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