Looking Through (and Understanding) Clouds and Hazes with JWST (and other things)

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Sagan Summer Workshop 2023 | #sagan2023 | July 27th, 2023
Clouds and Hazes are Fundamental Components of Planetary Atmospheres

Radiation

Chemistry

Dynamics

Atmospheric Escape

Atmosphere/Interior Interactions
What Are Exoplanet Clouds and Hazes Like?
Equilibrium chemistry predicts a diverse set of condensates with temperature
How do cloud particles form?

- Homogeneous Nucleation
- Heterogeneous Nucleation
Cloud formation can be inhibited by the nucleation barrier

\[ J \propto e^{f(\sigma^3)} \]

\( \sigma_{\text{TiO}_2} \sim 500 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{For}} \sim 436 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{Cor}} \sim 690 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{Fe}} \sim 1850 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{Cr}} \sim 1800 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{MnS}} \sim 2300 \text{ ergs cm}^{-2} \)
\( \sigma_{\text{KCl}} \sim 150 \text{ ergs cm}^{-2} \)

Gao+2020
Photochemical haze production is likely tied to abundance of simple “haze precursors”

Haze forms when CH$_4$ becomes dominant?

(Not necessarily)

Morley+2015

Lower UV

Lower CH$_4$

Elsie Lee
Laboratory experiments shed light on complexities of haze formation and composition.
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Moran+2020
Optical properties depend on size, composition, shape and impact the large scale thermal structure of exoplanets.

- $R = 1$ micron
- $R = 0.1$ micron

Spectral features

"Mie wiggles"

Decrease in extinction with increasing wavelength
Cloud particle size distributions (and shapes) can be complex.

Potential Exponential
Lognormal
Bins (cloud)
Bins (haze)

Gao+2021
Clouds and hazes are complicated
How do Clouds and Hazes Impact Exoplanet Atmospheres and Observations?
Global Scale ($T \sim \text{hours} - \text{days}$):

- Phase curve
- Energy balance
- Dynamics
- Gas composition (e.g. rain out)

Effects of exoplanet clouds and hazes range from global to local scales.
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Column Scale (T ~ hours – days):
- Transmission spectra
- Emission/reflection spectra
- Thermal structure
Effects of exoplanet clouds and hazes range from global to local scales

Local Scale (T ~ minutes – hours):

- Coagulation
- Particle distribution
Effects of exoplanet clouds and hazes range from global to local scales.

Particle Scale (T ~ seconds):
- Condensation/chemistry
- Composition
- Shape
- Optical properties
Insert image of inhomogeneous clouds on gas giants.
Heating by clouds/hazes creates inversion

Cooling due to cloud/haze scattering

Clear
Not Clear
Clouds and Hazes impact exoplanet atmospheres across a wide range of spatial and temporal scales.
How Do We Better Understand Clouds and Hazes?
Task 1: Look at Cloudy/Hazy-ness on a population level

Formation & sinking of silicate clouds

Formation of photochemical hazes

1.4 μm Water Band Amplitude (H)

Equilibrium Temperature (K)

Gravity (cm s⁻²)

G20 (g = 10 m s⁻²)

CK17 (modified)
Task 1: Look at Cloudy/Hazy-ness on a population level

Gao+Powell 2021

Parmentier+2016, 2021
Tholins

$\text{KCl}$

$\text{Na}_2\text{S}$

$\text{Mg}_2\text{SiO}_4$

$\text{Fe}_{\text{Al}}$$_2$\text{O}_3$

Task 2: Look for the spectral finger-prints of clouds and hazes

Updated laboratory measurements of optical constants needed
Task 3: Look for the lack of condensation
Task 3: Look for the lack of condensation
### Task 4: More lab work!

<table>
<thead>
<tr>
<th>Plasma</th>
<th>100x</th>
<th>1,000x</th>
<th>10,000x</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 K</td>
<td>$\theta \approx 78^\circ \pm 2^\circ$</td>
<td>$\theta \approx 45^\circ \pm 1^\circ$</td>
<td>$\theta \approx 82^\circ \pm 5^\circ$</td>
</tr>
<tr>
<td>400 K</td>
<td>$\theta \approx 103^\circ \pm 4^\circ$</td>
<td>$\theta \approx 65^\circ \pm 1^\circ$</td>
<td>$\theta \approx 92^\circ \pm 2^\circ$</td>
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<tr>
<td>300 K</td>
<td>$\theta \approx 87^\circ \pm 1^\circ$</td>
<td>$\theta \approx 33^\circ \pm 3^\circ$</td>
<td>$\theta \approx 85^\circ \pm 3^\circ$</td>
</tr>
</tbody>
</table>
Looking through clouds and hazes is not an option: Their impacts on planetary atmospheres are unavoidable

Understanding clouds and hazes requires a combination of observational, theoretical, and experimental efforts – every bit helps!

Review papers:


Helling 2019: https://ui.adsabs.harvard.edu/abs/2019AREPS..47..583H/abstract

Gao+2021: https://ui.adsabs.harvard.edu/abs/2021JGRE..12606655G/abstract