

Clouds on Extrasolar Planets

... do aliens get hit by rocks?

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Caroline Morley, Melanie Rowland



The University of Texas at Austin
Department of Astronomy



Clouds are Everywhere!

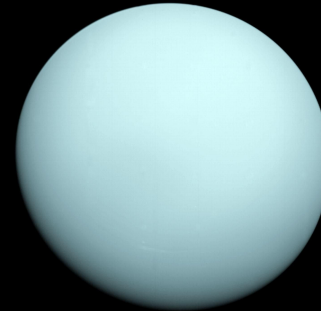
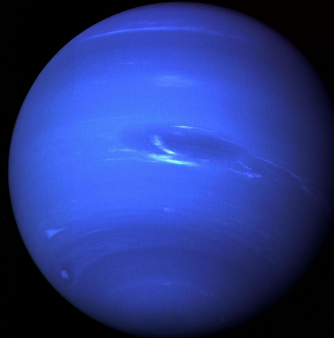
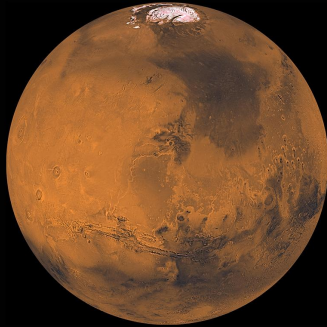
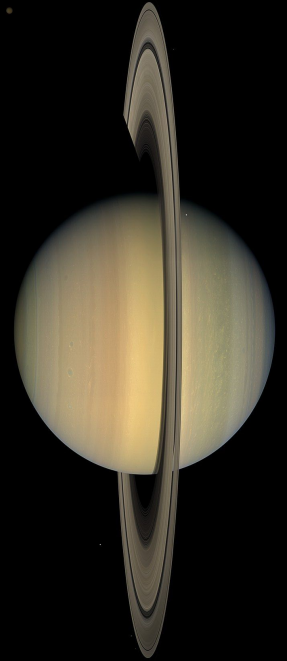
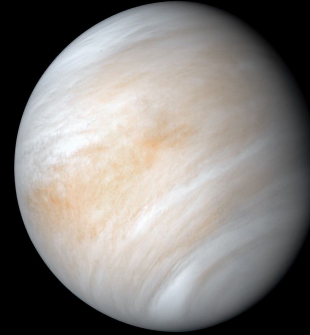
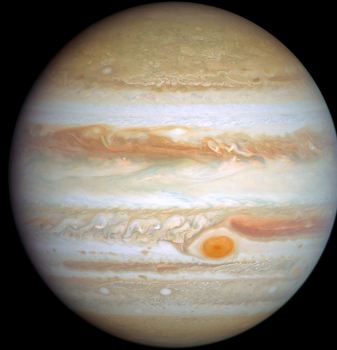
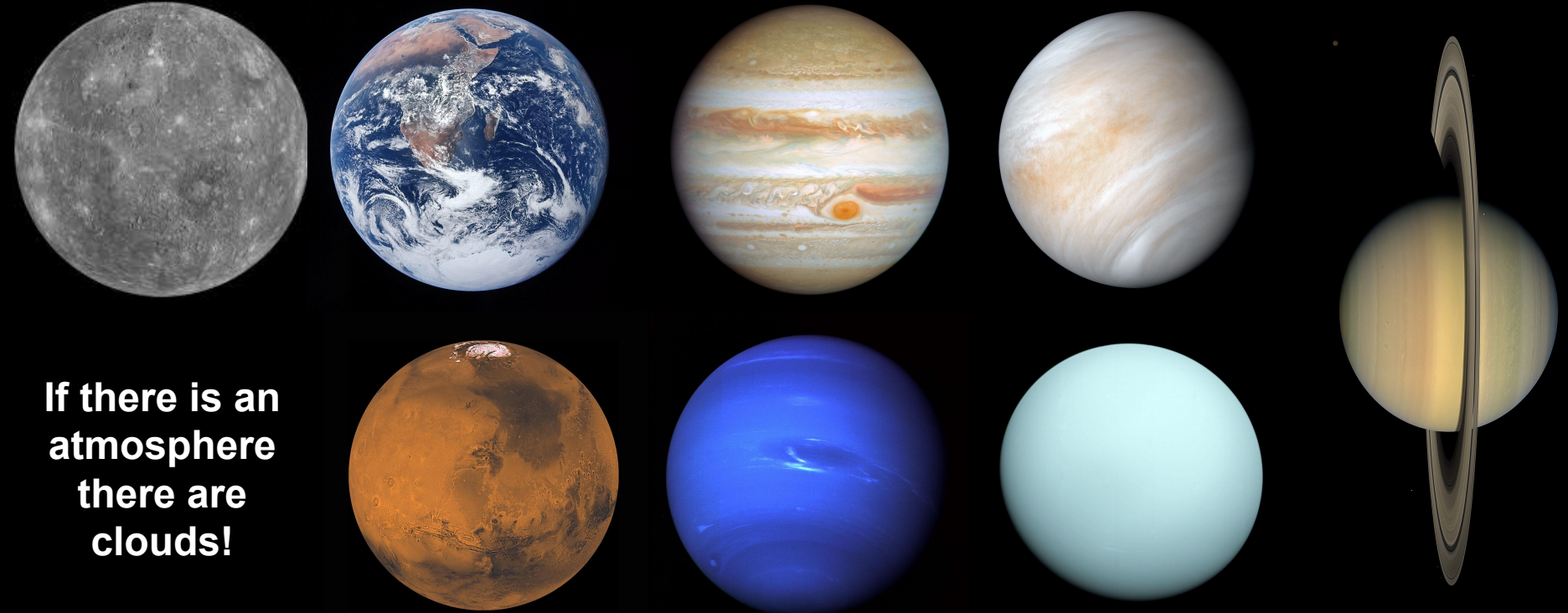


Image Credit: NASA

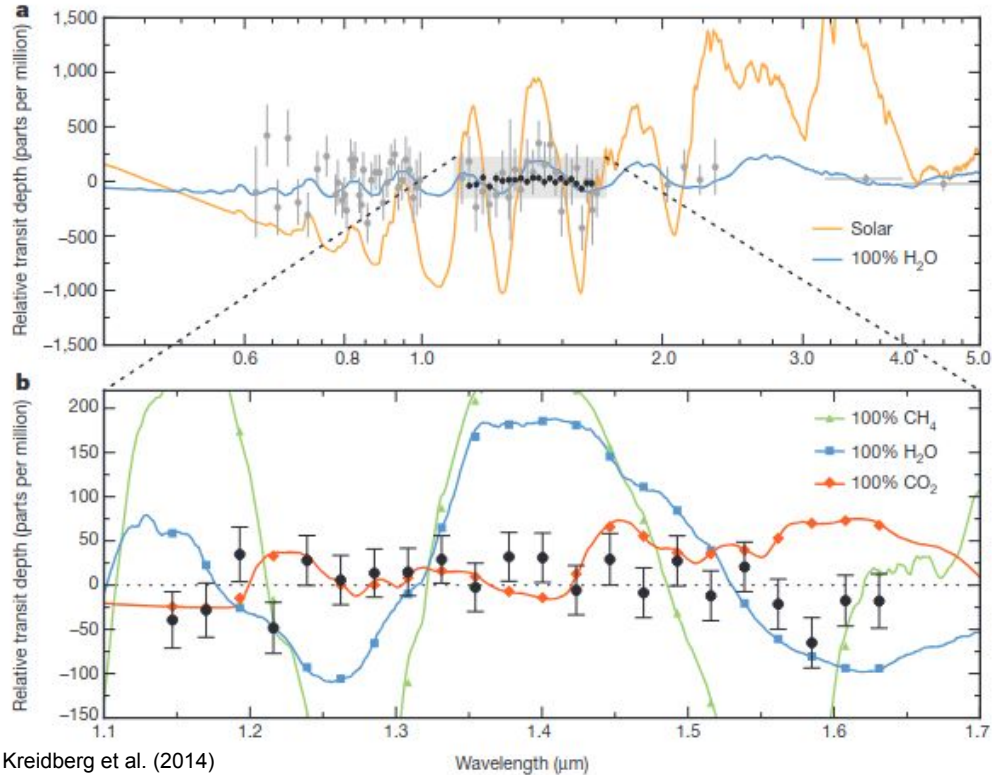
Clouds are (almost) Everywhere!



**If there is an
atmosphere
there are
clouds!**

Image Credit: NASA

Previous Observations of Exoplanet Clouds



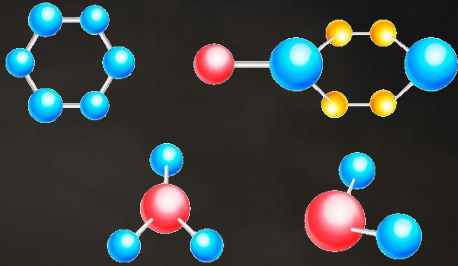
Just a flat line.

Only indirect proof of clouds.
A flat line it could also be a:

- Cloud free atmosphere
- Compact atmosphere

The Atmosphere of Exoplanets

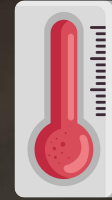
Chemistry



Clouds



Climate



Why hot Jupiters?

- 1) They are big!
- 2) They are fluffy!
- 3) They orbit quick!

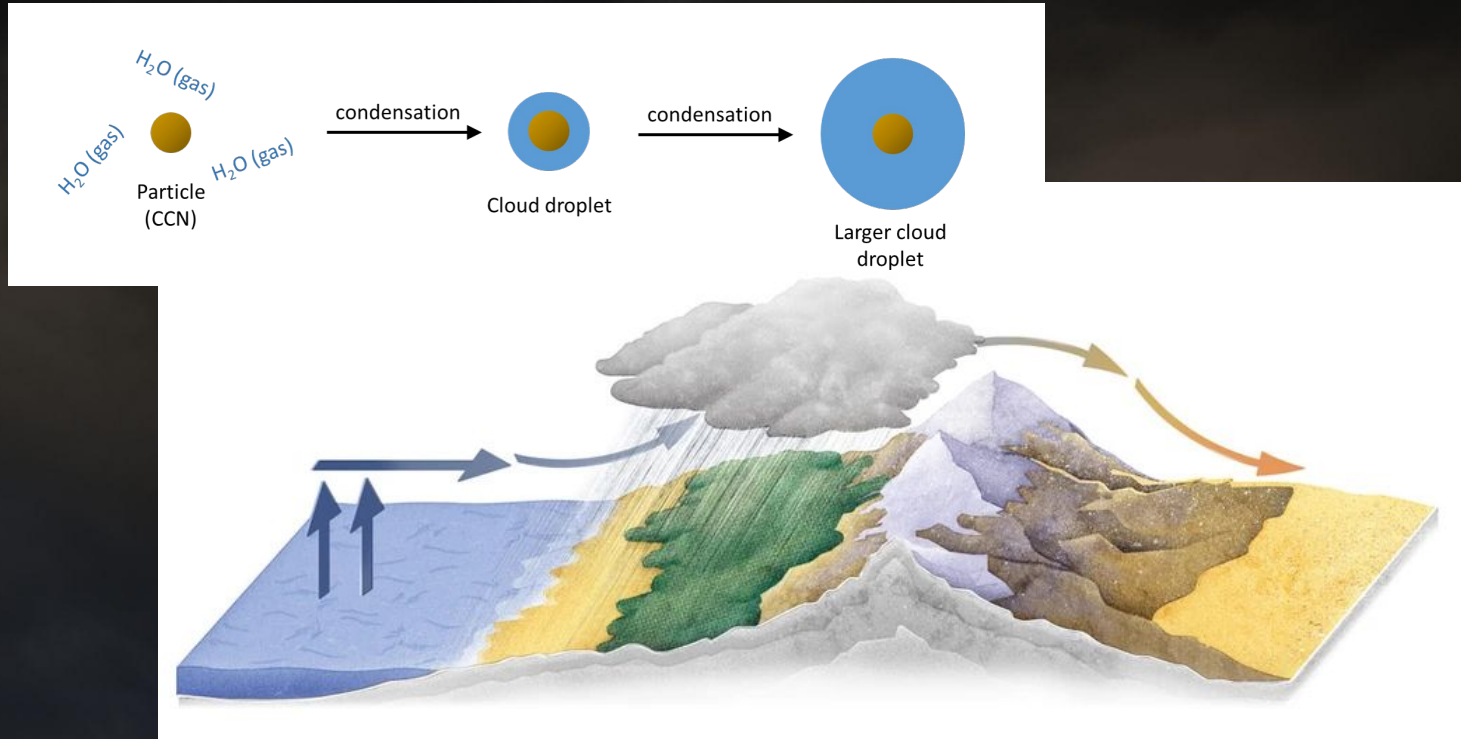
➡ Hot Jupiters are easy to observe

Image Credit: Freepik
Hot Jupiter: ESO

How Do Clouds Form on Planets?



How Do Clouds Form on Terrestrial Planets?

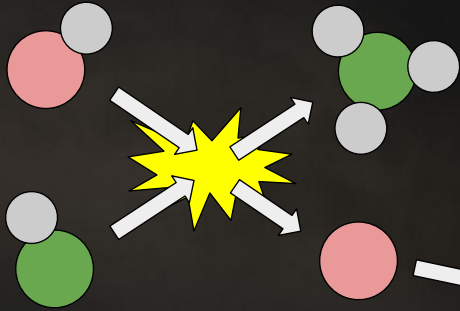


Top Image: Aerosols Department Of Physics And Astronomy Uppsala // Bottom Image: BBC science focus, Alexandra Franklin-Cheung

How Do Clouds Form on Gas-Giants?

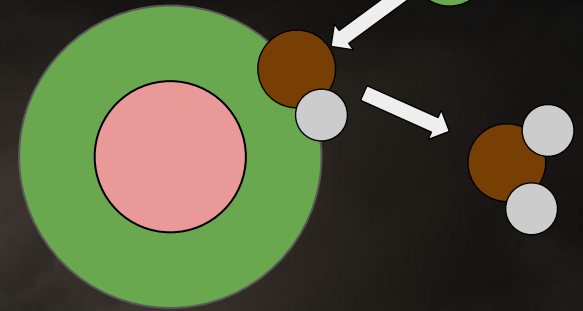
Atmospheric Chemistry

- N, C, H, O
- 100's of species
- 1000's of reactions



Nucleation

- Gas to solid
- TiO , SiO , KCl
- Creates aerosols

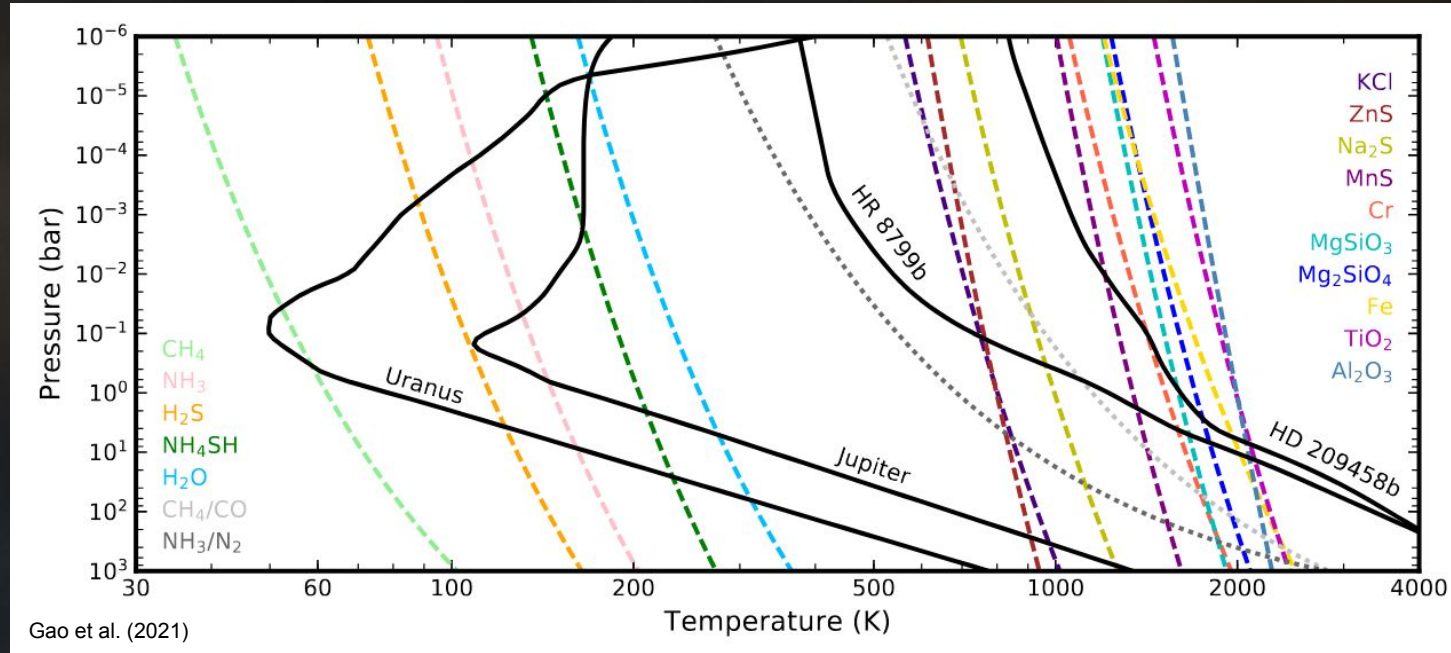


Condensation

- Gas grows onto aerosols
- MgSiO_3 , Fe_2O_3 , ZnS
- Can involve complex surface reactions

How Do Clouds Form on Gas-Giants?

Clouds can be made from many materials

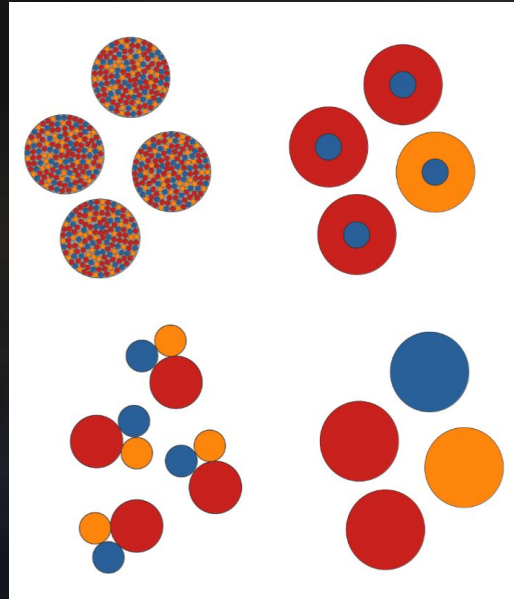


How Do Clouds Form on Gas-Giants?

Clouds can have complex morphologies

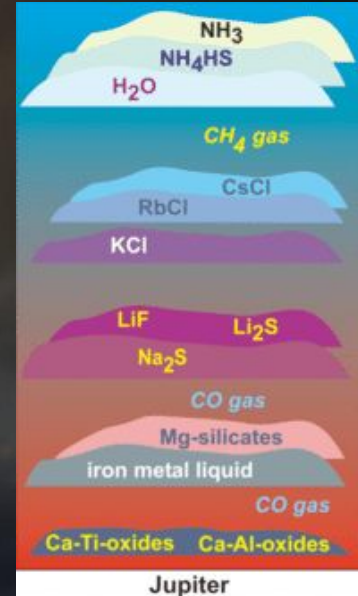


Image Credit: Dr. D. Samra



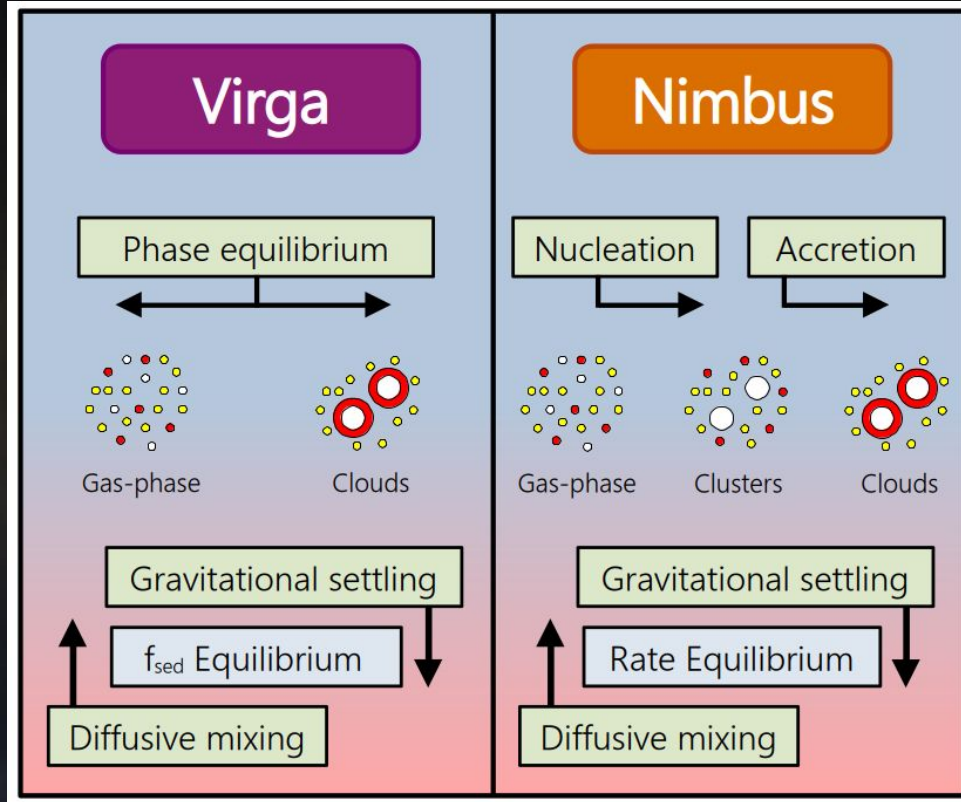
Kiefer et al. (2024)

Multiple cloud layers can form



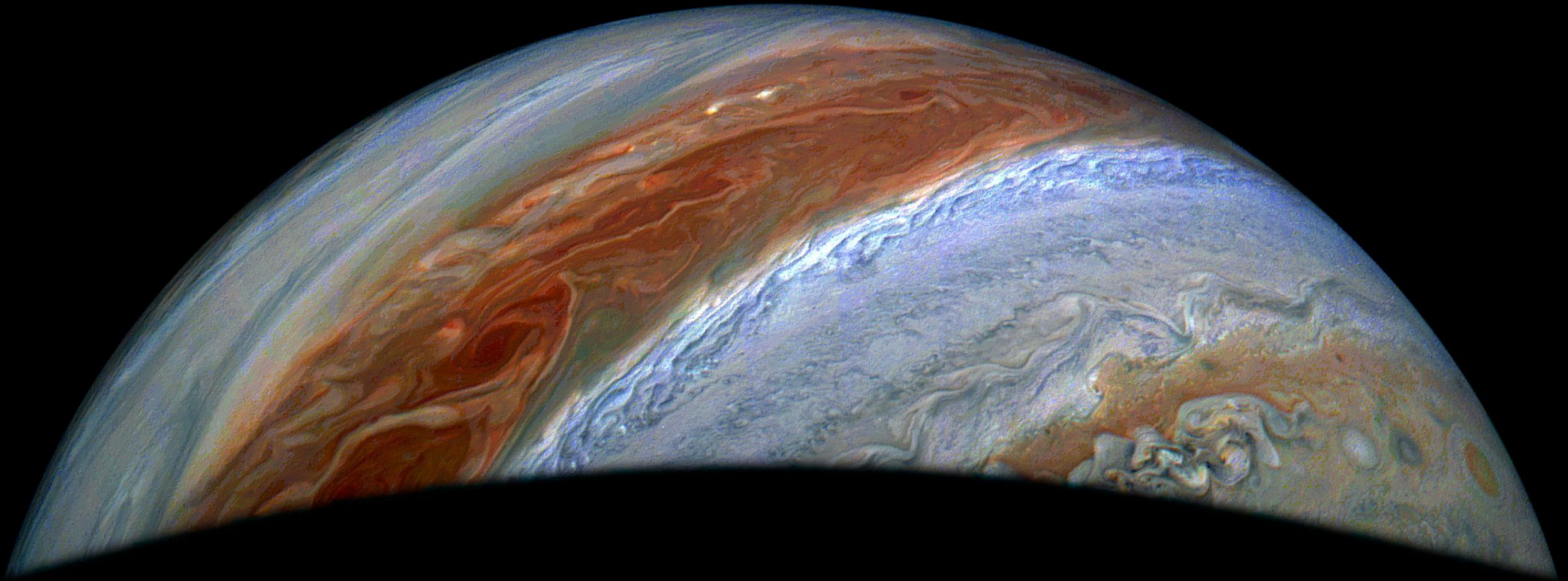
Lodders & Fegley (2006)

Our Cloud Formation Models

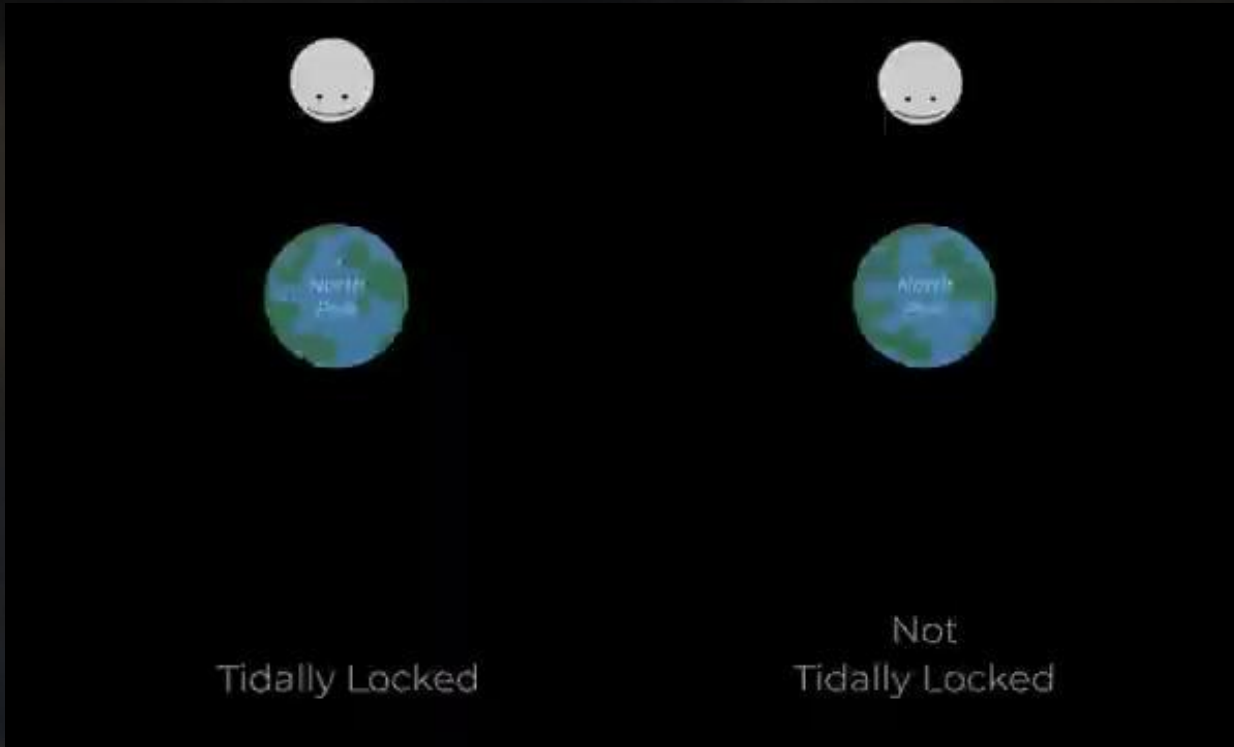


Exoplanet Atmospheres

... clouds are not alone!



The Climate of Tidally Locked Gas-Giants



**Most famous
example:**



The Climate of Tidally Locked Gas-Giants

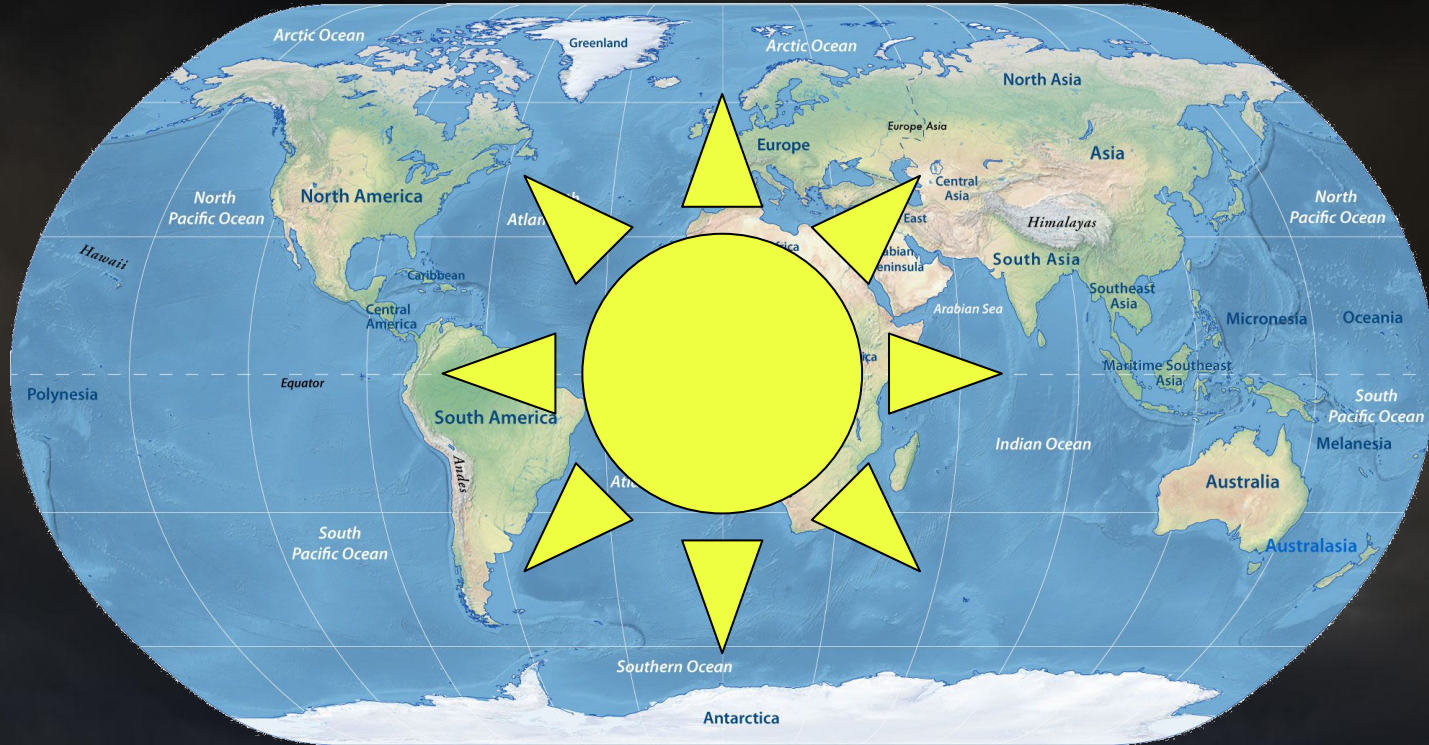
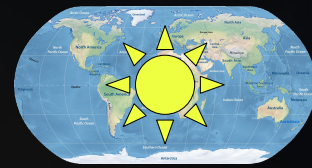


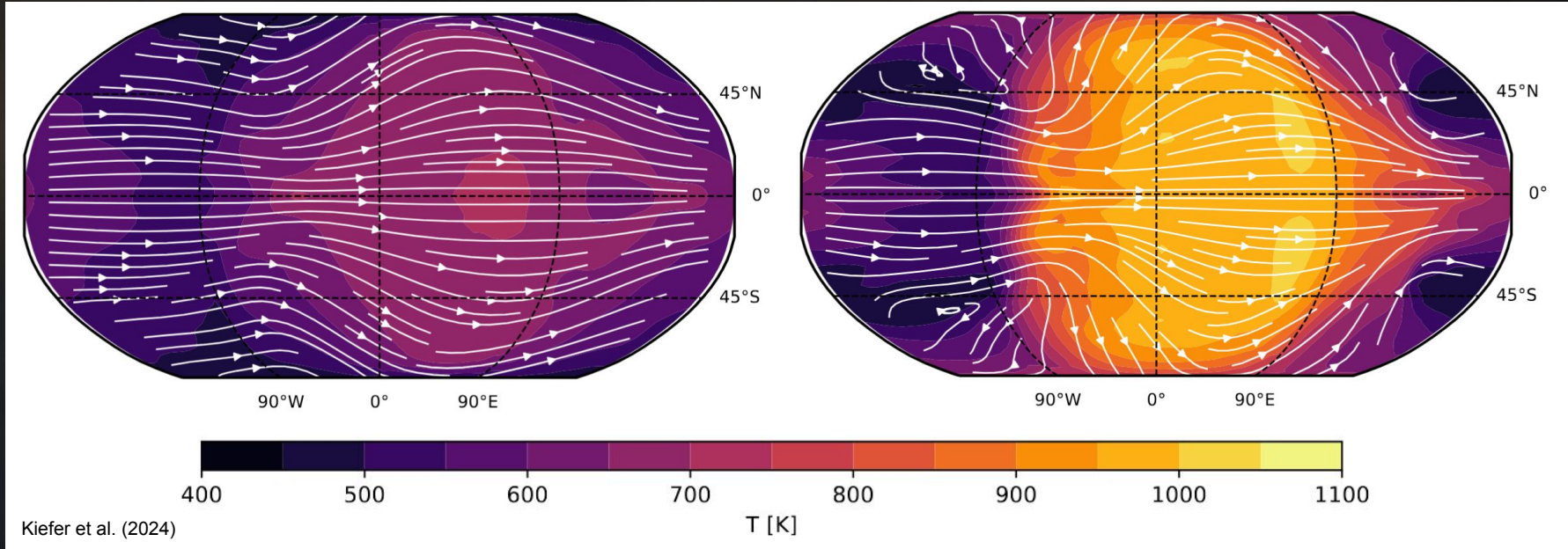
Image Credit: nationsonline

The Climate of Tidally Locked Gas-Giants

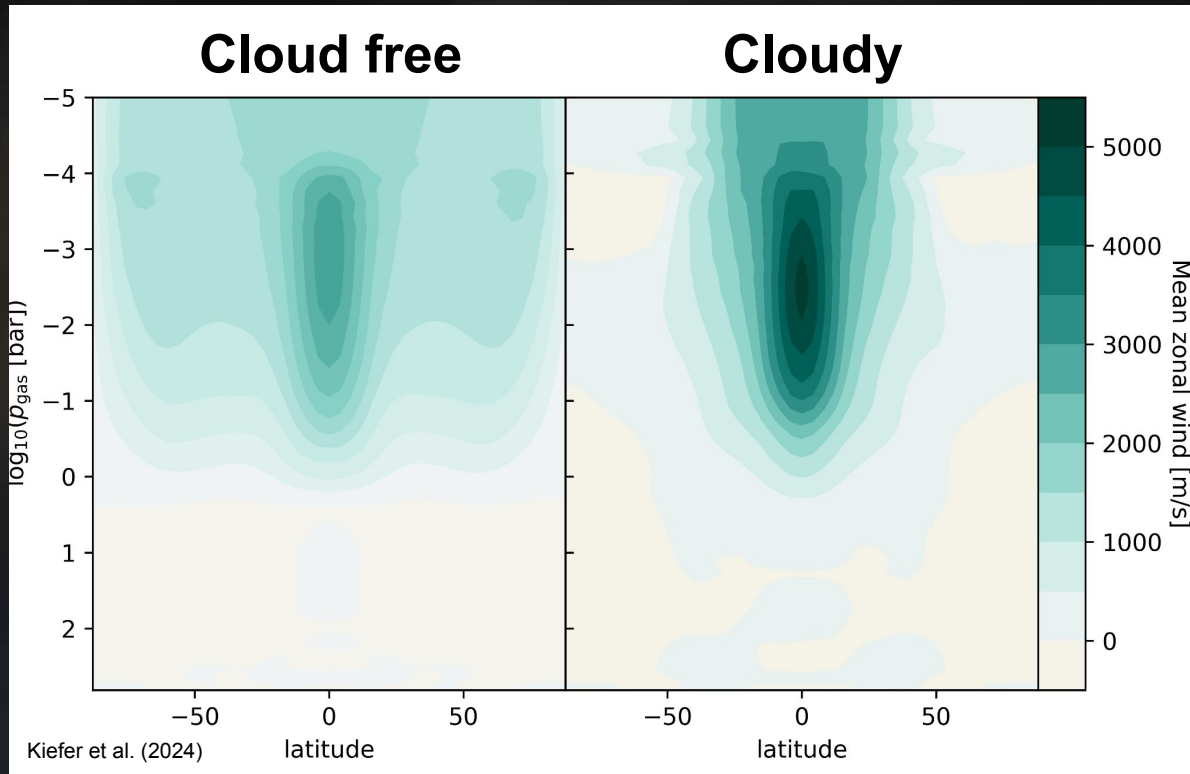


Cloud free

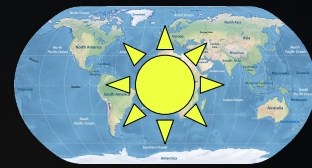
Cloudy



The Climate of Tidally Locked Gas-Giants



The Climate of Tidally Locked Gas-Giants



Morning terminator

Evening terminator

MnS

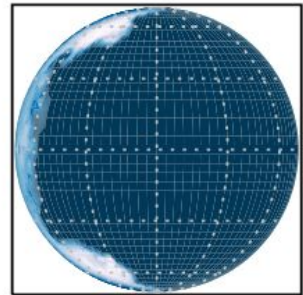
MgSiO₃

Fe

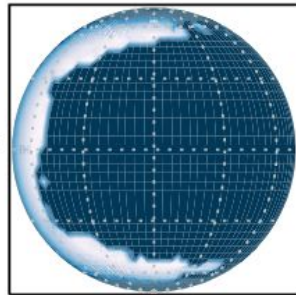
Al₂O₃

Total Cloud

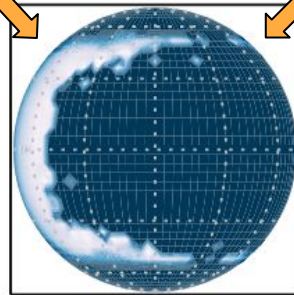
Dayside



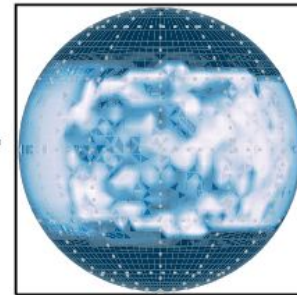
0.00 0.06 0.12 0.19
Albedo $\times \mu_0$



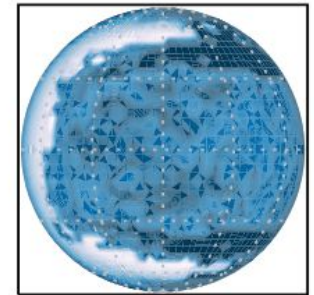
0.00 0.18 0.35 0.53
Albedo $\times \mu_0$



0.00 0.04 0.08 0.12
Albedo $\times \mu_0$



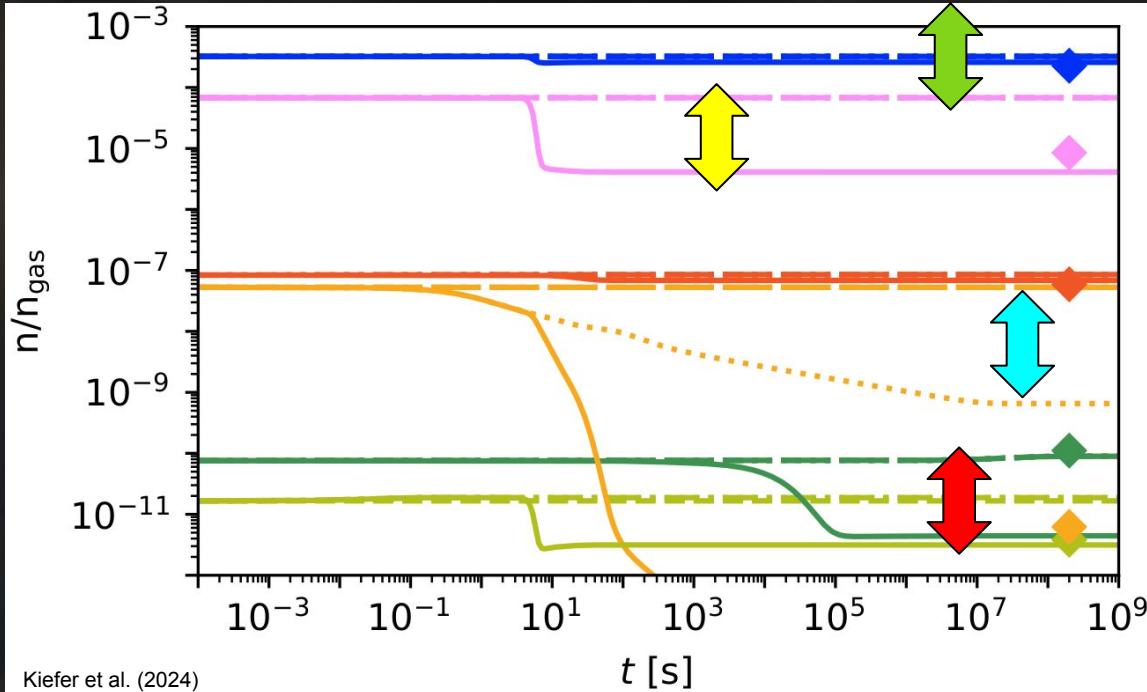
0.00 0.06 0.11 0.17
Albedo $\times \mu_0$



0.00 0.18 0.35 0.53
Albedo $\times \mu_0$

Roman & Rauscher (2024)

The Cloud-Chemistry Interaction



Chemistry

+ Nucleation

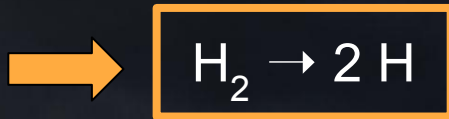
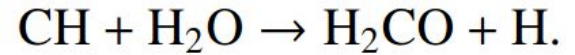
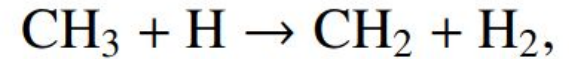
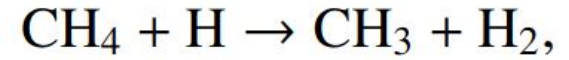
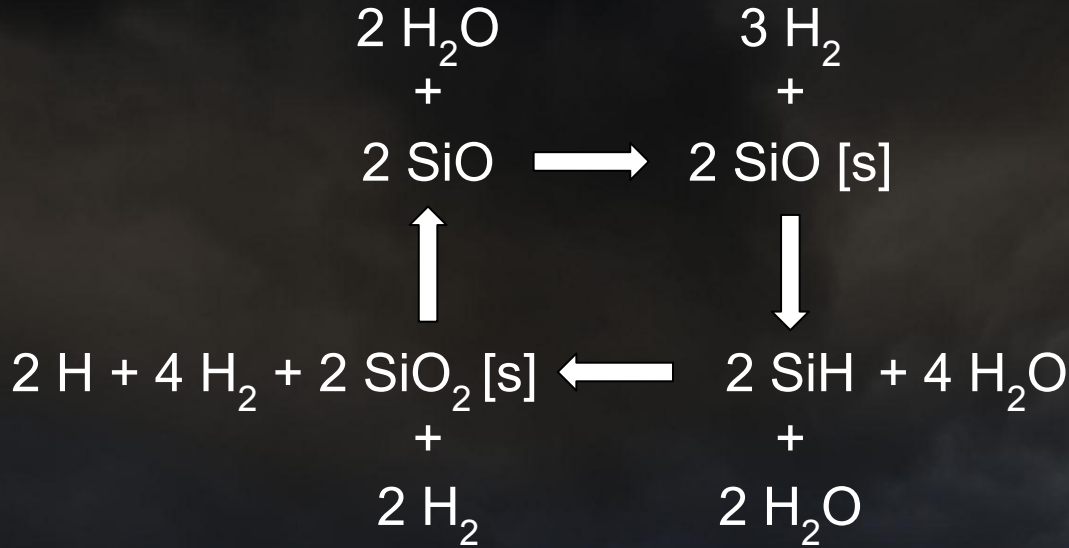
+ Condensation

Depletion:

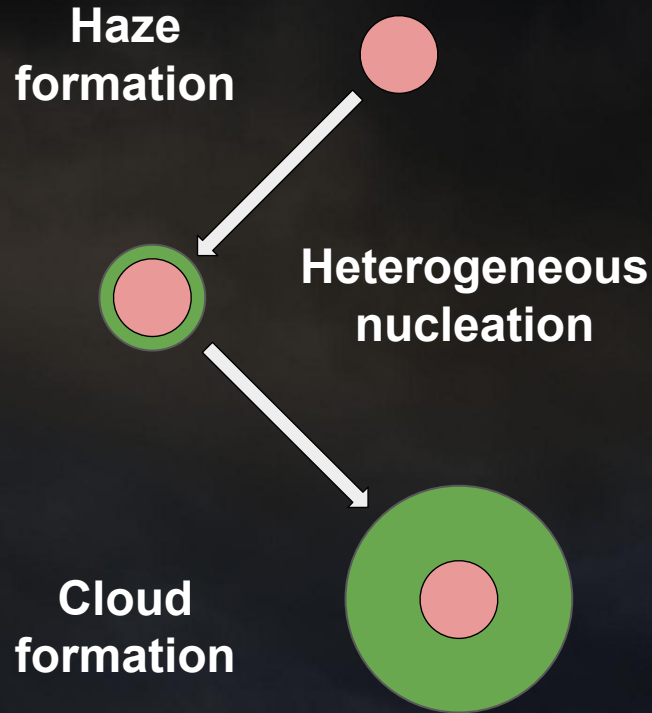
→ TiO₂ → Cloud Material
 → Oxygen → Methane

Kiefer et al. (2024)

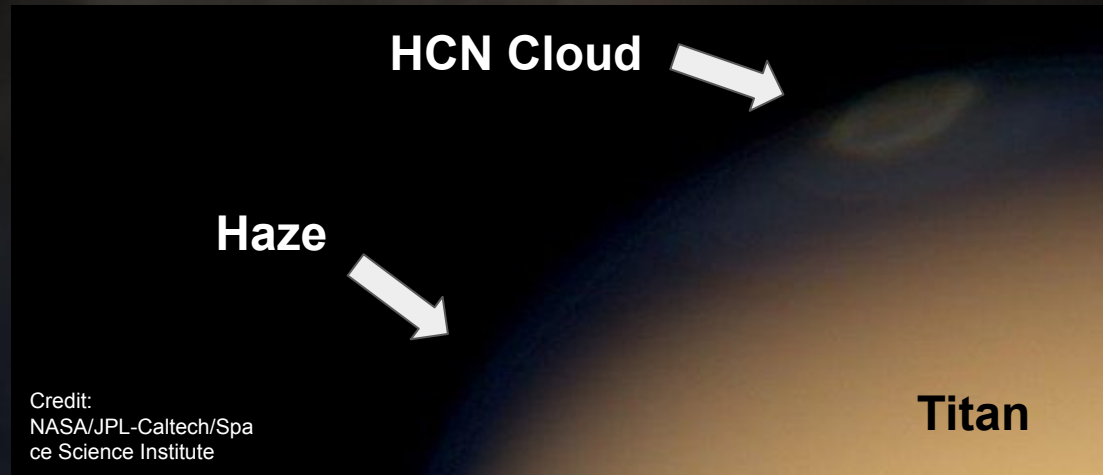
SiO-SiO₂ Cycle



The Connection of Clouds and Hazes



- Hazes can act as aerosols and provide other materials a surface to grow onto
- The transition from one material to another is called heterogeneous nucleation





How Do We Probe Exoplanet Atmospheres?

The Effects of Clouds on Sunsets

Mars

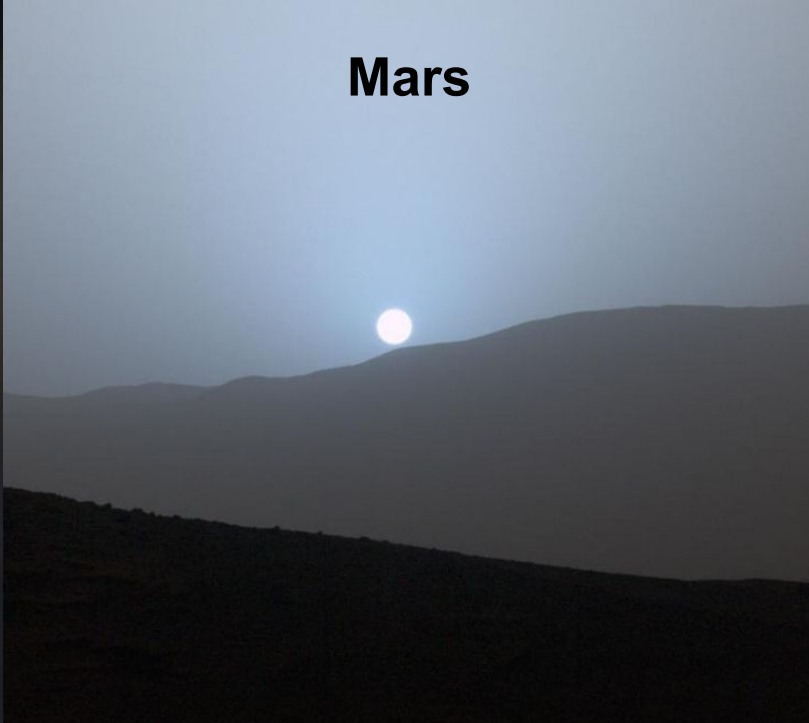


Image Credit: NASA/JPL-Caltech/MSSS/Texas A&M Univ.

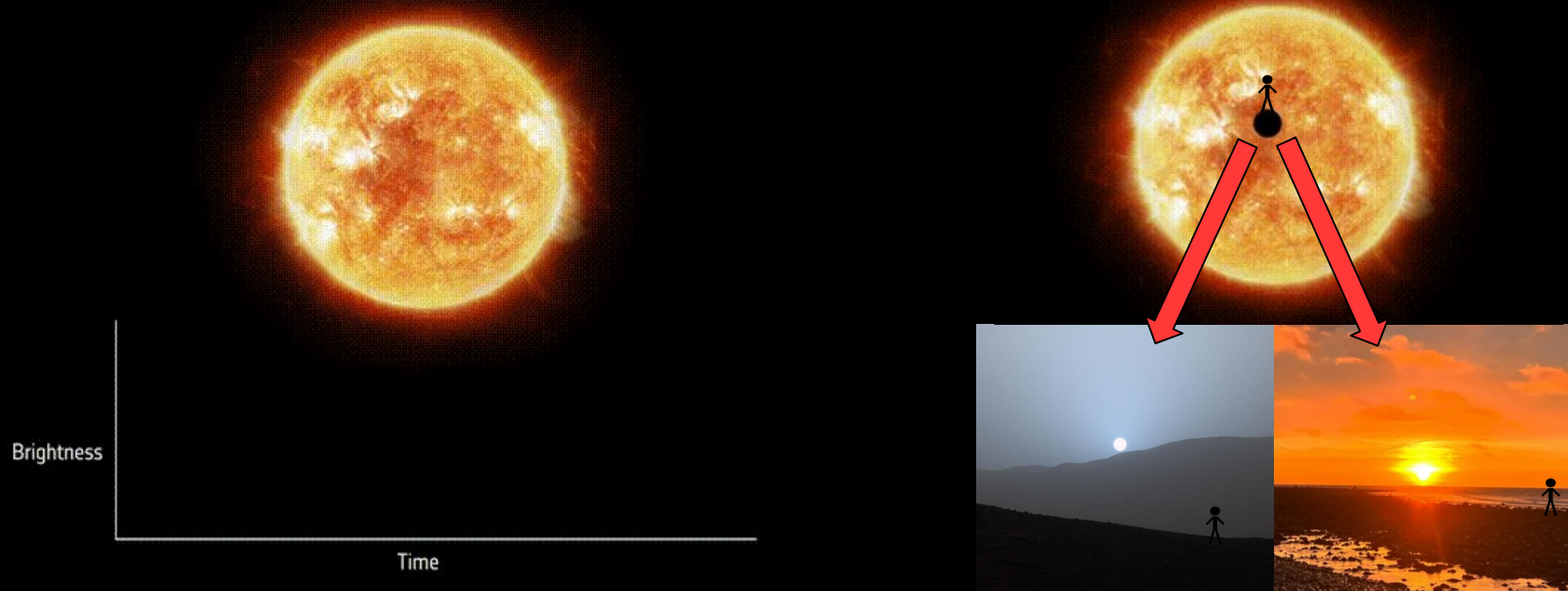
Earth



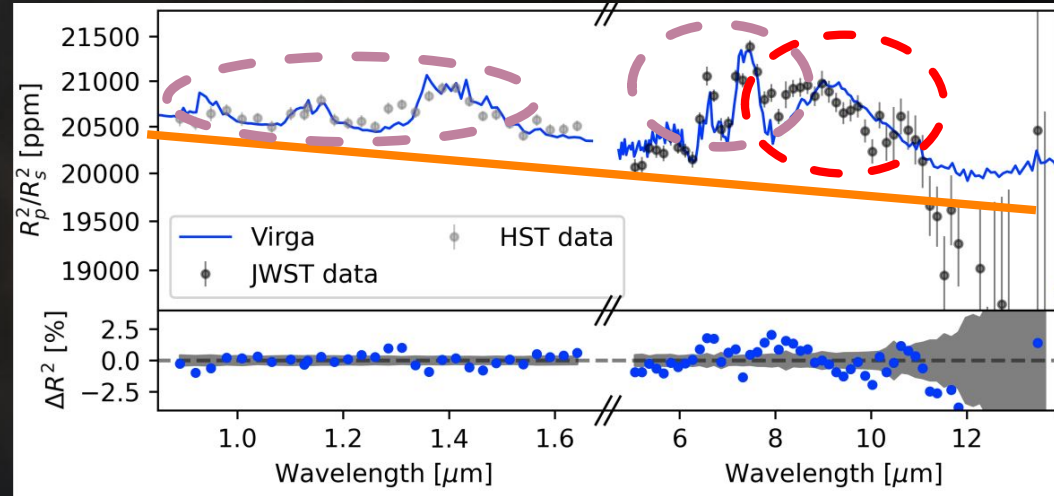
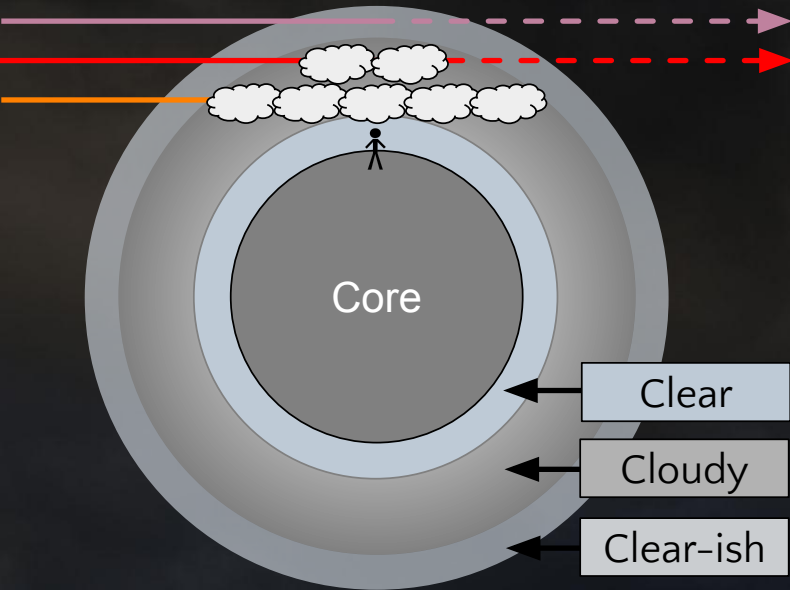
Image Credit: BBC Weather Watchers

Transmission spectra

Image Credit: ESA



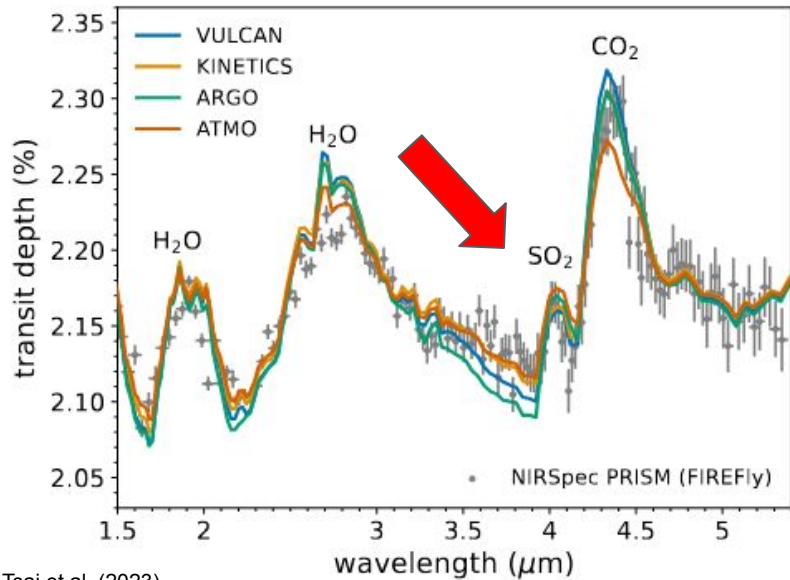
Transmission Spectra - WASP-107b



- Clouds determine how deep we can probe
- Cloud materials have spectral features
- Gases can only be observed above the clouds

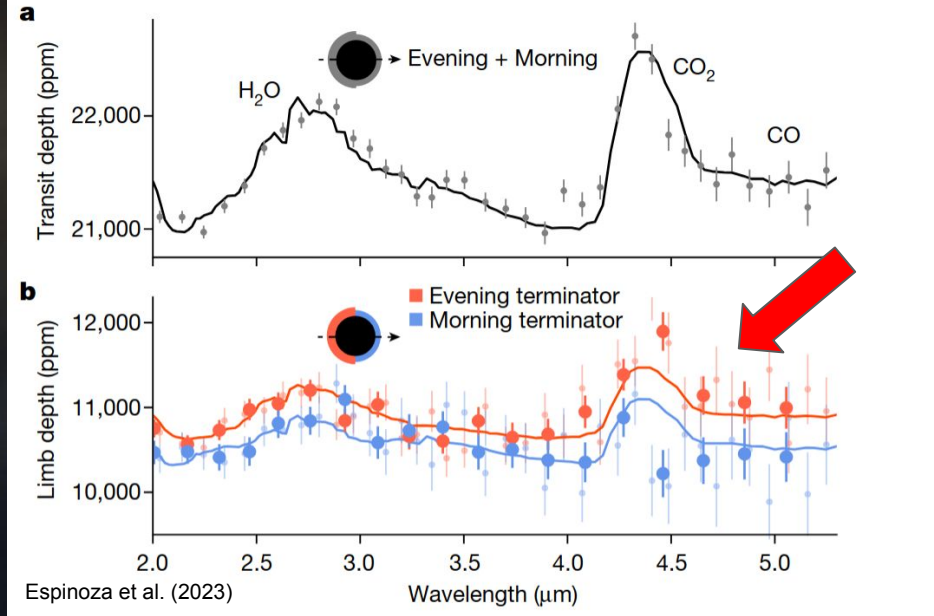
Transmission Spectra - WASP-39b

Photochemically produced SO_2



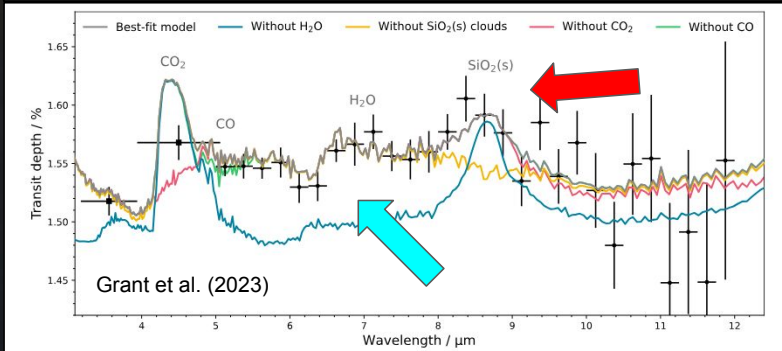
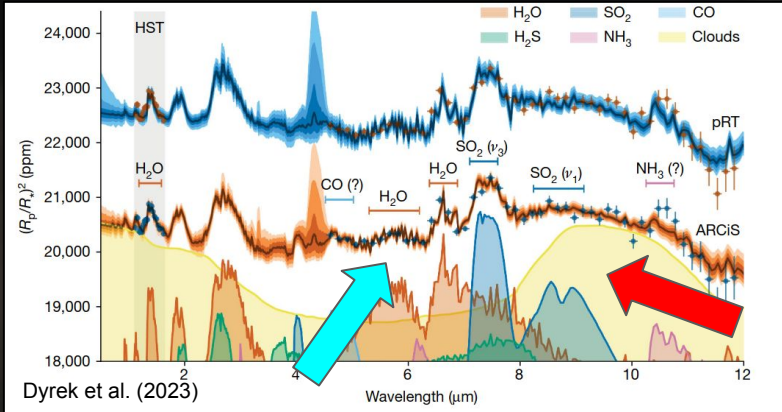
Tsai et al. (2023)

Global inhomogeneities in CO_2

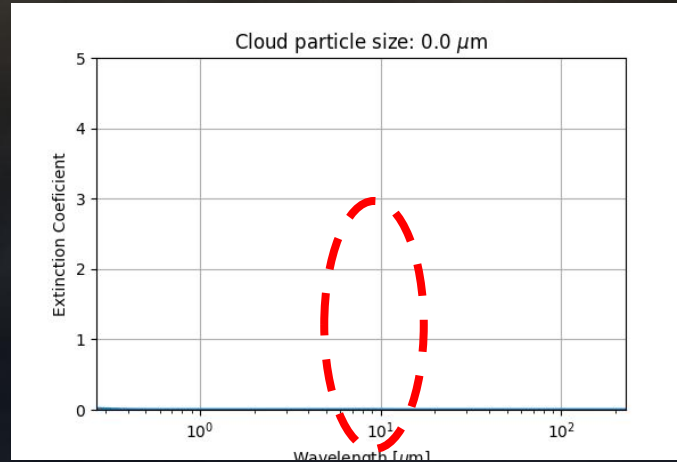


Espinoza et al. (2023)

Transmission Spectra - WASP-107b & WASP-17b

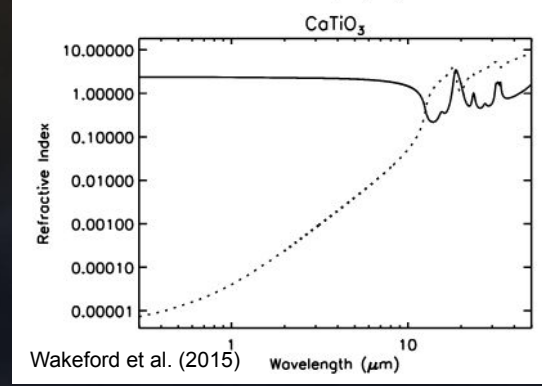
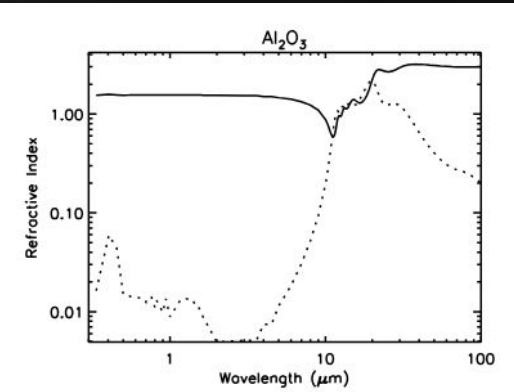
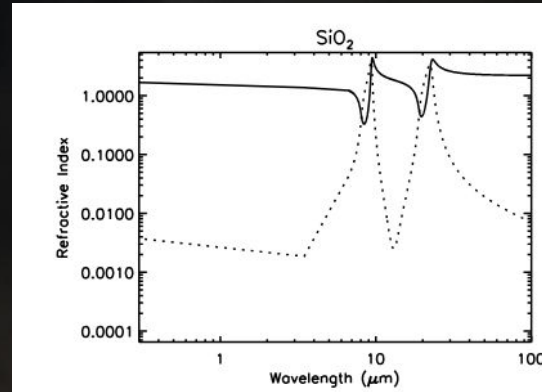
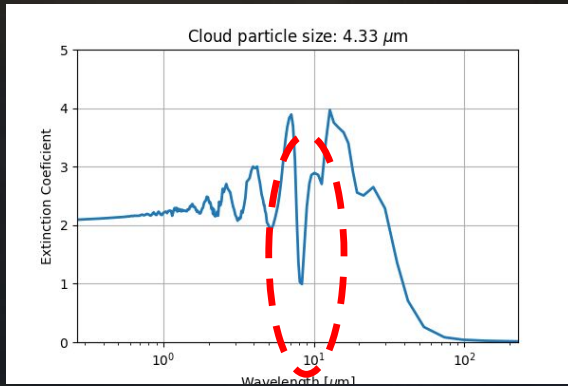
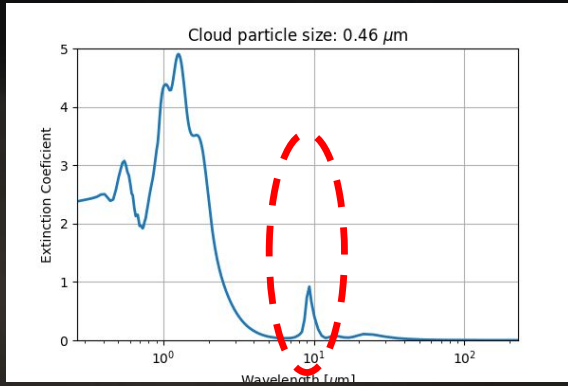


- Si-O bond features detected in WASP-17b and WASP-107b
- Molecular Muting + Si-O feature constraints cloud structures!



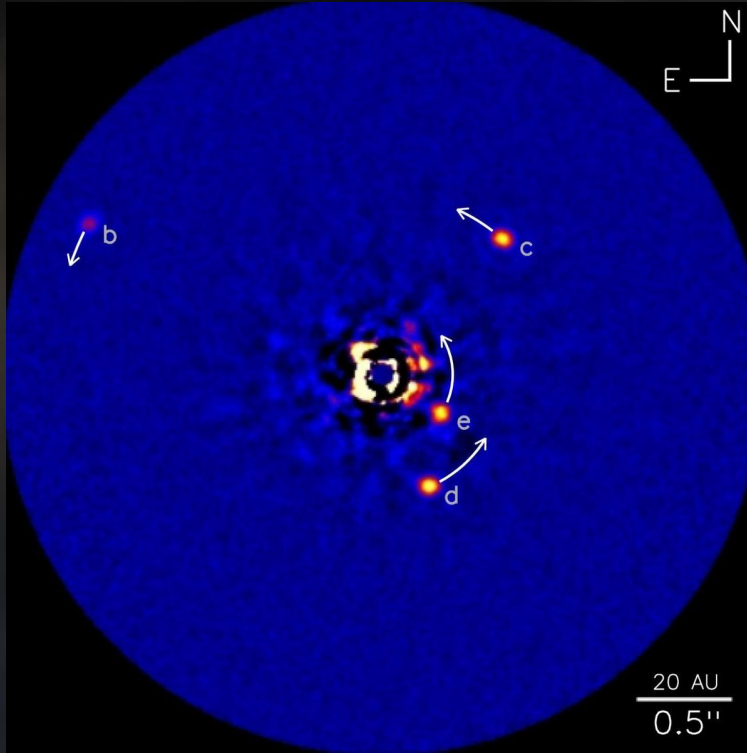
Material:
SiO

Transmission Spectra - What have we found?



- Only small cloud particle have material features
- The shape of the feature is material dependent

Thermal Emission Spectra

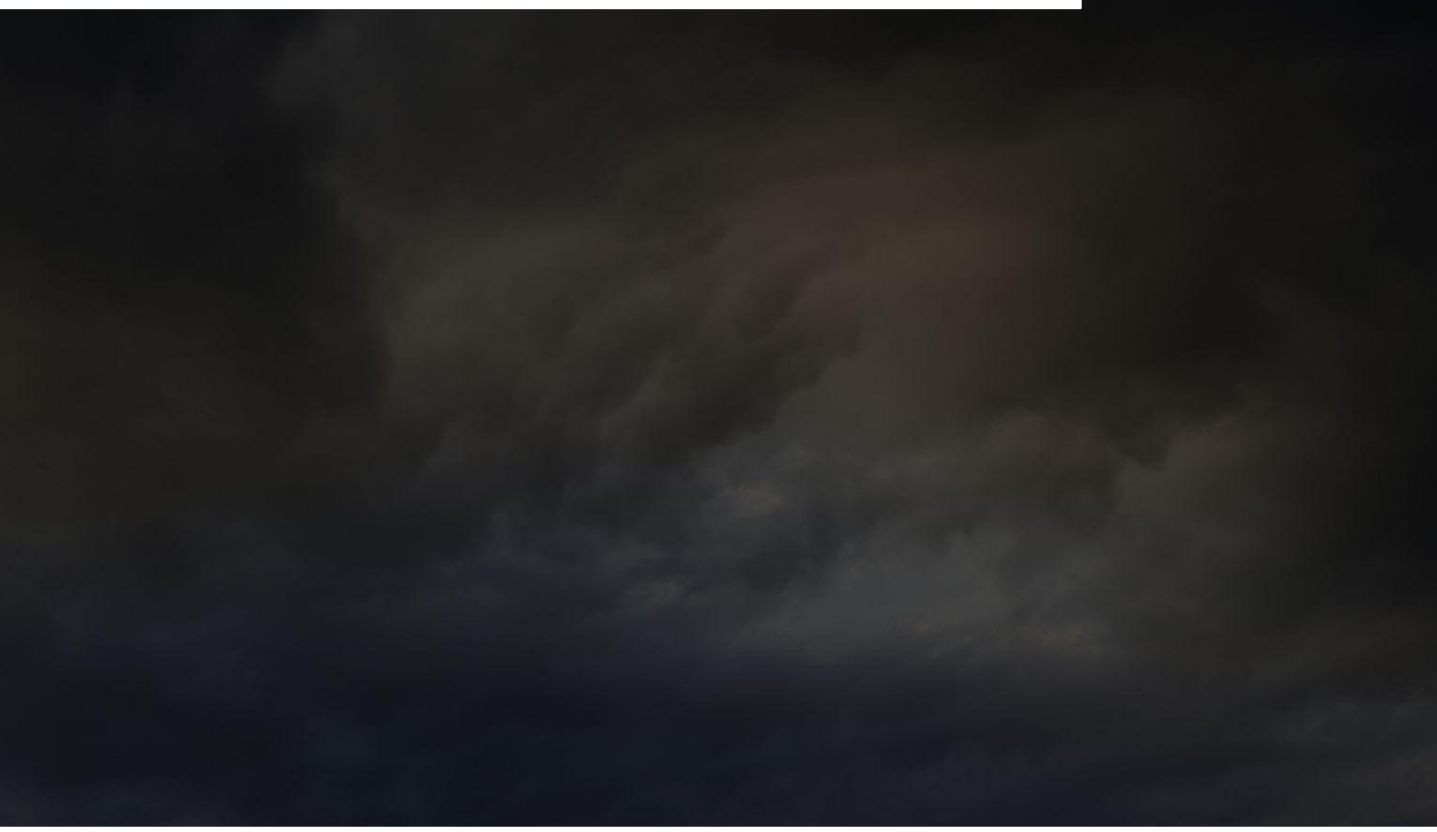
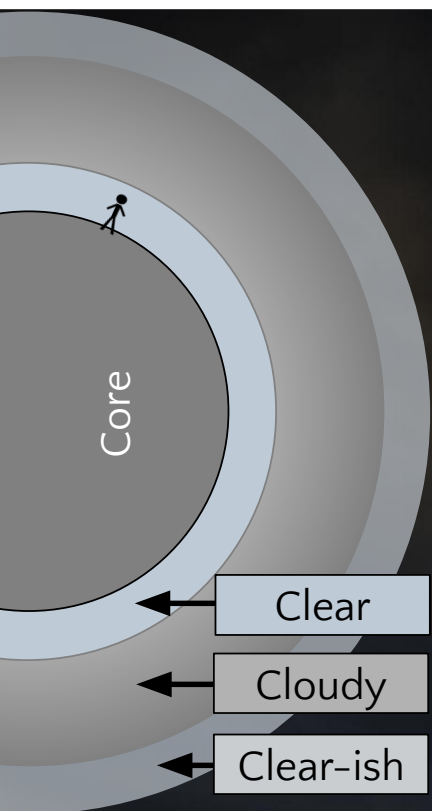


Direct Imaging:

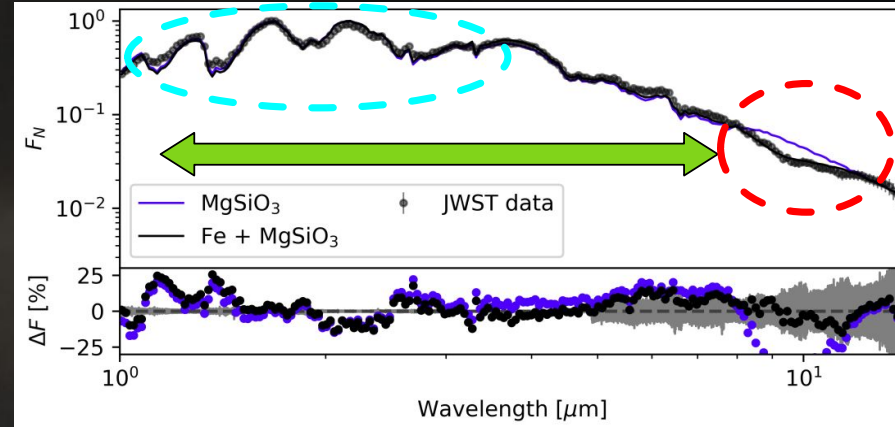
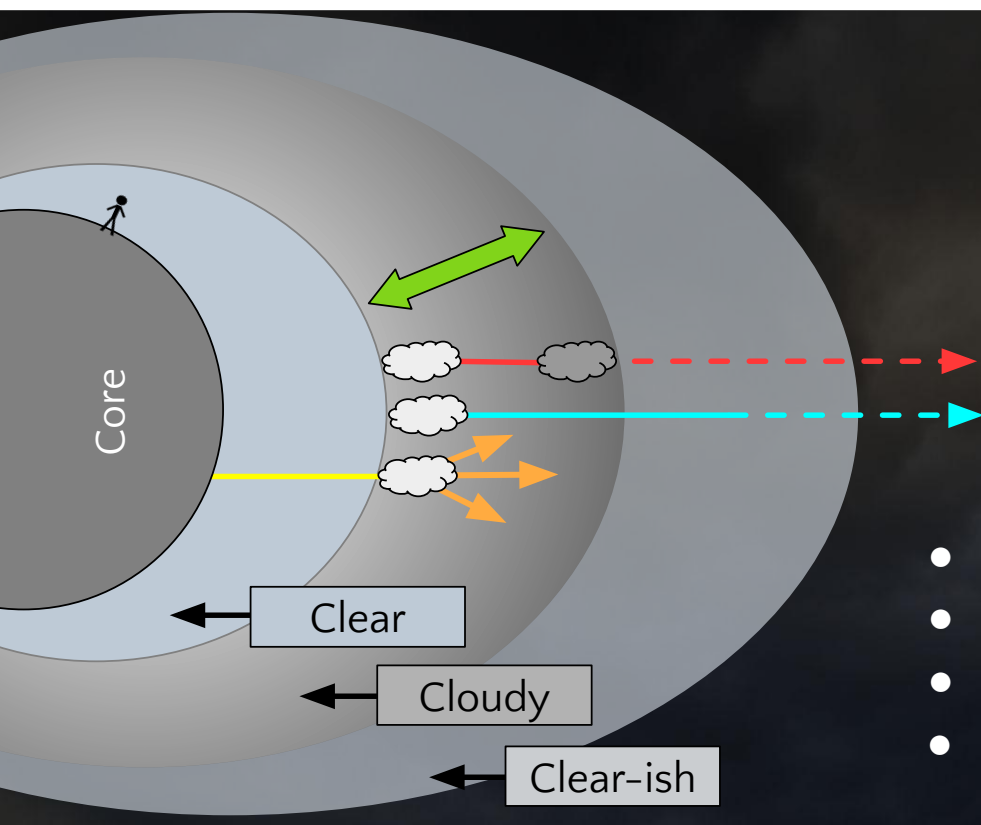
- Large planets on wide orbits
- Many are close to brown dwarfs
- Only young planets are observed

Image Credit: NRC-HIA, C. Marois, and Keck Observatory

Thermal Emission Spectra - VHS-1256b

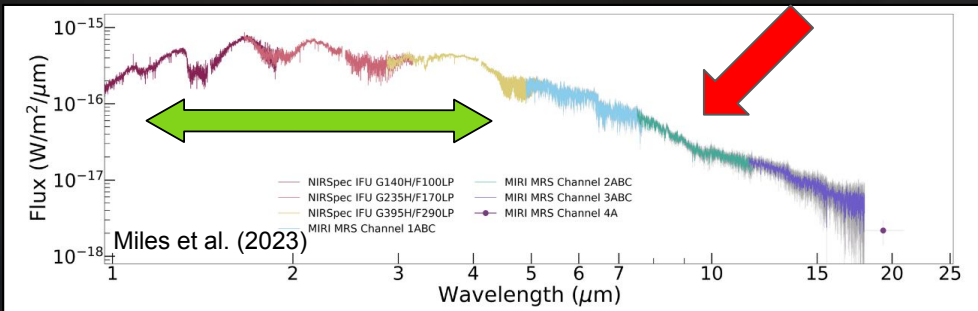
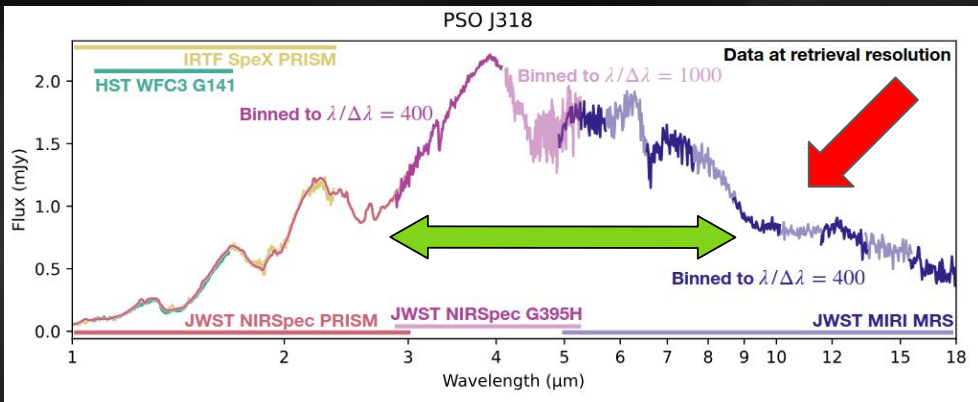


Thermal Emission Spectra - VHS-1256b

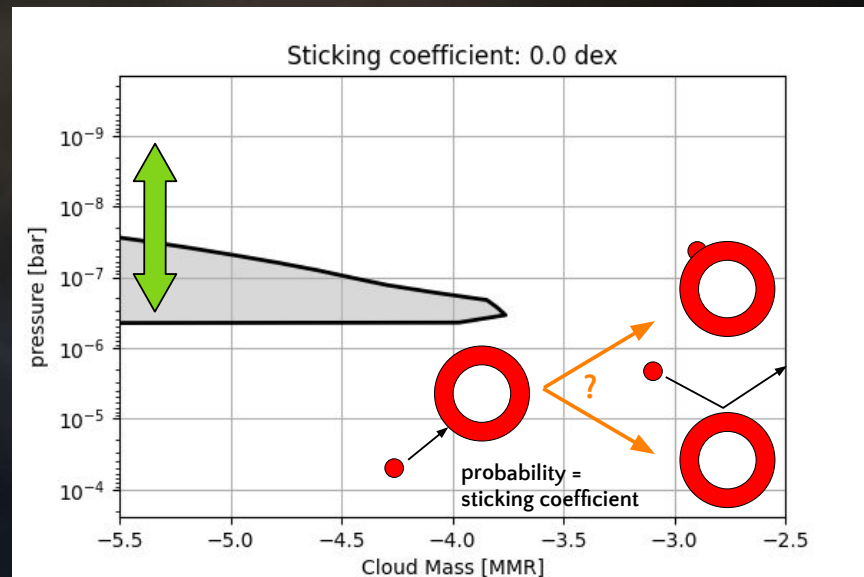


- Clouds block all light from below
- Clouds determine the blackbody width
- Cloud features occur only at high altitudes
- Molecular features occur at high altitudes

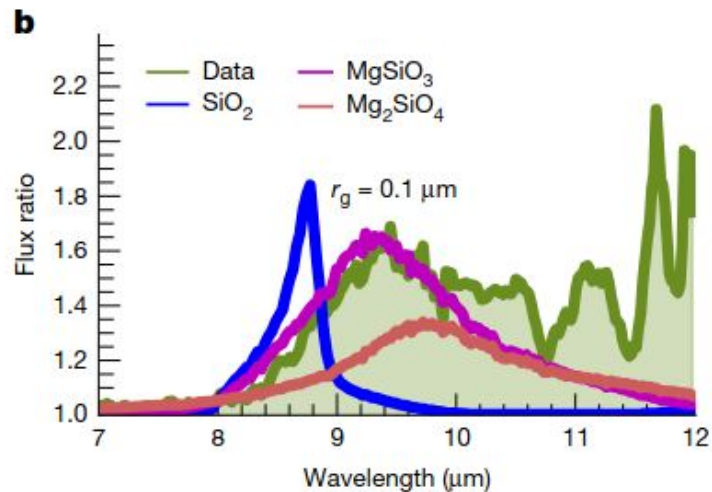
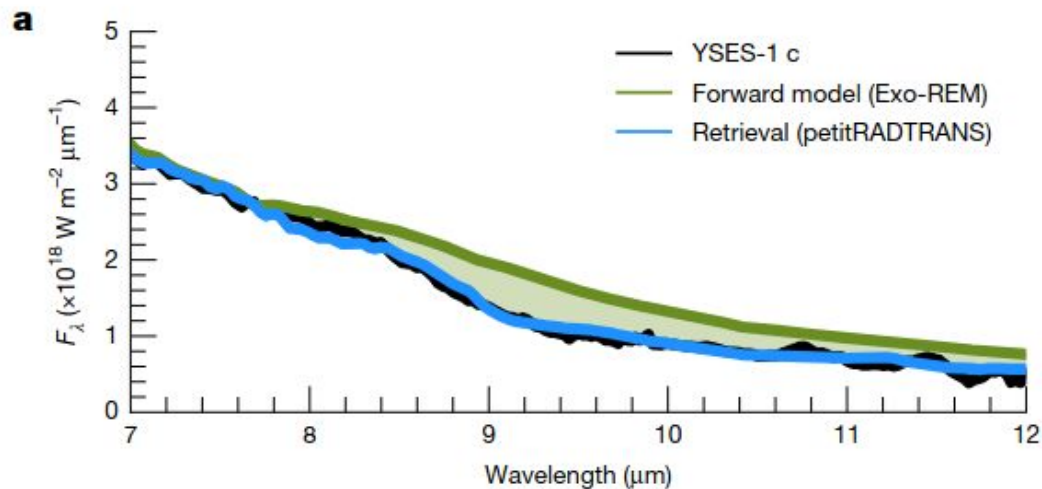
Thermal Emission Spectra – PSO J318 & VHS-1256b



- Width is sensitive to microphysics
- Si-O features detected!

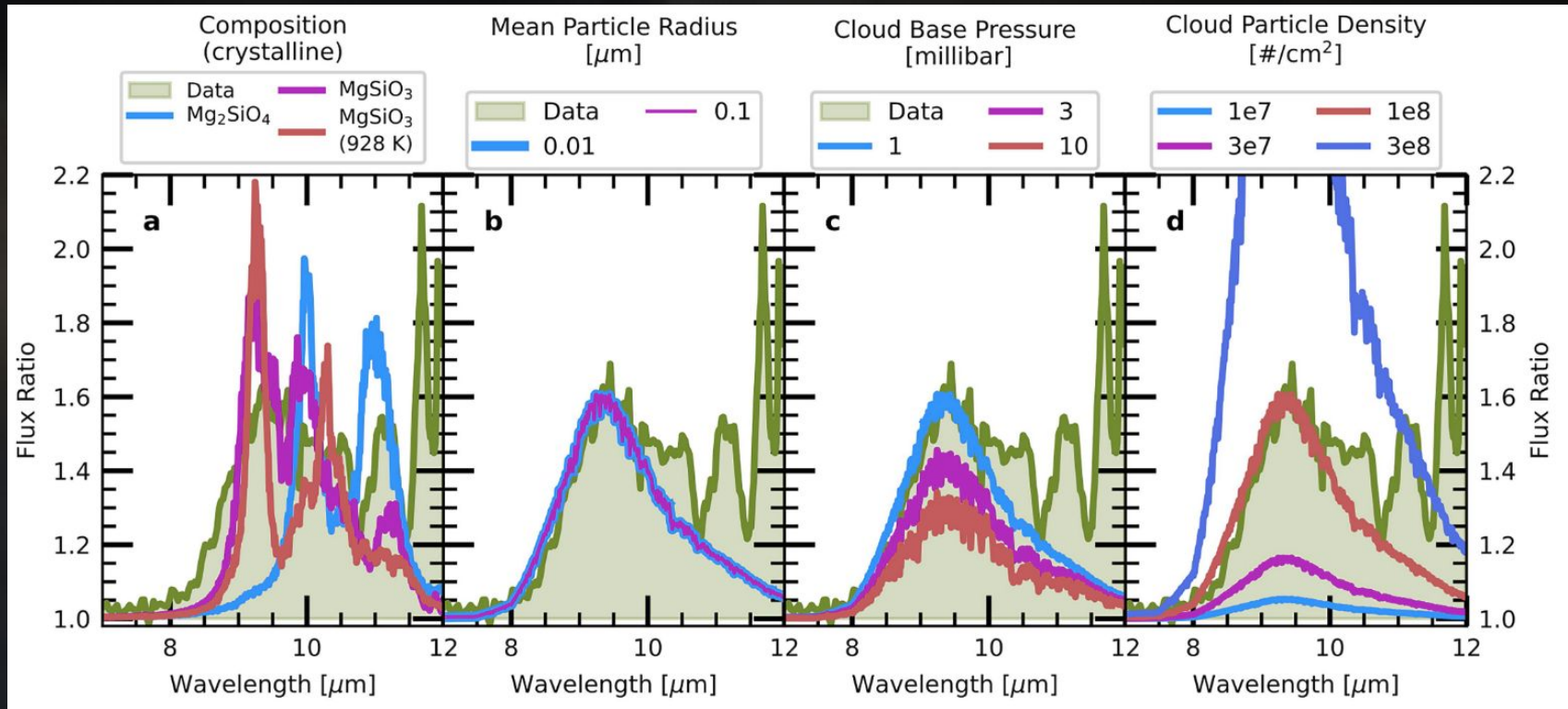


Thermal Emission Spectra - Fitting Cloud Features



Hoch et al. (2025)

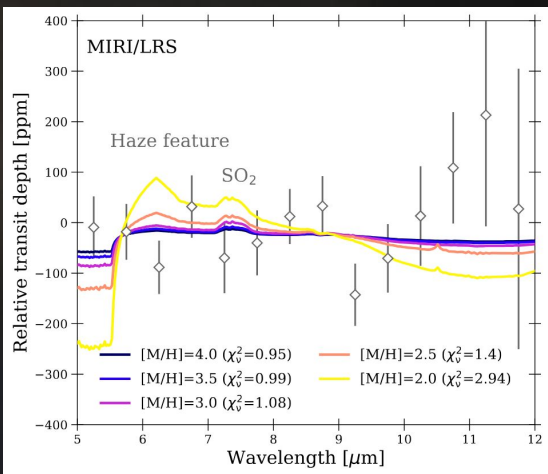
Thermal Emission Spectra - Fitting Cloud Features



Hoch et al. (2025)

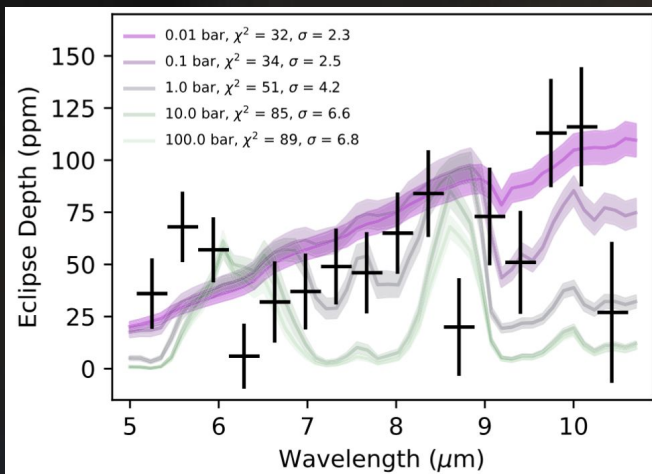
What about Rocky Planets?

GJ 1214 b



Ohno et al. (2023) // Kempton et al. (2025)

LTT 1445A b



Wachiraphan et al. 2025

Rocky planets can have similar clouds as hot Jupiters.

While they orbit fast, they are neither big nor fluffy.

➔ Good targets to push our current understanding of exoplanet atmospheres.

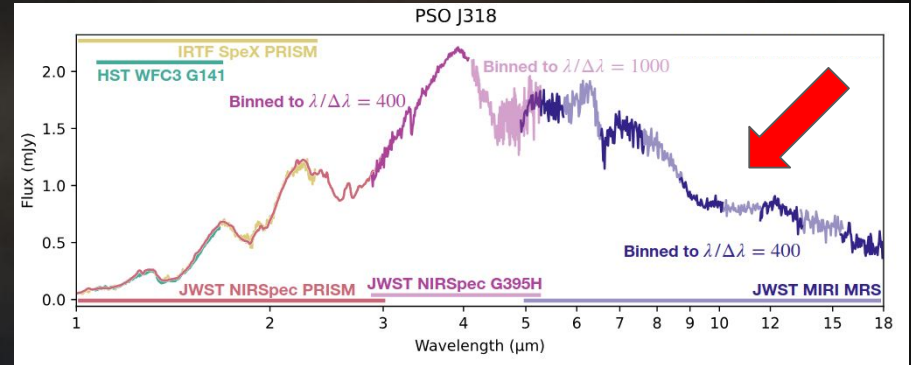
➔ Bad targets to study cloud physics (for now).



What comes next?

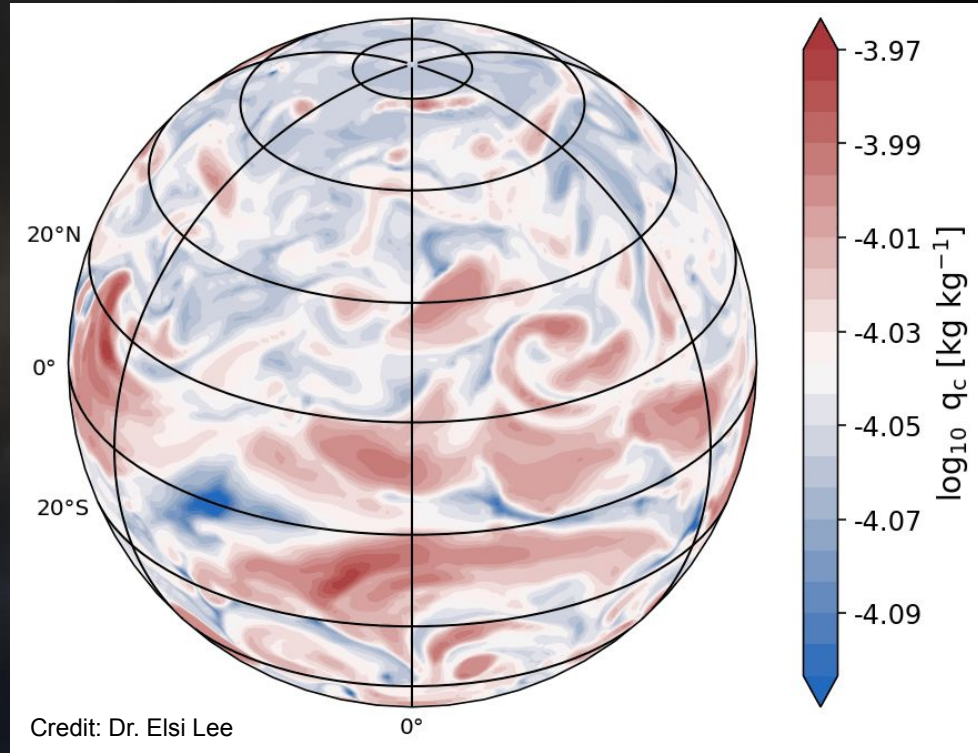
What Comes Next?

1. **Solving the silicon conundrum:**
How do small Si-O particles reach high altitudes?



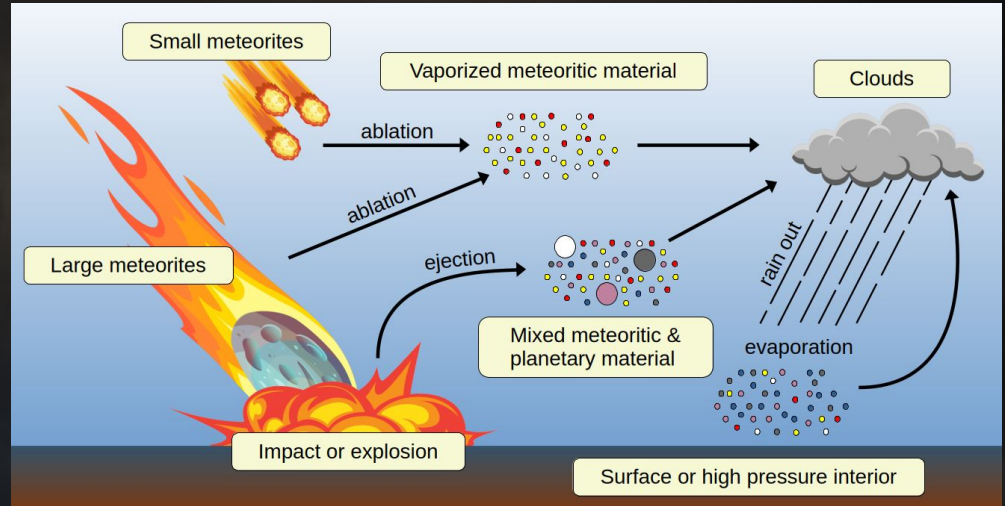
What Comes Next?

1. **Solving the silicon conundrum:**
How do small Si-O particles reach high altitudes?
2. **From climate to weather:**
How do clouds drive the variability of exoplanet atmospheres?



What Comes Next?

1. **Solving the silicon conundrum:**
How do small Si-O particles reach high altitudes?
2. **From climate to weather:**
How do clouds drive the variability of exoplanet atmospheres?
3. **Meteorites on Exoplanets:**
Cloud formation from meteoritic mass flux and catastrophic events



What Comes Next?

Extremely Large Telescope



Habitable Worlds Observatory

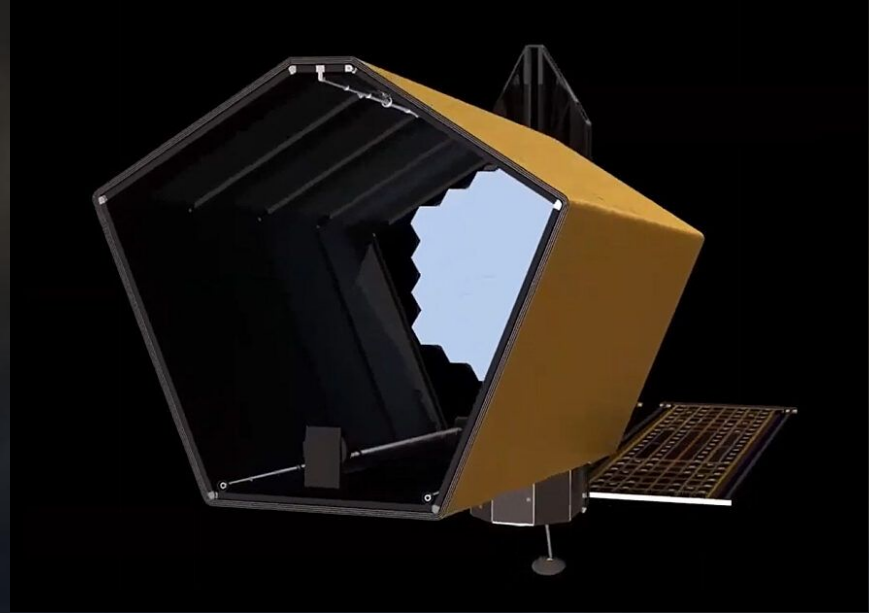


Image Credit: ESA // NASA

Summary



Contact me!
kiefersv.github.io
sven.kiefer@utexas.edu



Cloud and Aerosol formation is complex

- Clouds can be heterogeneous
- Growth through surface reactions

Cloud, Climate, and Chemistry are connected

- Feedback between all three
- Clouds and Hazes are connected

Spectra of Exoplanets are sensitive to cloud physics

- Si-O feature determines materials
- Width of panchromatic spectra allows insights into cloud height

