Aggregate Hazes in Exoplanet Atmospheres

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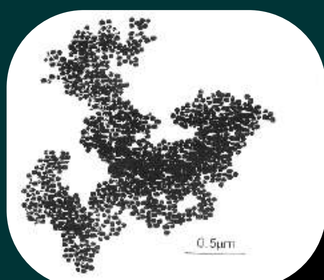
Introduction

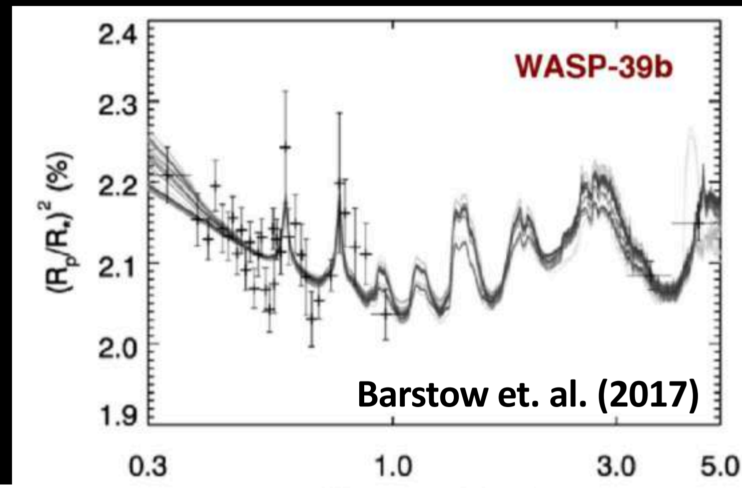
- Several exoplanet transmission spectra display scattering slopes & weak molecular features

→ Clouds? Hazes?

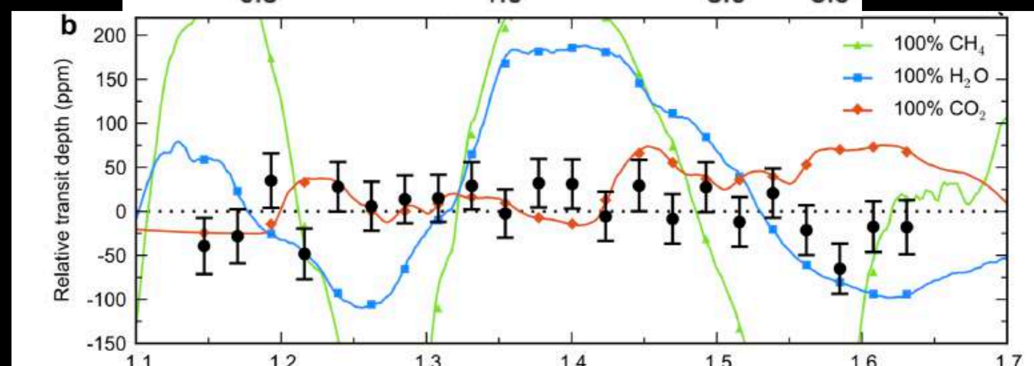
- Photochemical, hydrocarbon hazes are present in the solar system
- Some hazes are composed of aggregates:

$$N = \left(\frac{R}{r_m}\right)^{D_f}$$





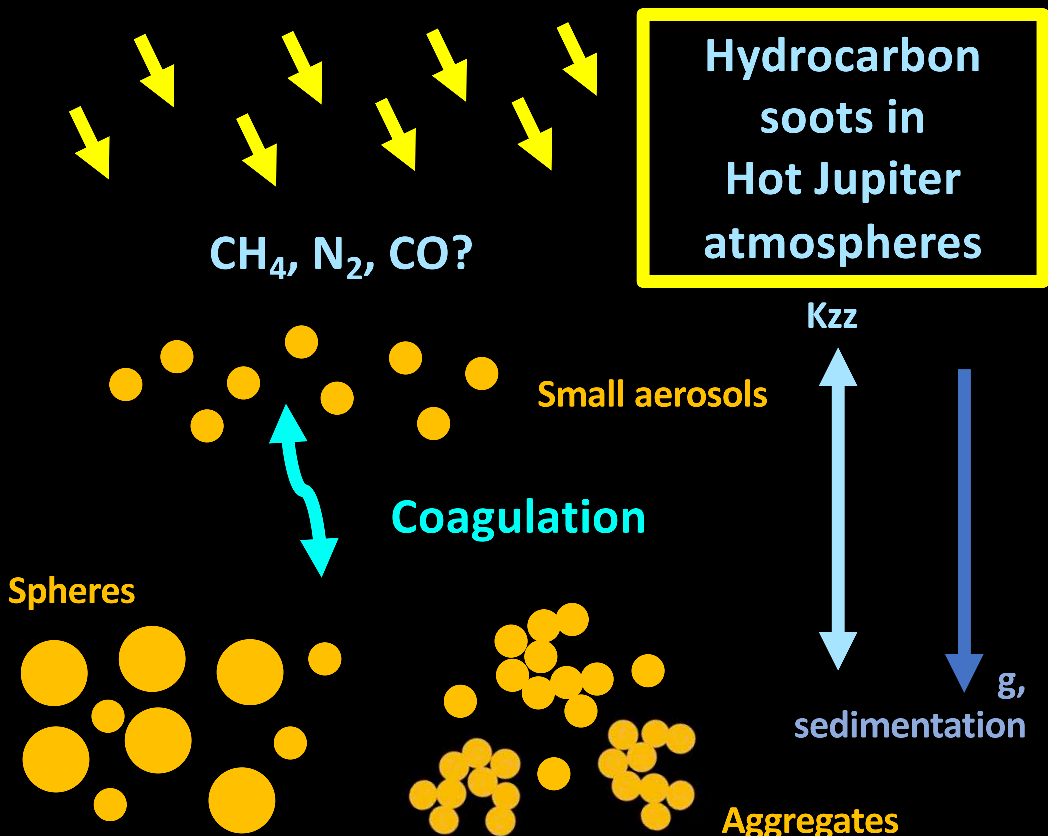
Barstow et. al. (2017)



GJ 1214b

Kreidberg et. al. (2014)

Methodology



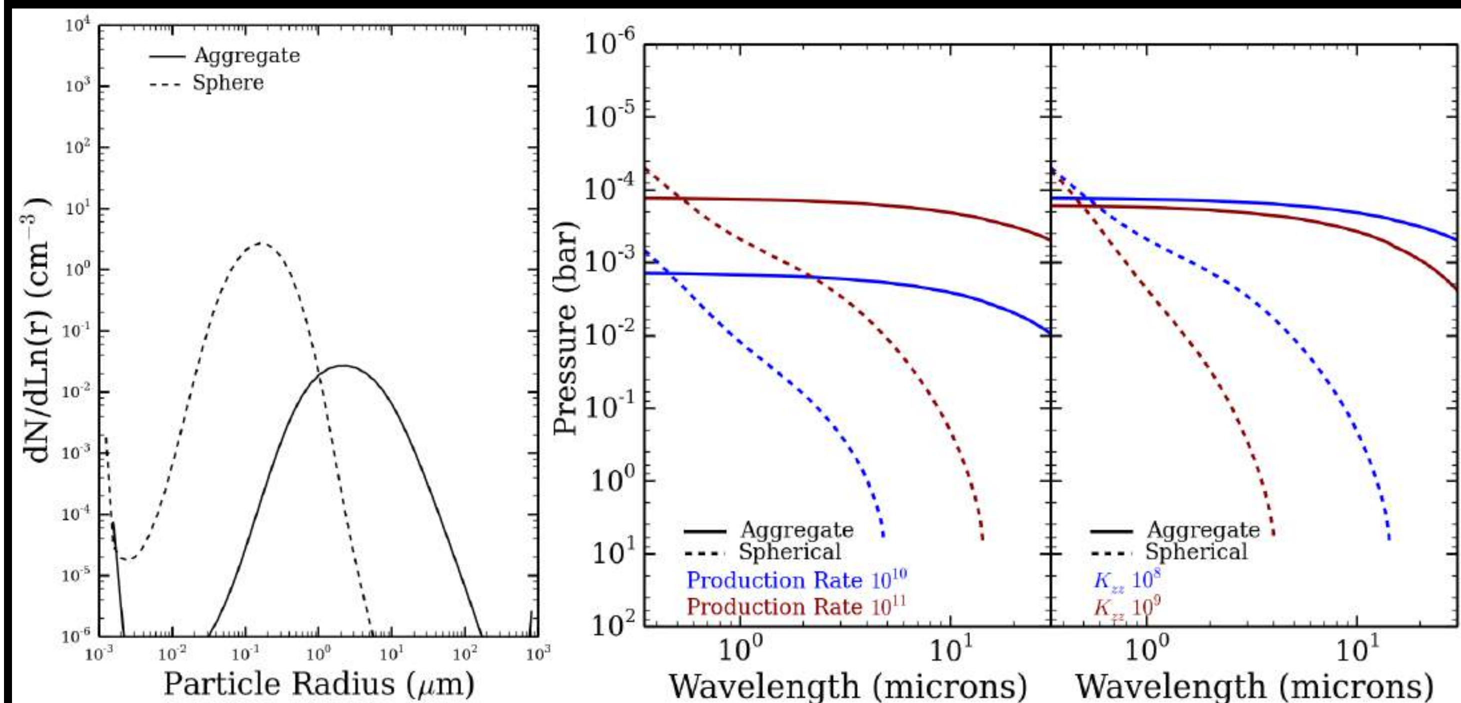
We ask:

- How does particle shape (spherical vs. aggregate) affect haze opacity? Spectral features?

- How do these hazes respond when varying:
  - Production rate
  - Eddy diffusivity

- Do spherical or aggregate hazes fit GJ 1214b observations better?

Results: Haze Opacity

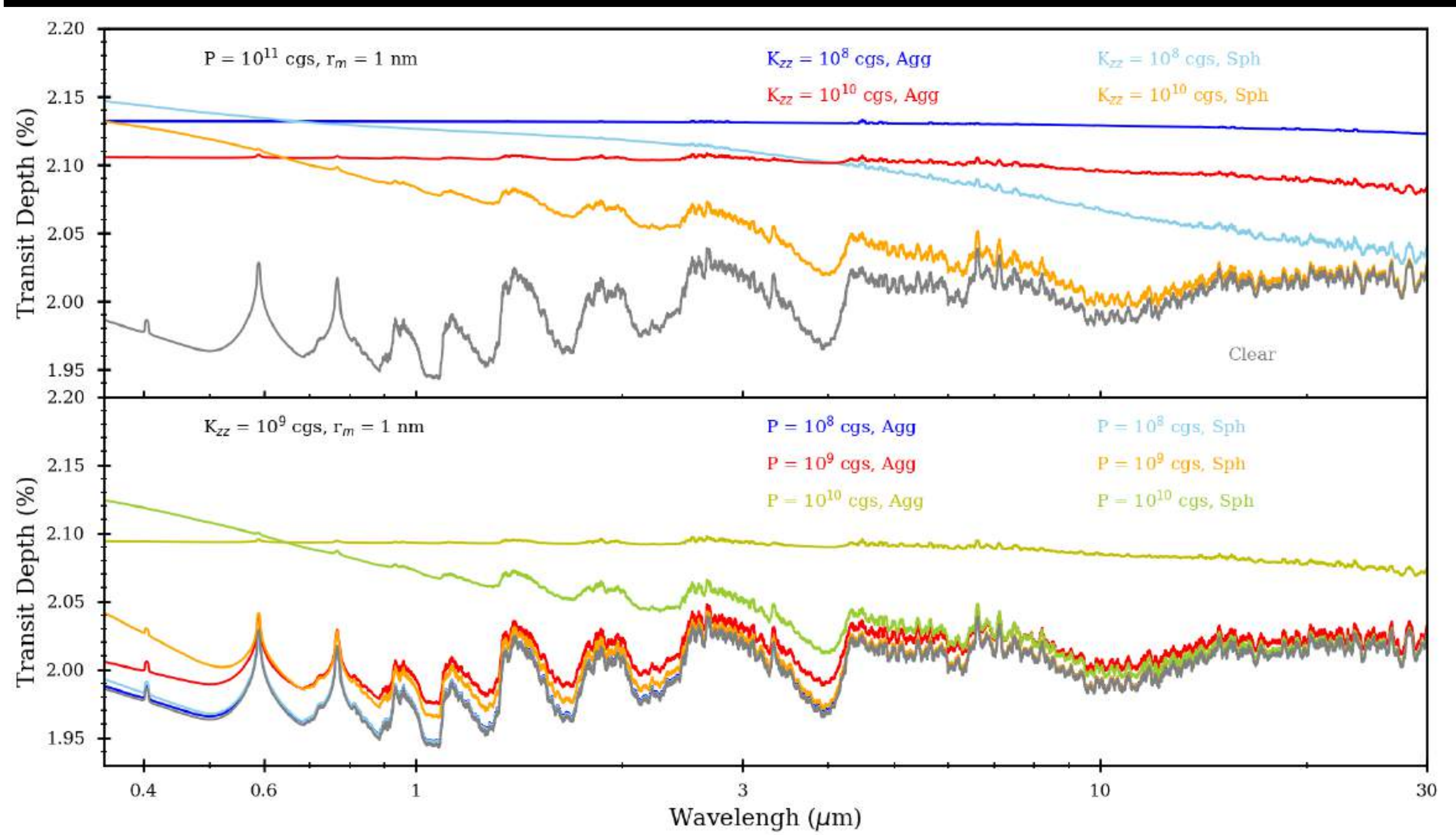


Interpretation:

- **Aggregates grow to larger sizes than spheres**
- **Aggregate hazes are more optically thick (especially at long wavelengths)**
- Increased **production rate** increases collision frequency
- Increased **Kzz** results in less time for coagulation

At 2.8 mbar, about half of the total atmospheric depth

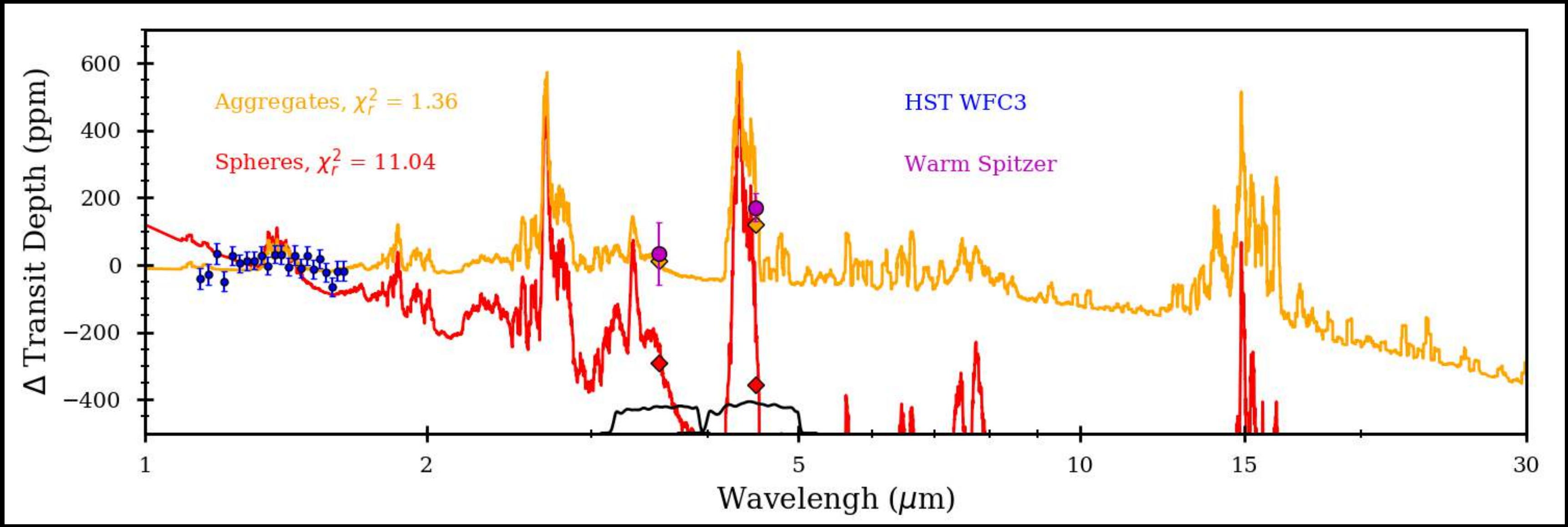
Results: Synthetic Spectra



Aggregate hazes produce flatter spectra than spherical hazes

Small changes in **poorly constrained parameters** can produce significant effects on spectra.

Application to GJ 1214b



Interpretation:

- **The flat spectra produced by aggregate hazes are a better fit to Spitzer and HST observations than the sloped spectra of spherical hazes.**

Summary

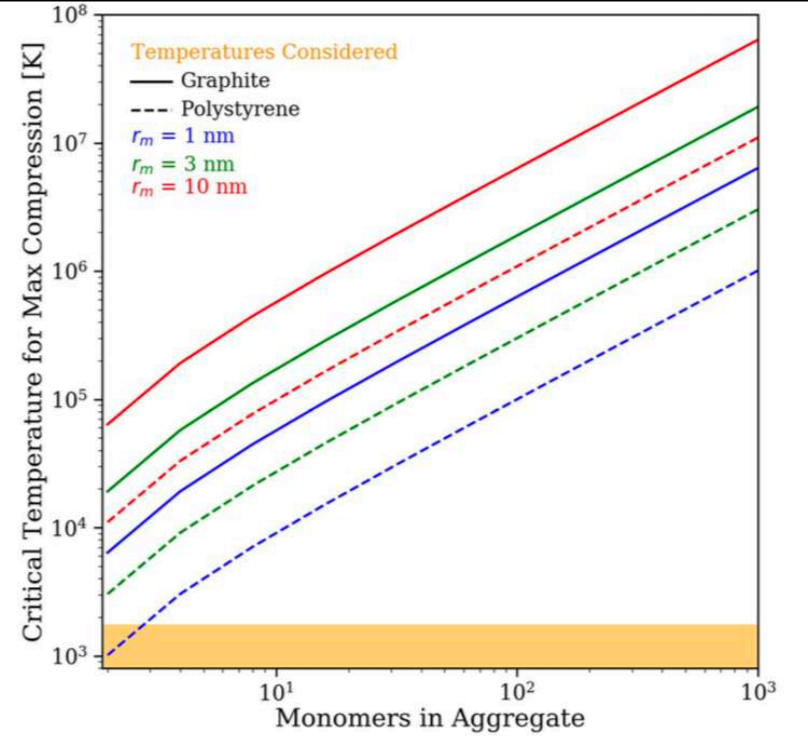
- This was the **first study** to consider the microphysics of **aggregate hazes** at exoplanets
- **Aggregate** haze particles grow to **larger sizes**, are **more optically thick**, and produce **flatter spectra** than spherical hazes.
- The flat spectra produced by aggregate hazes **fit GJ 1214b** spectral observations better than spherical hazes.
- Synthetic spectra are **sensitive to small** changes in **poorly constrained** parameters (production rate, eddy diffusivity)

Back-up Slides: Haze Survival

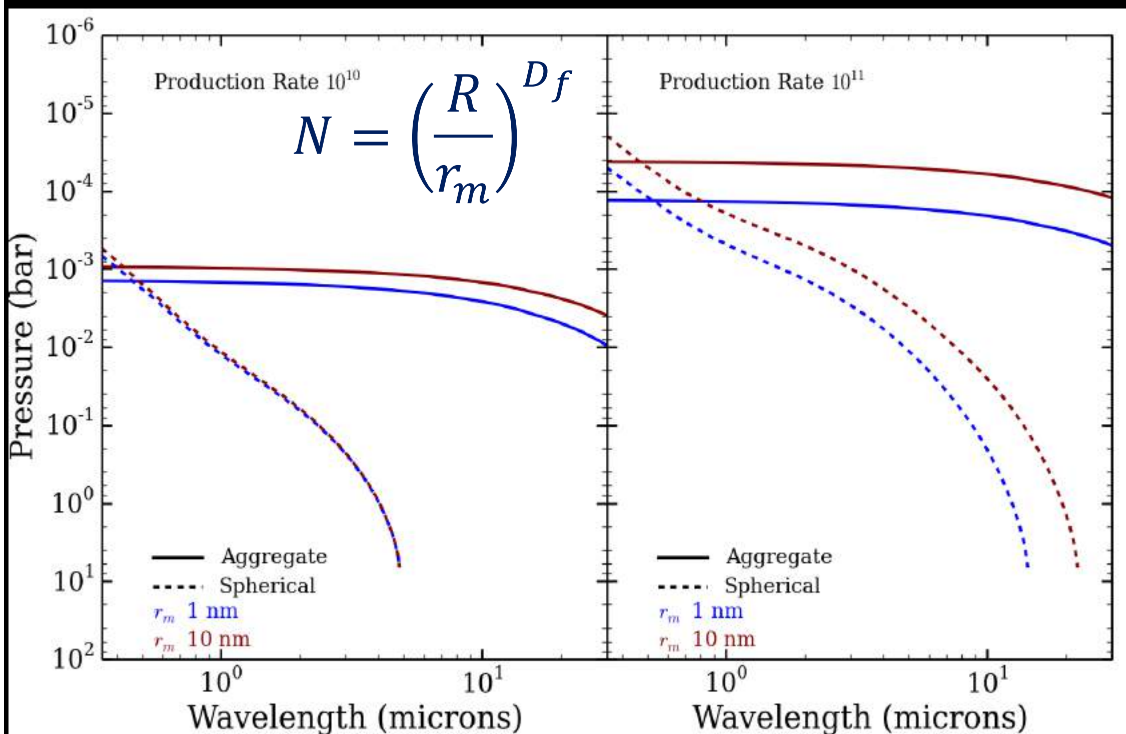
Compare effective collisional energies to critical energies for aggregate restructuring computed in Dominik & Tielens (1997).

$$E_{eff} = \frac{1}{2} M v_{col}^2 \qquad v_{col} = \sqrt{\frac{8kT}{\pi M}}$$

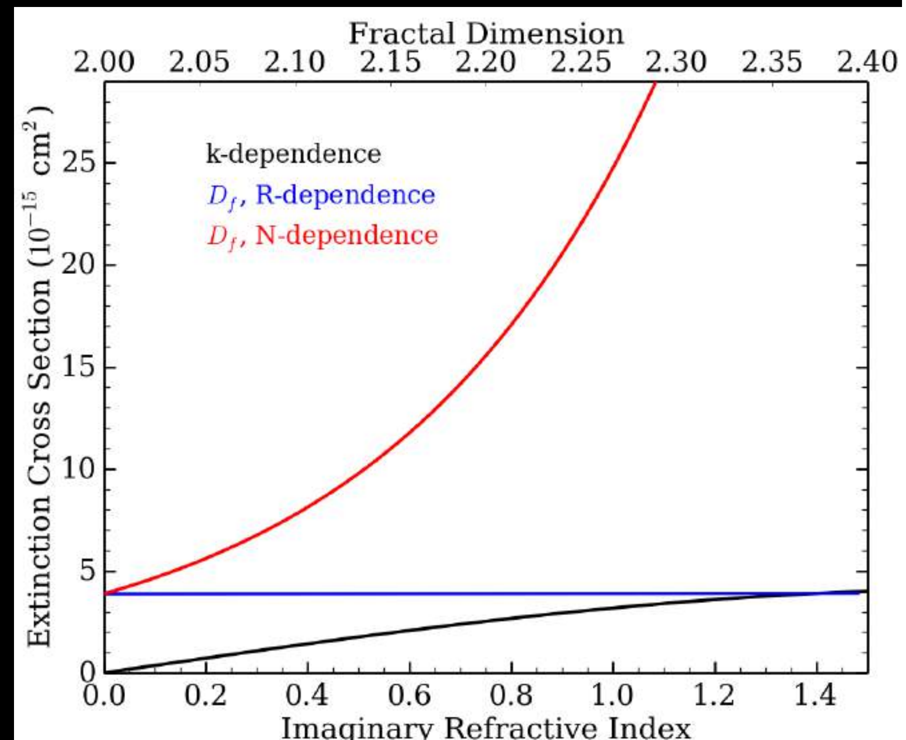
	Critical energy	$r_m = 1$ nm	$r_m = 3$ nm	$r_m = 10$ nm
sticking without visible restructuring	$E_{eff} < 5E_{roll}$	$T_G = 31850\ K$ $T_P = 5050\ K$	$T_G = 99560\ K$ $T_P = 15150\ K$	$T_G = 318530\ K$ $T_P = 50480\ K$
losing monomers upon collision	$E_{eff} > 3n_c E_{break}$	$T_G = 12520\ K$ $T_P = 1070\ K$	$T_G = 54170\ K$ $T_P = 4610\ K$	$T_G = 269750\ K$ $T_P = 22960\ K$
maximum compression	$E_{eff} = 1n_c E_{roll}$	$T_G = 6371\ K$ $T_P = 1010\ K$	$T_G = 19112\ K$ $T_P = 3029\ K$	$T_G = 63706\ K$ $T_P = 10997\ K$
catastrophic destruction	$E_{eff} > 10n_c E_{break}$	$T_G = 41740\ K$ $T_P = 3550\ K$	$T_G = 180580\ K$ $T_P = 15370\ K$	$T_G = 899160\ K$ $T_P = 76530\ K$



Back-up Slides: Monomer Radius



$$N = \left(\frac{R}{r_m}\right)^{D_f}$$



Back-up Slides: P & Kzz

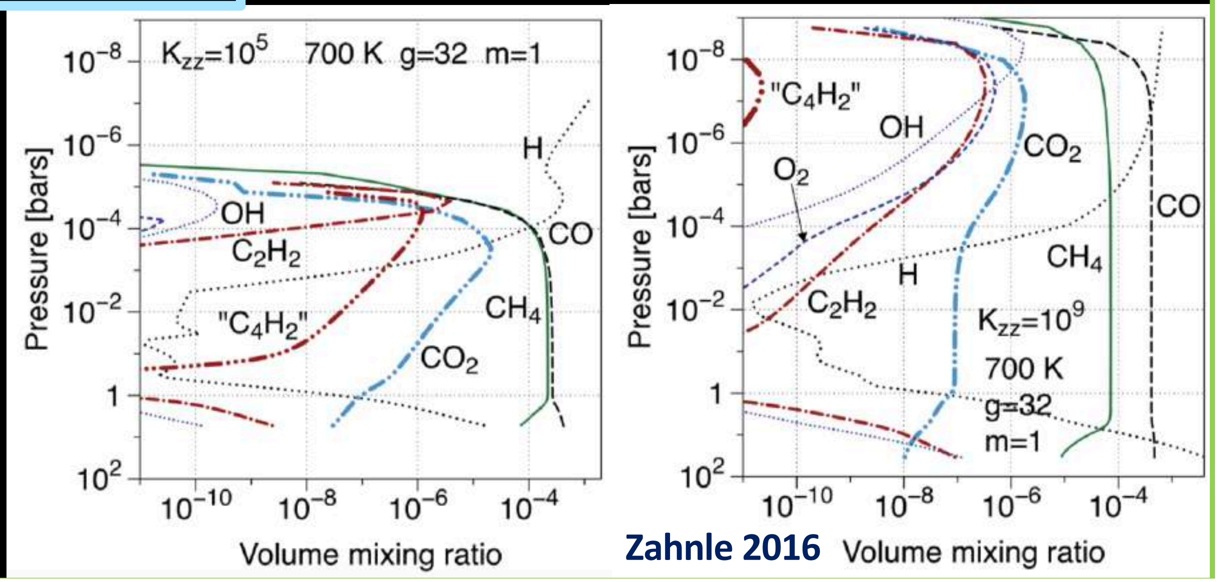
Lavvas 2017:

Decrease Kzz, decrease or constant CH4

Planet/Production:	Kzz	0.1 x Kzz	0.01 x Kzz
HD 209458b / CH4:	1.1e-22	7.5e-25	4.7e-25
HD 189733b / CH4:	8.1e-14	7.1e-17	1.9e-18

Zahnle 2016:

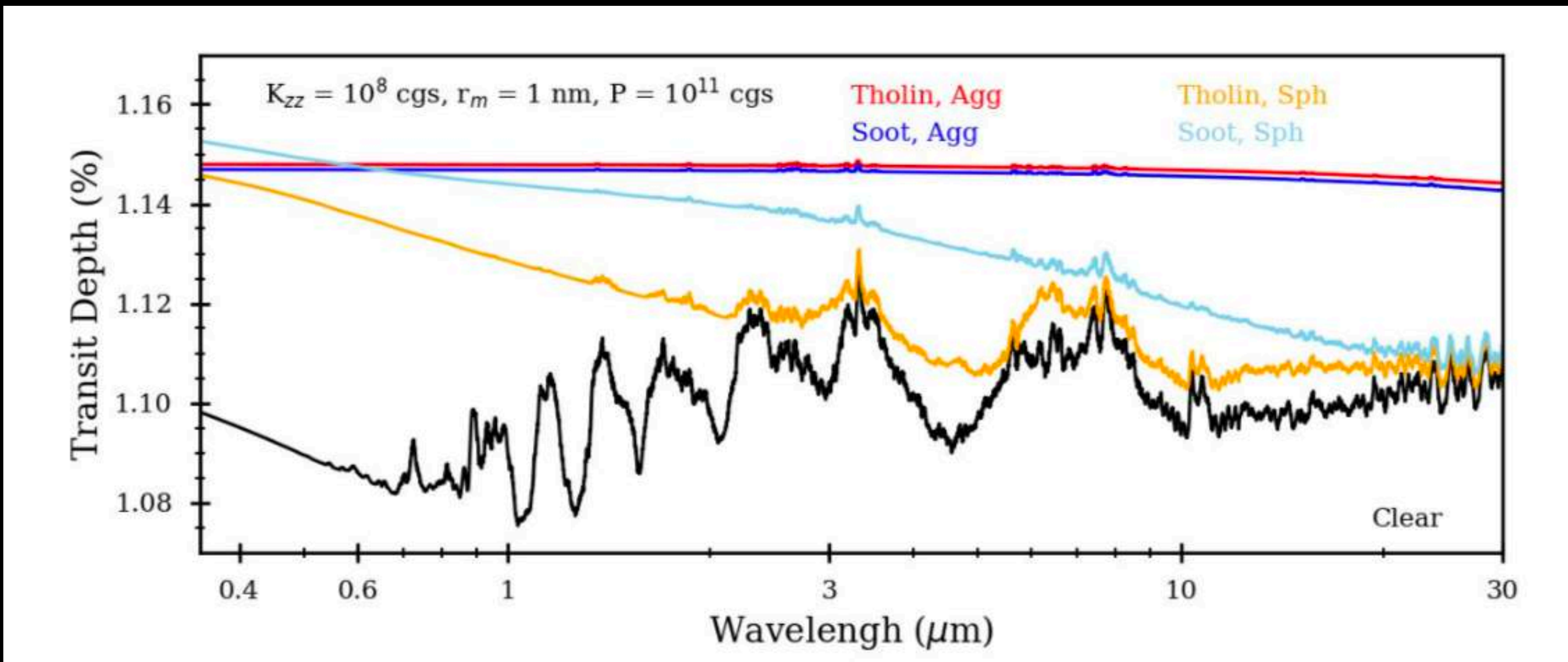
DECREASE Kzz, INCREASE CH4



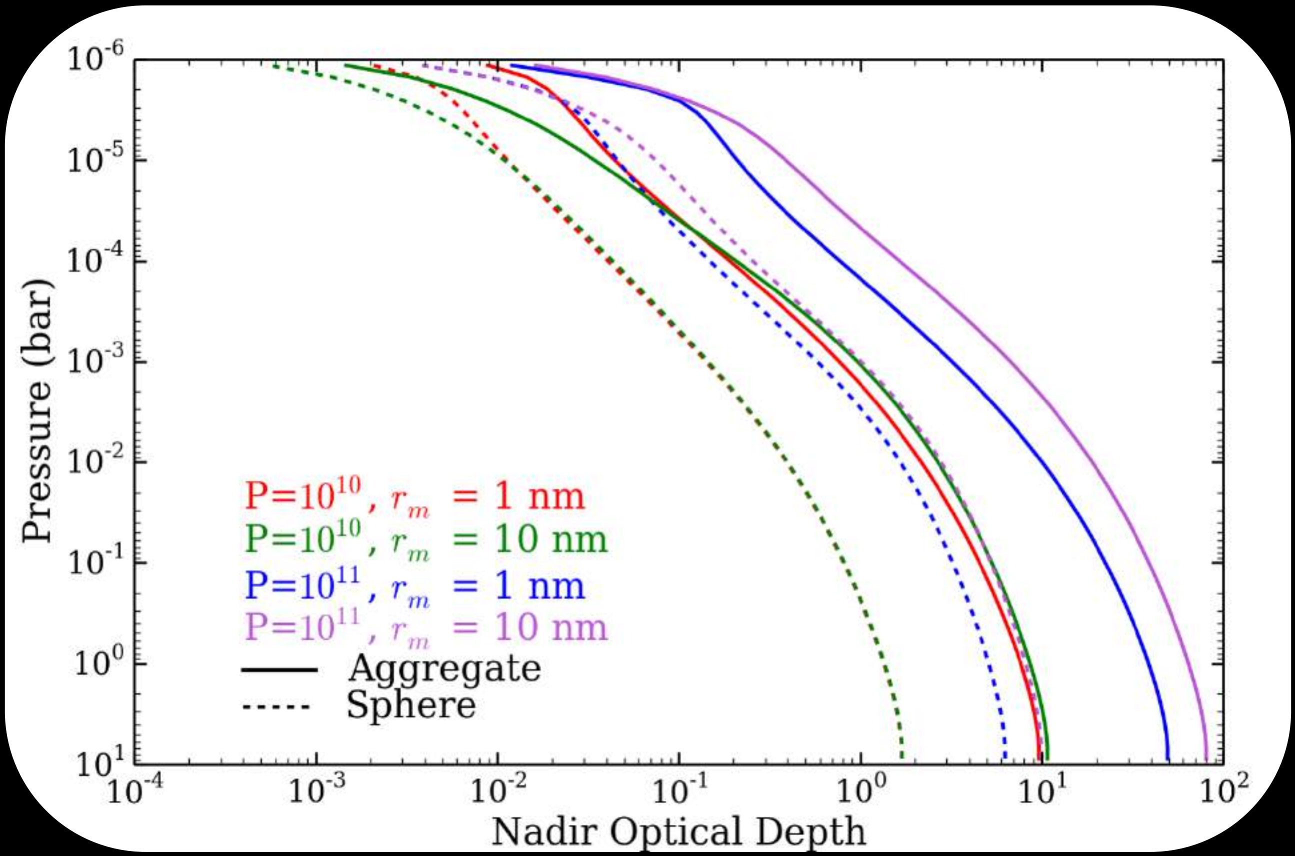
SO:

- Kzz and Production Rate are not independent
- Their dependence is complex

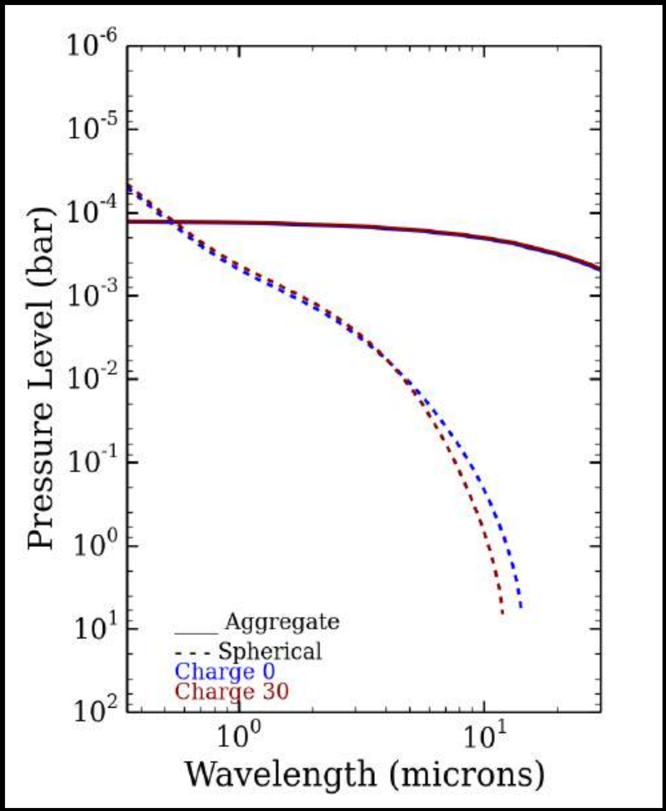
Back Up Slides: Tholin



Back Up Slides: Effect of Monomer Radius



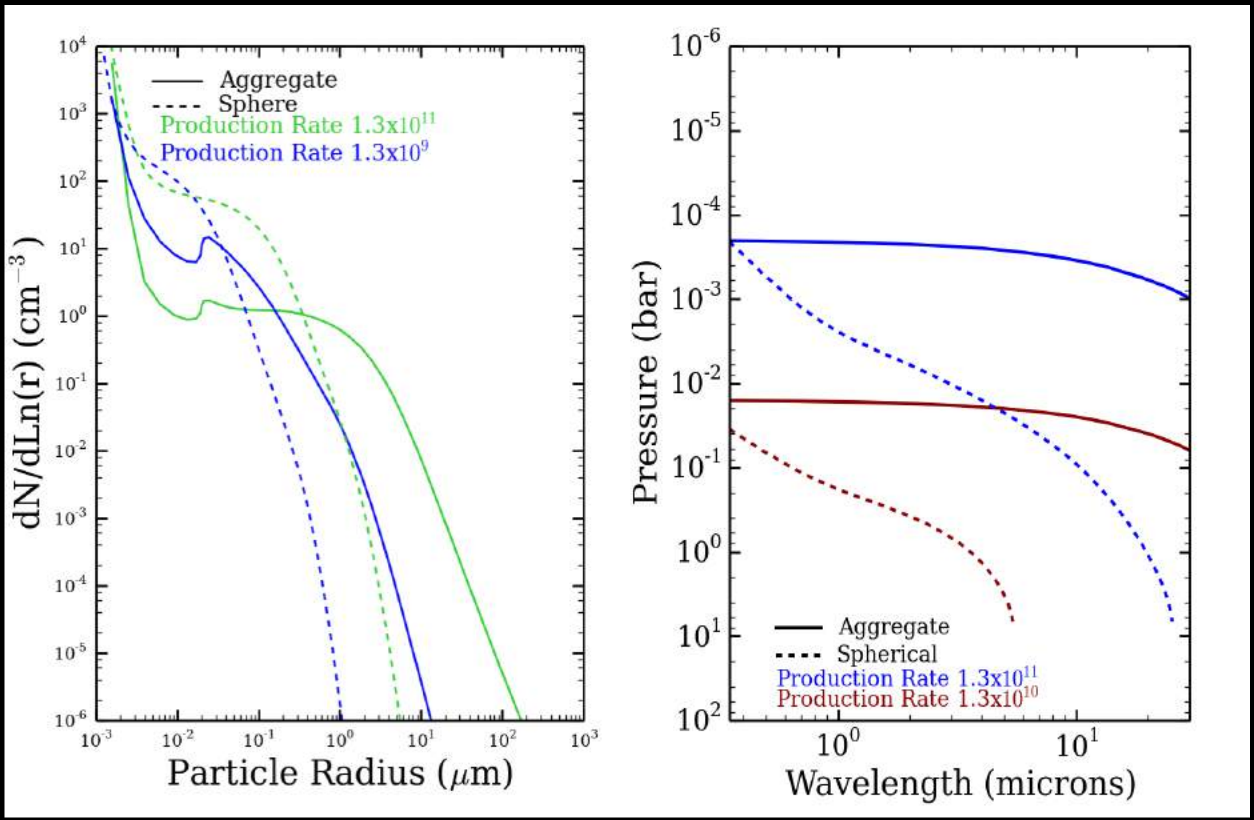
Back-up Slides: Charge



Spherical hazes: charge affects particle growth

Aggregate hazes: The coagulation rate is sufficiently fast that charge effects become negligible.

Backup: Step-wise Application to GJ 1214b



Interpretation:

- **Aggregates grow to larger sizes than spheres**
- **Aggregate hazes are more optically thick (especially at long wavelengths)**
- Depth of $\tau = 1$ responds significantly to an increased **production rate**

Backup: Model

- 1-D Community Aerosol and Radiation Model for Atmospheres

$$\frac{\partial n_p}{\partial t} = \frac{1}{2}\sum_{i=1}^{i=p-1} K_{i,p-i} n_i n_{p-i} - n_p \sum_{i=1}^{i=N} K_{i,p} n_i - \frac{1}{z^2}\frac{\partial (z^2 \Phi)}{\partial z} + \delta_{p,1}\delta_{z,z_{top}} P$$

Increase n_p via coagulation of smaller particles

Decrease n_p via coagulation into larger particles

Vertical transport

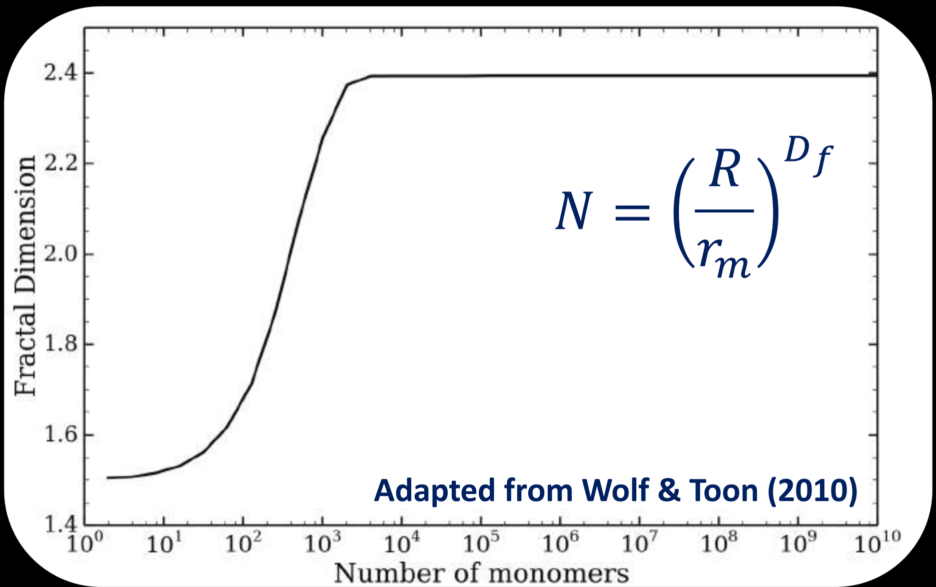
Haze production (only at 1 microbar)

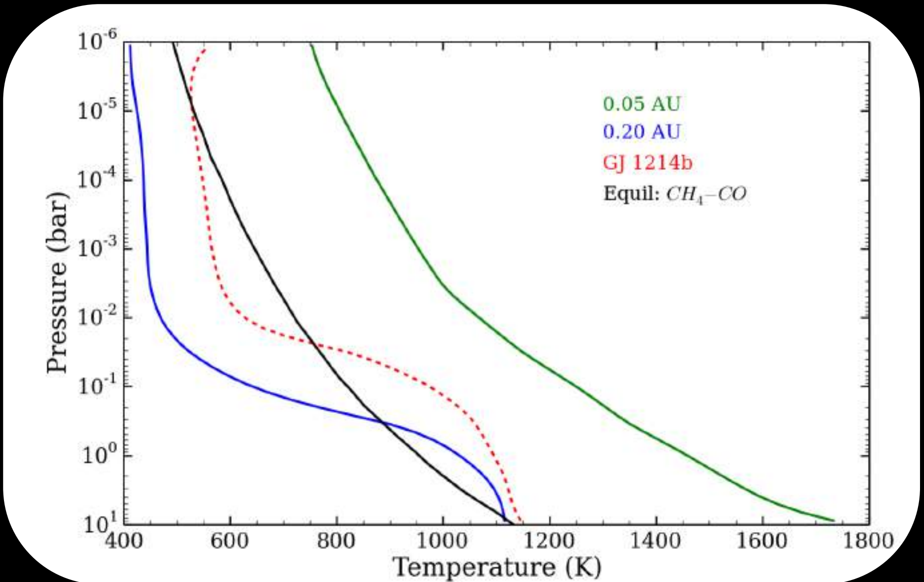
Particle flux: $\mathbf{\Phi = -w_{sed} n - K_{zz} n \frac{\partial (n(v_p)/n}{\partial z}}$

- Optical Properties (Grainger et. al., 2004; Rannou et. al., 1997)

$$\tau_{nadir,z}(\lambda, z) = \sum_{i=1}^{z} Q_e(\lambda, i) n_p \pi r_p^2$$

Backup: Methodology





First to consider the microphysics of aggregates at exoplanets.

Two T-P profiles at 0.05 and 0.20 AU:

1x solar metallicity
1D Radiative-Convective Model
(e.g., McKay 1989)

GJ 1214b: 100x solar metallicity