Mineral Snowflakes: Cloud formation on Exoplanets and Brown Dwarfs

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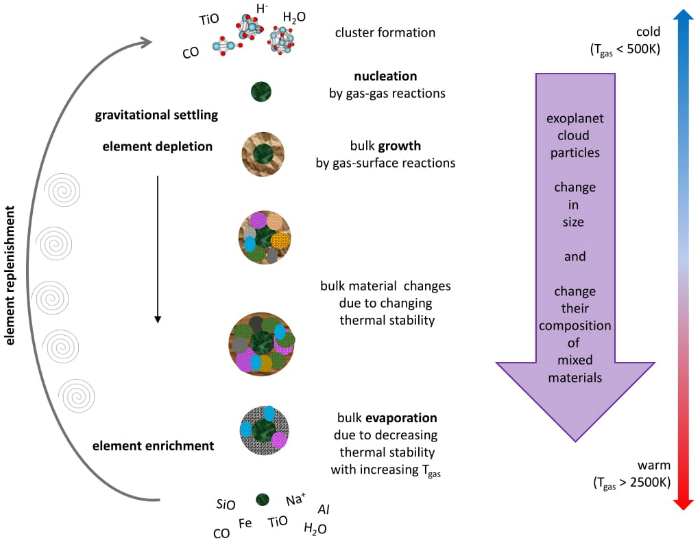
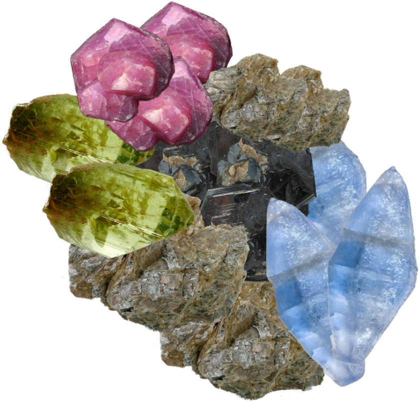
Cloud formation theory



Taken from Helling (2018)

Making cloud particles more realistic

Model: Compact, Spherical



Reality: Non-Compact, Non-Spherical

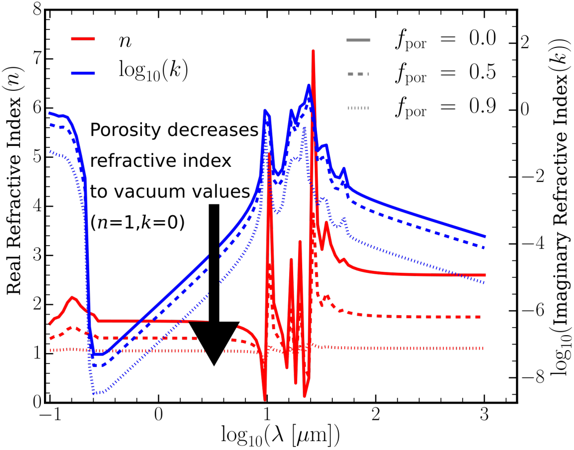
Micro-porous 'Mineral Snowflakes'

- Introduce f_{por} varying between $0 - 1$, hence

$$\rho_{\text{s}}^{\text{eff}} = \rho_{\text{s}}\,(1 - f_{\text{por}})$$

- Optical effects included using effective medium theory with the Bruggeman mixing rule (Bruggeman, 1935)

Samra et al. (2020)



Refractive indices of Mg_2SiO_4 with micro-porosity

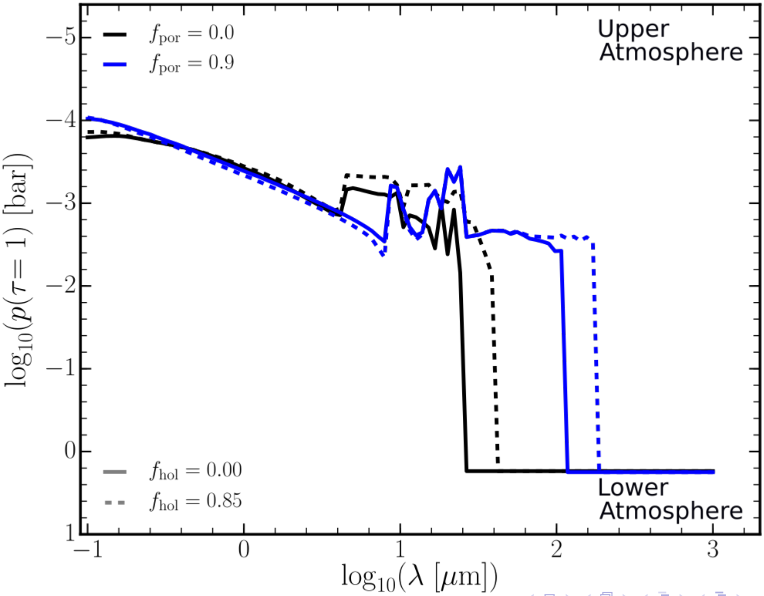
Particle shape by distribution of hollow spheres

- Averaging over statistical distribution represents particle shape (Min et al., 2008)
- Hollow spheres: material mantle + vacuum core defined by

$$f_{\mathrm{hol}} = \frac{a^3_{\mathrm{core}}}{a^3_{\mathrm{mant}}}$$

As f_{hol} increases so does radius, mantle volume is conserved

Optical depth of non-spherical, non-compact particles



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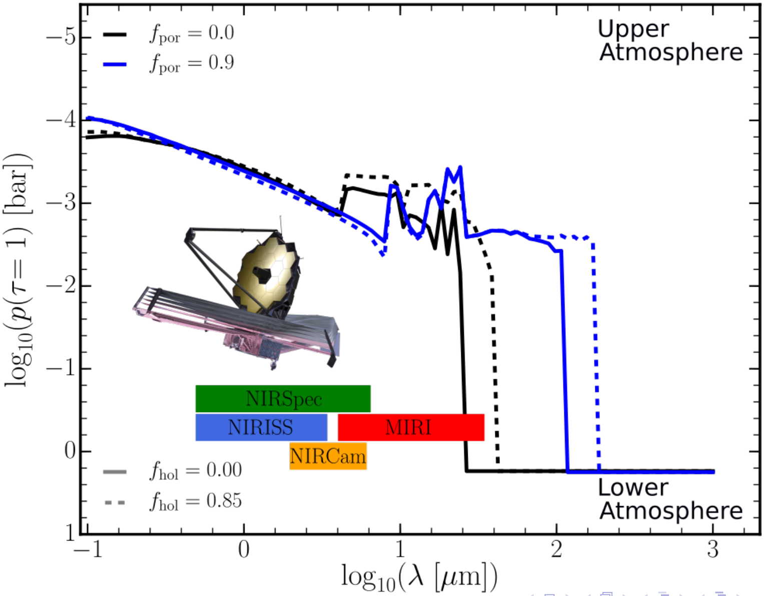
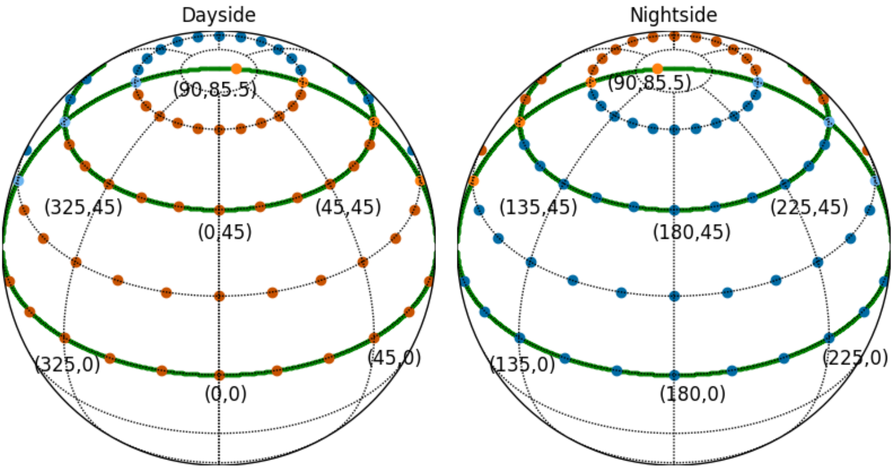
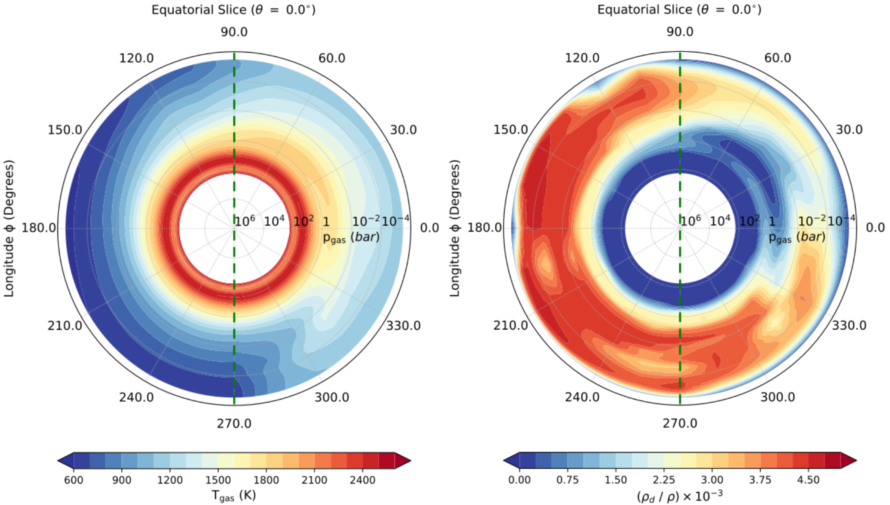


Global cloud distribution - Hierarchical approach



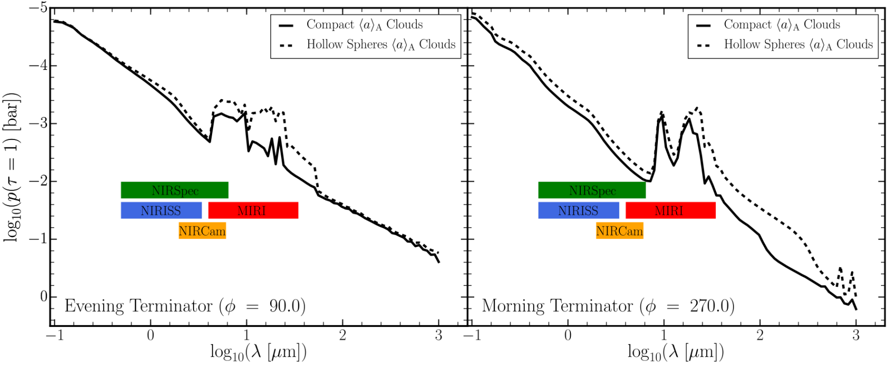
Use 1D $p_{\rm gas} - T_{\rm gas}$ profiles extracted from 3D GCM to model cloud formation
Helling et al. (2019, 2020)

Global cloud distribution (WASP-43b)



Adapted from figures in Helling et al. (2020)

Asymmetric Terminators (WASP-43b)



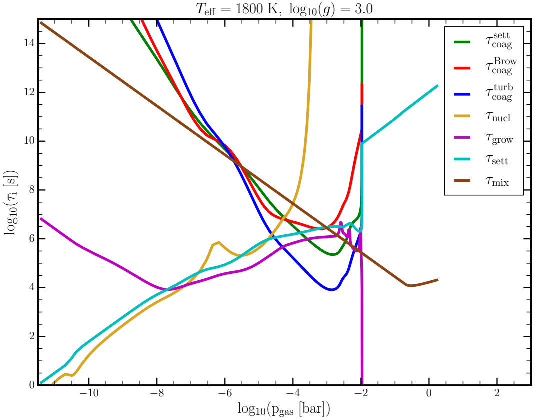
Adapted from figures in Helling et al. (2020)

Coagulation - Timescales

- Assume Monodisperse (all particles have size a)
- Define timescale based on relative velocities:

$$\tau_{\rm coag} = \frac{a\,\rho_{\rm s}}{\Delta v_{\rm coag}\,\rho_{\rm d}}$$

- Three sources of $\Delta v_{\rm coag}$:
    - Brownian motion (Brow)
    - Differential settling (sett)
    - Turbulence (turb)



Timescales for $T_{\rm eff} = 1800\,{\rm K}$, $\log_{10}(g\,[{\rm cms^{-2}}]) = 3.0$ atmosphere

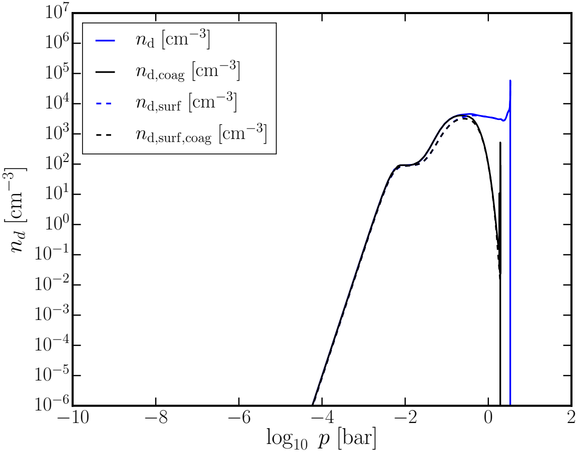
Coagulation - TwoPoppy

- Based on work done for protoplanetary disks (Birnstiel et al., 2012)
- Define double Dirac delta distribution where:

$$a_0 = const.$$

$$a_1 = a_0 \exp\left(\frac{t_{\mathrm{step}}}{\tau_{\mathrm{coag}}}\right)$$

- Second population has upper limit defined by drift and fragmentation



PRELIMINARY RESULTS
$T_{\mathrm{eff}} = 1200\,\mathrm{K},\ \log_{10}(g\,[\mathrm{cms}^{-2}]) = 5.0$

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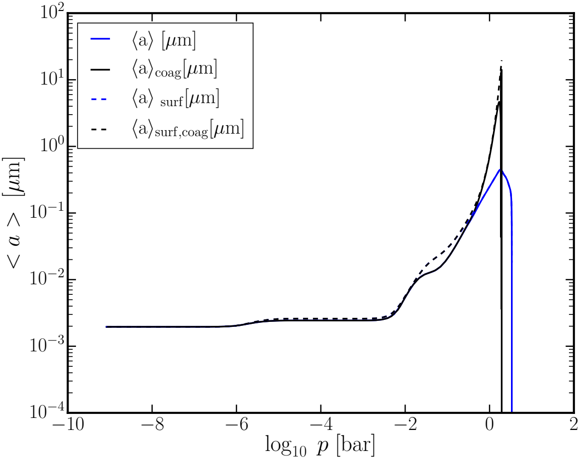

PRELIMINARY RESULTS
for $T_{\rm eff} = 1200\,\mathrm{K}$, $\log_{10}(g\,[\mathrm{cms}^{-2}]) = 5.0$

Conclusion

- Micro-porosity and particle shape affect the optical depth of clouds for $\lambda > 10\,\mu\mathrm{m}$
- Asymmetric formation of cloud between the terminators
- Cloud particle micro-physics and global asymmetries in clouds will be observable by $\mathrm{JWST\ MIRI}$
- Coagulation occurs in the deep atmosphere of exoplanets due to low cloud particle densities

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