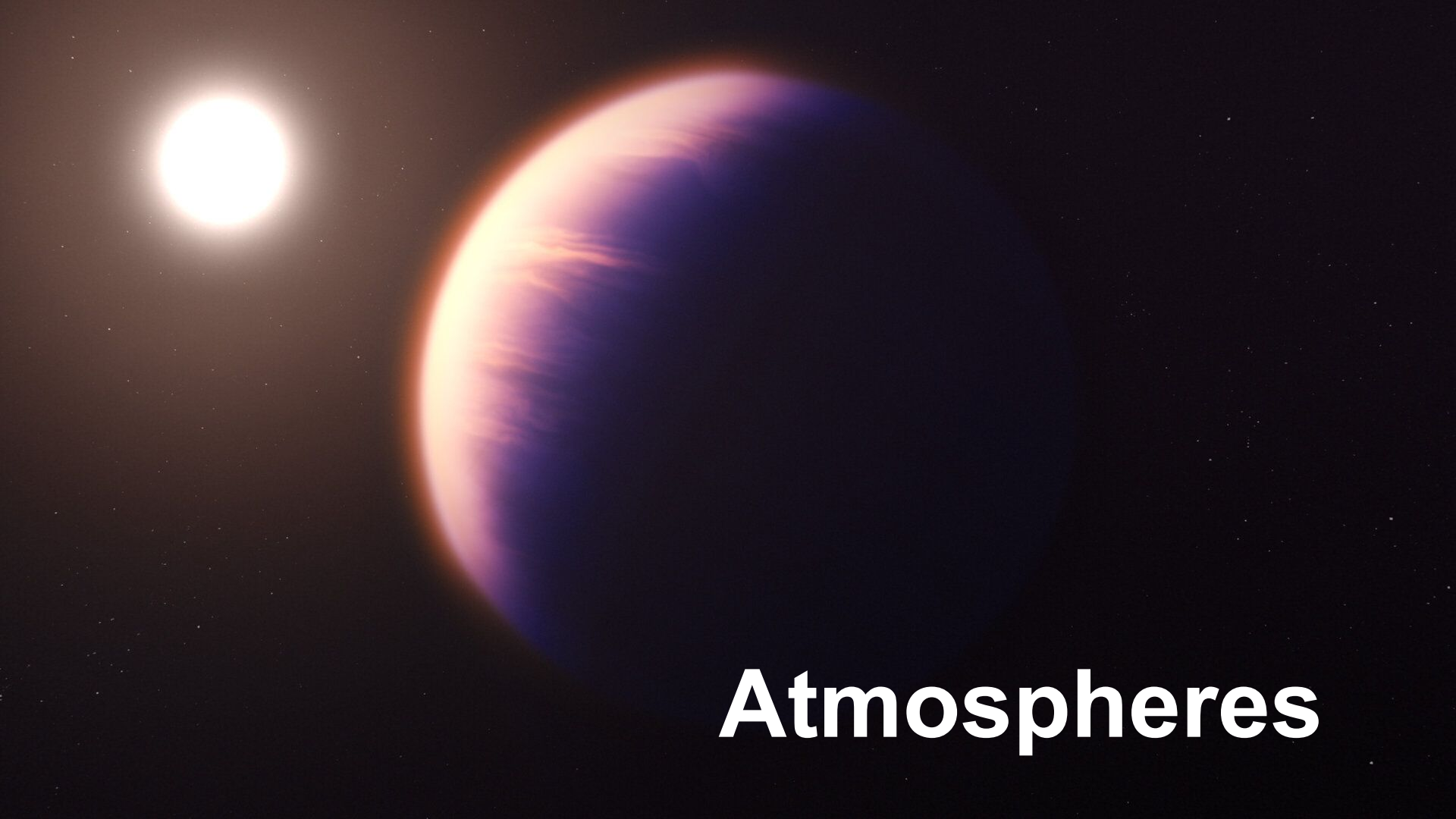
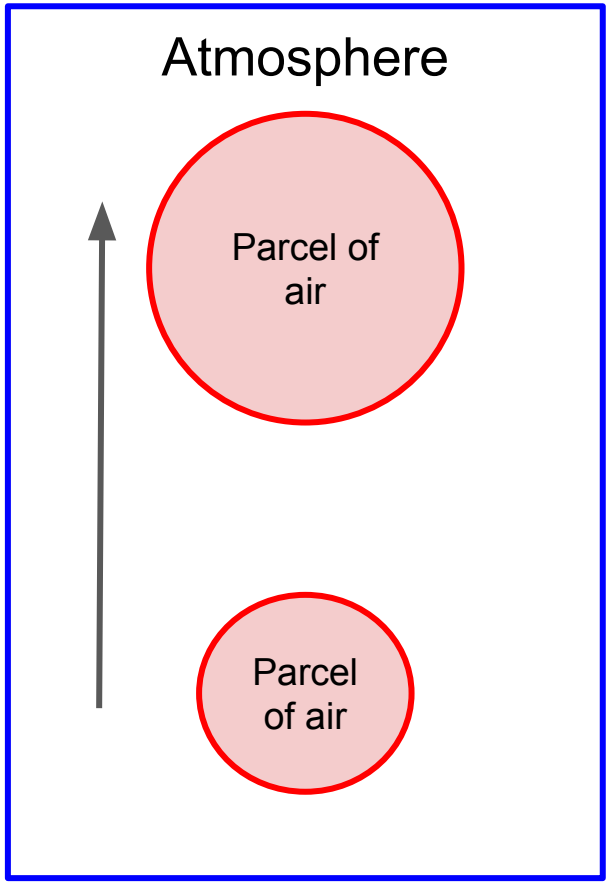

Atmospheres

Atmospheres Theory

- Global Energy Balance (temperature of a planet)
- Hydrostatic Equilibrium Atmosphere
- **Adiabatic Lapse Rate**
- Chemistry and Clouds Basics

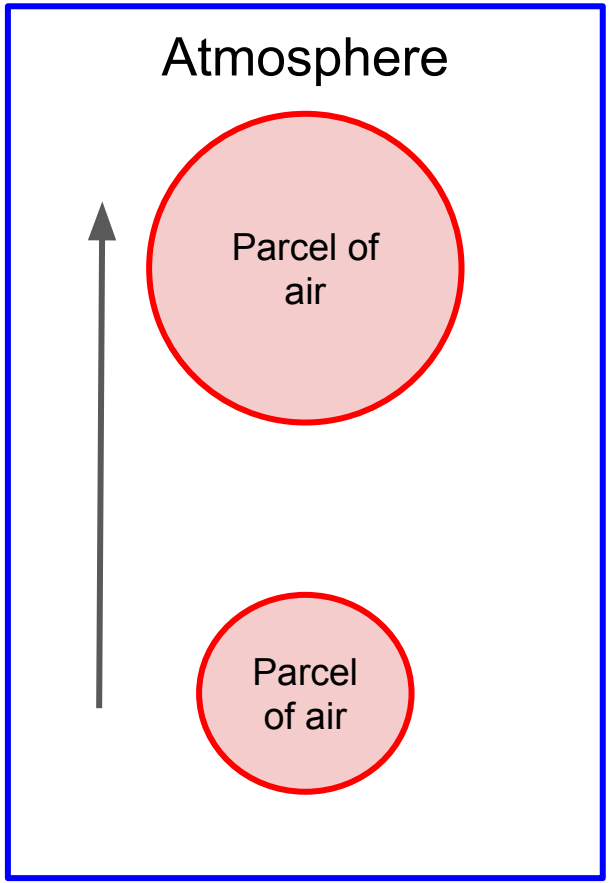
Adiabatic and Diabatic Processes

- **Adiabatic process (dQ = 0)**
  Process by which no energy is exchanged between a system (parcel of air) and its surroundings (atmosphere)
- **Diabatic process (dQ > 0 or dQ < 0)**
  - Condensation/evaporation
  - Deposition/sublimation
  - Freezing melting
  - Radiative heating/cooling



Adiabatic and Diabatic Processes

- Raising air parcel adjusts to the lower pressure and expands
- Ideal gas law:
  $p = nkT$
- If pressure goes down, temperature goes down
- Hotter air is less dense and rises!
  - If the air parcel is now **hotter** than its surrounding, it will **continue to rise**
  - If the air parcel is now **colder** than its surrounding, it will **fall back down**



Adiabatic and Diabatic Processes

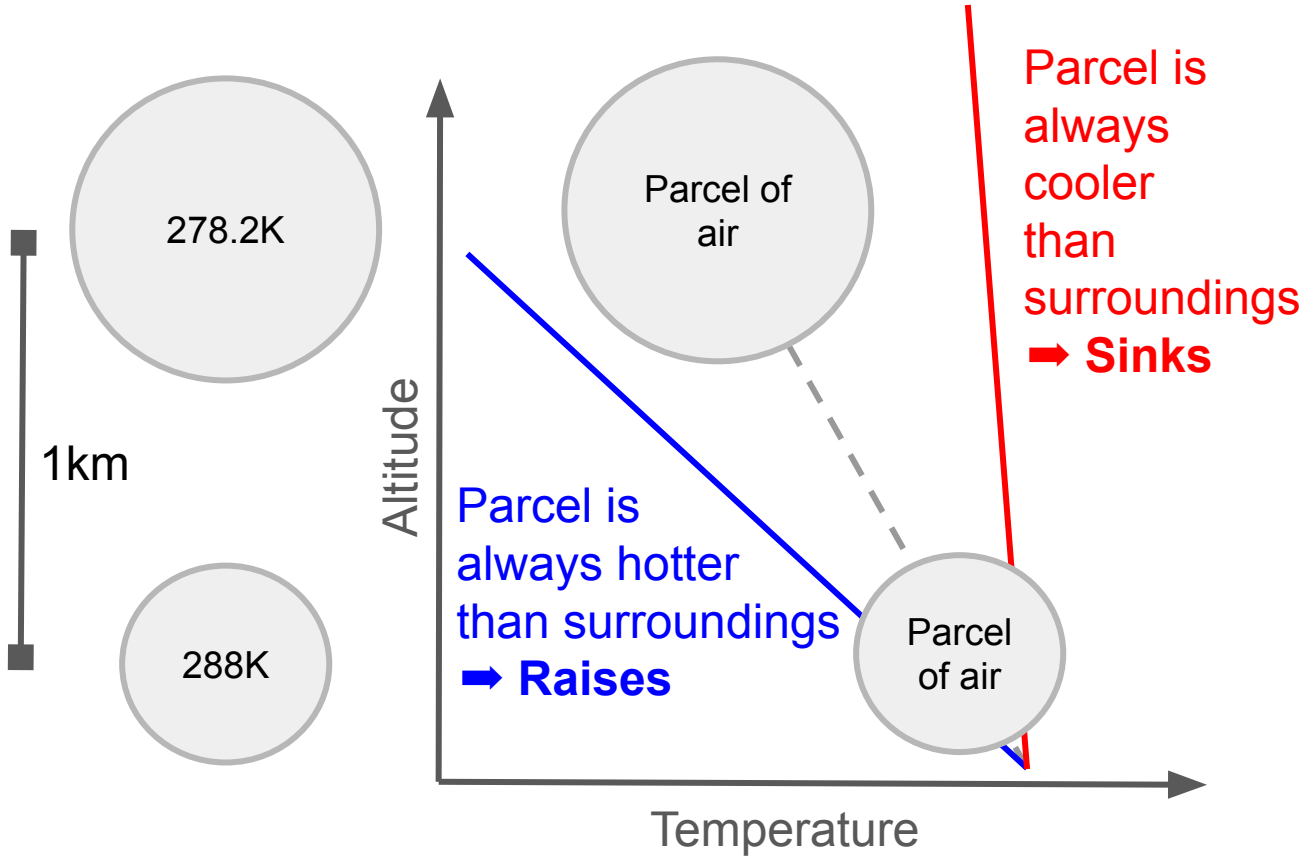
1) Rising air expands
2) Expansion leads to cooling

➡ Rising air cools

On Earth:

Unsaturated air cools 9.8 K per 1 km rise in altitude

➡ Dry adiabatic lapse rate Γd = 9.8 K/km

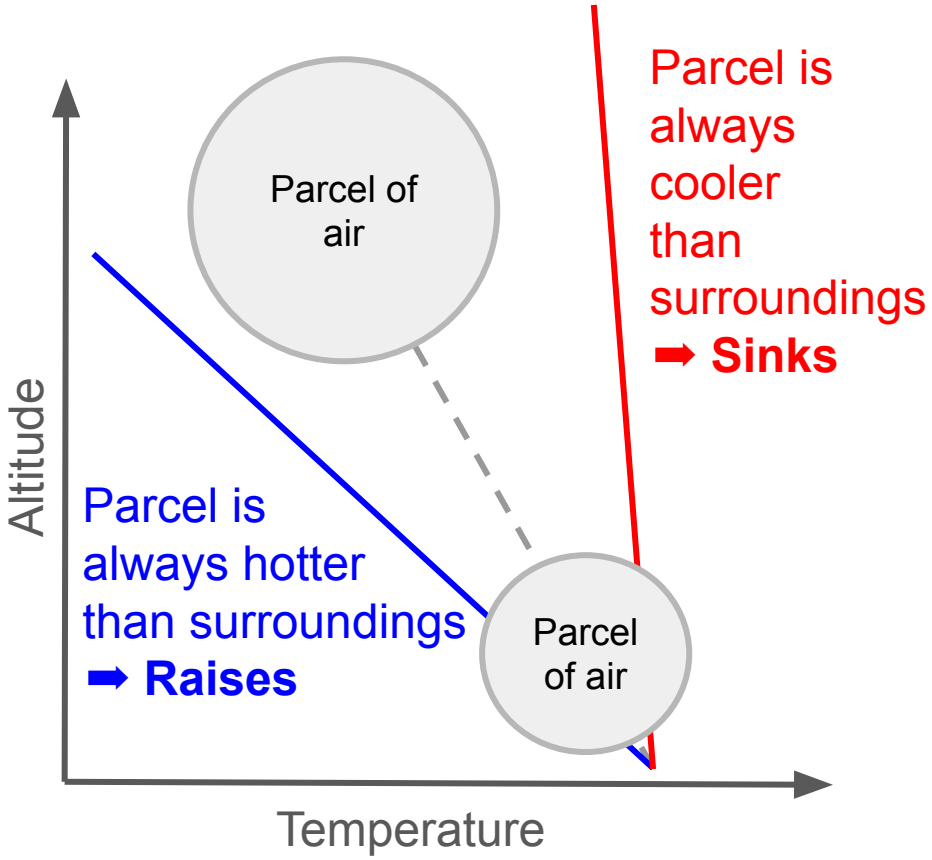


Adiabatic and Diabatic Processes

This is convection

As hot air rises it “releases” energy into it’s surrounds causing a heating at higher altitudes. As cool air sinks it “absorbs” energy from its surroundings and cools the deeper layers.

There exists a T-altitude profile such that the air neither rises or sinks



Adiabatic and Diabatic Processes

Important Concept

- IF the environmental temperature falls off more rapidly with altitude than this “critical” slope, then convection will seek to deliver warm blobs of air to “heat” the atmosphere above such that the environment approaches the critical rate
- IF the environmental temperature falls off less steeply than this “critical” slope, then the atmosphere is stable and the environment does not need to change
- How do we determine this “critical” slope/rate??

Derivation of the adiabatic lapse rate

Question what is dT / dz?

- Hydrostatic Equilibrium (HSE)
  dP / dz = - ϱ g

How are dP and dT related?

- First Law of Thermodynamic:
  dU = N cv dT & dW = P dV
  0 = dQ = dU + dW = cv dT + P dV
- Ideal gas: V P = N R T
  R = (cp - cv) / N
  V dP + P dV = N R dT = (cp - cv) dT
- First Law + Ideal gas
  dP = dT cp N / V

Some useful equations:

- Density: ϱ = N m / V
- Specific heat capacity: Cp = cp / m

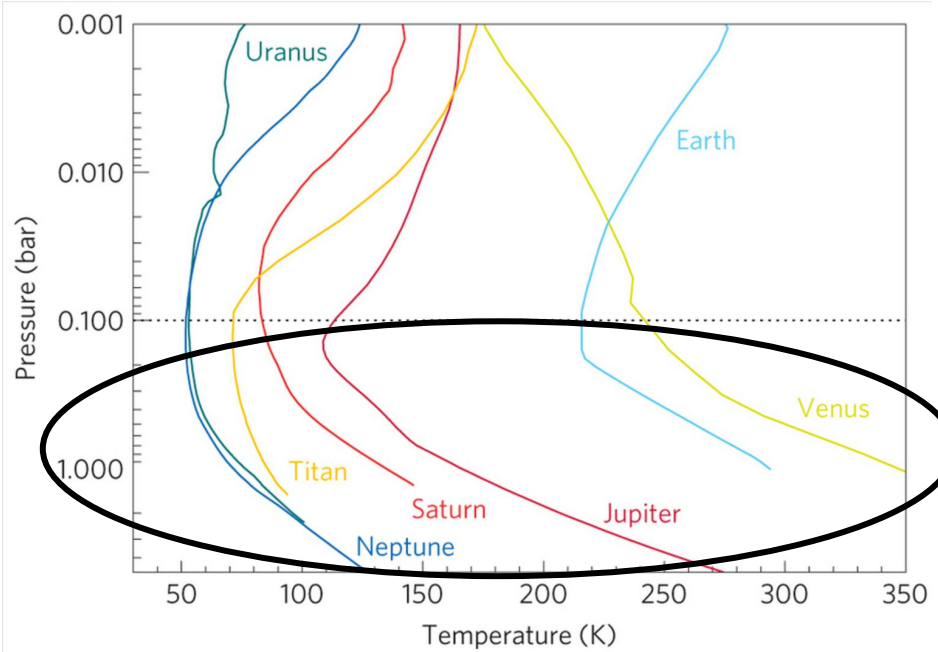
Let's put everything together

- cp N / V = ϱ Cp & dP = dT ϱ Cp
- **dT / dz = - g / Cp**

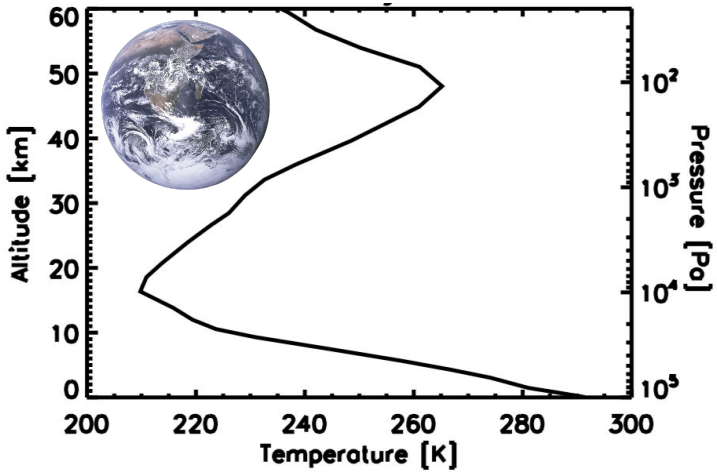
Important definitions:

- Specific heat at constant p: Cp
- Specific heat at constant V: Cv
- Adiabatic index: γ = Cp / Cv

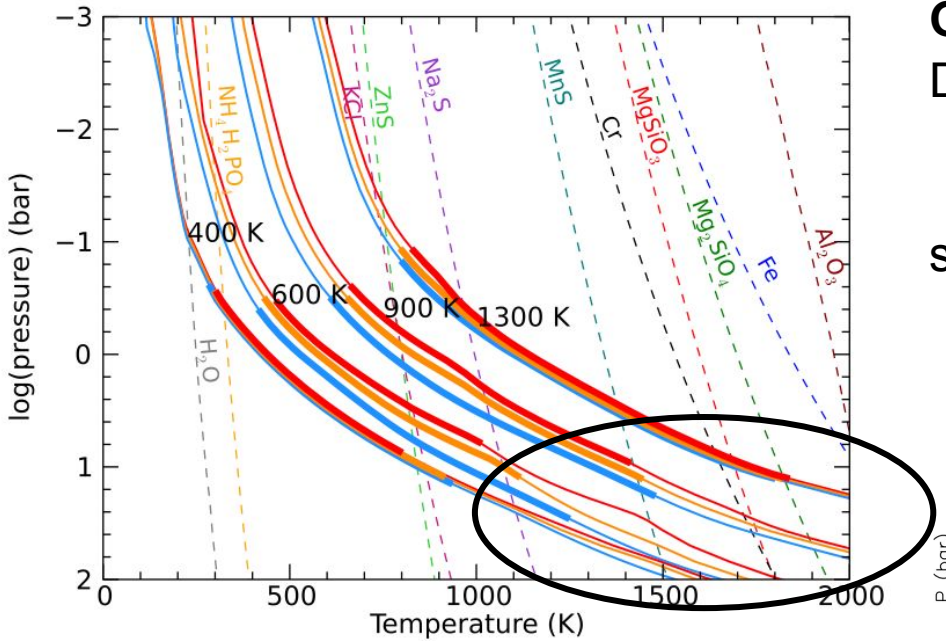
Thermal structure of Solar System atmospheres



- Earth has a steep deep T gradient because the surface is heated
- A temperature inversion leads to stability ➡ Tropopause



Exoplanets and Brown Dwarfs

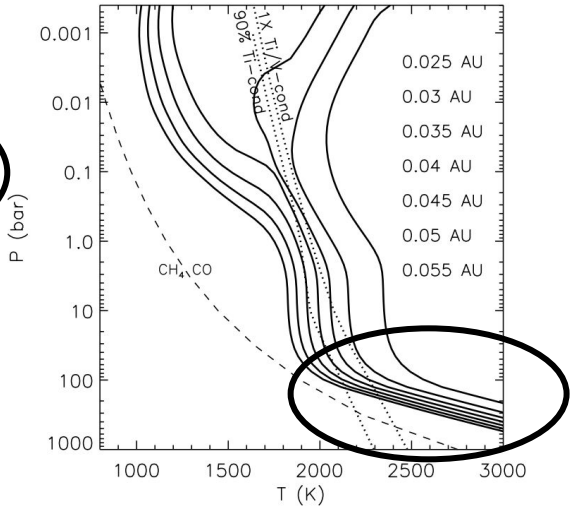


Gaseous planets:

Deep in the atmosphere opacities are high:

- $dT/dz = -3/16\ F_{int}\ \kappa/(\sigma T^3)$

sharp gradient for high F_{int} and/or κ

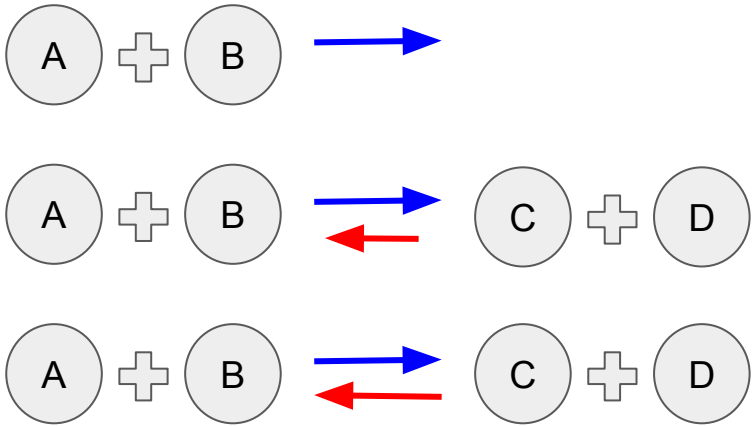


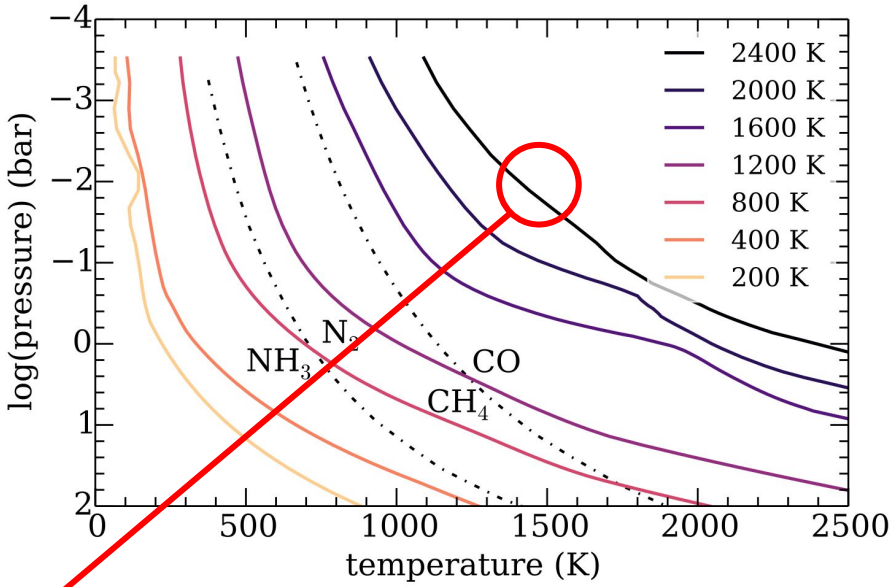
Atmospheres Theory

- Global Energy Balance (temperature of a planet)
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- **Chemistry and Clouds Basics**

Chemical Equilibrium

A simple way to model compositions is with chemical equilibrium.





After a long time, all reactions are in dynamic equilibrium.

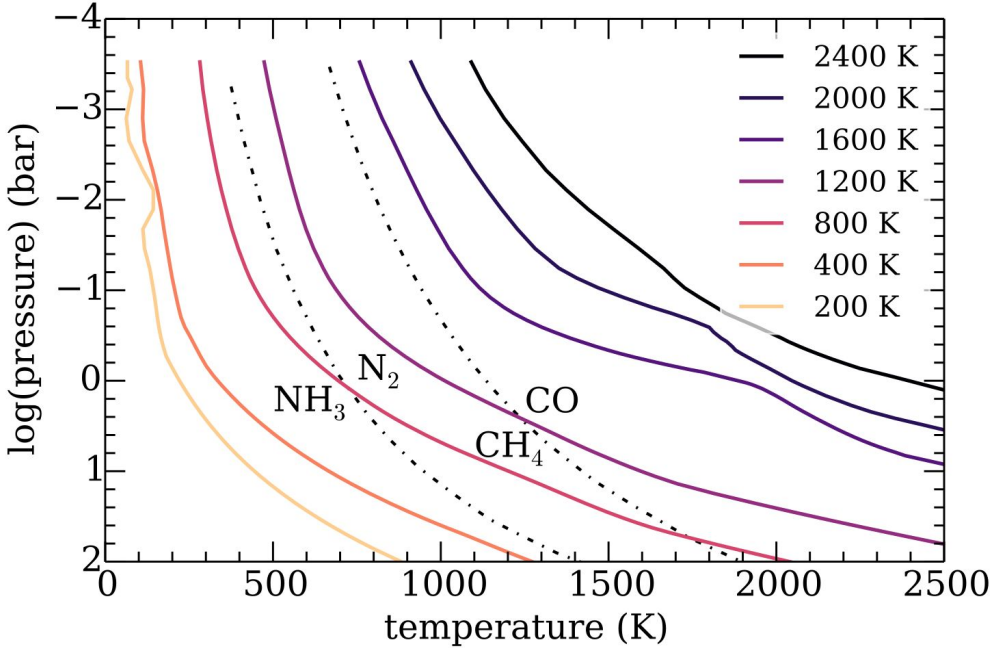
This state maximizes Entropy
➡ Gibbs Energy is minimized

Based on:
- T,P conditions
- elemental abundance

➡ expected chemistry

Ideal:
Minimize the Gibbs free energy of the whole system, with all reactions of all species, for each P, T, [M/H], etc. point

Poll!



- What (carbon/nitrogen) composition would a 2000 K planet likely have?

N2 and CO

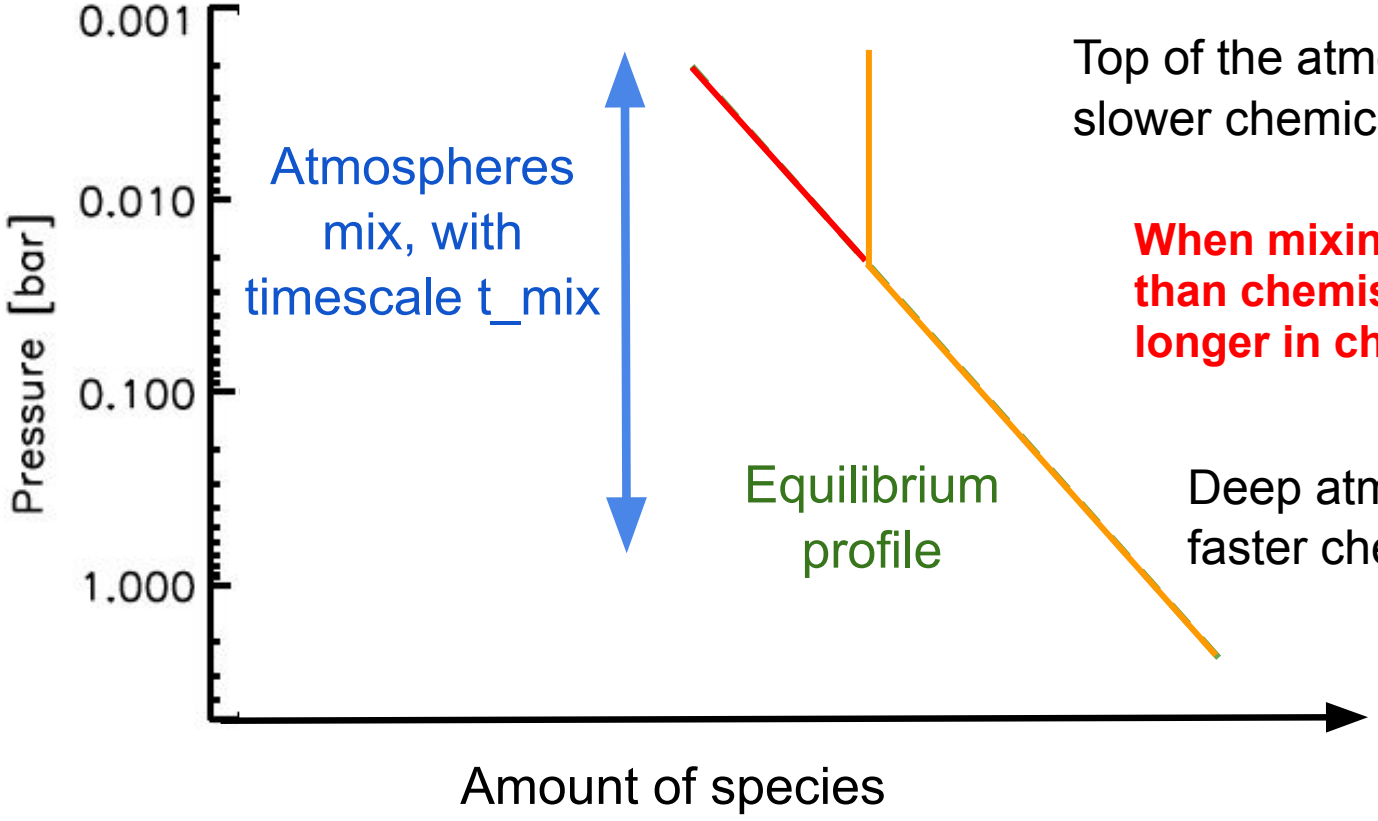
- A 200 K planet?

NH3 and CO

- At what temperature do we transition from CO-rich to CH4-rich?

700 ~ 1200 K

Chemical Disequilibrium - Kinetic



Top of the atmosphere = colder = slower chemical timescales

When mixing happens faster than chemistry, we are no longer in chemical equilibrium

Deep atmosphere = hotter = faster chemical timescales

Chemical Disequilibrium - Photochemistry

UV light can photodissociate molecules, resulting in extra chemical reactions

$$\begin{aligned} \mathrm{H_2O} + h\nu &\rightarrow \mathrm{H} + \mathrm{OH} \\ \mathrm{OH} + \mathrm{H_2} &\rightarrow \mathrm{H_2O} + \mathrm{H} \\ \hline \mathrm{Net:}\ \ \mathrm{H_2} &\rightarrow 2\,\mathrm{H}, \end{aligned}$$

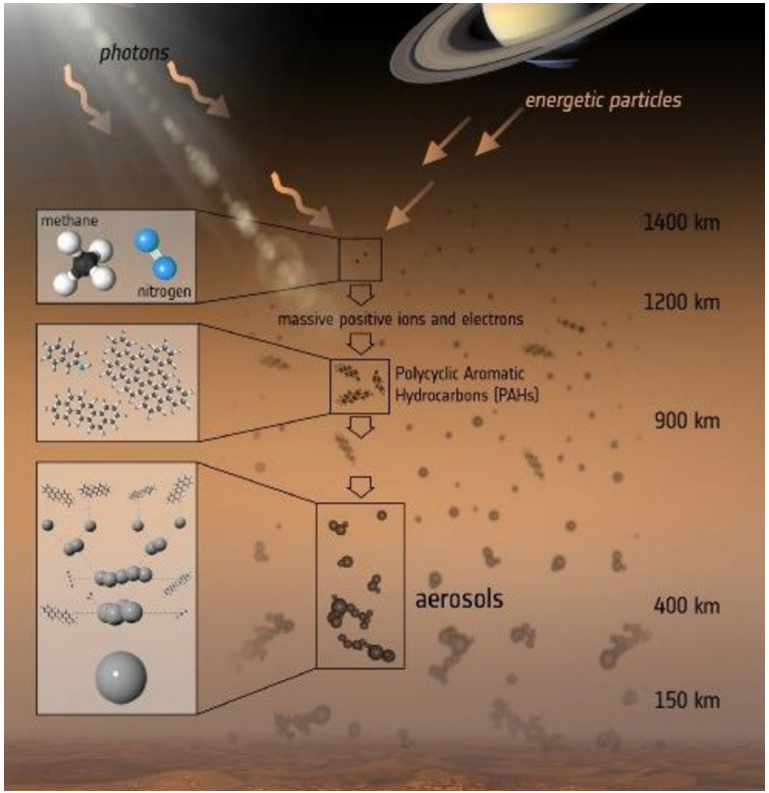
Reaction chains can be very complex and can involve multiple species

$$\begin{aligned} \mathrm{H_2O} + h\nu &\rightarrow \mathrm{OH} + \mathrm{H} \\ \mathrm{N_2} + \mathrm{H} &\rightarrow \mathrm{N} + \mathrm{NH} \\ \mathrm{NH} + \mathrm{H} &\rightarrow \mathrm{N} + \mathrm{H_2} \\ \mathrm{N} + \mathrm{OH} &\rightarrow \mathrm{NO} + \mathrm{H} \\ \hline \mathrm{Net:}\ \ \mathrm{H_2O} + \mathrm{N_2} &\rightarrow \mathrm{N} + \mathrm{NO} + \mathrm{H_2} \end{aligned}$$



Chemical Disequilibrium - Photochemistry

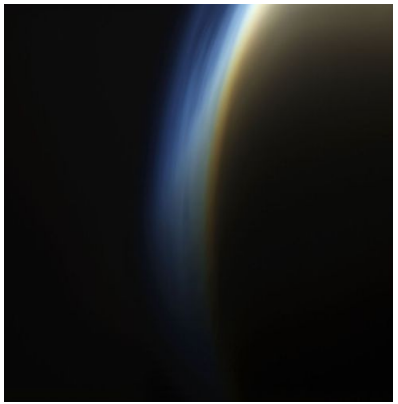
Photochemistry on Titan



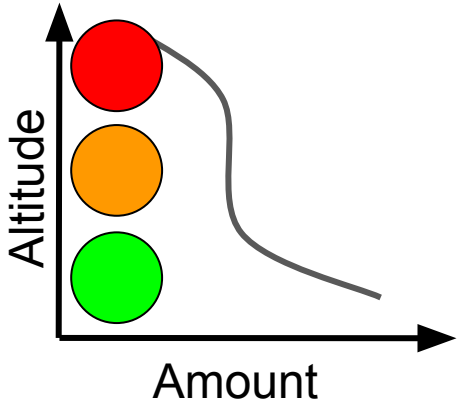
Photochemistry on Earth

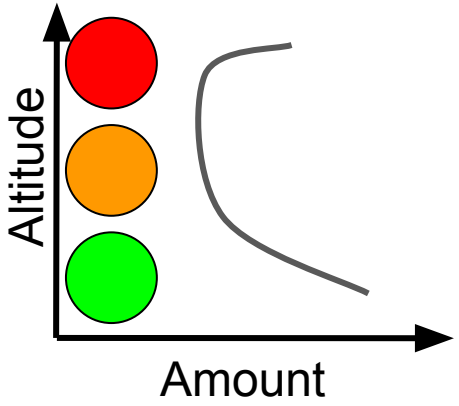


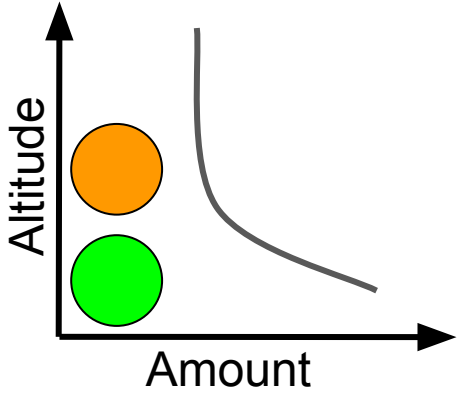


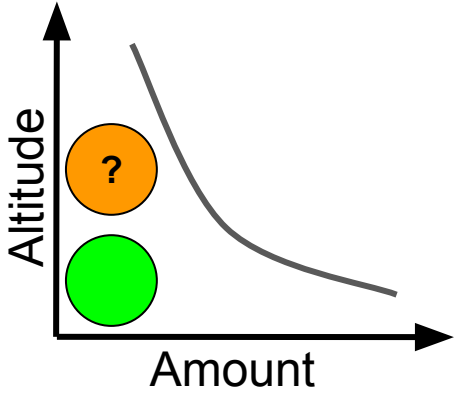


Poll: Which profiles show which effects?







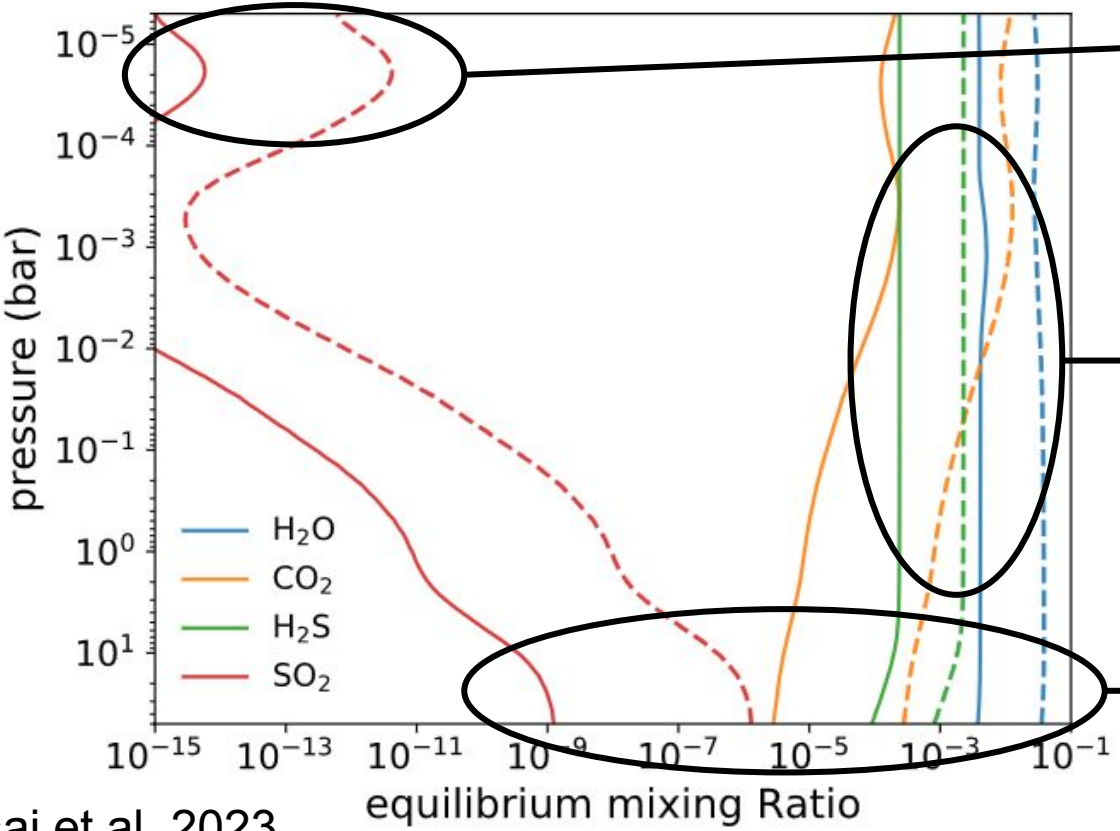


Equilibrium

Kinetic Diseq.

Photochemistry

Example - First detection of Photochemistry



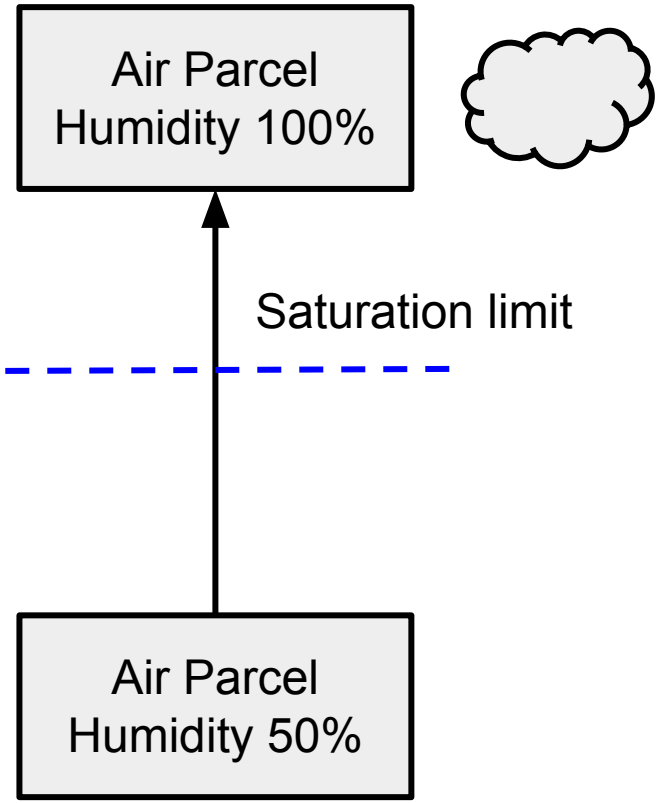
Photochemically produced SO_2

Kinetic disequilibrium

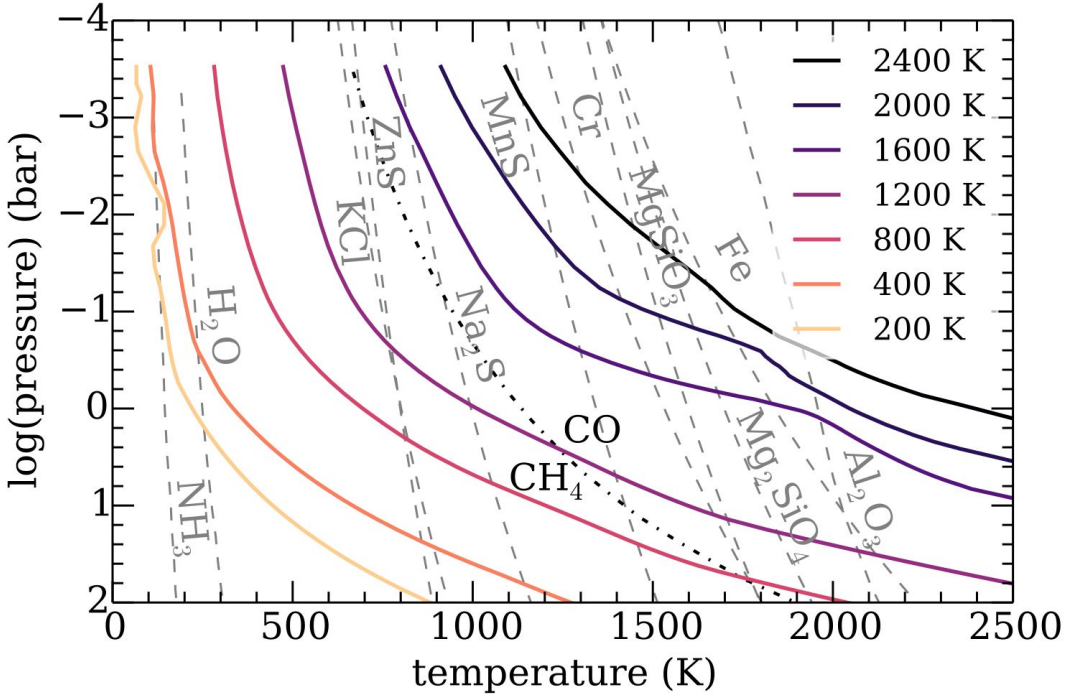
Equilibrium Chemistry

Tsai et al. 2023

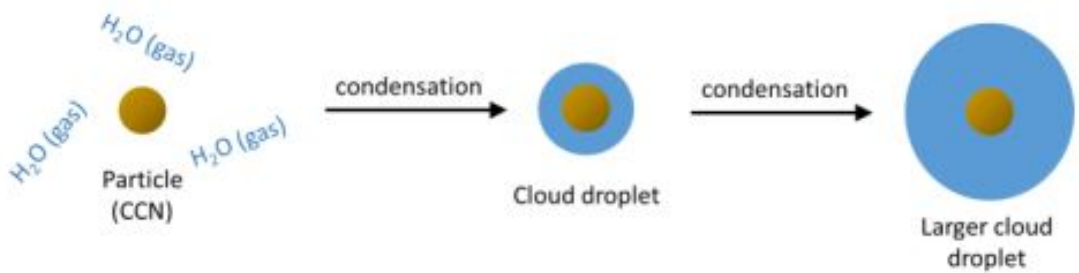
Clouds



In exoplanets, clouds can form from a diverse set of materials like iron, silicate, calcium, etc.



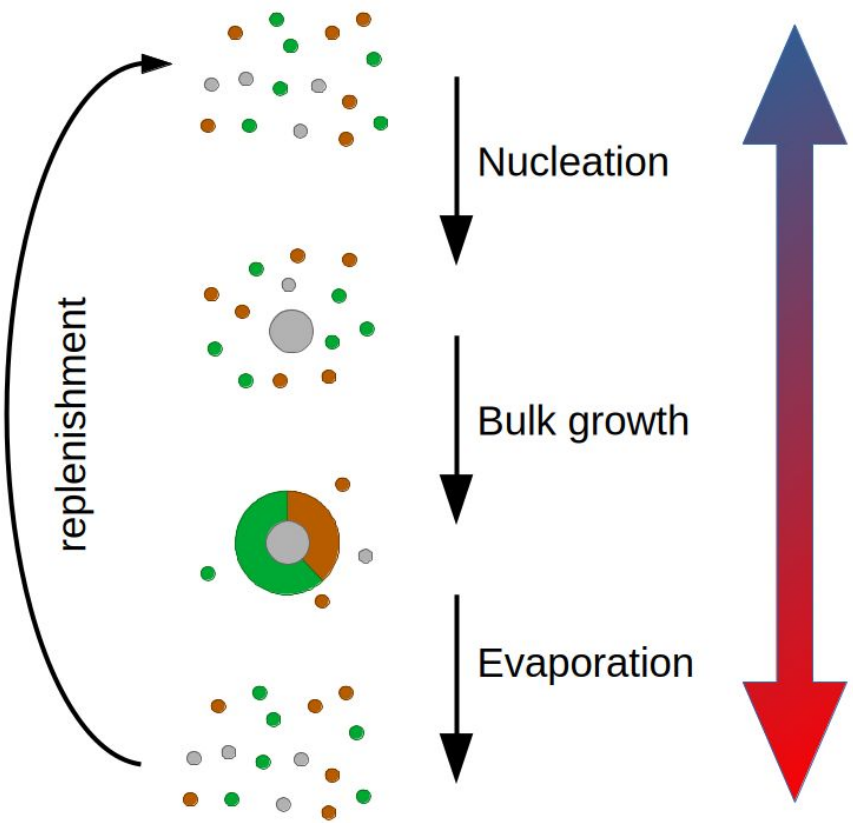
Clouds - On Earth





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

Clouds - Physical processes



Gravitational coalescence

