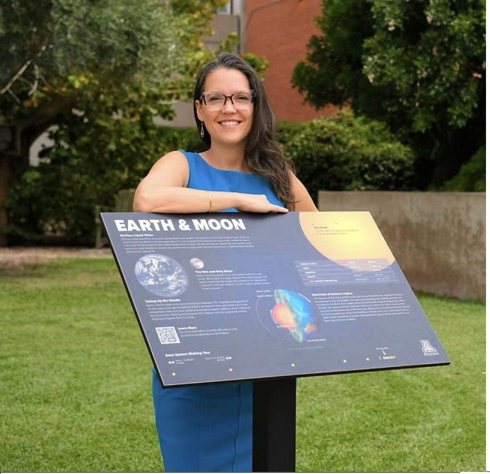
Structure, Physics, and Modeling of Giant Planet Atmospheres

Zarah Brown, PhD
University of Arizona,
Lunar and Planetary Laboratory

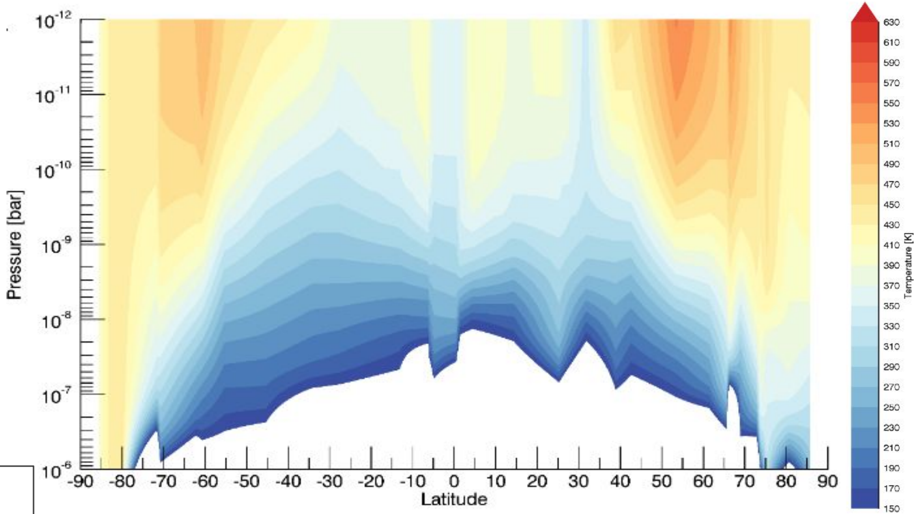
Sagnick Mukherjee, PhD
Arizona State University

Dr. Zarah Brown

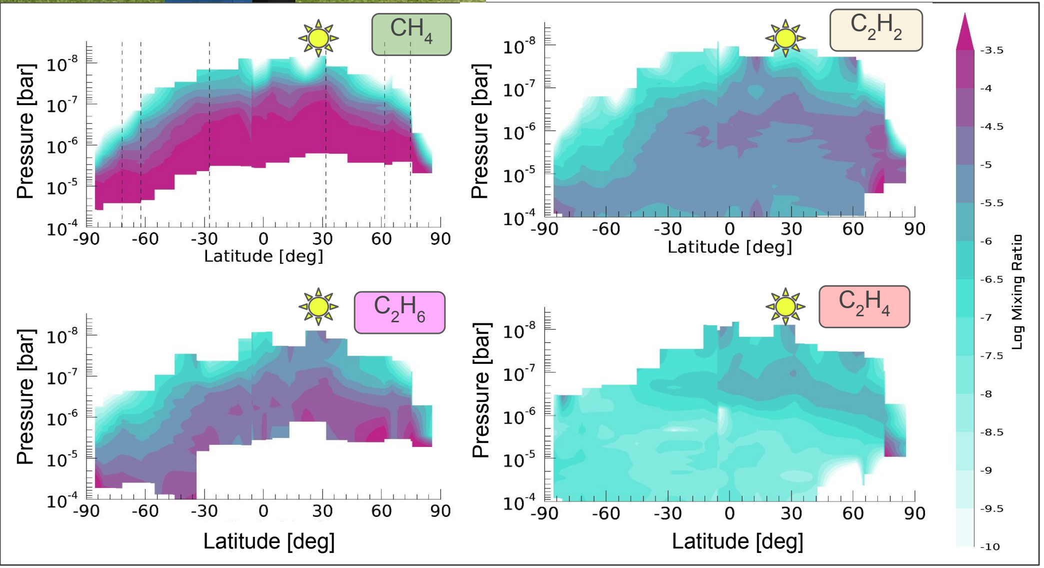


PhD University of Arizona, LPL

Postdoc with Ty Robinson



Brown et al. (2020)



Brown et al. (2024)

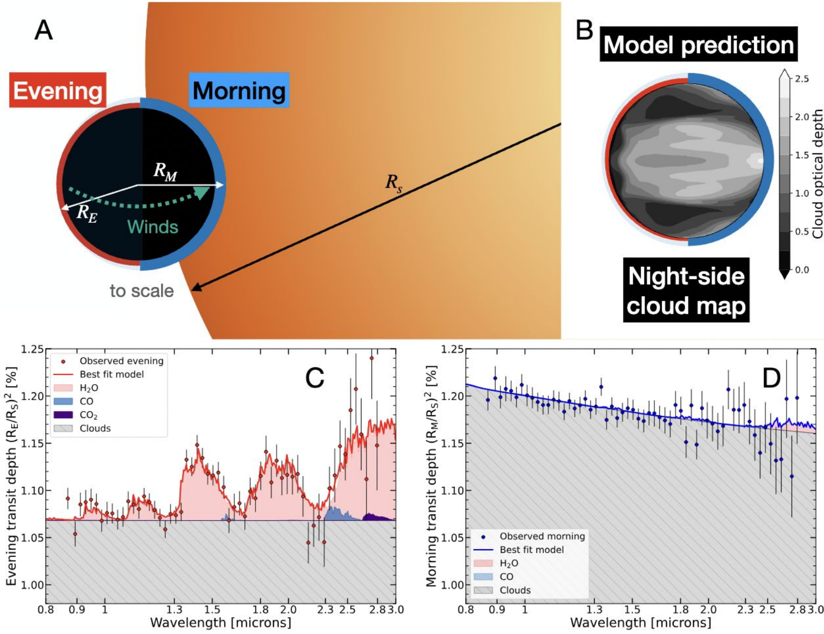
Currently working on grid of patchy cloud atmospheric models to add to the Sonora family of models to support Roman.

Dr. Sagnick Mukherjee

PhD University of California, Santa Cruz

51 Pegasi b Postdoctoral Fellow at ASU

PICAS



Mukherjee et al. (2025b)

Currently working on understanding interior-atmosphere interactions in sub-Neptune exoplanets & properties of transiting brown dwarfs

Overview

1. Energy Balance
2. Atmospheric Structure
3. Radiative Transfer
4. Scattering (Gases, Clouds and Hazes)
5. Convection & Vertical Mixing
6. Opacities

30 minute break

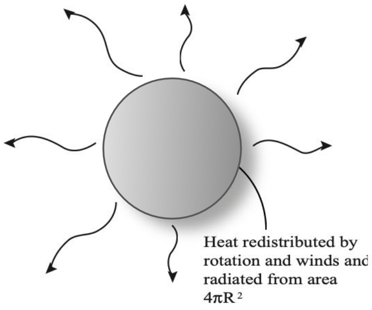
7. Chemistry (Sagnick)
8. Giant Planet Evolution (Sagnick)
9. Forward Models & Retrievals (Zarah)

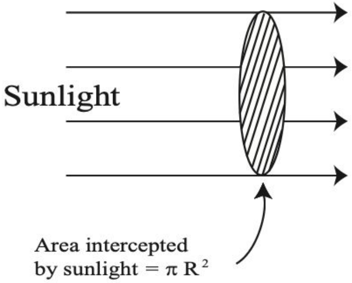
Energy Balance

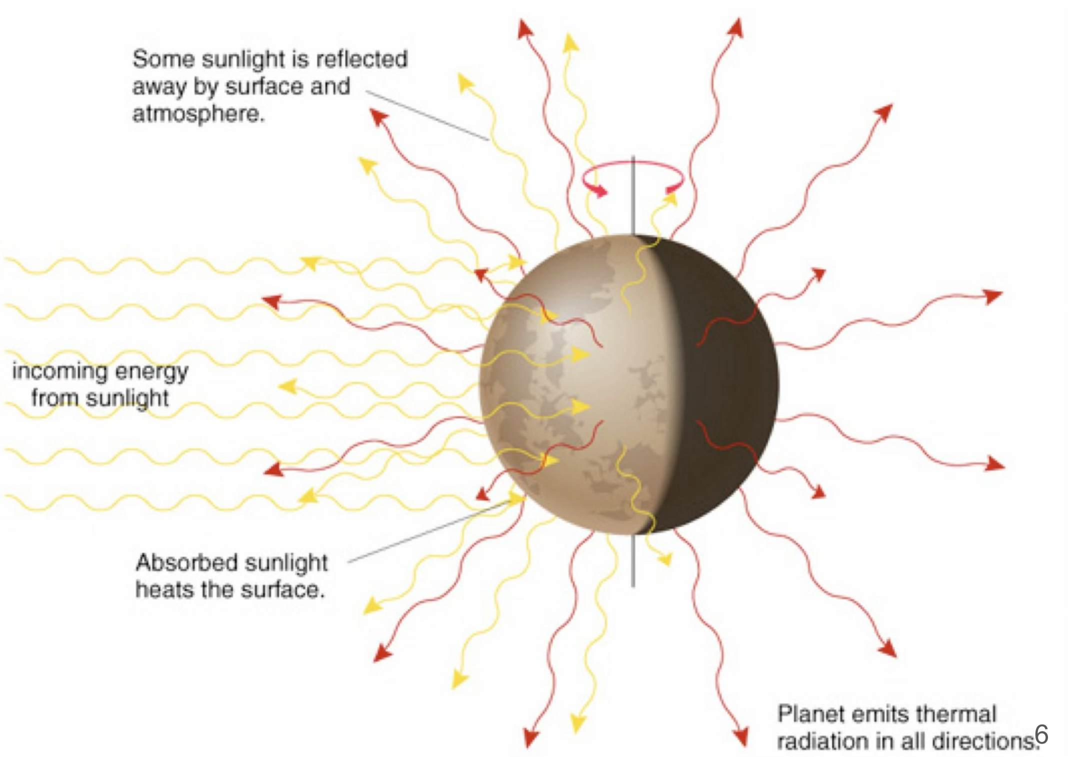
Energy Balance in Irradiated Planets

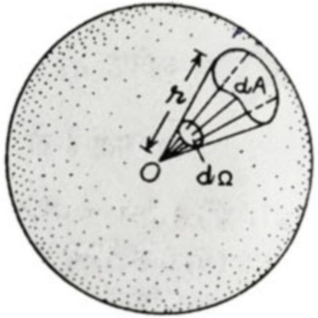
$$F_{\text{out}} = F_{\text{int}} + F_{\text{irr}}$$

$$4\pi R^2 \sigma T_{eff}^4 = \ (1-A)\pi R_p^2 F_* + F_{int}$$







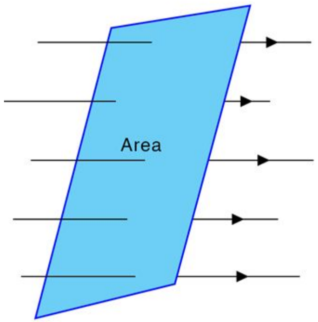


Intensity (also called **radiance**) is the radiative energy per unit time per unit area per unit solid angle traveling in a given direction.

$$\text{Intensity} = \frac{\text{Energy}}{\text{time} \times \text{solid angle} \times \text{area}}$$

Specific intensity (often shortened to intensity) is the intensity per unit frequency/wavelength

$$Specific\ Intensity = \frac{Energy}{time \times solidangle \times area \times wavelength}$$

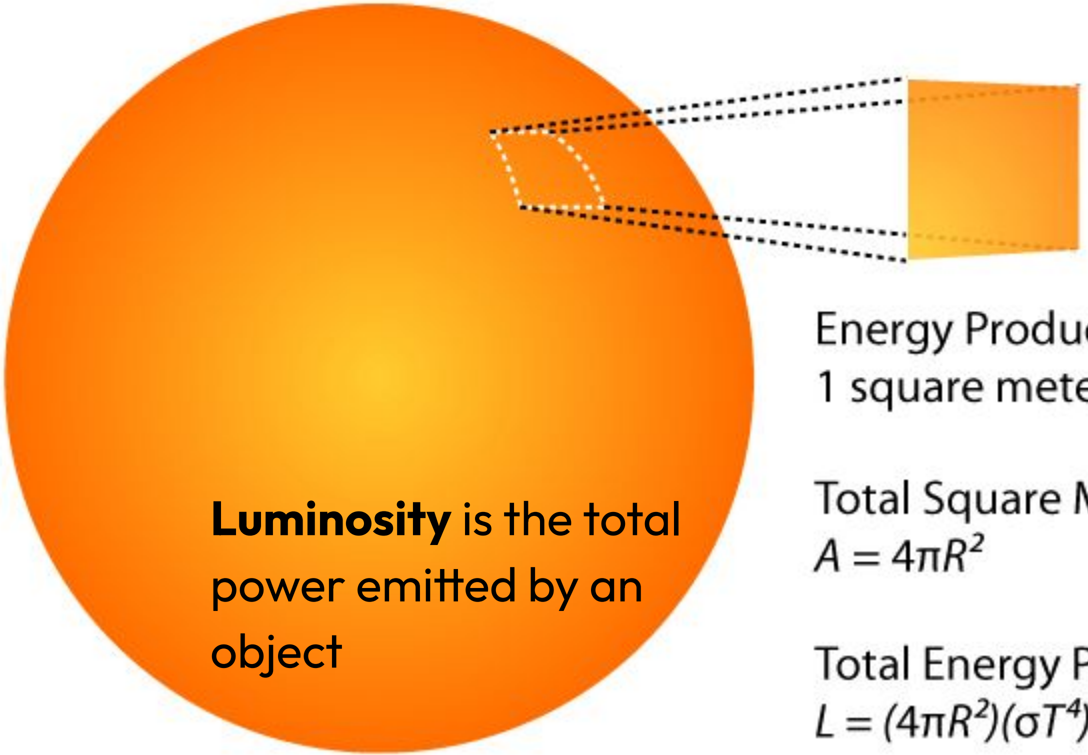


Bolometric Flux (also called **irradiance** or simply **flux**) is the radiative energy per unit time per unit area incident on (or traveling through) a surface. Thus, flux is intensity integrated over solid angle.

$$\text{Flux} = \frac{\text{Energy}}{\text{time} \times \text{area}}$$

Specific/Monochromatic Flux is the flux per unit frequency/wavelength.

$$\text{Specific Flux} = \frac{\text{Energy}}{\text{time} \times \text{area} \times \text{frequency}}$$



Luminosity is the total power emitted by an object

Energy Produced by
1 square meter = σT^4

Total Square Meters
$A = 4\pi R^2$

Total Energy Produced
$L = (4\pi R^2)(\sigma T^4)$

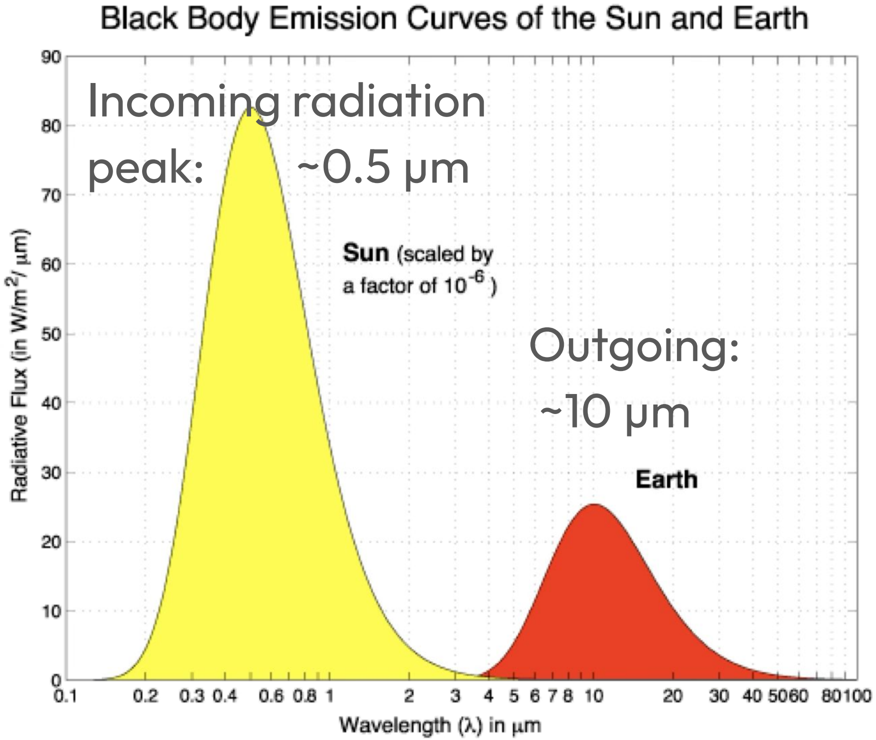
$$L = \int_{\text{surface}} F \, dA$$

$$L = \frac{Energy}{time}$$

Specific Luminosity
total power per frequency/wavelength

$$SpecificLuminosity = \frac{Energy}{time \times frequency}$$

Energy Balance in Irradiated Planets



$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T}} - 1}$$

Evaluate the integral and you get the Stefan-Boltzmann law:

$$F_{bb}(T) = \pi \int B_\lambda(T) d\lambda$$

$$F_{bb}(T) = \sigma T^4$$

T_{eff}, T_{int}, T_{eq}

$$T_{\rm eff}^4 = T_{\rm eq}^4 + T_{\rm int}^4$$

T_{int}, internal temperature - the flux from the planet's interior

T_{eq}, equilibrium temperature - the final, stable temperature reached by a system when heat loss equals heat gain, resulting in zero net energy exchange

$$\sigma T_{\rm eq}^4 = \frac{(1-A)}{4} F_\star$$

T_{eff}, effective temperature - the temperature of a blackbody of the same radius that would emit the equivalent flux as the real planet

$$\sigma T_{\rm eff}^4 = \frac{(1-A)}{4} F_\star + \frac{L_{\rm int}}{4\pi R_p^2}$$

Reflected Light vs. Self-Luminous Planets

Reflected Light (Star-Illuminated)

The observed planet flux is a fraction of the stellar flux reflected by the planet.

$$\frac{F_p}{F_*} = A_g\,\Phi(\alpha)\left(\frac{R_p}{a}\right)^2$$

Where:

- A_g = geometric albedo
- $\Phi(\alpha)$ = phase function (depends on star-planet-observer angle)
- R_p = planet radius
- a = star-planet separation

- Strong dependence on **orbital separation**
- Spectra shaped by **clouds, hazes, and atmospheric absorption**
- Dominates for **cool planets or large separations**
- Doesn't depend on **star properties**

Self-Luminous Planets (Thermal Emission)

Young giant planets emit intrinsic heat from formation.

$$F_p = \pi B_\lambda(T_p)\left(\frac{R_p}{d}\right)^2$$

Where:

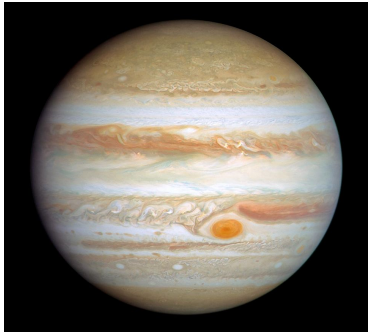
- $B_\lambda(T_p)$ = Planck function at planet temperature
- T_p = planet effective temperature
- R_p = planet radius
- d = distance to observer

- Flux largely determined by **internal temperature**
- Strongest in the **infrared**
- Dominant for **young, hot giant planets**
- Need to divide by F_* - **stellar properties** are important

The Challenges of Modeling: RL vs SL Modeling

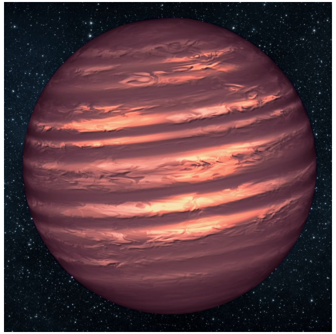
Reflected light modeling focused primarily on the location because phase angle is important to the brightness

Uncertainty due to the combination of phase and location within the inner and outer working angles > uncertainty in albedo



Self-luminous modeling is not constrained by phase angle and will be brighter and easier to observe

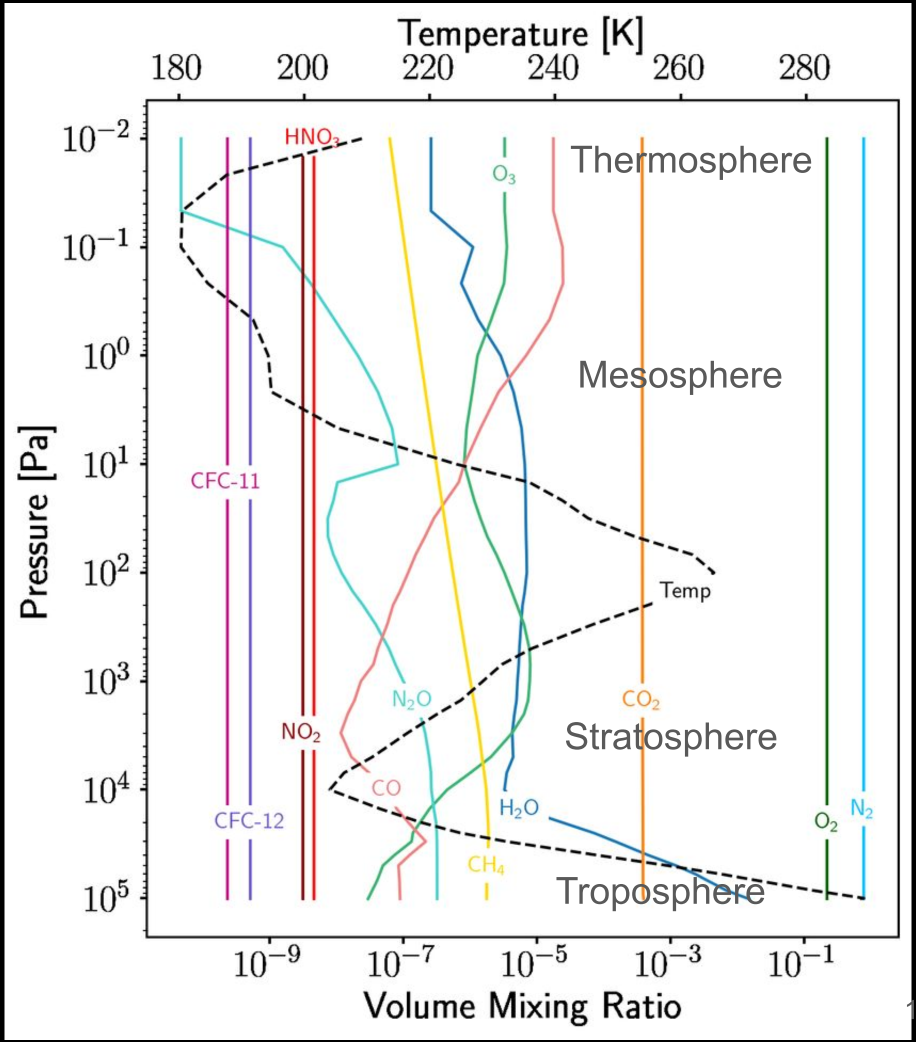
Uncertainties in flux ratios are driven by the planet's flux ← atmosphere



Atmospheric Structure

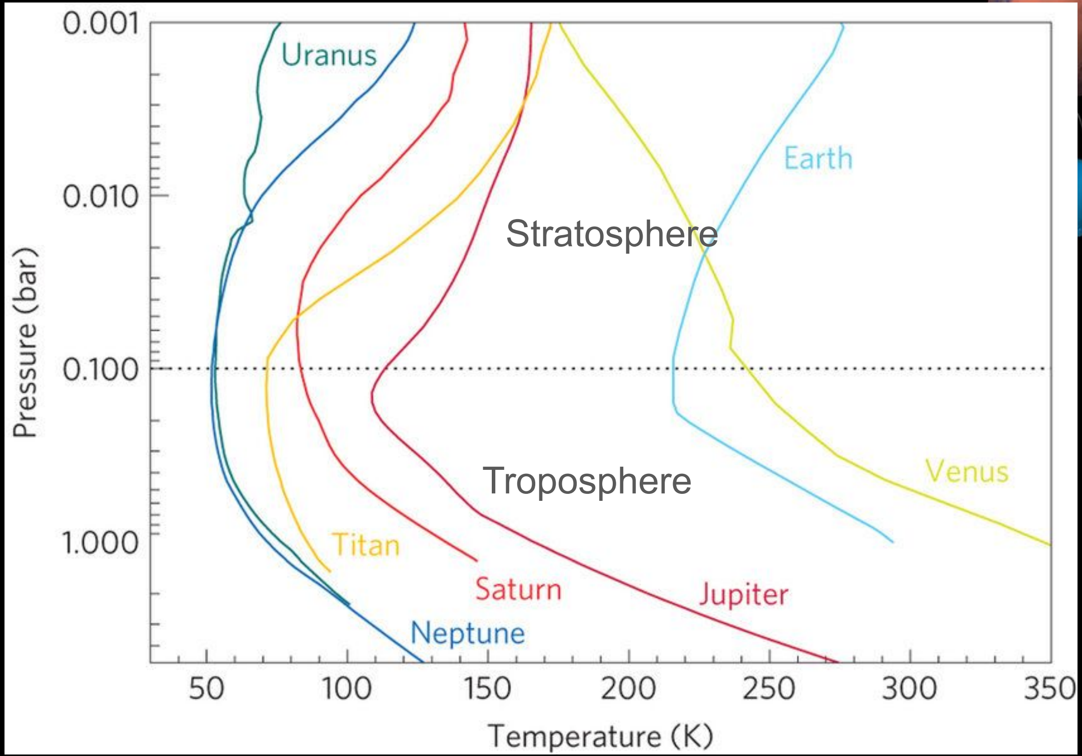
Atmospheric Structure

Chemical and thermal



Lustig-Yaeger+ 2023

Solar System Temperature Profiles



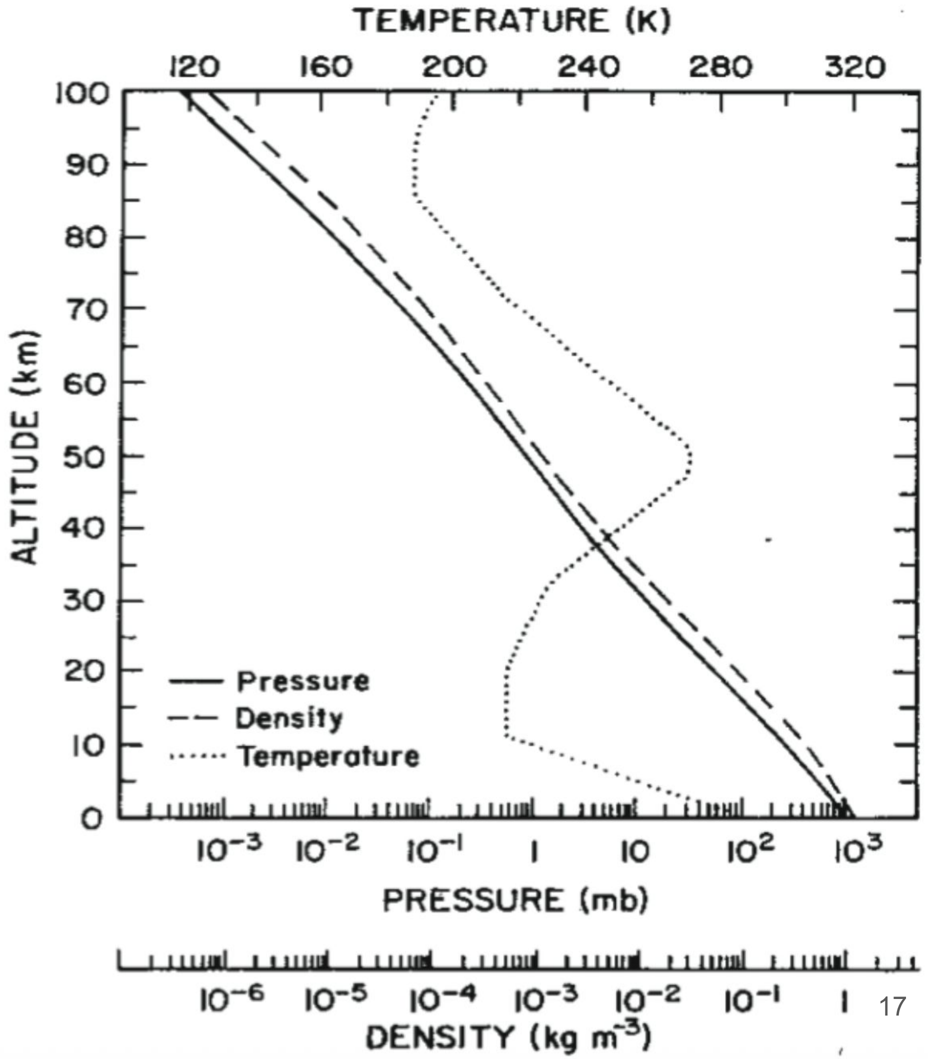
Robinson + Catling 2013

Despite the wide variety of planets in the solar system, they have similar temperature structures.

Density/Pressure

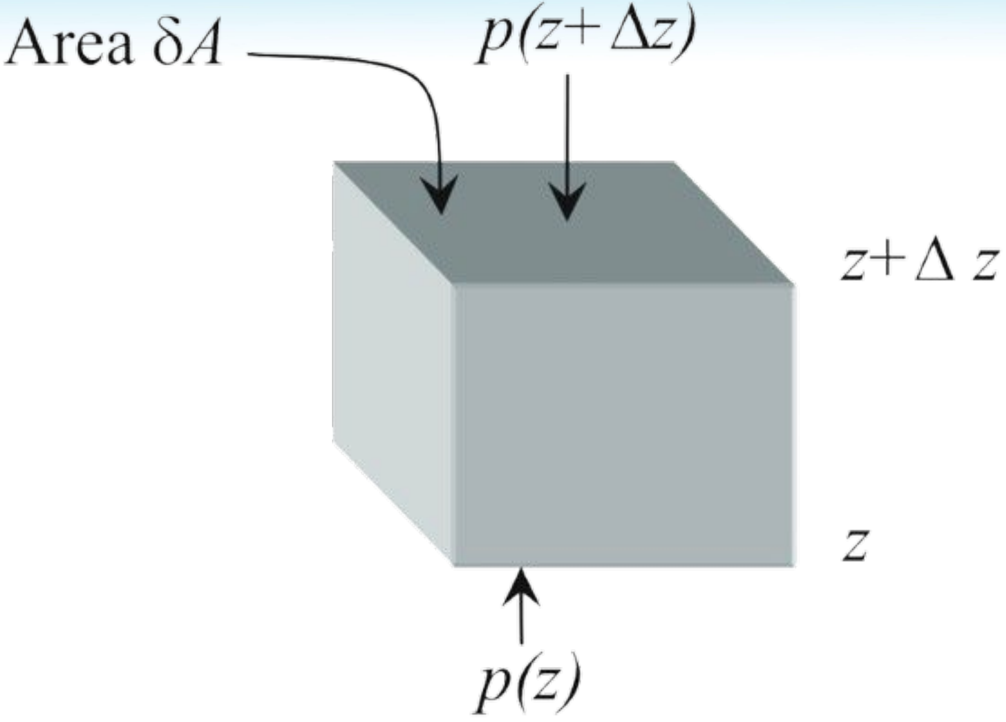
Relationship between pressure and density with altitude is ~exponential

And why is that?



Hydrostatic Equilibrium

Consider a parcel of air that is vertically static:



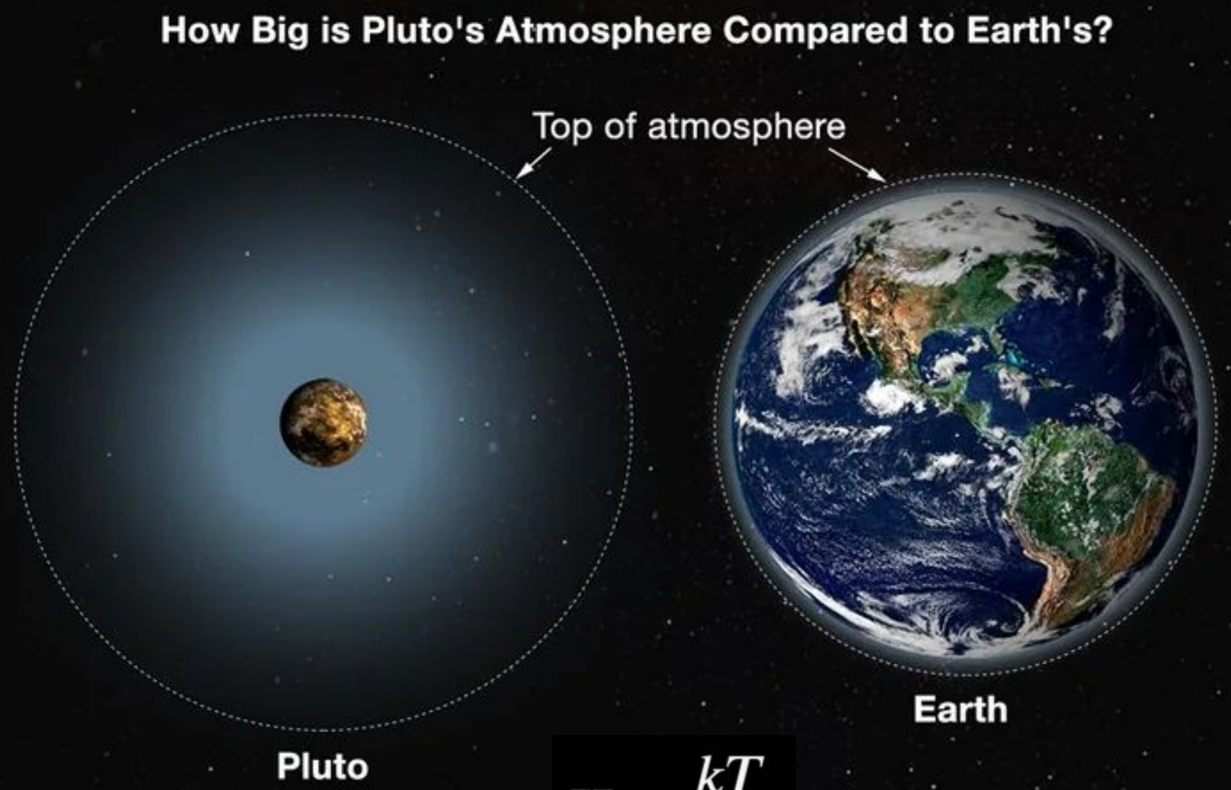
By setting the net forces = 0:

→ $$\frac{dp}{dz} = -\rho g$$

Assuming an ideal gas (P=nkT):

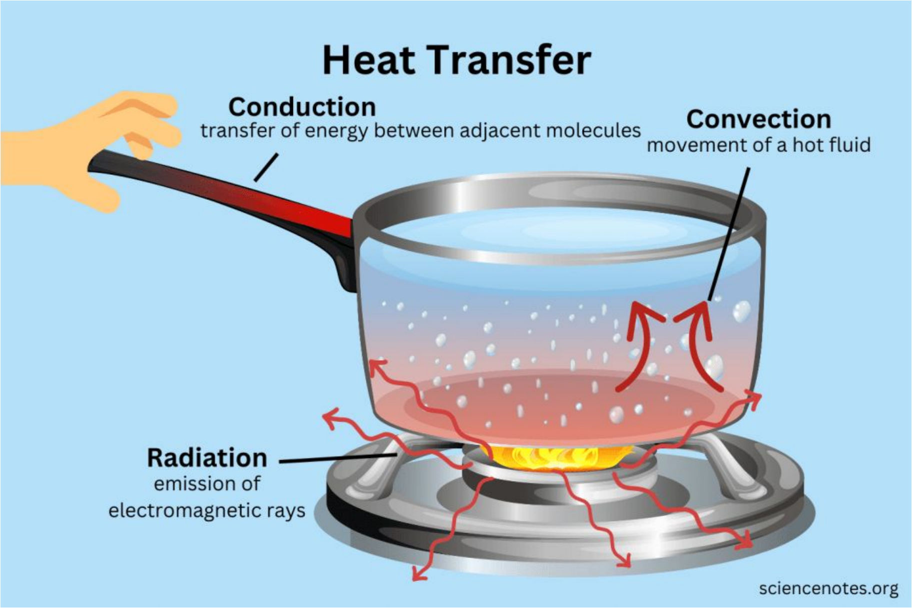
→ $$P(z) = P_0 e^{-\frac{mgz}{kT}}$$

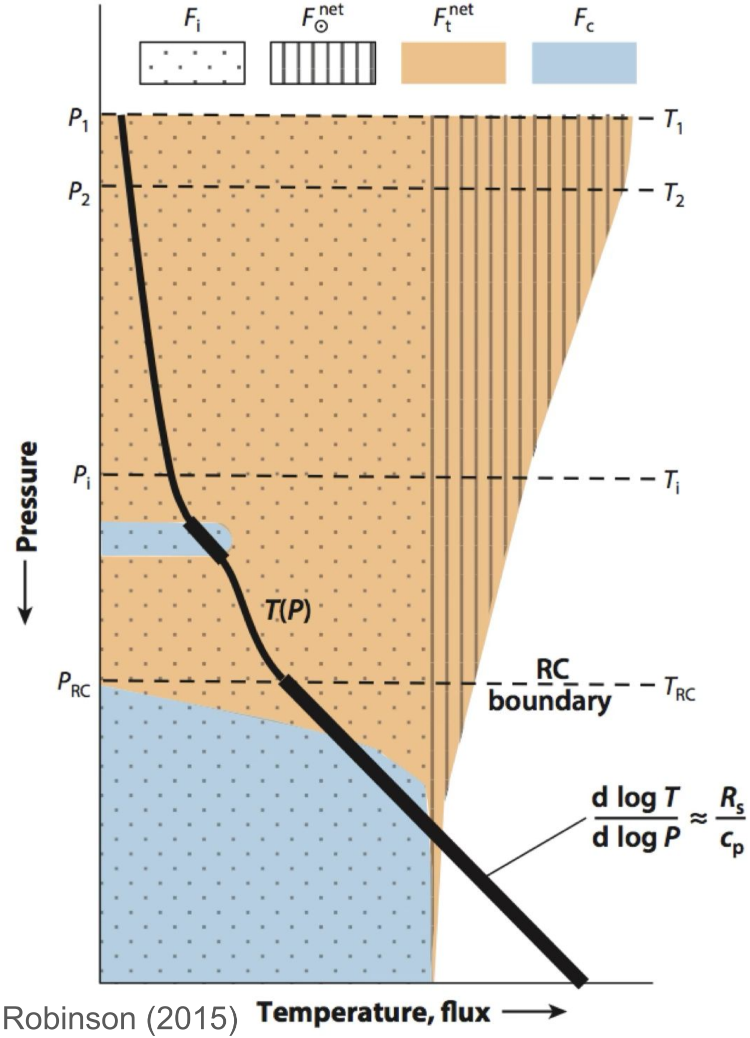
Where **scale height** is: $H = \frac{kT}{mg}$


How Big is Pluto's Atmosphere Compared to Earth's?
Top of atmosphere
Earth
Pluto

$$H = \frac{kT}{mg}$$

Radiative-Convective Structure





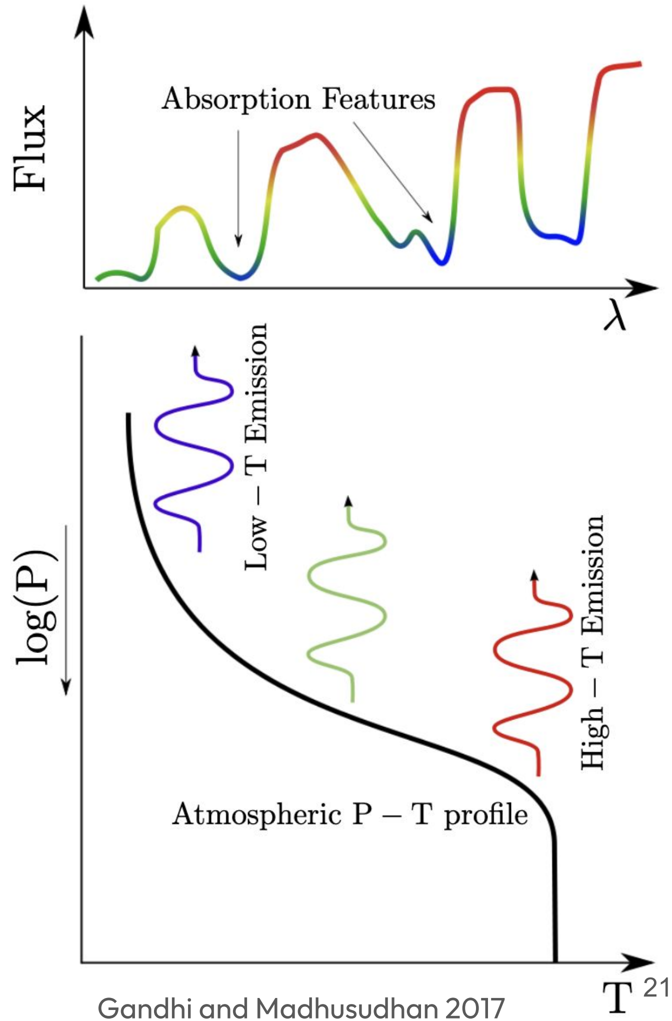
Marley & Robinson (2015)

Climate and Spectra

Thermal emission spectrum

At each wavelength, the radiation escapes where $\tau \sim 1$

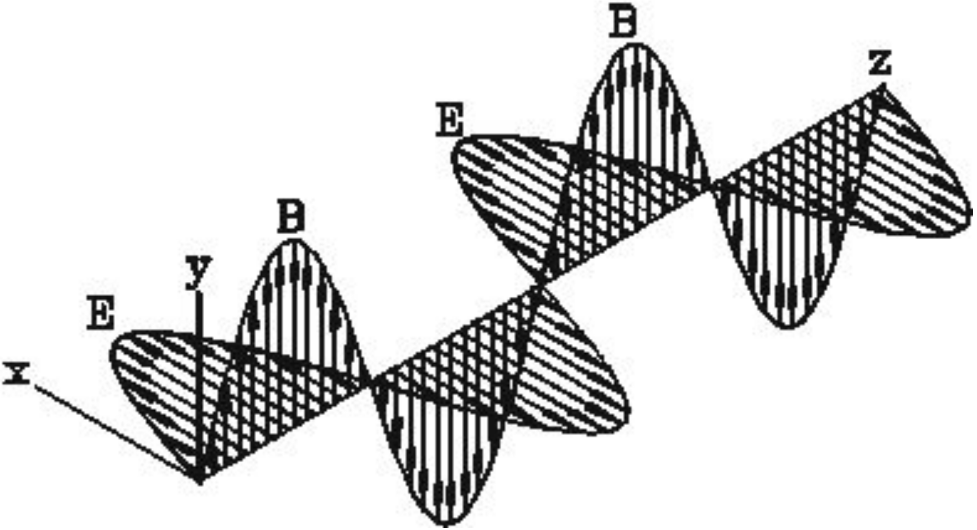
Because atmospheric opacity varies with wavelength and with molecular species, different wavelengths probe different pressures in the atmosphere.

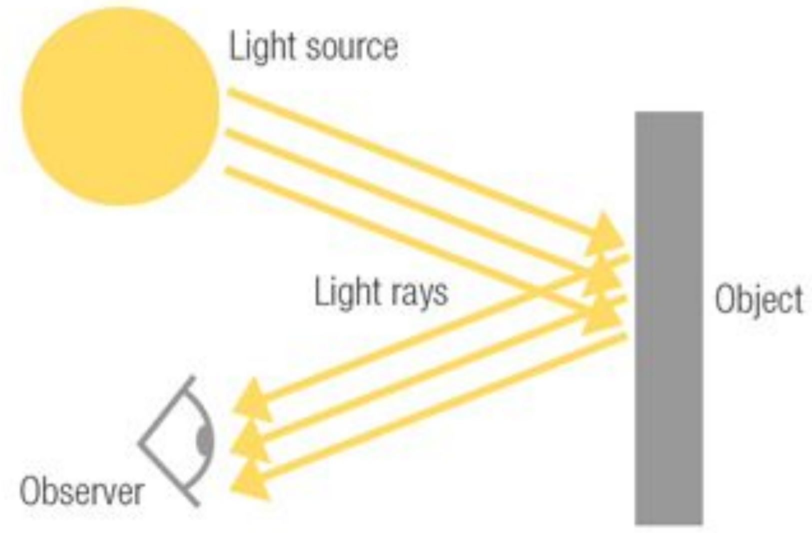


Gandhi and Madhusudhan 2017

Radiative Transfer

Maxwellian vs. Geometric Optics

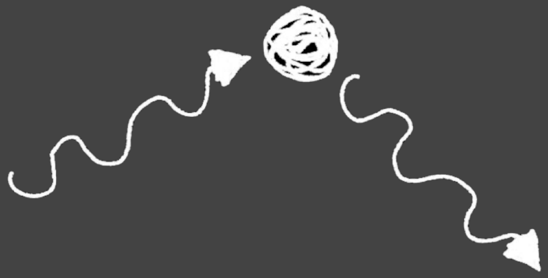




Can be important for scattering and other astrophysical processes

Here geometric optics (light is considered to propagate along rays) is OK

Basics of Radiative Transfer

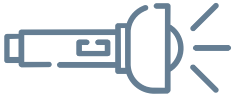


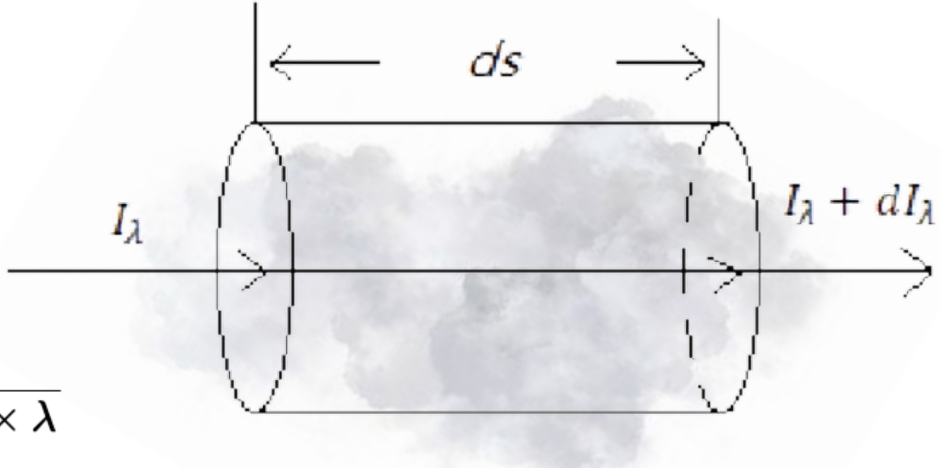
Scattering (the photon changes direction)

Absorption (the photon is destroyed)

Emision (the photon is created)

Basics of Radiative Transfer





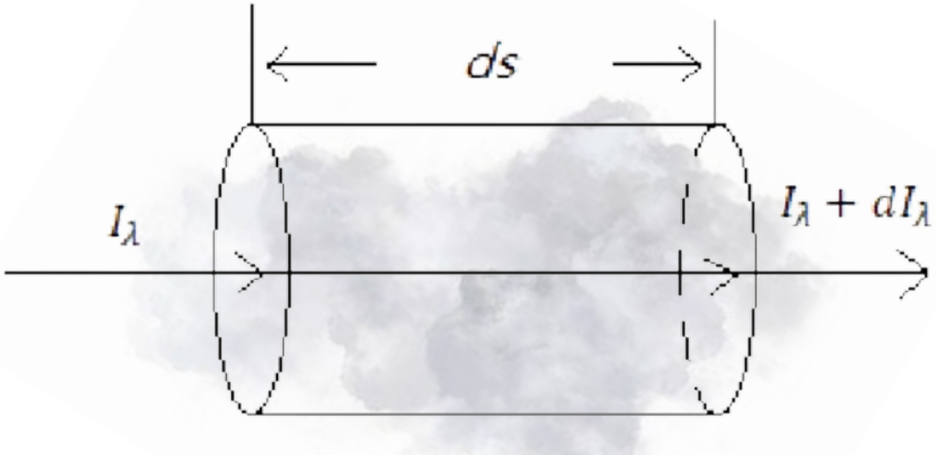
$$I_\lambda = \frac{Energy}{time \times \Omega \times area \times \lambda}$$

Gains — Losses

$$\frac{dI_\lambda}{ds}$$ = Emitted + Scattered In + Absorbed + Scattered Out

dI_λ/ds: rate of change of specific intensity ($I\lambda$) [erg/cm2/s/Hz/sr] along distance, ds

Basics of Radiative Transfer



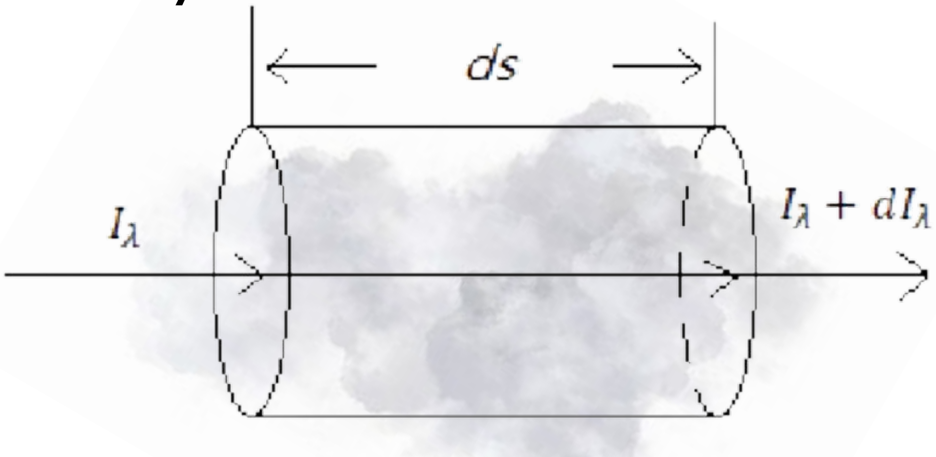
Emission Extinction

$$\frac{dI_\lambda}{ds} = j_\lambda - \alpha_\lambda I_\lambda$$

Emissivity (**j**): energy added to a beam via emission and scattering

Extinction Coefficient (**α**): A measure of how strongly a chemical species absorbs and scatters light

RTE - Absorption Only (No Emission)

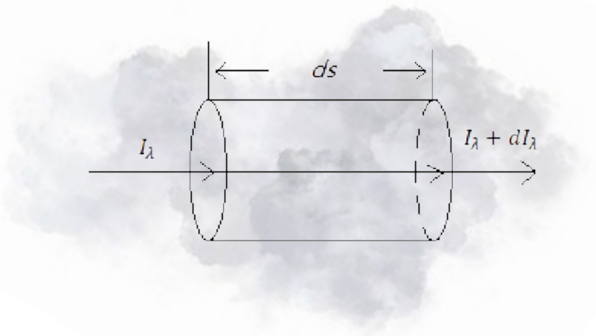


Emission Extinction

$$\frac{dI_\lambda}{ds} = j_\lambda - \alpha_\lambda I_\lambda$$

$$dI_\lambda = -\alpha_\lambda I_\lambda ds$$

RTE - Absorption Only (No Emission)



$$dI_\lambda = -\alpha_\lambda I_\lambda ds$$

$$I_\lambda(s) = I_{\lambda 0} e^{-\alpha_\lambda s}$$

$$\tau_\lambda = \int \alpha_\lambda(s) ds$$

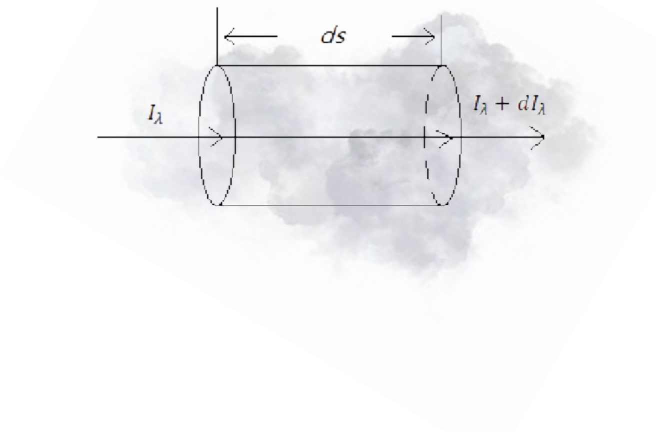
Optical Depth (τ): A dimensionless quantity defining how much light is absorbed/scattered

$\tau = 1 \rightarrow 1/e$ (37%)

$\tau \gg 1$ optically thick

$\tau \ll 1$ optically thin

RTE - Absorption & Emission (w.r.t. Tau)



$$\tau_\lambda = \int \alpha_\lambda(s)ds$$

$$\frac{dI_\lambda}{ds} = j_\lambda - \alpha_\lambda I_\lambda \qquad \frac{d\tau_\lambda}{ds} = \alpha_\lambda$$

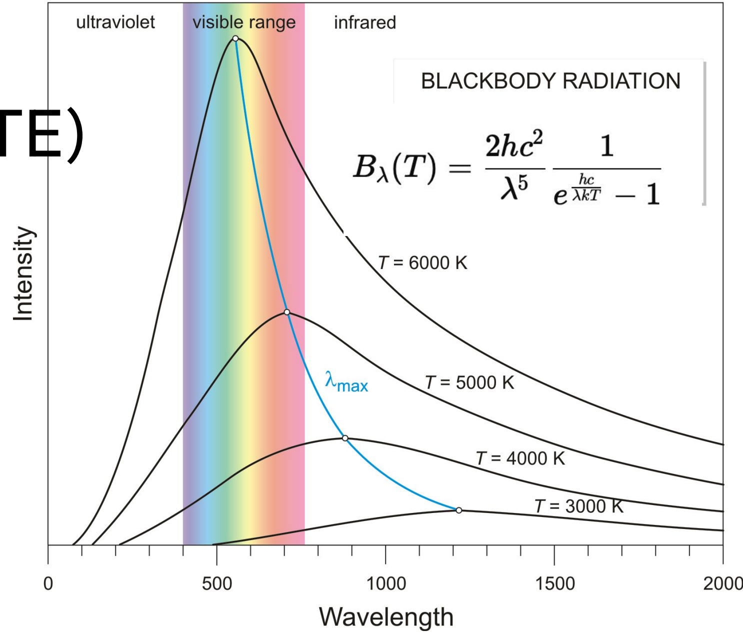
$$[\frac{dI_\lambda}{d\tau} = j_\lambda - \alpha_\lambda I_\lambda]\frac{ds}{d\tau_\lambda}$$

$$\frac{dI_\lambda}{d\tau_\lambda} = \frac{j_\lambda}{\alpha_\lambda} - I_\lambda$$

$$S_\lambda = \frac{j_\lambda}{\alpha_\lambda}$$

Source Function (S): describes how radiation is created and absorbed by a medium

Local Thermodynamic Equilibrium (LTE)



Thermodynamic equilibrium: a system with no net flows of energy or matter and no time evolution of its macroscopic properties.

Local Thermodynamic Equilibrium (LTE): A state in non-equilibrium systems where small, localized volumes act as if they are in full thermodynamic equilibrium

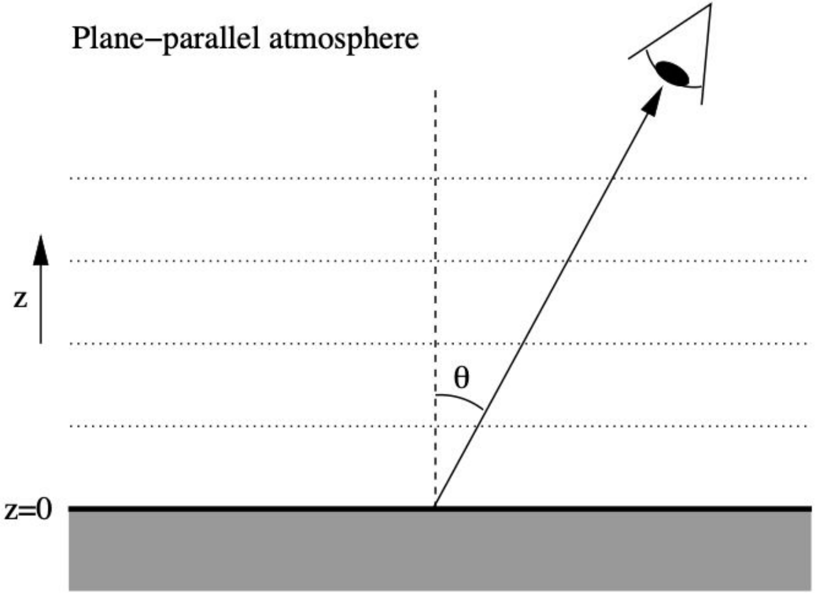
Under LTE the source function becomes:

$$S_\nu = B_\nu(T)$$

$$I_\lambda = B_\lambda(T)$$

LTE can be taken as a given for most problems in the lower and middle atmosphere because the atmospheric density is comparatively high and therefore collisions are frequent.

1D Plane Parallel RT Problems



Photons still move in 3D but we neglect x and y and treat it as up/down

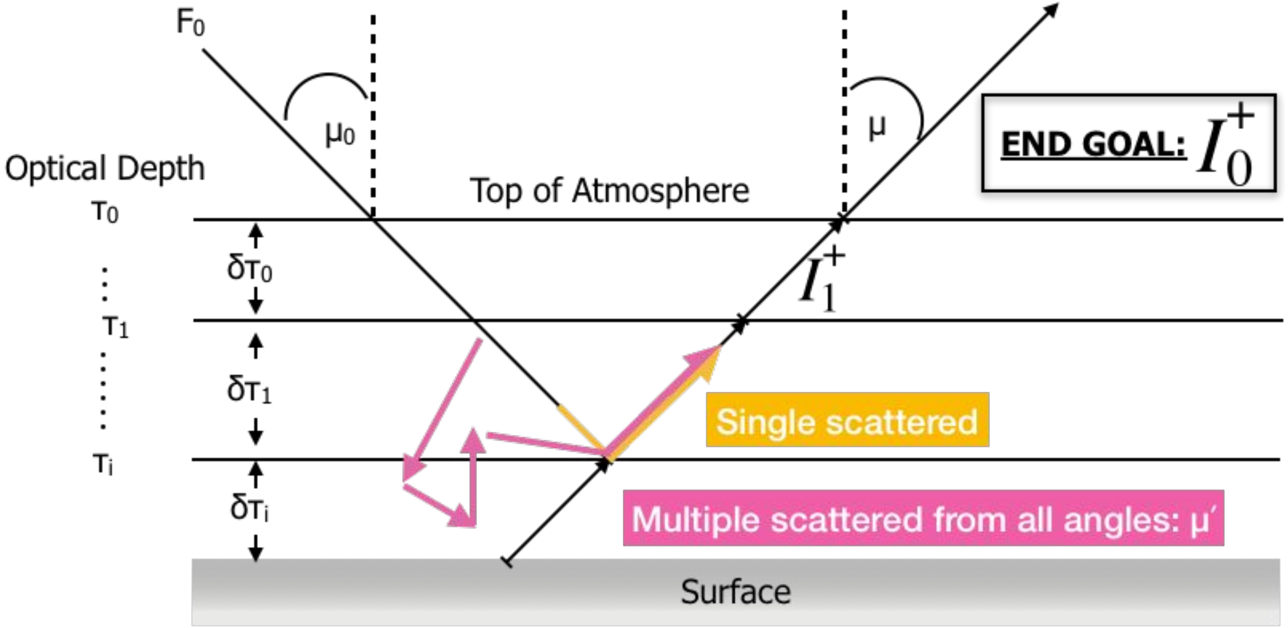
Picaso's RTE

$$I(\tau_i,\mu)=I(\tau_{i+1},\mu)e^{\delta\tau_i/\mu}-\int_0^{\delta\tau_i} S(\tau',\mu)e^{-\tau'/\mu}d\tau'/\mu.$$

Azimuthally averaged intensity emergent from the top of layer with opacity (τ) and outgoing angle (μ)

Incident intensity on the lower boundary of the layer attenuated by the optical depth within the layer (δτ)

Source function=Single-scattered radiation+multiple-scattered radiation

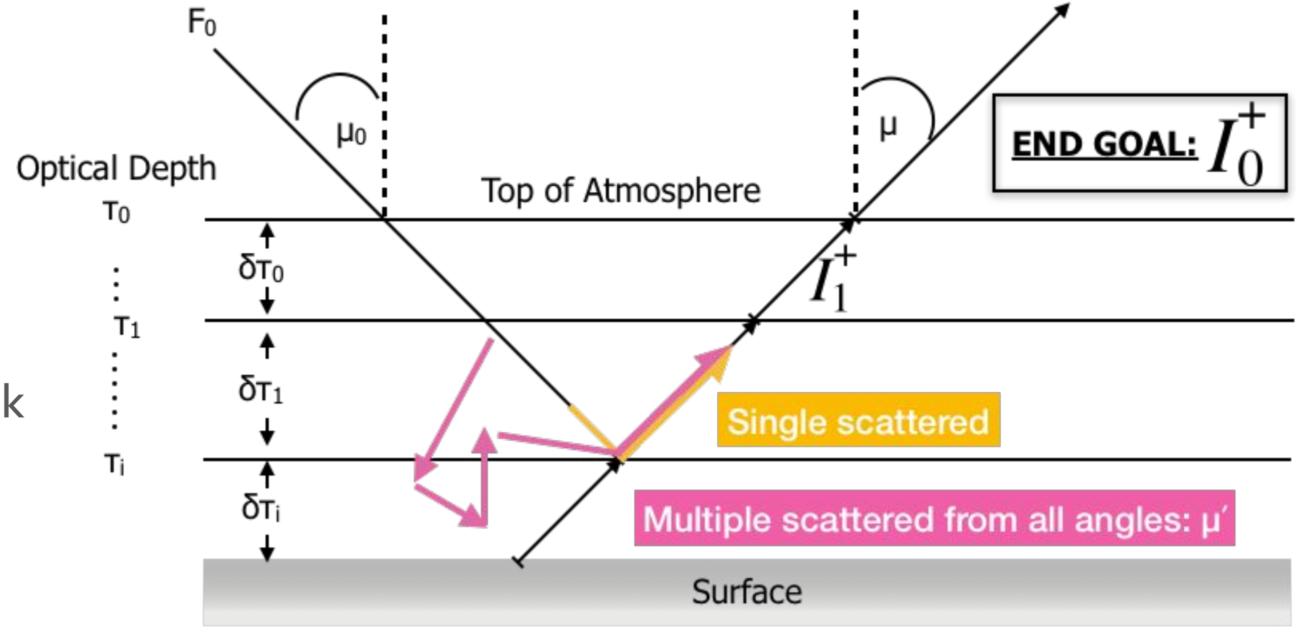


Scattering - Gases, clouds and hazes

Single and Multiple Scattering

Scattering usually separated into forward scattering and back scattering

In dense atmospheres or thick clouds, photons can scatter many times before escaping.



Scattering Regimes

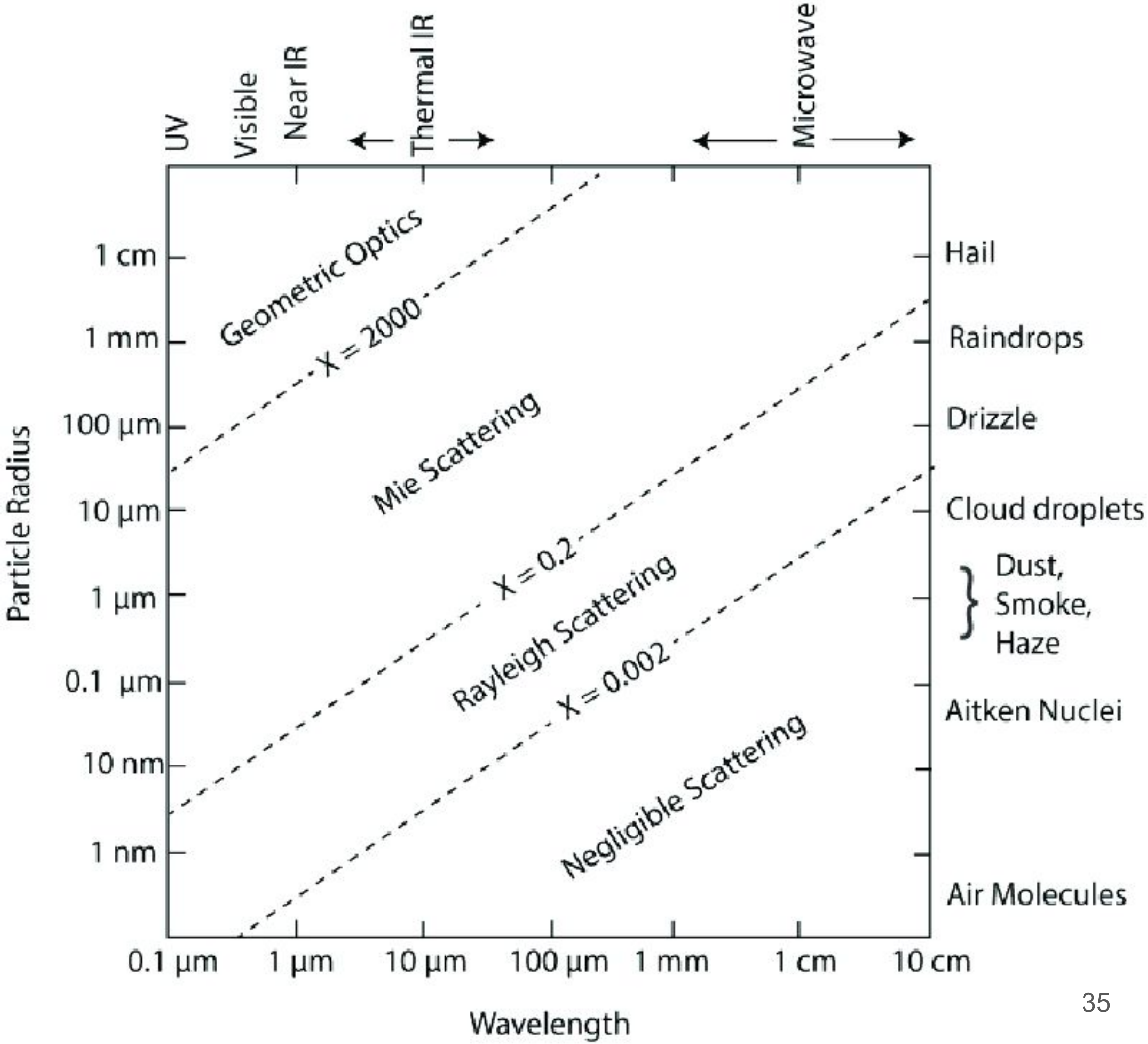
For Scattering of radiation by particles, size matters

Rayleigh Theory - small, randomly oriented particles

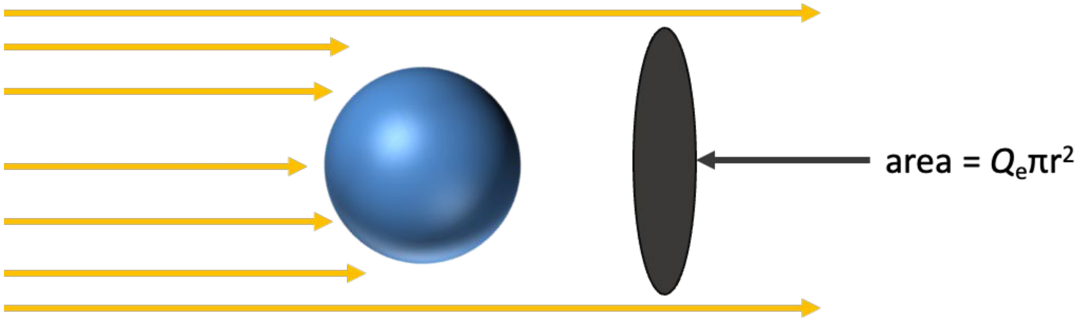
Mie Theory - spheres of arbitrary size

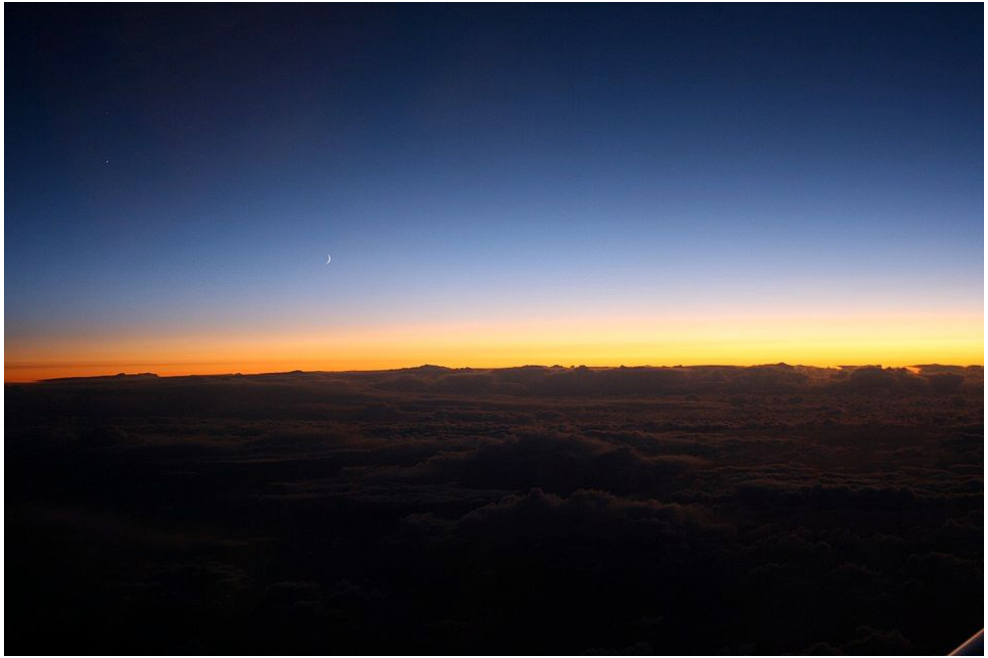
Molecules, haze particles, cloud droplets, hailstones

Shape may be important



Rayleigh Scattering





Rayleigh scattering occurs when the wavelength of light is much larger than the size of the particle with which it interacts.

For particles << radiation's wavelength, the scattering cross section is ~$\propto \lambda^{-4}$

On Earth, extincion via scattering is 9.3 x stronger at 0.4 micron than at 0.7 micron

Sky is blue, sunsets are red

Scattering Phase Function

Describes how radiation is redistributed in direction when it is scattered by a particle.

The phase function: $$P(\theta)$$

P(θ) gives the angular distribution of scattered light.

It is usually normalized so that: $$\int_{4\pi} P(\theta)\, d\Omega = 1$$

θ = scattering angle

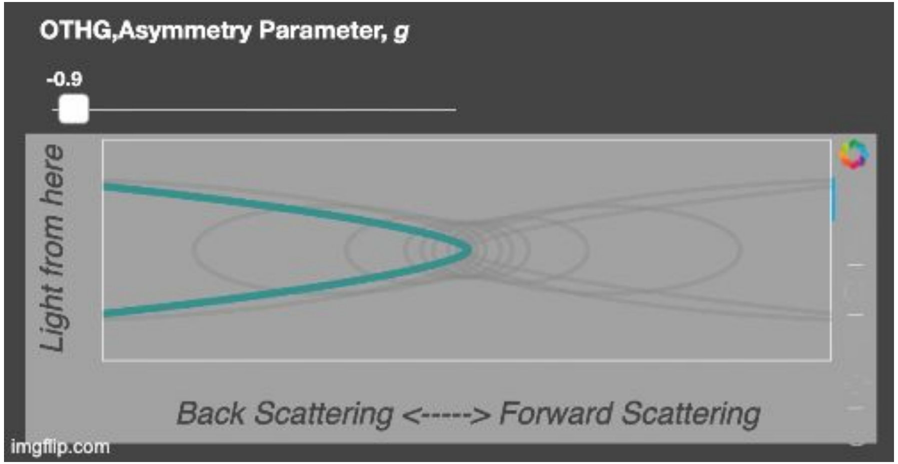
$\theta = 0^\circ$ → forward scattering

$\theta = 180^\circ$ → backscattering

Asymmetry Parameter and Single Scattering Albedo

The asymmetry parameter is the mean cosine of the scattering angle:

$$g = \langle \cos \theta \rangle$$



g value	Scattering behavior
(g = 1)	purely forward scattering
(g = 0)	isotropic scattering
(g = -1)	purely backward scattering

Single Scattering Albedo: The Fraction of extinction due to scattering

- $\omega_0 \approx 1$ → mostly scattering
- $\omega_0 \approx 0$ → mostly absorption

$$\omega_0 = \frac{\sigma_{scat}}{\sigma_{ext}}$$

Mie Scattering

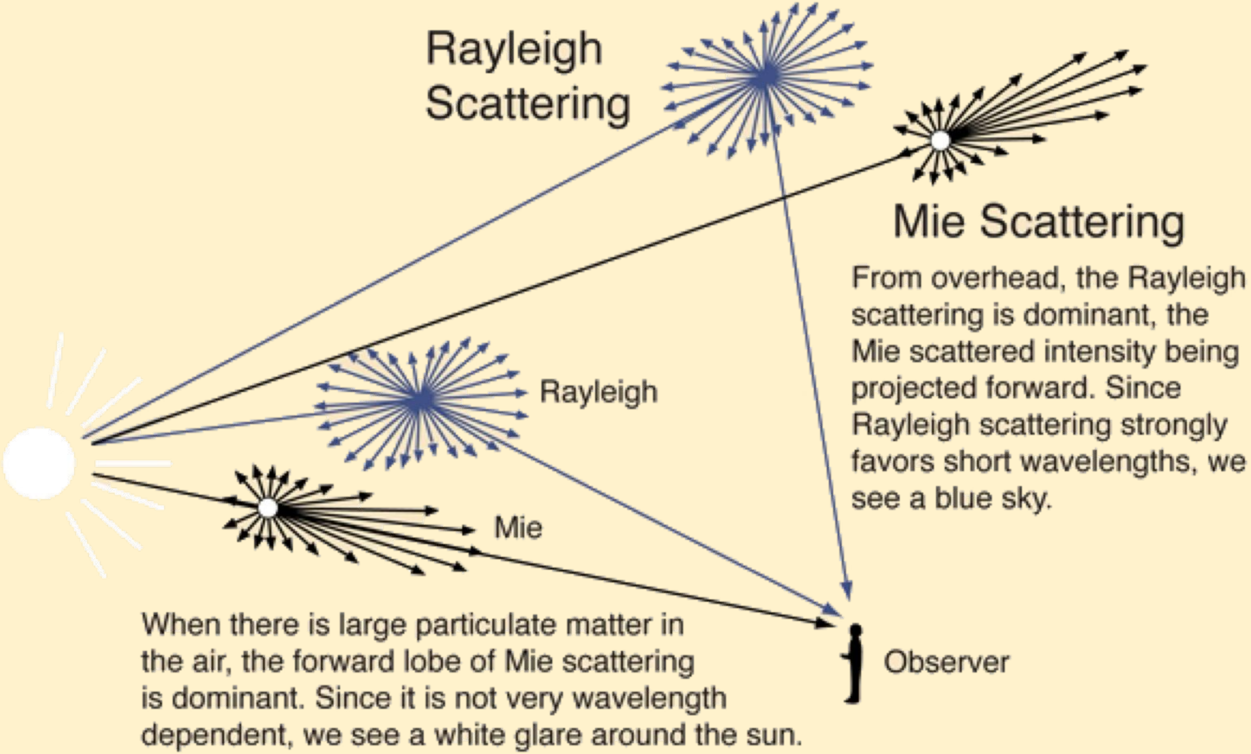
Occurs when particles are comparable to or larger than the wavelength.

Strong Forward Scattering

Common for:

- Clouds
- Aerosols
- Hazes

Mie vs. Rayleigh Scattering



Raman Scattering

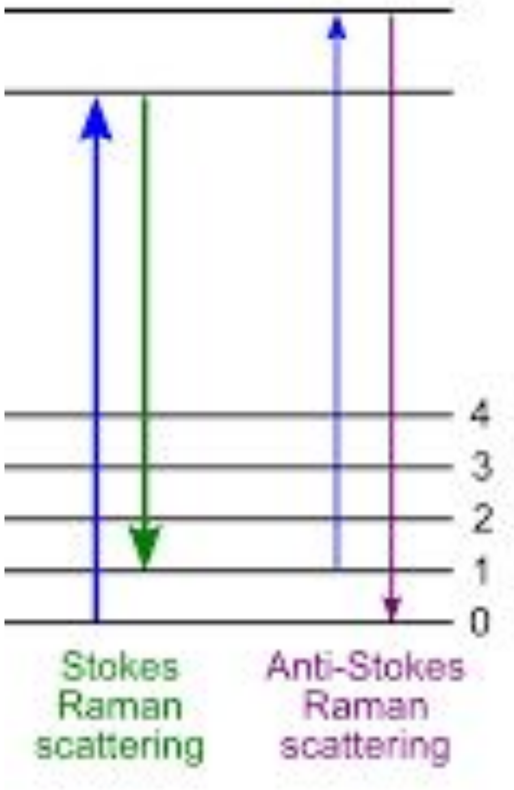
Photon interacts with a molecule and changes energy/wavelength

Common for H_2 and N_2

Photons shifted to longer wavelengths

Filling-in of absorption features can affect the absolute albedo level

For most spectral modeling purposes Raman scattering is a small effect, but it matters for high-precision albedo measurements, particularly at short wavelengths in the UV and blue optical (not very applicable to our purposes)



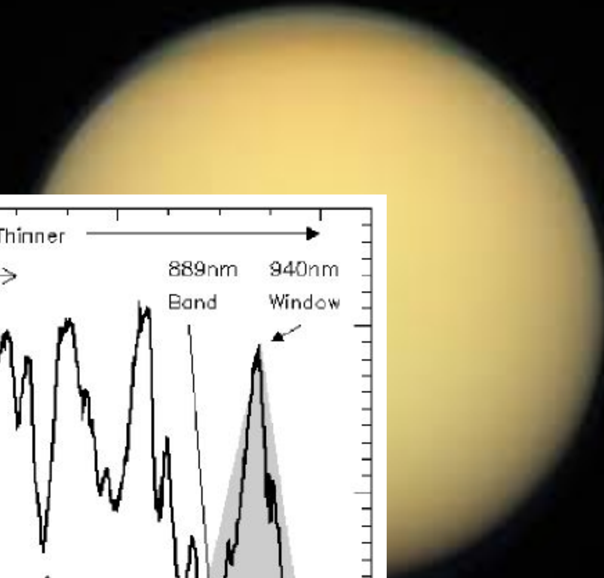
Hazes/Aerosols

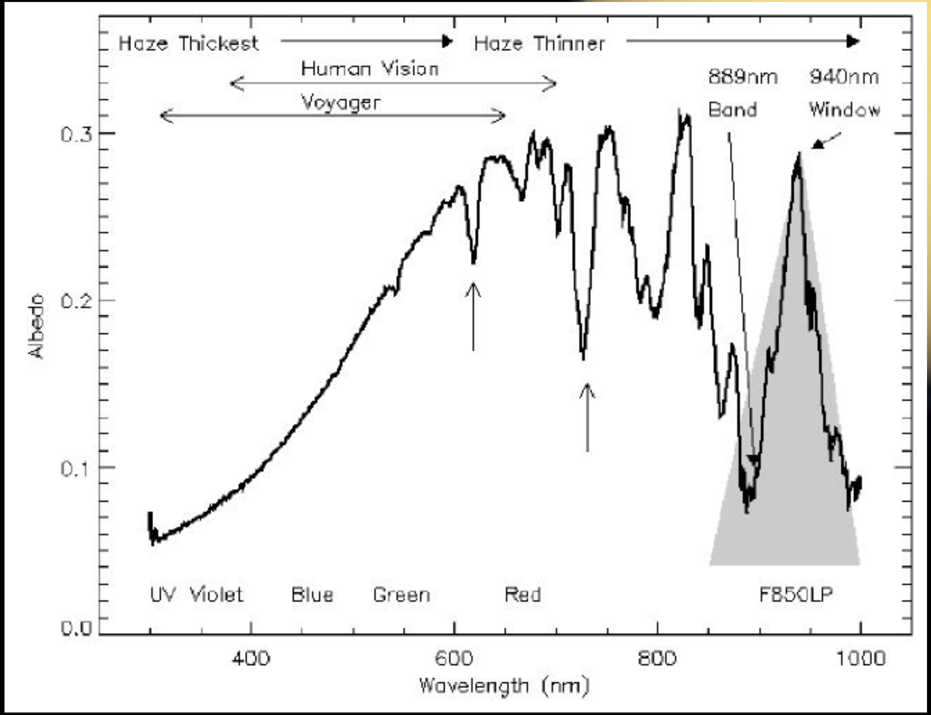
Hazes typically form by photochemistry high in the atmosphere

Flatten molecular absorption bands

Organic hazes - Large particles, tend to darken and redden spectra

Some aerosols (e.g. on sulfuric acid Venus) are mostly scattering/brightening

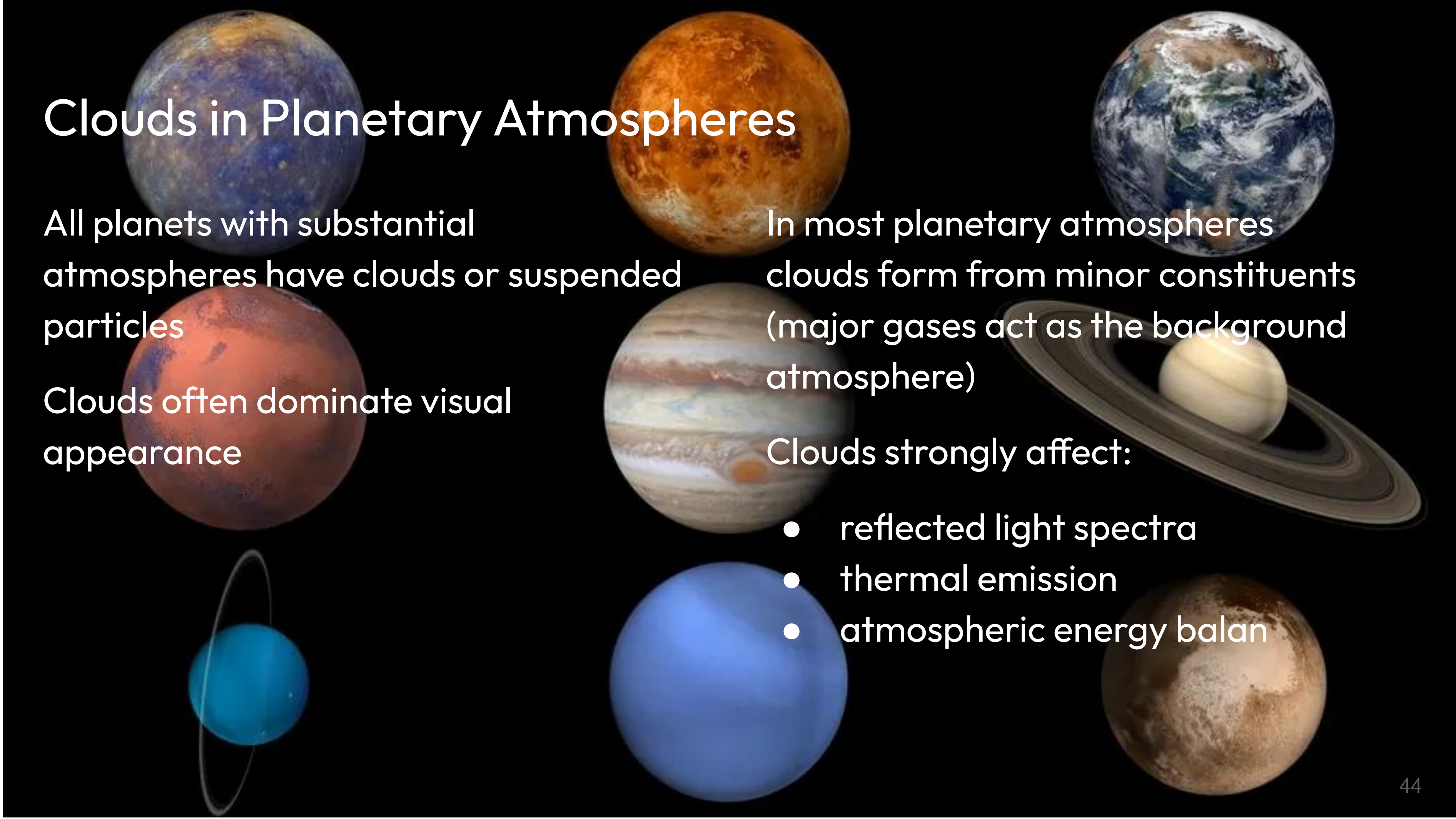




Lorenz et al. 2004

Convection & Vertical Mixing

Clouds in Planetary Atmospheres



All planets with substantial atmospheres have clouds or suspended particles

Clouds often dominate visual appearance

In most planetary atmospheres clouds form from minor constituents (major gases act as the background atmosphere)

Clouds strongly affect:

- reflected light spectra
- thermal emission
- atmospheric energy balan

Cloud Life Cycle

1. Nucleation
2. Growth
3. Evaporation
4. Vapor diffusion
5. Collection
6. Drop breakup
7. Fallout (precipitation)

Parameterized by fsed - tunable settling parameter

Larger fsed - rainout increases

Condensation and Latent Heat

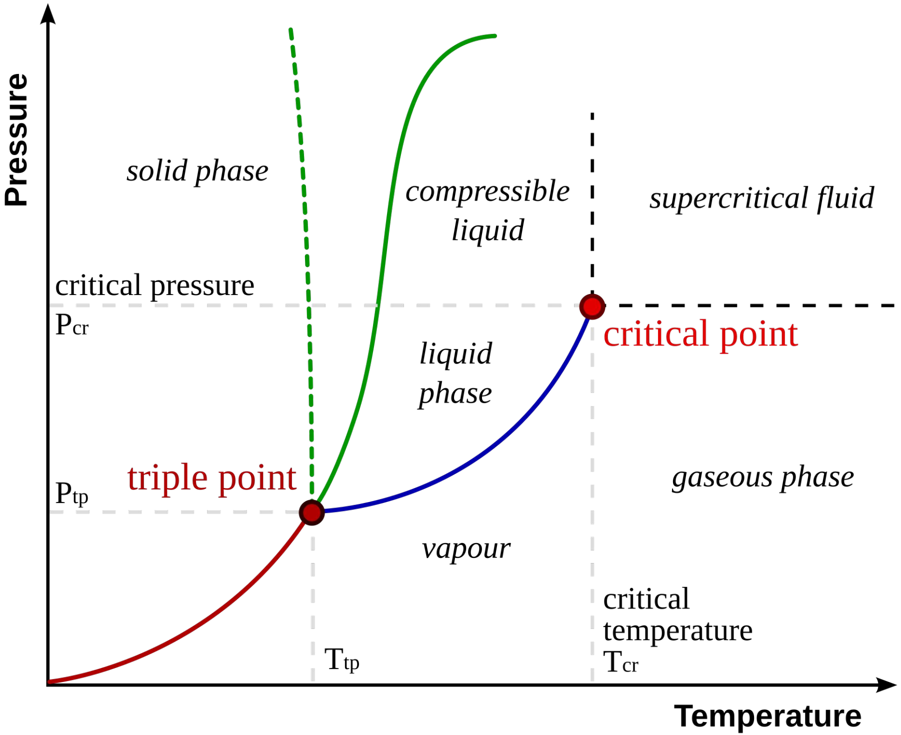
During condensation or evaporation, energy is exchanged with the atmosphere.

This energy is called latent heat.

- Condensation → latent heat released
- Evaporation → latent heat absorbed

Latent heat affects:

- atmospheric temperature structure
- convection
- cloud stability



Cloud Formation in Rising Parcels

When an air parcel rises:

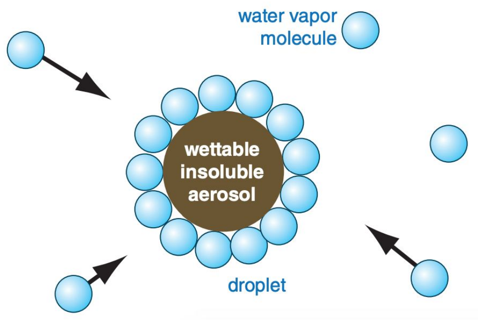
- pressure decreases
- temperature decreases

Eventually: $P_v \geq P_{vs}$

The gas becomes saturated, cloud formation then occurs.

Two types of nucleation:

- Heterogeneous nucleation
  - condensation onto particles



- Homogeneous nucleation
  - occurs when atmosphere is strongly supersaturated

Clausius–Clapeyron Equation

The saturation vapor pressure depends strongly on temperature.

For an ideal gas approximation:

$$\ln\left(\frac{P_2}{P_1}\right) = \frac{-\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

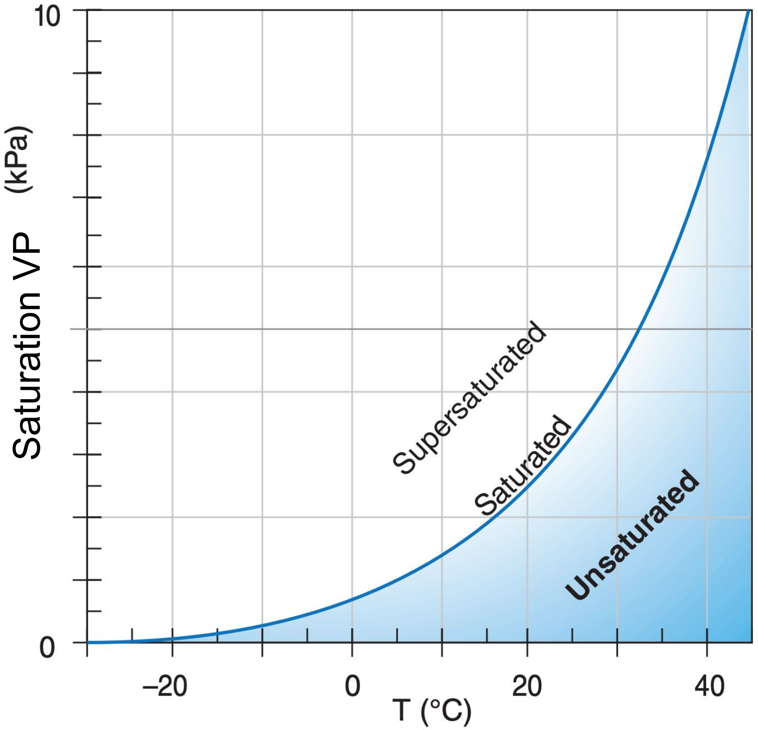
P: Pressure

T: Temperature (in Kelvin)

L or ΔH_{vap}: Latent heat or Enthalpy of vaporization

ΔV: Volume change of the phase transition

R: Ideal gas constant (≈ 8.314 J/(mol · K))



warmer air → higher saturation vapor pressure

colder air → condensation becomes easier

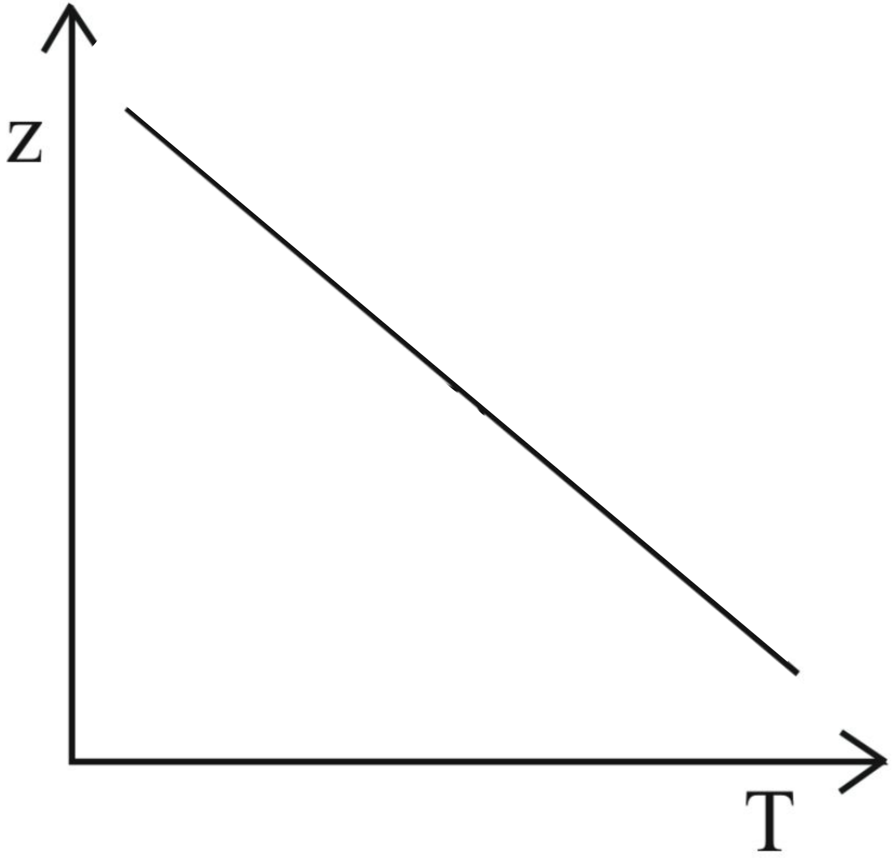
The Adiabat

Adiabatic - heat does not enter or leave the system.

- No energy is transferred when a parcel of gas ascends or descends.
- Temperature changes only from expansion/contraction

Lapse rate - the negative of the rate of temperature change with altitude change

$$\Gamma_d = -\left(\frac{\partial T_v}{\partial z}\right)_d$$



Adiabatic Lapse Rate and Convection

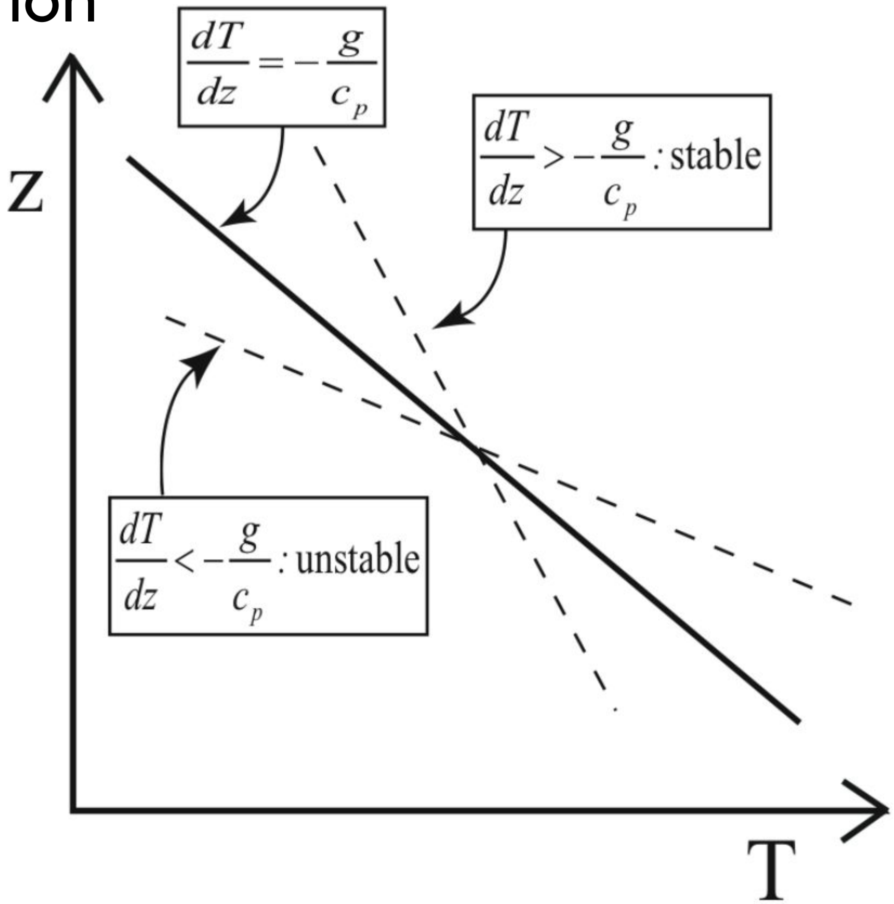
When a parcel moves vertically without heat exchange: $dQ = 0$

The temperature change is: $$\frac{dT}{dz} = -\frac{g}{c_p}$$ This is the **dry adiabatic lapse rate**.

When condensation occurs:

- latent heat modifies the lapse rate
- producing the moist adiabatic lapse rate: $$\Gamma_{\mathrm{m}} = -\left(\frac{\partial T_{\mathrm{v}}}{\partial z}\right)_{\mathrm{m}}$$

Stability to Convection



Cloud Bases and Extents

dT/dP never exceeds the adiabat

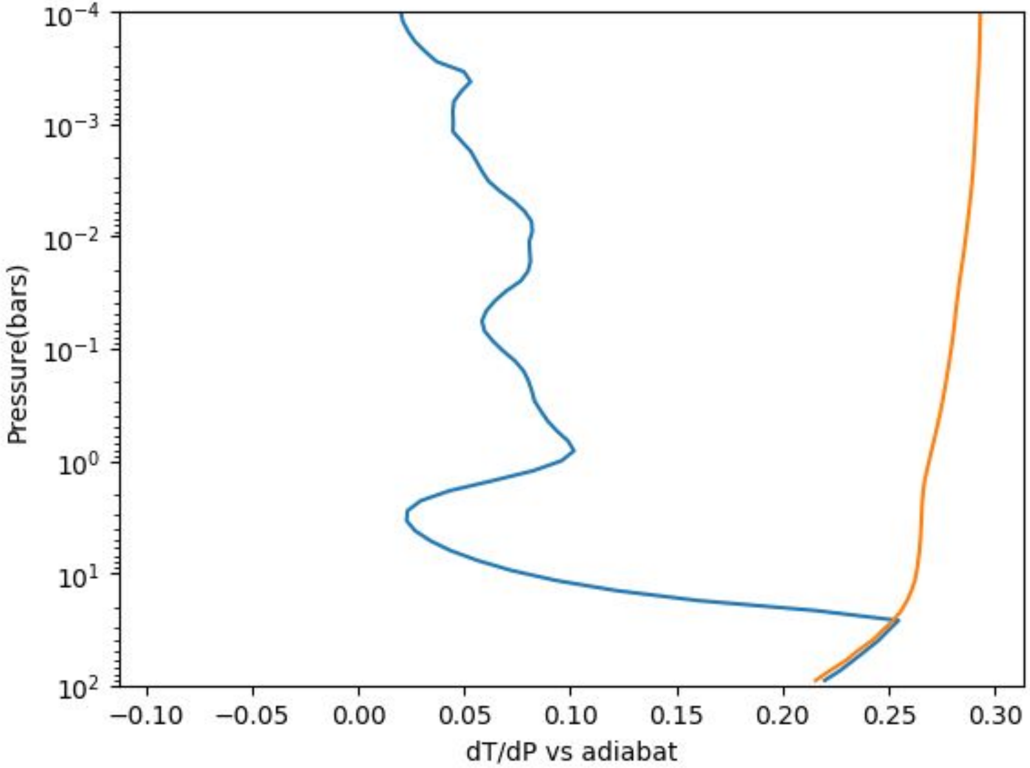
Cloud bases occur where the temperature profile intersects the condensation curve.

Cloud thickness depends on the cloud scale height, H_{cl}:

$$H_{cl} = \frac{R_v T_{cl}^2 c_p}{gL}$$

Compared to atmospheric scale height, H:

$$\frac{H_{cl}}{H} \sim 0.05 - 0.2$$

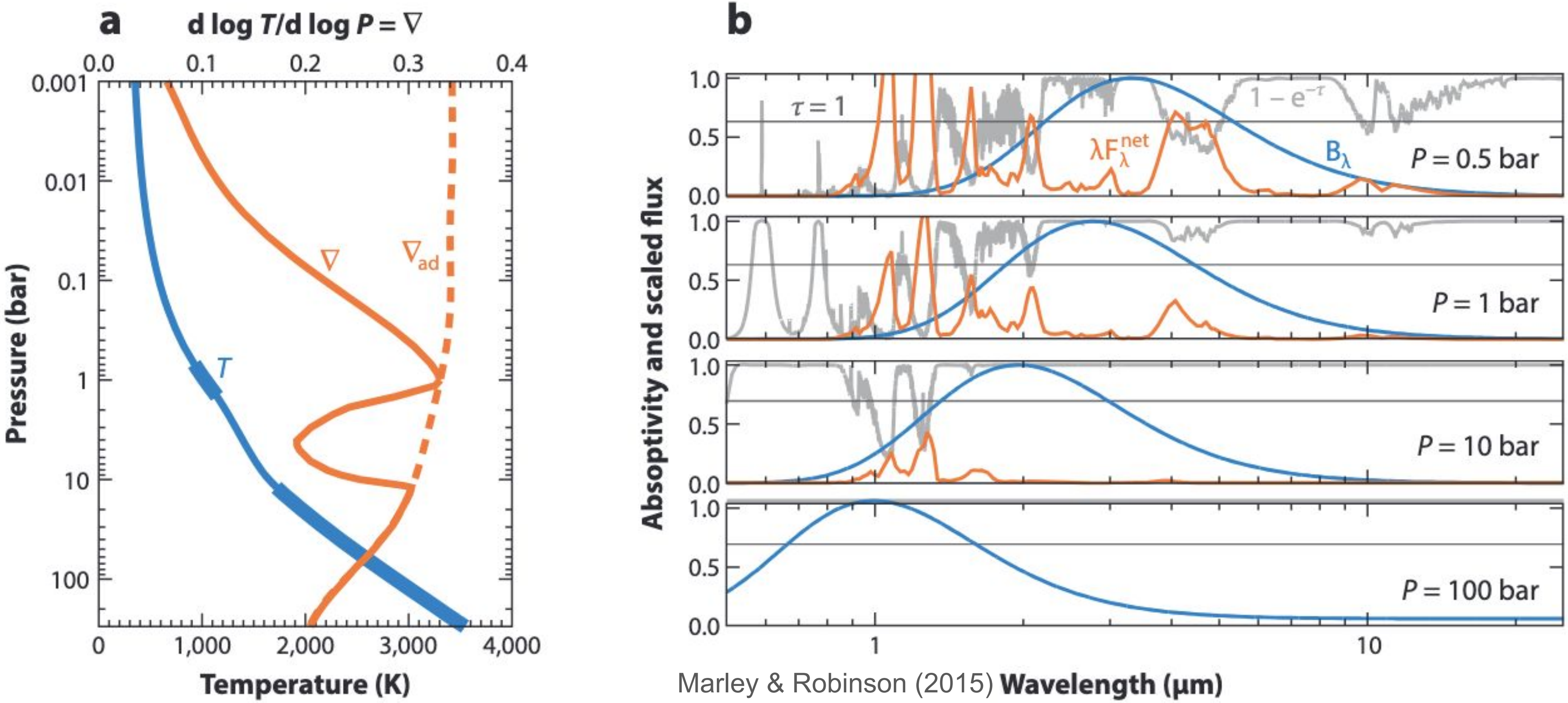


Modeling Convection - Convective Adjustment

Instead of modeling those motions directly (which is computationally expensive), models use convective adjustment:

- If the lapse rate exceeds the adiabatic lapse rate, the model adjusts the temperature profile back to the adiabatic profile.

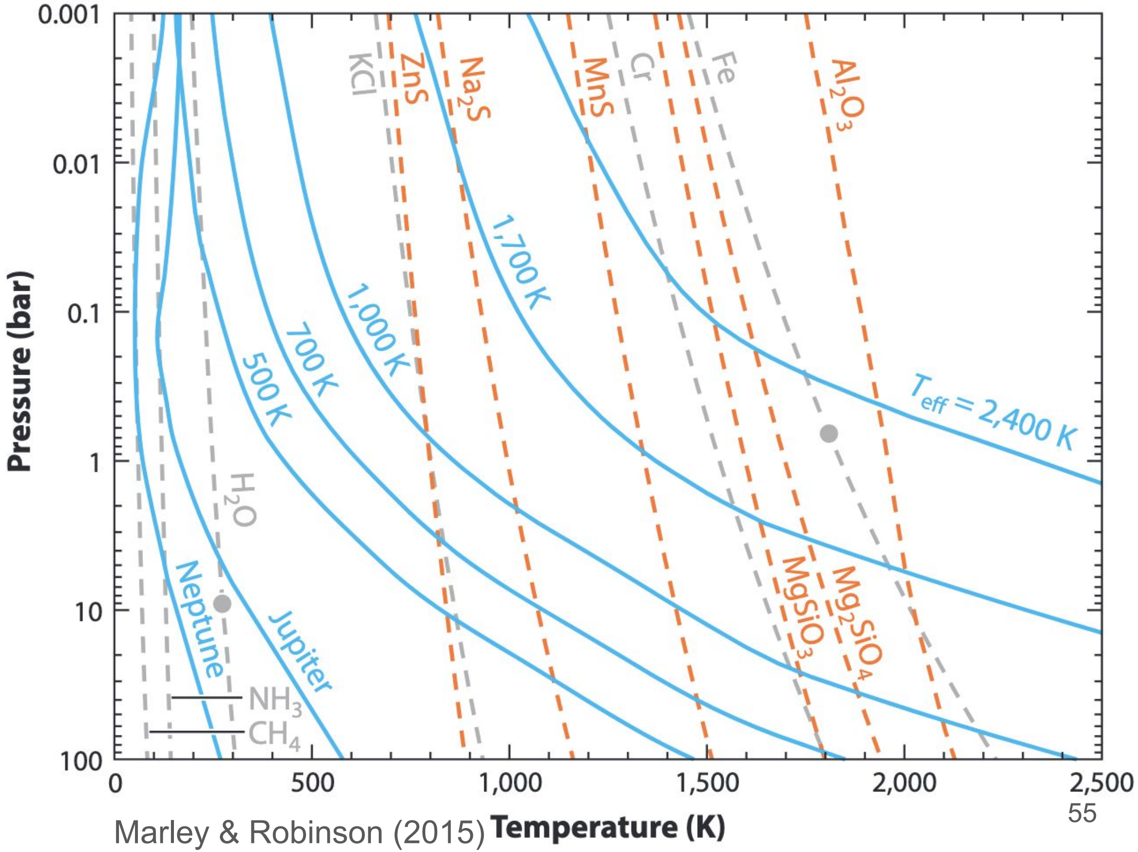
In other words, the model instantaneously mixes the unstable region until it becomes neutrally stable.



Marley & Robinson (2015)

Condensation Curves

The points where the two curves cross mark the cloud base for the specific condensate

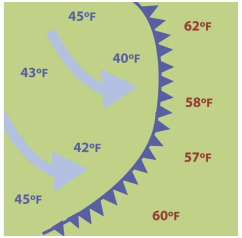


Marley & Robinson (2015)

Patchy Clouds

Clouds are hard…Sometimes they don't behave nicely with static 1-D climate models. To alleviate this or to represent the reality that clouds may not be uniformly covering the entire atmosphere, where we see variability in brown dwarfs, we can run patchy clouds! For more on this, you can read Morley et al. 2014a and Morley et al. 2014b

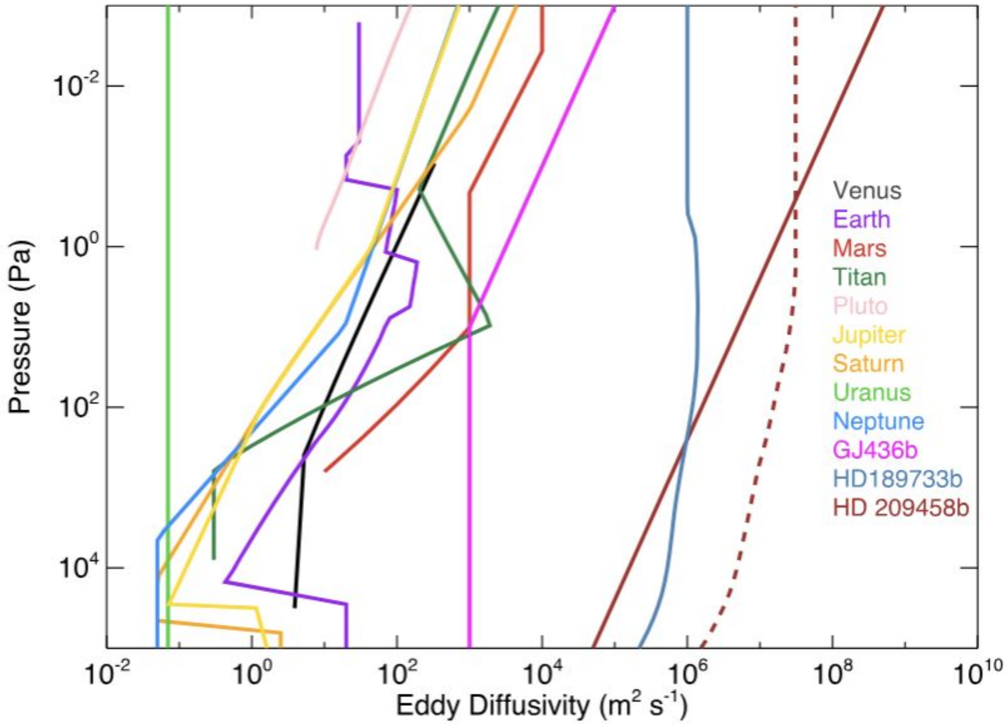
Eddy diffusion (Kzz)



Effective turbulence arising from atmospheric motions on large and small scales

Parameterization, not really measureable

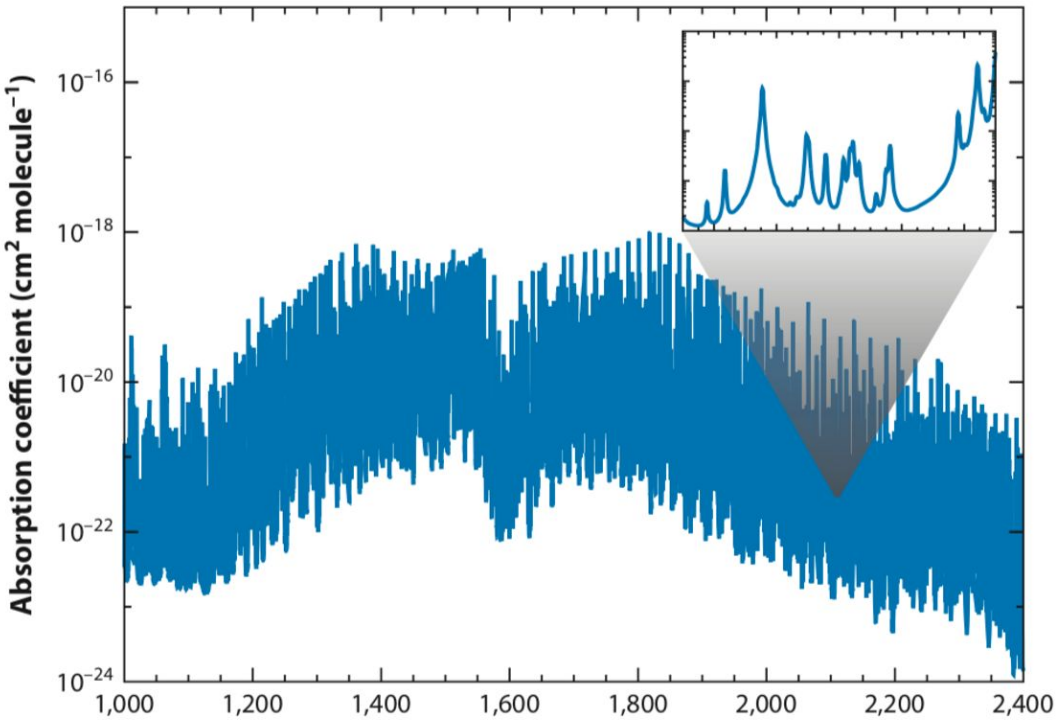
How changing Kzz changes the atmosphere



Zhang and Showman 2018

Opacities

Opacities



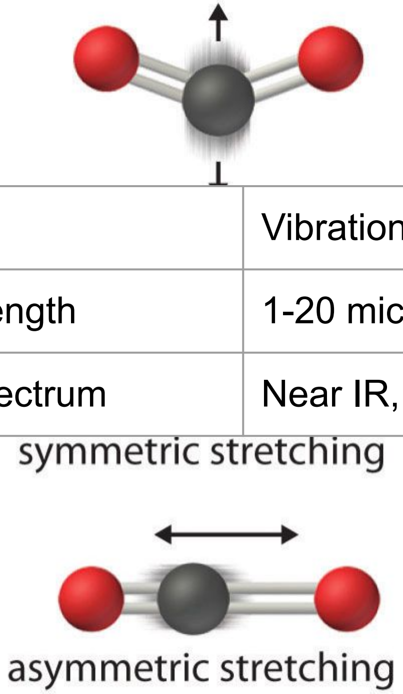
Each absorption band is formed from a collection of individual absorption lines described by:

- Line position
- Line strength
- Line shape function

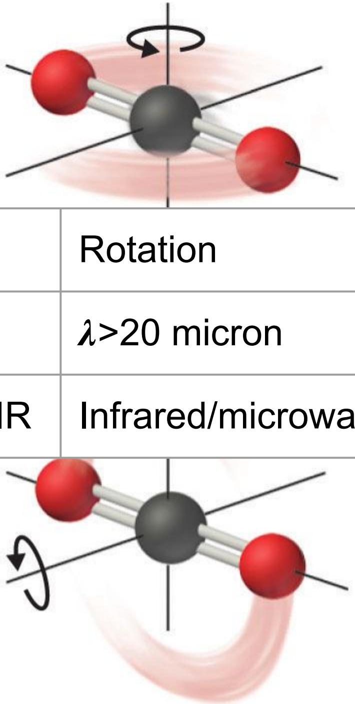
Those depend on the interaction of light and matter

Atomic and Molecular Absorption

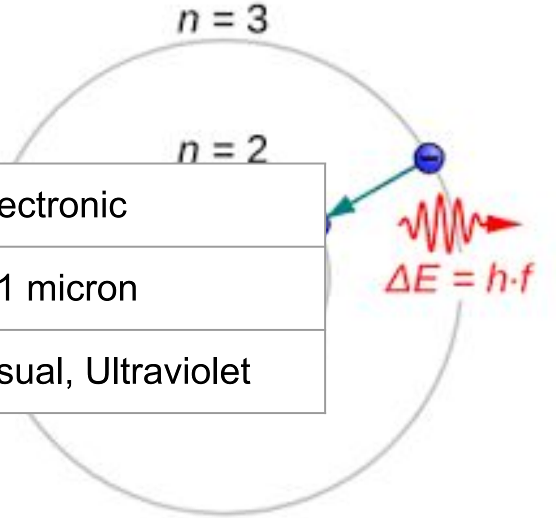
	Vibration	Rotation	Electronic
Wavelength	1-20 micron	λ>20 micron	< 1 micron
EM Spectrum	Near IR, Thermal IR	Infrared/microwave	Visual, Ultraviolet



Vibration

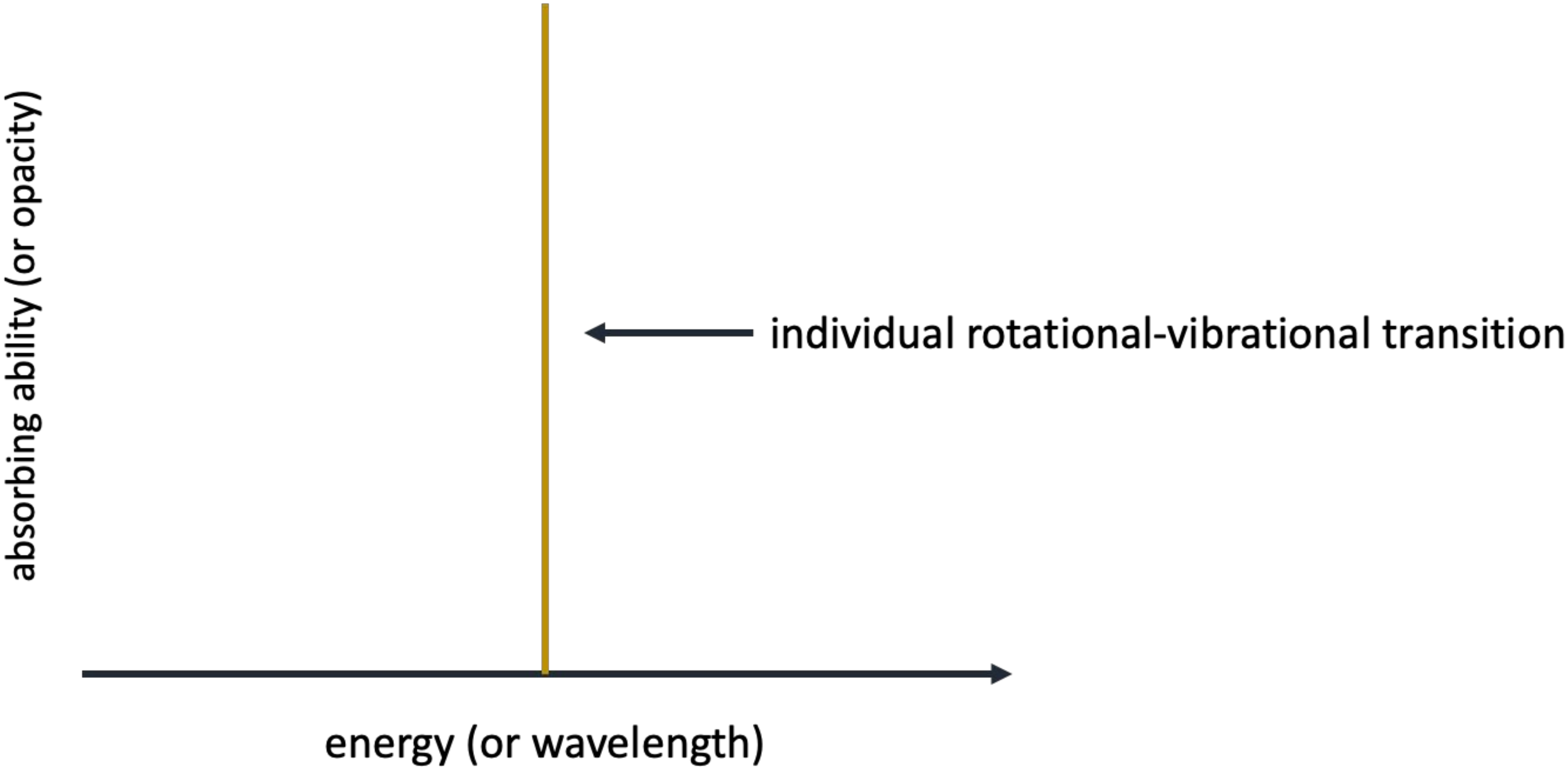


Rotation

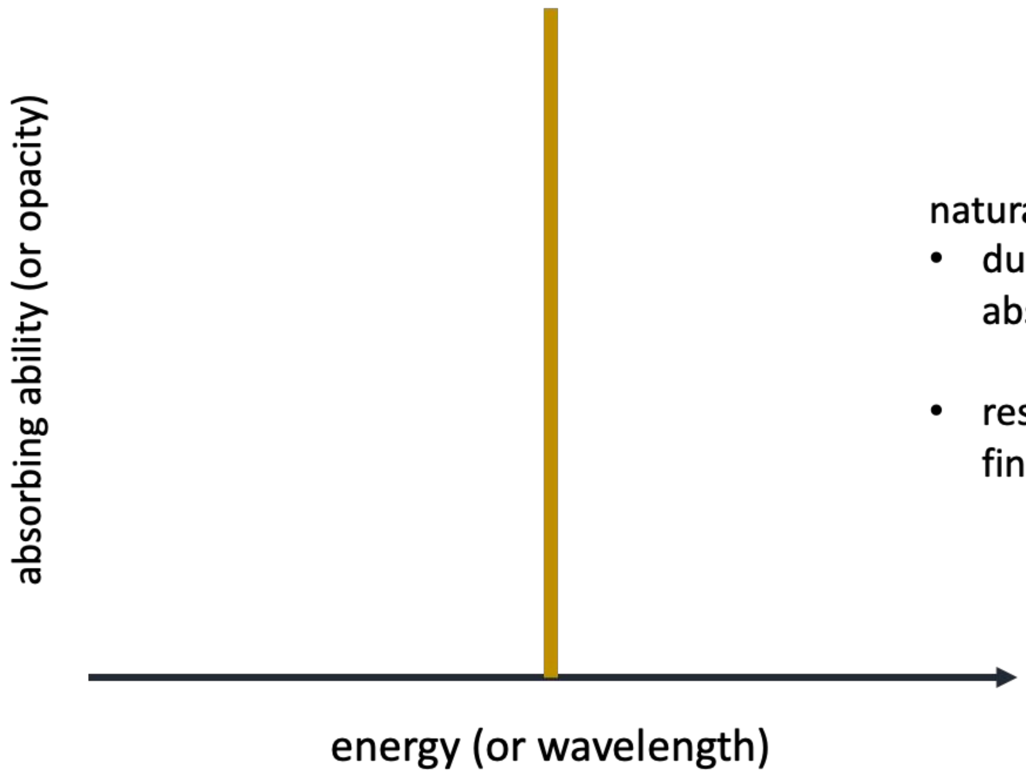


Electronic Transition

Line Broadening Mechanisms: Natural Broadening



Line Broadening Mechanisms: Natural Broadening

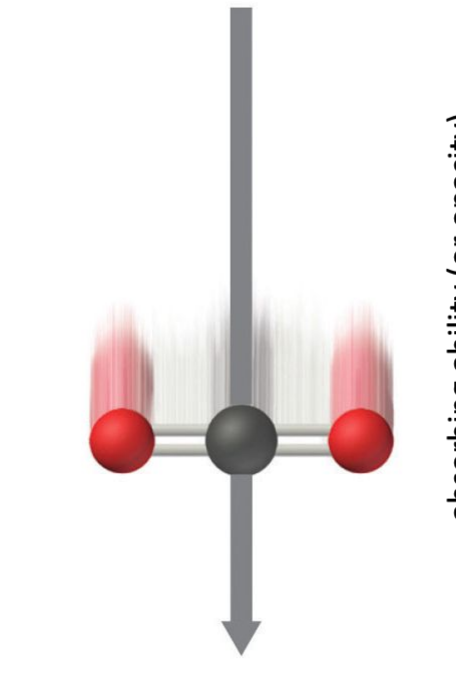


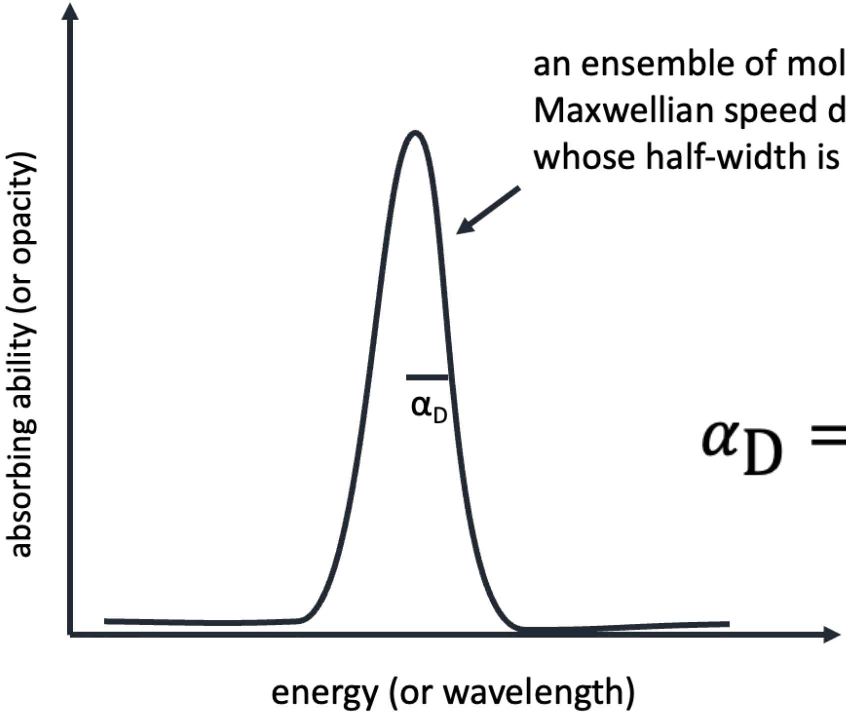
natural broadening:

- due to uncertainty principle and finite absorption time

- results in extremely narrow, but finite, broadening

Line Broadening Mechanisms: Doppler Broadening



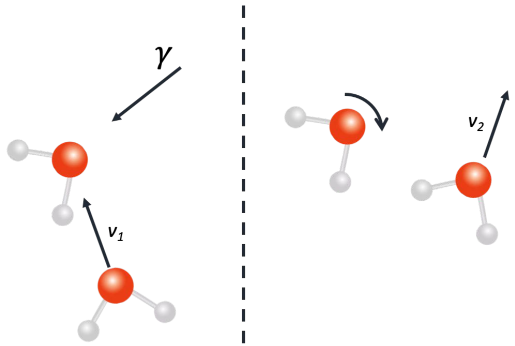


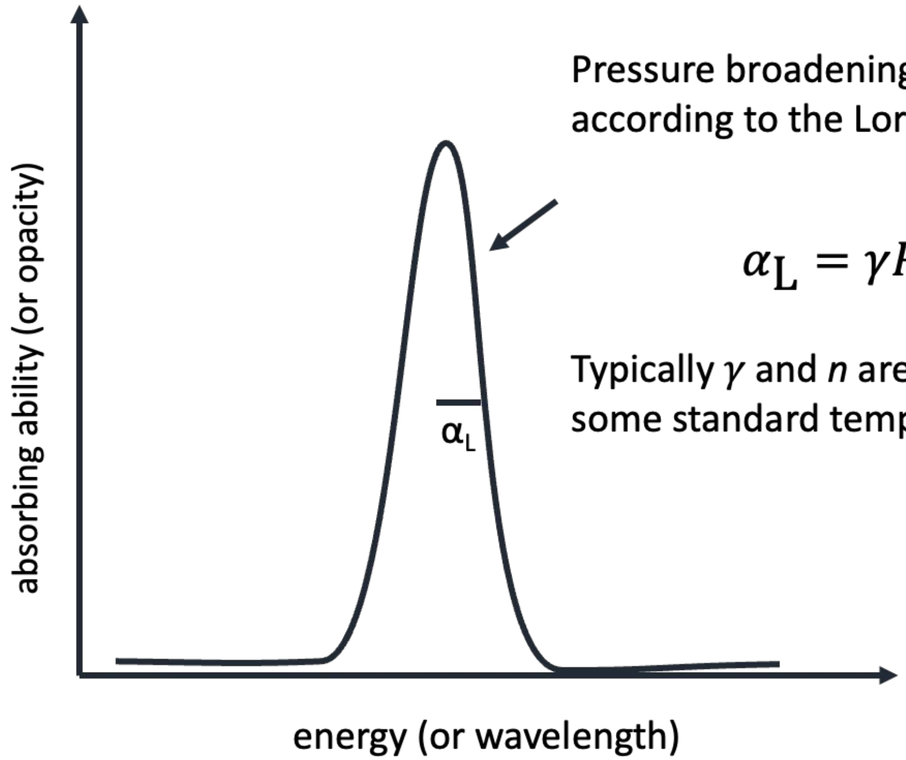
an ensemble of molecules moving according to a Maxwellian speed distribution generates features whose half-width is given by the Doppler half-width:

$$\alpha_D = \frac{\lambda}{c}\sqrt{2\ln 2\,\frac{k_B T}{m}}$$

Note: *T* is temperature and *m* is the molecular mass.

Line Broadening Mechanisms: Pressure Broadening



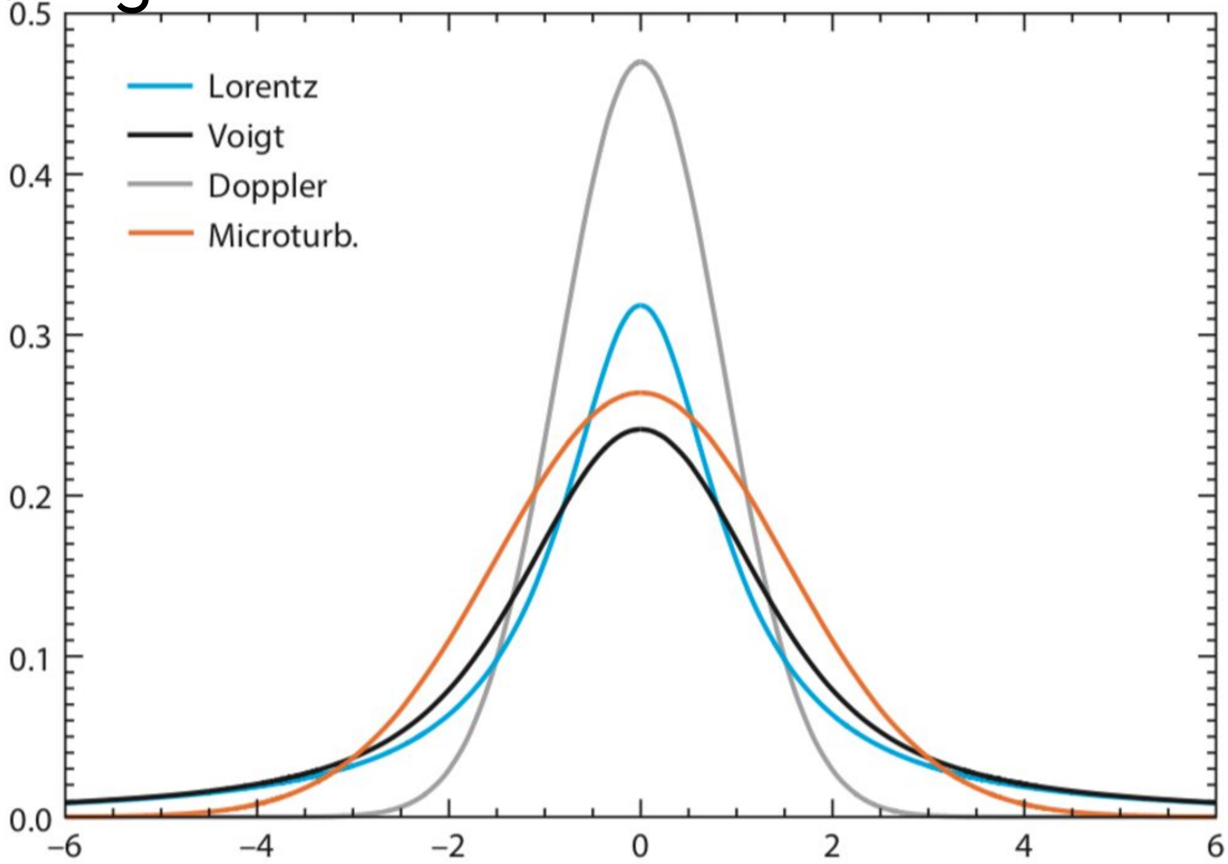


Pressure broadening widens absorption lines according to the Lorentzian half-width:

$$\alpha_{\mathrm{L}} = \gamma P \left(\frac{T}{T_0}\right)^n$$

Typically γ and *n* are measured in the lab (at some standard temperature T_0).

Line Broadening



Line-by-line versus Correlated-K

Line-by-line:

- Resolve each line
- Very expensive

Correlated-k:

- The general principle is to order spectral lines within a given spectral bin, producing a smooth cumulative distribution function to represent opacity, which can be more efficiently sampled
- Integrate statistically
- Used in PICASO grids

Giant Planet Evolution

Stars, brown dwarfs, and planets evolve over time

Loosing their gravitational energy of formation as heat

Equations of Planetary Interiors and Evolution

Hydrostatic Equilibrium & mass continuity combined

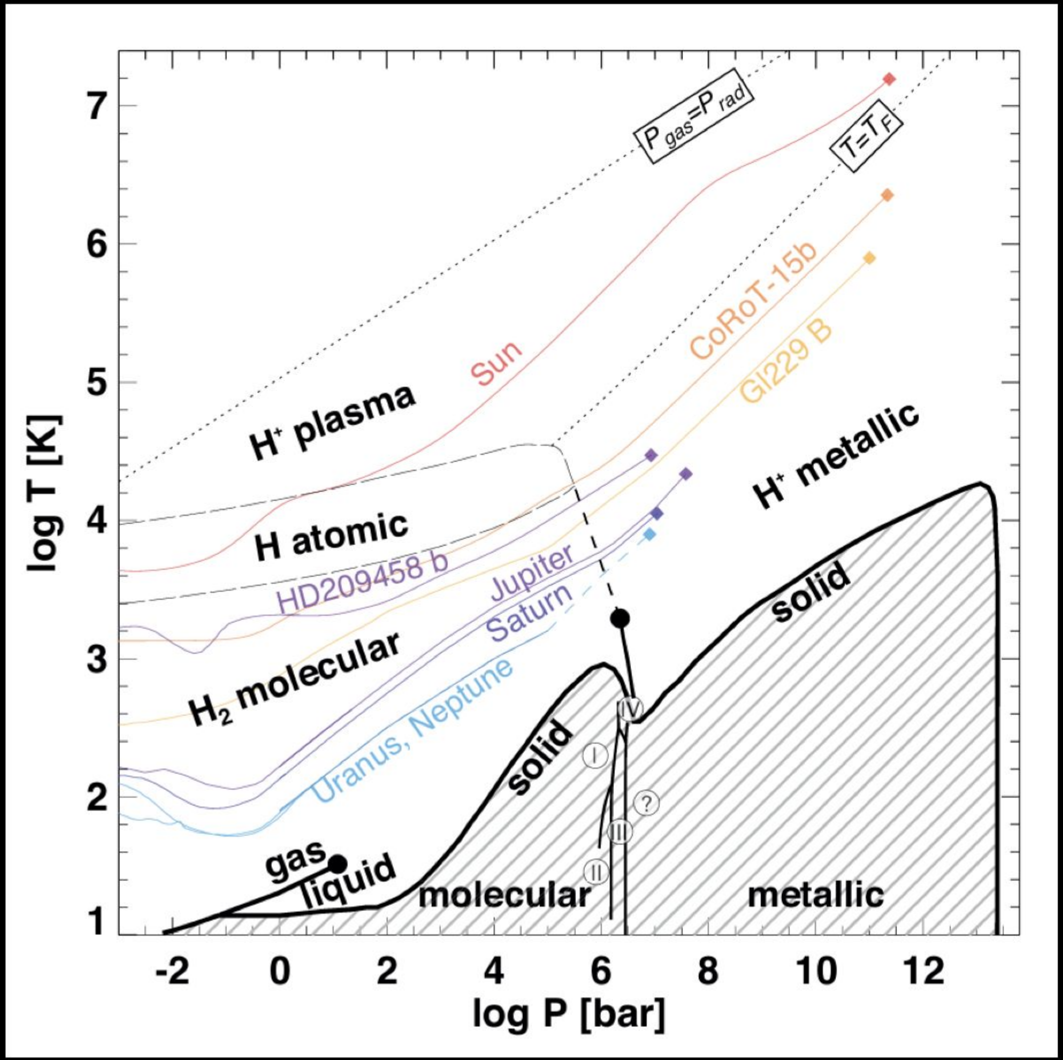
$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

Mass continuity

$$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}$$

Luminosity, nuclear burning, and thermal contraction

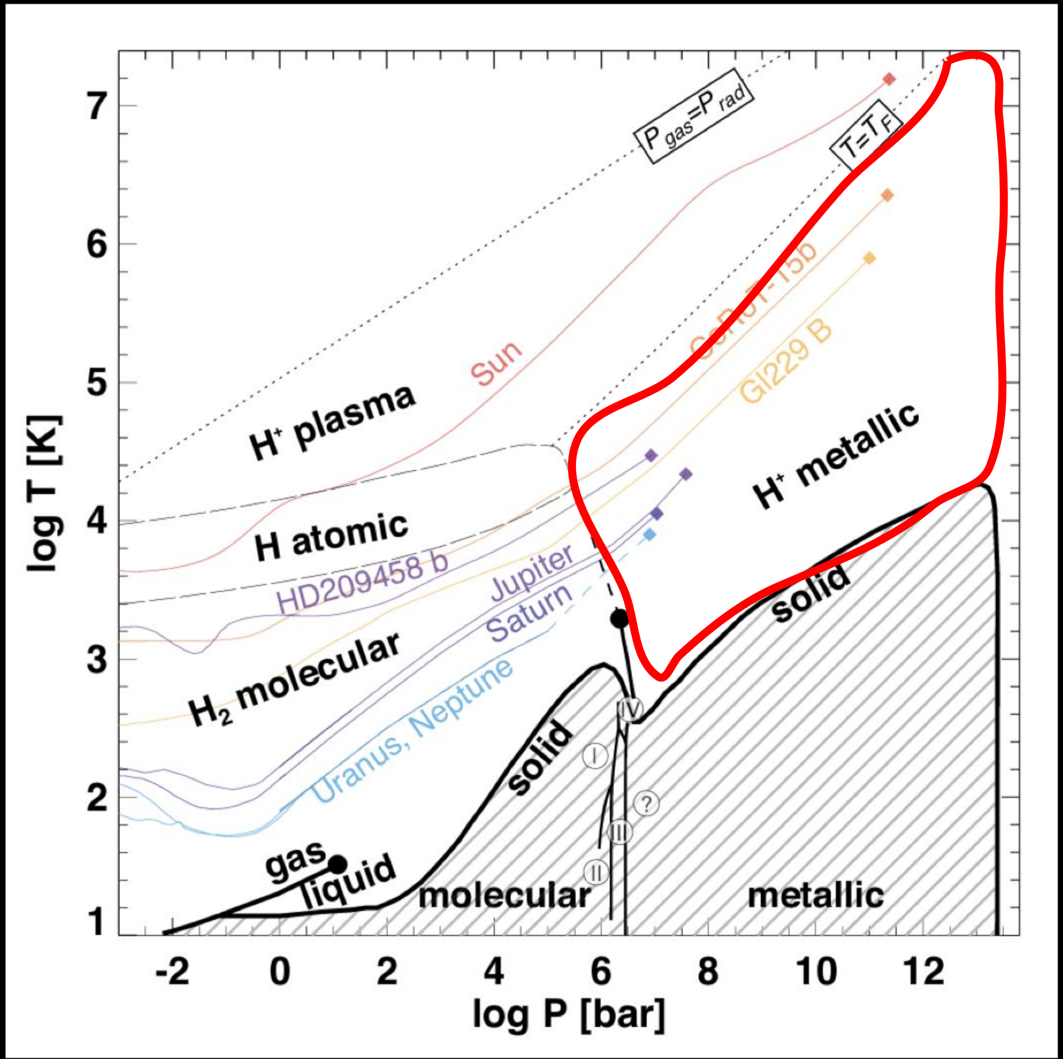
$$\left(L - \int_0^M \epsilon_{nuc} dm \right) dt = -\int_0^M T dS dm$$



Equation of State of Interiors

1. Extreme pressures and temperatures can be achieved in interiors
2. What are the phases of H and He at all these high T and P?
3. What is their equation of state? i.e., relation between P,T,ρ, and entropy (S)

Guillot and Gautier (2014)



Equation of State of Interiors

1. Planetary interiors can be degenerate in nature i.e., supported against gravity by electron degeneracy pressure.

Guillot and Gautier (2014)

Nuclear burning?

$$p + p \rightarrow d + e^+ + \nu_e$$

Bottleneck step, needs higher temperatures or pressures

$$p + d \rightarrow {}^3He + \gamma$$

Much faster, can occur at lower temperatures

1. If the interiors of planets reach T and P that are high enough, nuclear burning can start and slow down their contraction and cooling over time.

2. Typically, below ~12-13 Jupiter masses, the interiors do not reach such temperatures and nuclear burning can be ignored.

Nuclear burning?

$$p + p \rightarrow d + e^+ + \nu_e$$

$$p + d \rightarrow {}^3He + \gamma$$

Bottleneck step, needs higher temperatures or pressures

Much faster, can occur at lower temperatures

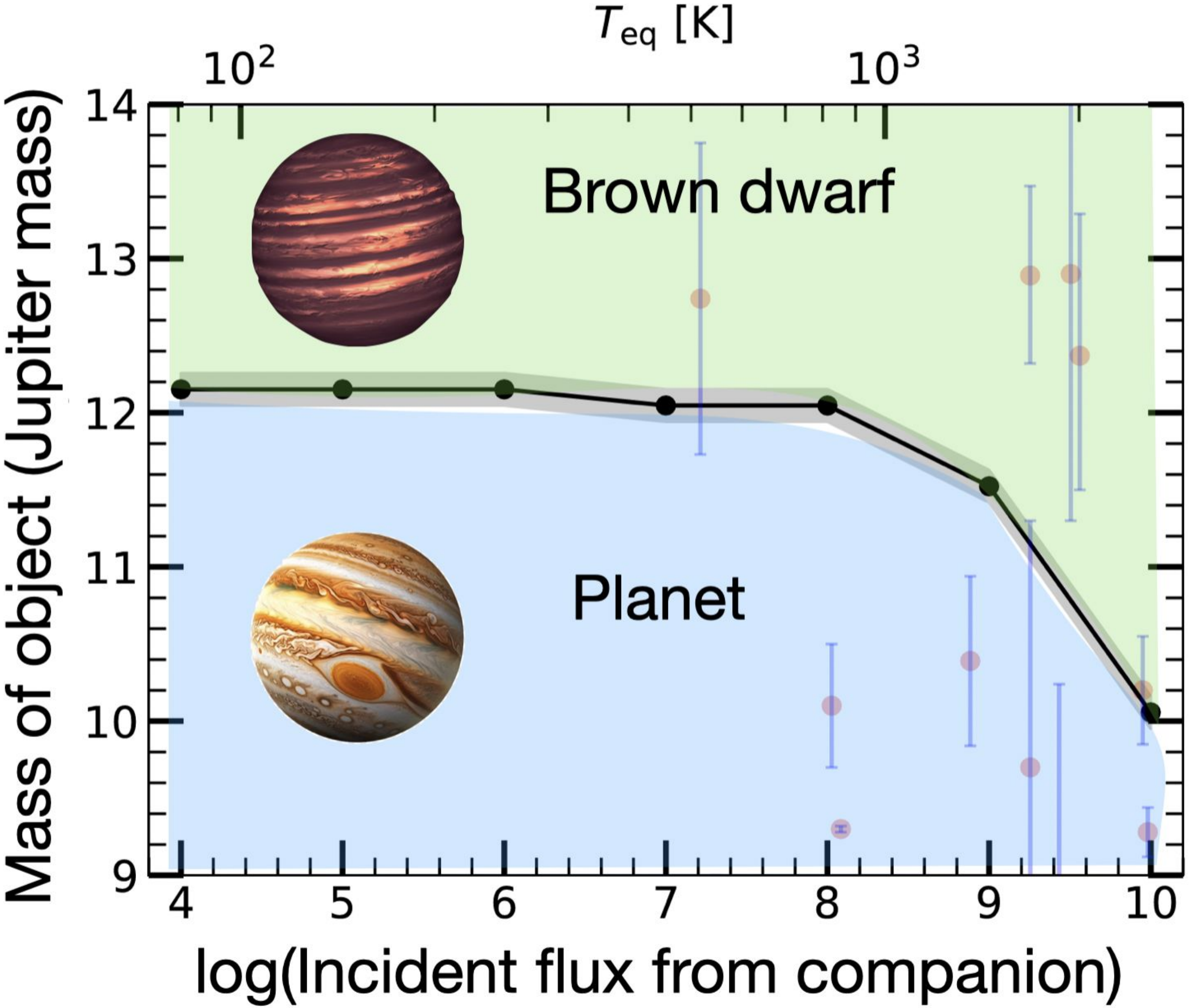
1. But multiple lines of evidence suggests that this boundary of 12 Jupiter mass is not absolute and depends on–

    1.1. **Stellar irradiation** (Mukherjee +(2026))

    1.2. **Clouds** (Morley+ (2024))

    1.3. **Composition** (Marley+ (2021), Spiegel+ (2011))

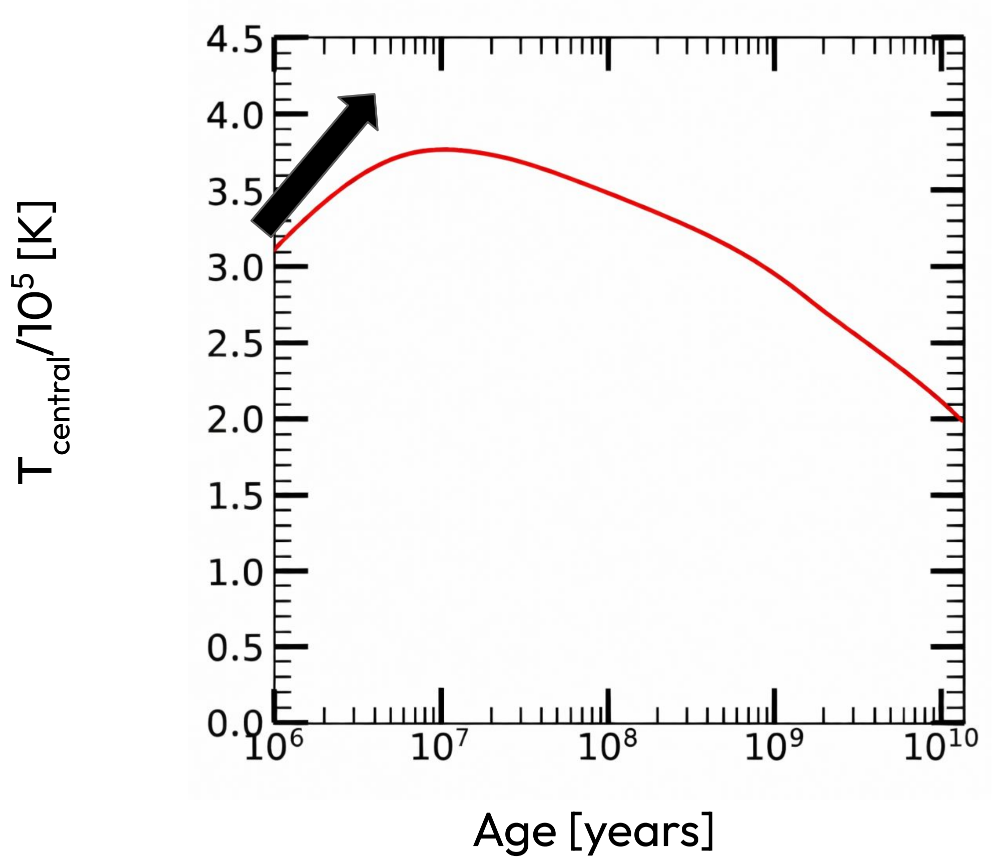
    1.4. **Presence of cores** (Molliere+(2012))



The planet-brown dwarf mass boundary can be strongly sculpted by how much irradiation does the object receives.

Mukherjee +(2026)

Evolution of substellar interiors

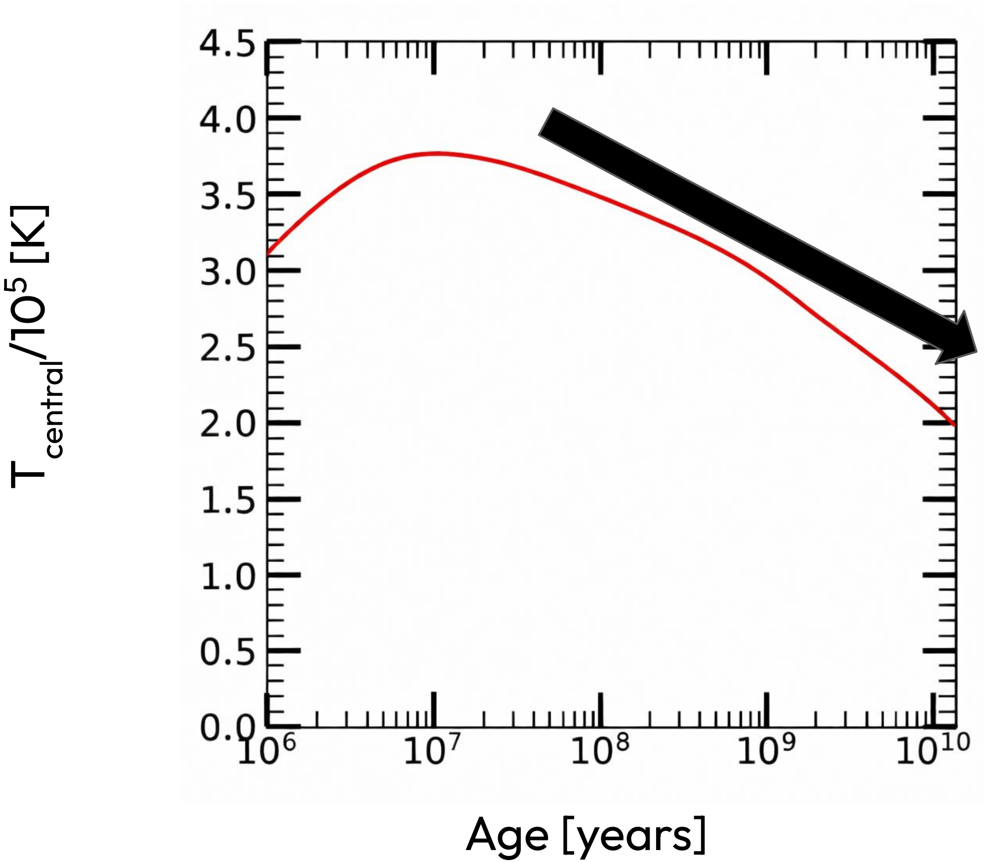


Planet loses heat to space, its total energy becomes more negative, its thermal energy increases. **So, initially, centre heats up as object looses energy**.

E = -K (virial theorem+energy conservation)

Mukherjee+ (2026)

Evolution of substellar interiors

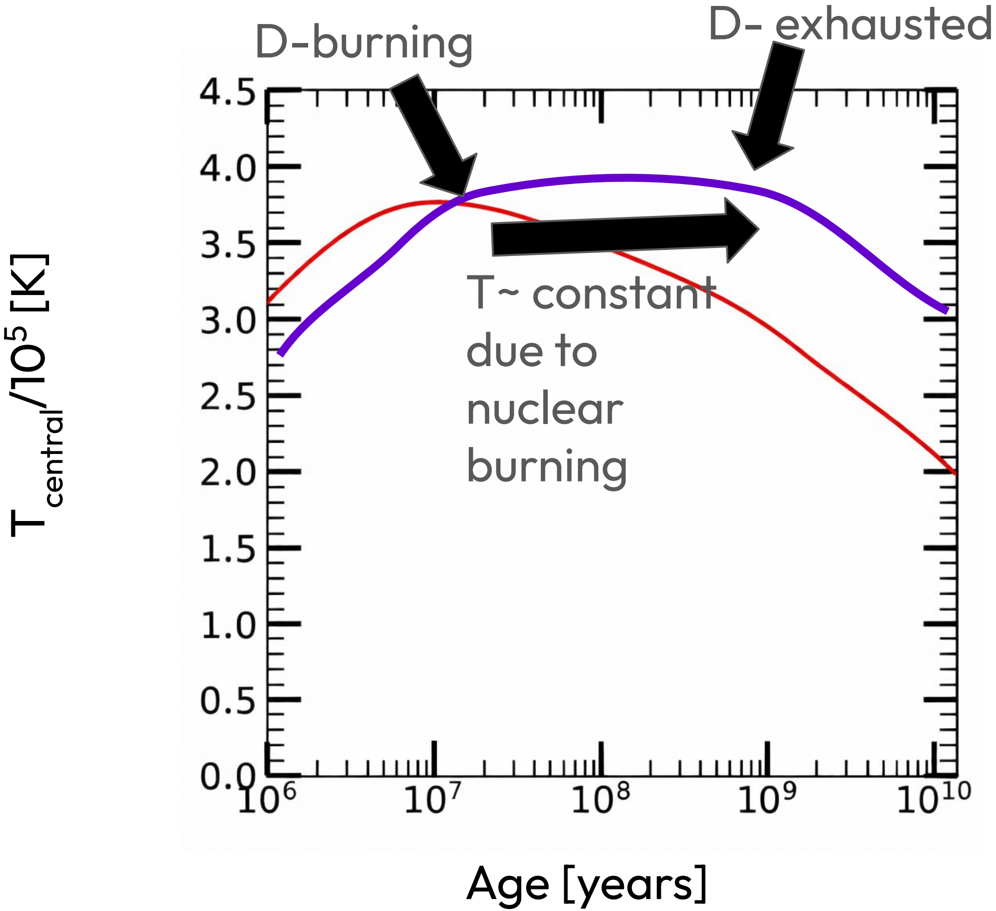


As the central T and P rises, the objects interior becomes more compact and eventually it becomes degenerate and supported by electron degeneracy pressure.

Pressure and temperature decouples, as gravity is supported by degeneracy pressure. Object no longer contracts and just cools over time.

Mukherjee+ (2026)

Evolution of substellar interiors

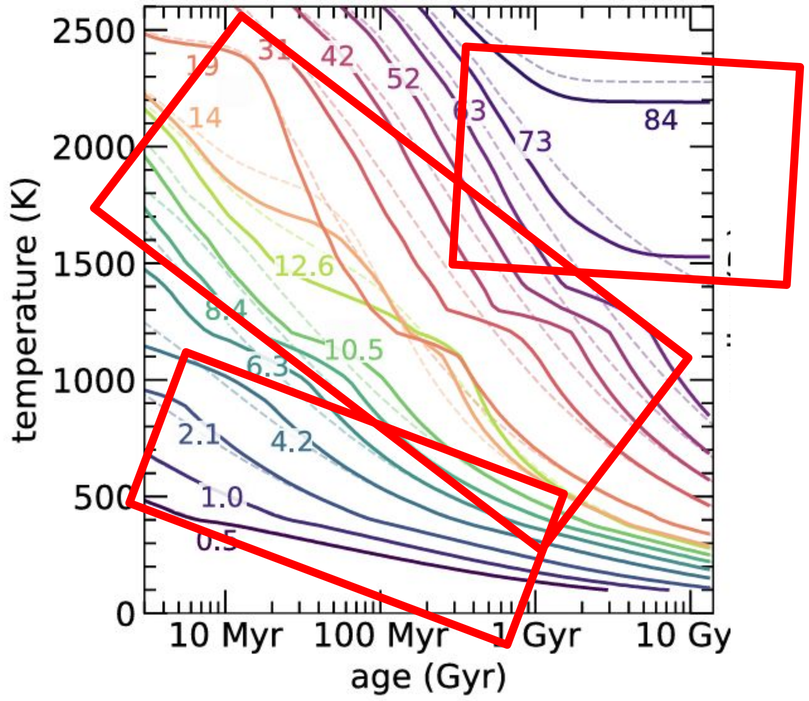


If the centre reaches T and P that are high enough to fuse deuterium, then the central T change can be halted by nuclear energy generation.

But soon the object will run out of primordial deuterium, and again start cooling as a degenerate body.

Mukherjee+ (2026)

Planets cool over time



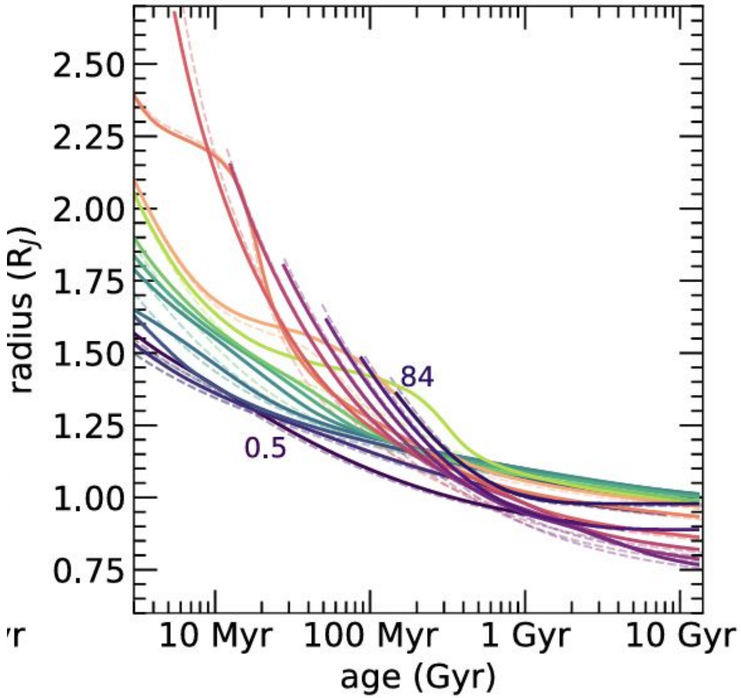
1. Planets lose their heat of formation to space and cool over time.

2. Younger planets are hotter than older planets, given same mass.

3. Nuclear burning can temporarily halt contraction in higher mass objects.

Morley+ (2024)

Planets contract over time



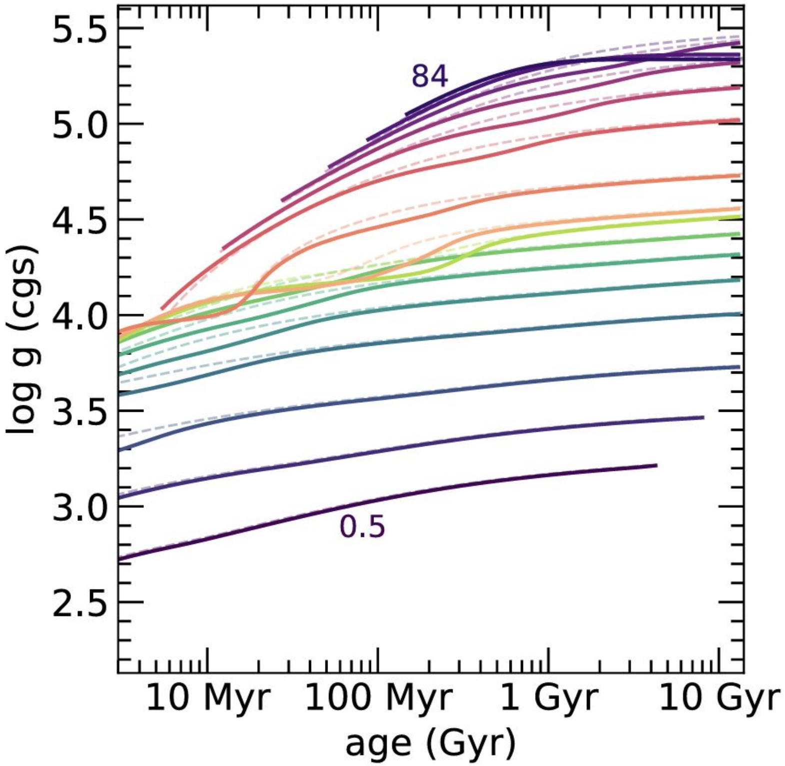
1. As planets cool they also contract.

2. But giant planets that are H/He dominated do not contract below 0.75-1 Jupiter radii.

3. This is due to electron degeneracy pressure in their interiors.

Morley+ (2024)

Planet gravity increases with time

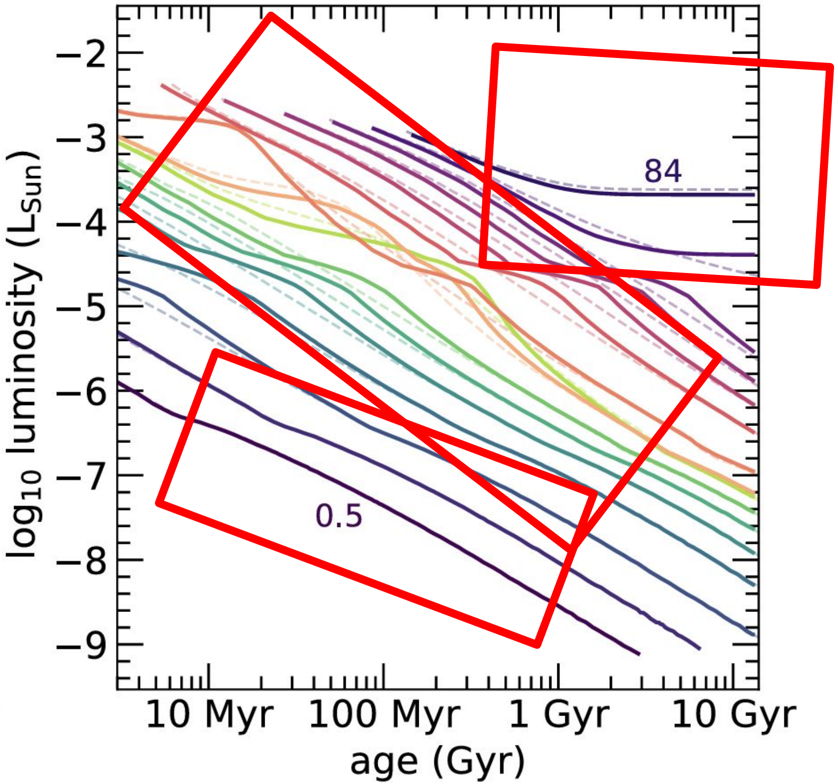


1. As planet radius decreases over time, their gravity increases.

2. Younger planets have lower gravity compared to older planets, given same mass.

Morley+ (2024)

Planet luminosity declines over time

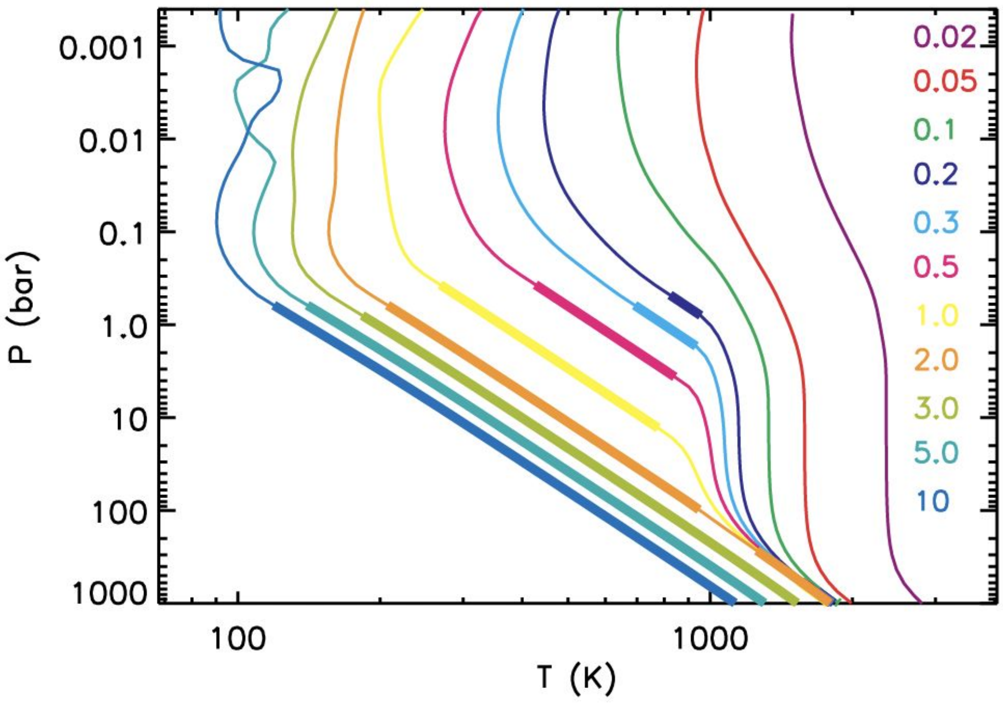


1. Planet luminosity declines over time as their temperature and radius declines over time.

2. Younger planets are much brighter than older planets, given same mass.

Morley+ (2024)

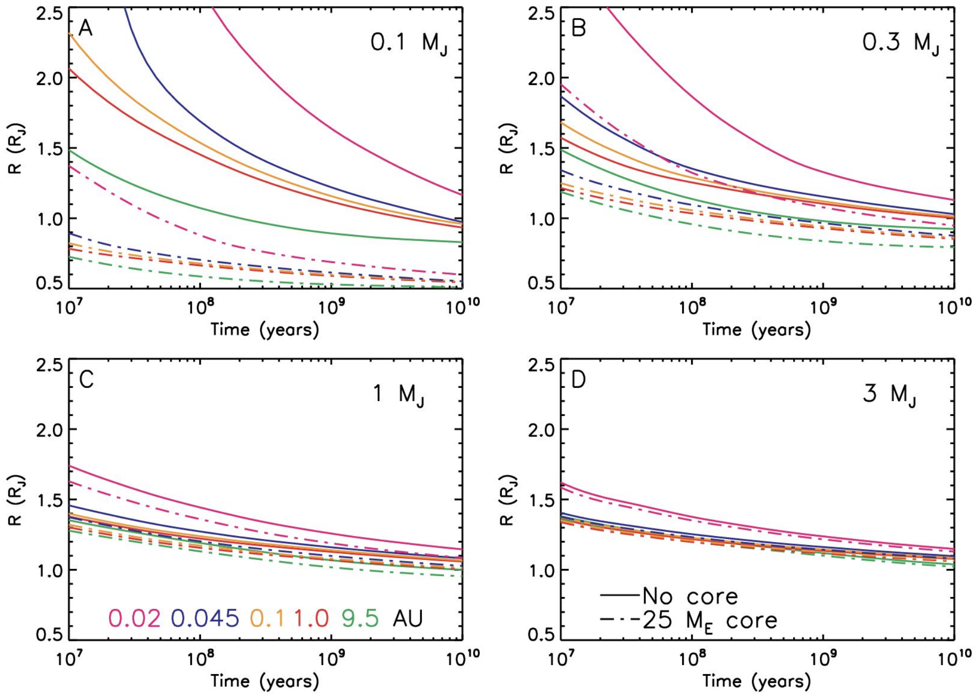
Effect of stellar irradiation on evolution



Irradiation pushes the radiative-convective boundary deeper, slowing down evolution

Fortney+ (2007)

Irradiated planets are more inflated, effect of cores



1. Irradiation inflates planets.
2. It slows down their evolution.
3. Effect is smaller for higher mass planets.
4. Metal cores shrink planets.

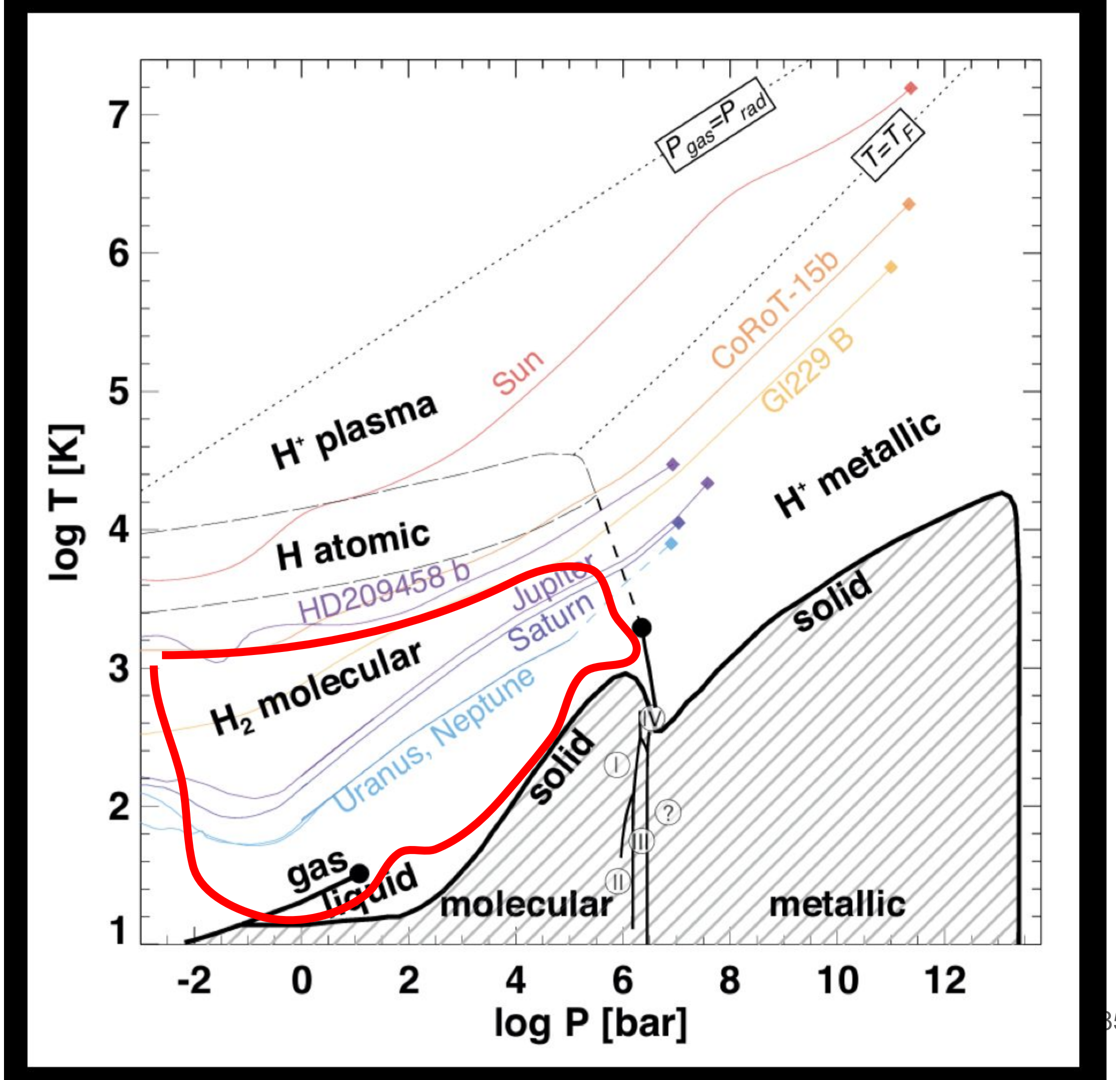
Fortney+ (2007)

Chemistry

Chemistry

Planetary atmospheres can be host to 1000s of chemical reactions among atoms, molecules, and ions.

This giant and complex network of chemical reactions drive the observable chemical composition of exoplanetary atmospheres.

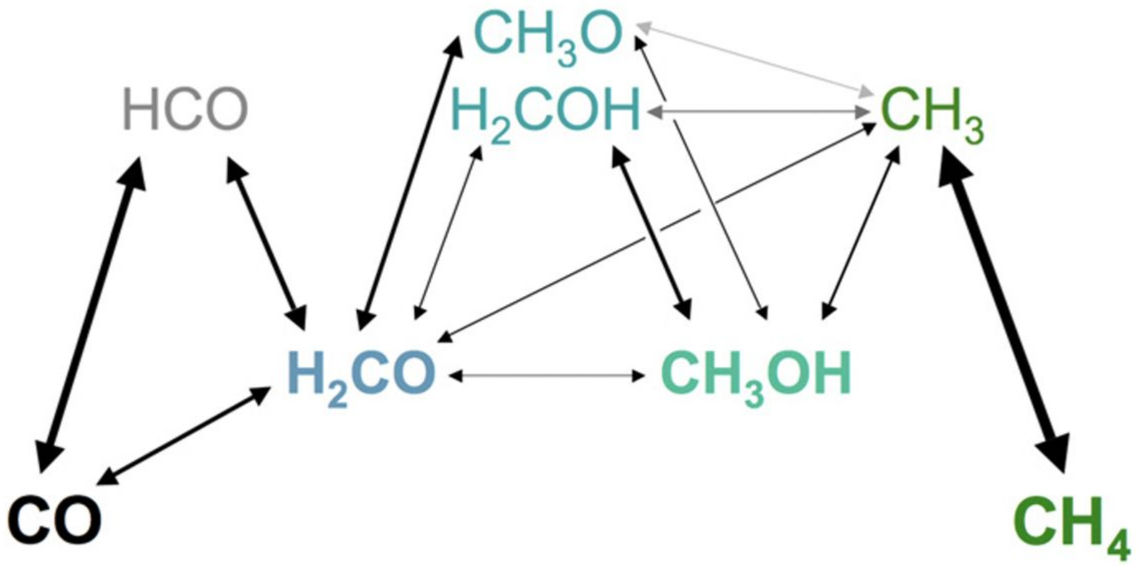


Chemical Equilibrium

$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$

$$t_{chem}$$

Works if t_{chem} is the fastest timescale in the atmosphere



Zahnle and Marley (2014)

Chemical Equilibrium

$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$

t_{chem}

Works if t_{chem} is the fastest timescale in the atmosphere

Chemical timescales are typically exponential functions of temperature i.e., reactions are very fast at high temperatures and pressures.

$$t_q = Ap^{-b}m^{-c}\exp(B/T).$$

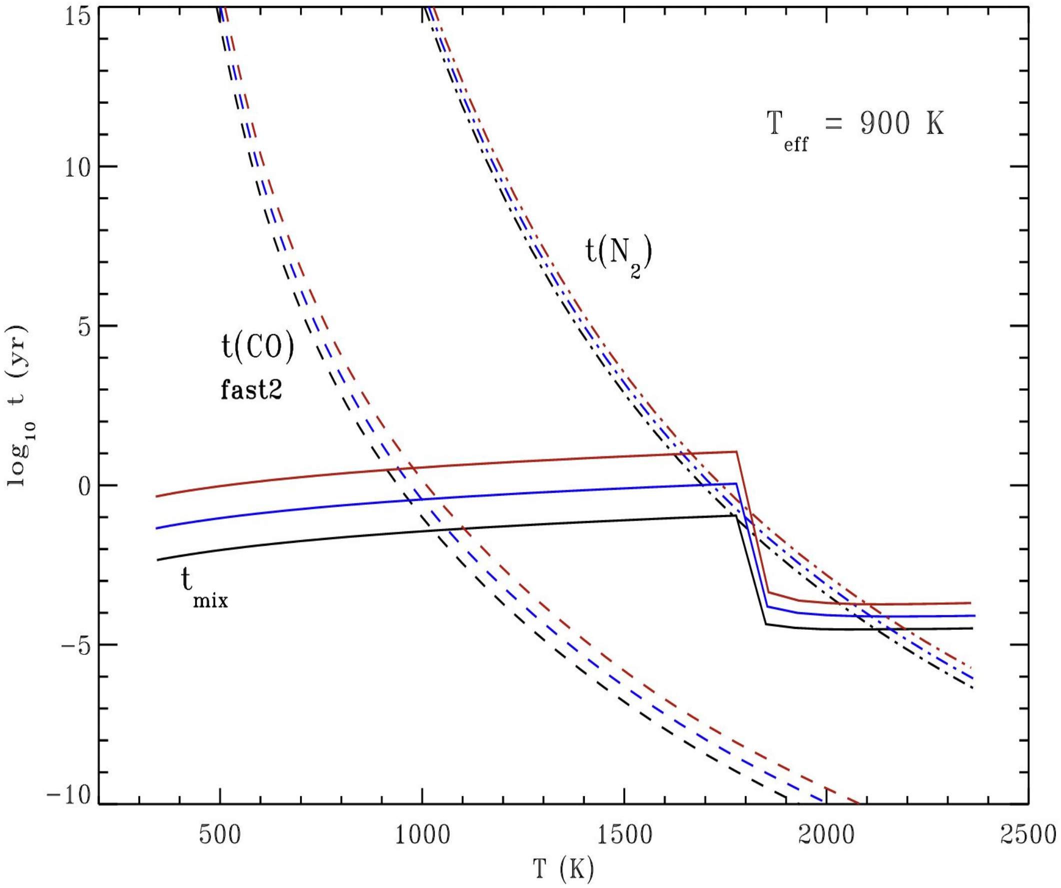
Zahnle and Marley (2014)

Chemical Equilibrium

$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$

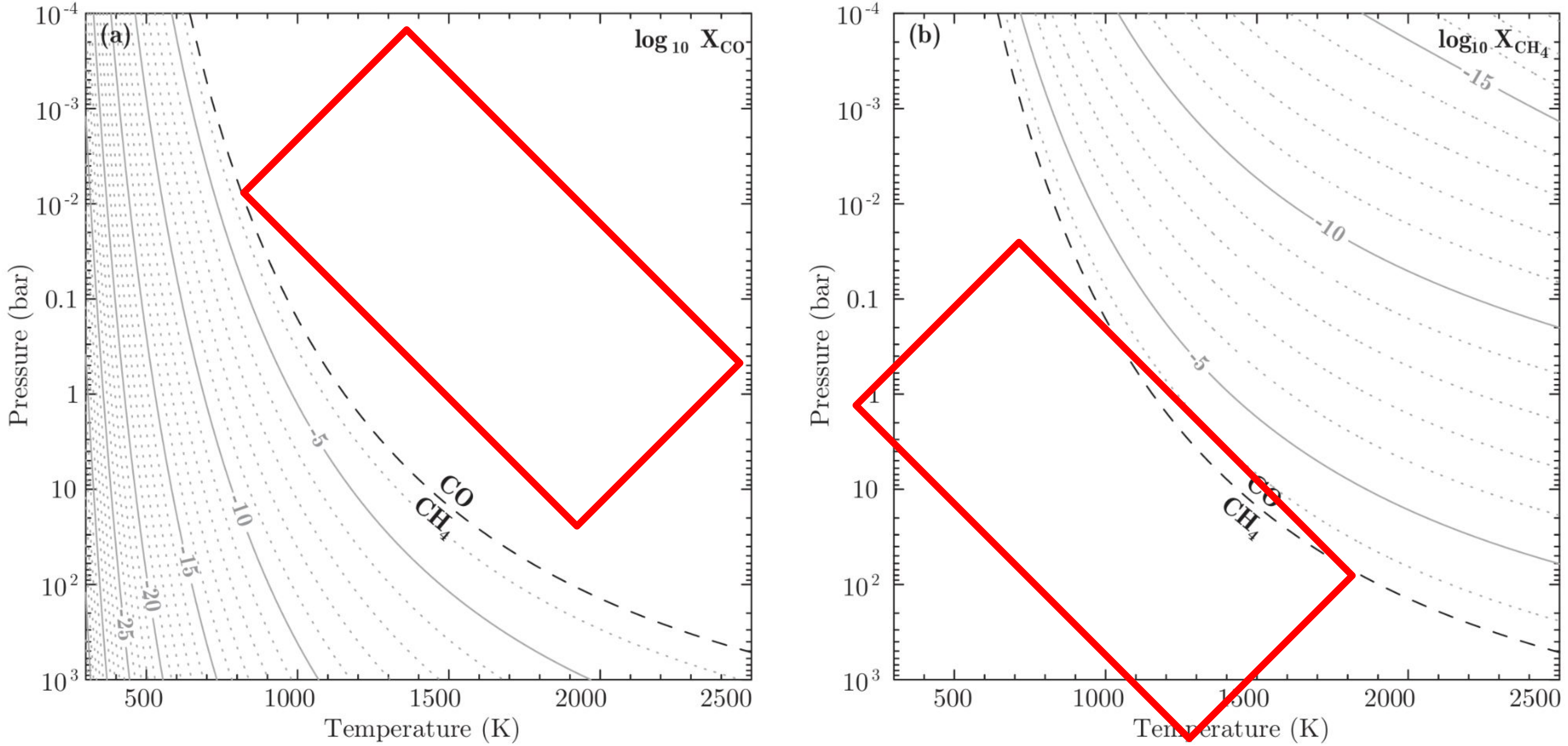
$t_{\rm chem}$

Works if $t_{\rm chem}$ is the fastest timescale in the atmosphere



Hubeny (2007)

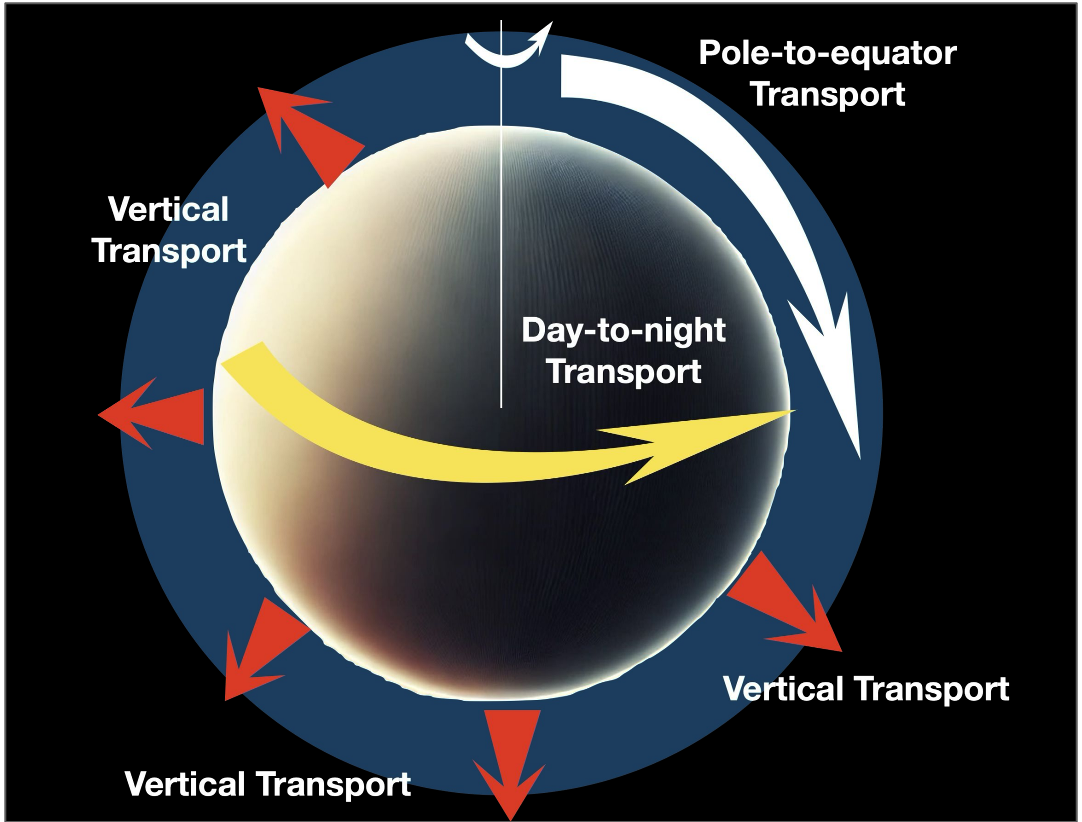
Chemical equilibrium abundances



CO is preferred at high temperatures, CH_4 at low temperatures

Visscher +(2010)

But chemical timescales are not the only timescales in planetary atmospheres



Chemical Equilibrium

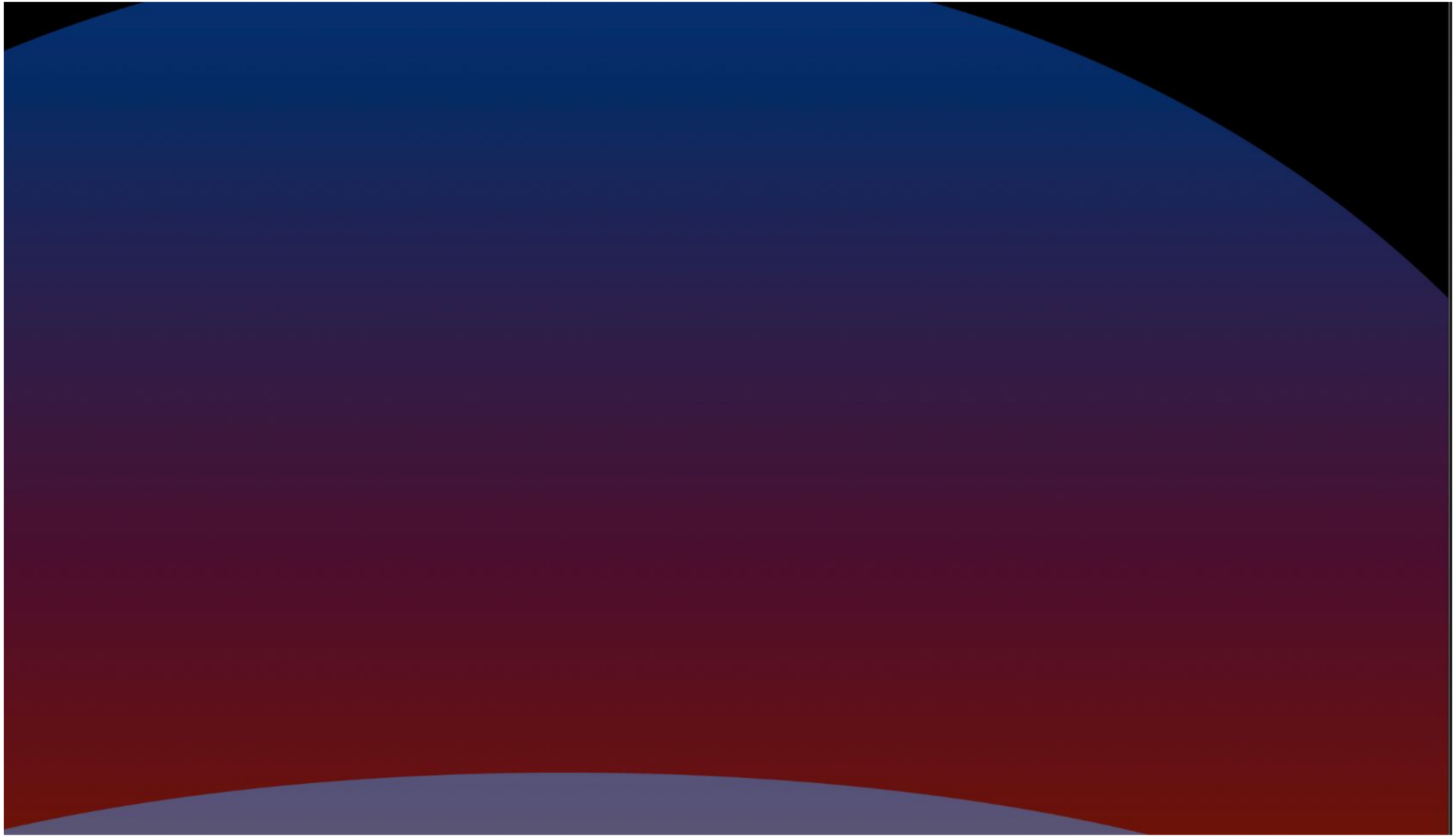
$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$

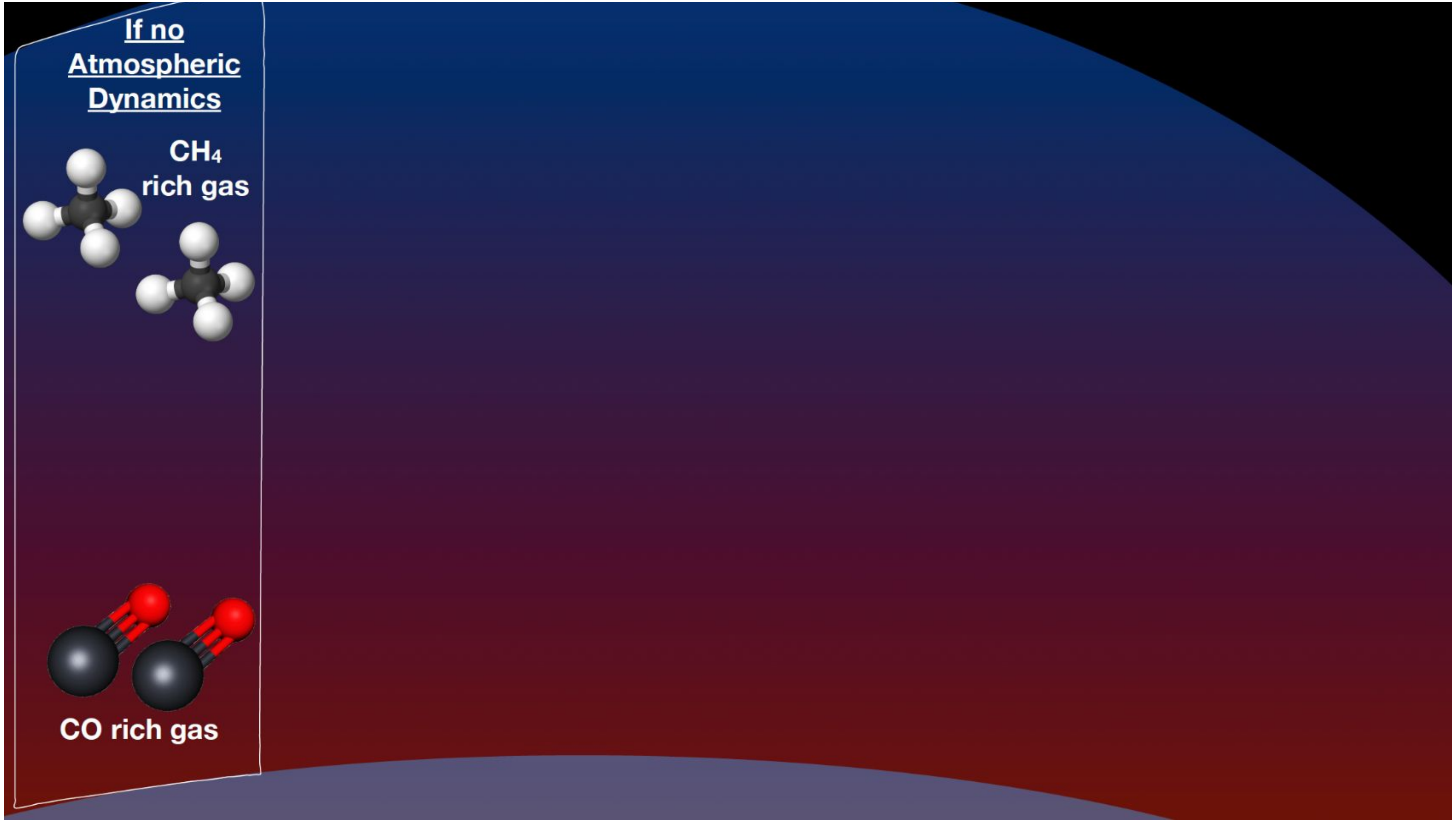
$$t_{\text{chem}}$$

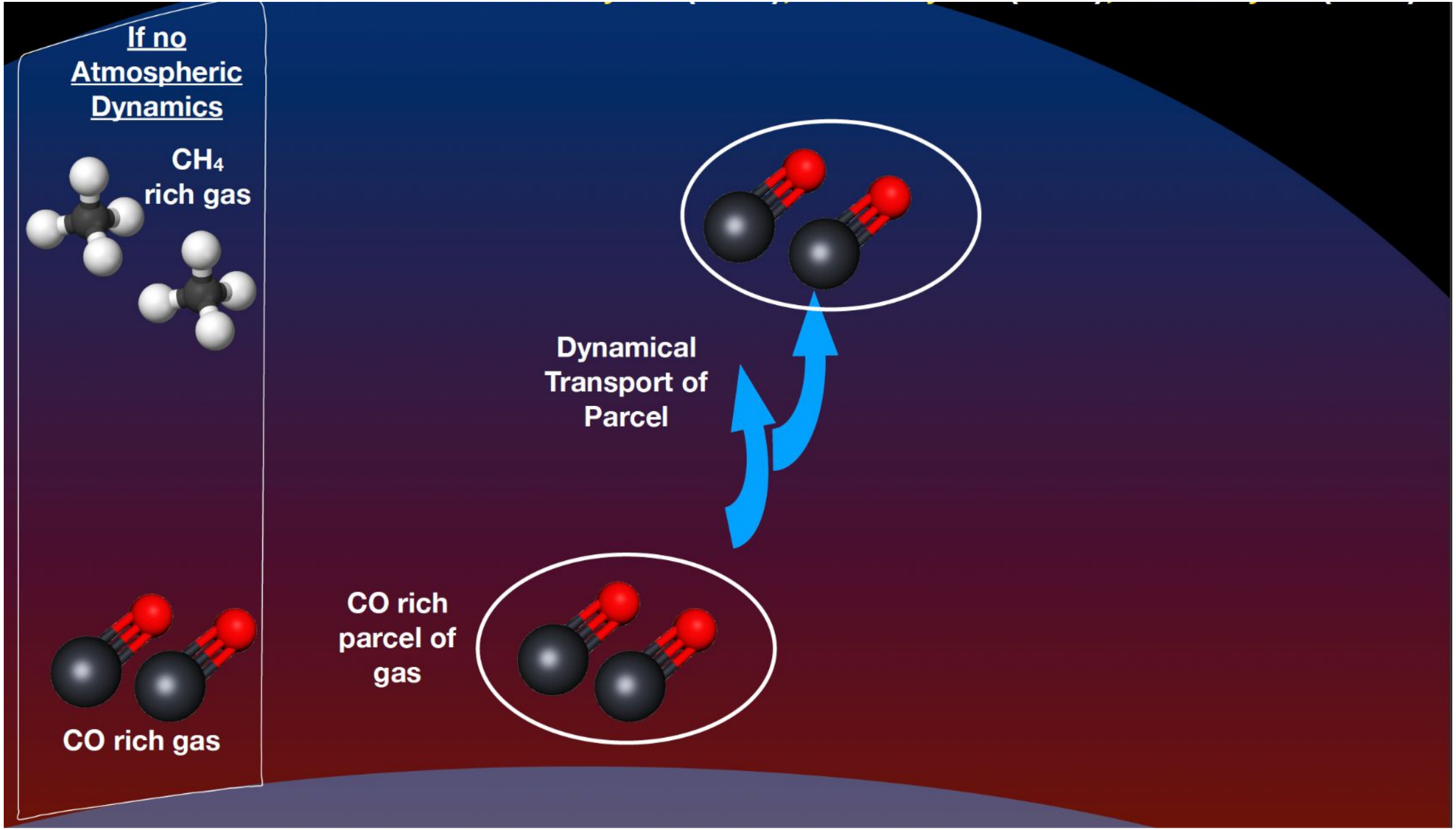
Works if t_{chem} is the fastest timescale in the atmosphere

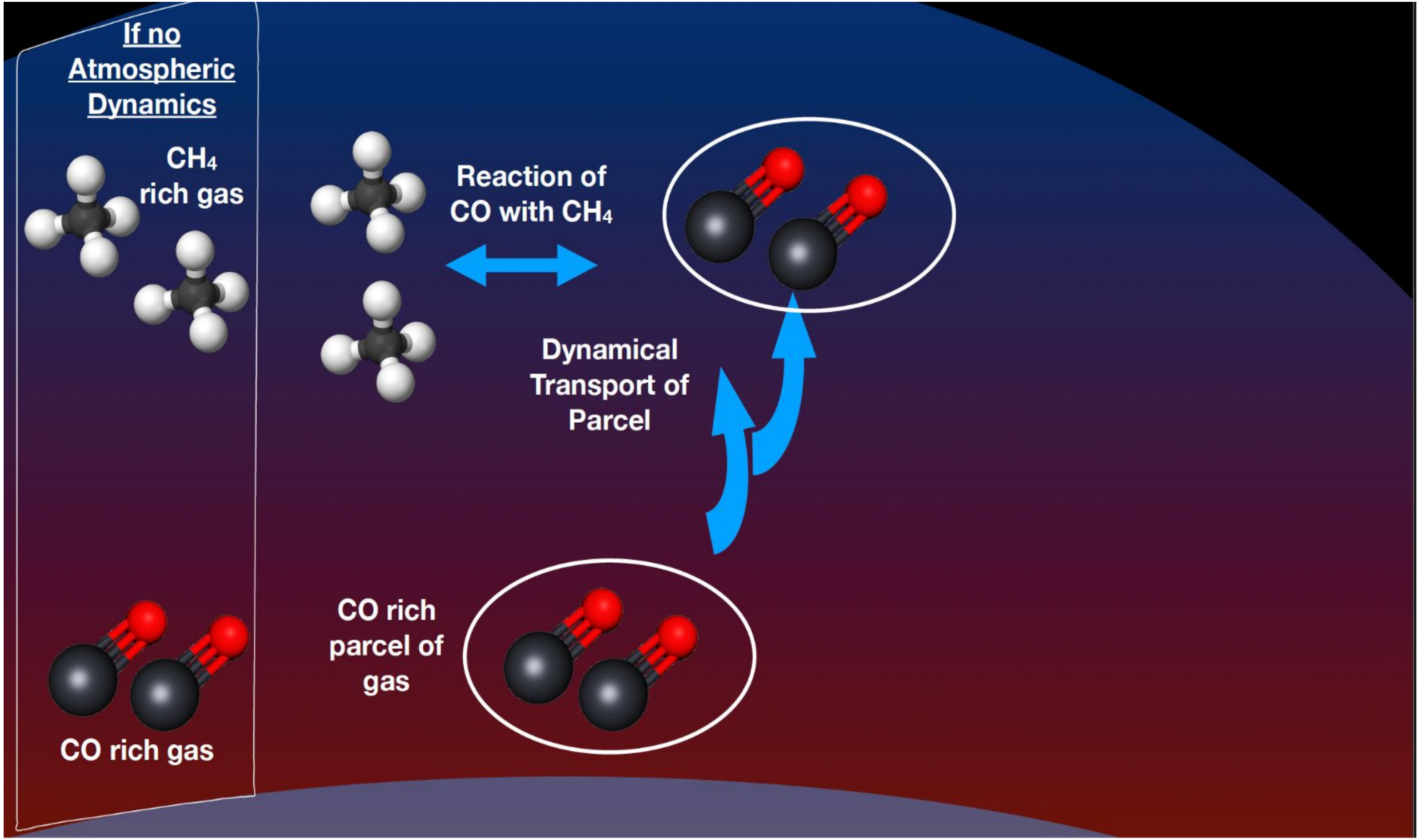
Atmospheric Dynamics (Vertical Mixing)

$$t_{\text{mix}}$$

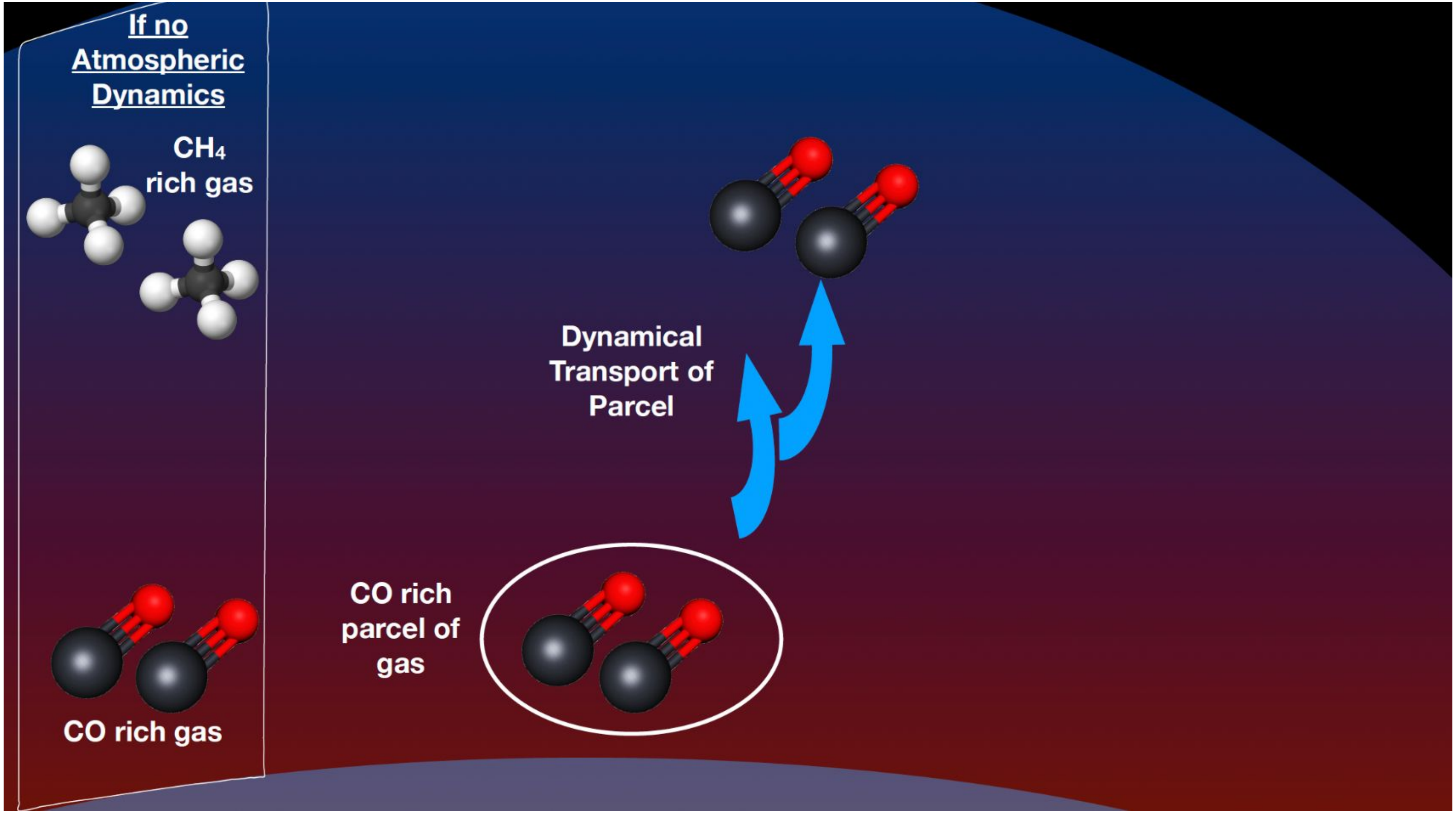



If no Atmospheric Dynamics
CH_4 rich gas
CO rich gas


If no Atmospheric Dynamics
CH4 rich gas
CO rich gas
Dynamical Transport of Parcel
CO rich parcel of gas



If no Atmospheric Dynamics
CH_4 rich gas
CO rich gas
Reaction of CO with CH_4
Dynamical Transport of Parcel
CO rich parcel of gas


If no Atmospheric Dynamics
CH4 rich gas
CO rich gas
Dynamical Transport of Parcel
CO rich parcel of gas

Approximating complex dynamics with a simple diffusion equation

$$\frac{d\chi_i}{dt} = K_{zz}\frac{d^2\chi_i}{dz^2}$$

Diffusion Equation of gas abundance

Dimensional Analysis

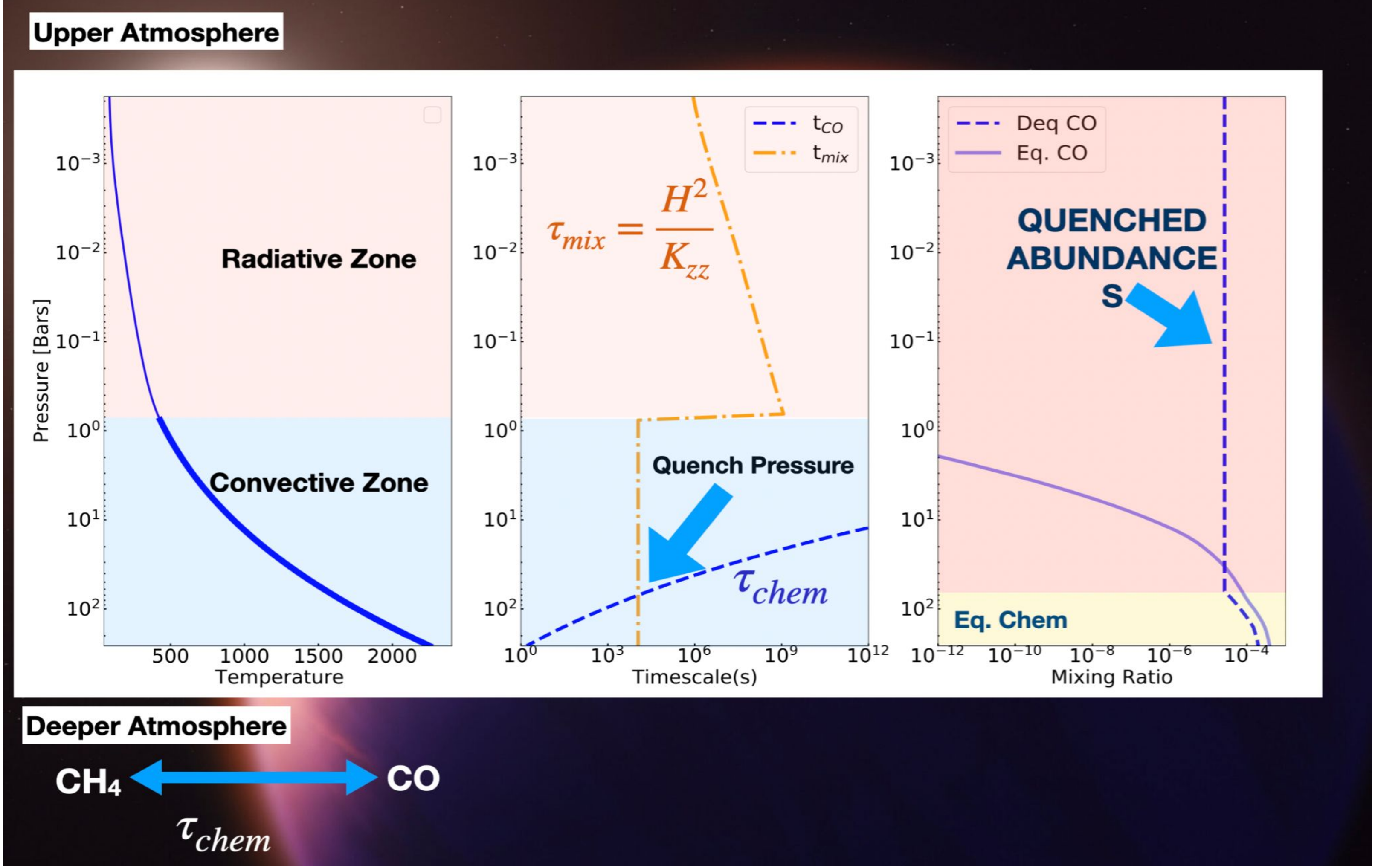
$$\tau_{mix} = \frac{H^2}{K_{zz}}$$

Diffusion Parameter

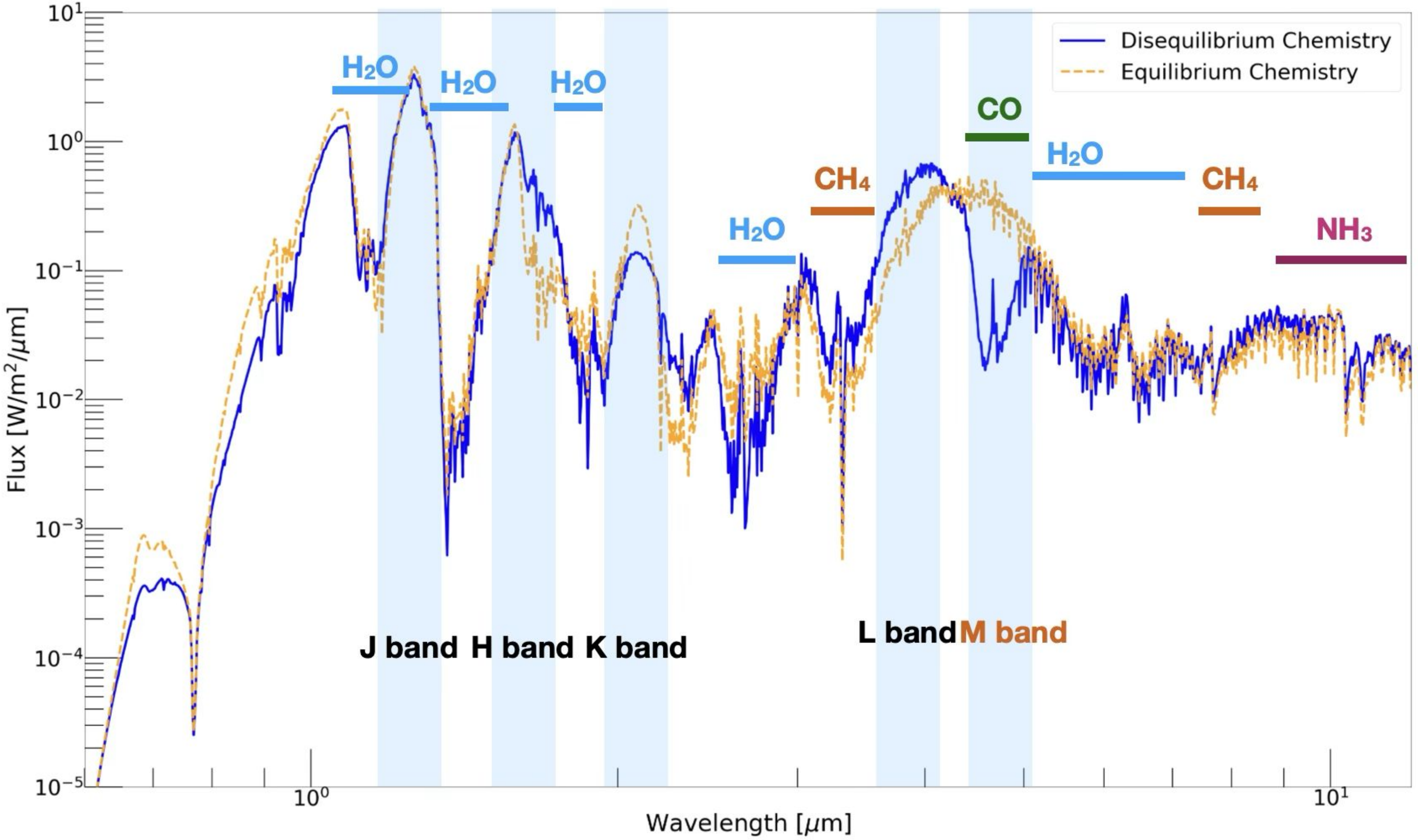
Approximating complex dynamics with a simple diffusion equation

$$\tau_{mix} = \frac{H^2}{K_{zz}}$$

K_{zz} is uncertain by 6-8 orders of magnitude – 10^2 to 10^{10} cm^2/s

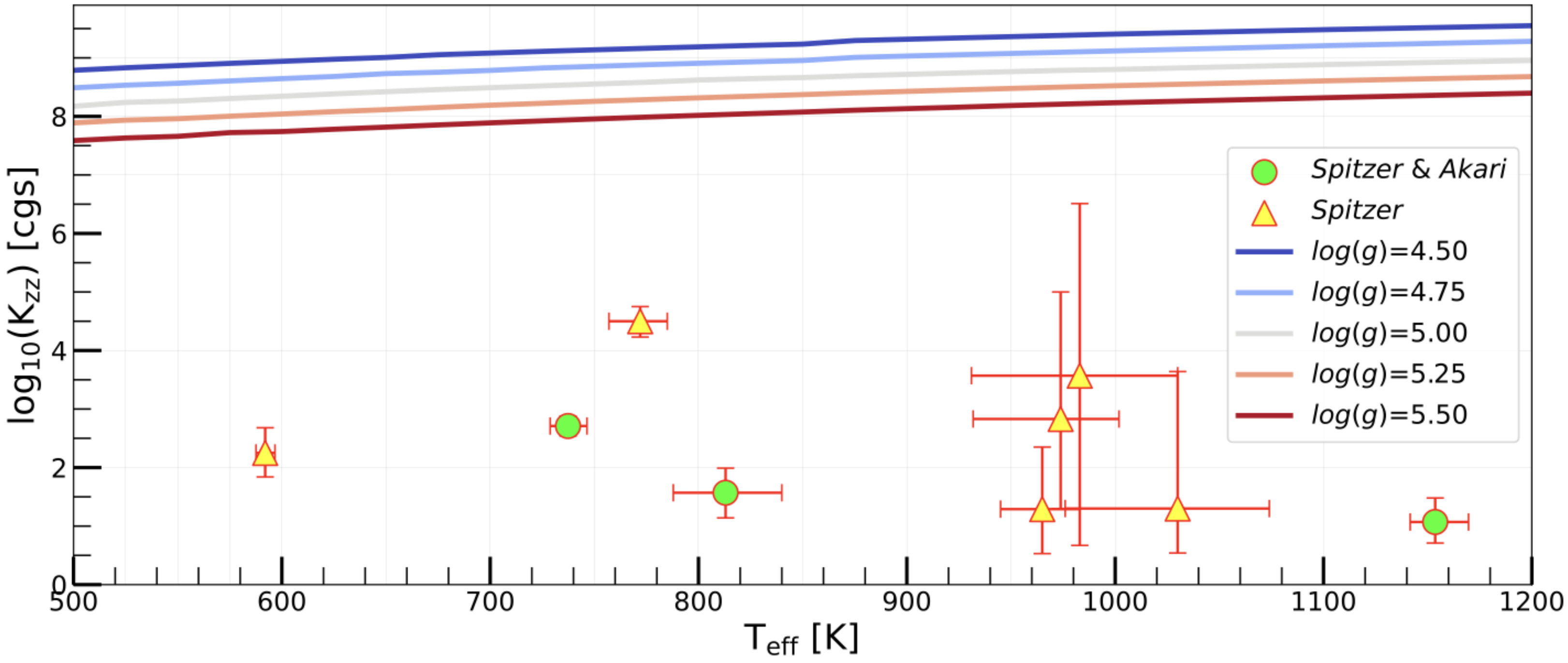


Mukherjee et al. (2022)



Mukherjee et al. (2022)

Constraints on K_{zz} from chemical compositions of brown dwarfs



Mukherjee+ (2024), Miles+ (2020)

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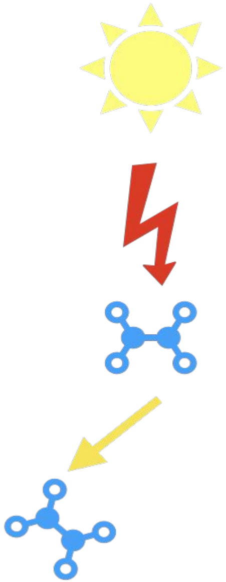
Works if t_{chem} is the fastest timescale in the atmosphere

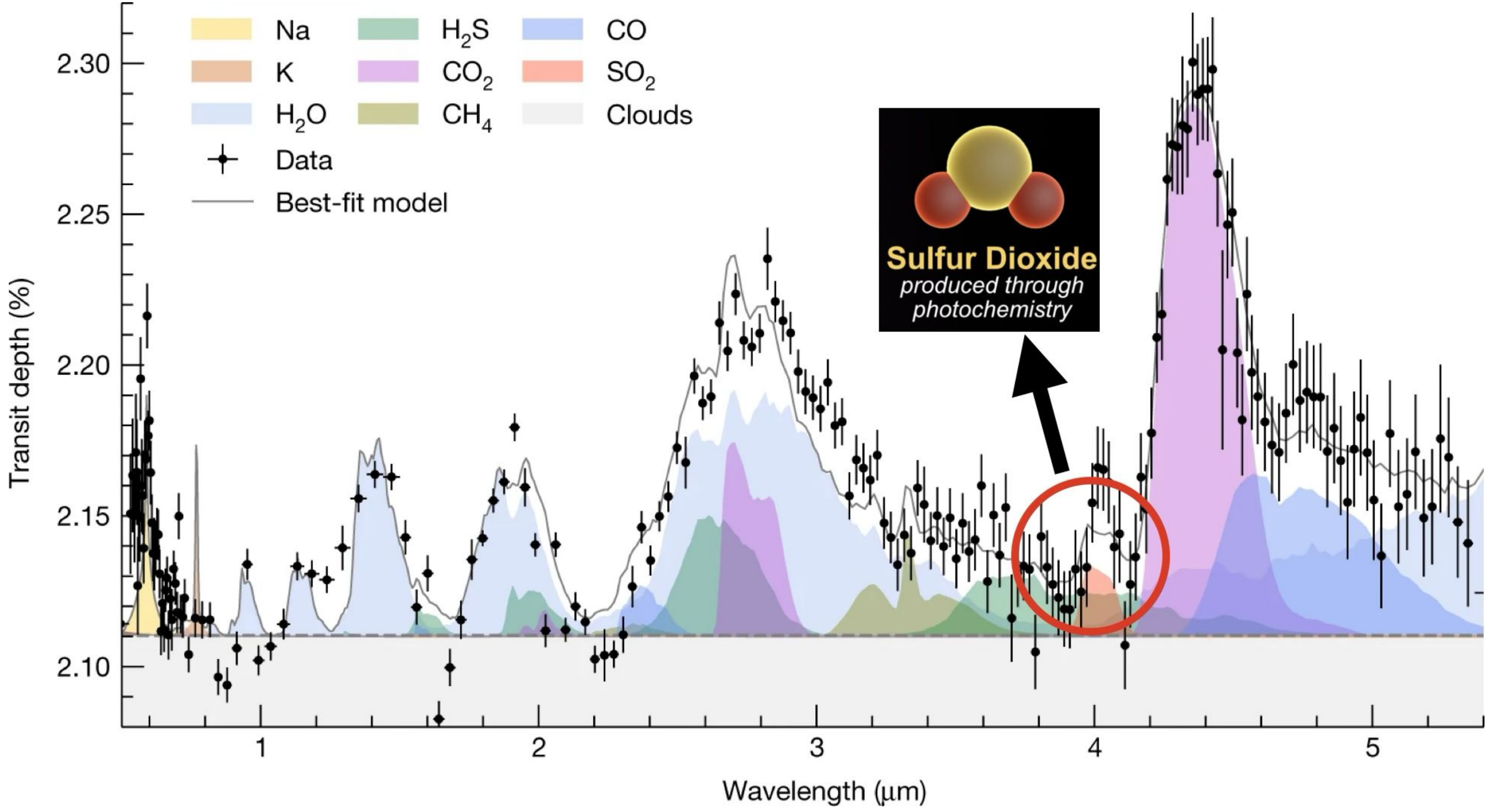
Atmospheric Dynamics (Vertical Mixing)

$$t_{mix}$$

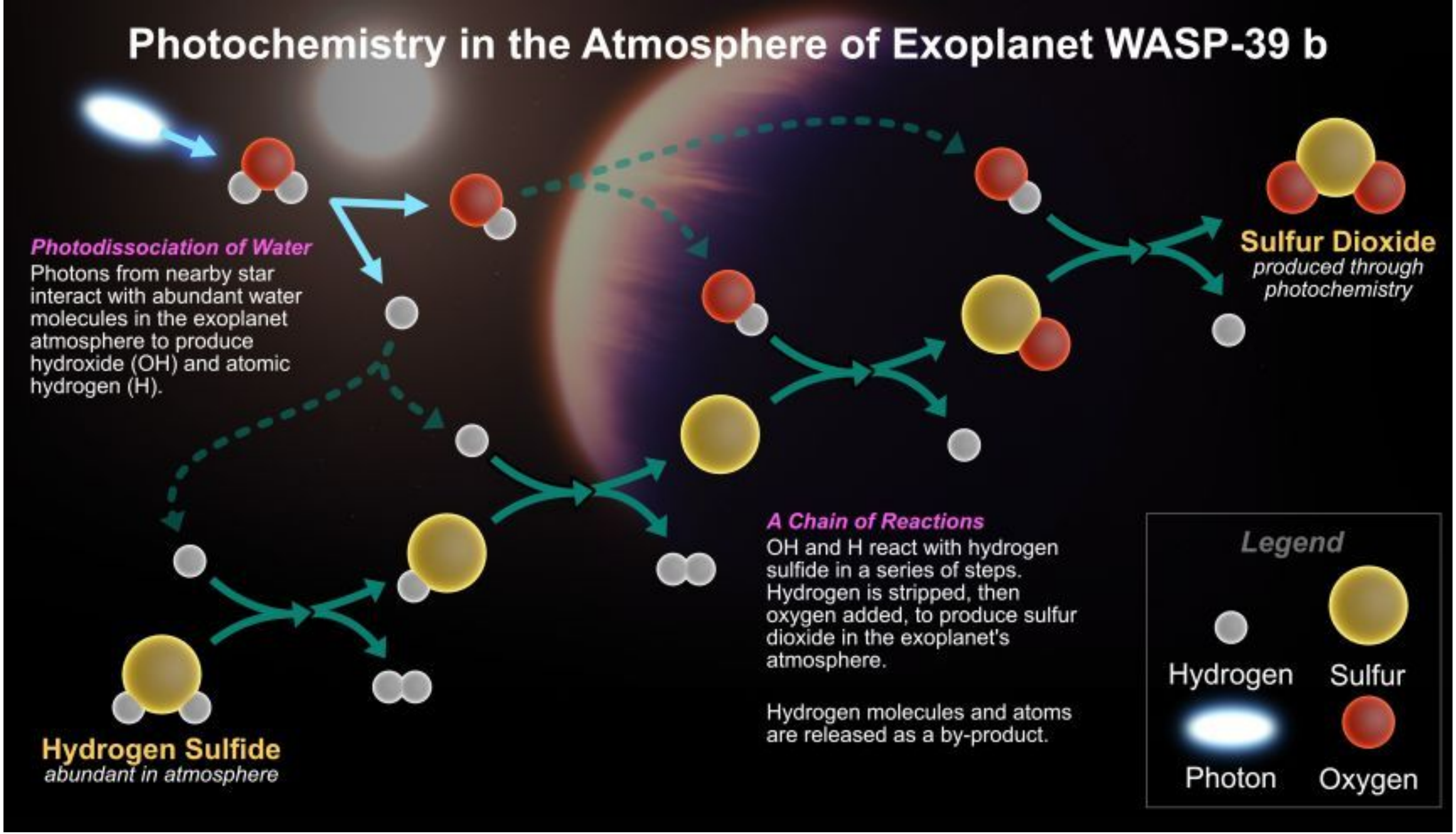
Photochemistry



Stellar high energy photons can dissociate weak molecular bonds

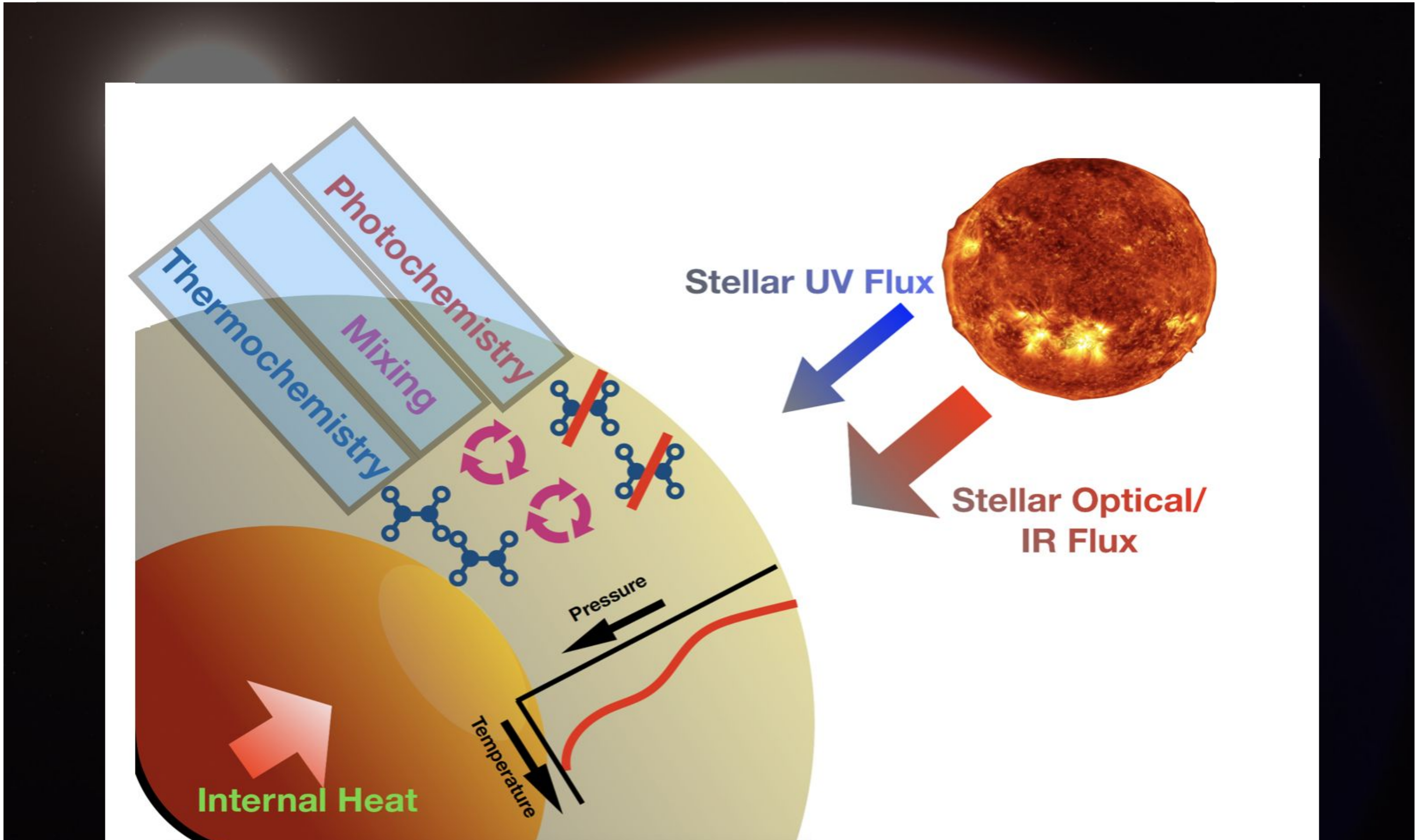


Rustamkulov+ (2023)



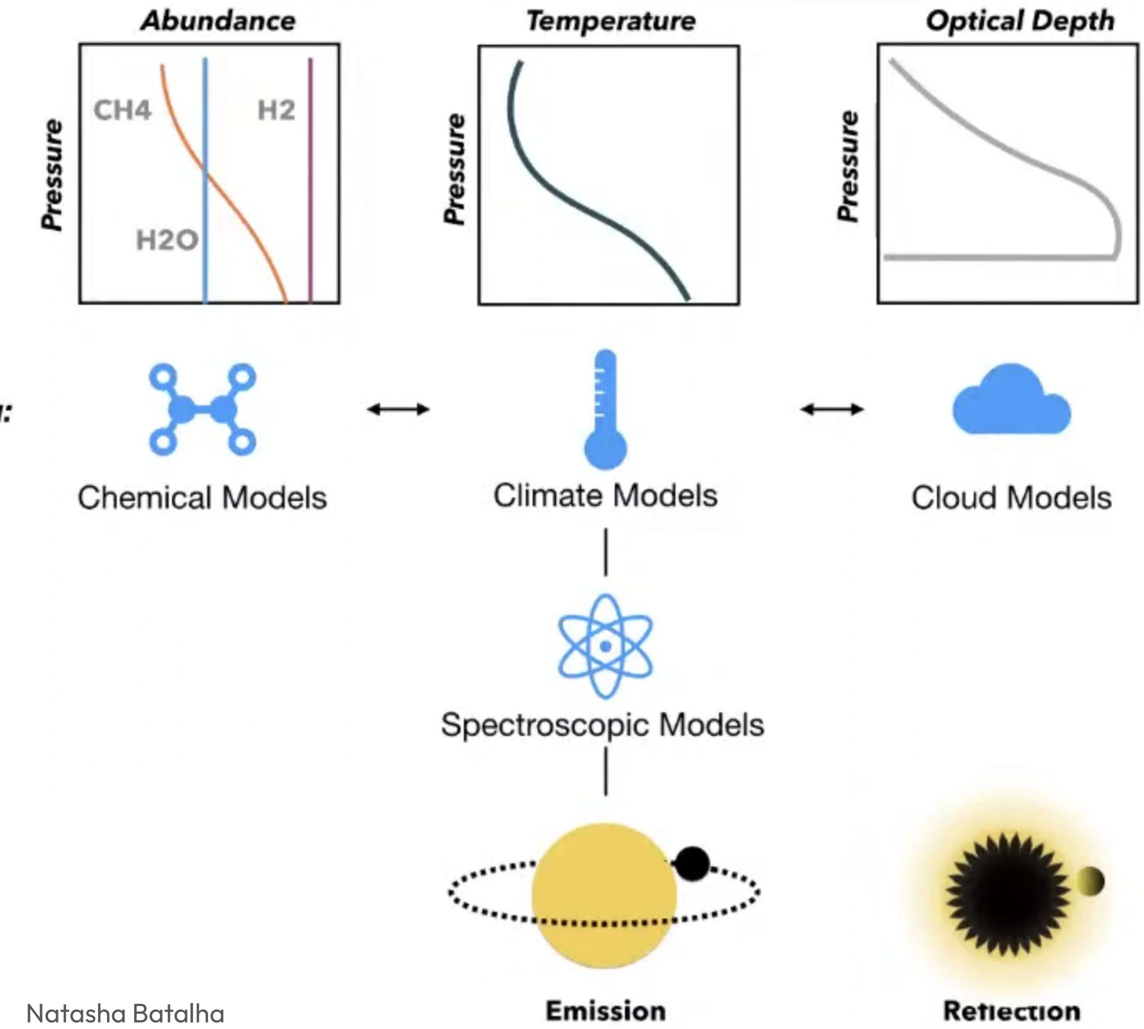
Tsai et al. (2023), NASA/JPL/Robert Hurt

Chemical Regimes in Planet Atmospheres



Relating Models to Data

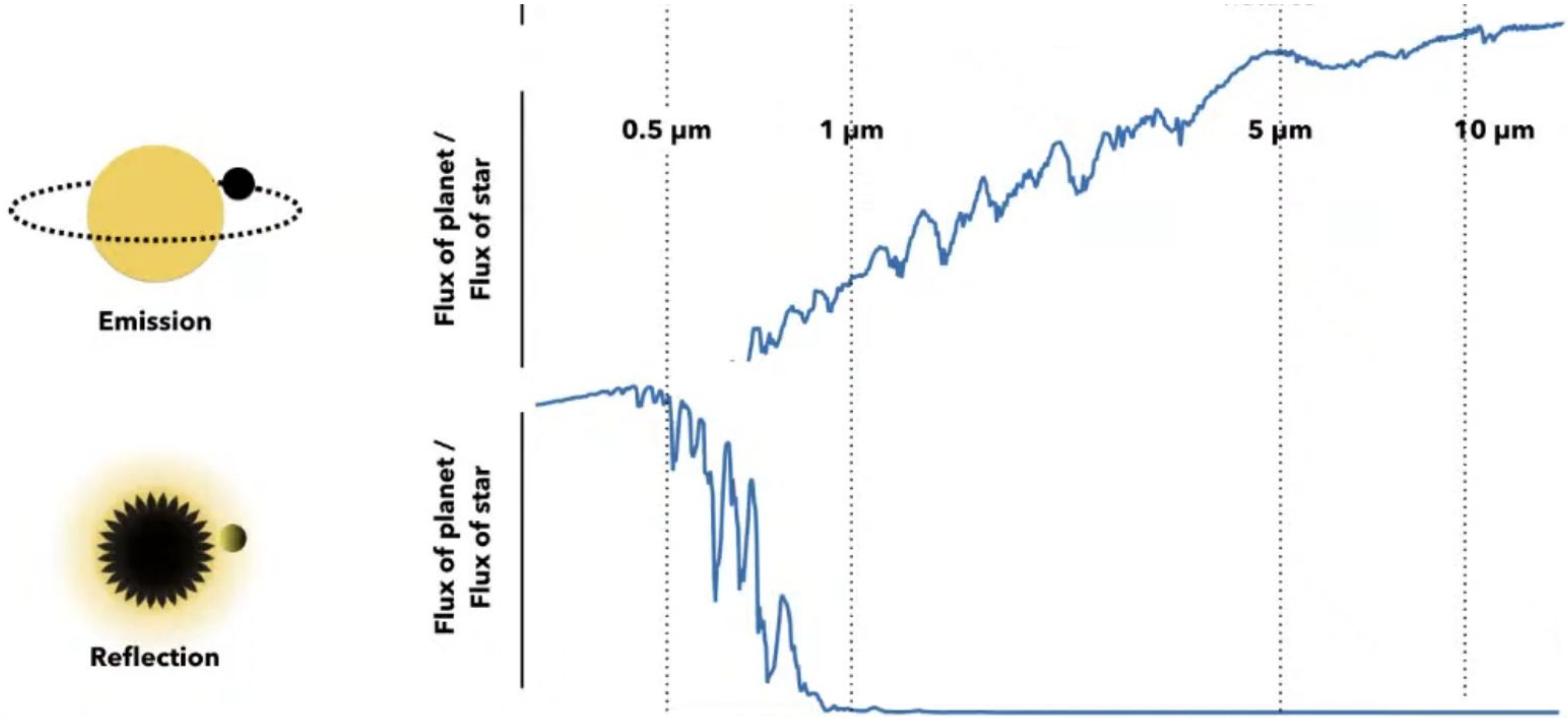
Modeling



These models depend on each other
→
Iteration to converge

Emission and reflection have different geometry
→
Your ultimate spectrum

Emission vs Reflected Spectra



Natasha Batalha

Various Climate Codes

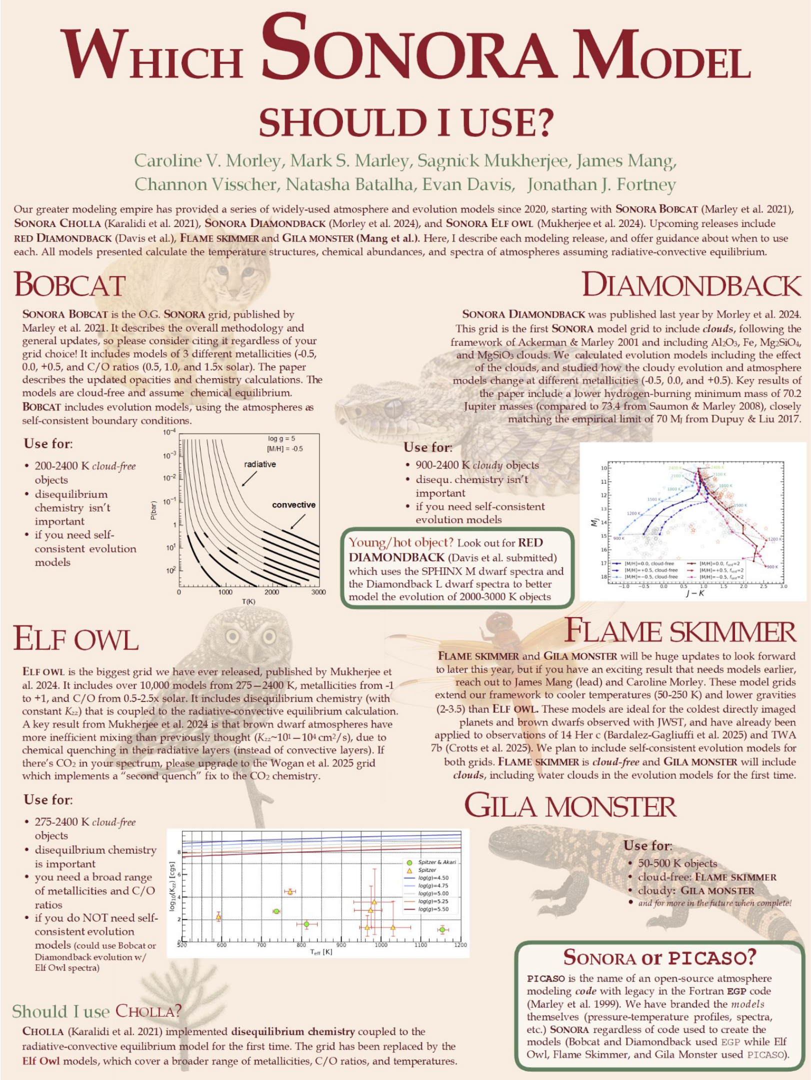
	Model	R-T Solver[1]	T-correction[2]	Parent code	Opacity	Convection	Clouds	Scattering
PHOENIX	Barman et al. 2001, 2005	Short characteristics+ALI	Unsöld-Lucy correction	PHOENIX	line-by-line	Yes	Yes	Yes
EGP	Fortney et al. 2006, 2008	2-stream source function	Linearise flux transfer	McKay et al. 1989	corr.-k	Yes	Yes	Yes
cool TLUSTY	Burrows et al. 2008	Feautrier/DFE+ALI	Rybicki	TLUSTY	line-by-line	Yes	Yes	Yes
RAD TRANS	Mollière et al. 2015, 2017	Feautrier	Variable Eddington factors	New	corr.-k	Yes	Yes	Yes
ATMO	Malik et al. 2017	2-stream approximation	Local flux balance	New	corr.-k	No	Yes	Yes
GENESIS	**This work**	Feautrier	Rybicki	New	line-by-line	Yes	No	Yes[†]

Gandhi and Madhusudhan 2017

The Sonora Suite of Models

Caroline Morley's Guide to using the suite of Sonora atmospheric model grids

Model	Temp Range (K)	Clouds	Chemistry
Bobcat (Marley+ 2021)	200–2400	No	Eq.
Diamondback (Morley+ 2024)	900–2400	Yes (Ackerman+Marley)	Eq.
Elf Owl (Mukherjee+ 2024)	275–2400	No	Diseq.
Flame Skimmer (Mang+ upcoming)	50–250	Yes (includes H_2O)	Eq.
Gila Monster	50–500	No	Eq.
Hummingbird 	1000-1800	Yes, patchy!	Eq.


Which Sonora Model Should I Use?

Caroline V. Morley, Mark S. Marley, Sagnick Mukherjee, James Mang, Channon Visscher, Natasha Batalha, Evan Davis, Jonathan J. Fortney

Our greater modeling empire has provided a series of widely-used atmosphere and evolution models since 2020, starting with Sonora Bobcat (Marley et al. 2021), Sonora Cholla (Karalidi et al. 2021), Sonora Diamondback (Morley et al. 2024), and Sonora Elf Owl (Mukherjee et al. 2024). Upcoming releases include Red Diamondback (Davis et al.), Flame Skimmer and Gila Monster (Mang et al.). Here, I describe each modeling release, and offer guidance about when to use each. All models presented calculate the temperature structures, chemical abundances, and spectra of atmospheres assuming radiative-convective equilibrium.

Bobcat

Sonora Bobcat is the O.G. Sonora grid, published by Marley et al. 2021. It describes the overall methodology and general updates, so please consider citing it regardless of your grid choice! It includes models of 3 different metallicities (-0.5, 0.0, +0.5, and C/O ratios (0.5, 1.0, and 1.5x solar). The paper describes the updated opacities and chemistry calculations. The models are cloud-free and assume chemical equilibrium. Bobcat includes evolution models, using the atmospheres as self-consistent boundary conditions.

Use for:
- 200-2400 K cloud-free objects
- disequilibrium chemistry isn't important
- if you need self-consistent evolution models

Diamondback

Sonora Diamondback was published last year by Morley et al. 2024. This grid is the first Sonora model grid to include clouds, following the framework of Ackerman & Marley 2001 and including Al_2O_3, Fe, Mg_2SiO_4, and $MgSiO_3$ clouds. We calculated evolution models including the effect of the clouds, and studied how the cloudy evolution and atmosphere models change at different metallicities (-0.5, 0.0, and +0.5). Key results of the paper include a lower hydrogen-burning minimum mass of 70.2 Jupiter masses (compared to 73.4 from Saumon & Marley 2008), closely matching the empirical limit of 70 M_J from Dupuy & Liu 2017.

Use for:
- 900-2400 K cloudy objects
- disequ. chemistry isn't important
- if you need self-consistent evolution models

Young/hot object? Look out for Red Diamondback (Davis et al. submitted) which uses the SPHINX M dwarf spectra and the Diamondback L dwarf spectra to better model the evolution of 2000-3000 K objects

Elf Owl

Elf Owl is the biggest grid we have ever released, published by Mukherjee et al. 2024. It includes over 10,000 models from 275–2400 K, metallicities from -1 to +1, and C/O from 0.5-2.5x solar. It includes disequilibrium chemistry (with constant K_{zz}) that is coupled to the radiative-convective equilibrium calculation. A key result from Mukherjee et al. 2024 is that brown dwarf atmospheres have more inefficient mixing than previously thought (K_{zz}~10^1-10^4 cm^2/s), due to chemical quenching in their radiative layers (instead of convective layers). If there's CO_2 in your spectrum, please upgrade to the Wogan et al. 2025 grid which implements a "second quench" fix to the CO_2 chemistry.

Use for:
- 275-2400 K cloud-free objects
- disequilbrium chemistry is important
- you need a broad range of metallicities and C/O ratios
- if you do NOT need self-consistent evolution models (could use Bobcat or Diamondback evolution w/ Elf Owl spectra)

Flame Skimmer

Flame Skimmer and Gila Monster will be huge updates to look forward to later this year, but if you have an exciting result that needs models earlier, reach out to James Mang (lead) and Caroline Morley. These model grids extend our framework to cooler temperatures (50-250 K) and lower gravities (2-3.5) than Elf Owl. These models are ideal for the coldest directly imaged planets and brown dwarfs observed with JWST, and have already been applied to observations of 14 Her c (Bardalez-Gagliuffi et al. 2025) and TWA 7b (Crotts et al. 2025). We plan to include self-consistent evolution models for both grids. Flame Skimmer is cloud-free and Gila Monster will include clouds, including water clouds in the evolution models for the first time.

Gila Monster

Use for:
- 50-500 K objects
- cloud-free: Flame Skimmer
- cloudy: Gila Monster
- and for more in the future when complete!

Should I use Cholla?

Cholla (Karalidi et al. 2021) implemented disequilibrium chemistry coupled to the radiative-convective equilibrium model for the first time. The grid has been replaced by the Elf Owl models, which cover a broader range of metallicities, C/O ratios, and temperatures.

Sonora or PICASO?

PICASO is the name of an open-source atmosphere modeling code with legacy in the Fortran EGP code (Marley et al. 1999). We have branded the models themselves (pressure-temperature profiles, spectra, etc.) Sonora regardless of code used to create the models (Bobcat and Diamondback used EGP while Elf Owl, Flame Skimmer, and Gila Monster used PICASO).

Grid Fitting

- Grid fitting compares observed spectra or photometry to a precomputed grid of atmospheric models.
- Compare models to observations using a goodness-of-fit metric (e.g. Chi squared)
- Advantages
  - Simple and computationally efficient
  - Uses physically self-consistent atmosphere models
  - Useful for interpreting low-resolution spectra or photometry
- Limitations
  - Resolution limited by grid spacing
  - Can miss solutions between grid points
  - Parameter degeneracies are difficult to quantify
- Large model grids encompass thousands of models, so accept often tradeoffs in precision vs. speed

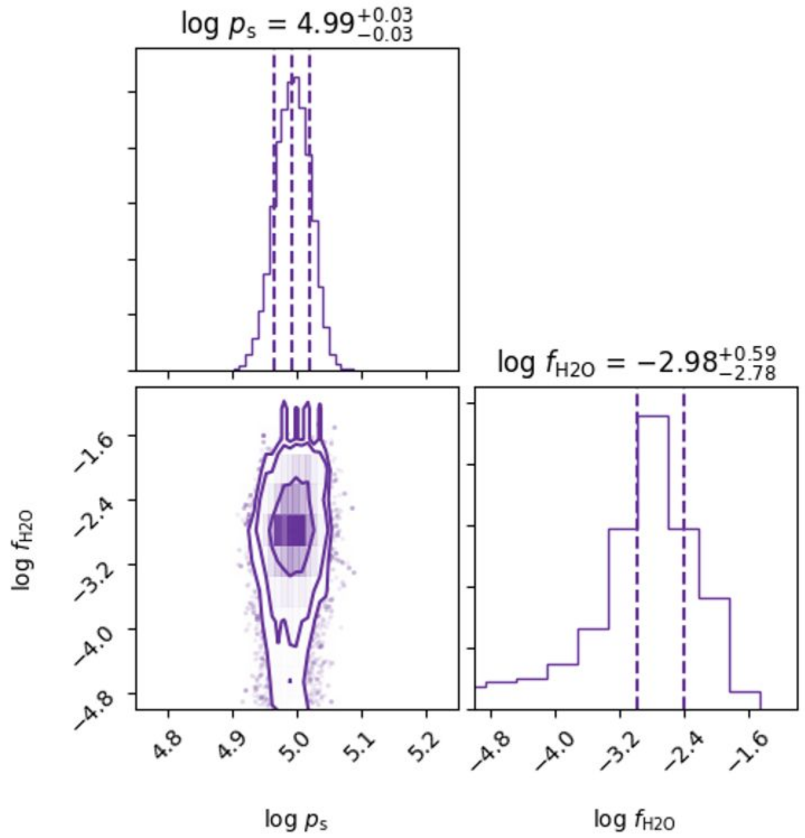
Retrievals

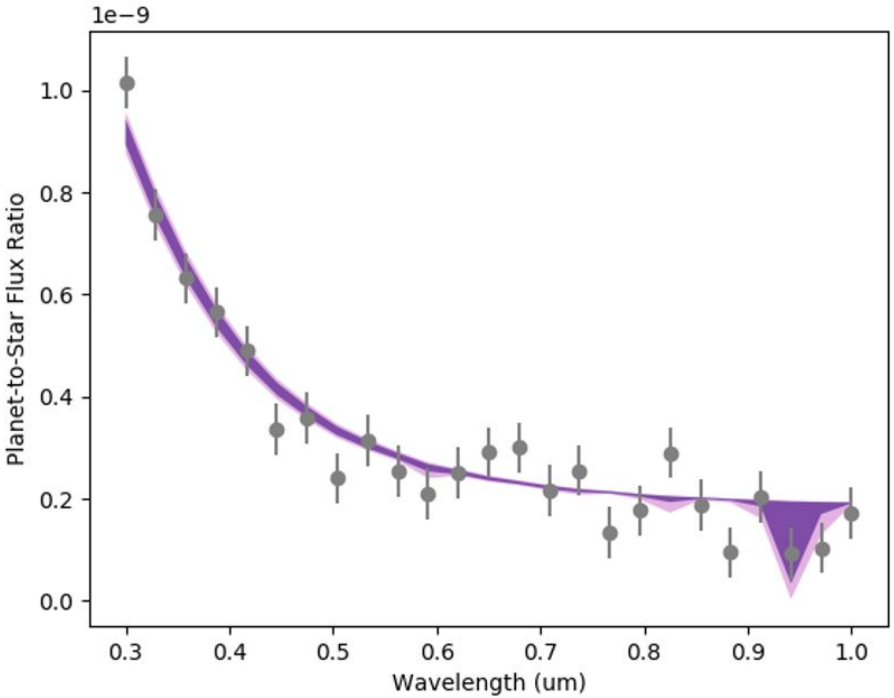
Instead of searching a fixed grid, retrievals explore parameter space continuously using statistical sampling methods (e.g., Bayesian inference).

What Retrievals Provide

- Probability distributions for atmospheric parameters
- Quantified uncertainties and degeneracies
- Statistical validity of inferred conclusions

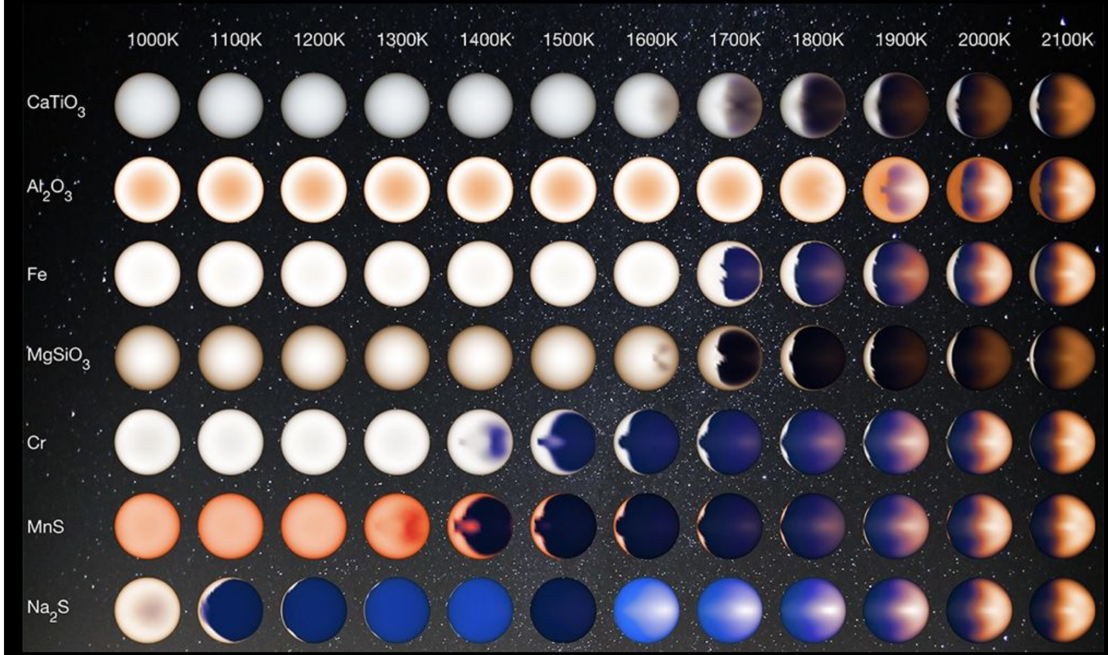
Retrieval Example





A note about 3D Modeling

- Atmospheres are 3D structures so this aspect can be captured
- Model choices and computing power typically limit the radiative transfer and chemistry within these codes (but that is changing)
- Essential to understand day-night contrasts, circulation, cloud coverage fraction, etc.



Parmentier et al. 2016

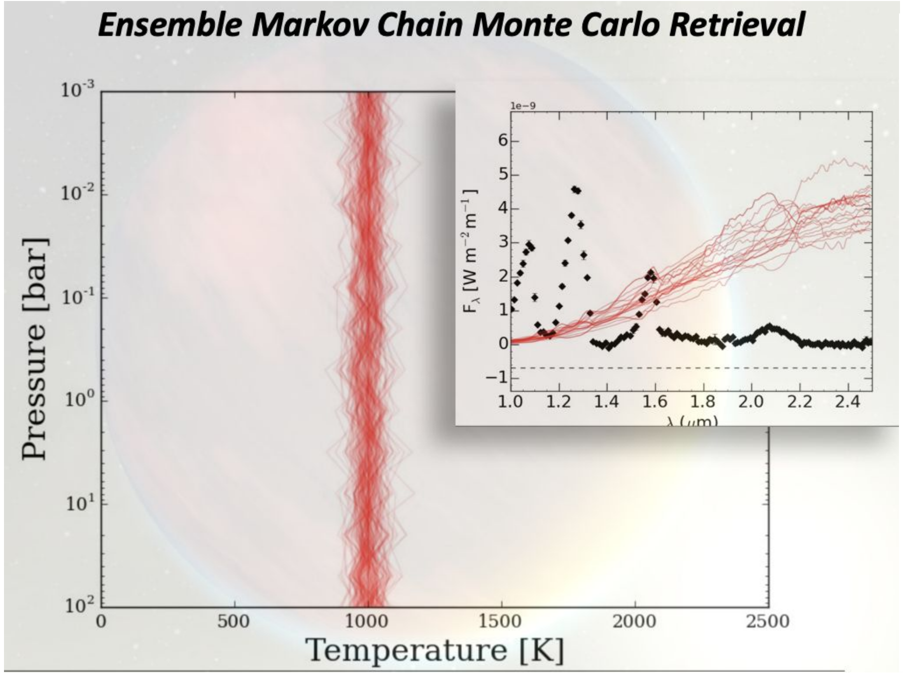
Resources

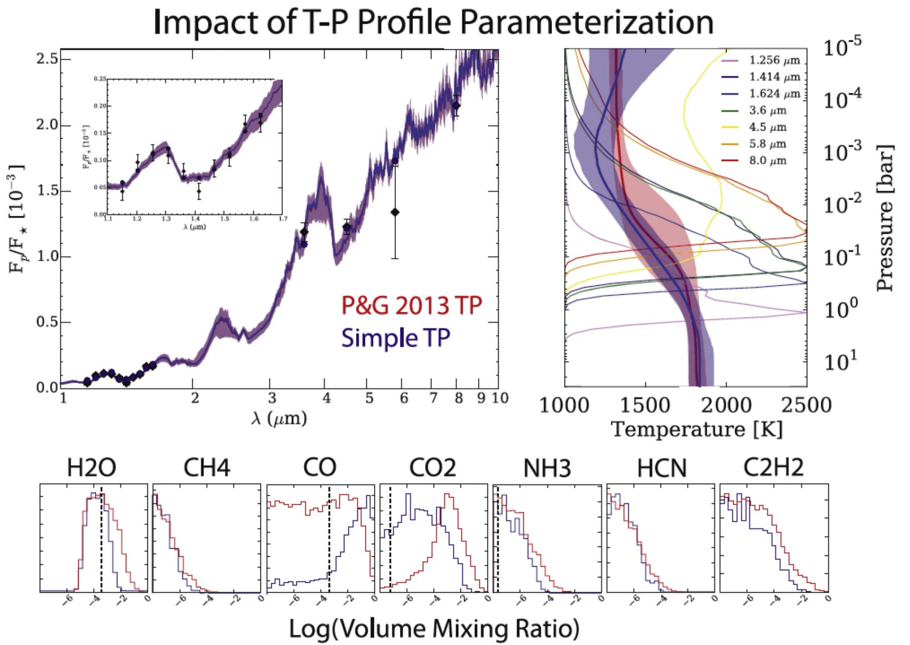
An Introduction to Planetary Atmospheres (Sanchez-Lavega)

On the Cool Side (Marley and Robinson, 2015)

Backup Slides

More on retrievals





Retrieval/Post-Processing Codes

	Emission	Reflection	Open Source?
NEMESIS; Barstow, Irwin+	✓	✓	
ATMO; Tremblin+	✓	✓	
PICASO;Batalha+	✓	✓	🎁
CHIMERA;Line+	✓		🎁
TauRex3;Waldmann+	✓		🎁
BART; Harrington+	✓		🎁
petitRADTRANS;Molliére+	✓		🎁
PLATON;Zhang+	✓		🎁
SCARLET Benneke+	✓		
PyratBay;Cubilllos+in prep	✓		
Helios-r2;Kitzman+	✓		🎁
ExoTransmit;Kempton			🎁
MassSpec; De Witt+2016			
METIS;Lacy+2020			
POSEIDON;MacDonald+			
ARCiS;Min+			
ExoREL; Hu+		✓	
APOLLO; Howe+	✓		🎁
Madhusudhan & Seager 2009	✓		
Lacy,Madhusudhan,Burrows		✓	

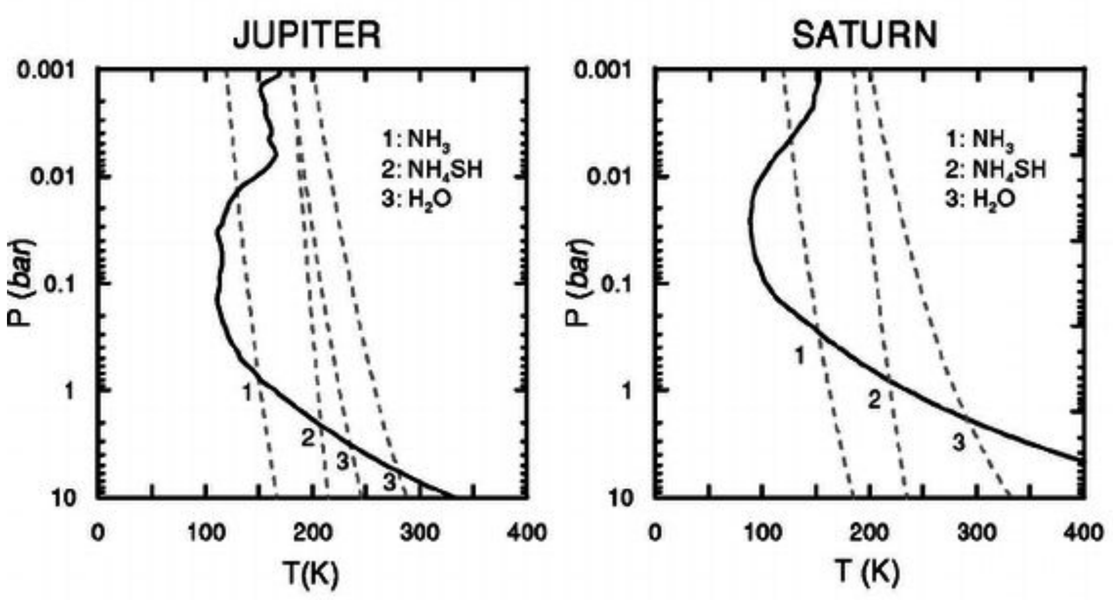
The availability of reflected light codes has been limited by the availability of data.

This is pre-JWST, there are others

Picaso is the only open source reflection code

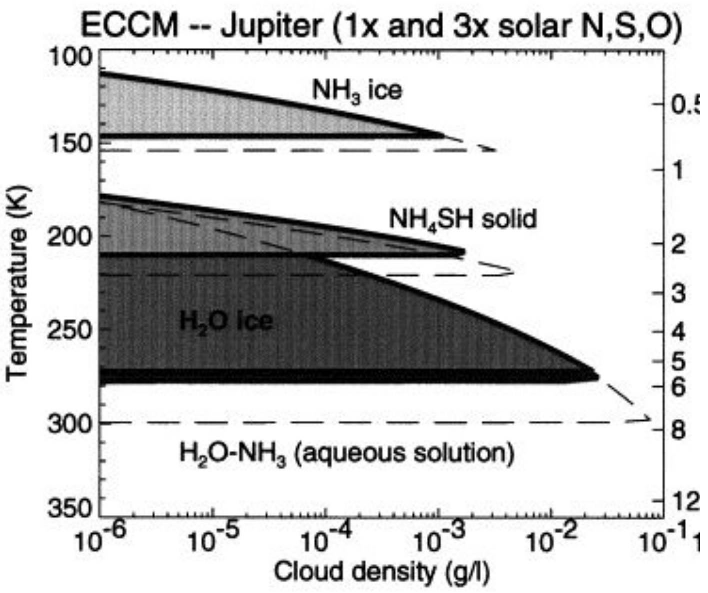
Condensation Level and Cloud Formation

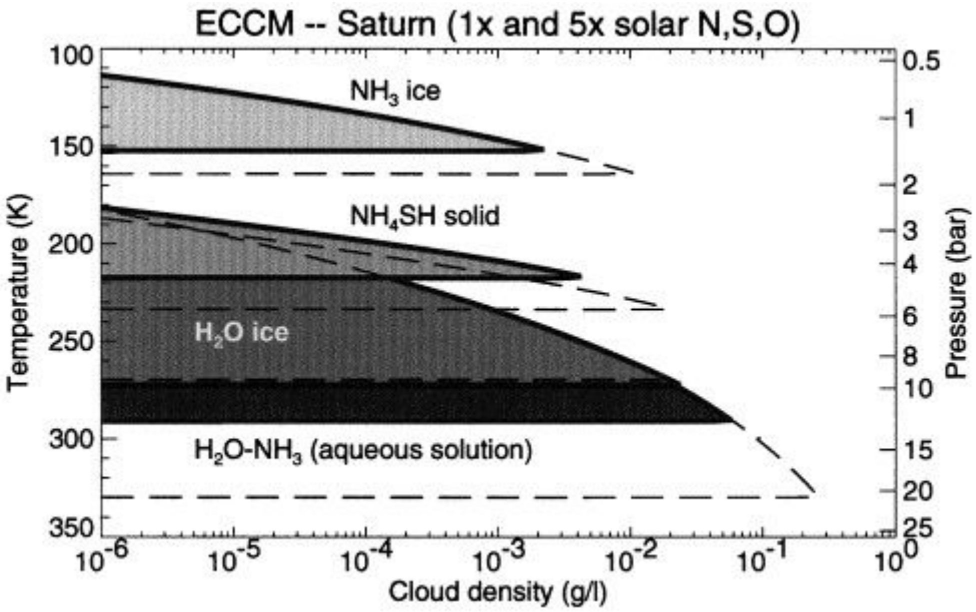
The points where the two curves cross mark the cloud base for the specific condensate



Sanchez-Lavega et al. 2004

Condensation Level and Cloud Formation





Attreya et al. 1999

Deriving Hydrostatic Equilibrium

Consider a parcel of air that is vertically static:

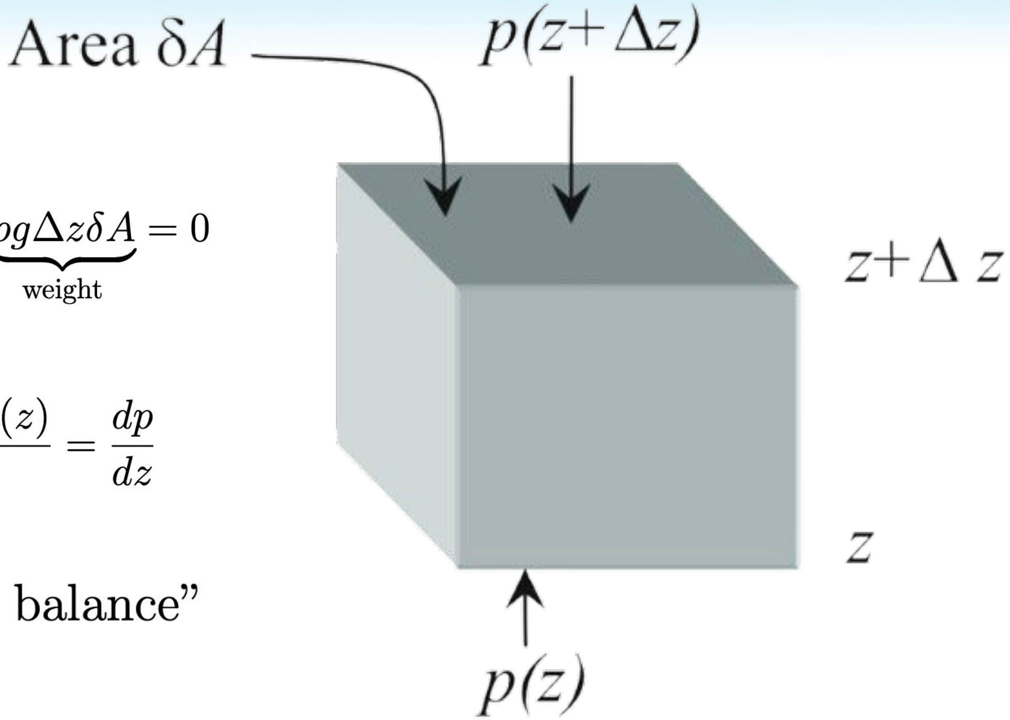
$$\text{Net force} = 0$$

$$\underbrace{[p(z+\Delta z) - p(z)]\delta A}_{\text{difference in surface forces}} + \underbrace{\rho g \Delta z \delta A}_{\text{weight}} = 0$$

Since

$$\lim_{\Delta z \to = 0} \frac{p(z+\Delta z) - p(z)}{\Delta z} = \frac{dp}{dz}$$

we have $\boxed{\frac{dp}{dz} = -\rho g}$ "Hydrostatic balance"



Deriving Scale Height

Combine with the Ideal Gas Law:

$$\rho = \frac{Pm}{kT}$$

$$\frac{dP}{dz} = -\left(\frac{Pm}{kT}\right) g$$

$$\frac{dP}{P} = -\left(\frac{mg}{kT}\right) dz$$

Integrating from pressure P0 (at z=0) to P (at height z), assuming constant T and g:

$$\ln\left(\frac{P}{P_0}\right) = -\frac{mgz}{kT}$$

$$P(z) = P_0 e^{-\frac{mgz}{kT}}$$

The term in the exponent is - z/H:

$$H = \frac{kT}{mg}$$

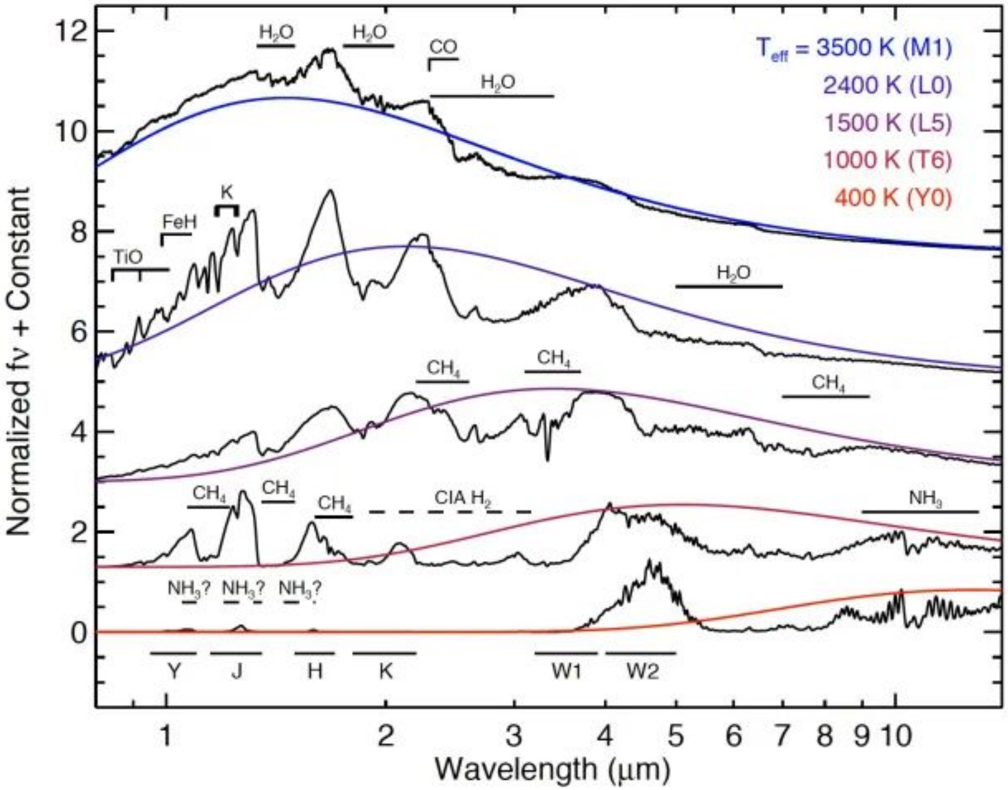
✓ Controls atmospheric thickness

✓ Controls pressure at τ = 1

✓ Affects line broadening regimes

✓ Sets depth of photosphere

Backup Slides



https://blog.backyardworlds.org/2017/03/22/the-colors-of-cold-brown-dwarfs/

Eddington–Barbier Approximation?

If the medium is optically thick but it has a temperature gradient, the intensity you observe is roughly equal to the source function at the location where the optical depth is $\tau_\nu = 2/3$

$$I_\nu^{\text{observed}} \simeq S_\nu(\tau_\nu = 2/3)$$

For media in LTE this means: you observe a blackbody intensity of temperature T at the location where the optical depth toward you is 2/3:

$$I_\nu^{\text{observed}} \simeq B_\nu(T(\tau_\nu = 2/3))$$