Deriving the thermal & compositional structure of Exoplanets: Examples

Prior Talks:

- Radiative Transfer Calculations ✓
- Lessons from Planetary Science ✓
- What learned from Exoplanetary Data ✓

This talk:

- Consider HD209458b dayside spectra
- Play with Radiative Transfer models.
- How do we proceed with an analysis?
- What do learn?

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Questions about hot Jupiters

What happens when Jupiter is moved 100 times closer to the Sun and locked into synchronous orbit?

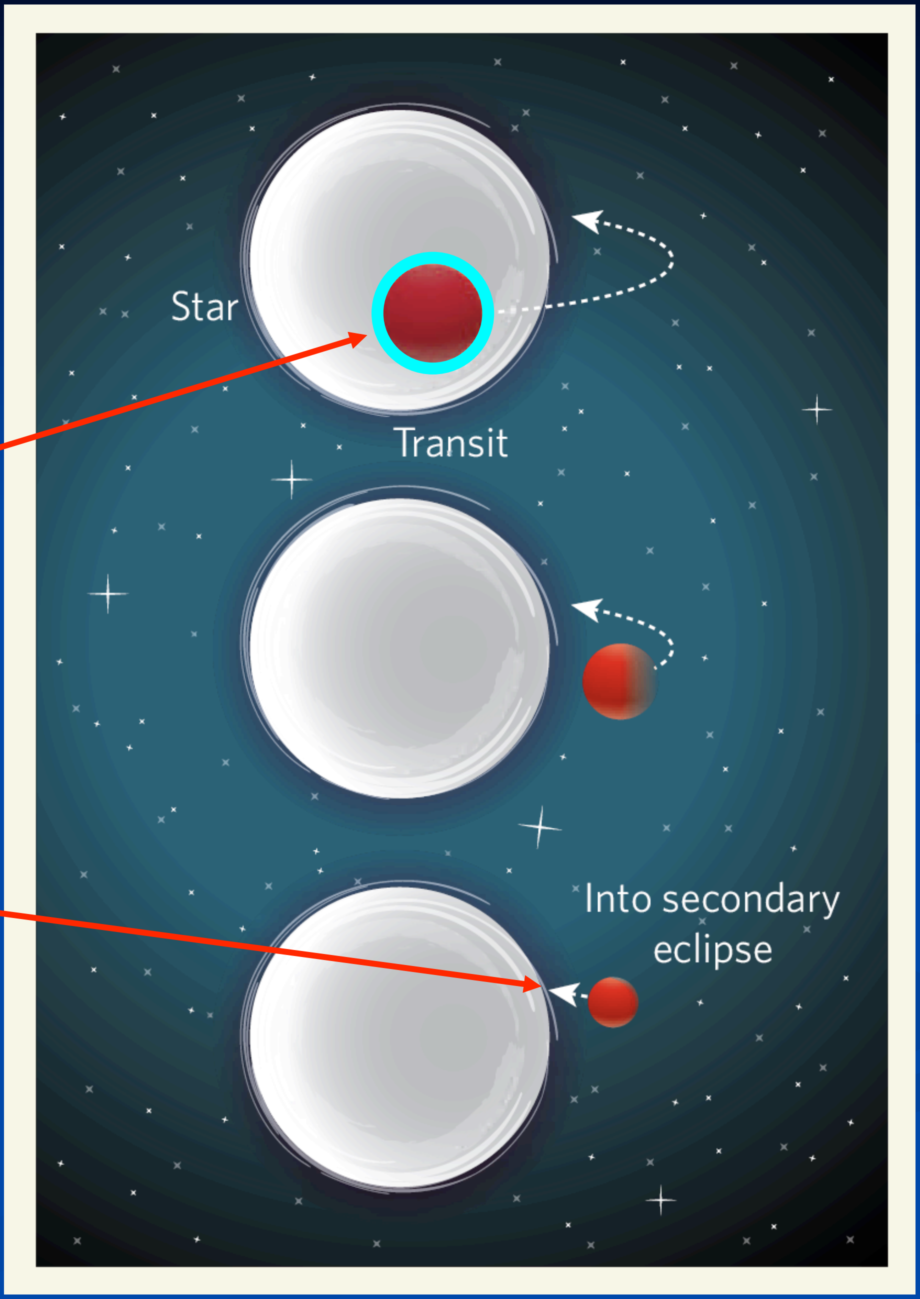
- How efficiently is heat transferred from the day to the night side?
- How does the atmosphere partition energy?
- What governs the chemistry: thermochemistry, photochemistry, ion chemistry?
- What are the dynamics & circulation like?
- What is the ionosphere & magnetosphere like?

Exoplanet Spectroscopy

Transmission during primary eclipse

Emission during secondary eclipse

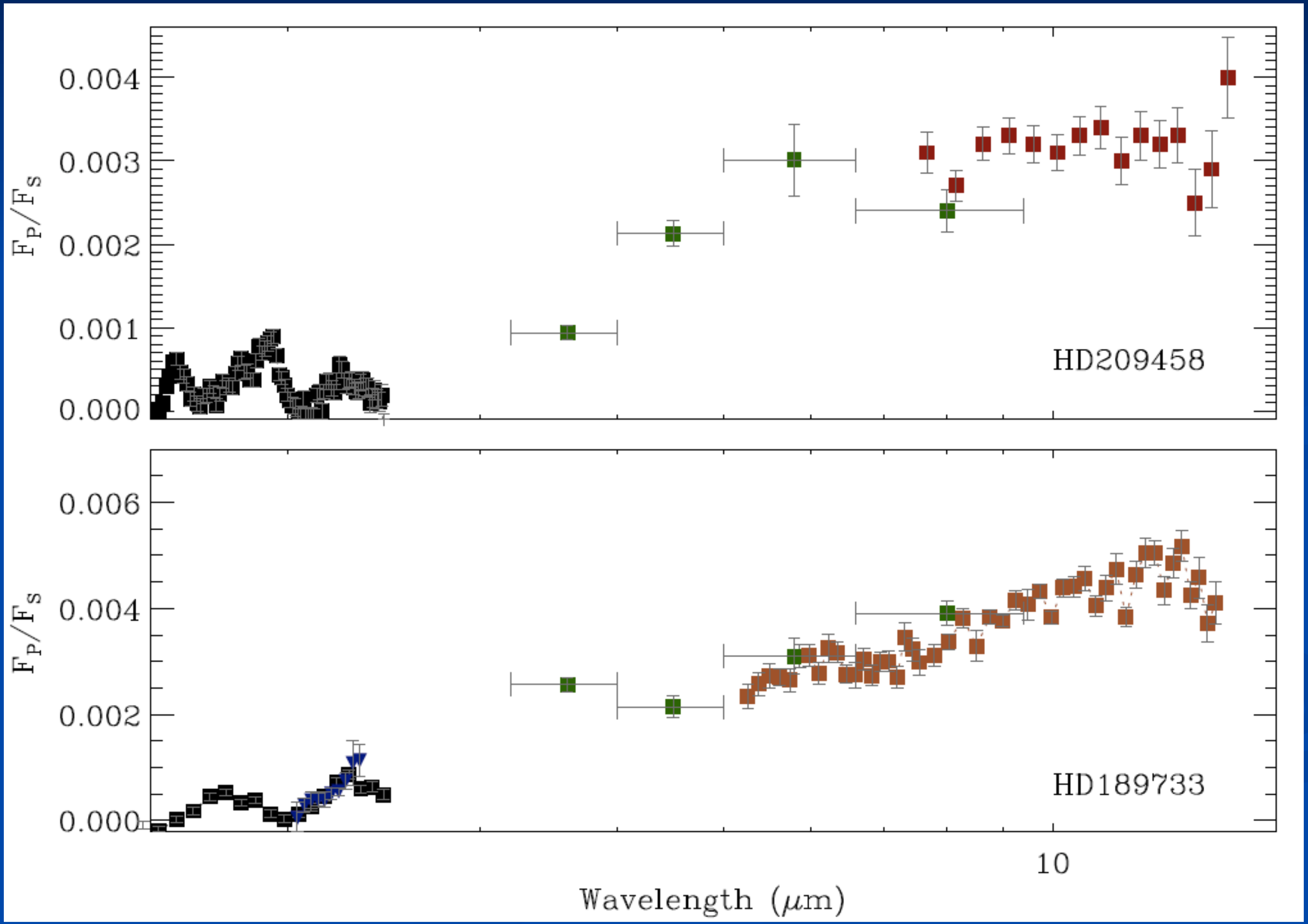
Obital phase variations



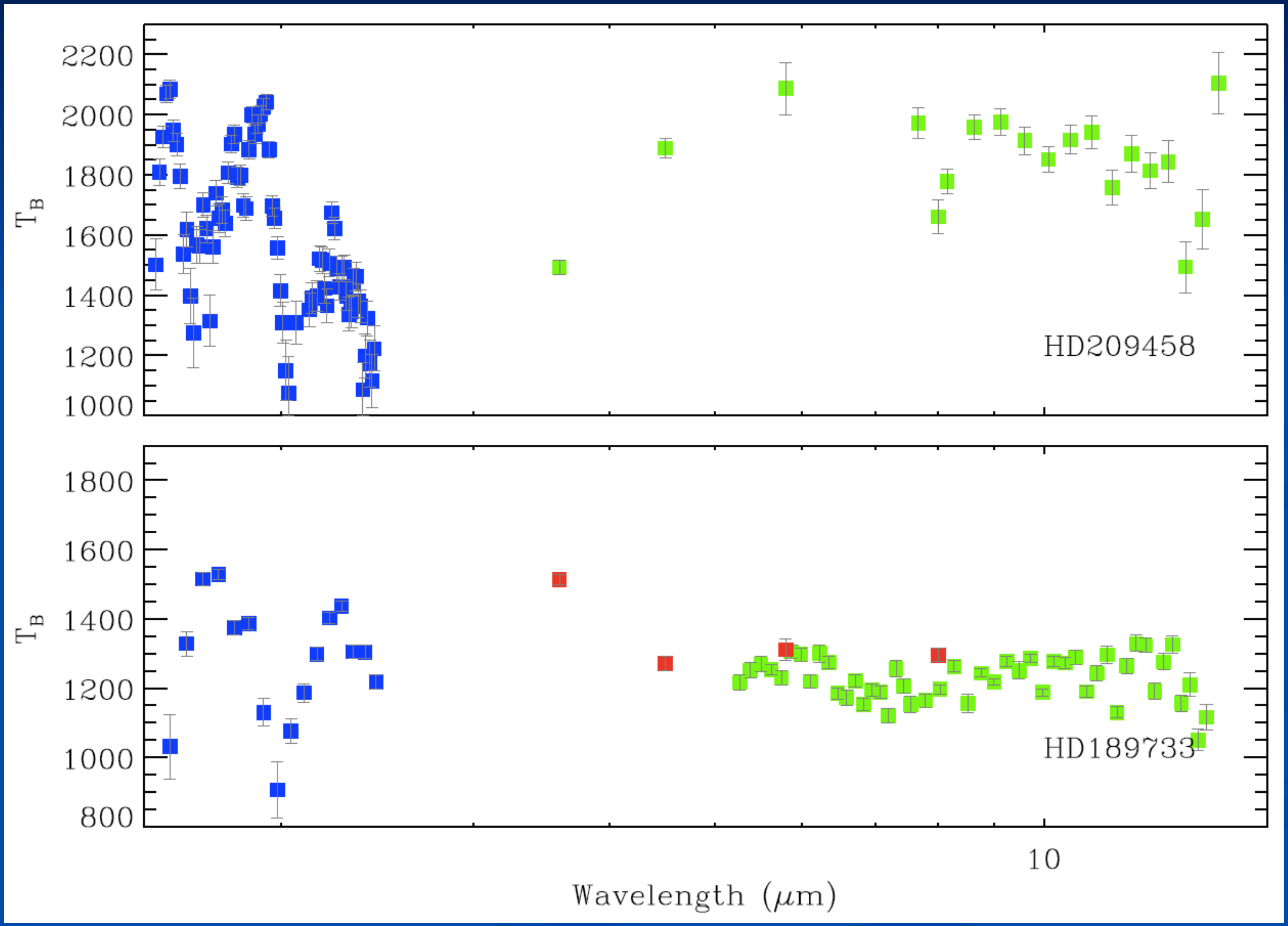
HD209458b

STAR:	
Distance	47 pc
Spectral Type	G0 V
Apparent Magnitude V	7.65
Mass	1.01 (± 0.066) M_{sun}
Age	4 (± 2) Gyr
Effective Temperature 5942 K	ref.
Radius	1.146 (± 0.059) R_{sun}
Metallicity [Fe/H]	0.04
Right Asc. Coord.	22 03 10
Decl. Coord.	+18 53 04
PLANET:	
Mass	0.685 MJ
Semi major axis	0.047
Orbital Period	3.5247 days
Eccentricity	0.07
Radius	1.32 RJ
Inclination	86.677

Dayside Flux



Dayside T_B



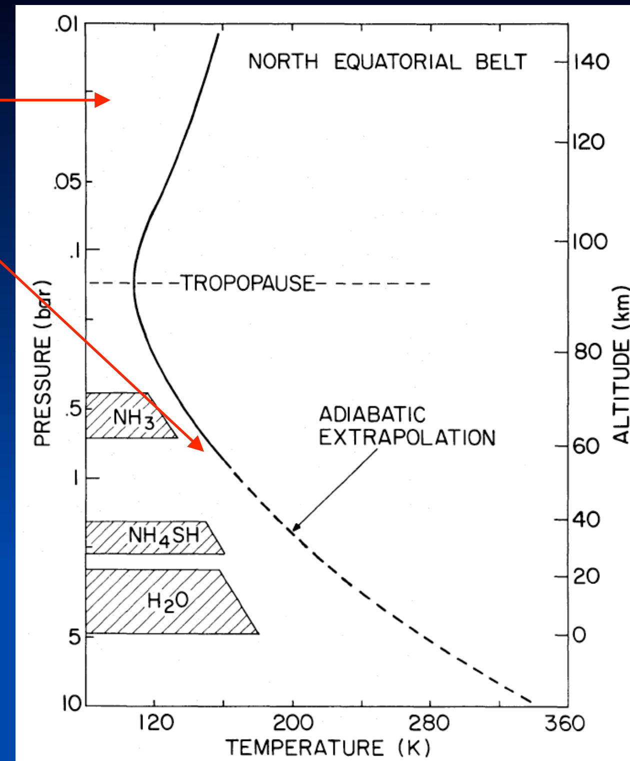
Demming et al. 2005, Knutson et al. 2007, Charbonneau et al. 2008, Grillmair et al. 2008, Swain et al. 2009, 2008

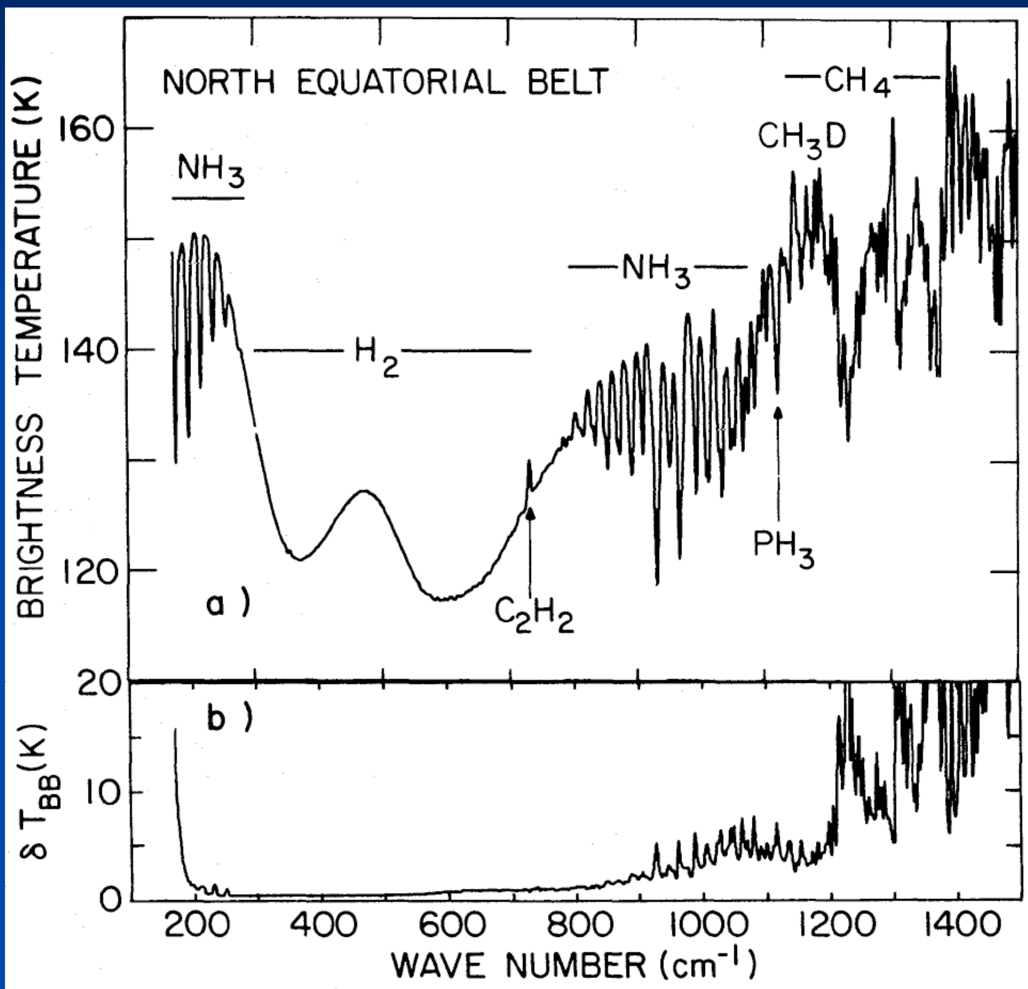
An Aside:

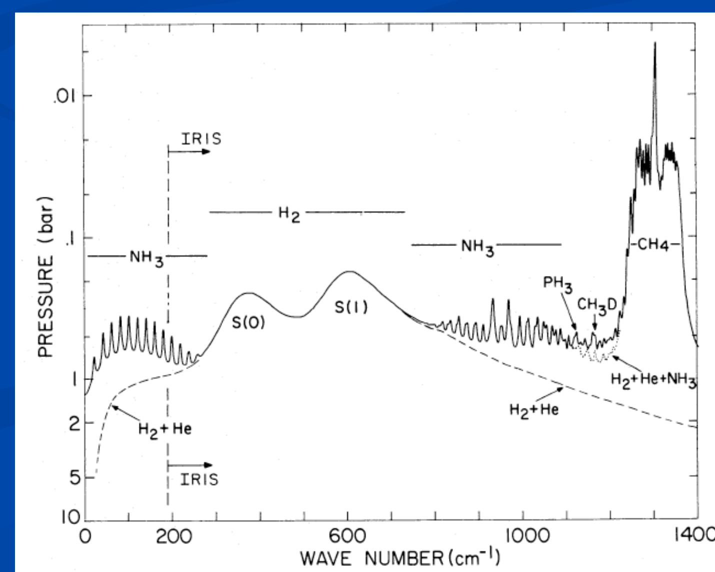
Jupiter IR

$\Delta\lambda = 0.01\ cm^{-1}$

$\Delta\lambda = 0.08\ cm^{-1}$

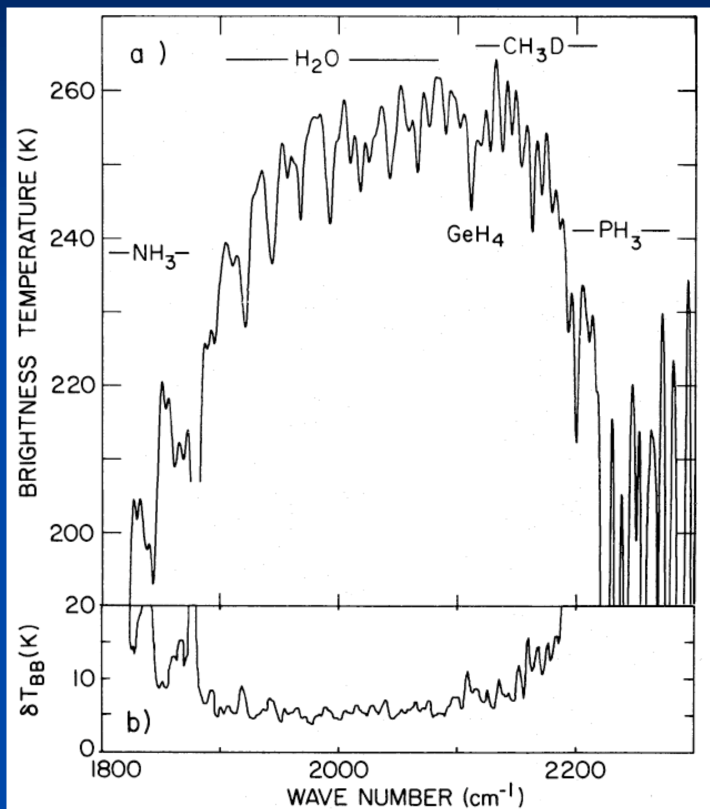


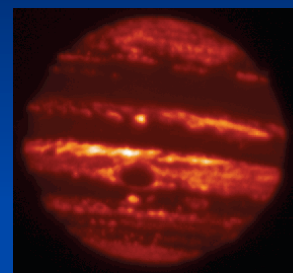


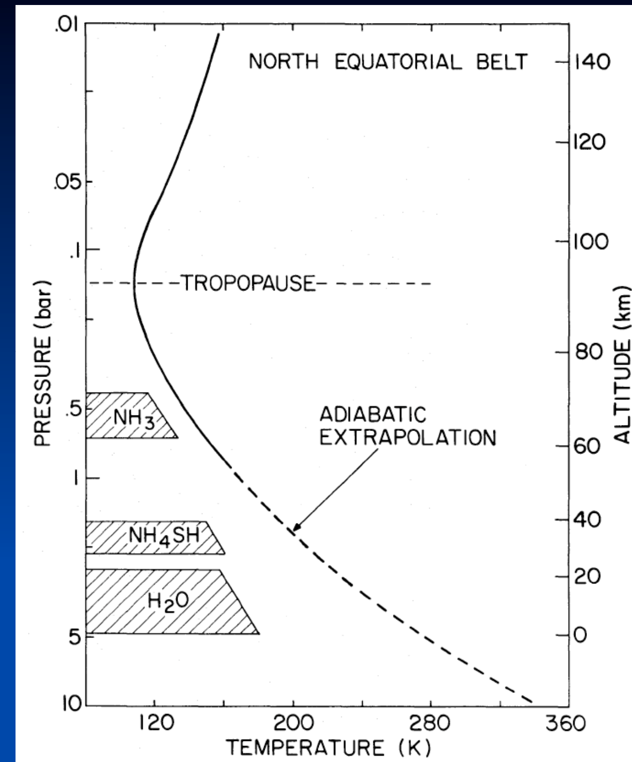


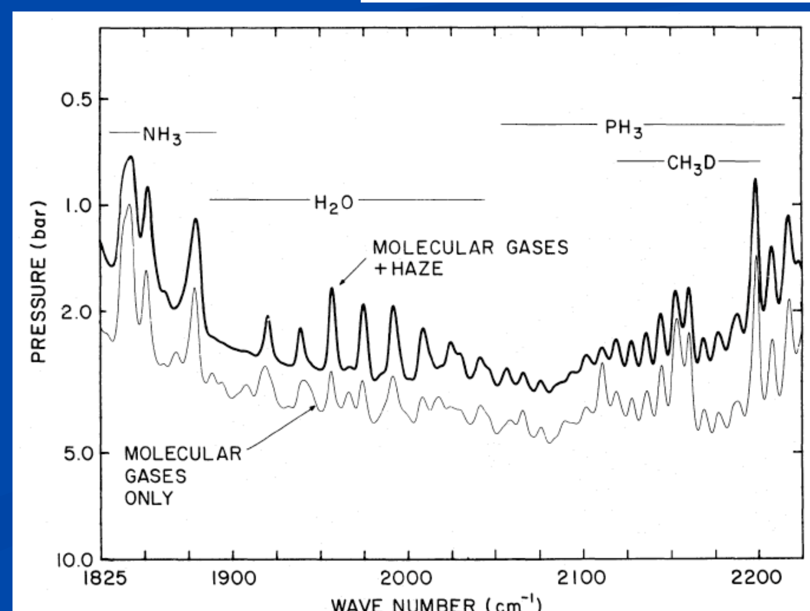
Kunde et al 1982

Jupiter NEB at 5 um









Kunde et al 1982

Radiative Transfer

Sara's

$$\frac{dI(s,\nu,t)}{ds} = \varepsilon(s,\nu,t) - \kappa(s,\nu,t)I(s,\nu,t)$$

$S_\nu = \varepsilon/\kappa$

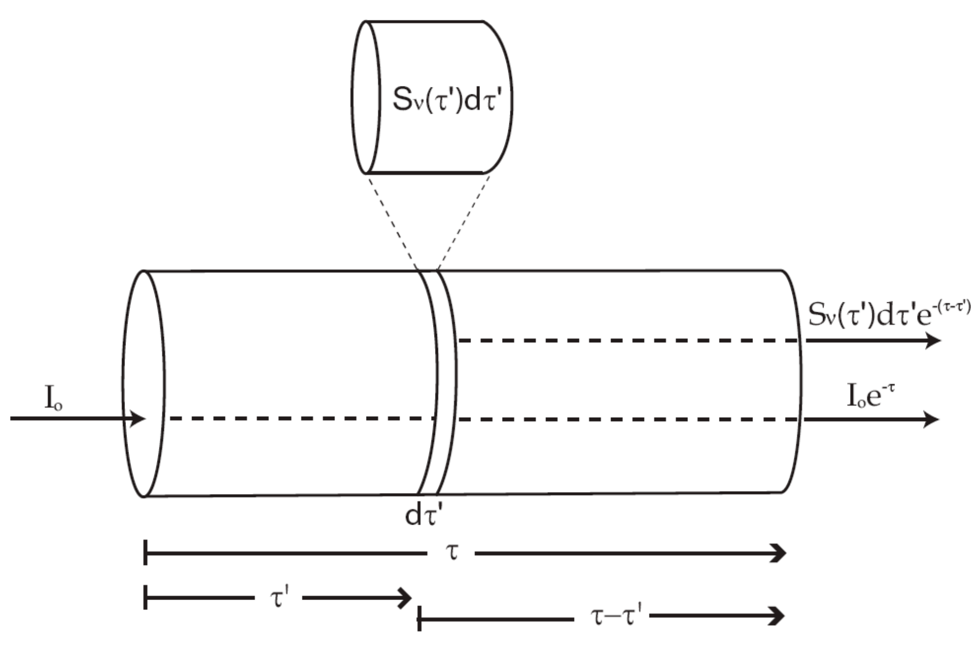
$d\tau = \kappa\, ds$

General Equation: $$\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$$

Multiply both sides of equation by e^τ .

General Solution: $$I_\nu(\tau_\nu) = I_\nu(0)\ e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu e^{-(\tau_\nu - \tau_\nu')} d\tau'$$

The final intensity equals the original intensity attenuated by absorption & scattering events plus contributions from the source function, S, along the path. The source function includes thermal emission and scattering back into the beam.



I_ν = intensity at wavenumber, ν

S_ν = source fn. at wavenumber, ν

τ_ν = optical depth at wavenumber, ν

Radiative Transfer

General Solution: $$I_\nu(\tau_\nu) = I_\nu(0)\ e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu e^{-(\tau_\nu - \tau'_\nu)} d\tau'$$

Source terms for scattering of light into the beam make the equation messy, because S then includes the probability, p, that light, I(θ',φ'), is scattered in the direction of the beam (θ,φ)

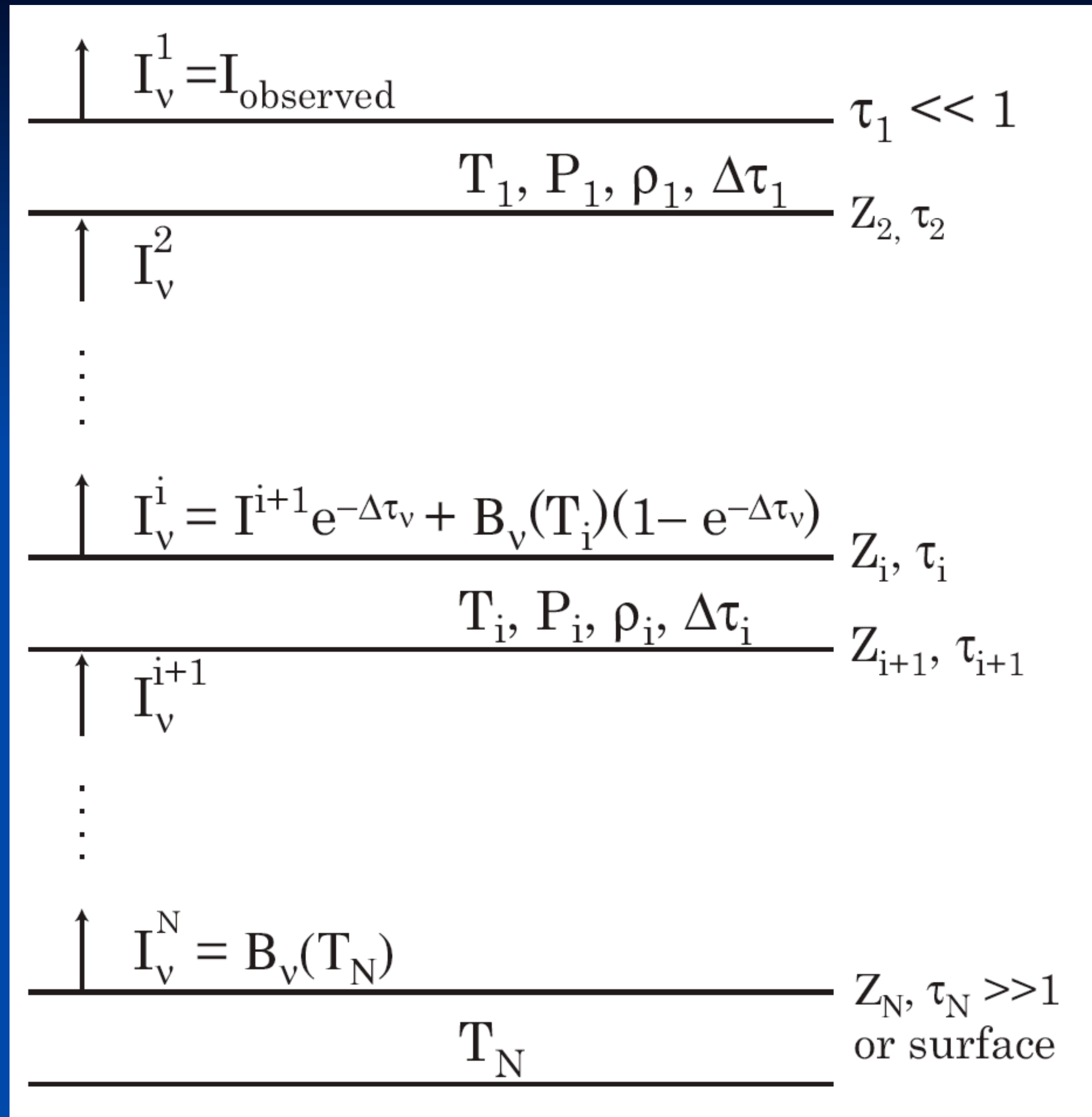
$$S_\nu = \frac{j_\nu}{k_\nu} = \frac{\kappa_s}{\kappa_e} \int_{4\pi} I_\nu(\theta', \phi')\ \frac{p(\theta', \phi'; \theta, \phi)}{4\pi} d\Omega'.$$

For HD209's IR spectrum no scattering is indicated. We can assume LTE. the source function is the Planck function, B_ν, which for a constant local temperature is constant.

$$I_\nu(\tau_\nu) = I_\nu(0)\ e^{-\tau_\nu} + B_\nu(1 - e^{-\tau_\nu})$$

Divide the atmosphere into 80 layers of constant temperature from 10 bars to 10^{-7} bar. Each layer has a specified composition, pressure, temperature, and thus τ_ν & B_ν

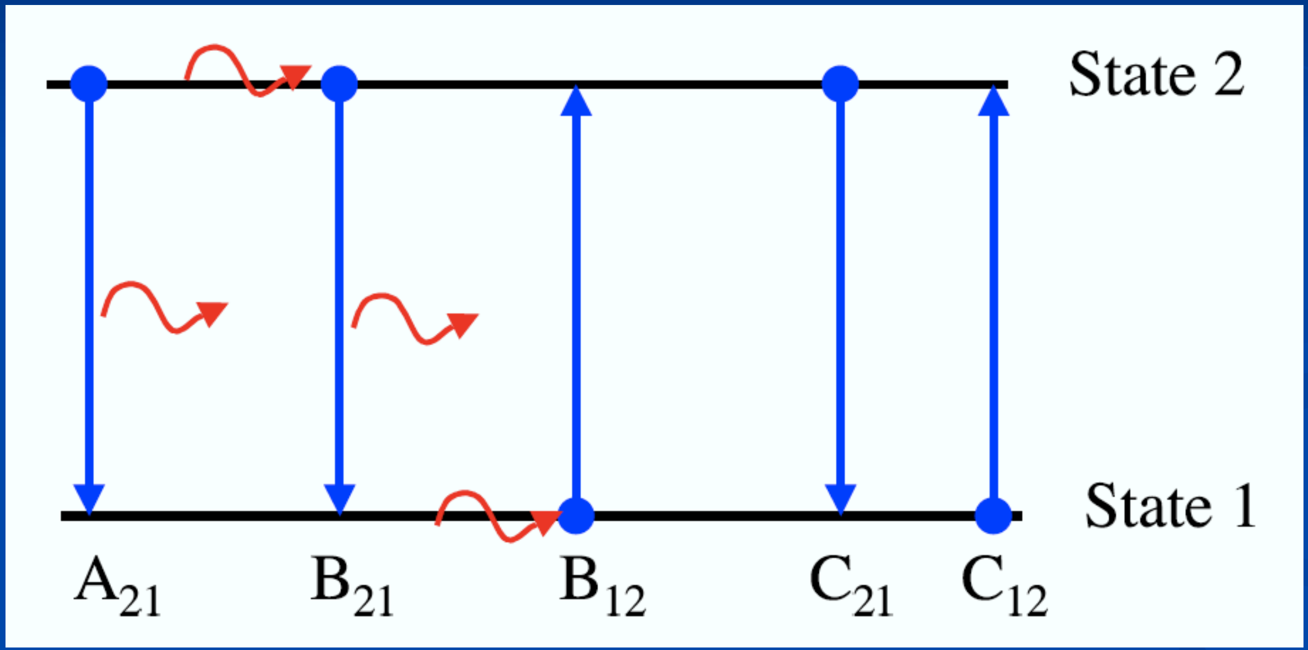
Radiative Transfer Calculation



Range of Brightness Temperatures

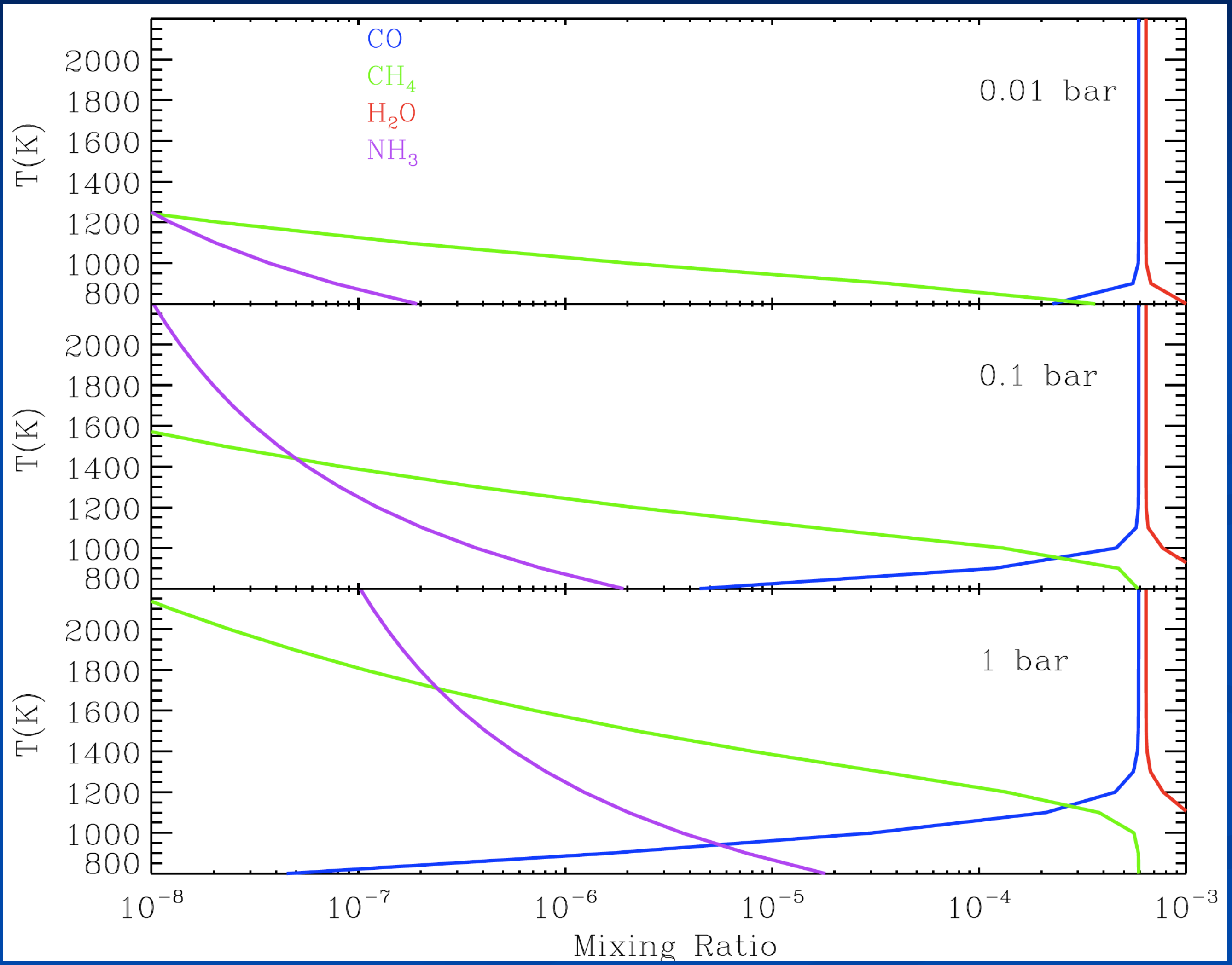
800 K < T_B <2200 K

If LTE, then T_B is a measure of the probed temperatures



Hypothetical molecule w. 2 discrete energy levels changes states by spontaneous & stimulated emission, absorption, and collisional excitation & de-excitation. If collisions dominate, we have LTE.

Thermochemical Equilibrium Composition

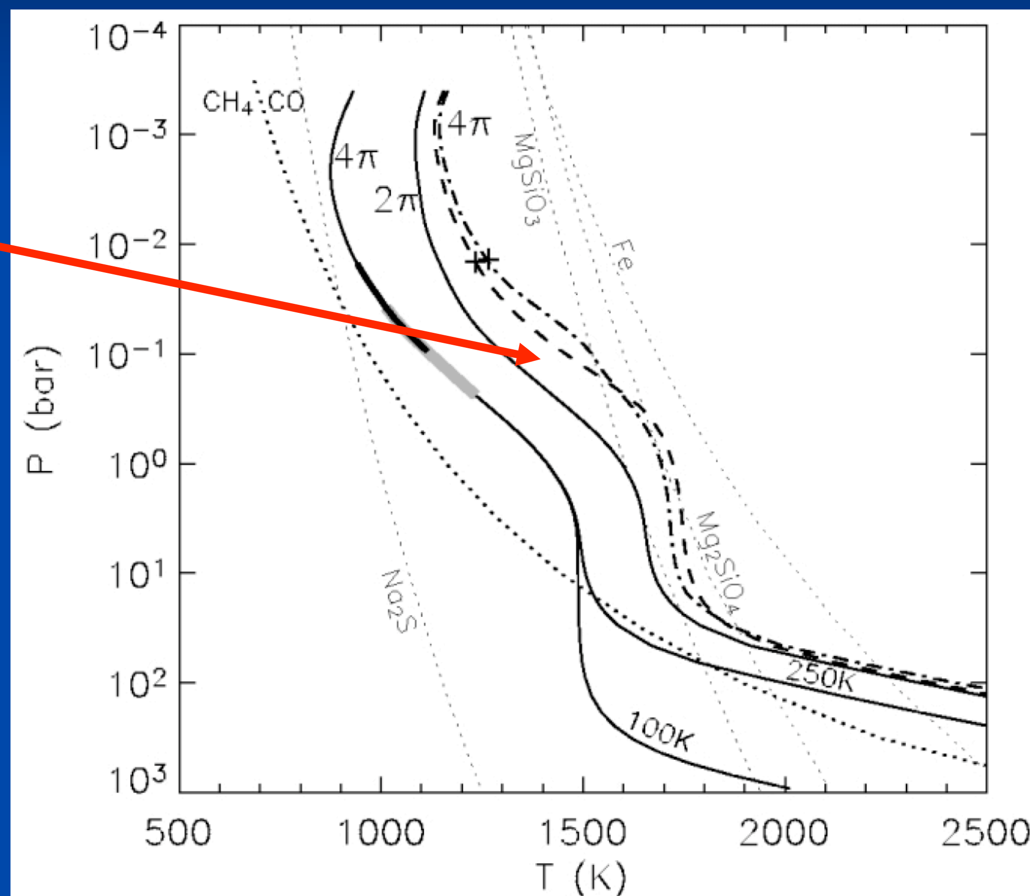


CO_2 abundance: roughly 10^{-7} to 10^{-6}

Estimate Temperature Profile

Assume thermochemical equilibrium abundance with solar metalicity
Heat fully distributed from day to night (4π reradiated heat)

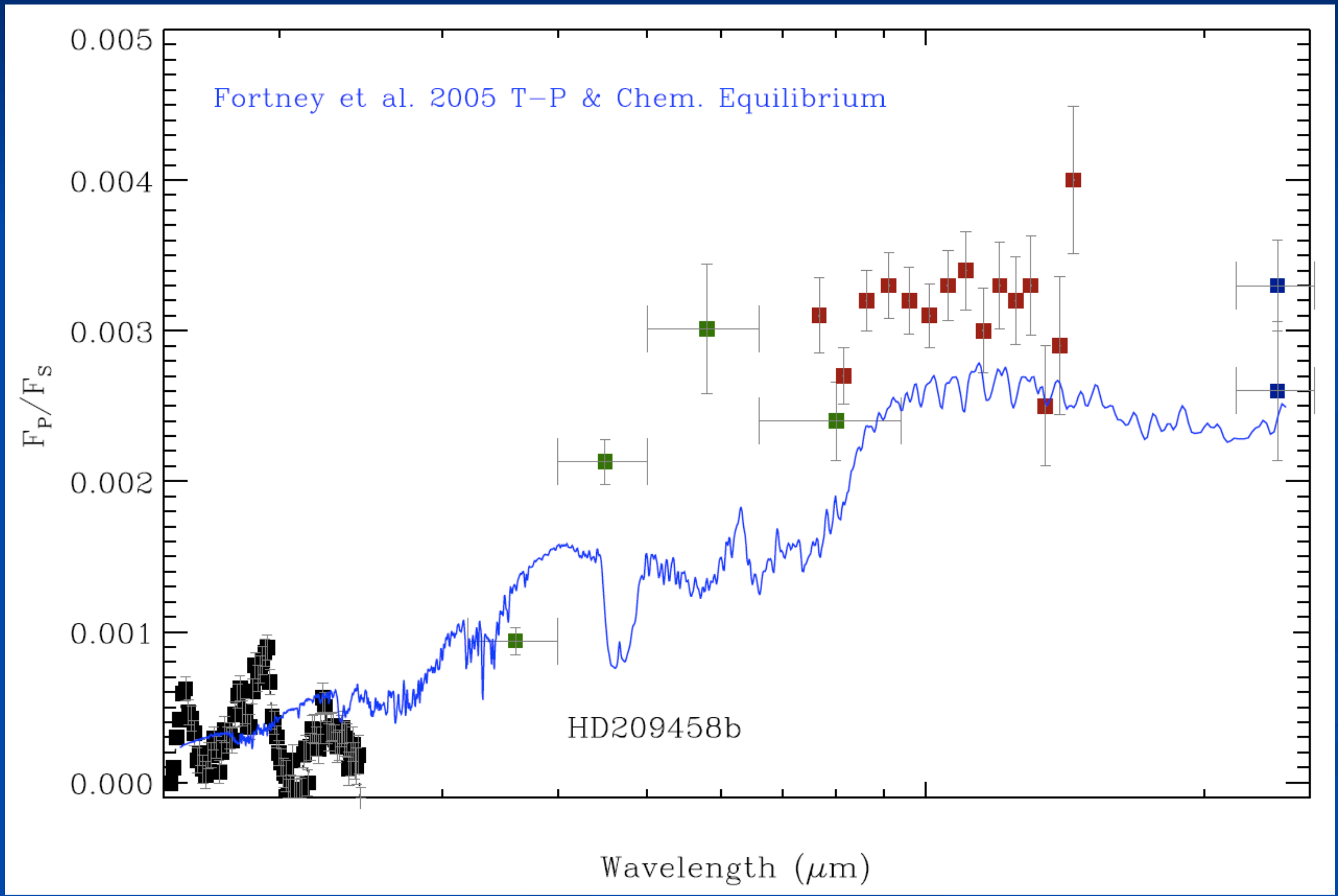
HD209458b
(Dashed)



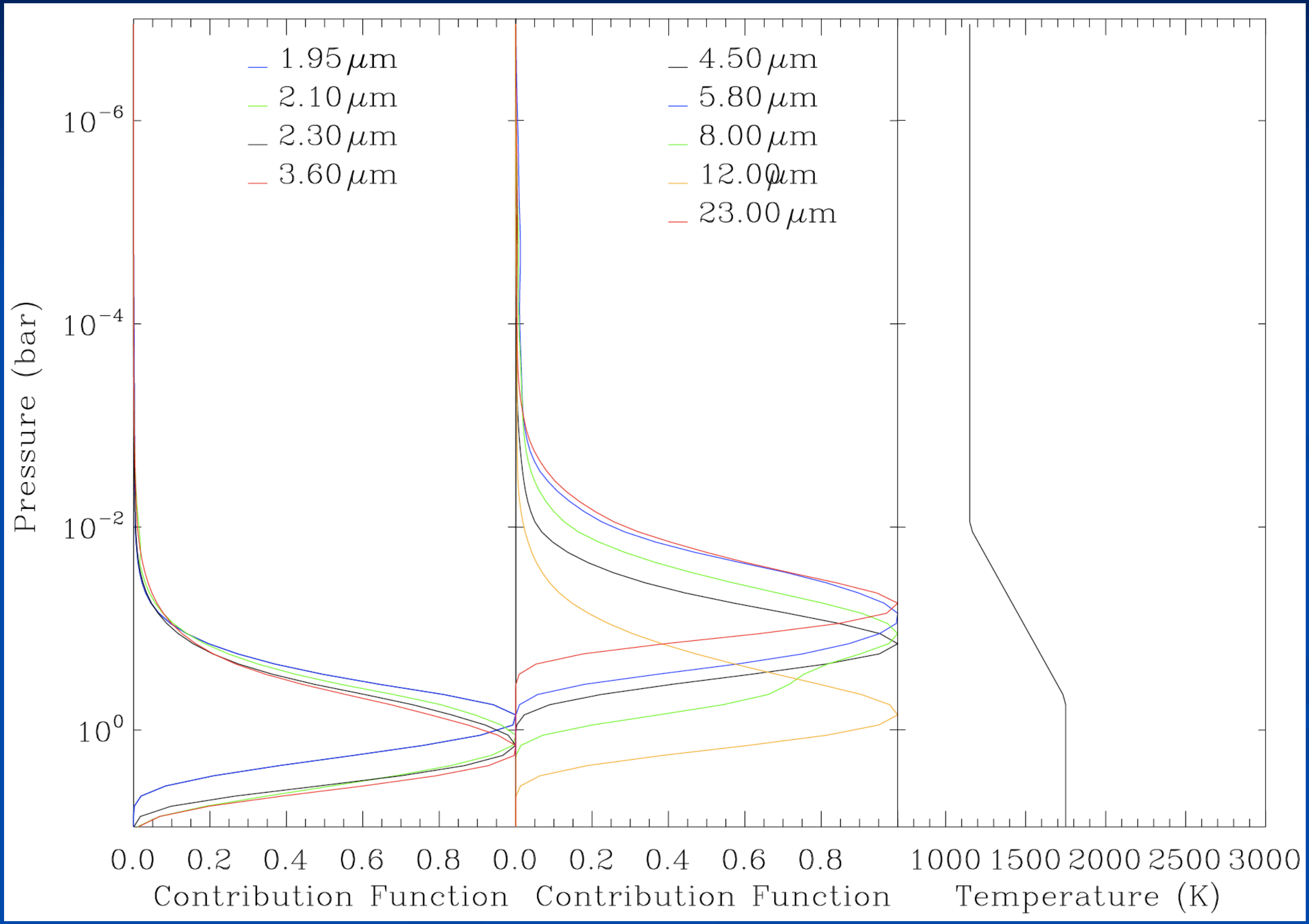
Fortney et al. 2005

Model largely uncorrupted by spectra

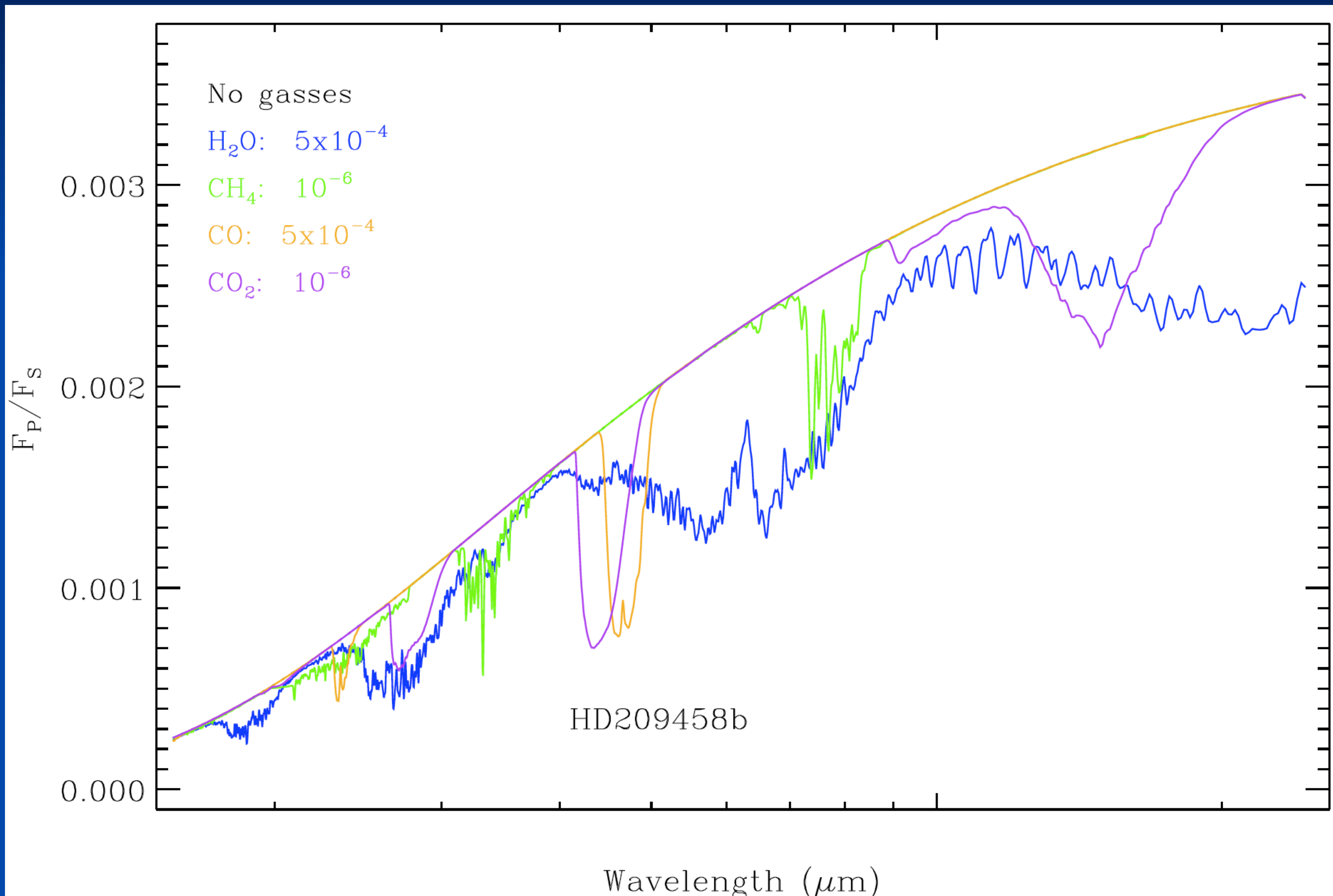
Fit the HD209458b dayside data?



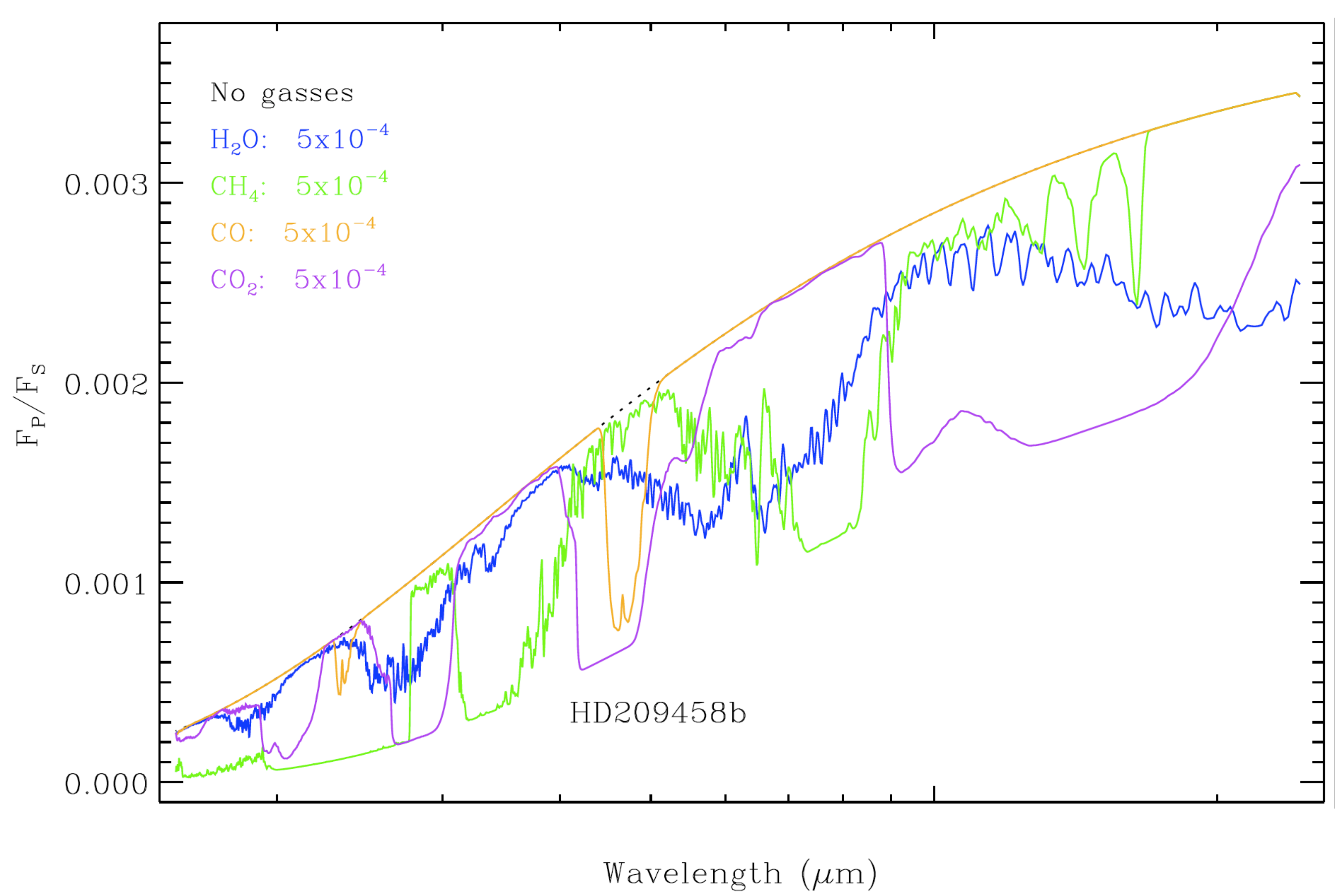
Contribution Functions



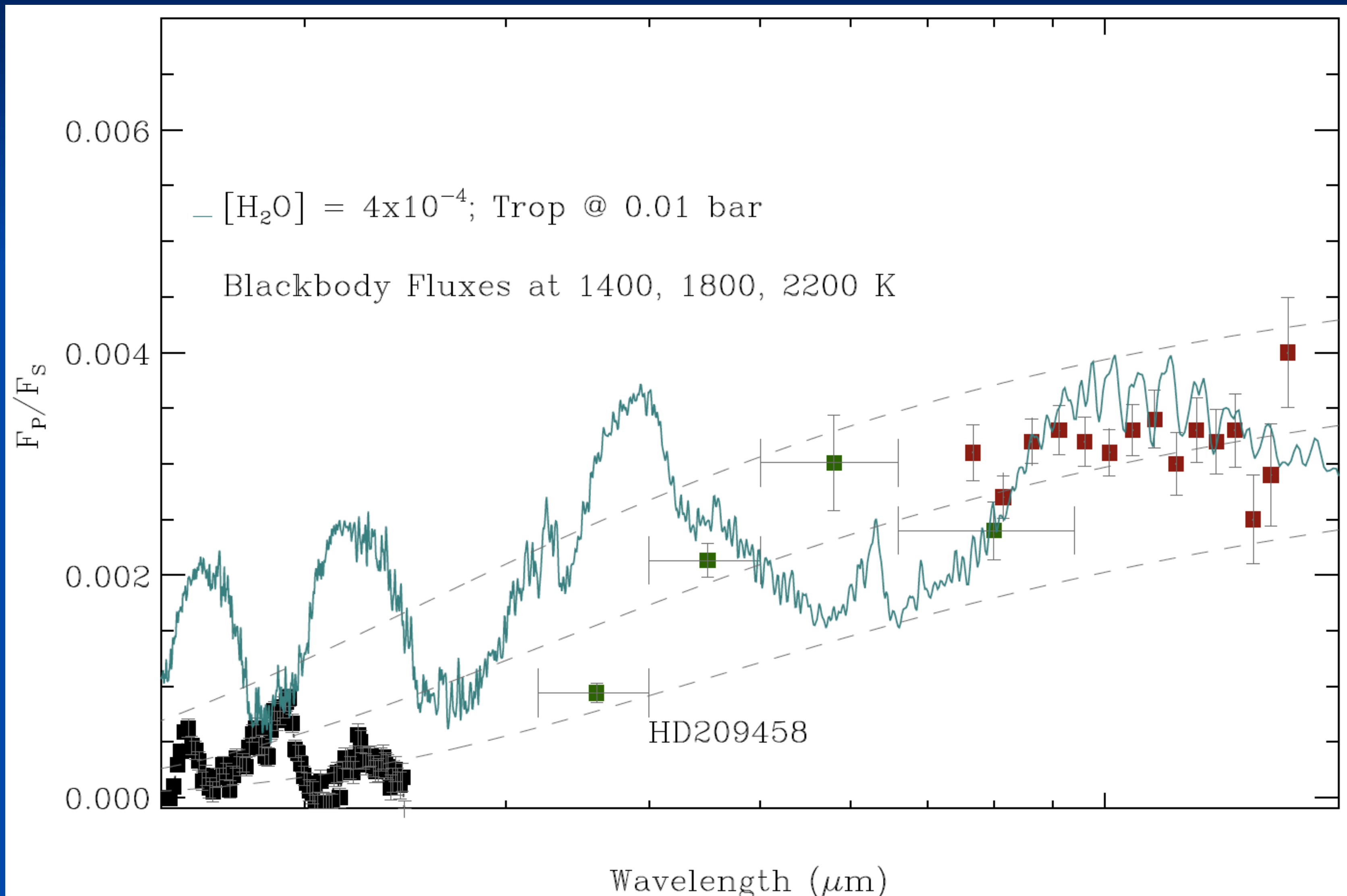
Affects of each gas: water dominates



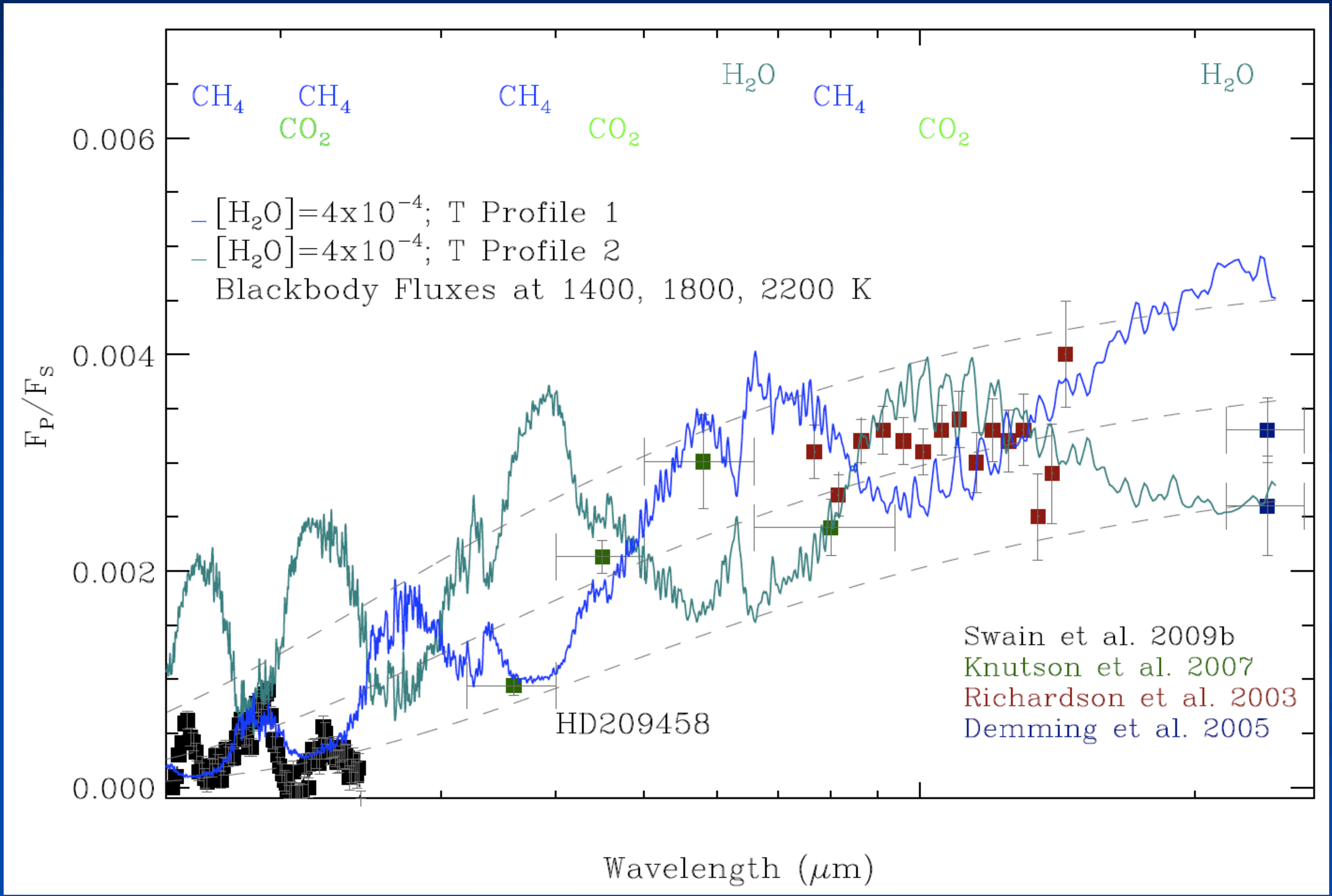
Similar abundances: CH_4 dominates



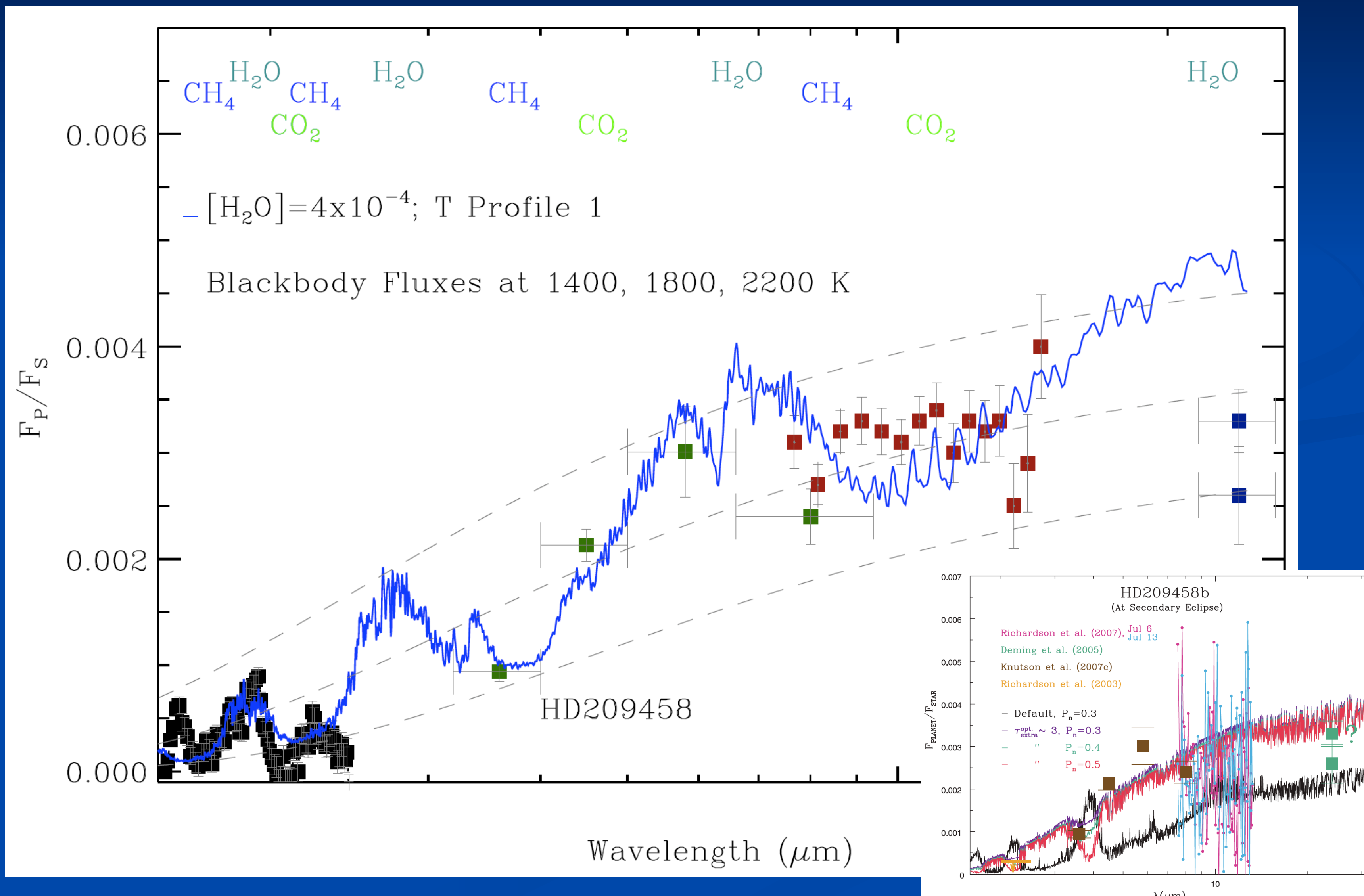
Consider water only & no inversion



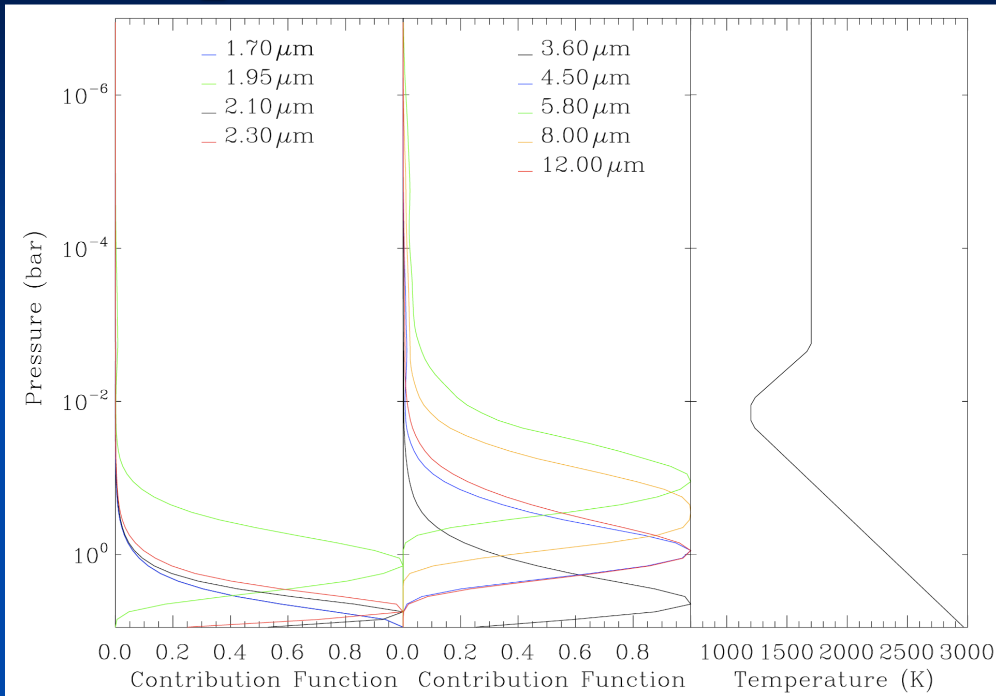
Flip the Temperature

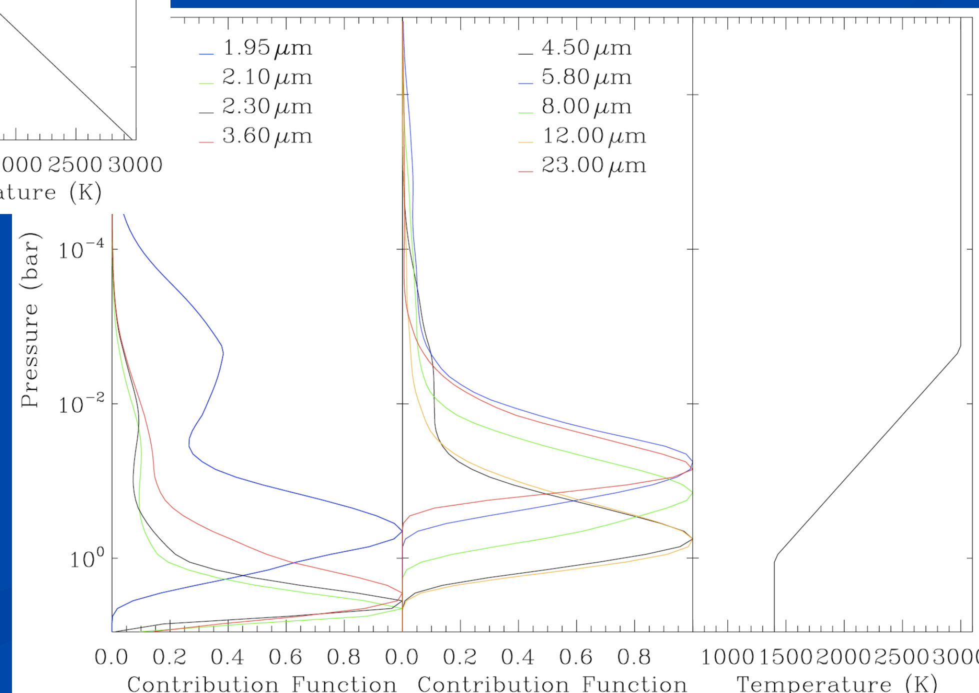


Flip the Temperature



Temperatures & Contribution Functions





Contribution functions

Emerging energy, assuming LTE & no incident radiation:

$$I_\nu(\tau_\nu) = B_\nu(\tau_{surf})\ e^{-\tau/\mu} + \frac{1}{\mu}\int_{\tau_{surf}}^{0} B_\nu e^{-\tau/\mu} d\tau.$$

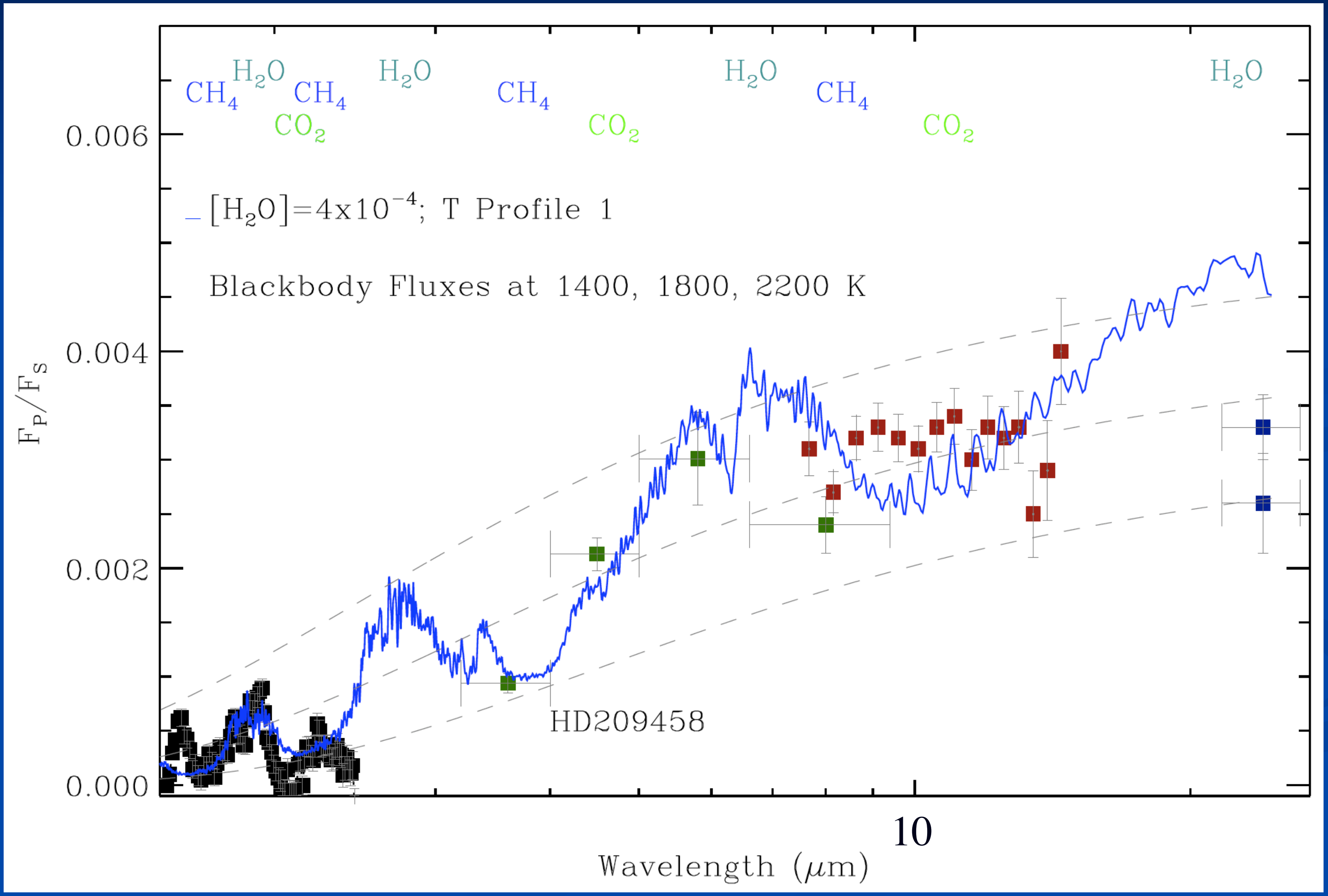
For a bottomless atmosphere:

$$I_\nu(\tau_\nu) = \frac{1}{\mu}\int_{\infty}^{0} B_\nu e^{-\tau/\mu} d\tau.$$

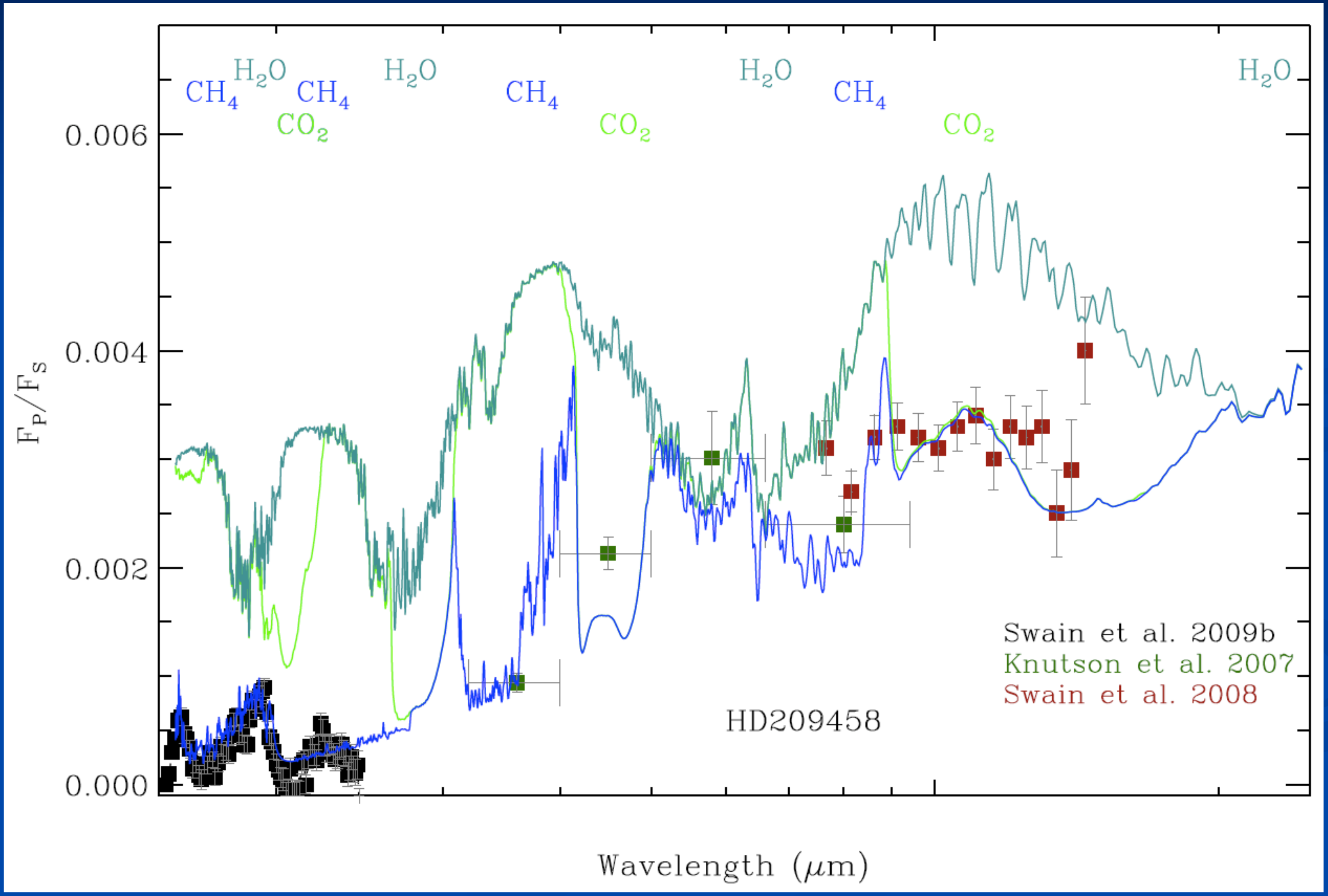
$$I_\nu(\tau_\nu) = \int_{\infty}^{0} CF(P)\ d\ln P.$$

$$CF(P) = B_\nu e^{-\tau/\mu} \frac{d(\tau/\mu)}{d\ln P}$$

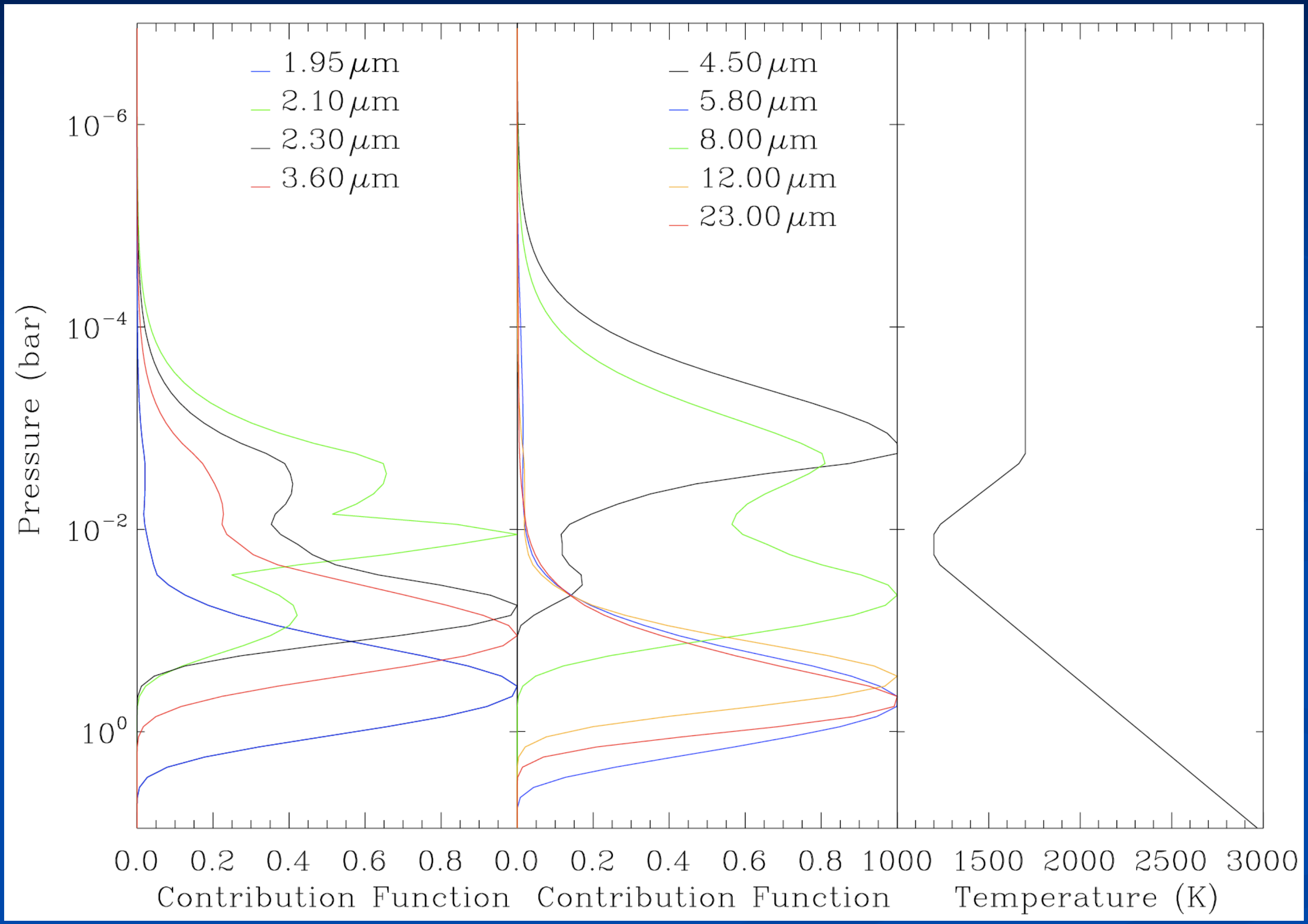
Let CH_4 define the 2 um features



Let CH_4 define the 2 um features

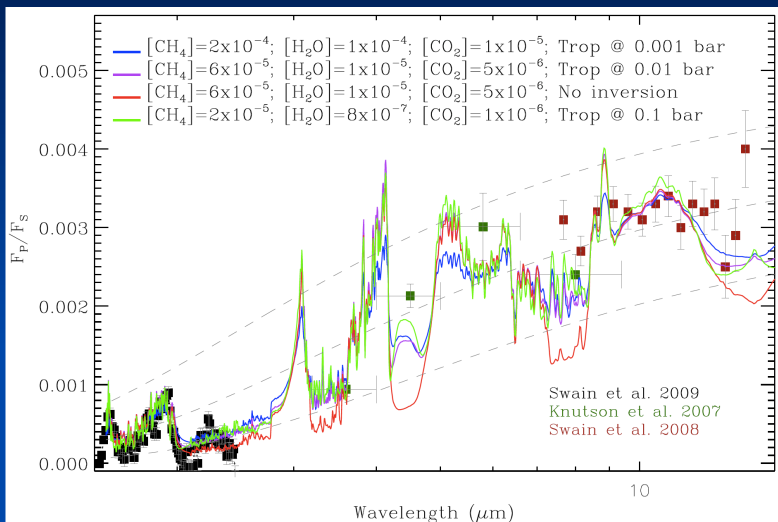


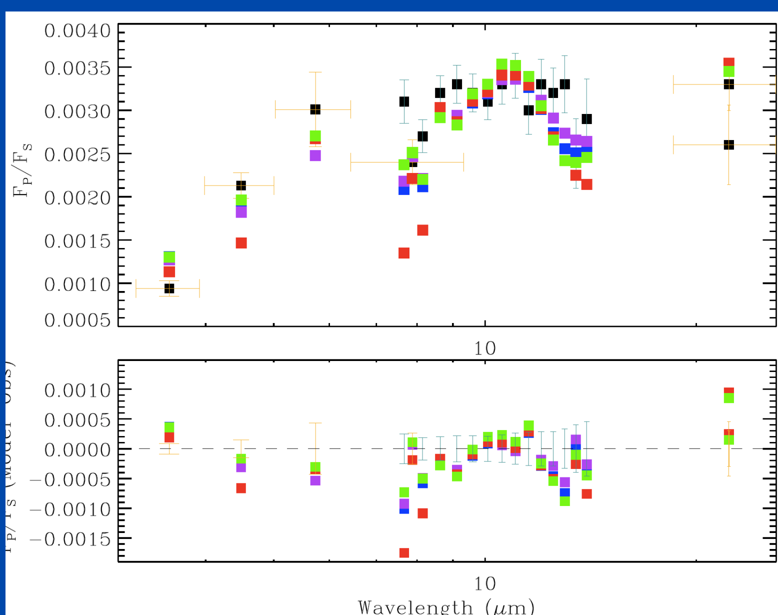
Temperature Inversion indicated by 2 points!

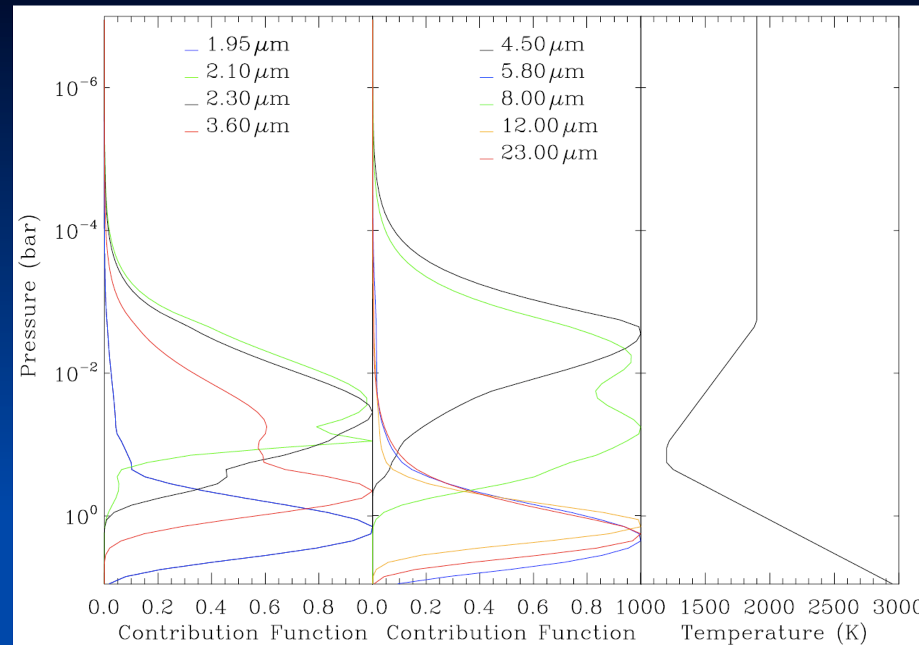


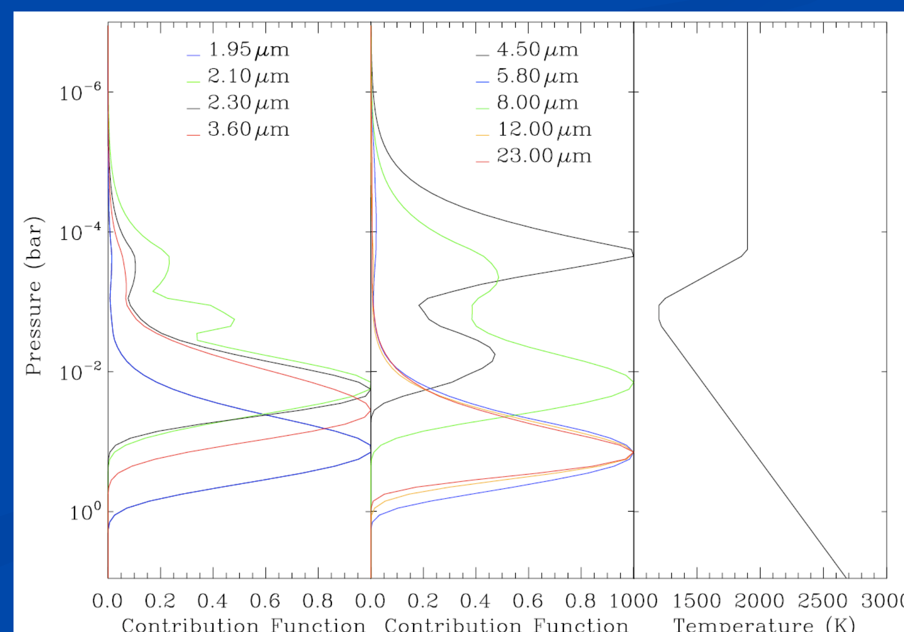
Is this the final solution?

No, for example:

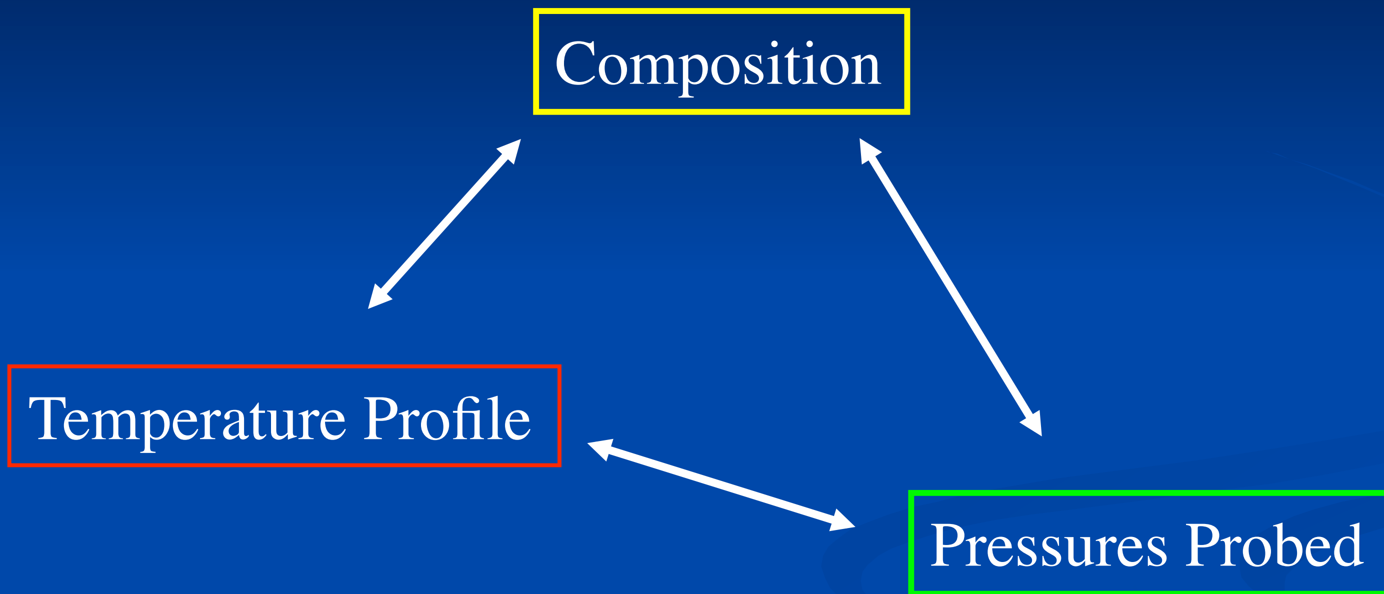






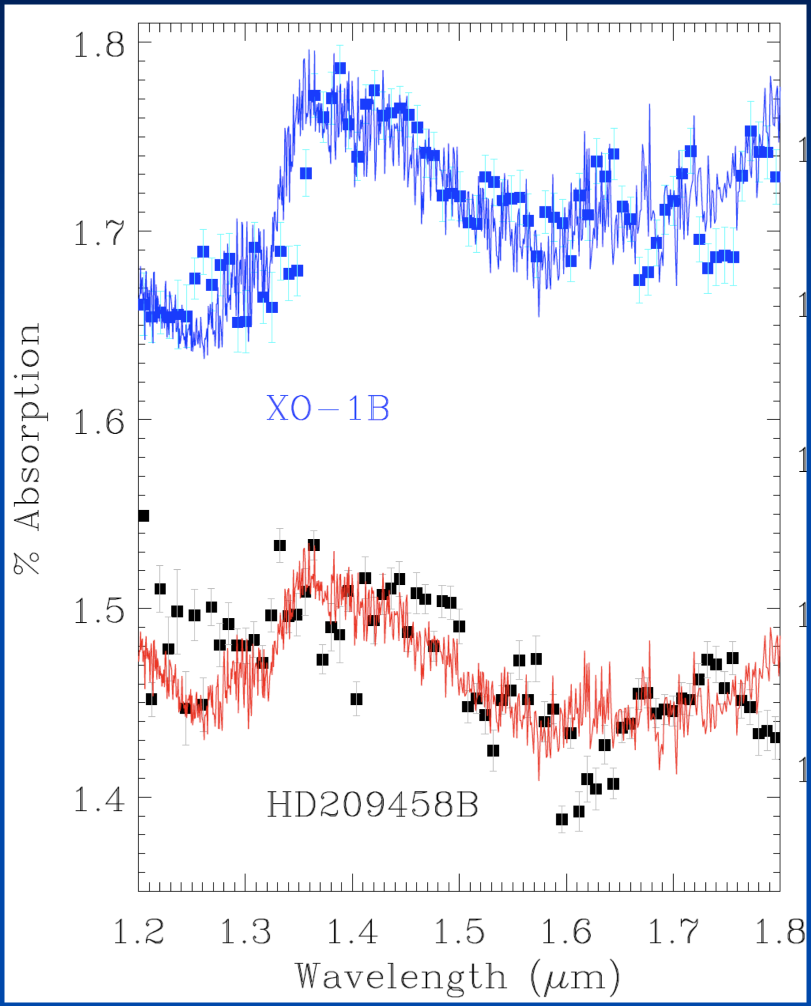


Situation: Leigh's Lesson # 7



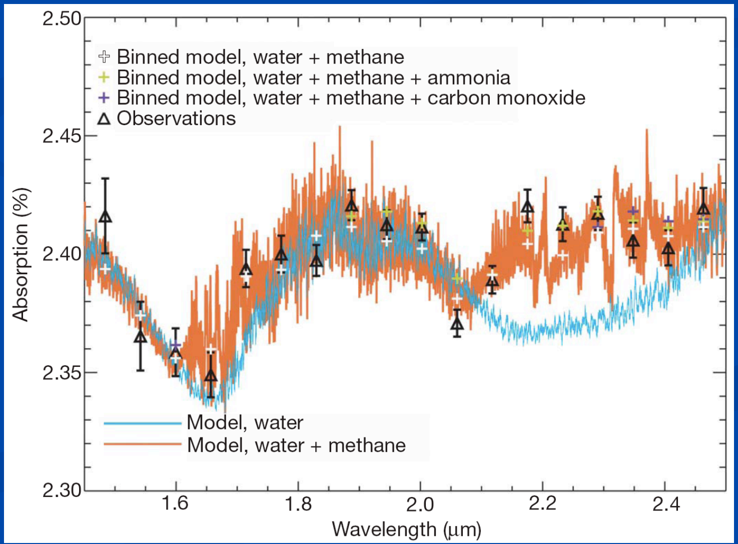
Other constraint: Energy out = Energy in

Limb Transmission



(Tinetti et al. in preparation)

Spectra are consistent!
Can't discuss analysis now.



HD189733b (*Swain et al. 2008*)

Aside to Jupiter

Occultation of β Scorpii by Jupiter

Consider the ideal gas law,

$$\rho = \frac{Pm}{RT},$$

and integrate this expression:

$$\int_{P_0}^{P} \frac{dP}{P} = -\int_{z_0}^{z} \frac{gm}{RT} dz \qquad (2)$$

That is:

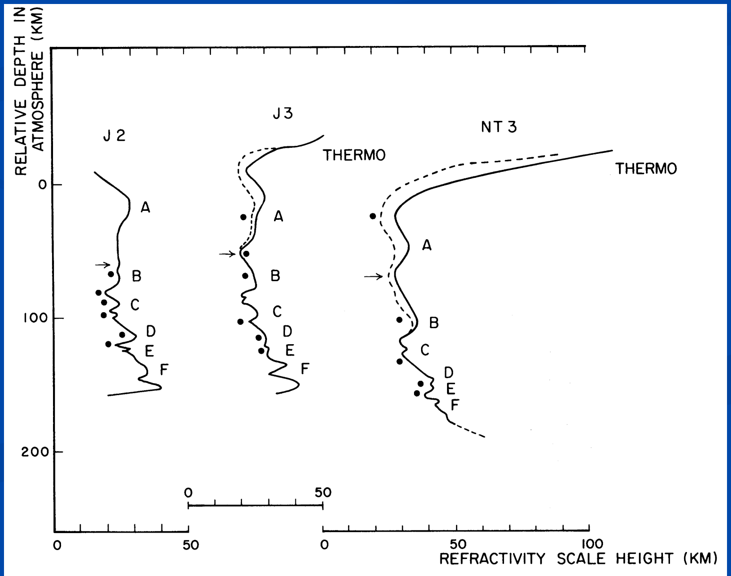
$$P = P_0 \ exp[-\int_{z_0}^{z} \frac{gm}{RT} dz] = P_0 \ exp[-\int_{z_0}^{z} \frac{dz}{H}].$$

Here we have introduced the pressure scale height, H:

$$H = \frac{RT}{mg} \qquad (3)$$

Note that for an isothermal atmosphere (over little change in g), H is constant and is the e-folding distance for changes in ρ and P. That is:

$$P = P_0 \ exp[-z/H].$$



-> Jupiter has a hot high atmosphere
(that is T > 300 K)

Hubbard et al. 1972

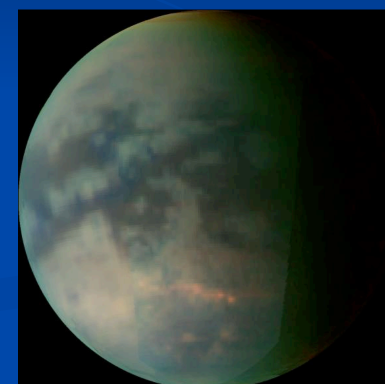
Particulates?

1) Effects of particulates.
   - No indication of its effects in mid-IR
   - Indications at optical wavelengths

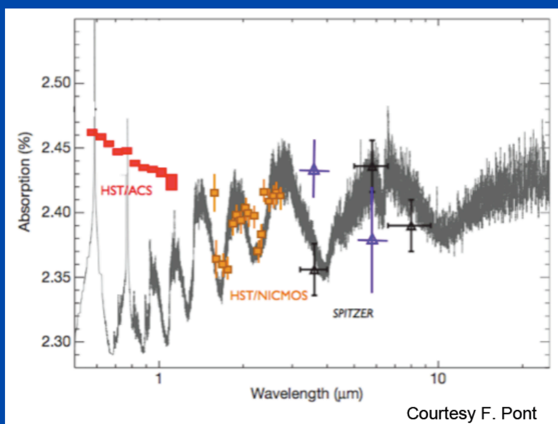
0.2-1.0 um
Haze particles

Titan @ ~0.6 um

cloudless

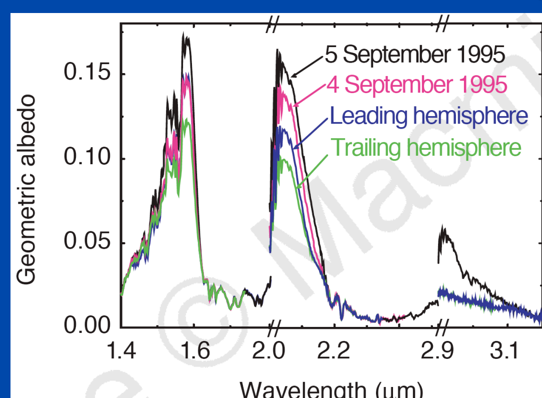


Titan @ 2-5 um



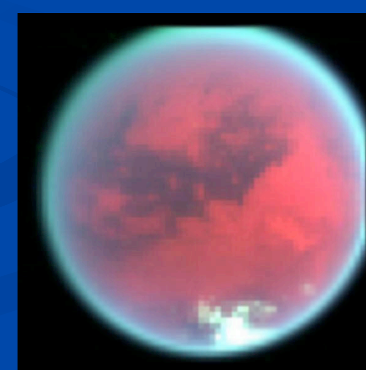
Haze: effects short λ

Clouds: mirror at all λ



(Griffith et al. 1998)

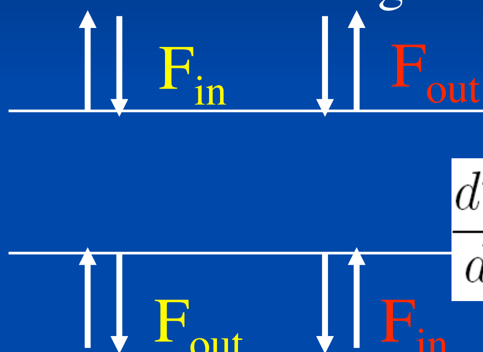
>5um cloud
particles



Assume a thermal profile?

1) Radiative Equilibrium?

Conserve flux* throughout the atmosphere

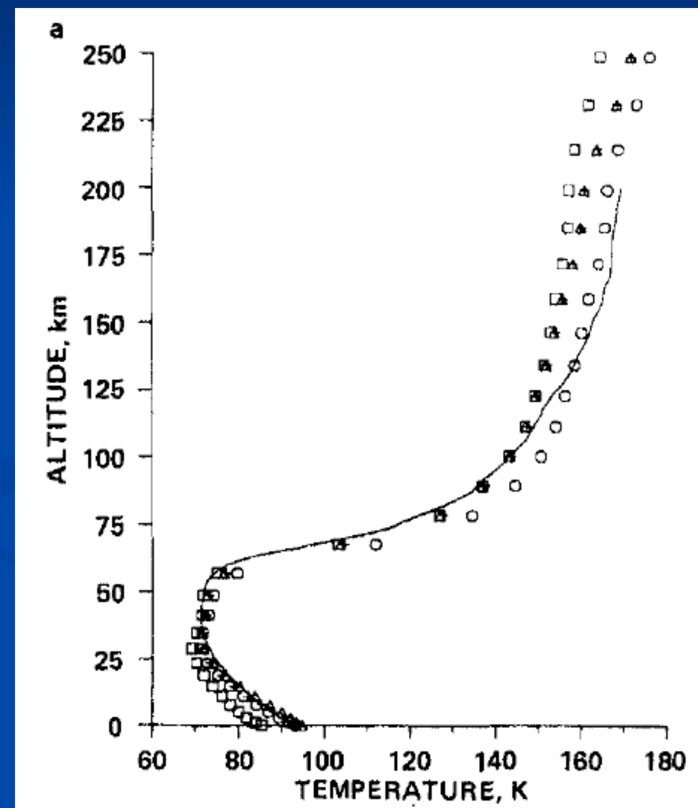


$$\frac{dT}{dt} = -\frac{1}{\rho c_p}\frac{dF}{dz}$$

2) GCM derived profile?

- Continual dialog.
- Clearly distinguish observational from theoretical constraints

Titan Structure



Radiative equilibrium on Titan (T_{eff} = 85 K, τ_{rad} = 148 yrs)

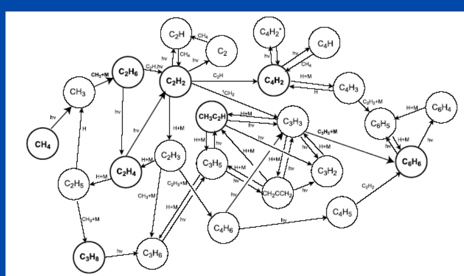
- Flux is the integrated intensity component in a particular direction and over all frequencies. It represents the energy / time / area propogated in a particular direction.

Should assume the chemistry?

1) Thermochemical Equilibrium?
2) Photochemical Model?

Both too early perhaps
Again there is a dialog

Titan Chemistry



Before Cassini

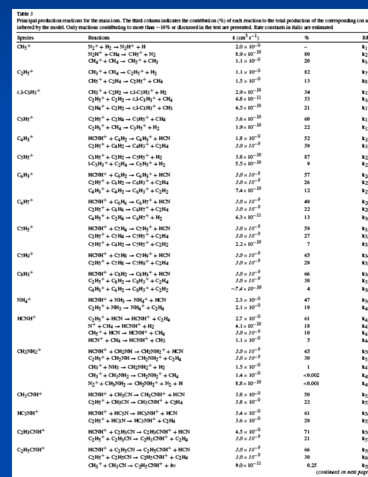
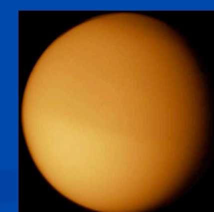


Table 3
Principal production reactions for the main ions. The third column indicates the contribution (%) of each reaction to the total production of the corresponding ion as inferred by the model. Only reactions contributing to more than ~10% or discussed in the text are presented. Rate constants in italic are estimated

Species	Reactions	k ($cm^3 s^{-1}$)	%	R#
CH_5^+	$N_2^+ + H_2 \rightarrow N_2H^+ + H$	2.0×10^{-9}	–	k_1
	$N_2H^+ + CH_4 \rightarrow CH_5^+ + N_2$	8.9×10^{-10}	80	k_2
	$CH_4^+ + CH_4 \rightarrow CH_5^+ + CH_3$	1.1×10^{-9}	20	k_3
$C_2H_5^+$	$CH_3^+ + CH_4 \rightarrow C_2H_5^+ + H_2$	1.1×10^{-9}	82	k_7
	$CH_5^+ + C_2H_4 \rightarrow C_2H_5^+ + CH_4$	1.5×10^{-9}	13	k_8
c,l-$C_3H_3^+$	$CH_3^+ + C_2H_2 \rightarrow$ c,l-$C_3H_3^+ + H_2$	2.9×10^{-10}	34	k_{15}
	$C_2H_5^+ + C_2H_2 \rightarrow$ c,l-$C_3H_3^+ + CH_4$	6.8×10^{-11}	33	k_{16}
	$C_2H_4^+ + C_2H_2 \rightarrow$ c,l-$C_3H_3^+ + CH_3$	6.5×10^{-10}	21	k_{17}
$C_3H_5^+$	$C_2H_5^+ + C_2H_4 \rightarrow C_3H_5^+ + CH_4$	3.6×10^{-10}	60	k_{11}
	$C_2H_3^+ + CH_4 \rightarrow C_3H_5^+ + H_2$	1.9×10^{-10}	22	k_{12}
$C_4H_3^+$	$HCNH^+ + C_4H_2 \rightarrow C_4H_3^+ + HCN$	1.8×10^{-9}	52	k_{18}
	$C_2H_5^+ + C_4H_2 \rightarrow C_4H_3^+ + C_2H_4$	*3.0×10^{-9}*	39	k_{19}
$C_5H_5^+$	$C_3H_5^+ + C_2H_2 \rightarrow C_5H_5^+ + H_2$	3.8×10^{-10}	87	k_{22}
	l-$C_3H_3^+ + C_2H_4 \rightarrow C_5H_5^+ + H_2$	5.5×10^{-10}	9	k_{23}
$C_6H_3^+$	$HCNH^+ + C_6H_2 \rightarrow C_6H_3^+ + HCN$	*3.0×10^{-9}*	57	k_{24}
	$C_2H_5^+ + C_6H_2 \rightarrow C_6H_3^+ + C_2H_4$	*3.0×10^{-9}*	26	k_{25}
	$C_4H_3^+ + C_4H_2 \rightarrow C_6H_3^+ + C_2H_2$	7.4×10^{-10}	12	k_{27}
$C_6H_7^+$	$HCNH^+ + C_6H_6 \rightarrow C_6H_7^+ + HCN$	*3.0×10^{-9}*	49	k_{28}
	$C_2H_5^+ + C_6H_6 \rightarrow C_6H_7^+ + C_2H_4$	*3.0×10^{-9}*	22	k_{29}
	$C_4H_5^+ + C_2H_4 \rightarrow C_6H_7^+ + H_2$	6.3×10^{-11}	13	k_{30}
$C_7H_5^+$	$HCNH^+ + C_7H_4 \rightarrow C_7H_5^+ + HCN$	*3.0×10^{-9}*	59	k_{31}
	$C_2H_5^+ + C_7H_4 \rightarrow C_7H_5^+ + C_2H_4$	*3.0×10^{-9}*	27	k_{32}
	$C_5H_5^+ + C_4H_2 \rightarrow C_7H_5^+ + C_2H_2$	2.2×10^{-10}	7	k_{33}
$C_7H_9^+$	$HCNH^+ + C_7H_8 \rightarrow C_7H_9^+ + HCN$	*3.0×10^{-9}*	65	k_{34}
	$C_2H_5^+ + C_7H_8 \rightarrow C_7H_9^+ + C_2H_4$	*3.0×10^{-9}*	29	k_{35}
$C_8H_3^+$	$HCNH^+ + C_8H_2 \rightarrow C_8H_3^+ + HCN$	*3.0×10^{-9}*	66	k_{36}
	$C_2H_5^+ + C_8H_2 \rightarrow C_8H_3^+ + C_2H_4$	*3.0×10^{-9}*	30	k_{37}
	$C_4H_3^+ + C_6H_2 \rightarrow C_8H_3^+ + C_2H_2$	*$\sim 7.4 \times 10^{-10}$*	4	k_{38}
NH_4^+	$HCNH^+ + NH_3 \rightarrow NH_4^+ + HCN$	2.3×10^{-9}	47	k_{39}
	$C_2H_5^+ + NH_3 \rightarrow NH_4^+ + C_2H_4$	2.1×10^{-9}	19	k_{40}
$HCNH^+$	$C_2H_5^+ + HCN \rightarrow HCNH^+ + C_2H_4$	2.7×10^{-9}	61	k_{42}
	$N^+ + CH_4 \rightarrow HCNH^+ + H_2$	4.1×10^{-10}	18	k_{43}
	$CH_5^+ + HCN \rightarrow HCNH^+ + CH_4$	*3.0×10^{-9}*	10	k_{41}
	$HCN^+ + CH_4 \rightarrow HCNH^+ + CH_3$	1.1×10^{-9}	5	k_{44}
$CH_2NH_2^+$	$HCNH^+ + CH_2NH \rightarrow CH_2NH_2^+ + HCN$	*3.0×10^{-9}*	65	k_{50}
	$C_2H_5^+ + CH_2NH \rightarrow CH_2NH_2^+ + C_2H_4$	*3.0×10^{-9}*	30	k_{51}
	$CH_3^+ + NH_3 \rightarrow CH_2NH_2^+ + H_2$	1.5×10^{-9}	1	k_{47}
	$CH_3^+ + CH_3NH_2 \rightarrow CH_2NH_2^+ + CH_4$	1.4×10^{-9}	<0.002	k_{48}
	$N_2^+ + CH_3NH_2 \rightarrow CH_2NH_2^+ + N_2 + H$	8.8×10^{-10}	<0.001	k_{49}
CH_3CNH^+	$HCNH^+ + CH_3CN \rightarrow CH_3CNH^+ + HCN$	3.8×10^{-9}	50	k_{52}
	$C_2H_5^+ + CH_3CN \rightarrow CH_3CNH^+ + C_2H_4$	3.8×10^{-9}	22	k_{53}
HC_3NH^+	$HCNH^+ + HC_3N \rightarrow HC_3NH^+ + HCN$	3.4×10^{-9}	61	k_{54}
	$C_2H_5^+ + HC_3N \rightarrow HC_3NH^+ + C_2H_4$	3.6×10^{-9}	29	k_{55}
$C_2H_3CNH^+$	$HCNH^+ + C_2H_3CN \rightarrow C_2H_3CNH^+ + HCN$	4.5×10^{-9}	71	k_{56}
	$C_2H_5^+ + C_2H_3CN \rightarrow C_2H_3CNH^+ + C_2H_4$	*3.0×10^{-9}*	21	k_{57}
$C_2H_5CNH^+$	$HCNH^+ + C_2H_5CN \rightarrow C_2H_5CNH^+ + HCN$	*3.0×10^{-9}*	66	k_{59}
	$C_2H_5^+ + C_2H_5CN \rightarrow C_2H_5CNH^+ + C_2H_4$	*3.0×10^{-9}*	30	k_{60}
	$CH_3^+ + CH_3CN \rightarrow C_2H_5CNH^+ + h\nu$	9.0×10^{-11}	0.25	k_{58}

(continued on next page)

after



Now need to consider C_6H_6 =1-7x10^{-10} at 1 mbar 10^{-5} at 1 μbar

Mechanisms for the formation of benzene in the atmosphere of Titan Photochemistry (Wilson et al. 2003)

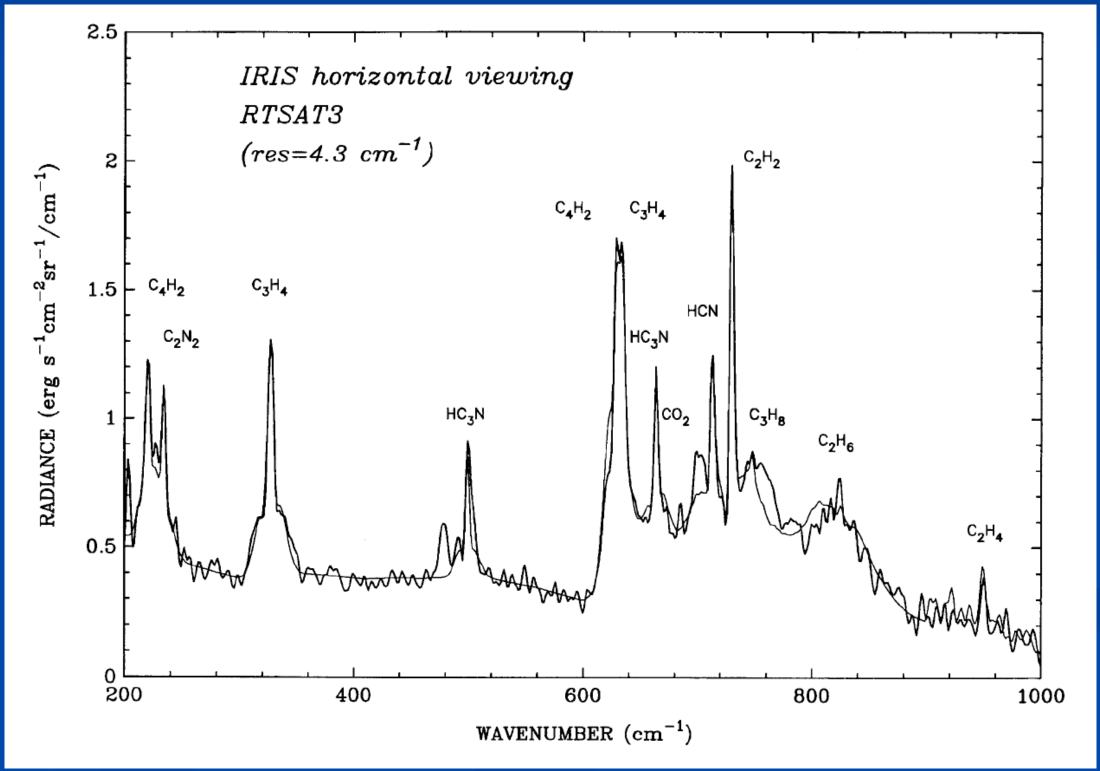
Formation and distribution of benzene on Titan Ion Chemistry (Vuitton et al. 2008)

Cassini measured negative ions with masses exceeding 1000 Daltons!

Ignored minor constituents

1) A problem? Yes, but…
   - Need features (data)
   - Little info on hot lines*

Titan IR spectrum

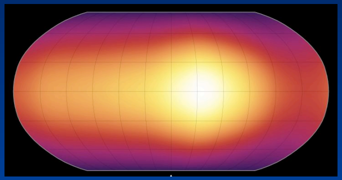


Minor species dominate Titan's spectrum!

** We have hot lines information on H_2O, CO, CO_2, and some CH_4*

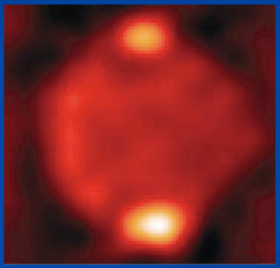
Ignored Stuff

1) Longitudinal variations
   - Increasingly more information



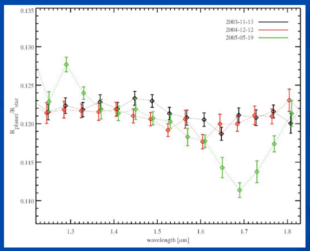
HD189733b

2) Latitudinal variations
   - No data yet



Jupiter @ 3.3 um
Aurora heated H_3^+
emissions

3) Temporal variations
   - Mysterious data under analysis



Deroo in prep

Wish List

1) Coincident observations over large wavelength regions
    - Observed variations make modelers nervous

2) Fuller spectral coverage data
    - This will refine models (of the largely featureless spectra)

3) High resolution spectra
    - Resolve temperature through line strengths

4) Spectra of more objects
    - Study processes in a range of conditions

5) Line parameters for hot transitions (esp. CH_4)
    - Necessary

Outline

1) Consider an analysis of HD209458b's dayside spectra
   - Estimate temperatures, composition and play with RT
     - What assumptions can we make?
     - How well can we constrain this beast?
     - What are the challenges?
2) Consider, episodically, jovian or planetary counterparts
   - Understanding composition, temperatures, and structure
3) What do we need in the future to understand exoplanets?
   - Additional Observations?
   - Additional Theoretical Calculations?
   - Additional Lab work

Wish List

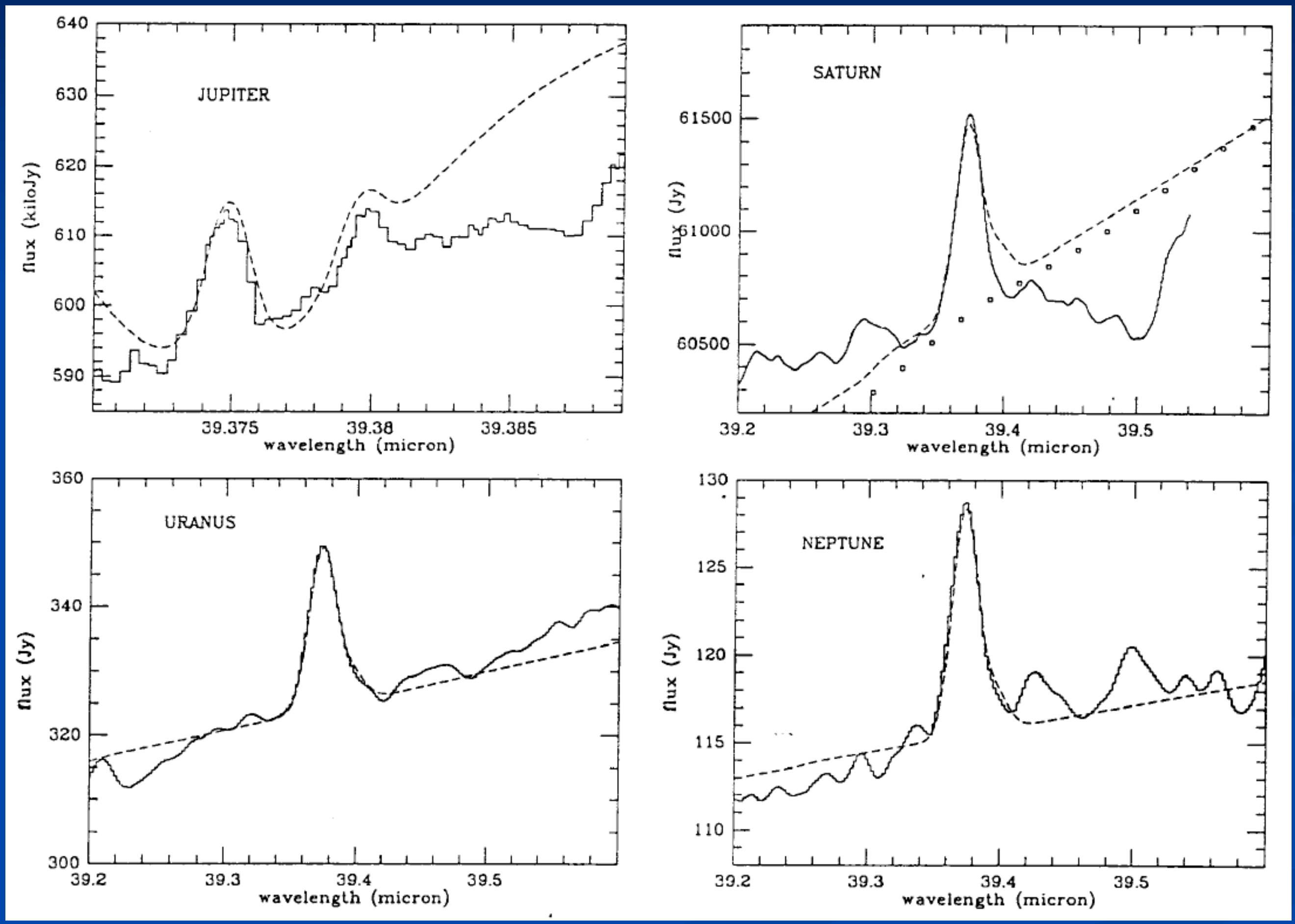
Jupiter (Case Example)

How does one determine the vertical profiles of:

temperature
[H_2]
[He]
[CH_4]
[NH_3]
[H_2O]
[CO]
[CO_2]

H2O 2-5 bar in Jupiter

Stratospheric water

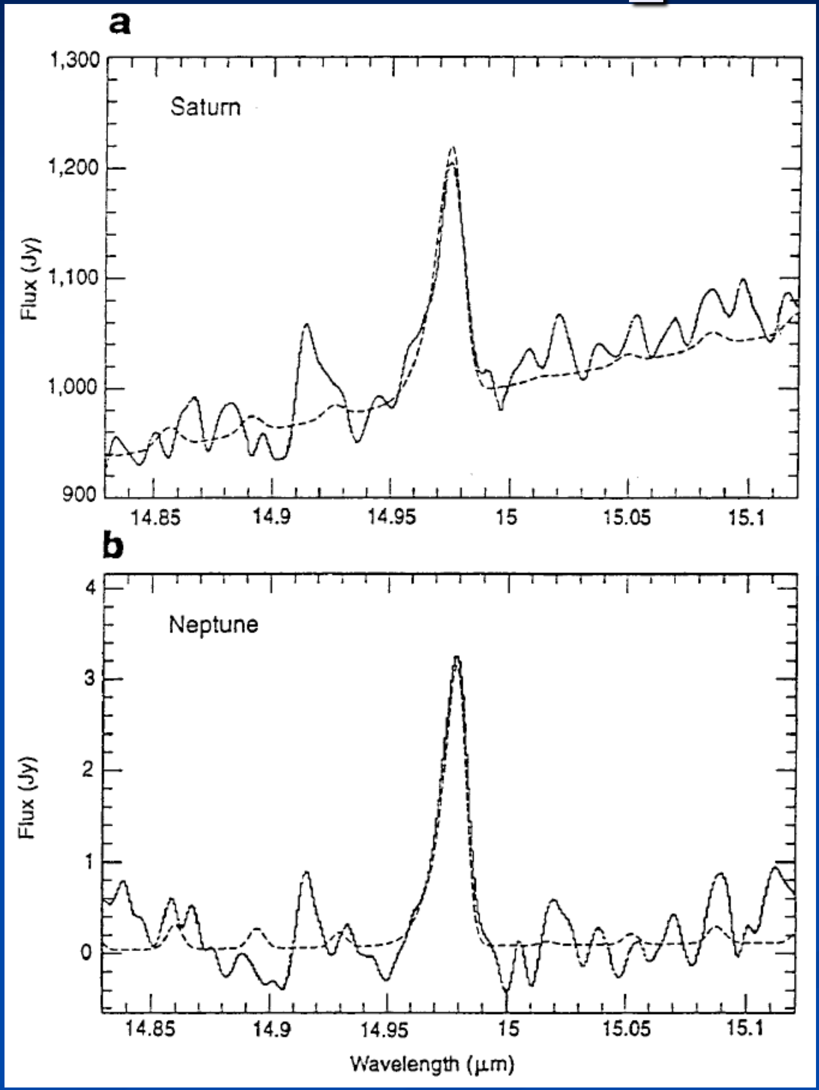


$[H_2O]=10^{-9}$ at roughly 10 mbar - 10 ubar

Detection of CO_2

De Graauw et al. 1997

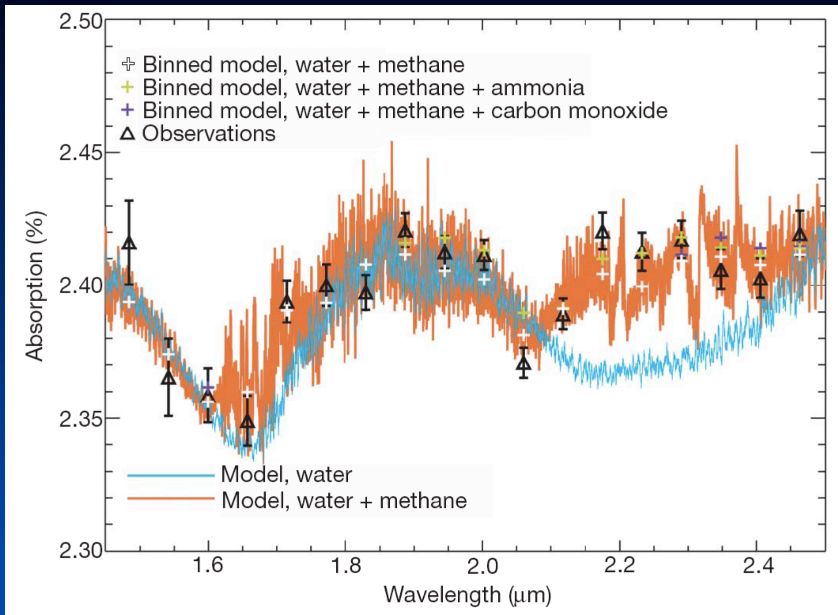
Feuchtgruber et al. 1997



"Dieu n’est pas pour les gros bataillons, mais pour ceux qui tirent le mieux" ("God is not on the side of the big battalions, but of the best shots")

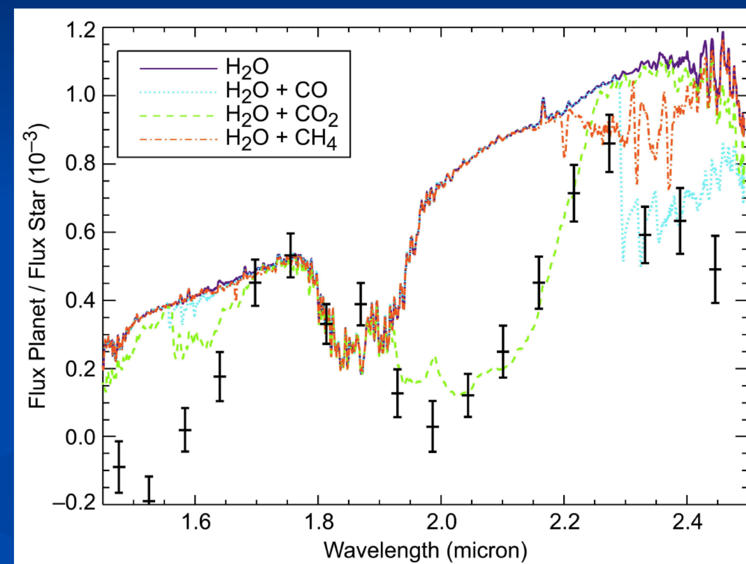
– Voltaire

Giovanna & gang

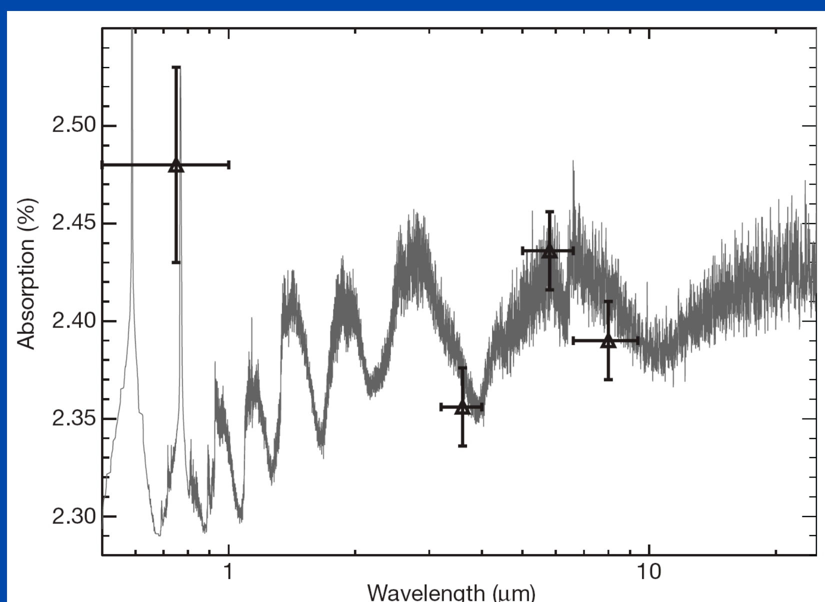


CH_4

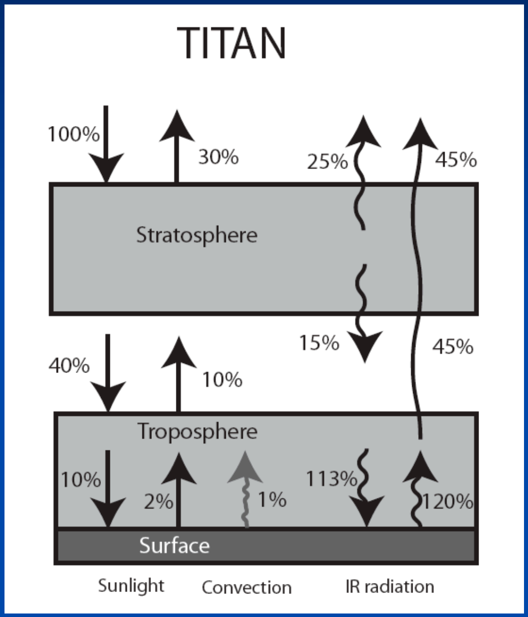
CO_2

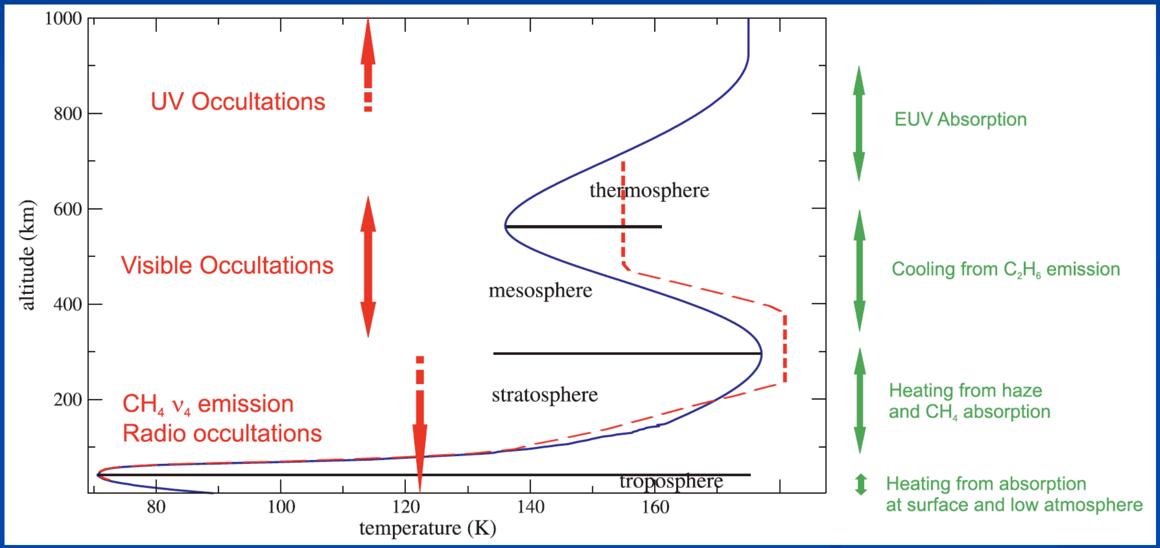


H_2O



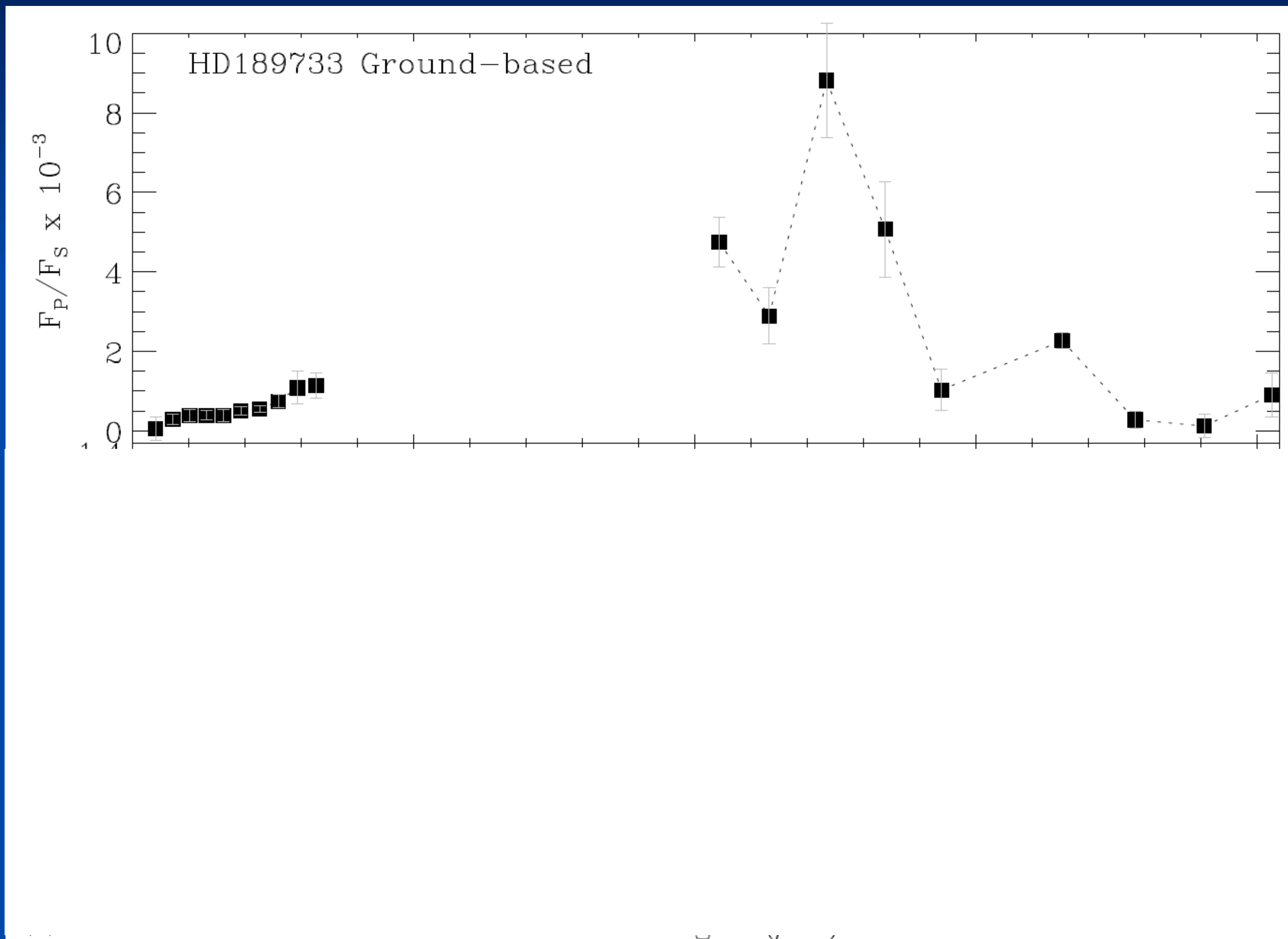
How is heat partitioned in the atmosphere?



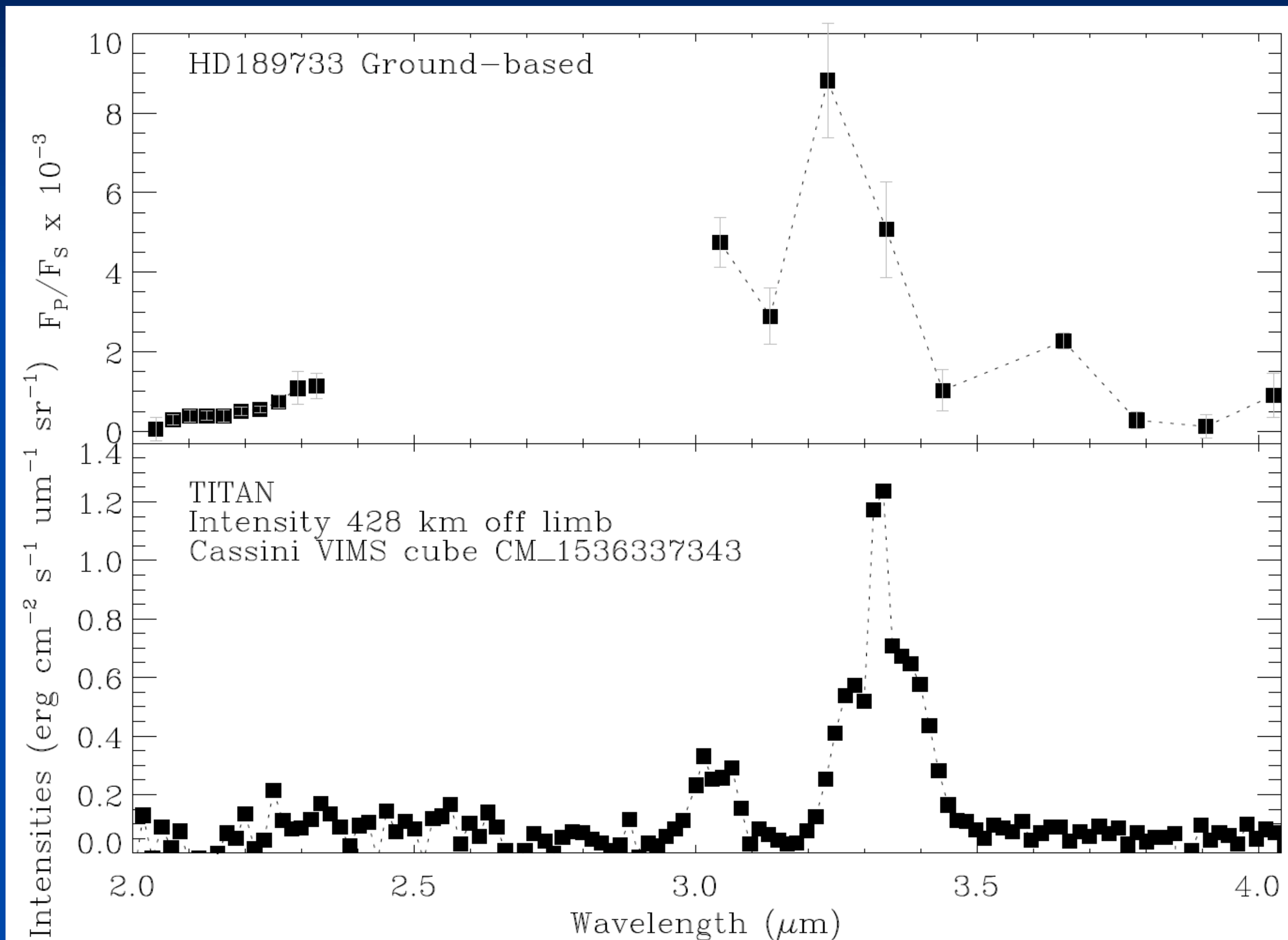


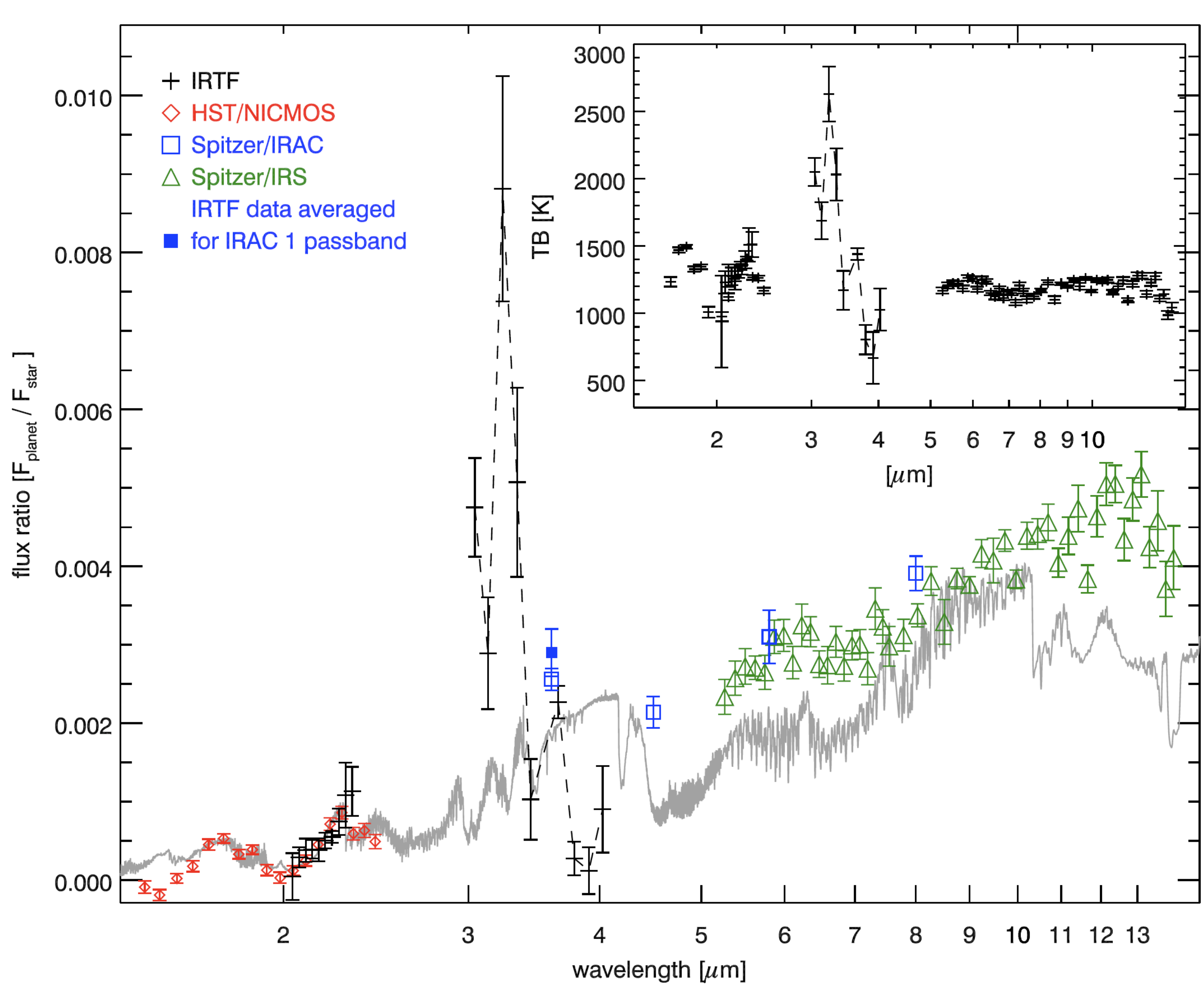
Calculate the radiative balance of the atmosphere.
Compare to observations to constrain dynamical effects.

New Result



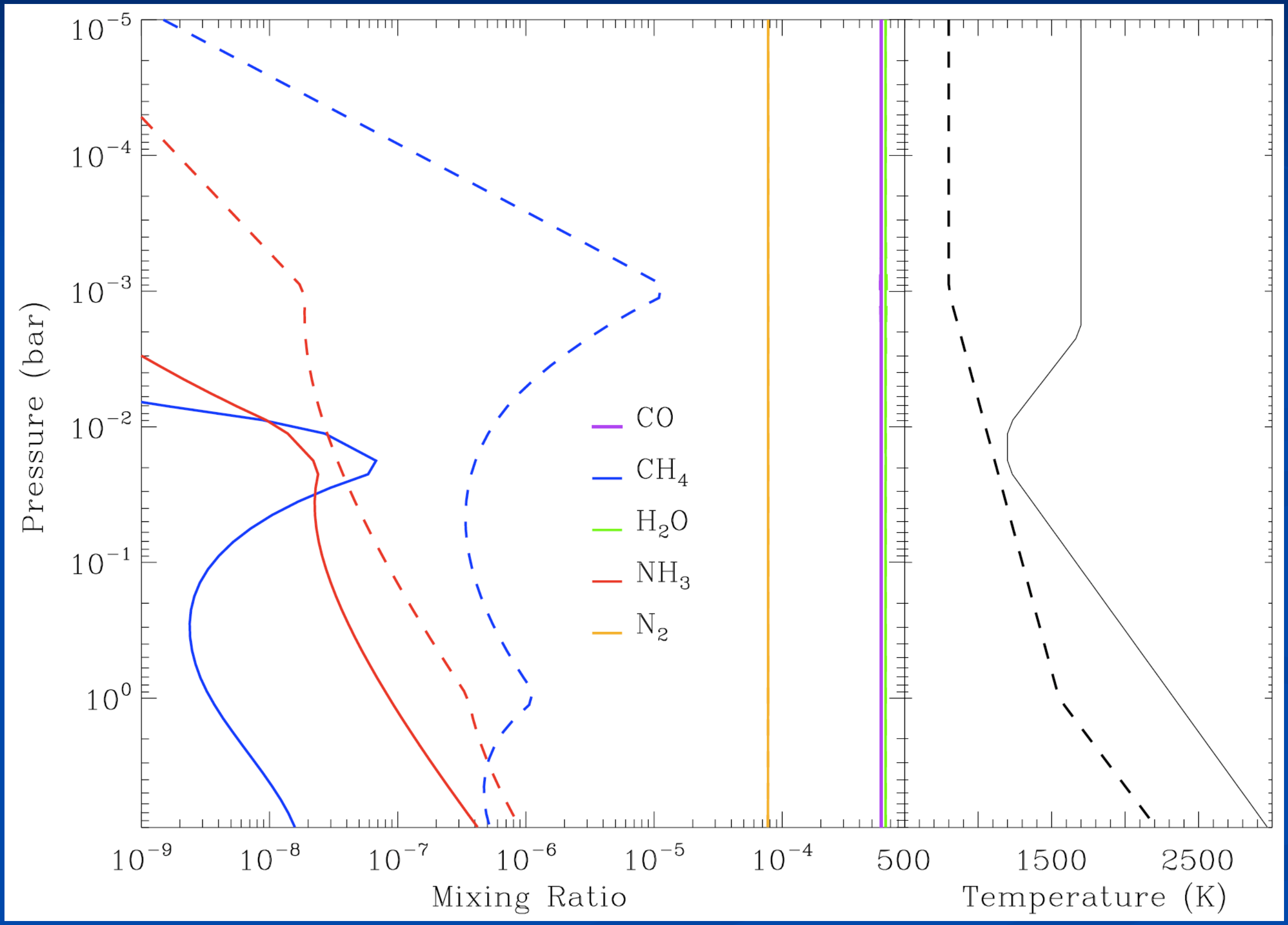
New Result


HD189733 Ground−based
TITAN
Intensity 428 km off limb
Cassini VIMS cube CM_1536337343
F_P/F_S x 10^{-3}
Intensities (erg cm^{-2} s^{-1} um^{-1} sr^{-1})
Wavelength (μm)
10
8
6
4
2
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2.0
2.5
3.0
3.5
4.0



IRTF
HST/NICMOS
Spitzer/IRAC
Spitzer/IRS
IRTF data averaged
for IRAC 1 passband
flux ratio [F_{planet} / F_{star}]
0.000
0.002
0.004
0.006
0.008
0.010
2
3
4
5
6
7
8
9
10
11
12
13
wavelength [μm]
TB [K]
500
1000
1500
2000
2500
3000
[μm]

What determines the atmospheric chemistry?



Thermochemical equilibrium calculations are not enough

How do planetary processes scale with a planet's mass and semi-major axis?

Exoplanet	Mass	Semi-major axis	Eccentricity	Primary	Spectra
HD209459B	0.63 M_J	0.0467 AU	0.07	G0V / 5942 K	UV to 24 μm
HD189733B	1.13 M_J	0.0310 AU	0	K2V / 4980 K	0.5-24 μm
XO-1B	0.90 M_J	0.0488 AU	0	G1V	1.4-2.4 μm
TrES-1	0.61 M_J	0.0393 AU	0	K0V	photometry
HD80606B	4.00 M_J	0.453 AU	0.936	G5 / 5370 K	photometry
Gl436B	0.072 M_J	0.0287 AU	0.15	M2.5 / 3684 K	photometry
Gl876D	0.018 M_J	0.0208 AU	0	M4V / 3350 K	photometry