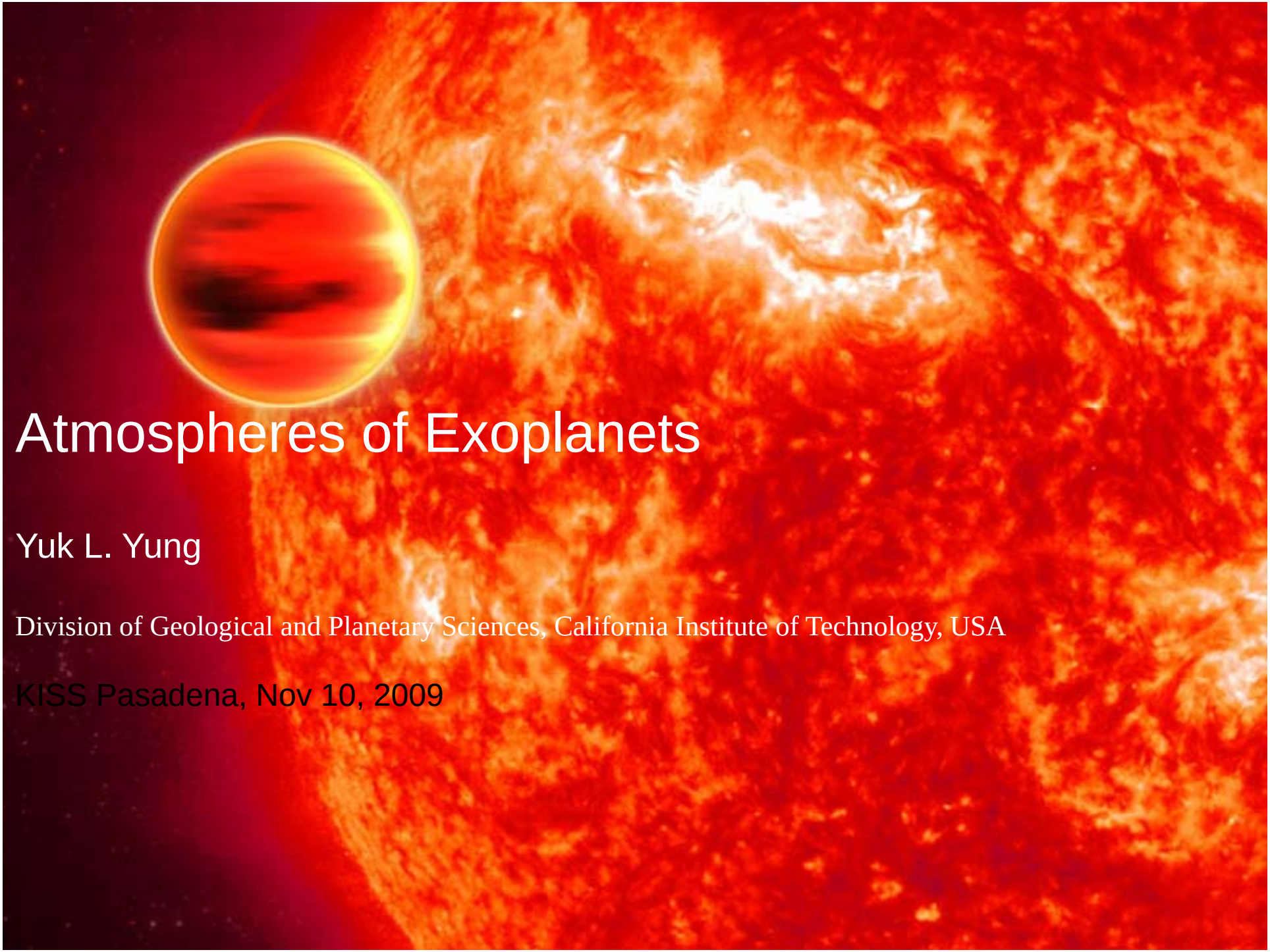

Atmospheres of Exoplanets

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Today's Outline

- Compare with our planets
- H_2O, CO, CO_2, CH_4
- Hydrocarbons?
- Sulfur, Nitrogen species?
- Lessons from solar system

Table 1.3 List of three most abundant gases in planetary atmospheres. Mixing ratios are given in parenthesis. All compositions refer to the surface or 1 bar.

Jupiter	H_2 (0.93)	He (0.07)	CH_4 (3×10^{-3})
Saturn	H_2 (0.96)	He (0.03)	CH_4 (4.5×10^{-3})
Uranus	H_2 (0.82)	He (0.15)	CH_4 (2.3×10^{-2})
Neptune	H_2 (0.80)	He (0.19)	CH_4 $(1 - 2 \times 10^{-2})$
Titan	N_2 $(0.95 - 0.97)$	CH_4 (3.0×10^{-2})	H_2 (2×10^{-3})
Triton	N_2 (0.99)	CH_4 (2.0×10^{-4})	CO (< 0.01)
Pluto	N_2 (?)	CH_4 (?)	CO (?)
Io	SO_2 (0.98)	SO (0.05)	O (0.01)
Mars	CO_2 (0.95)	N_2 (2.7×10^{-2})	Ar (1.6×10^{-2})
Venus	CO_2 (0.96)	N_2 (3.5×10^{-2})	SO_2 (1.5×10^{-4})
Earth	N_2 (0.78)	O_2 (0.21)	Ar (9.3×10^{-3})

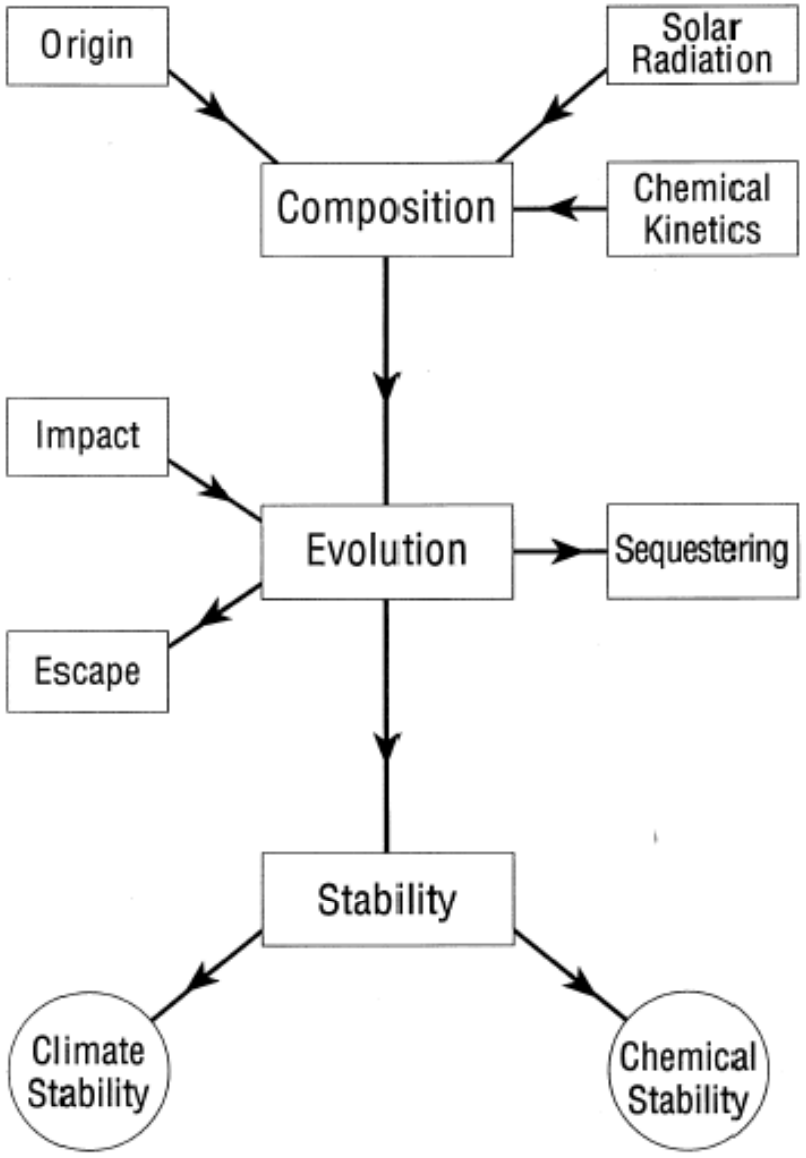
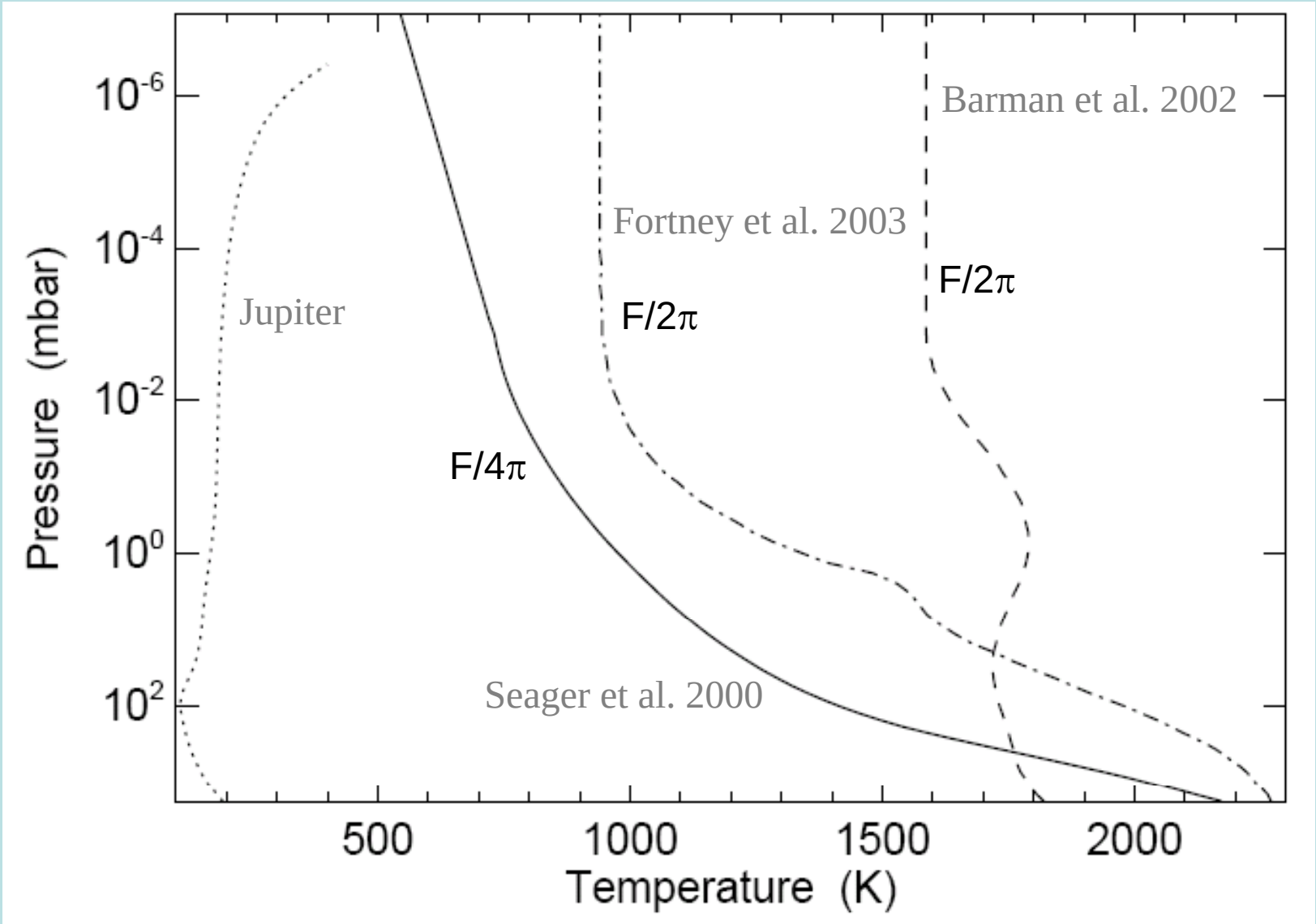
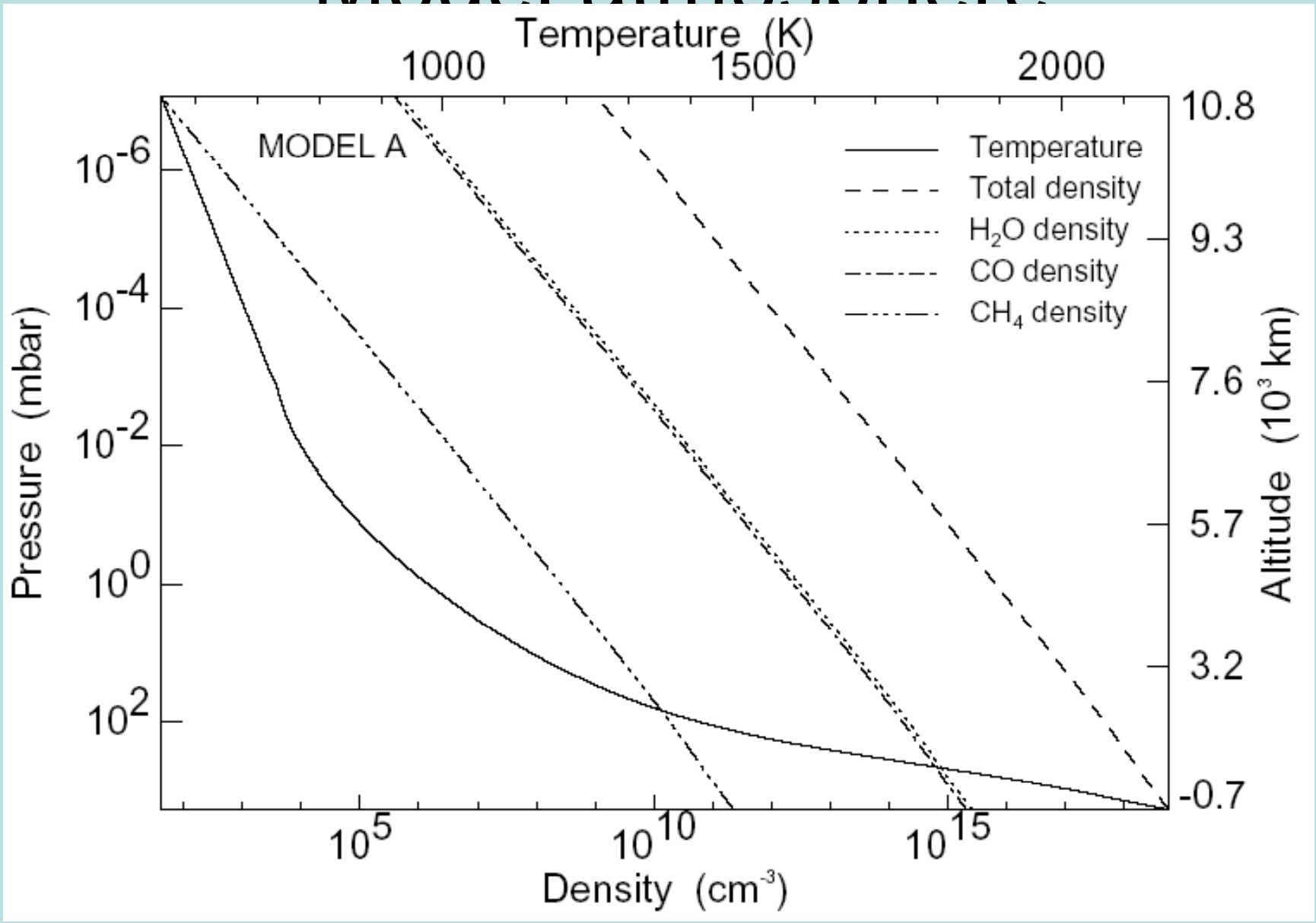

Origin
Solar Radiation
Composition
Chemical Kinetics
Impact
Evolution
Sequestering
Escape
Stability
Climate Stability
Chemical Stability

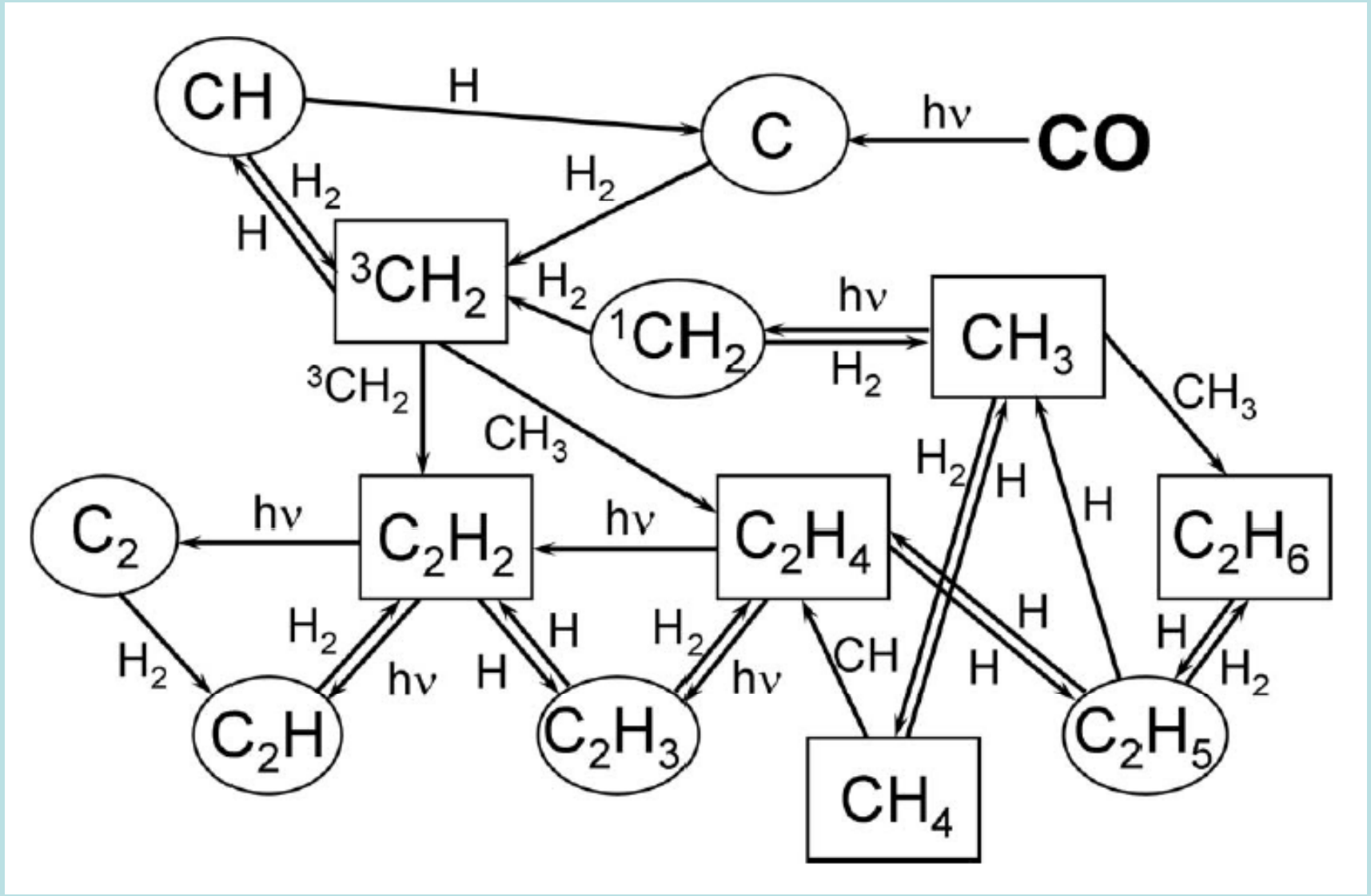
Figure 1.1

Temperature profiles

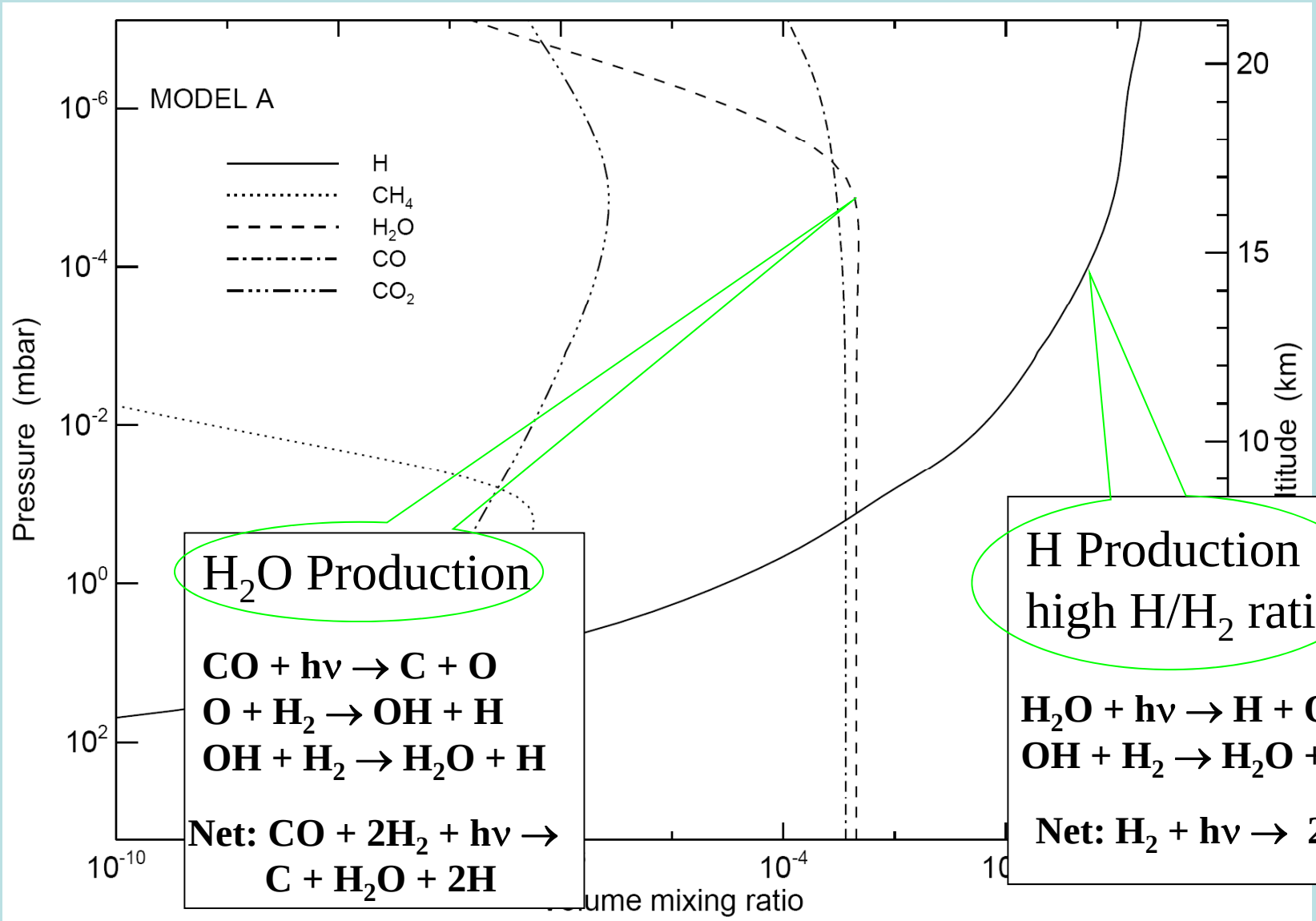


Model atmosphere



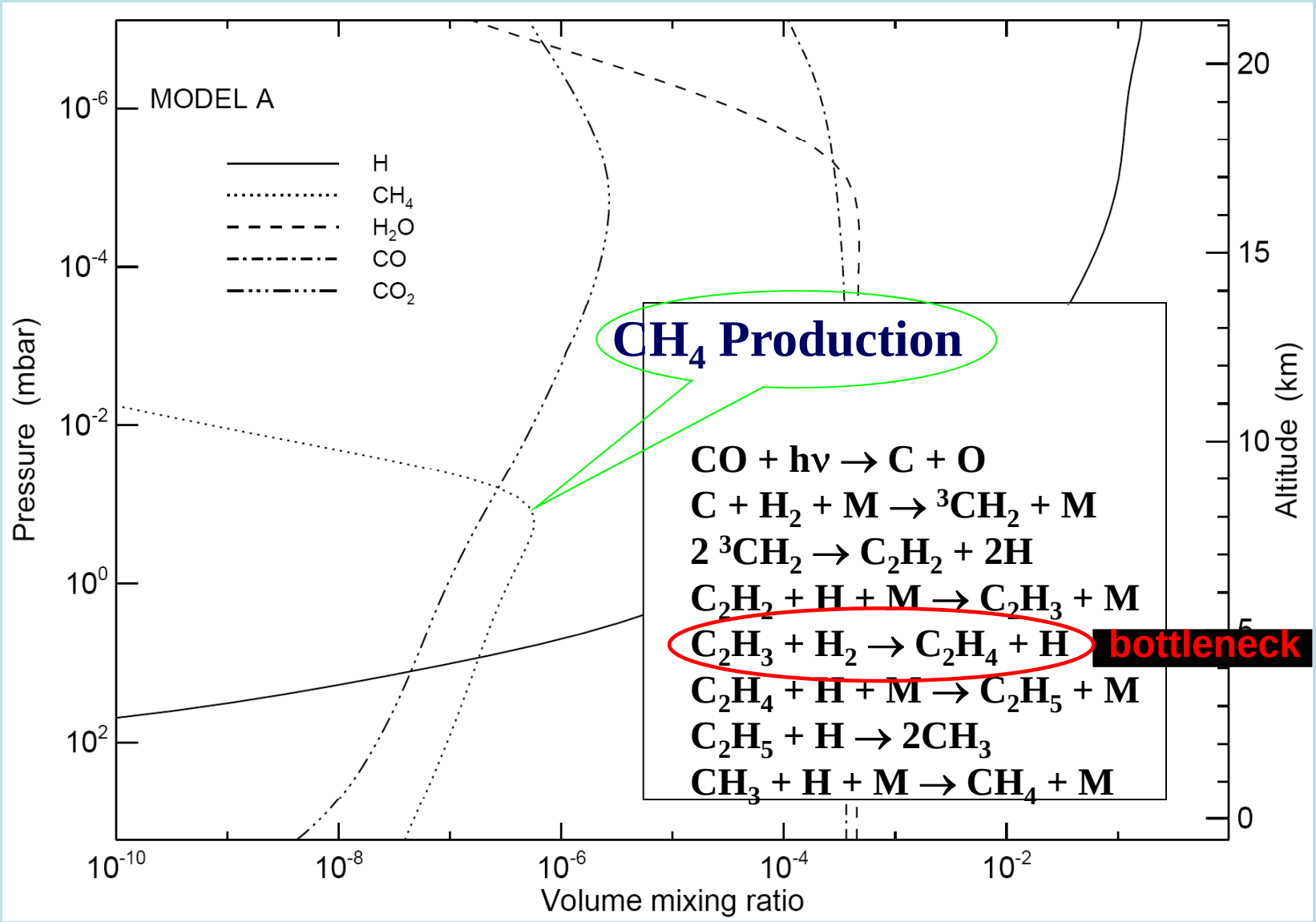

CH
H
C
hν
CO
H2
H2
H
3CH2
H2
1CH2
hν
H2
CH3
3CH2
CH3
CH3
H2
H
H
C2
hν
C2H2
hν
C2H4
C2H6
H2
H2
hν
H
H2
hν
CH
H
H
H
H2
C2H
C2H3
CH4
C2H5

Atomic Hydrogen




HD209458b

Hydrocarbons



$2\times[CO + h\nu \rightarrow C + O]$

$2\times[C + H_2 + M \rightarrow {}^3CH_2 + M]$

${}^3CH_2 + {}^3CH_2 \rightarrow C_2H_2 + 2H$

$C_2H_2 + H + M \rightarrow C_2H_3 + M$

$C_2H_3 + H_2 \rightarrow C_2H_4 + H$

$C_2H_4 + H + M \rightarrow C_2H_5 + M$

$C_2H_5 + H \rightarrow 2CH_3$

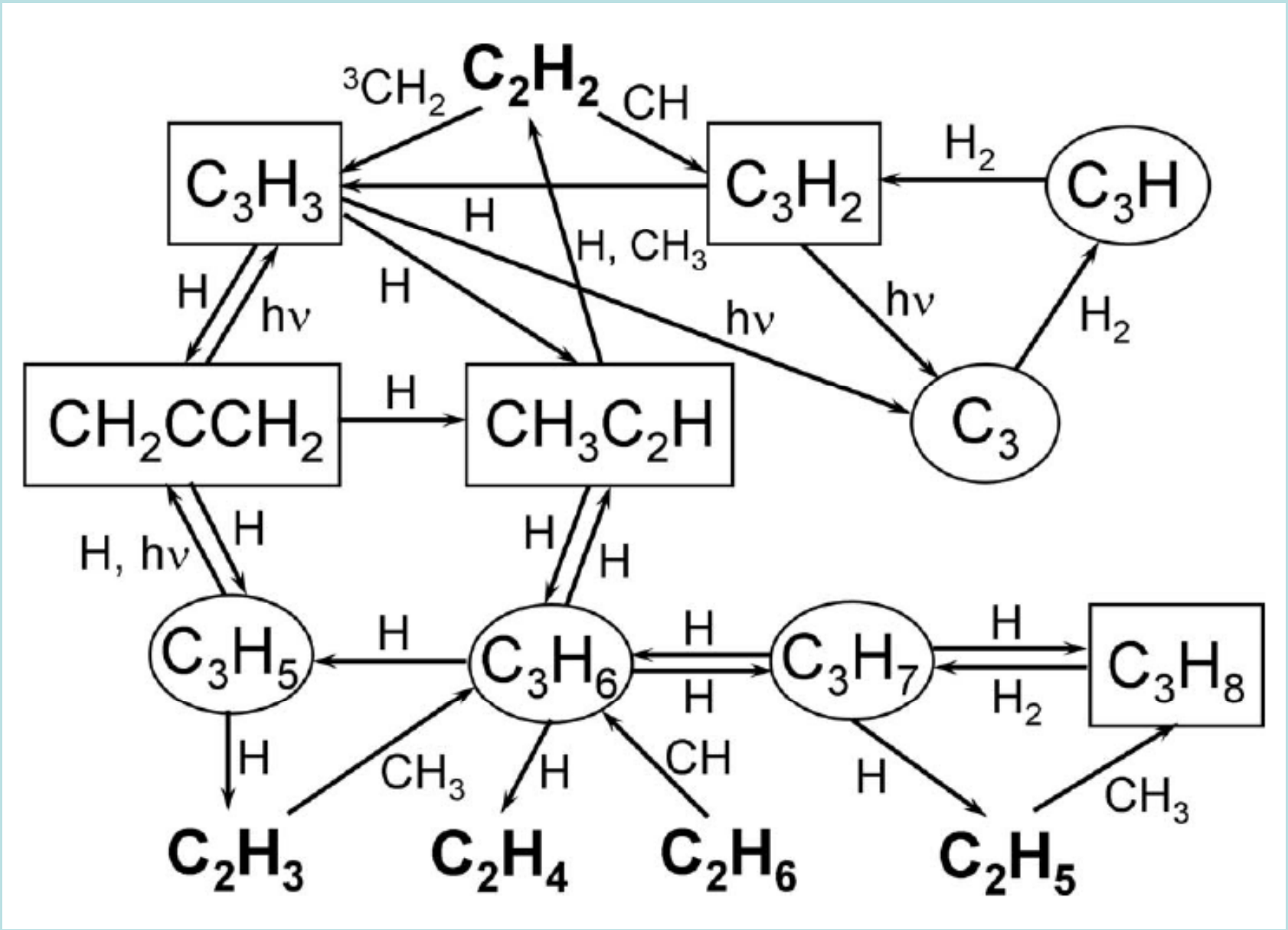
$2\times[CH_3 + H + M \rightarrow CH_4 + M]$

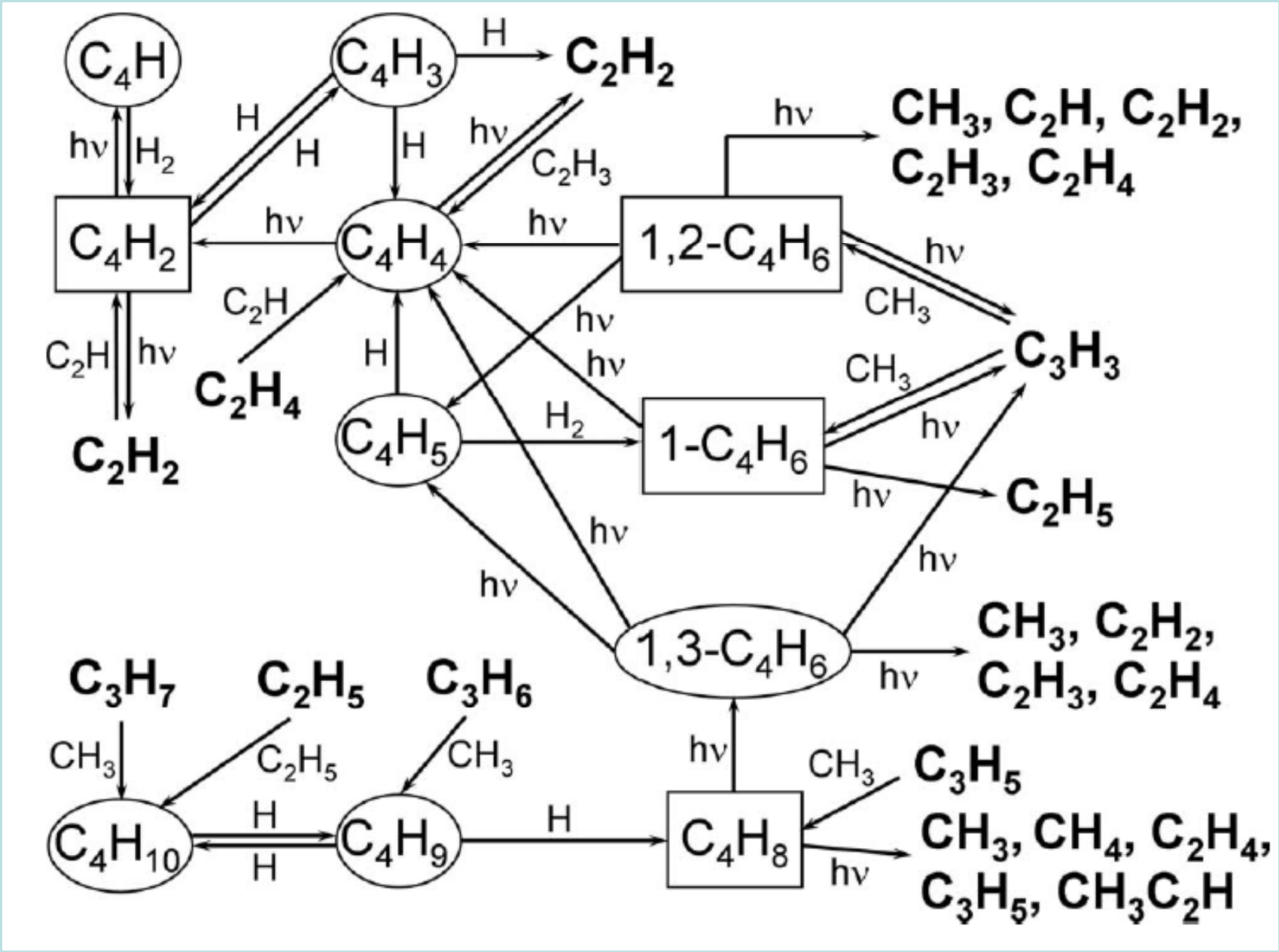
$2\times[O + H_2 \rightarrow OH + H]$

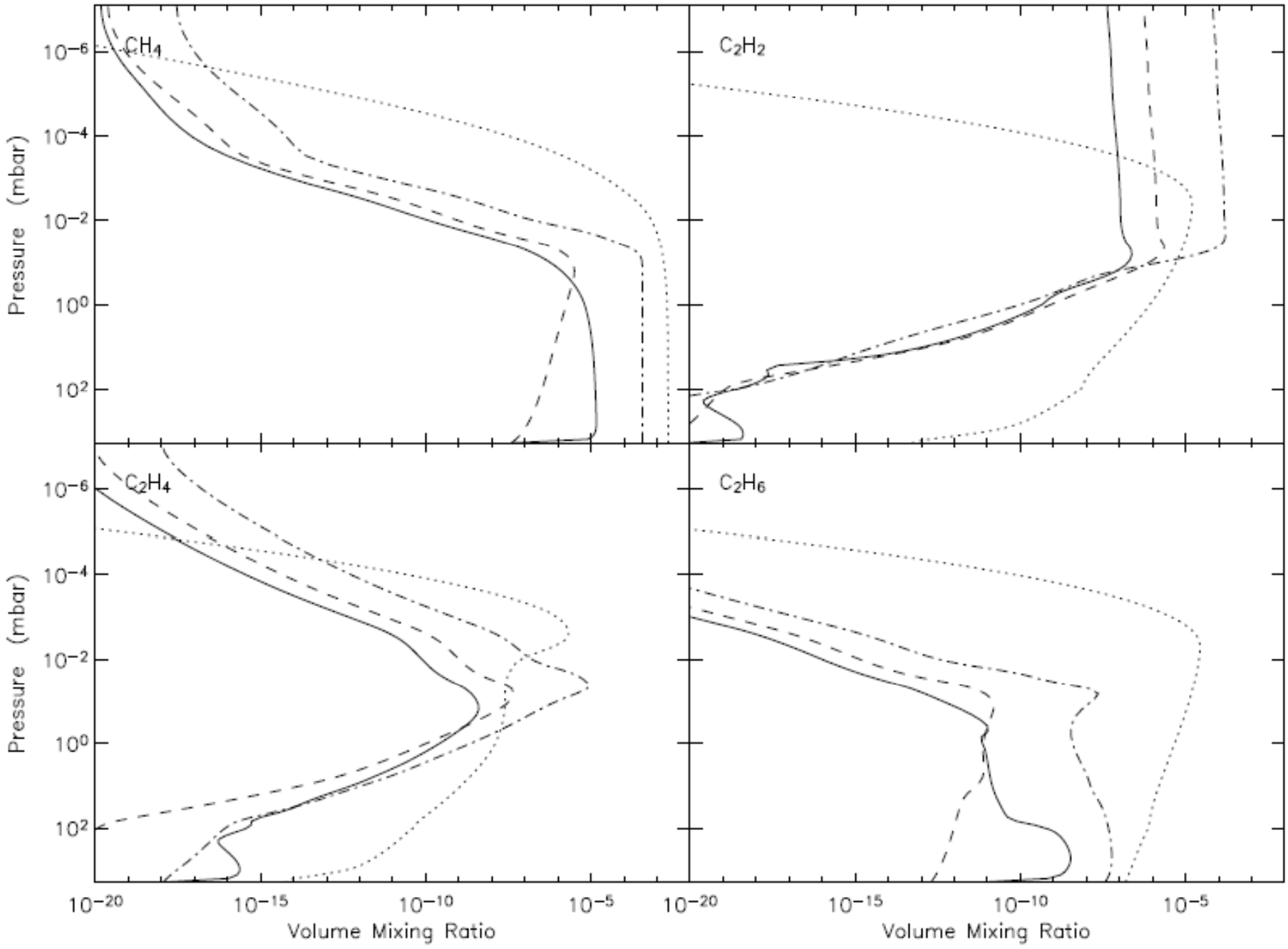
$2\times[OH + H_2 \rightarrow H_2O + H]$

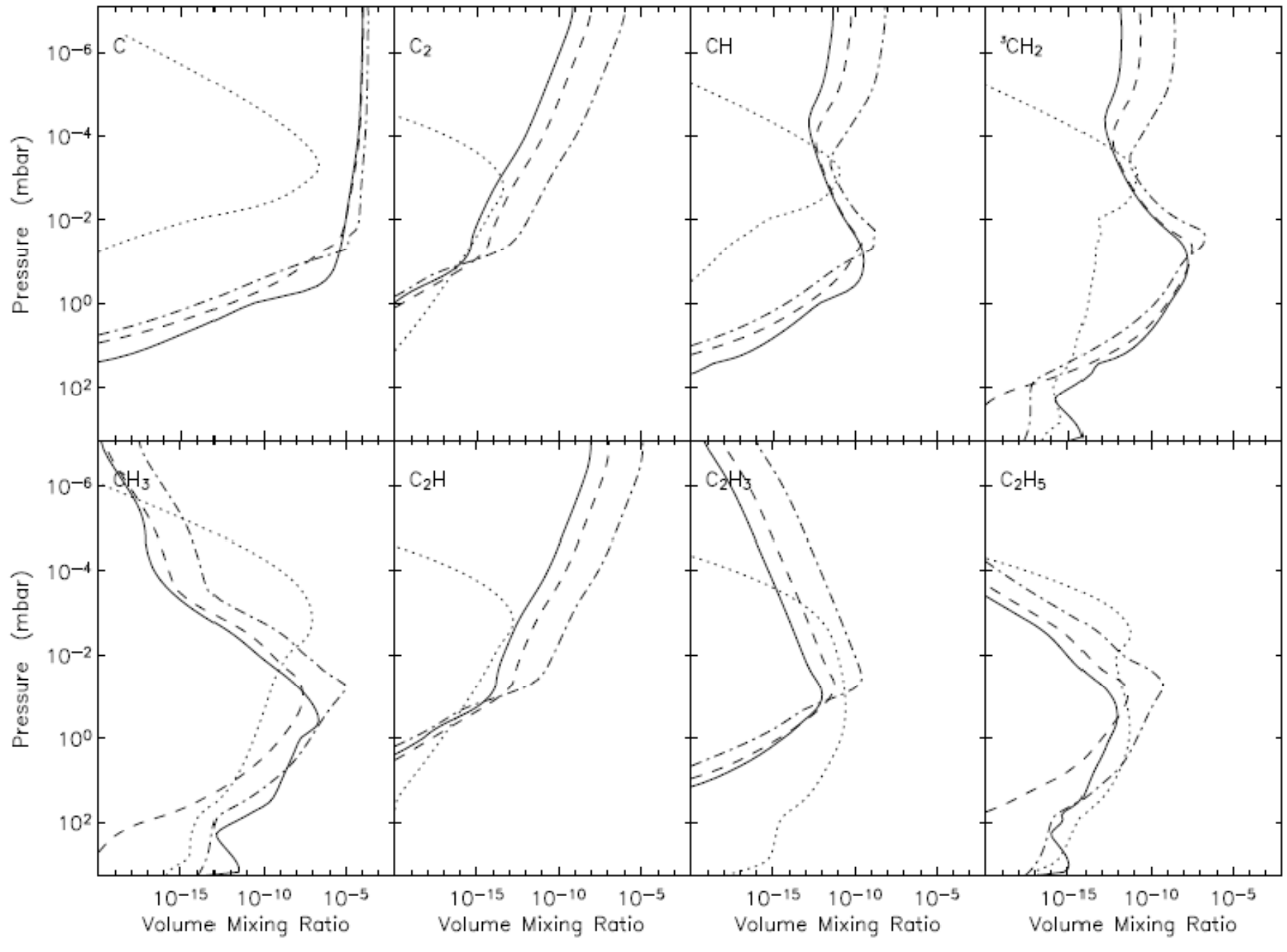
$2\times[H + H + M \rightarrow H_2 + M]$

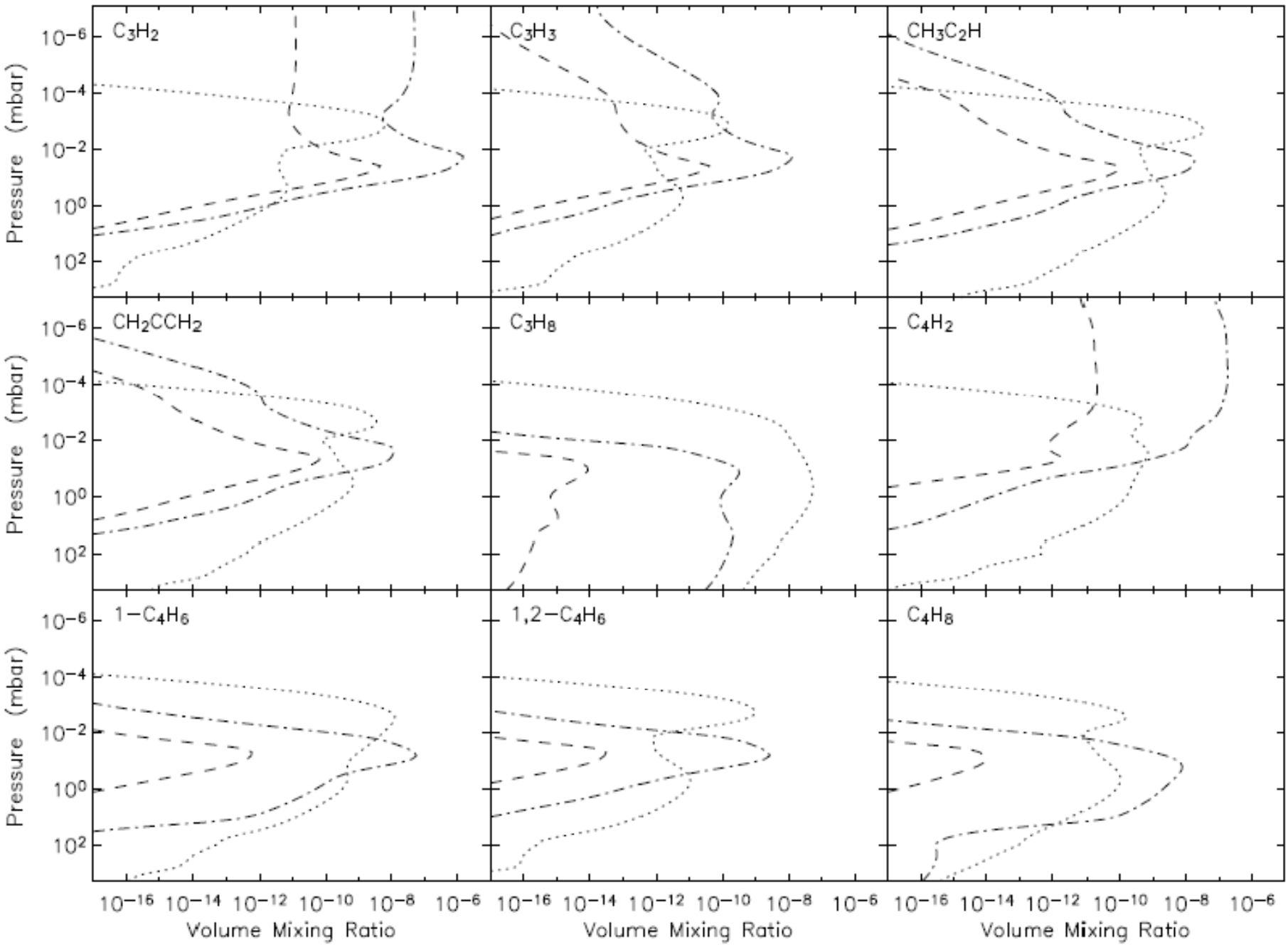
net $2CO + 3H_2 \rightarrow CH_4 + 2H_2O$

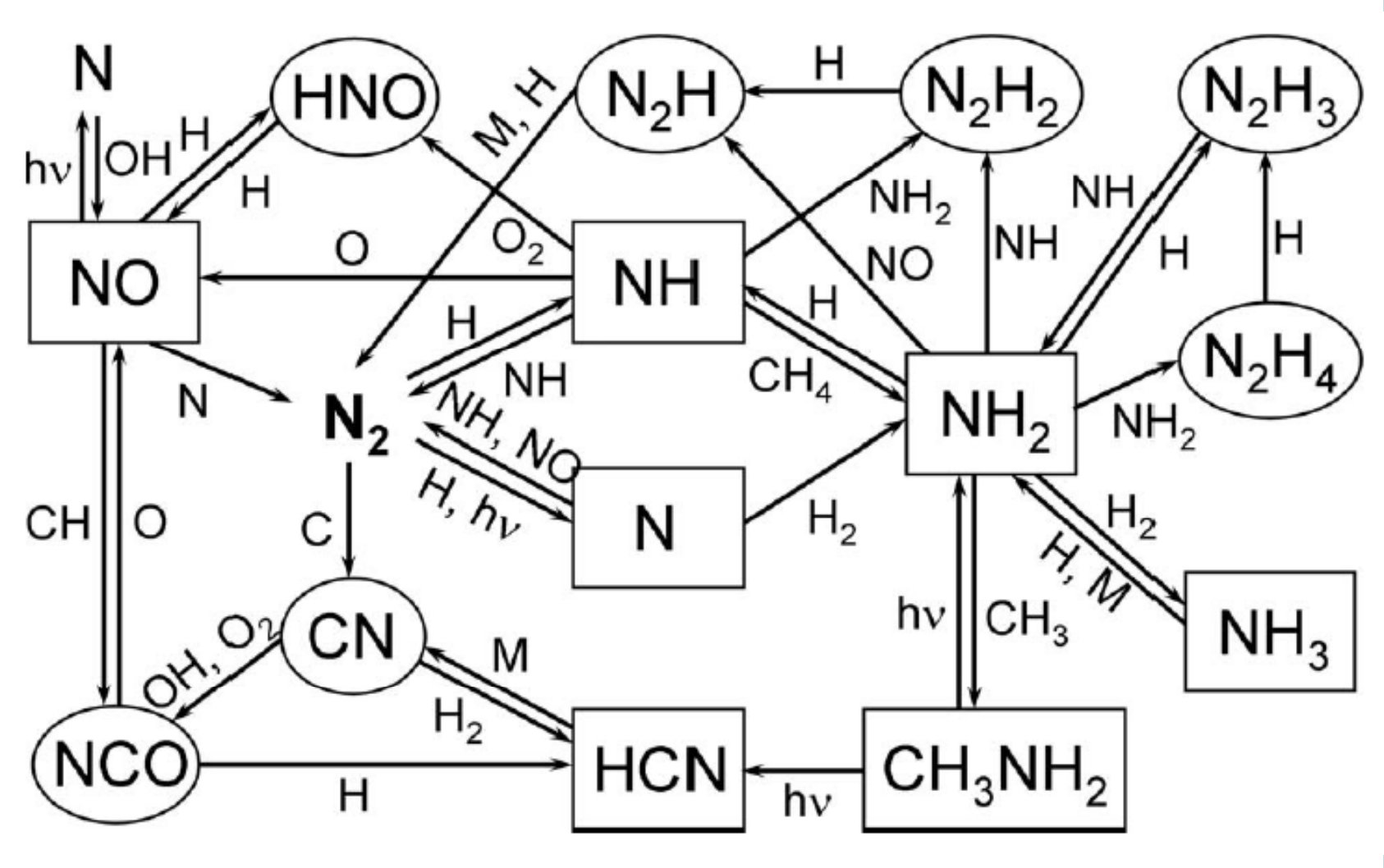

$^3CH_2$
C_2H_2
CH
C_3H_3
C_3H_2
H_2
C_3H
H
H, CH_3
H
H
hν
hν
hν
H_2
CH_2CCH_2
H
CH_3C_2H
C_3
H, hν
H
H
H
C_3H_5
H
C_3H_6
H
H
C_3H_7
H
H_2
C_3H_8
H
CH_3
H
CH
H
CH_3
C_2H_3
C_2H_4
C_2H_6
C_2H_5

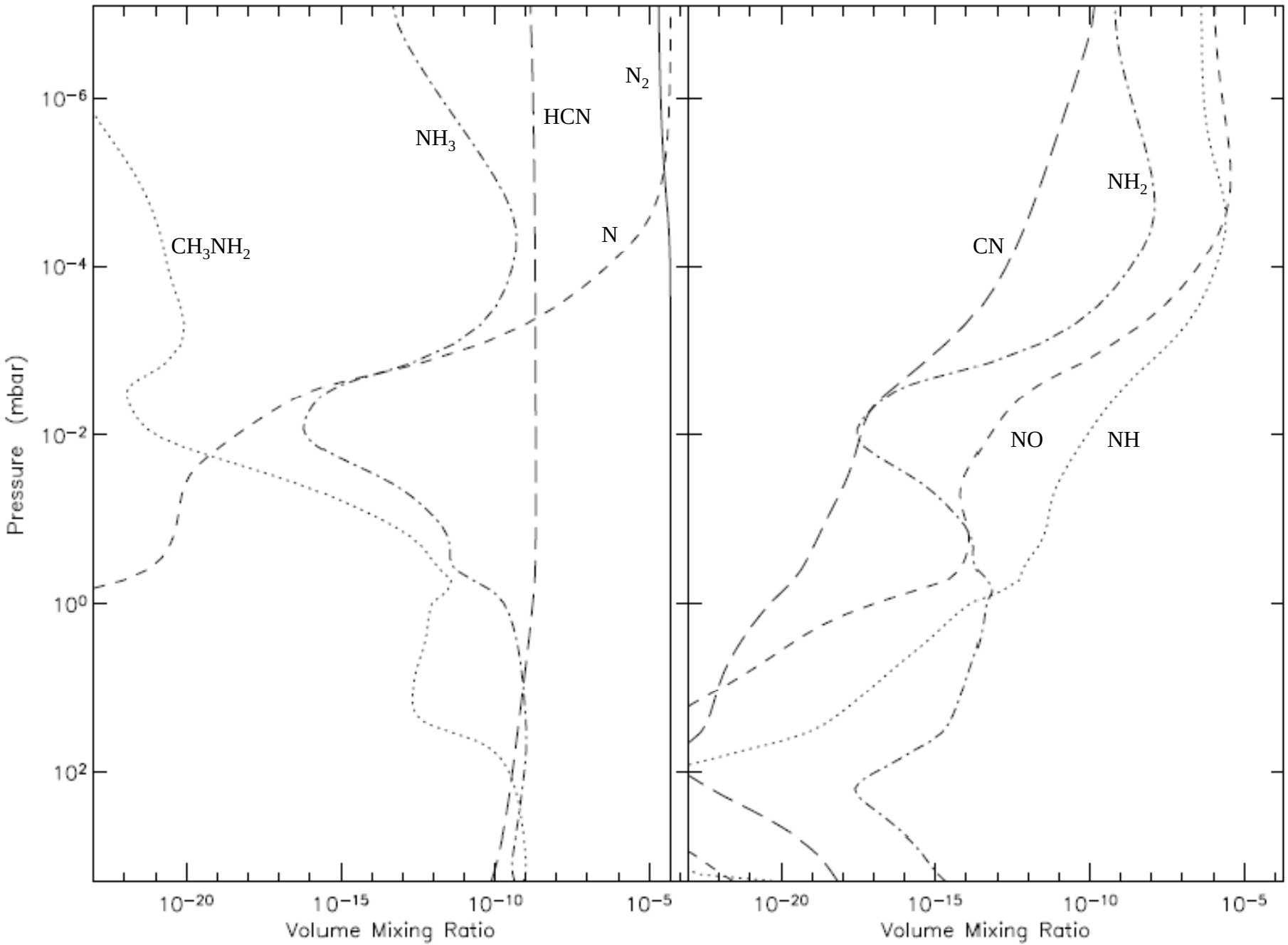

C4H
C4H3
H
C2H2
hν
H2
H
H
H
hν
C2H3
hν
CH3, C2H, C2H2,
C2H3, C2H4
C4H2
hν
C4H4
hν
1,2-C4H6
hν
CH3
C2H
hν
hν
C2H
hν
C2H4
H
CH3
C3H3
hν
C4H5
H2
1-C4H6
hν
C2H2
hν
C2H5
hν
hν
hν
1,3-C4H6
CH3, C2H2,
C2H3, C2H4
hν
C3H7
C2H5
C3H6
CH3
C2H5
CH3
hν
CH3
C3H5
H
H
C4H10
C4H9
H
C4H8
hν
CH3, CH4, C2H4,
C3H5, CH3C2H

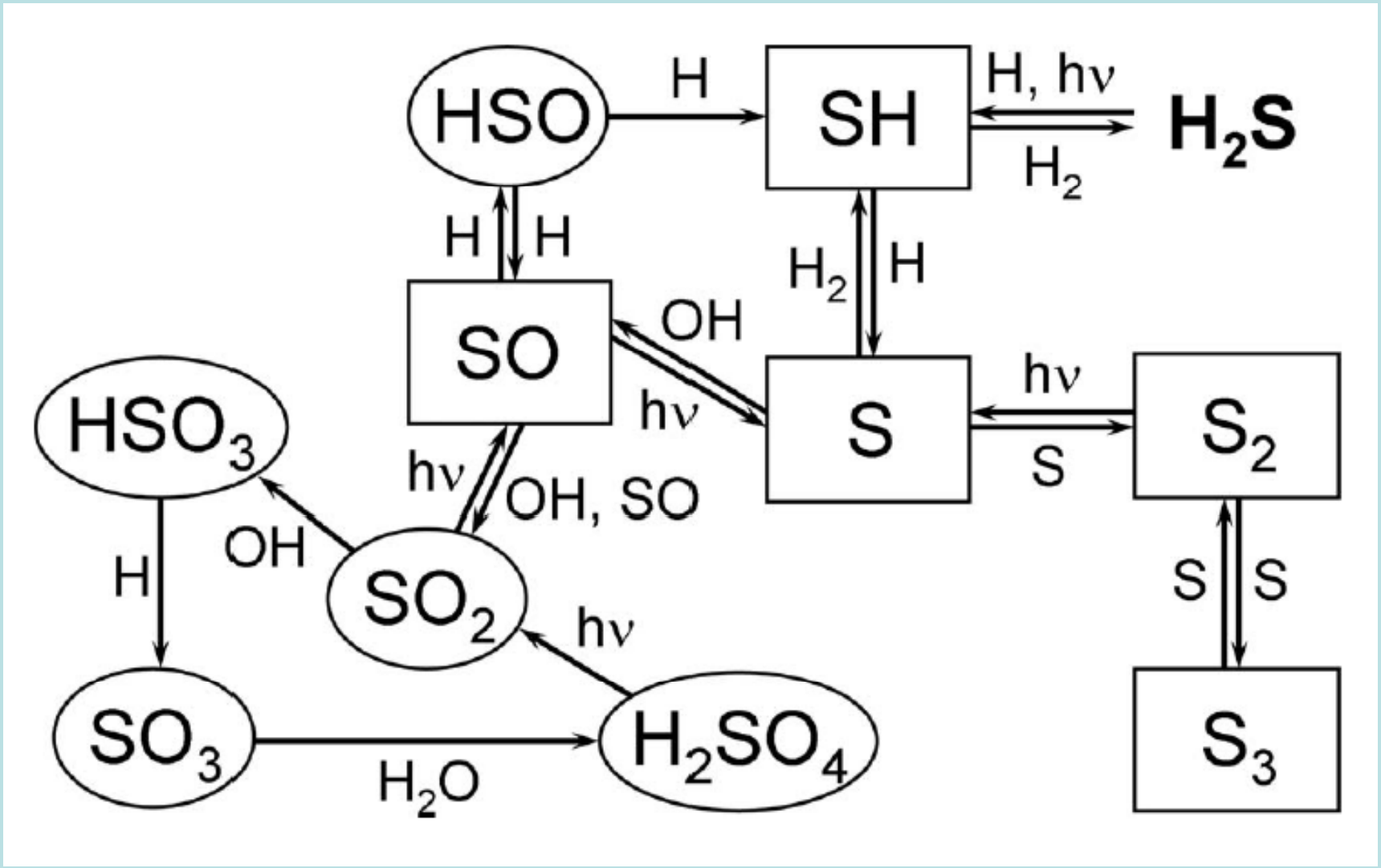

CH4
C2H2
C2H4
C2H6
Pressure (mbar)
Volume Mixing Ratio
10−6
10−4
10−2
100
102
10−20
10−15
10−10
10−5

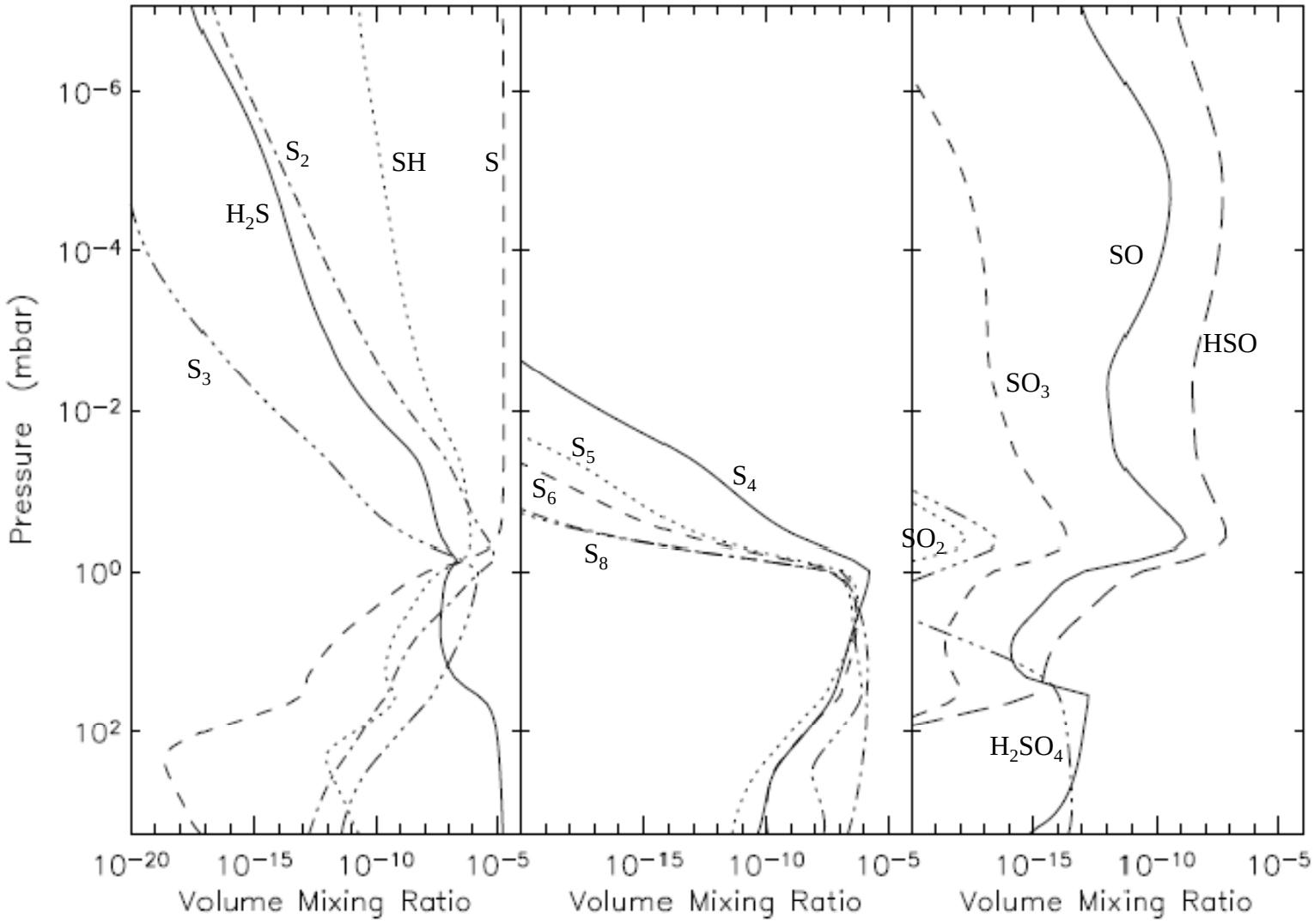

C
C2
CH
3CH2
CH3
C2H
C2H3
C2H5
Pressure (mbar)
10−6
10−4
10−2
100
102
10−15
10−10
10−5
Volume Mixing Ratio


C3H2
C3H3
CH3C2H
CH2CCH2
C3H8
C4H2
1−C4H6
1,2−C4H6
C4H8
Pressure (mbar)
10−6
10−4
10−2
100
102
10−16 10−14 10−12 10−10 10−8 10−6
Volume Mixing Ratio


N
HNO
N_2H
N_2H_2
N_2H_3
hν
OH
H
H
M, H
H
NH_2
NH
NO
O_2
O
NO
NH
NH
H
H
N_2H_4
H
NH
CH_4
N
N_2
NH, NO
H, hν
NH_2
NH_2
CH
O
C
N
H_2
H_2
H, M
hν
CH_3
NH_3
OH, O_2
CN
M
H_2
NCO
H
HCN
hν
CH_3NH_2


Pressure (mbar)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
N_2
HCN
NH_3
CH_3NH_2
N
CN
NH_2
NO
NH
10^{-20}
10^{-15}
10^{-10}
10^{-5}
Volume Mixing Ratio
10^{-20}
10^{-15}
10^{-10}
10^{-5}
Volume Mixing Ratio

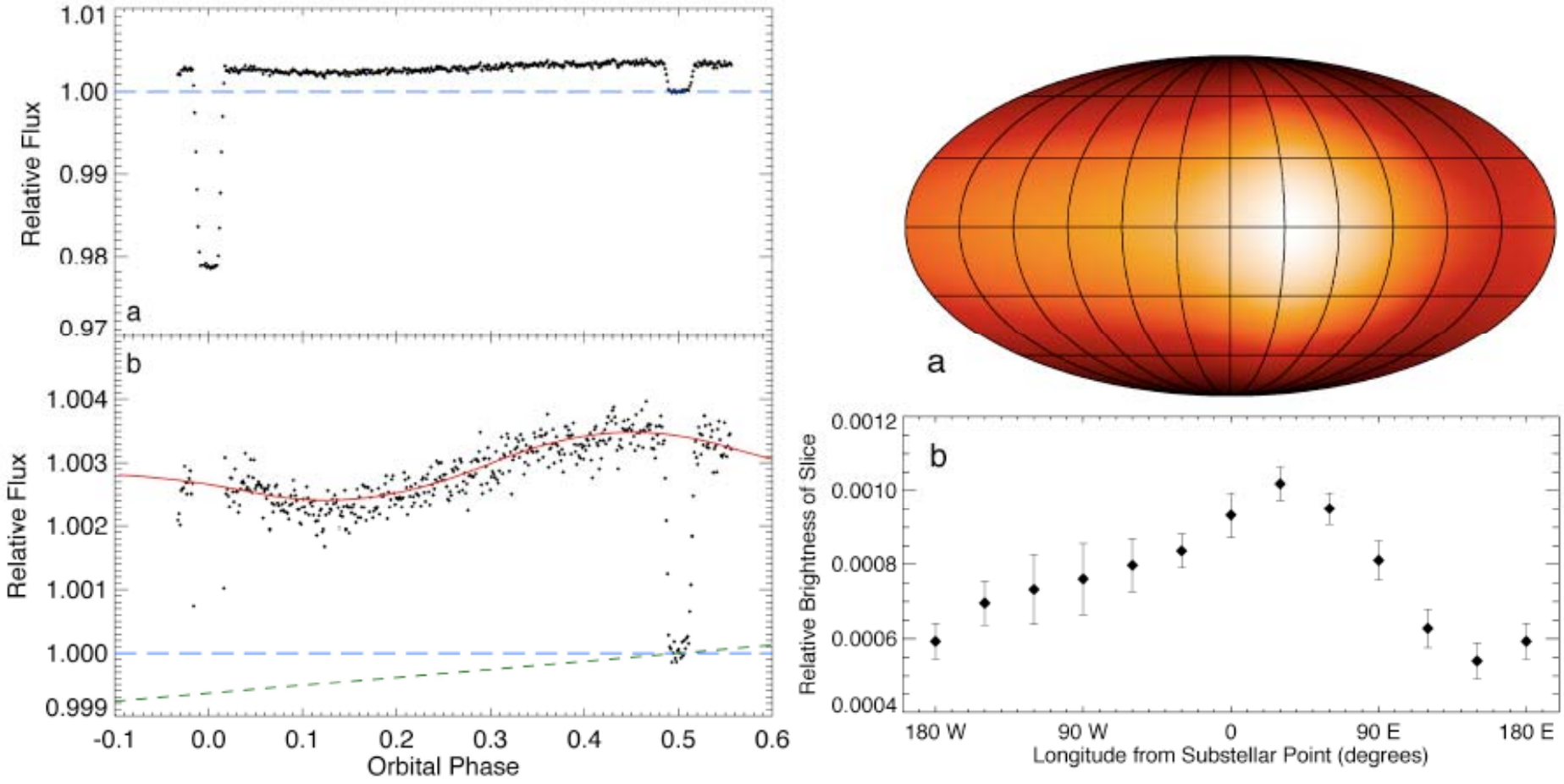

HSO
H
SH
H, hν
H2S
H2
H
H
H2
H
SO
OH
hν
S
hν
S2
S
HSO3
hν
OH, SO
OH
H
SO2
hν
S
S
SO3
H2O
H2SO4
S3


Pressure (mbar)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
S_2
SH
S
H_2S
S_3
S_5
S_6
S_8
S_4
SO
HSO
SO_3
SO_2
H_2SO_4
10^{-20} 10^{-15} 10^{-10} 10^{-5}
Volume Mixing Ratio
10^{-15} 10^{-10} 10^{-5}
Volume Mixing Ratio
10^{-15} 10^{-10} 10^{-5}
Volume Mixing Ratio

Properties of hot planets

- Radiative lifetime varies as T^{-3}
- Chemical lifetime could as exp(-B/T)
- Transport time varies as R/U

The Result: First Longitudinal Temperature Profile for an Extrasolar Planet

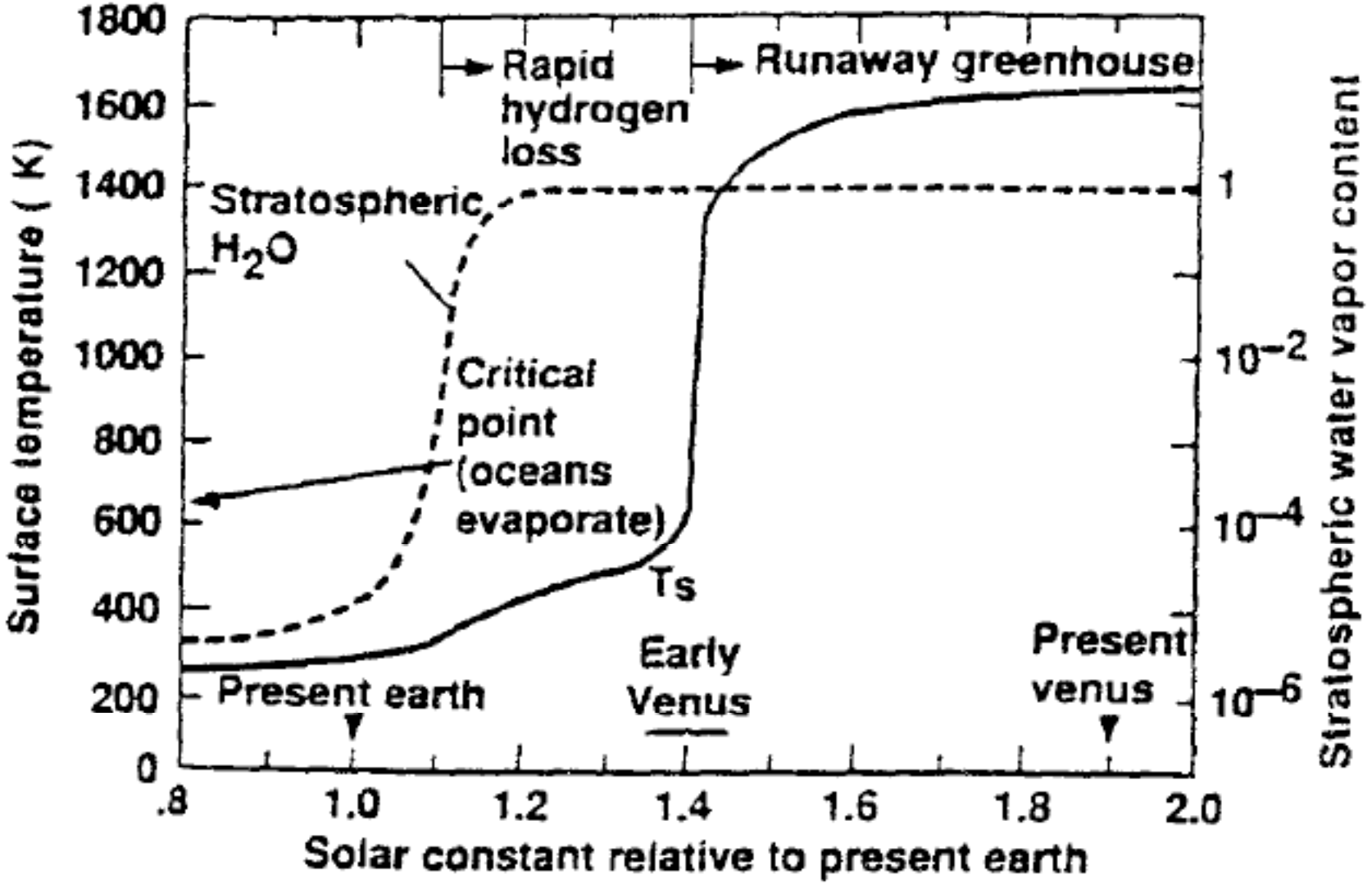


Figures from Knutson et al. 2007b, *Nature* 447, 183

Superearths

- GL 581c
- GL 581d

Parameter		Circular case		
		Gl 581 b	**Gl 581 c**	**Gl 581 d**
P	[days]	5.3687±0.0003	12.931±0.007	83.4±0.4
T	[JD-2400000]	52999.99±0.05	52996.74±0.45	52954.1±3.7
e		0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
V	[km s^{-1}]		-9.2115 ± 0.0001	
ω	[deg]	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
K	[m s^{-1}]	12.42 ± 0.19	3.01±0.16	2.67±0.16
$a_1 \sin i$	[10^{-6} AU]	6.129	3.575	20.47
$f(m)$	[$10^{-13} M_\odot$]	10.66	0.365	1.644
$m_2 \sin i$	[$M_{\rm Jup}$]	0.0490	0.0159	0.0263
$m_2 \sin i$	[$M_\oplus$]	15.6	5.06	8.3
a	[AU]	0.041	0.073	0.25



Kasting 1996

Conclusions

Common photochemistry: hundreds of molecules, thousands of reactions

Similar Processes: Catalytic cycles, evolution, hydrodynamic escape, thermal inversion

Acknowledgements

- NASA and ESA
- Yung’s Group at Caltech
- Liang Ph.D. Thesis 2005
- Yung and DeMore (1999) Book

Back-up slides

Properties of HD 209458b

- “Best known” planet
  - First discovered transiting planet (Henry et al. 2000)
  - First atmosphere detection (Charbonneau et al. 2001)
  - First exosphere detection (Vidal-Madjar et al. 2003)
- Orbiting HD 209458 G0V-type star
  - ~0.05 AU or 3.5 days
- Inclination angle ~85°
- Radius 1.54 R_J and mass 0.68 M_J

Chemical processes

- Chemical composition different from that of Jupiter
  - CO and H_2O are abundant; CH_4 not abundant
- UV radiation a lot more enhanced
  - Can break up more molecules
  - Boost subsequent chemical reactions
- Performing photochemical calculation for HD 209458b

One-dimensional photochemical model

- Solving mass continuity equation
  - $\frac{\partial n_i}{\partial t} + \frac{\partial \varphi_i}{\partial z} = P_i - L_i$
  - $\varphi_i = -\frac{\partial n_i}{\partial z}(D_i + K_{zz}) - n_i(\frac{D_i}{H_i} + \frac{K_{zz}}{H_{atm}}) - n_i \frac{\partial T}{\partial z}[\frac{(1+\alpha_i)D_i + K_{zz}}{T}] + n_i w_i$
  - $K_{zz} = K_0 \times n^{-\gamma}$, $\gamma \approx 0.5$
- Temperature profile from thermochemical calculation
- Chemical reactions from, for example, Yung and DeMore (1999)