Overview of Solar System Planet Atmospheres

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Sagan Exoplanet Summer Workshop
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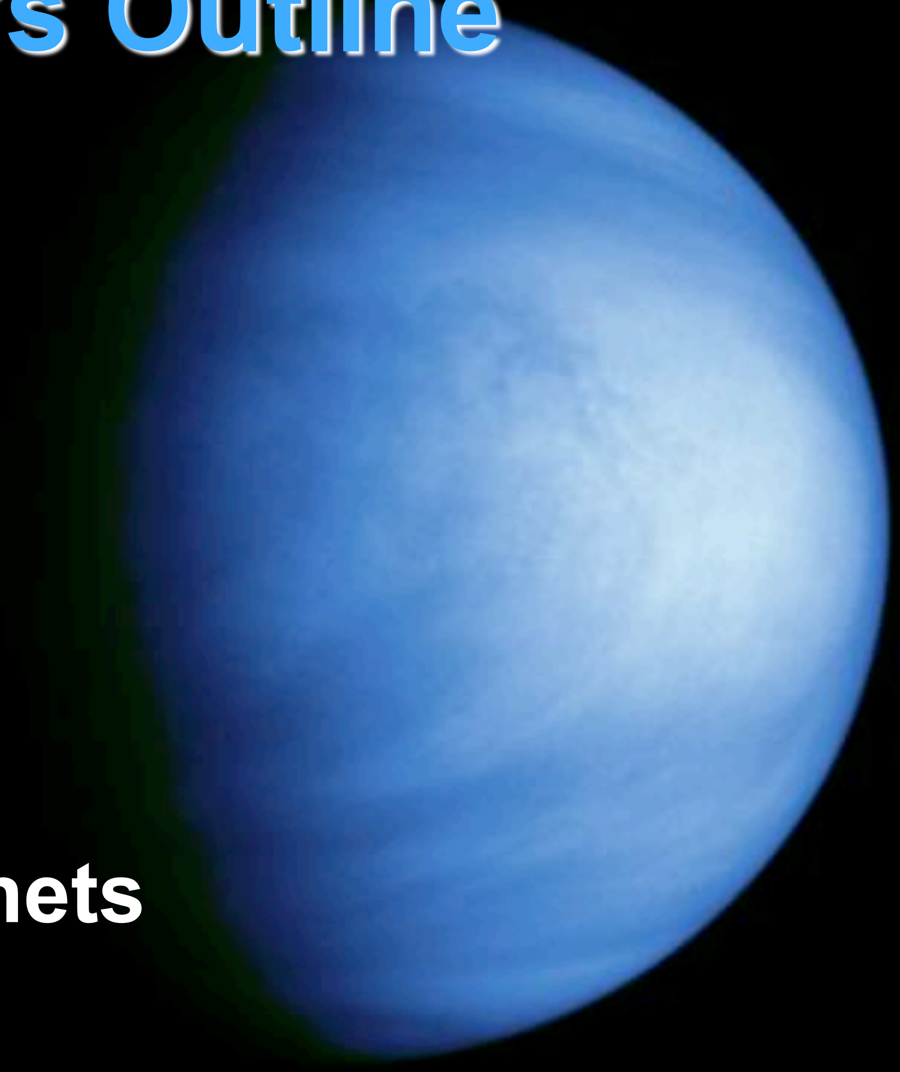
Today’s Outline



- Origins
- Giant planets
- Small bodies
- Terrestrial planets
- Conclusions

Atmospheres of the Solar System

- Giant planets
  - Primary atmospheres (H_2, He, CH_4…)
  - Little evolution (no surface, little escape)
- Terrestrial planets (Earth, Venus, Mars, Titan)
  - Secondary atmospheres (CO_2 / N_2, N_2 / O_2, N_2 / CH_4)
  - Outgassed and strongly evolved (escape, surface interaction)
- Tenuous atmospheres (Pluto, Triton, Io, Enceladus)
  - In equilibrium with surface ices or internal sources
- Exospheres (Mercury, Moon, other Galilean satellites)
  - Solar flux or solar wind action on surfaces

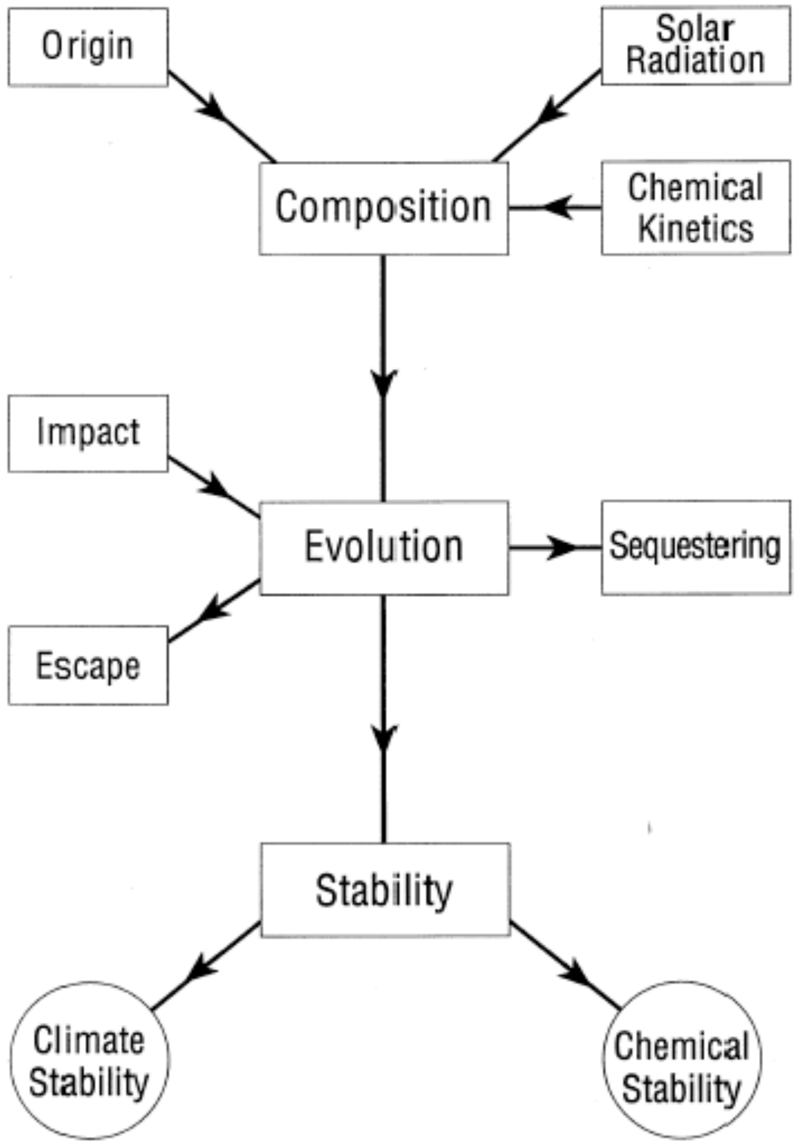
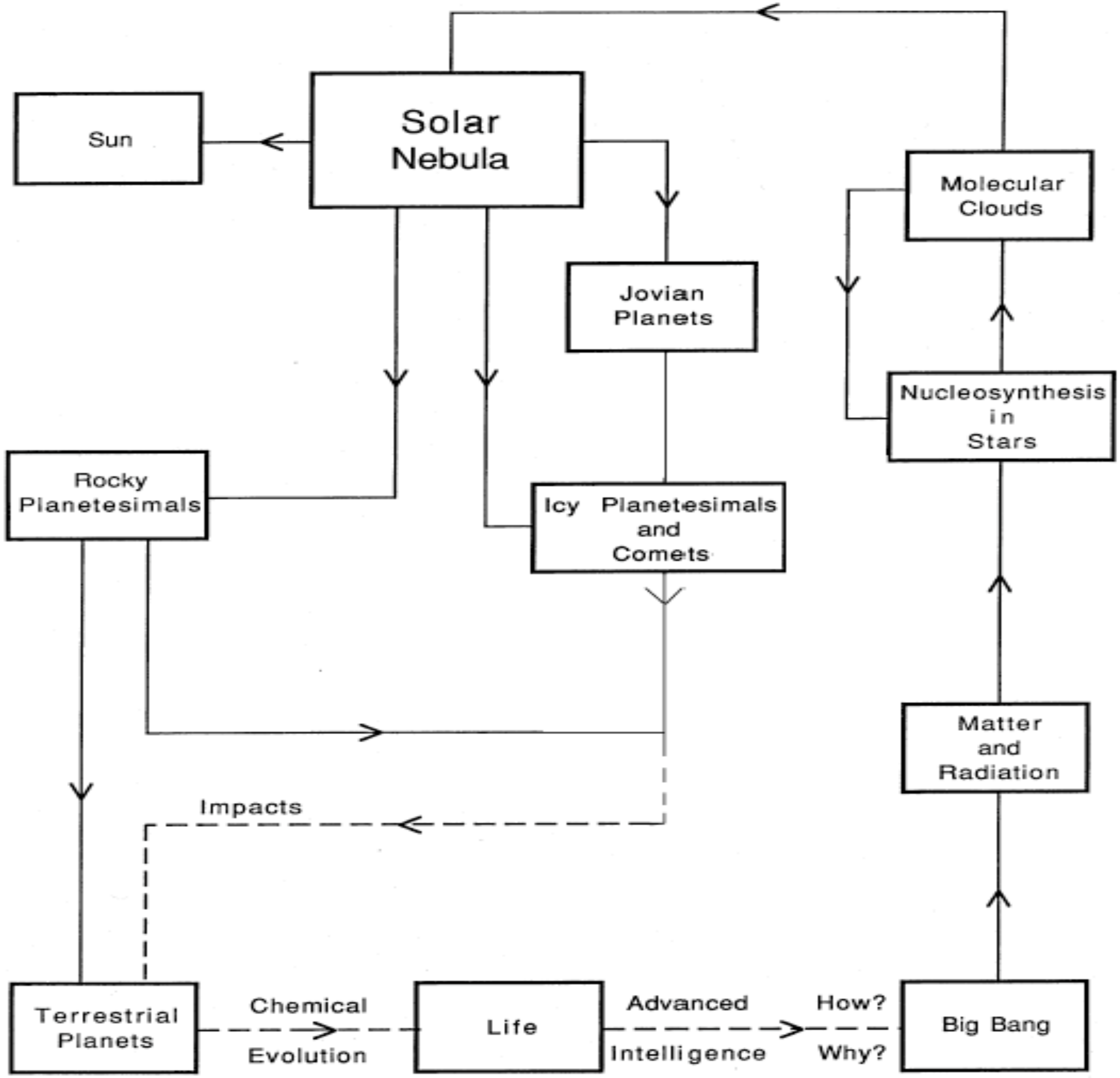
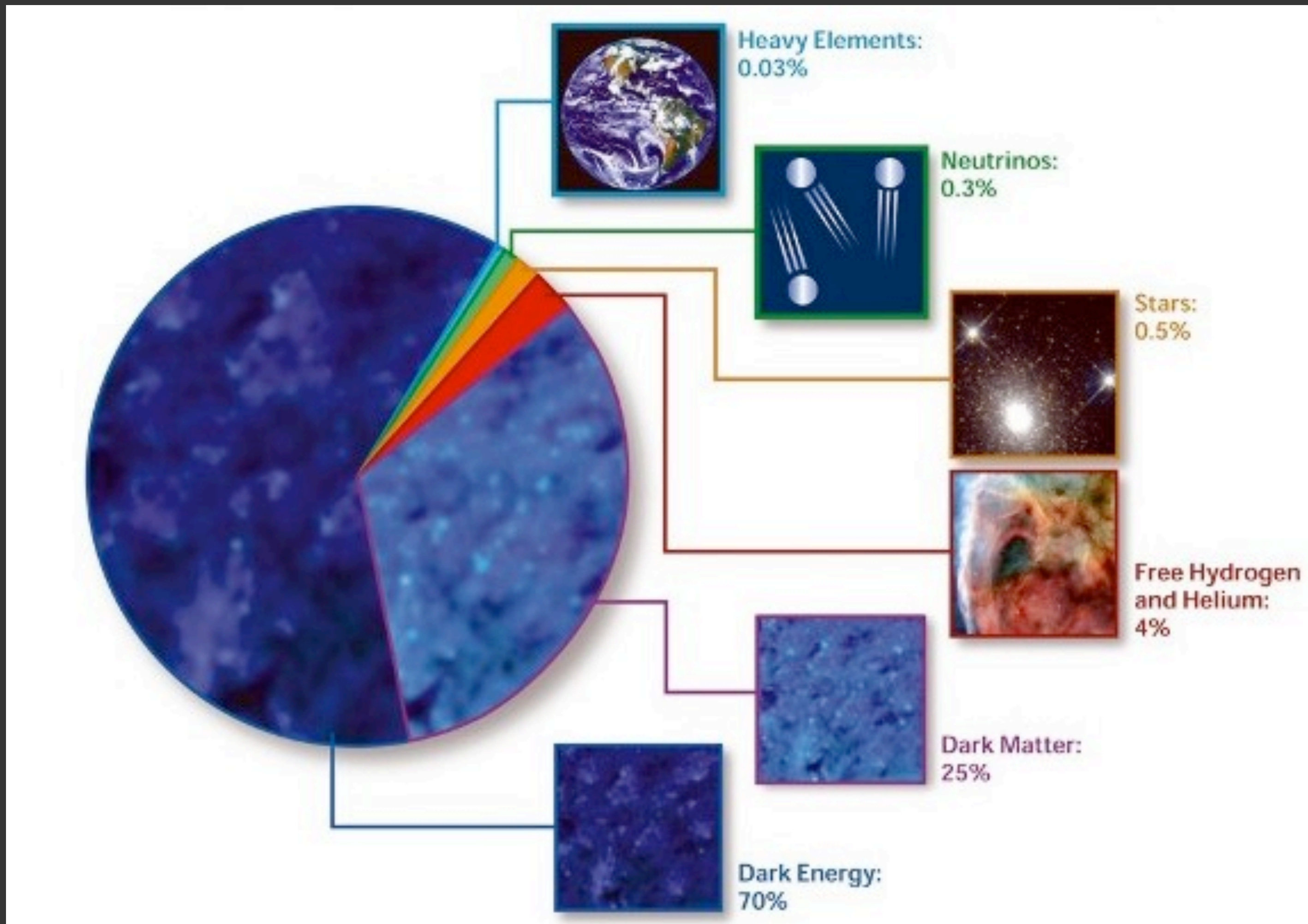
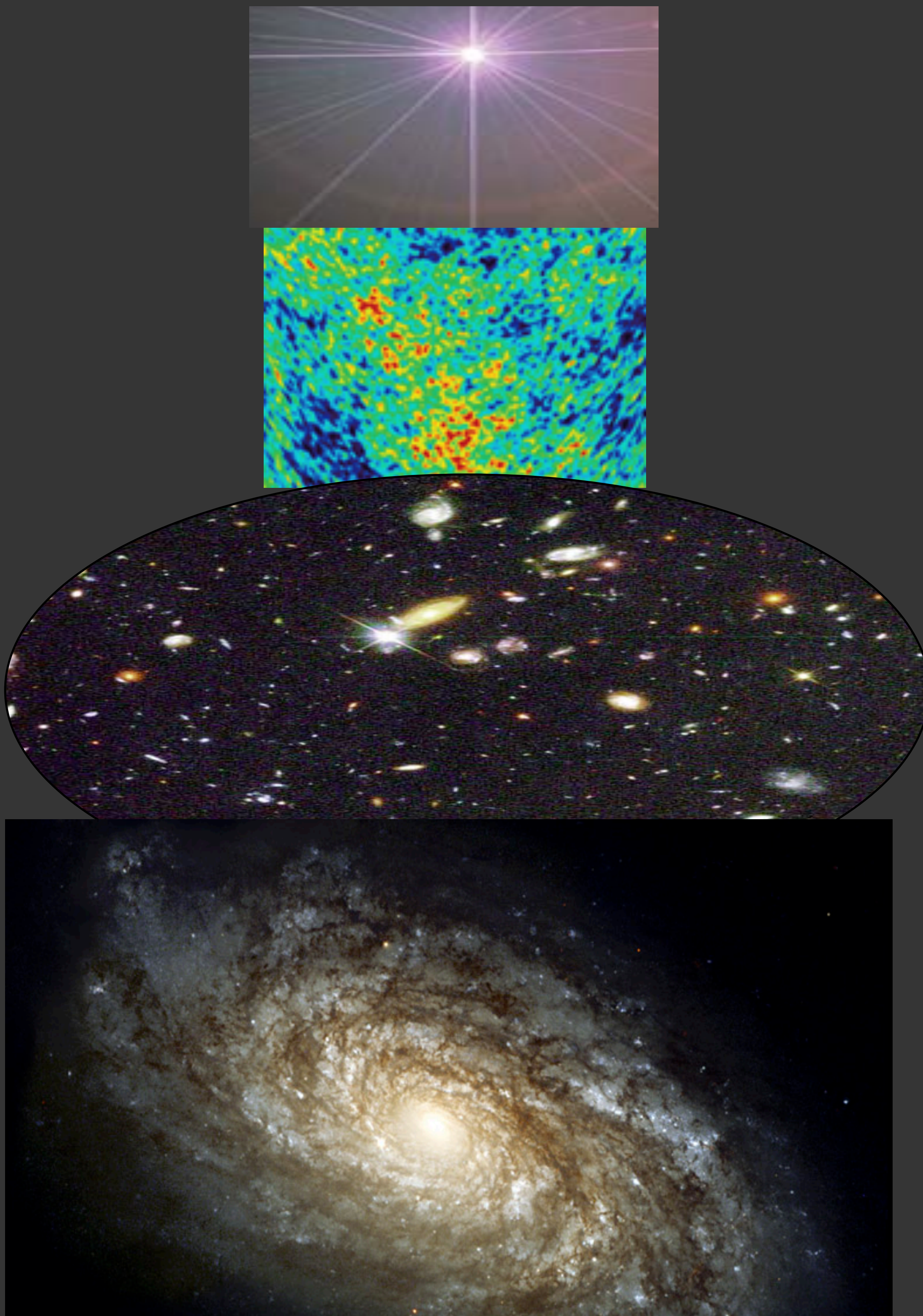

Origin
Solar Radiation
Composition
Chemical Kinetics
Impact
Evolution
Sequestering
Escape
Stability
Climate Stability
Chemical Stability

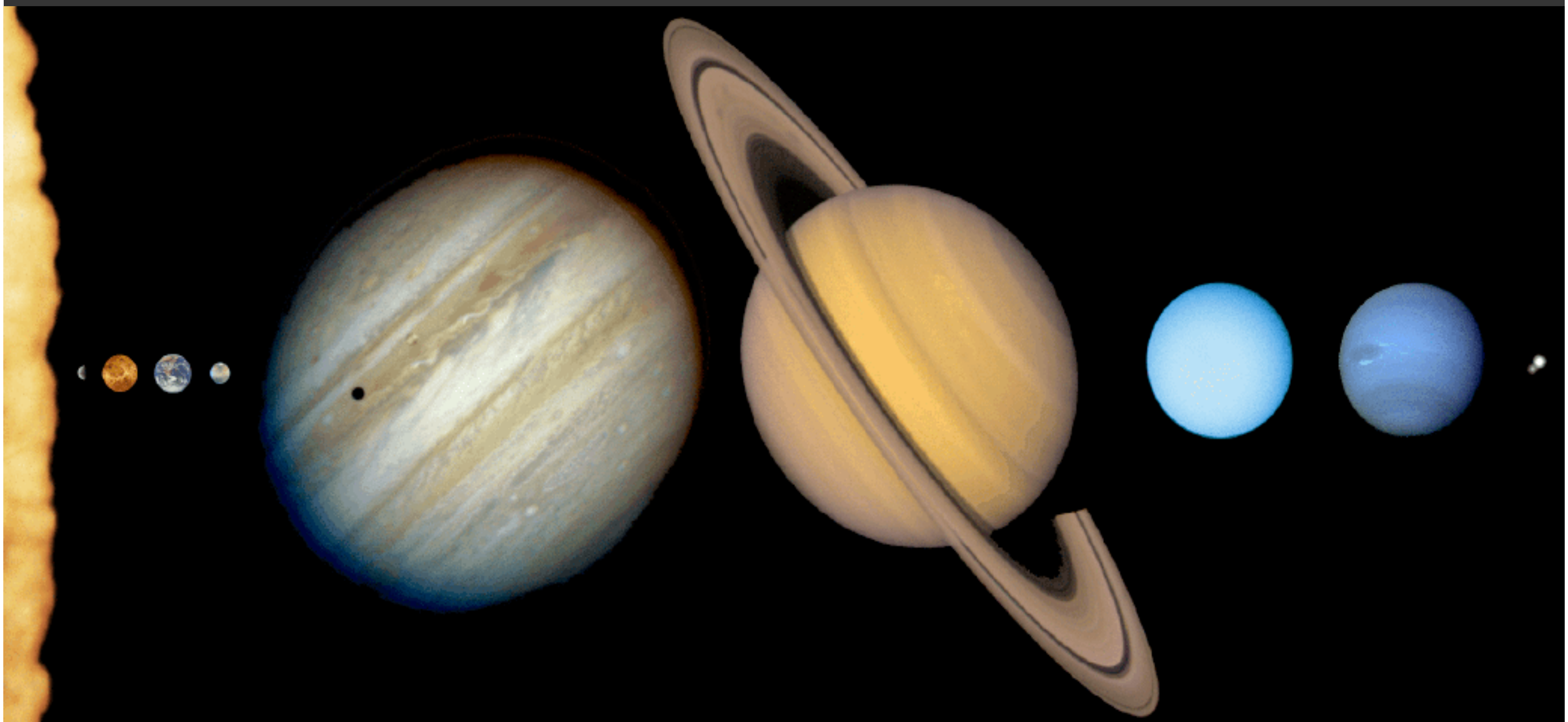
Figure 1.1

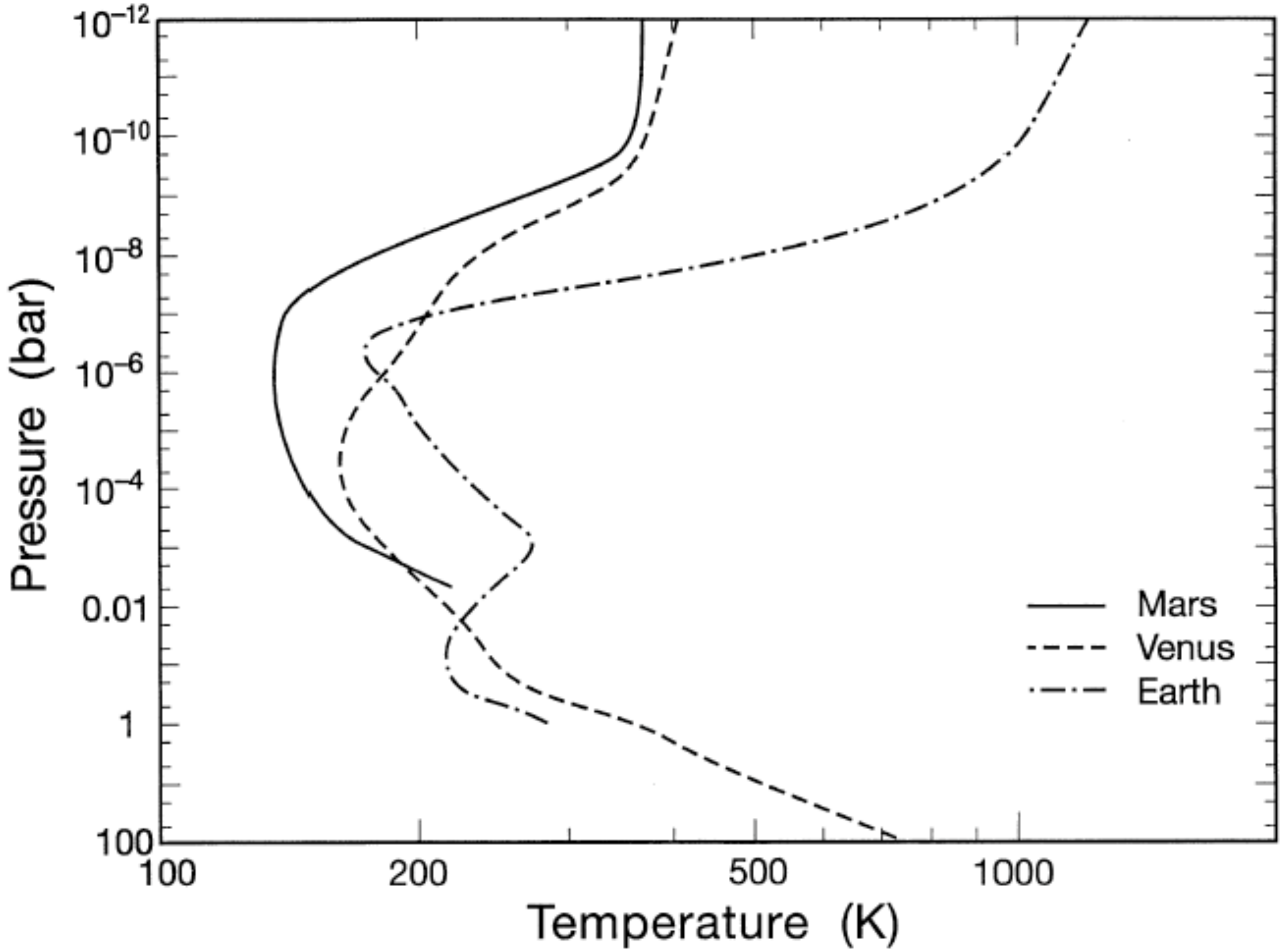

Solar Nebula
Sun
Jovian Planets
Molecular Clouds
Nucleosynthesis in Stars
Rocky Planetesimals
Icy Planetesimals and Comets
Matter and Radiation
Impacts
Terrestrial Planets
Chemical Evolution
Life
Advanced Intelligence
How?
Why?
Big Bang


Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter:
25%
Dark Energy:
70%

Big Bang!



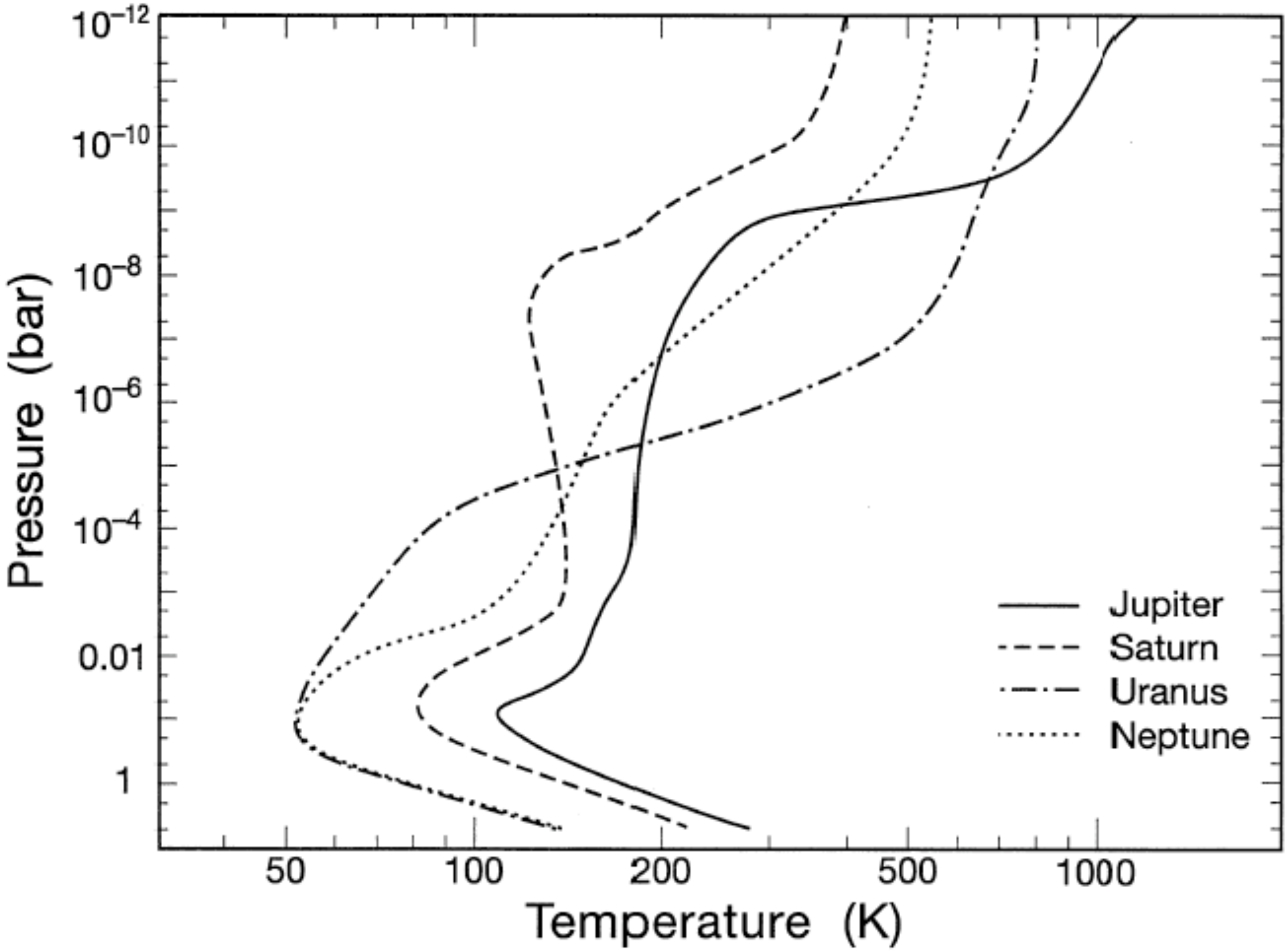




10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
100
Pressure (bar)
100
200
500
1000
Temperature (K)
Mars
Venus
Earth

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})



10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
Pressure (bar)
50
100
200
500
1000
Temperature (K)
Jupiter
Saturn
Uranus
Neptune

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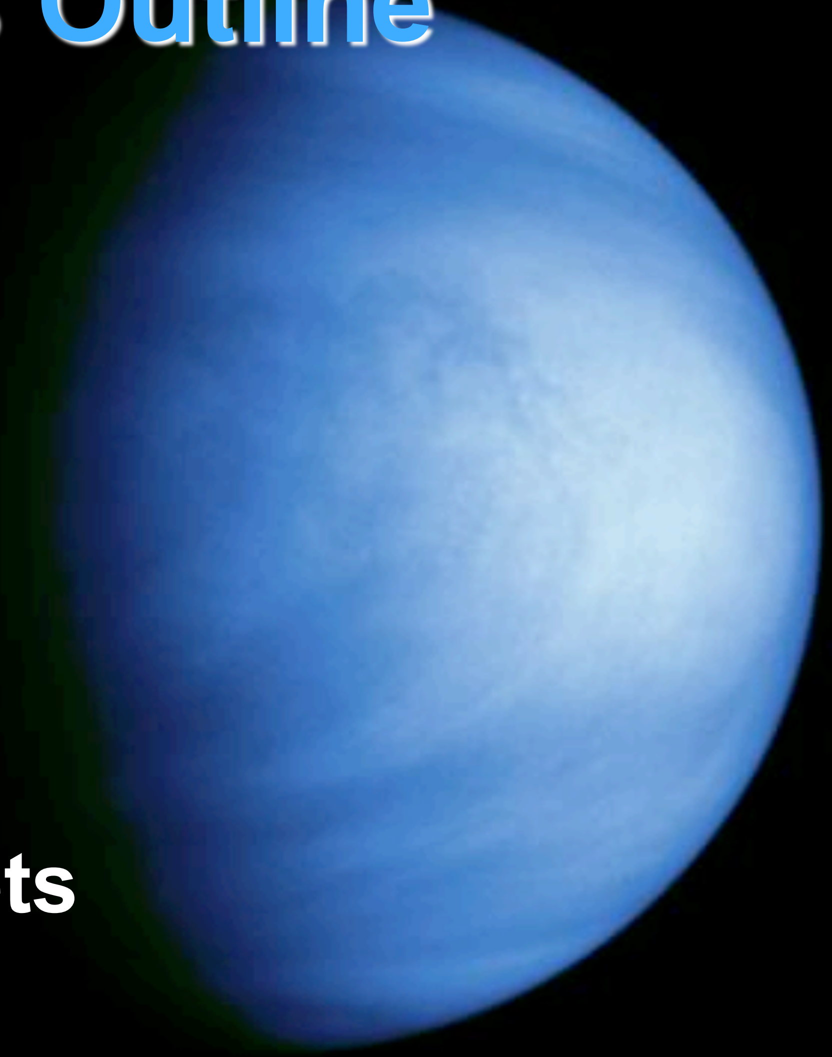
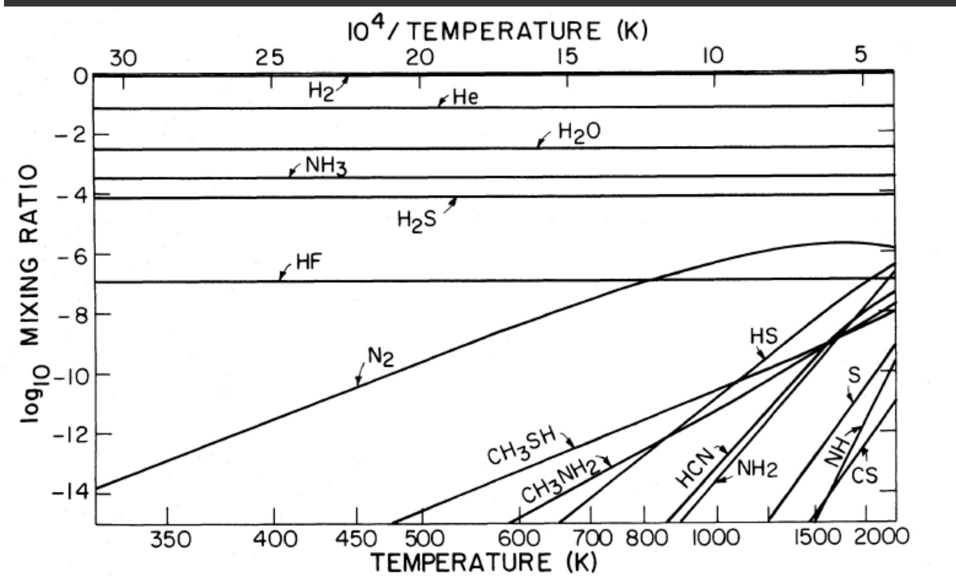
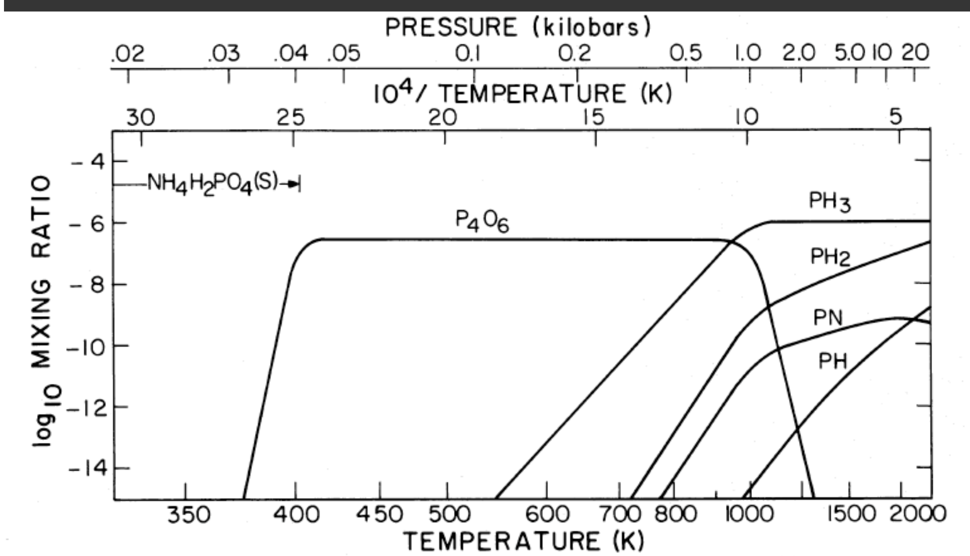


Equilibrium vs disequilibrium species in Giant Planets



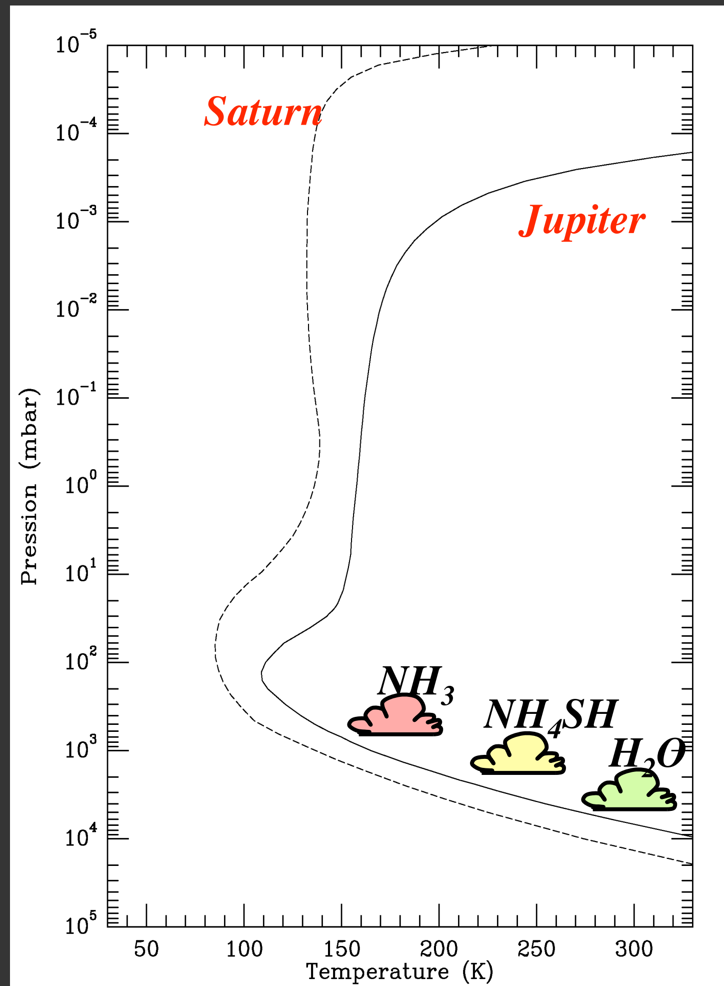


At the relevant T, NH_3 is the thermodynamical equilibrium form of N
→ In principle NH_3 / H_2 gives the N/H ratio

… but PH_3 is NOT the equilibrium form of P

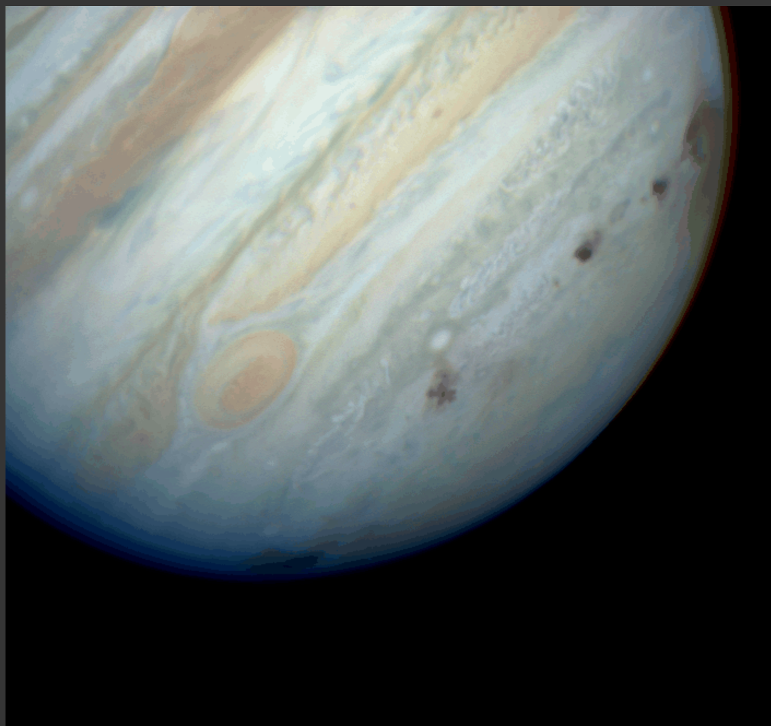
Competition between chemical destruction and vertical convective transport
Quench level : where $t_{chem} \sim t_{dyn}$
Occurs at T ~1200 K for phosphine

→ Observed PH_3 abundance still gives P/H ratio !

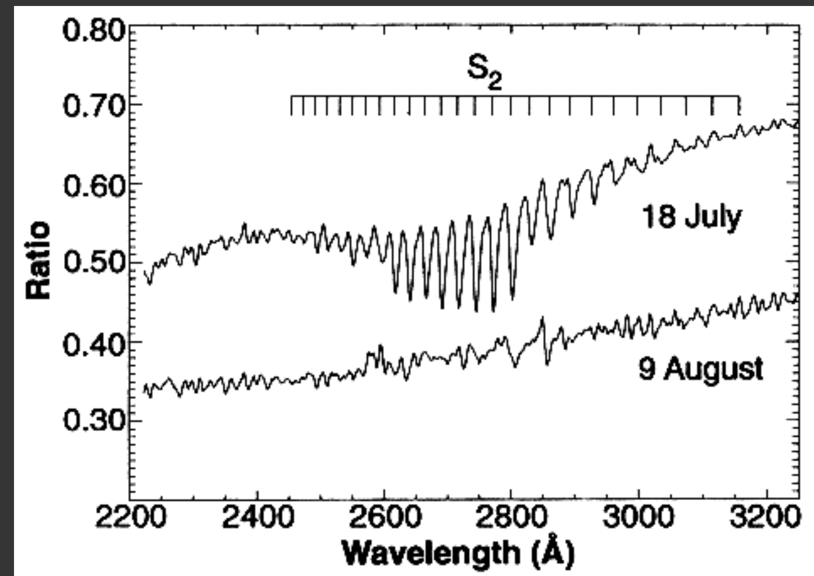


Saturn
Jupiter
NH_3
NH_4SH
H_2O
Pression (mbar)
Temperature (K)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
50
100
150
200
250
300

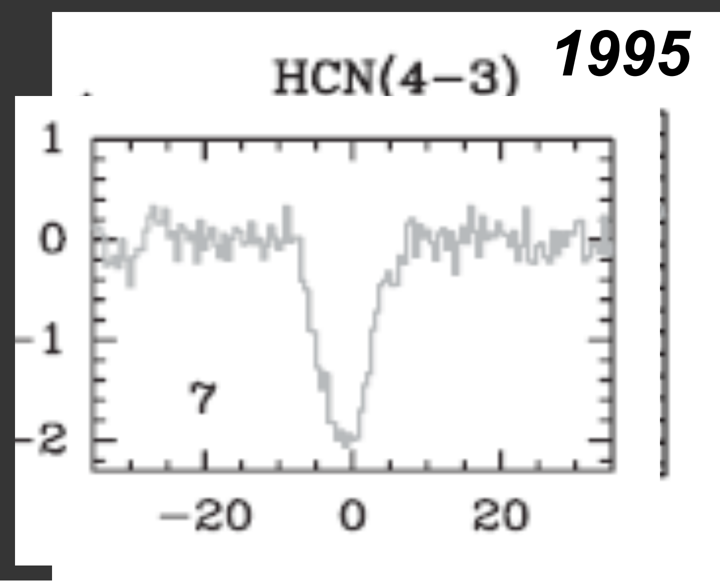
Comets are sources for atmospheres



16-23 July 1994



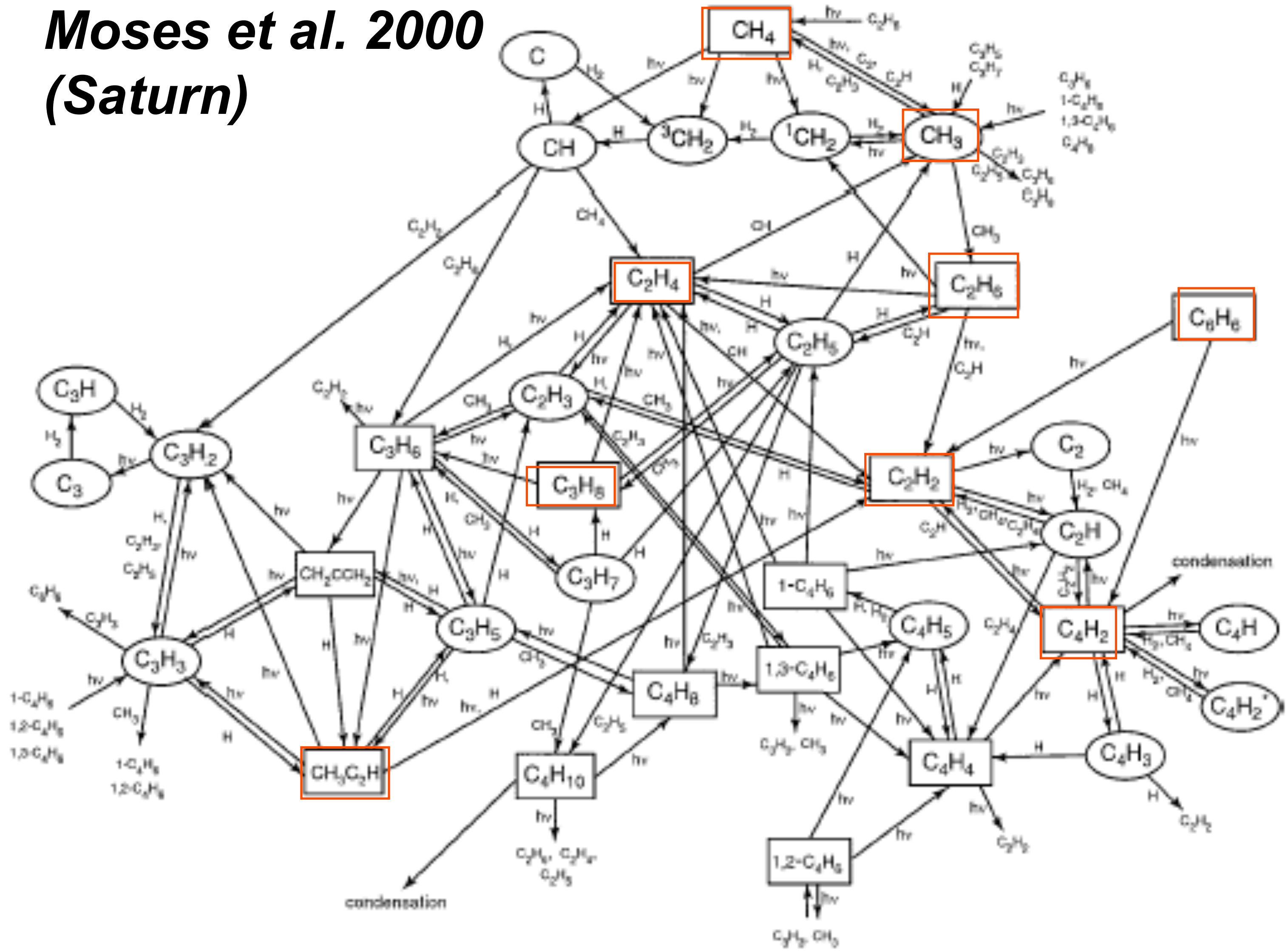
HST Noll et al. 1995

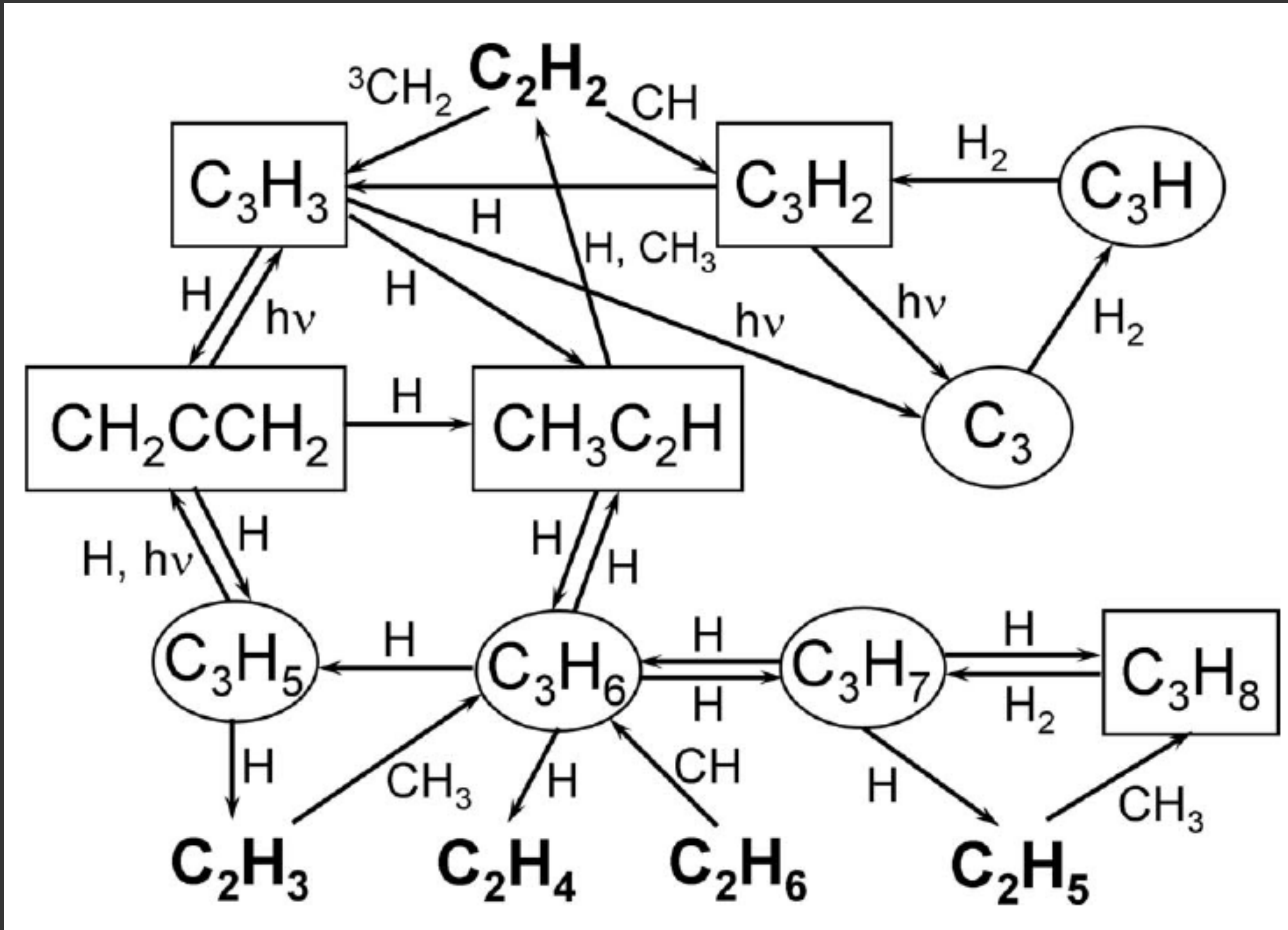


JCMT 15-m
Moreno et al. 2003

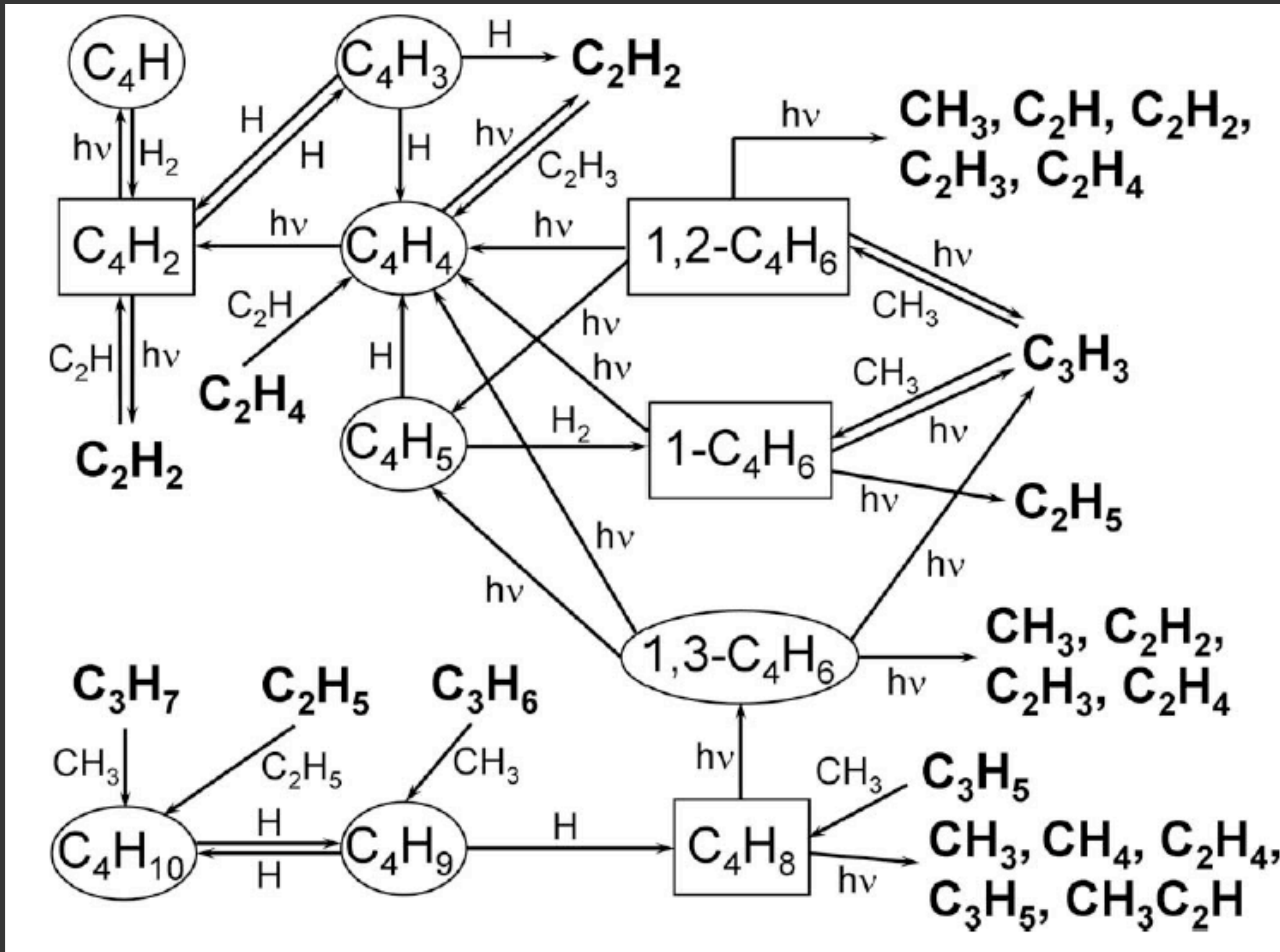
Methane photochemistry in Giant Planets (a recent view…)

Moses et al. 2000 (Saturn)

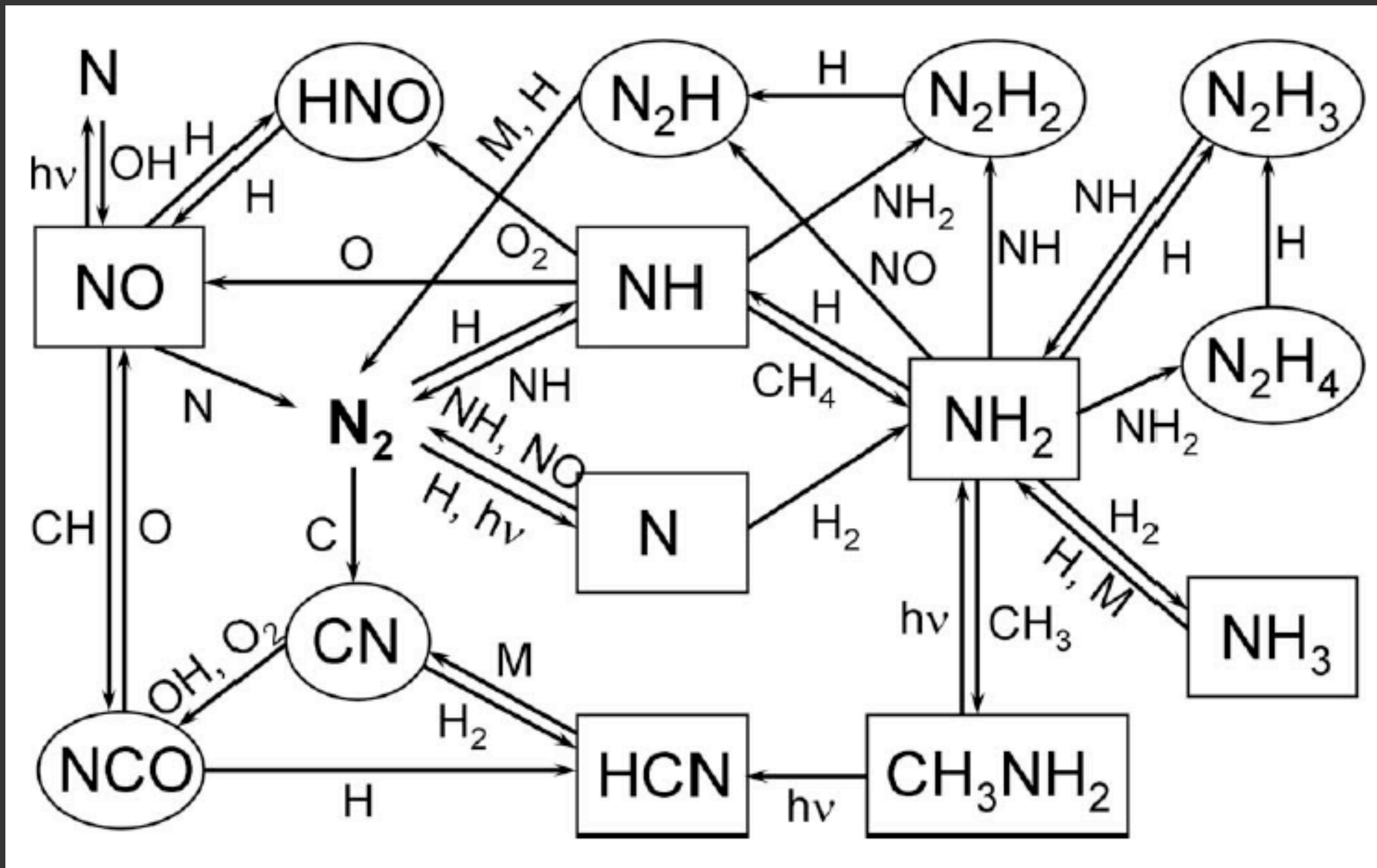




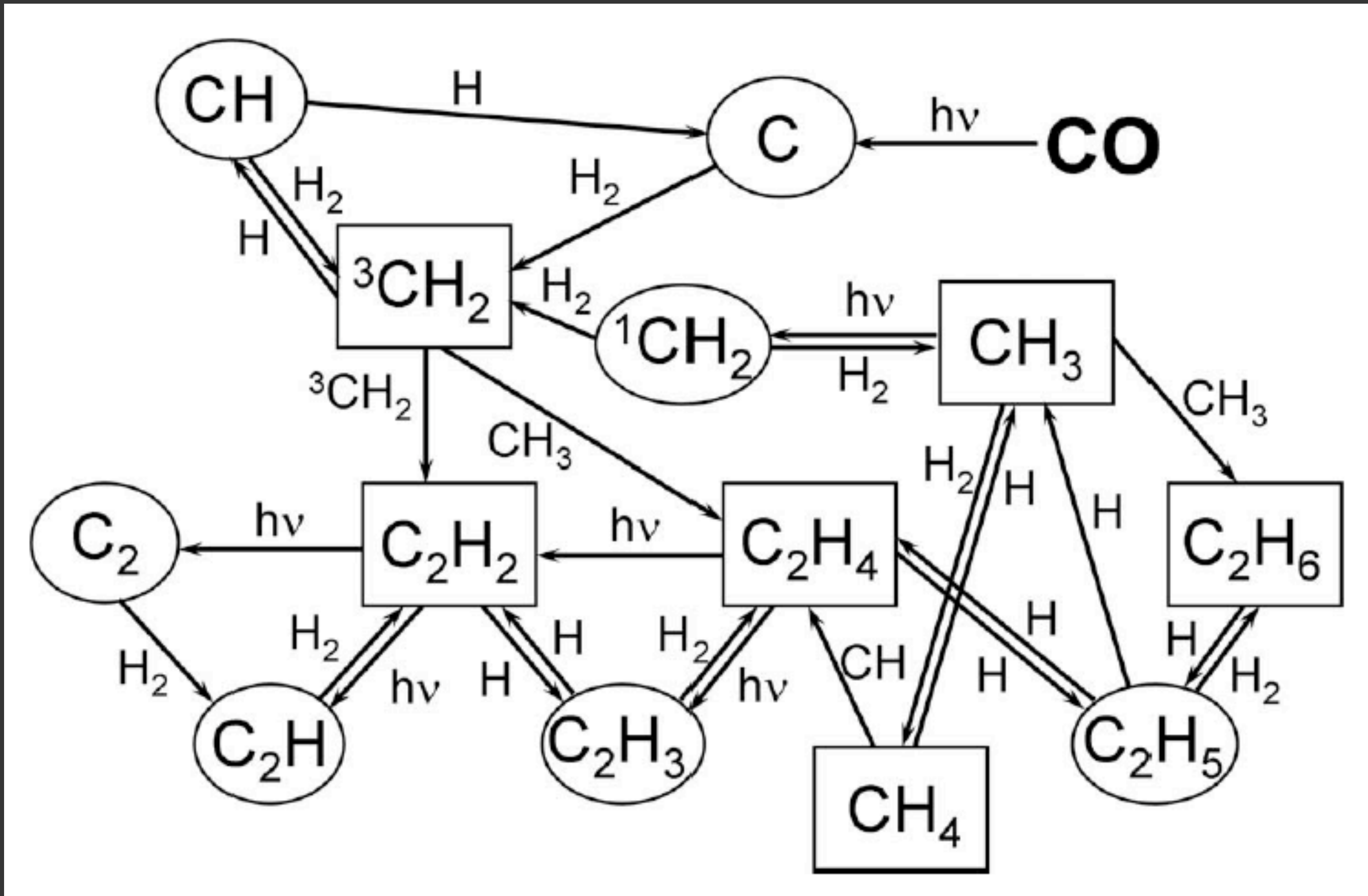
C_2H_2
$^3CH_2$
CH
C_3H_3
C_3H_2
C_3H
H_2
H
H, CH_3
H
hν
hν
hν
H_2
CH_2CCH_2
CH_3C_2H
C_3
H
H, hν
H
H
H
C_3H_5
C_3H_6
C_3H_7
C_3H_8
H
H
H
H
H_2
H
CH_3
H
CH
H
CH_3
C_2H_3
C_2H_4
C_2H_6
C_2H_5

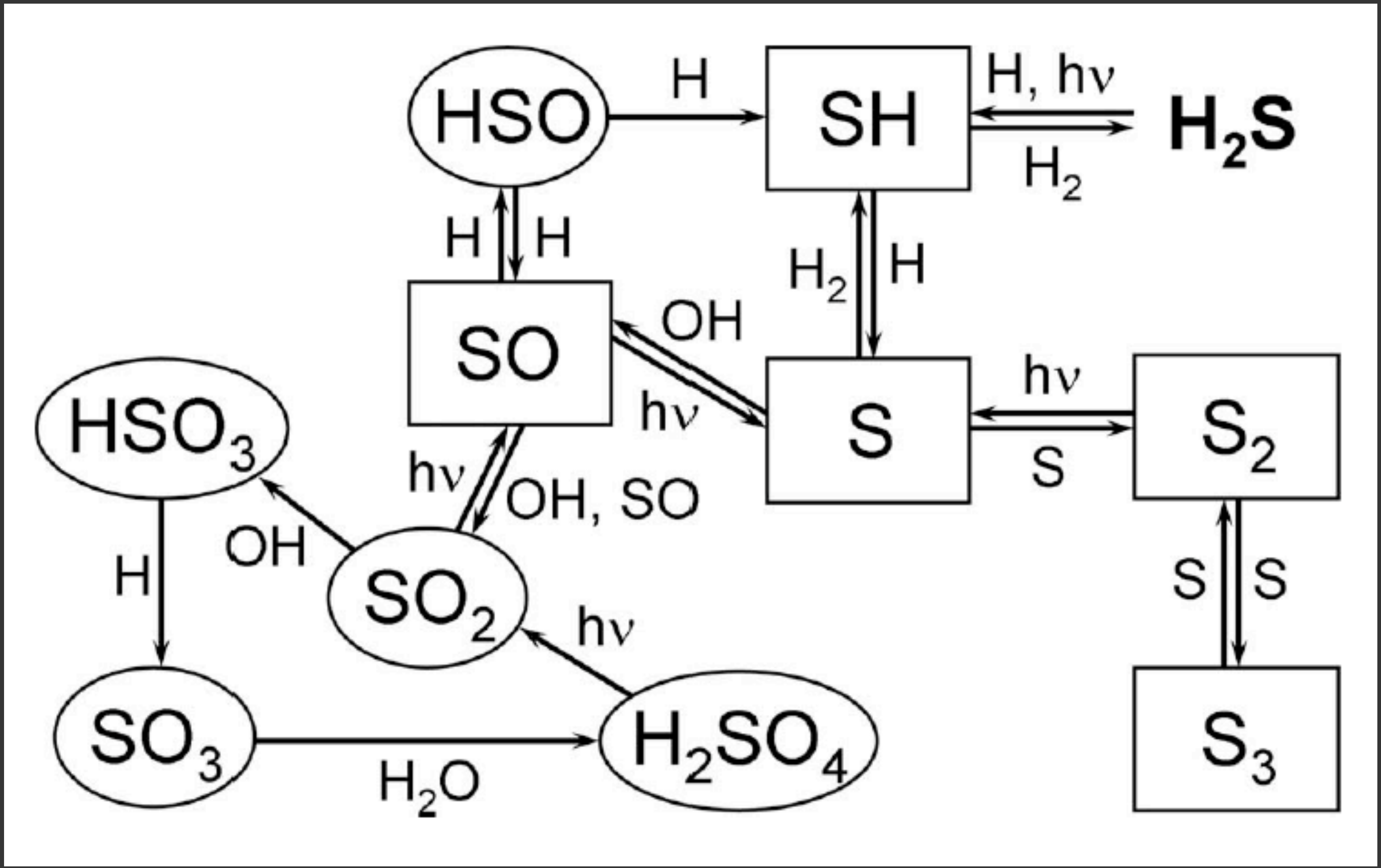


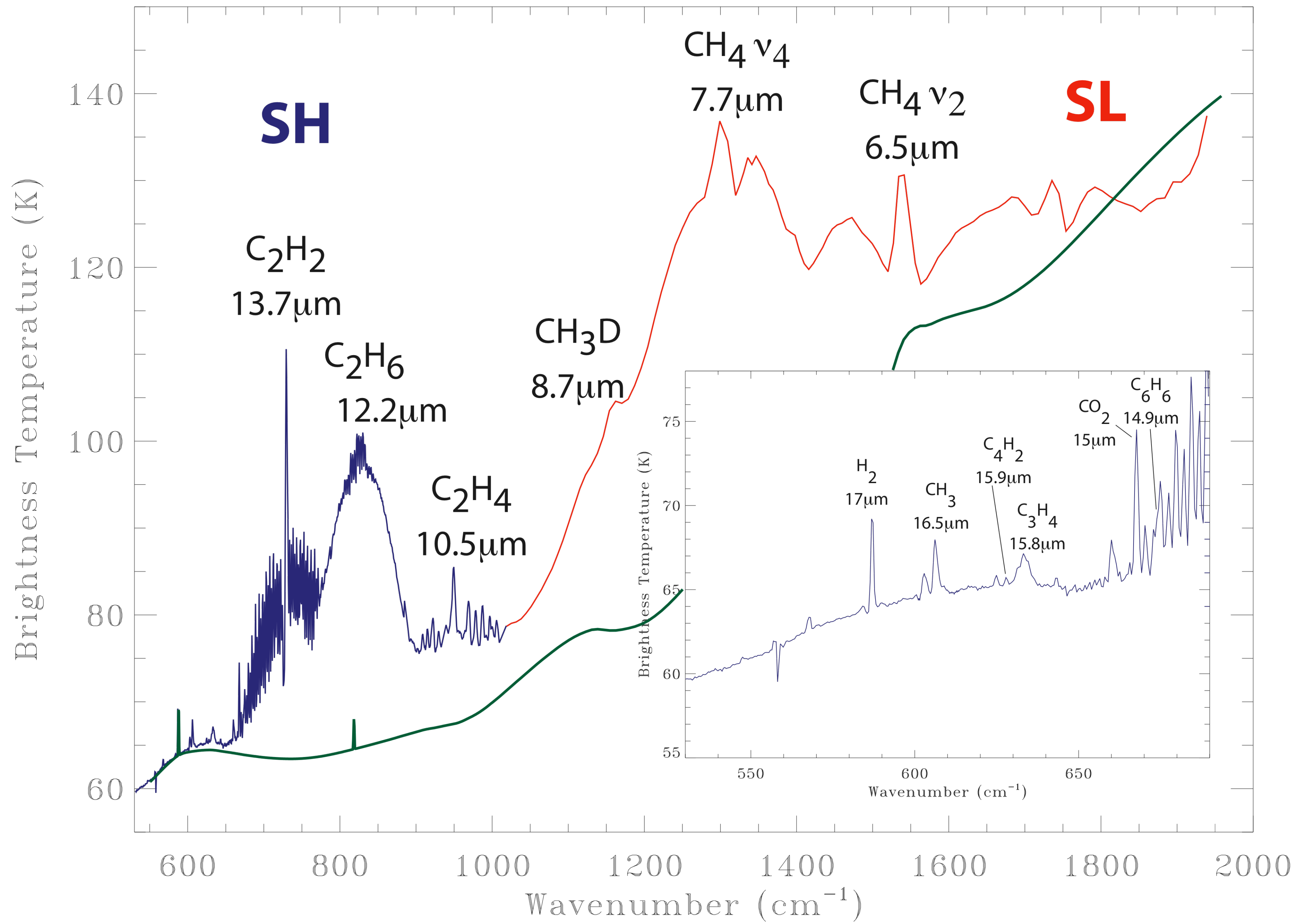
C_4H
C_4H_3
H
C_2H_2
hν
H_2
H
H
H
hν
C_2H_3
hν
CH_3, C_2H, C_2H_2,
C_2H_3, C_2H_4
C_4H_2
hν
C_4H_4
hν
1,2-C_4H_6
hν
CH_3
C_2H
hν
C_2H
hν
C_2H_4
H
hν
hν
CH_3
C_3H_3
C_2H_2
C_4H_5
H_2
1-C_4H_6
hν
hν
C_2H_5
hν
hν
hν
1,3-C_4H_6
CH_3, C_2H_2,
C_2H_3, C_2H_4
hν
C_3H_7
C_2H_5
C_3H_6
CH_3
C_2H_5
CH_3
hν
CH_3
C_3H_5
C_4H_{10}
H
H
C_4H_9
H
C_4H_8
CH_3, CH_4, C_2H_4,
C_3H_5, CH_3C_2H
hν



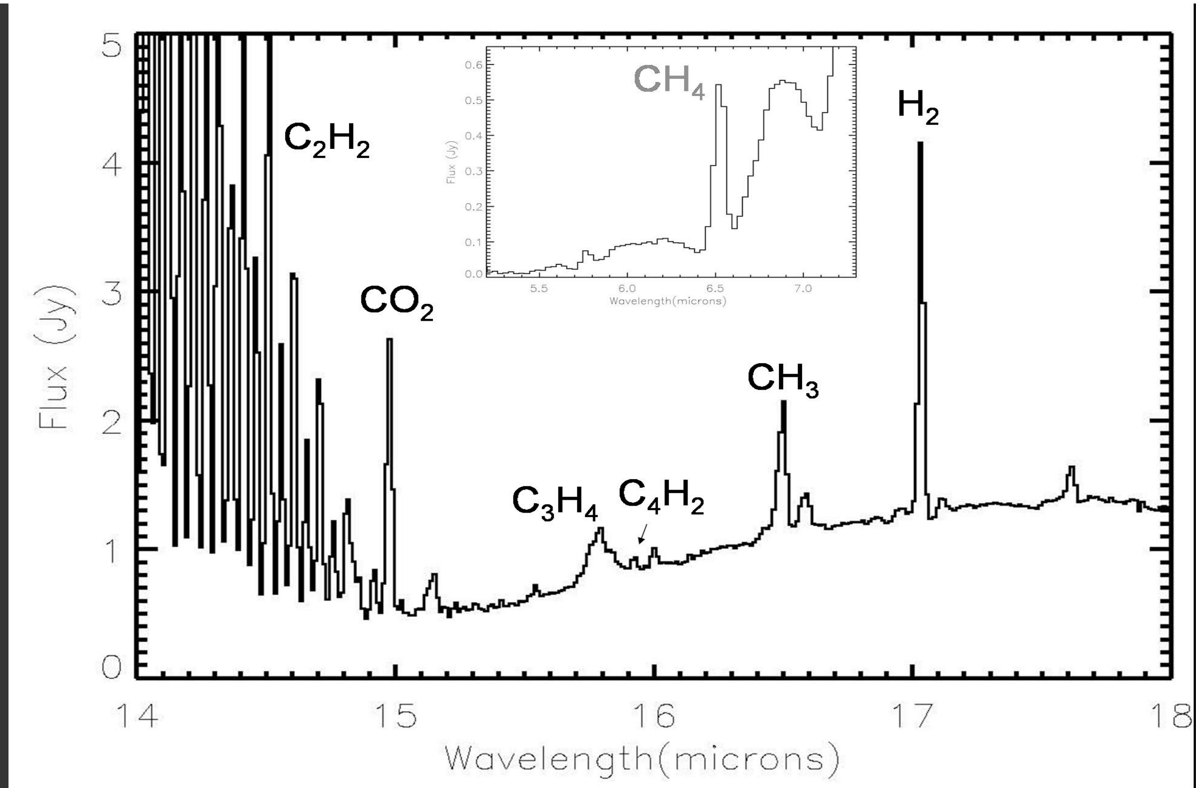
N
HNO
N_2H
N_2H_2
N_2H_3
NO
NH
NH_2
N_2H_4
N_2
N
NH_3
CN
NCO
HCN
CH_3NH_2
hν
OH
H
H
M, H
H
O
O_2
NH_2
NO
NH
NH
H
H
H
N
H
NH
CH_4
NH_2
NH, NO
H, hν
H_2
H_2
H, M
C
CH
O
hν
CH_3
OH, O_2
M
H_2
H
hν


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

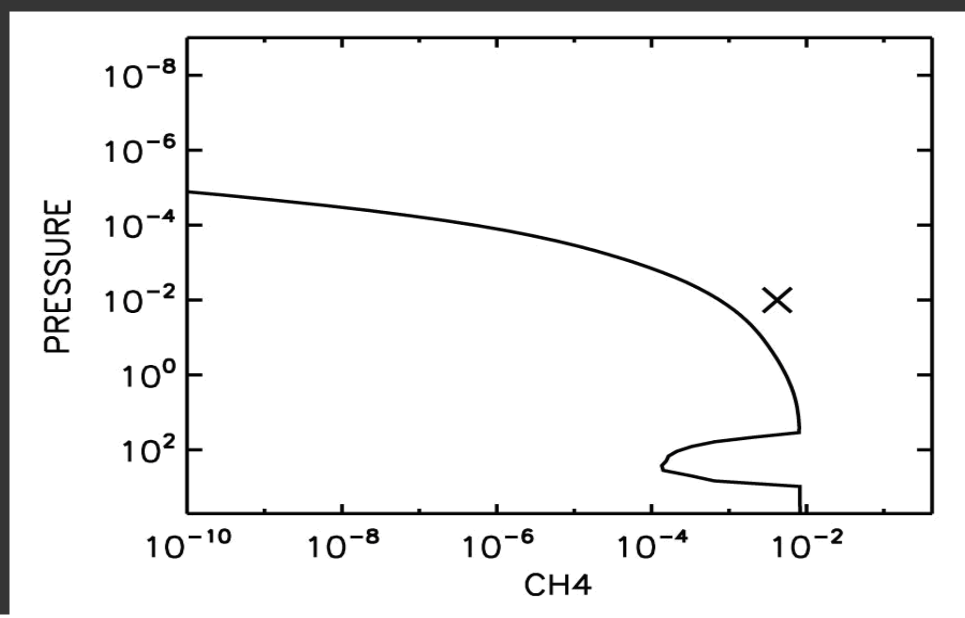

HSO
H
SH
H, hν
H₂S
H₂
H
H
H₂
H
SO
OH
hν
S
hν
S₂
S
HSO₃
hν
OH, SO
OH
H
SO₂
hν
S
S
SO₃
H₂SO₄
H₂O
S₃



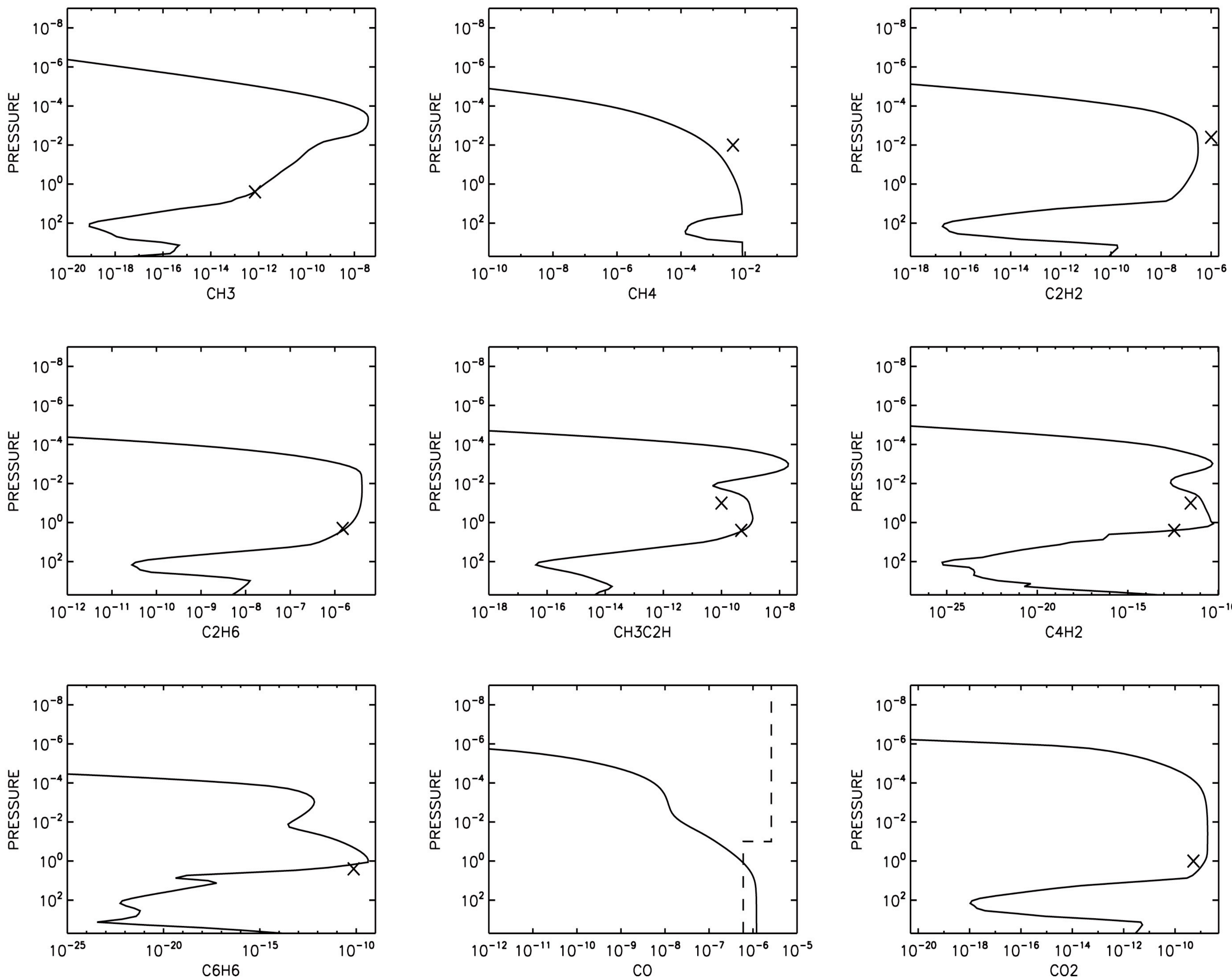
SH
SL
C_2H_2 13.7µm
C_2H_6 12.2µm
C_2H_4 10.5µm
CH_3D 8.7µm
CH_4 ν4 7.7µm
CH_4 ν2 6.5µm
Brightness Temperature (K)
Wavenumber (cm^{-1})
140
120
100
80
60
600
800
1000
1200
1400
1600
1800
2000
H_2 17µm
CH_3 16.5µm
C_4H_2 15.9µm
C_3H_4 15.8µm
CO_2 15µm
C_6H_6 14.9µm
75
70
65
60
55
550
600
650



C_2H_2
CO_2
C_3H_4
C_4H_2
CH_3
H_2
CH_4
Flux (Jy)
Wavelength(microns)



PRESSURE
CH4



PRESSURE
CH3
CH4
C2H2
C2H6
CH3C2H
C4H2
C6H6
CO
CO2

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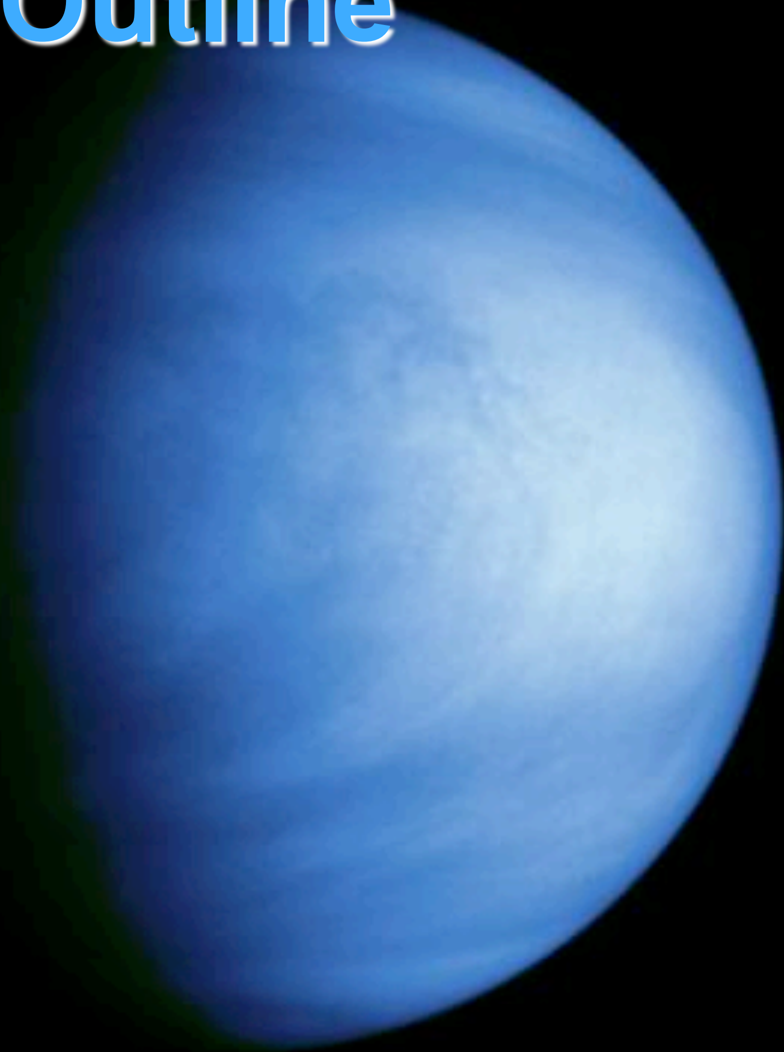
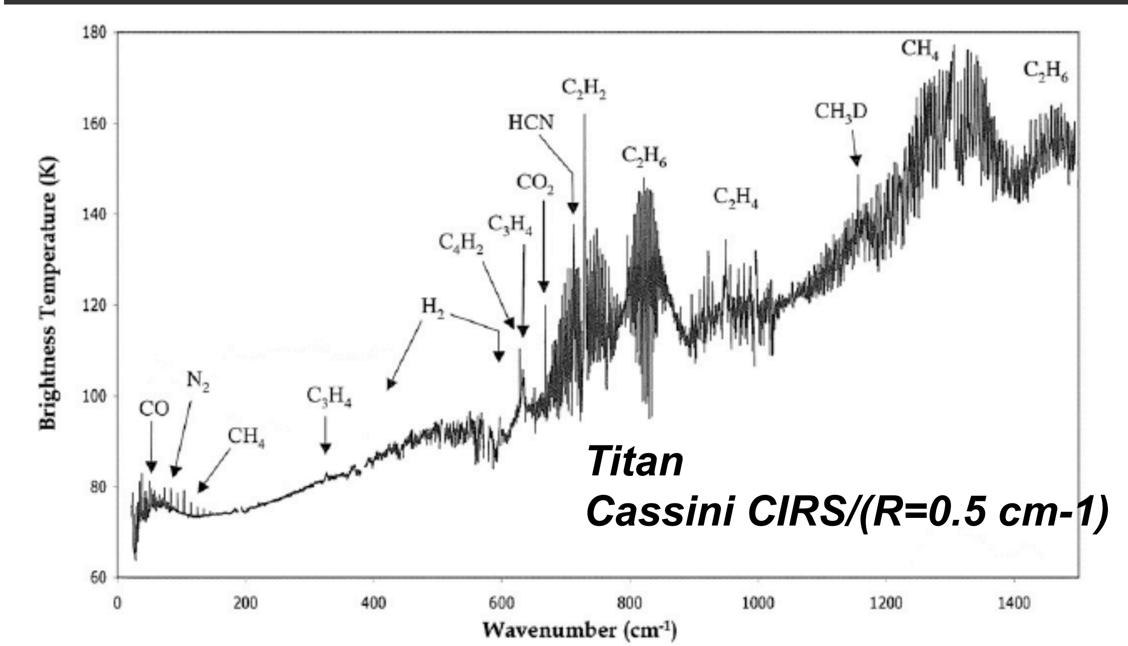
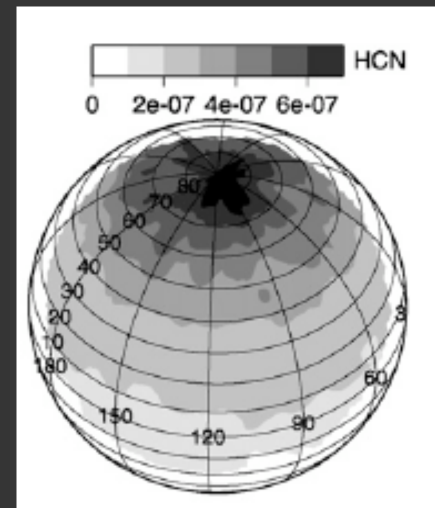
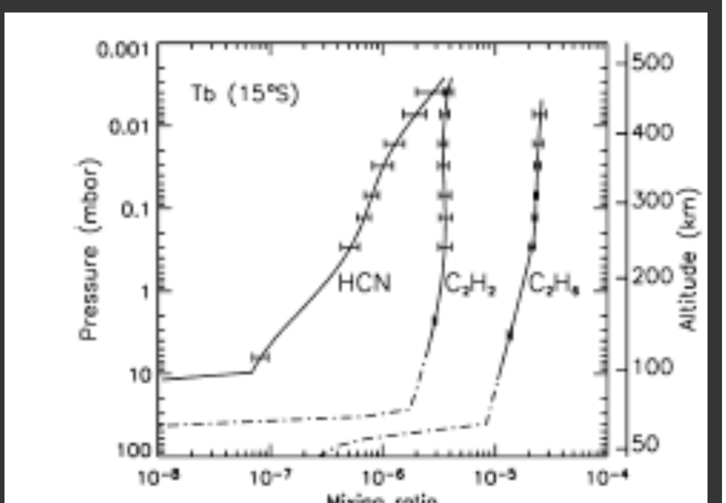
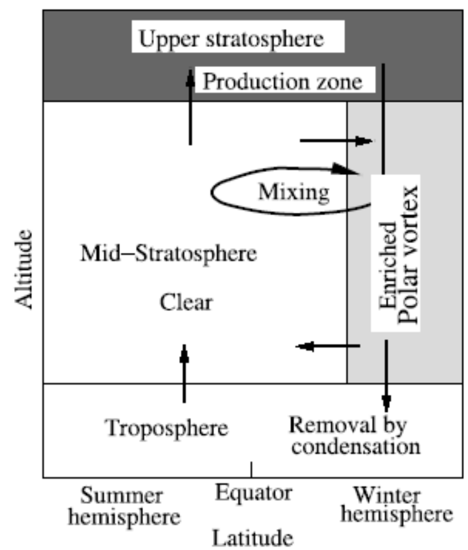


Spectroscopy from recent space missions: the 3-D view









Study of couplings between chemistry and dynamics

… but no new detections (except many isotopes)…

In situ measurements: the chemical complexity of Titan's upper atmosphere from Cassini / INMS

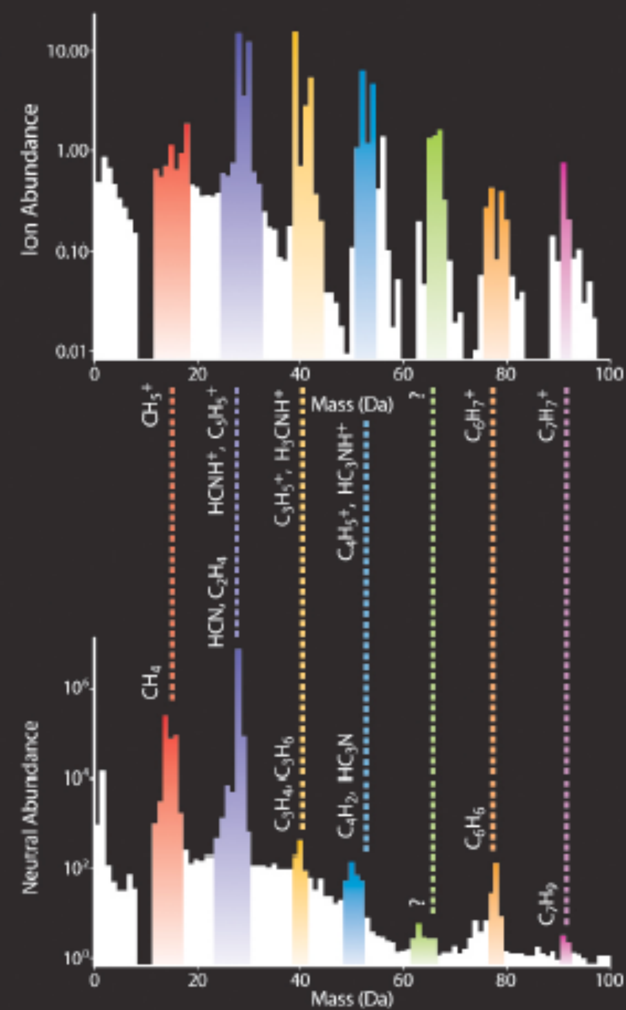
Molecules detected on Titan by INMS (≈1100 km)

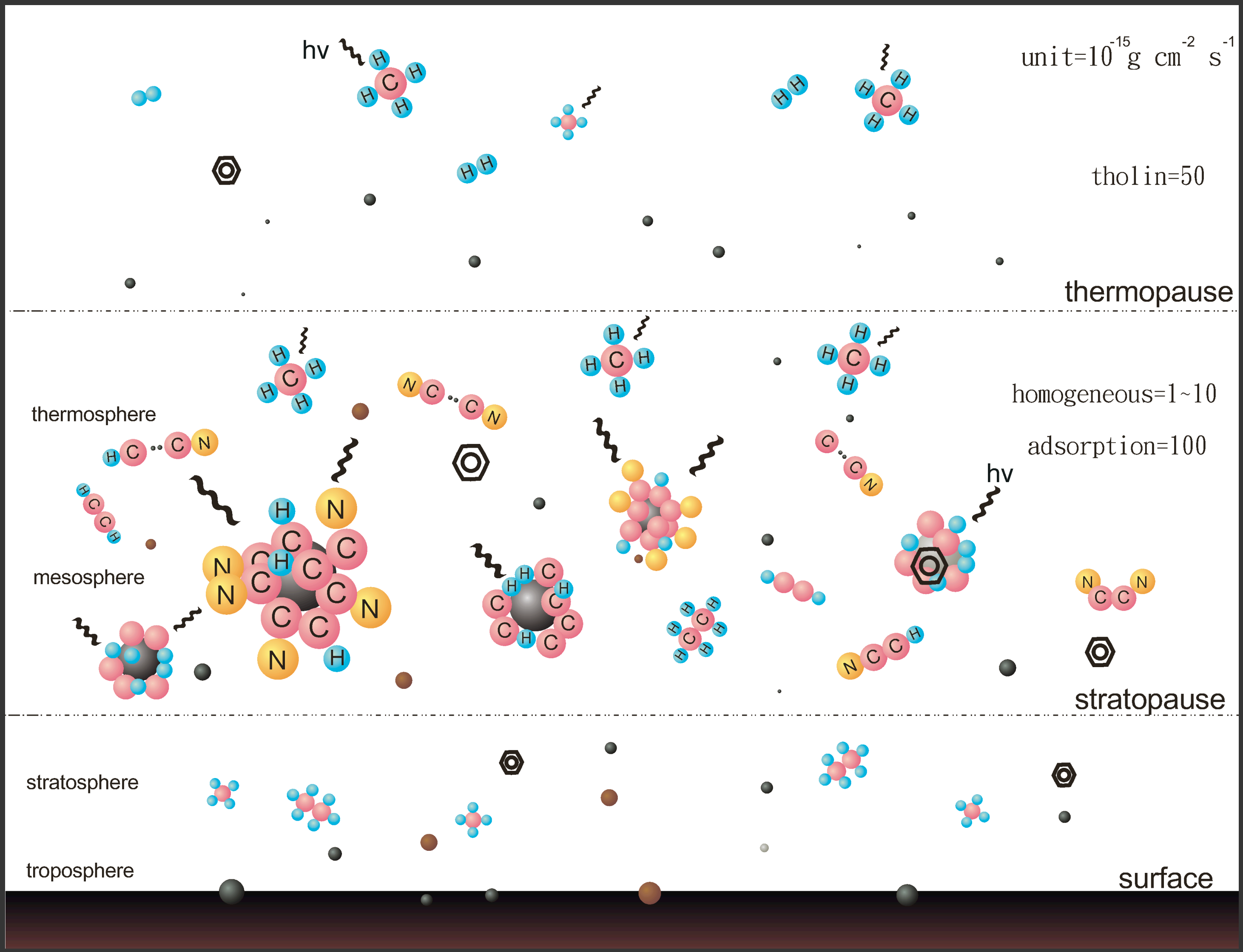
> 10 ppm	< 10 ppm	≈ ppm
C_2H_2	C_3H_4	C_6H_2
C_2H_4	C_3H_8	CH_3C_6H
C_2H_6	C_6H_6	C_8H_2
C_4H_2	$CH_3C_6H_5$	CH_3C_3N
HCN	CH_3CN	HC_5N
C_2H_3CN	C_2H_5CN	CH_3C_5N
HC_3N	C_2N_2	C_5H_5N
CH_2NH	NH_3	C_6H_7N

Neutral mode   Ion mode

Neutral + Ion mode

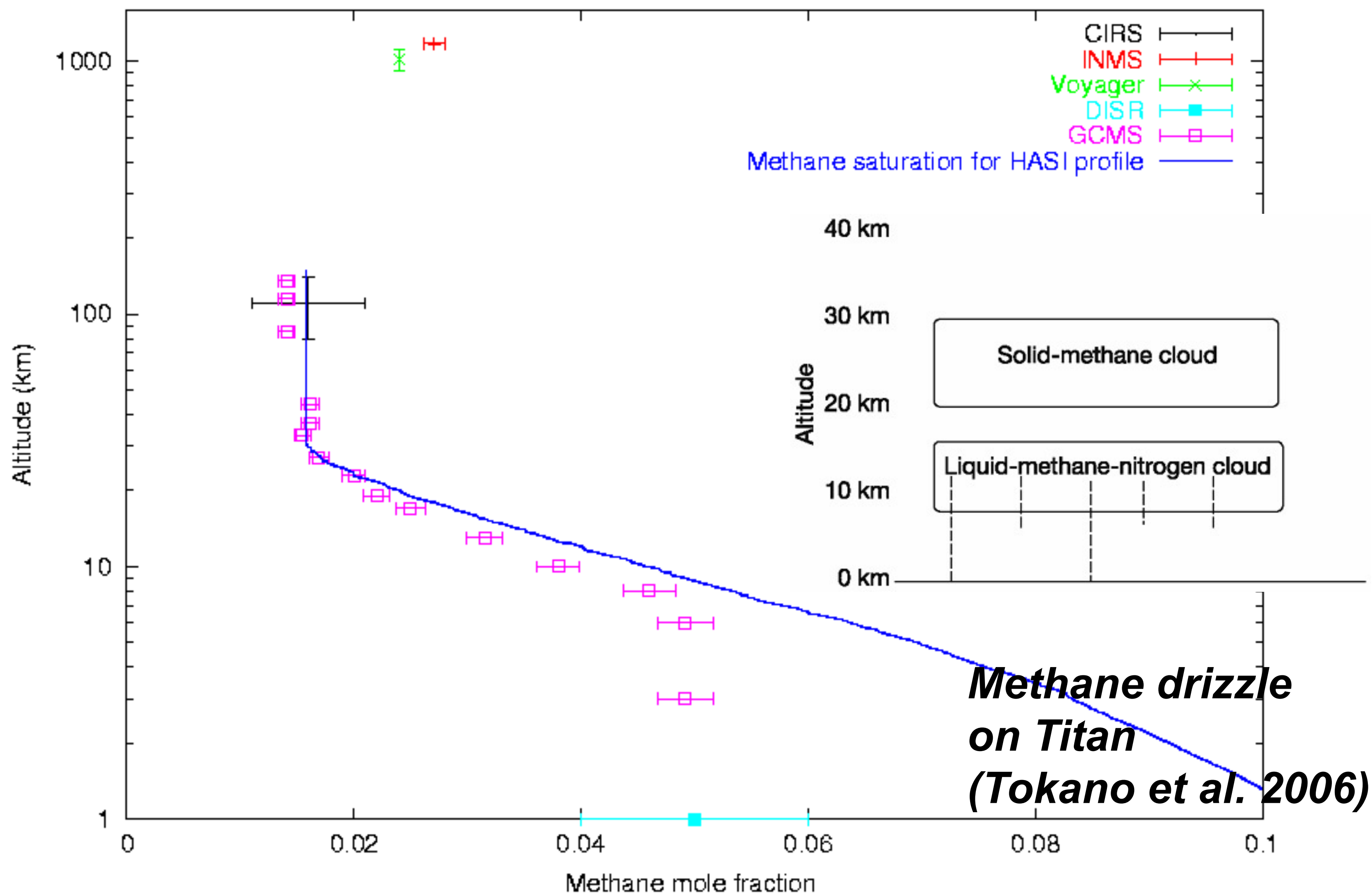
Tentative identification





hv
unit=10^-15 g cm^-2 s^-1
tholin=50
thermopause
thermosphere
homogeneous=1~10
adsorption=100
hv
mesosphere
stratopause
stratosphere
troposphere
surface

In situ measurements: methane profile and meteorology in Titan's atmosphere from Huygens



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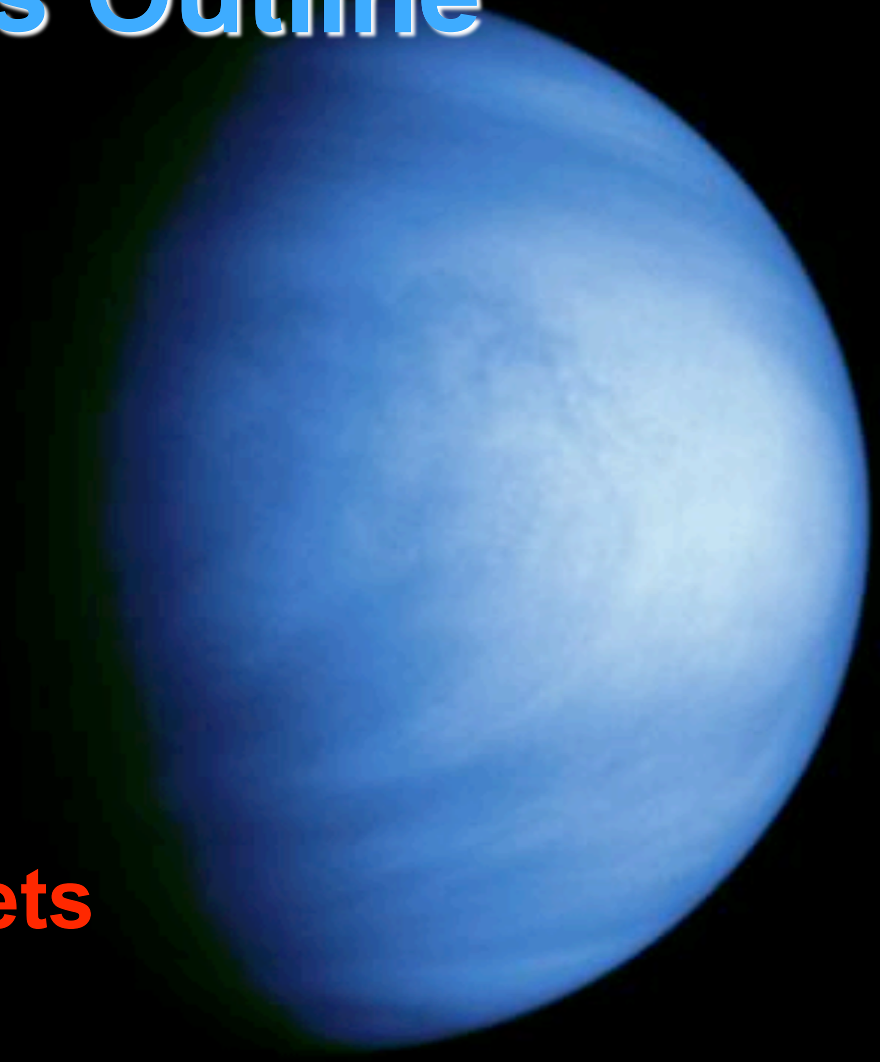
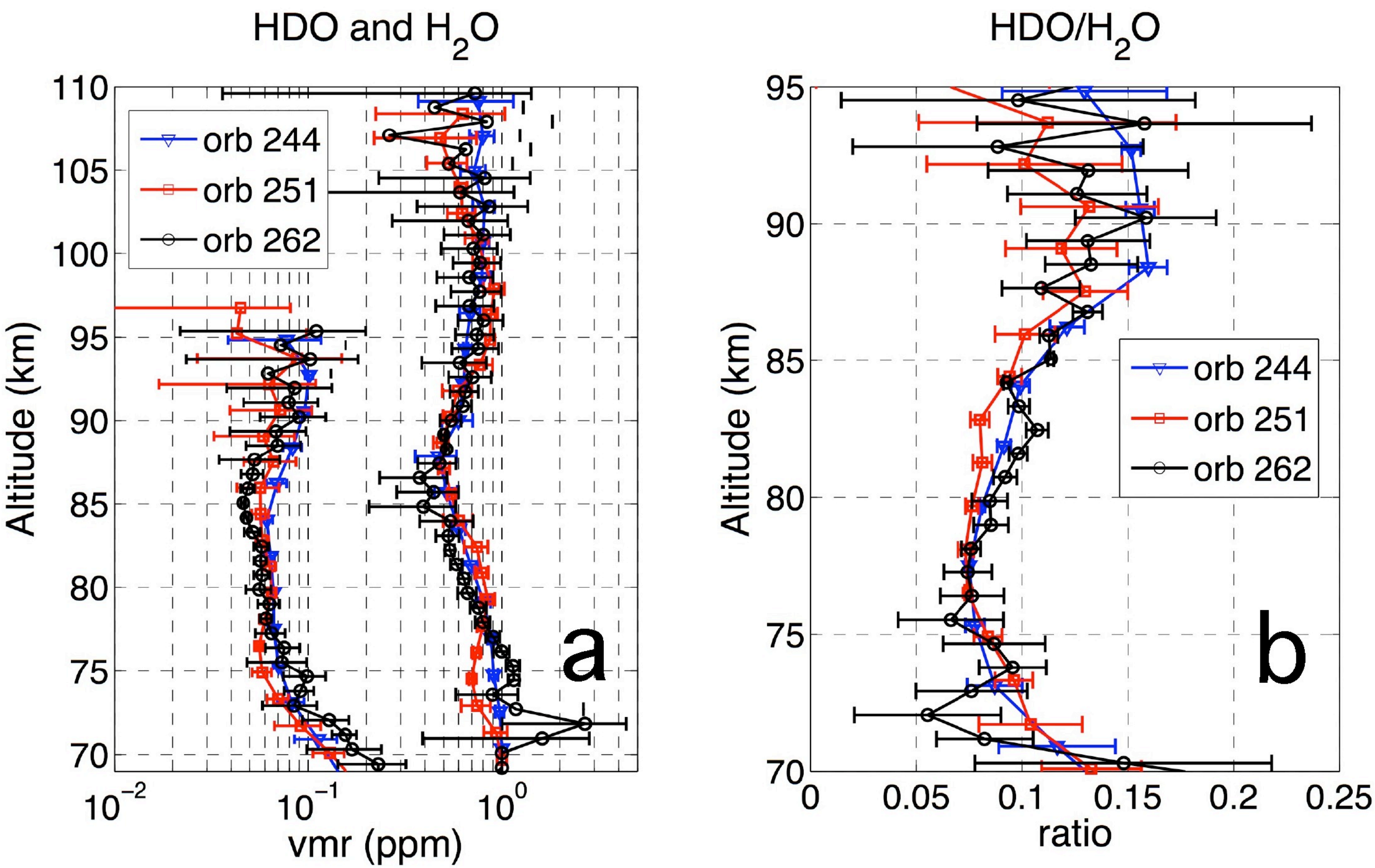


$$\left(\frac{D}{H}\right)_{Mars} = 5 \times \left(\frac{D}{H}\right)_{Earth}$$

$$\frac{D}{H}(t) = \frac{D}{H}(0)\left[\frac{H(0)}{H(t)}\right]^{1-f}$$



HDO and H_2O
orb 244
orb 251
orb 262
a
Altitude (km)
vmr (ppm)
110
105
100
95
90
85
80
75
70
10^{-2}
10^{-1}
10^{0}
HDO/H_2O
b
ratio
0
0.05
0.1
0.15
0.2
0.25

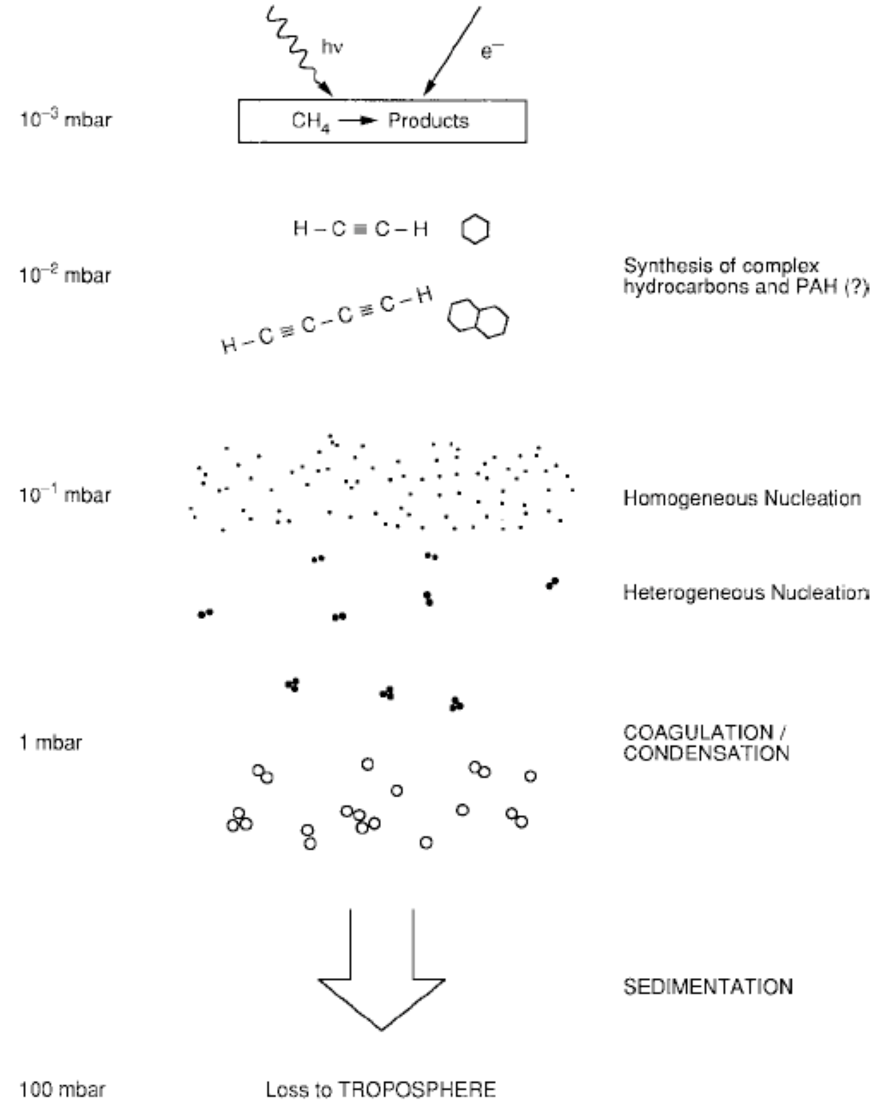
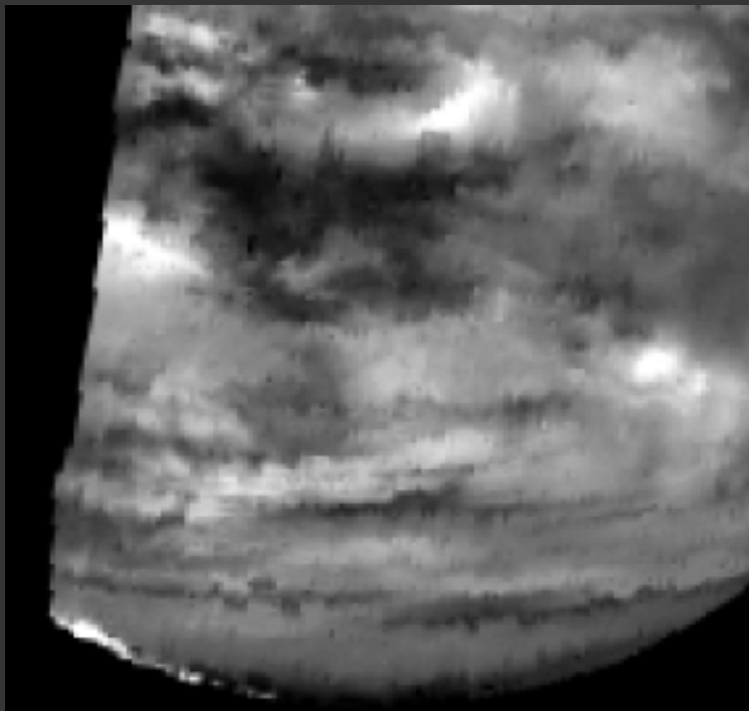


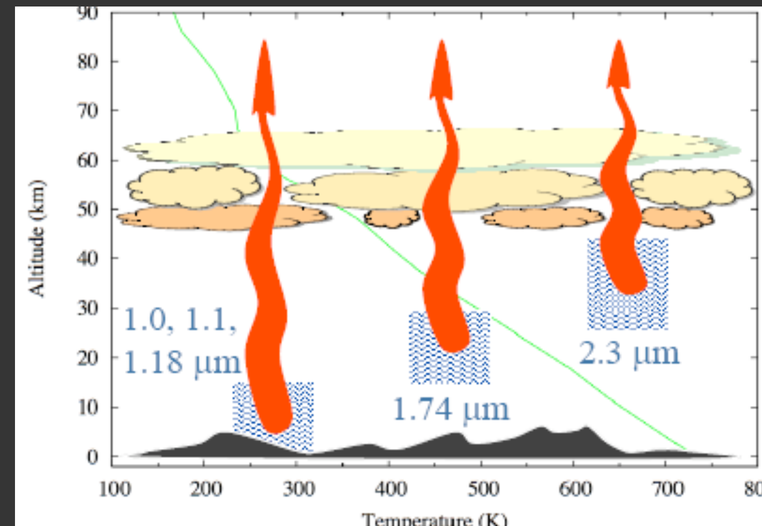
FIG. 1. Schematic diagram of physical processes included in the coupled chemical–aerosol microphysical model.

[Friedson *et al.*, Icarus, 2002]

Probing below Venus' clouds

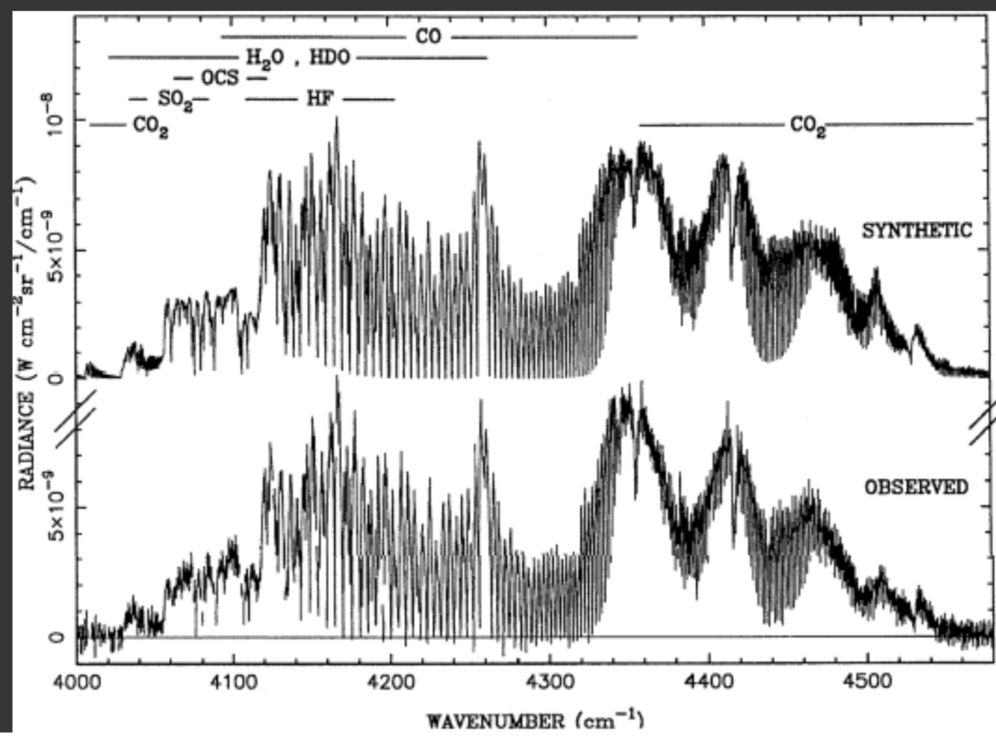


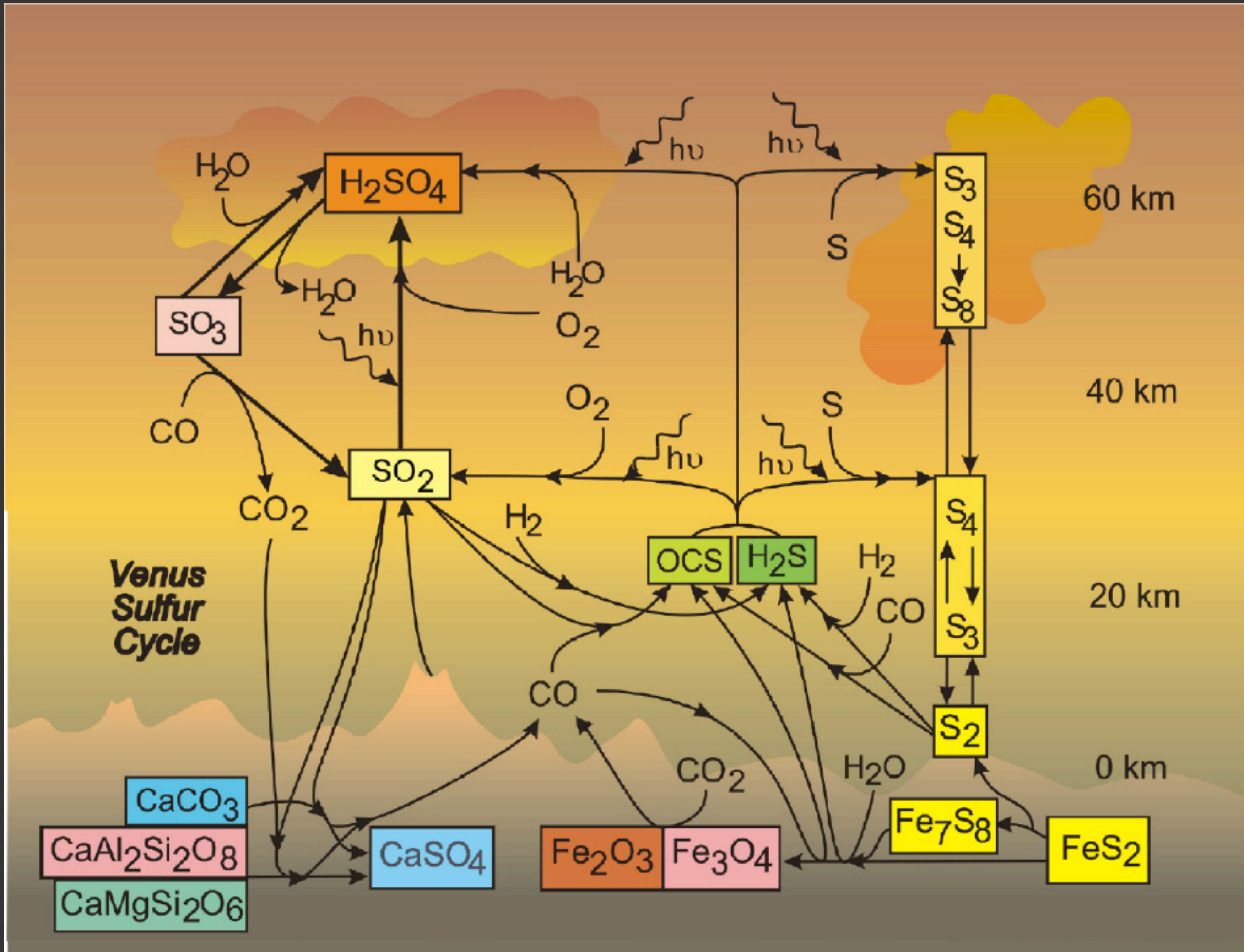
H_3^+ on Jupiter
FTS/CFHT, R= 25000
Bézard et al. 1989



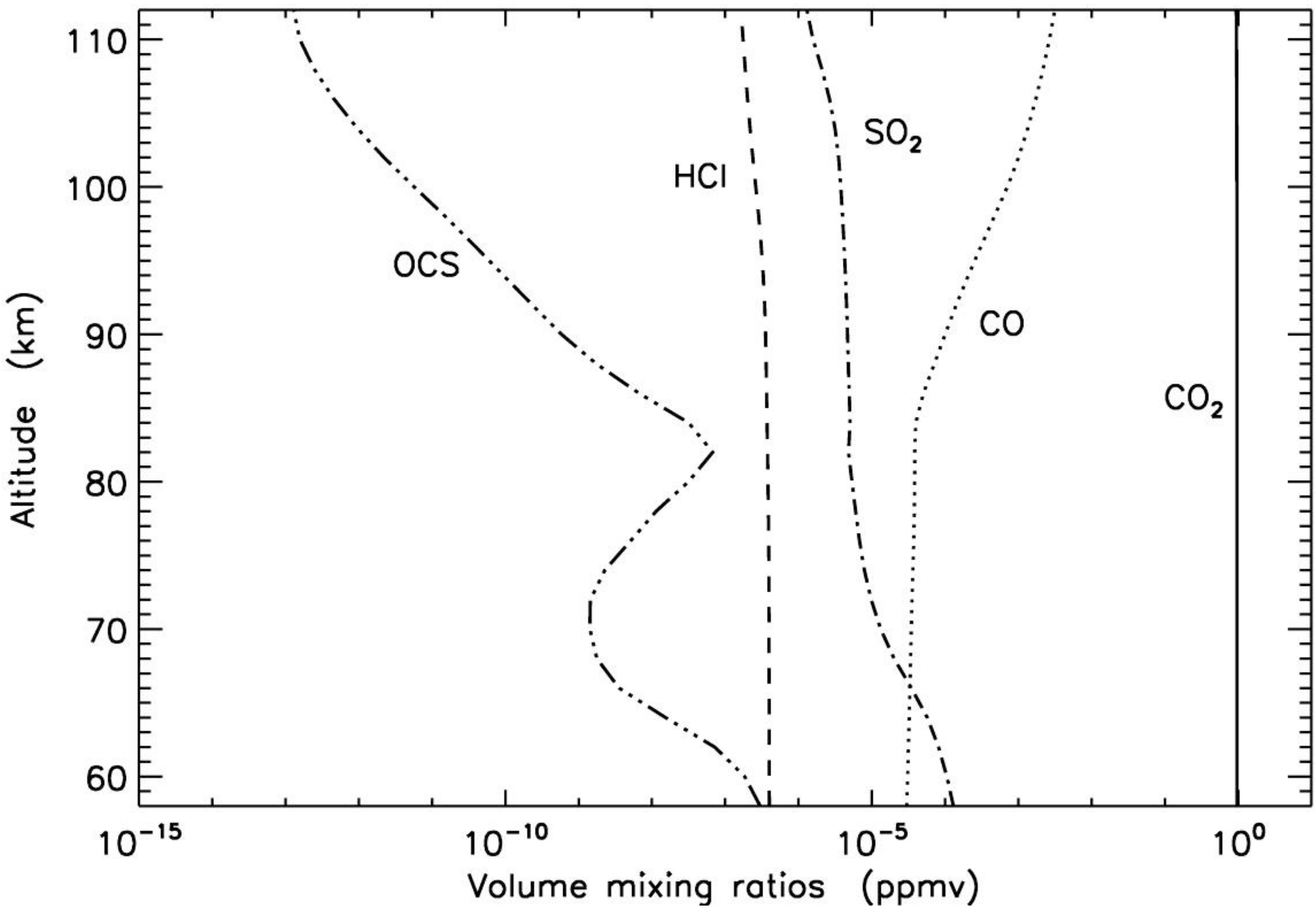
The uppermost clouds form a curtain and by day reflect sunlight back to dazzle us. By night, however, we become voyeurs able to peep into the backlit room behind

D. Allen, Icarus, 1987

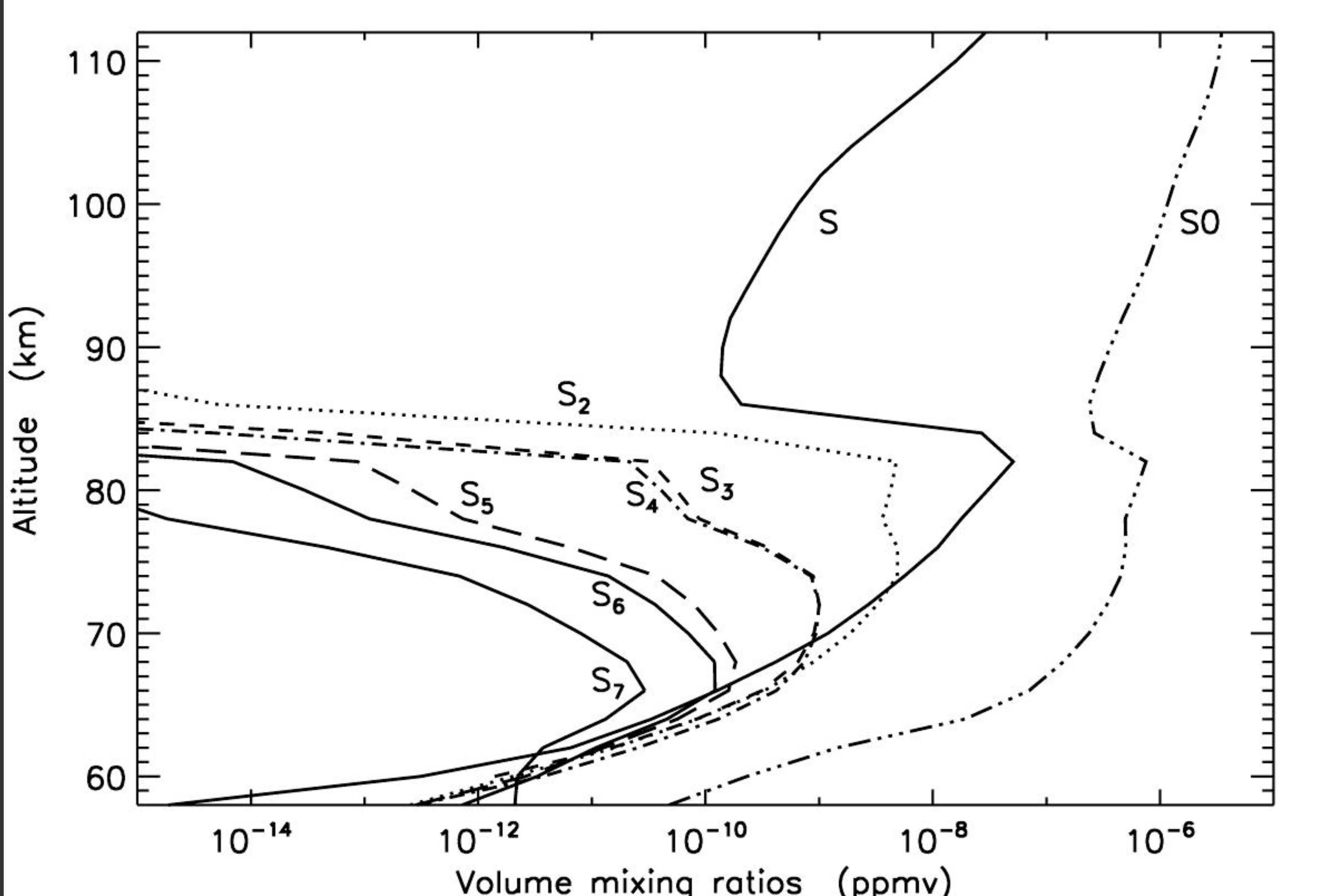




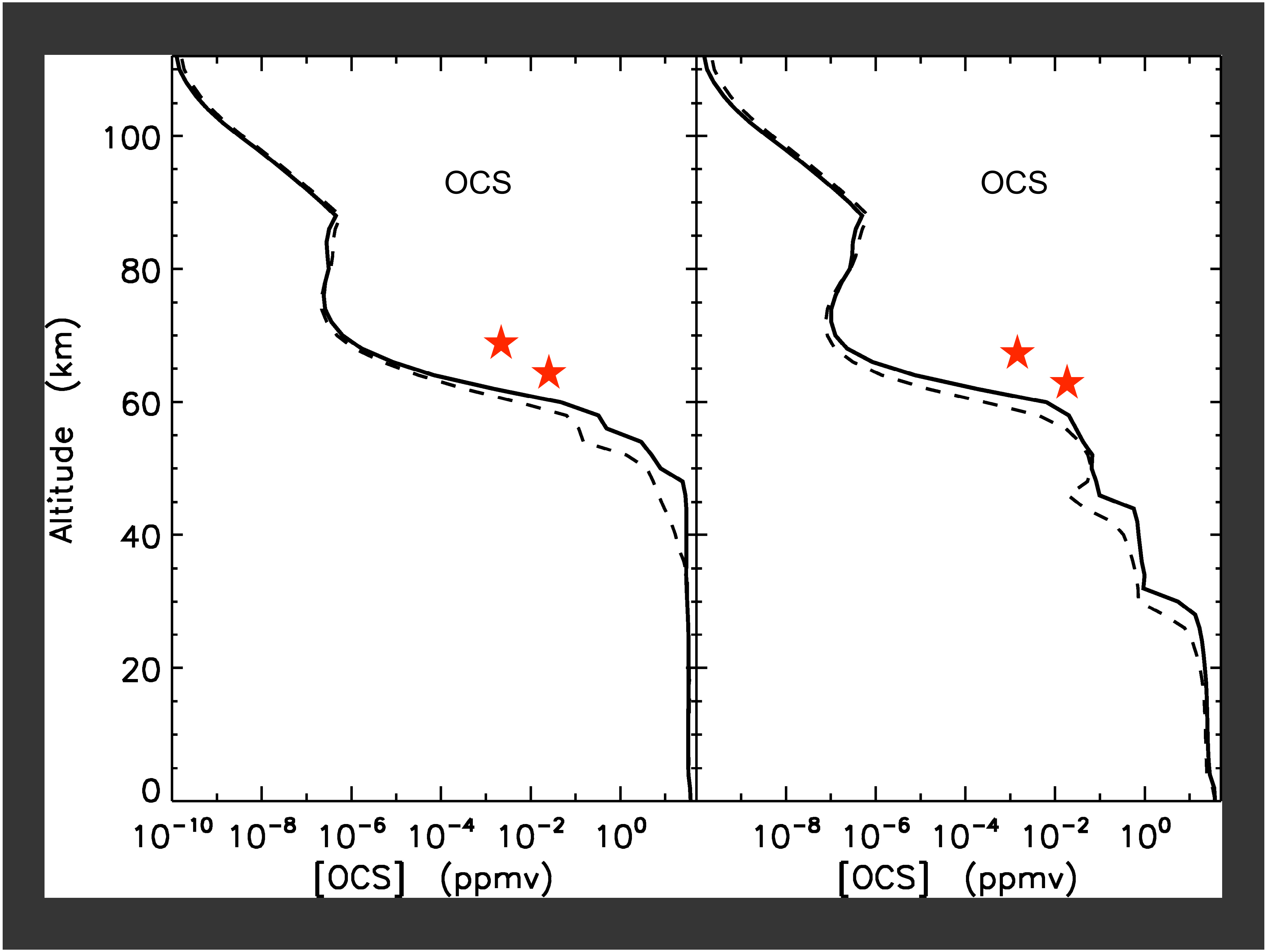
Venus
Sulfur
Cycle
H2SO4
H2O
SO3
H2O
hυ
H2O
O2
hυ
hυ
S
S3
S4
S8
60 km
40 km
CO
O2
S
SO2
hυ
hυ
CO2
H2
OCS
H2S
H2
S4
S3
CO
20 km
CO
S2
0 km
CO2
H2O
CaCO3
CaAl2Si2O8
CaMgSi2O6
CaSO4
Fe2O3
Fe3O4
Fe7S8
FeS2



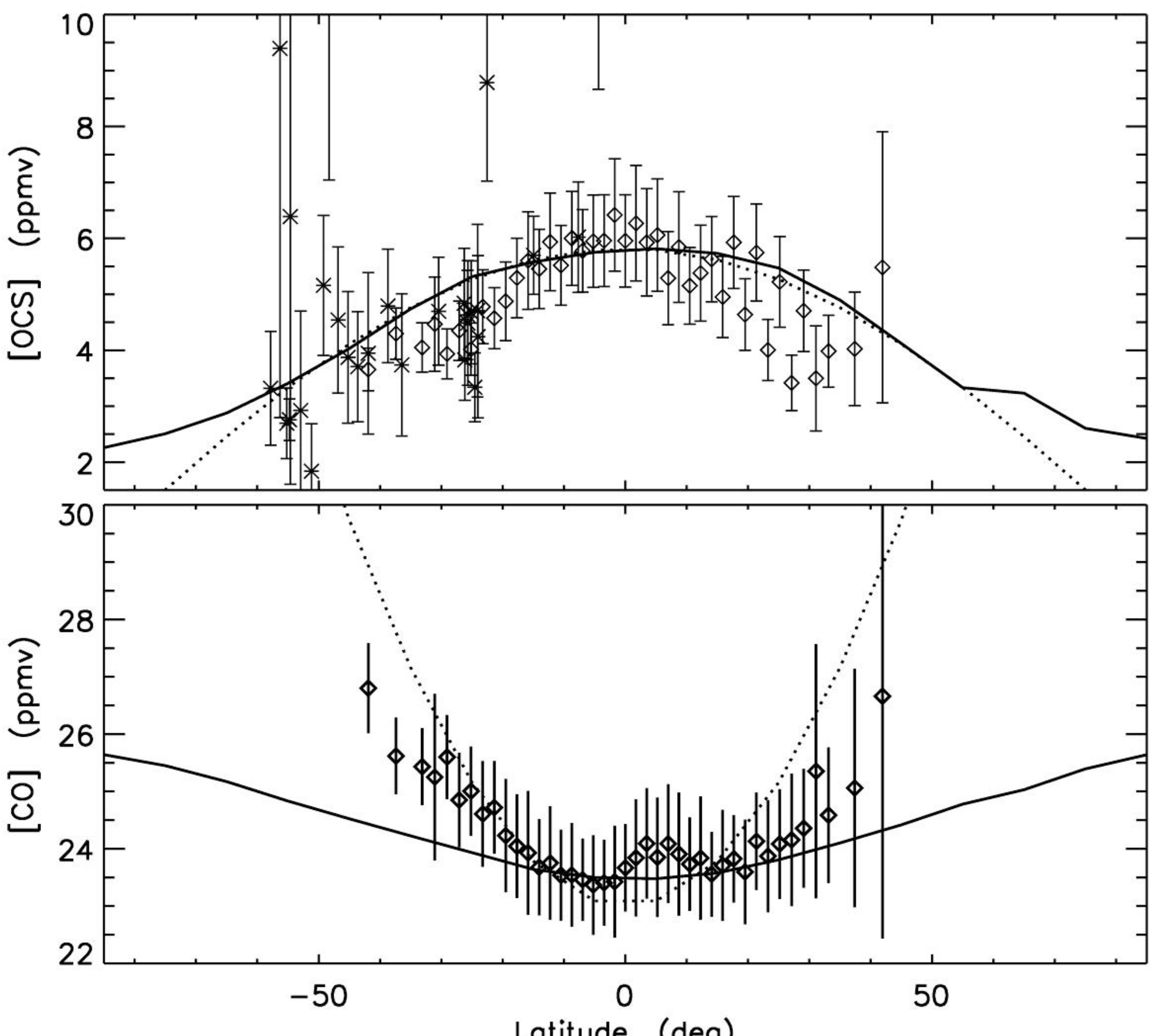
110
100
90
80
70
60
Altitude (km)
OCS
HCl
SO_2
CO
CO_2
10^{-15}
10^{-10}
10^{-5}
10^{0}
Volume mixing ratios (ppmv)



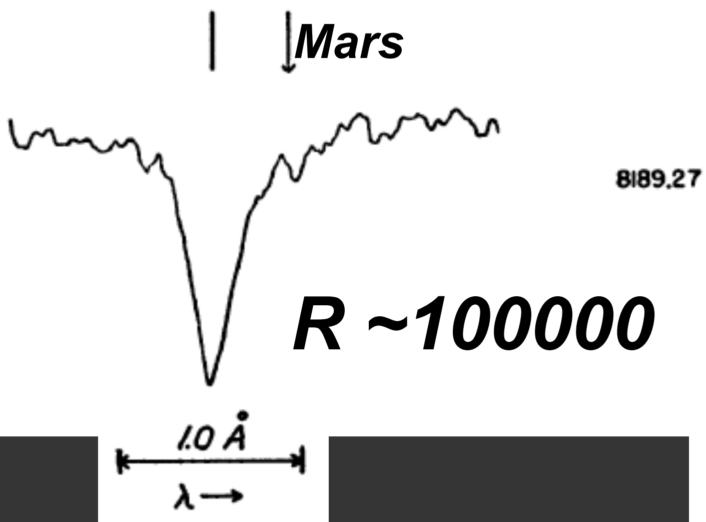
110
100
90
80
70
60
Altitude (km)
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
Volume mixing ratios (ppmv)
S
S0
S_2
S_3
S_4
S_5
S_6
S_7



OCS
OCS
Altitude (km)
0
20
40
60
80
100
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
[OCS] (ppmv)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
[OCS] (ppmv)


10
8
6
4
2
[OCS] (ppmv)
30
28
26
24
22
[CO] (ppmv)
−50
0
50
Latitude (deg)

Mars: discovery of atmospheric water in 1963

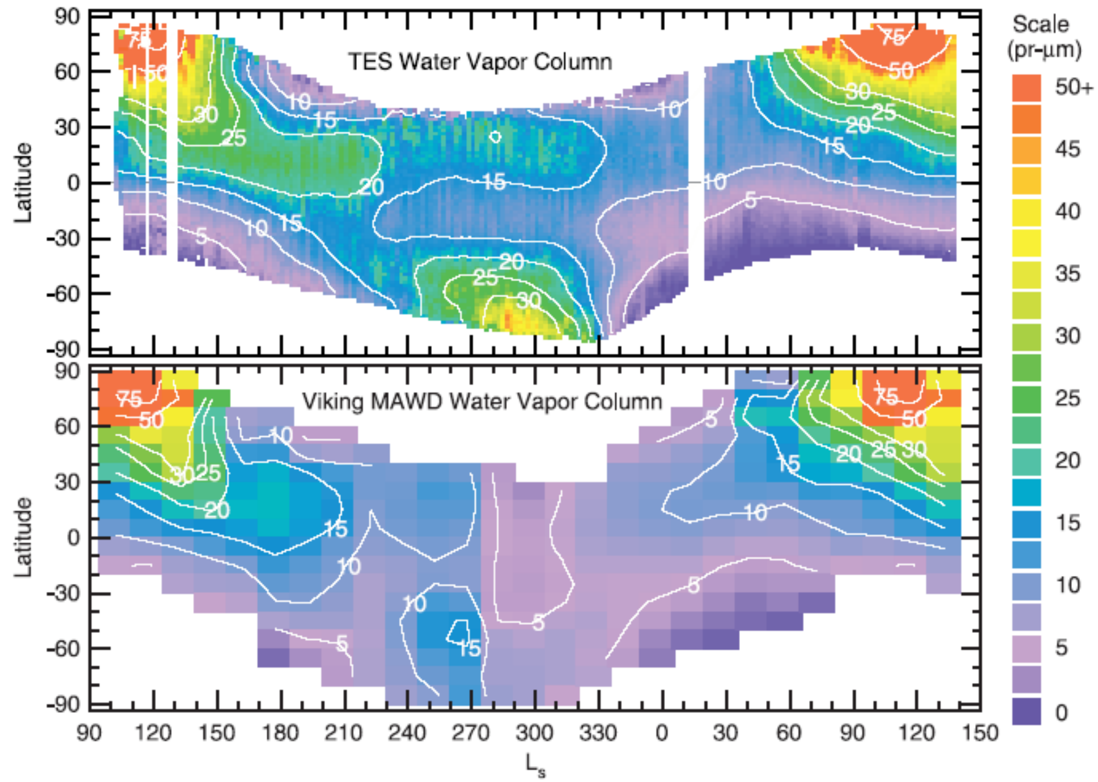


R ~100000

Detection of H_2O on Mars (Spinrad et al. 1963) at 0.82 micron:

"Watershed" discovery

Water cycle on Mars

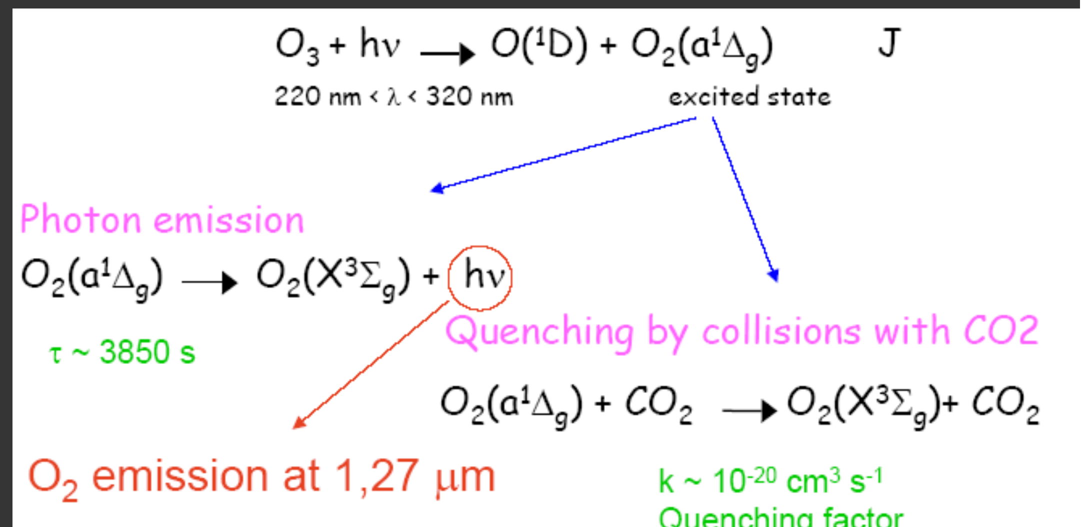


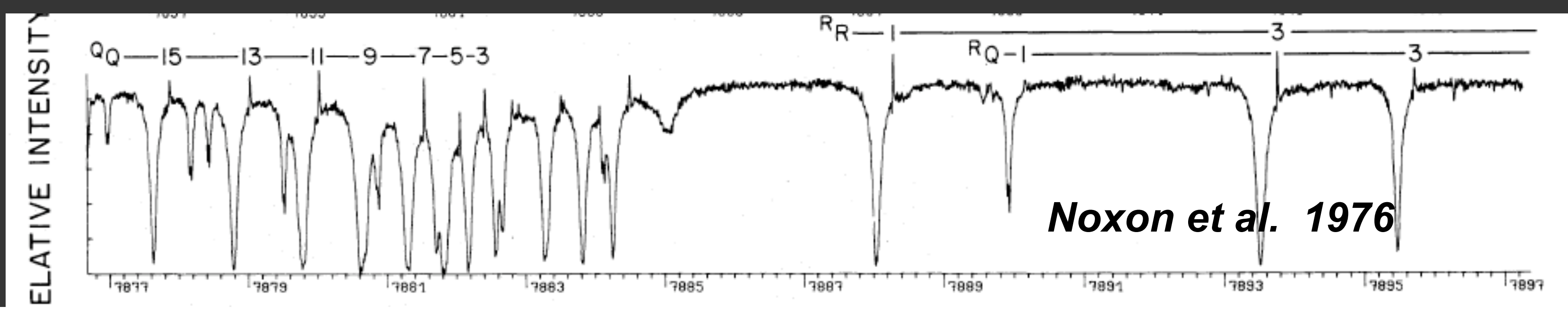
Mars' atmosphere: basic chemistry

** Detection of CO (1968) O_3 (1971), and O_2 (1972)*

** Detection of O_2 1.27 emission in 1976 → tracer of ozone (and not vice versa!)*

*$CO_2 + h\nu \rightarrow CO + O$
*$O + O + M \rightarrow O_2$
*$O_2 + O + M \rightarrow O_3$
*$H_2O + h\nu \rightarrow OH + H$
*$CO + OH \rightarrow CO_2 + H$
(stability of atmosphere)
*$OH \rightarrow HO_2 \rightarrow H_2O_2$
(not detected before 2005)





Conclusions

A fundamental understanding of chemistry in planets has been achieved

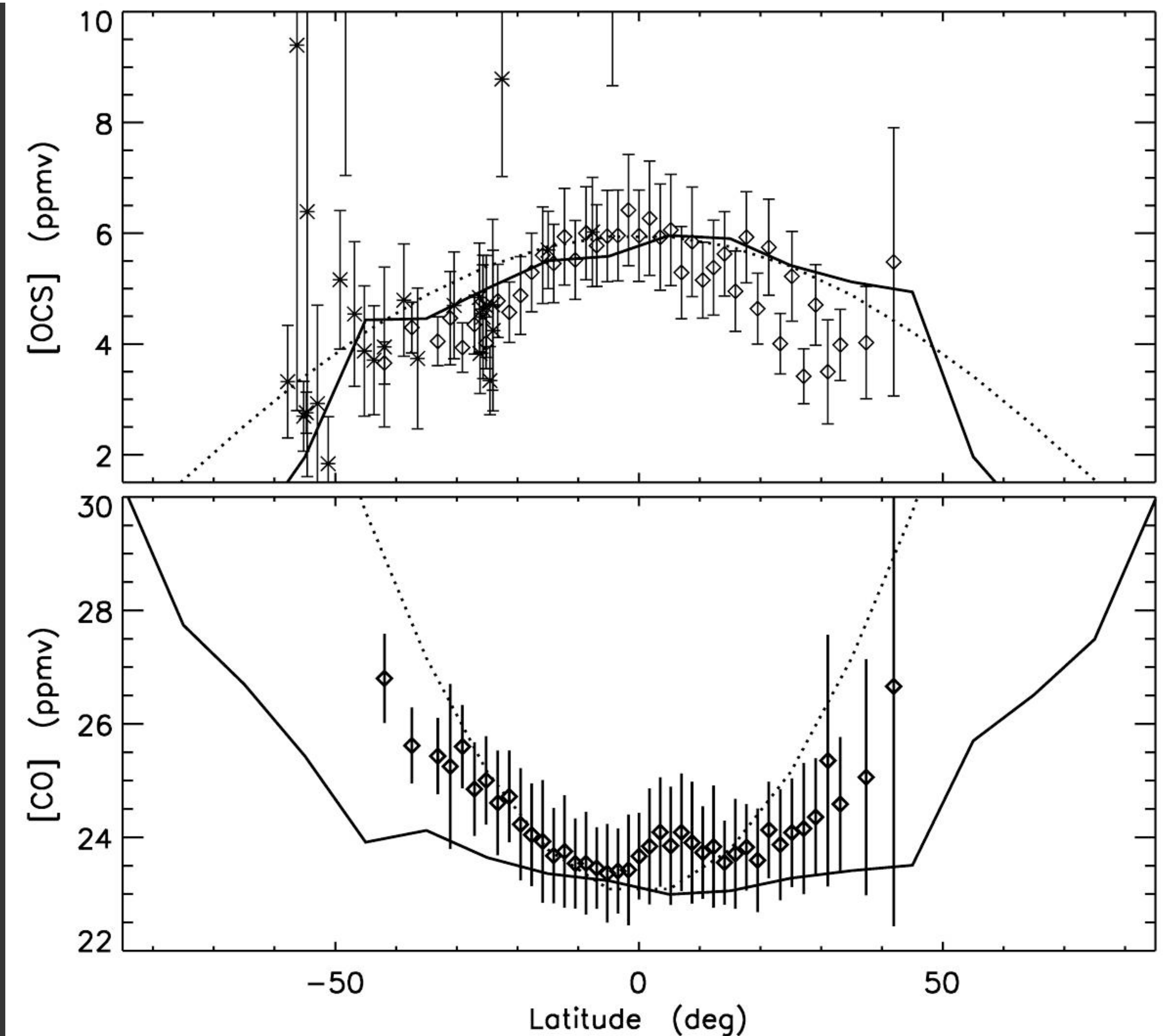
Common photochemistry: hundreds of molecules, thousands of reactions

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

Acknowledgements

- NASA and ESA
- Yung’s Group at Caltech
- Lellouch’s review 2008
- Meadows et al. 2008
- Yung and DeMore (1999) Book

Back-up slides



10
8
6
4
2
[OCS] (ppmv)
30
28
26
24
22
[CO] (ppmv)
−50
0
50
Latitude (deg)