Table 4.1 Basic atmospheric parameters for the giant planets.

Parameter	Jupiter	Saturn	Uranus	Neptune	References
Mean heliocentric distance (AU)	5.203	9.543	19.19	30.07	1
Geometric albedo ($A_{0,v}$)	0.52	0.47	0.51	0.41	1
Geometric albedo ($A_{0,ir}$)	0.274 ± 0.013	0.242 ± 0.012	0.208 ± 0.048	0.25 ± 0.02	3
Bond albedo	0.343 ± 0.032	0.342 ± 0.030	0.290 ± 0.051	0.31 ± 0.04	3
Phase integral	1.25 ± 0.10	1.42 ± 0.10	1.40 ± 0.14	1.25 ± 0.10	3
Effective temperature (K)	124.4 ± 0.3	95.0 ± 0.4	59.1 ± 0.3	59.3 ± 0.8	2
Equilibrium temperature (K)	110	81	58	46	Calc.[b]
Temperature ($P = 1$ bar) (K)	165.0	134.8	76.4	71.5	5
Tropopause temperature (K)	111	82	53	52	5
Mesosphere temperature (K)	160–170	150	140–150	140–150	4
Exobase temperature (K)	900–1300	800	750	750	6, 7
Tropopause pressure (mbar)	140	65	110	140	5
Scale height (at 1 bar) (km)	24	47	25	23	Calc.[c]
Adiabatic lapse rate (K/km)	1.9	0.84	0.85	0.86	4
Energy balance[a]	1.67 ± 0.09	1.78 ± 0.09	1.06 ± 0.08	2.61 ± 0.28	2

[a] Ratio (energy radiated into space)/(solar energy absorbed).

[b] Calculated with eq. (3.17) and $\epsilon = 1$.

[c] Calculated with eq. (4.2).

1: Yoder (1995). 2: Hubbard *et al.* (1995). 3: Conrath *et al.* (1989b). 4: Chamberlain and Hunten (1987). 5: Lindal (1992). 6: Atreya (1986). 7: Bishop *et al.* (1995).

Table 4.2 Basic atmospheric parameters for Venus, Earth, Mars and Titan.

Parameter	Venus	Earth	Mars	Titan	Reference
Mean heliocentric distance (AU)	0.723	1.000	1.524	9.543	1
Geometric albedo $A_{0,v}$	0.84	0.367	0.15	0.21	1, 3, 4
Bond albedo	0.75	0.306	0.25	0.20	1, 2, 3, 4, 5
Surface temperature (K)	737	288	215	93.7	1, 2, 3
Equilibrium temperature (K)	232	255	210	85	Calc.[a]
Exobase[b] temperature (K)	270–320	800–1250	200–300	149	2, 6, 7
Surface pressure (bar)	92	1.013	0.00636	1.47	1, 2, 3
Scale height at surface (km)	16	8.5	11	20	Calc.[c]

[a] Calculated with eq. (3.17) and $\epsilon = 1$. The globally and wavelength averaged emissivity for Earth is 0.96–0.98.

[b] A range of values is given for Venus, Earth and Mars, appropriate for a range of solar (low to high) activities.

[c] Calculated with eq. (4.2).

1: Yoder (1995), and http://nssdc.gsfc.nasa.gov/planetary/. 2: Chamberlain and Hunten (1987). 3: Fulchignoni *et al.* (2005). 4: Moroz (1983). 5: Hunten *et al.* (1984). 6: Waite *et al.* (2005). 7: Forbes *et al.* (2008).

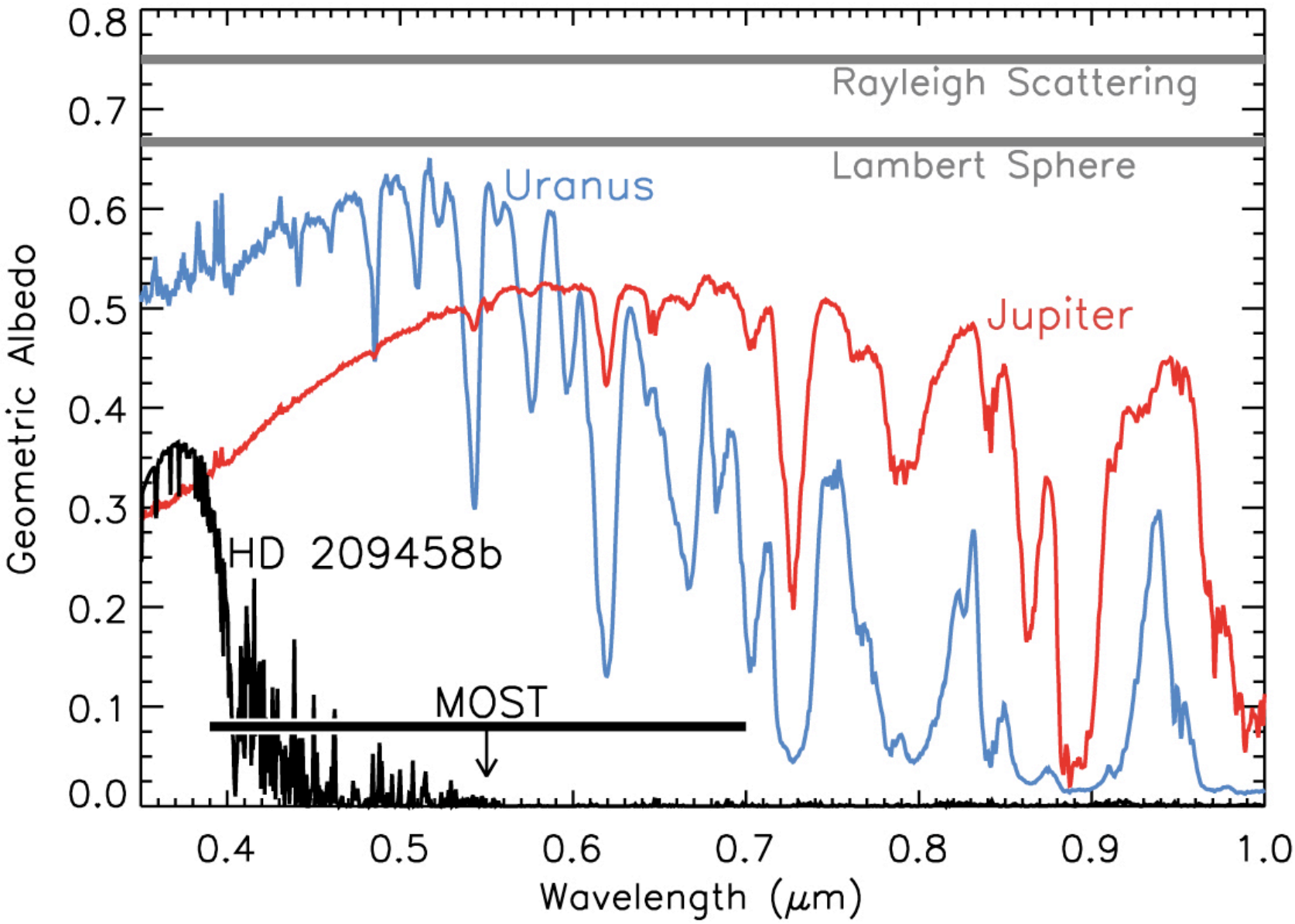
Table 4.3 Basic atmospheric parameters for Mercury, the Moon, Triton and Pluto.

Parameter	Mercury	Moon	Triton	Pluto	Reference
Mean heliocentric distance (AU)	0.387	1.000	30.069	39.48	1
Geometric albedo $A_{0,v}$	0.138	0.113	0.76	0.44–0.61	1, 2, 3, 5
Bond albedo	0.119	0.123	0.85	~0.3–0.7	1, 2, 3, 4, 5
Surface temperature (K)	100–725	277	38	~40–60	1, 2, 3, 5
Equilibrium temperature (K)	434	270	32	39	Calc.[a]
Exobase temperature (K)	600	270–320		58	4
Surface pressure (bar)	few $\times 10^{-15}$	3×10^{-15}	1.4×10^{-5}	1.5×10^{-5}	1, 2, 3, 4, 5
Scale height at surface (km)	13–95	65	14	33	Calc.[b]

[a] Calculated using eq. (3.17) and $\epsilon = 1$.

[b] Calculated using eq. (4.2).

1: Yoder (1995), and http://nssdc.gsfc.nasa.gov/planetary/. 2: Veverka *et al.* (1988). 3: Stern (2007). 4: Chamberlain and Hunten (1987). 5: McKinnon and Kirk (2007).


Rayleigh Scattering
Lambert Sphere
Uranus
Jupiter
HD 209458b
MOST
Geometric Albedo
Wavelength (μm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.4
0.5
0.6
0.7
0.8
0.9
1.0

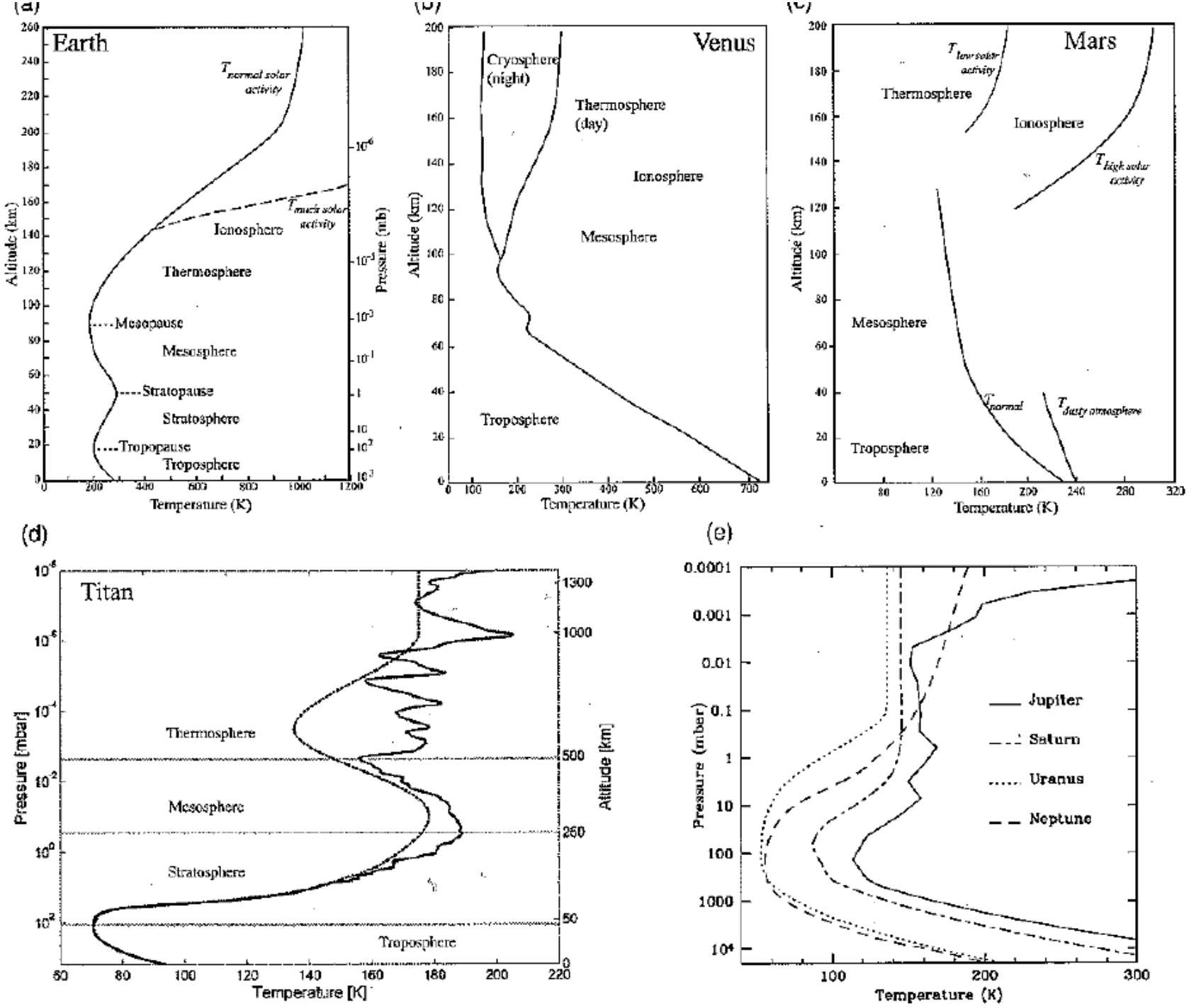

(a)
Earth
$T_{normal\ solar\ activity}$
$T_{much\ solar\ activity}$
Ionosphere
Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
Altitude (km)
Pressure (mb)
Temperature (K)
(b)
Venus
Cryosphere (night)
Thermosphere (day)
Ionosphere
Mesosphere
Troposphere
Altitude (km)
Temperature (K)
(c)
Mars
$T_{low\ solar\ activity}$
$T_{high\ solar\ activity}$
Thermosphere
Ionosphere
Mesosphere
T_{normal}
$T_{dusty\ atmosphere}$
Troposphere
Altitude (km)
Temperature (K)
(d)
Titan
Thermosphere
Mesosphere
Stratosphere
Troposphere
Pressure [mbar]
Altitude [km]
Temperature [K]
(e)
Jupiter
Saturn
Uranus
Neptune
Pressure (mbar)
Temperature (K)

TABLE 4.3 Atmospheric Composition of Earth, Venus, Mars and Titan.

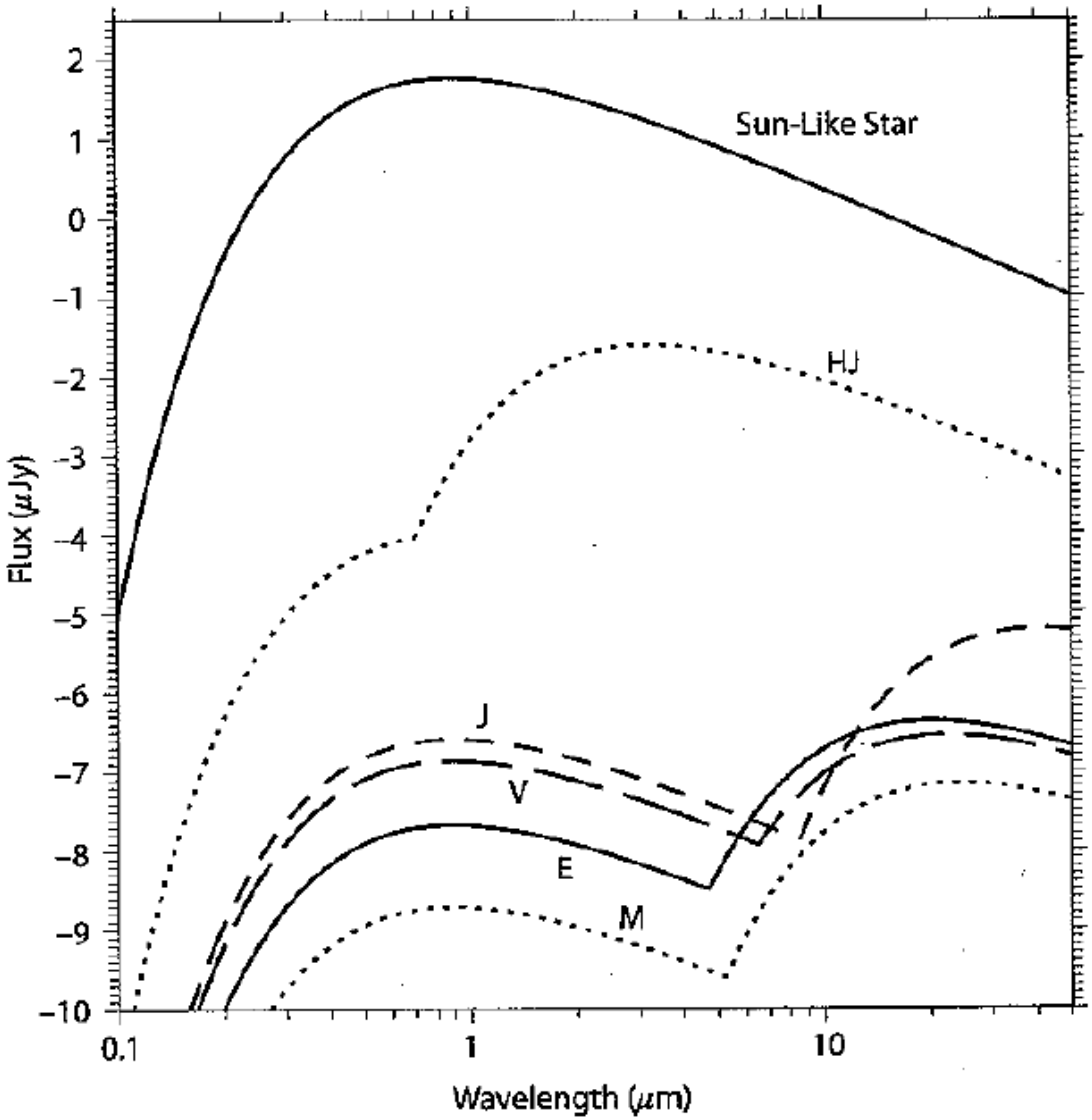
Constituent	Earth[a]	Venus	Mars	Titan	References
N_2	0.7808	0.035	0.027	0.90–0.97[b]	1, 2, 3, 4
O_2	0.2095	0–20 ppm	0.13 ppm		1, 2, 5
CO_2	345 ppm	0.965	0.953	10 ppb	1, 2, 4
CH_4	3 ppm			0.005–0.04	2, 3, 4, 6
H_2O	<0.03[c]	50 ppm	<100 ppm[c]	0.4 ppb	1, 7, 5
Ar	0.009	70 ppm	0.016	0.0–0.06[b]	2, 3, 4
CO	0.2 ppm	50 ppm	700 ppm	10 ppm	2
O_3	10 ppm		0.01 ppm		1, 2
HCN				0.1 ppm	4
HC_3N				10–100 ppb	8
C_2H_2	8.7 ppb			2 ppm	4, 9
C_2H_6	13.6 ppb			10 ppm	4, 9
C_3H_8	18.7 ppb			0.5 ppm	4, 9
C_2H_4	11.2 ppb			0.1 ppm	4, 9
C_4H_2				1 ppb	4
CH_3C_2H				30 ppb	8
C_2N_2				10–100 ppb	8
NO	<0.01 ppm		3 ppm		2
N_2O	0.35 ppm				1
SO_2	< 2[c] ppb	60 ppm			9, 10
H_2	0.5 ppm	?	10 ppm	0.002	2, 4
HCl		0.5 ppm			5
HF		5 ppb			5
COS		250 ppb			5
He	5 ppm	12 ppm			2
Ne	18 ppm	7 ppm	2.5 ppm	< 0.01	2, 8
Kr	1 ppm	0.2 ppm	0.3 ppm		2, 5
Xe	0.09 ppm	<0.1 ppm	0.08 ppm		2

All numbers are given in volume mixing ratios, as a fraction or ppm (part per million) or ppb (part per billion).

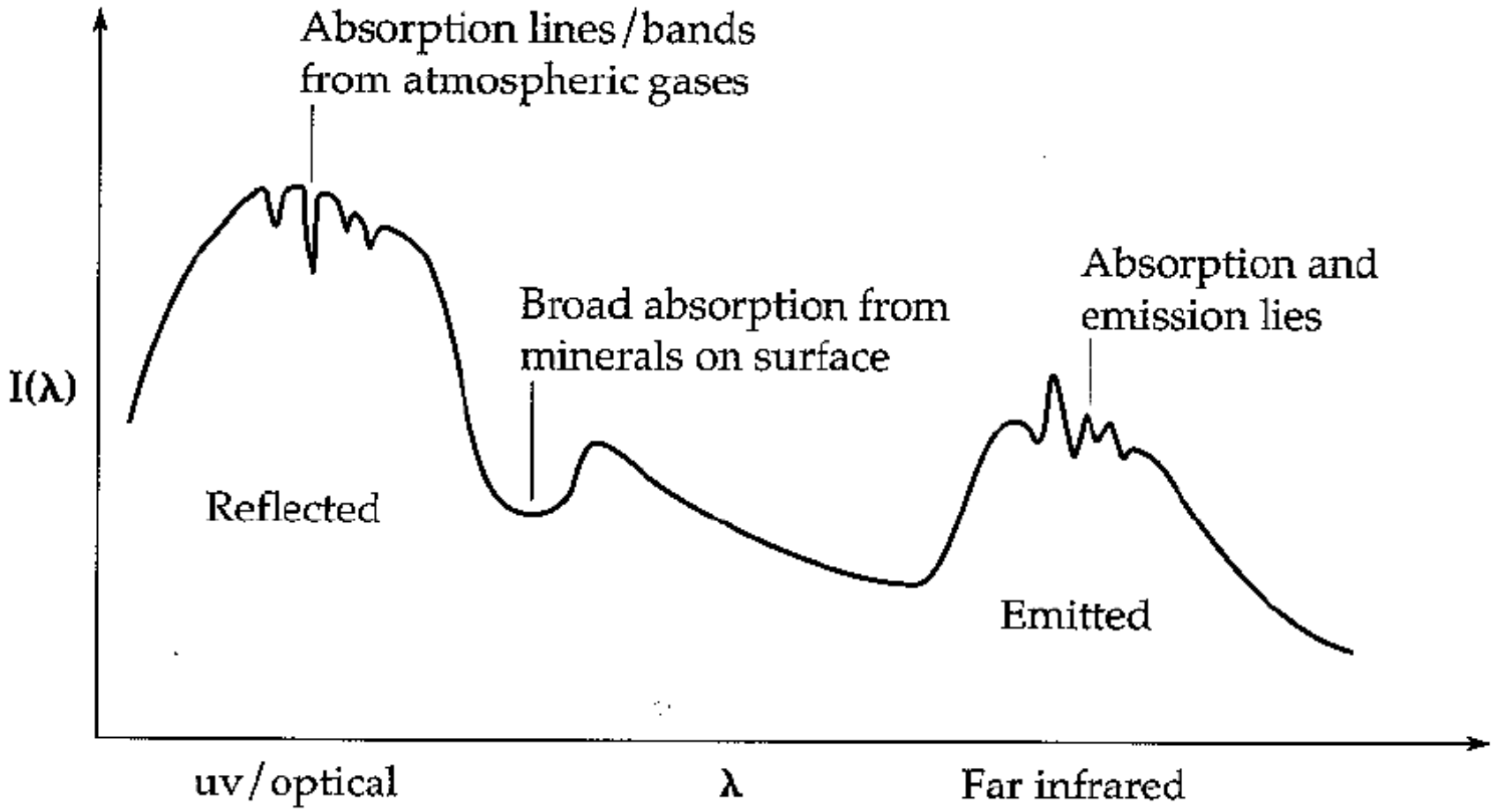
TABLE 4.5 Atmospheric Composition of the Giant Planets.

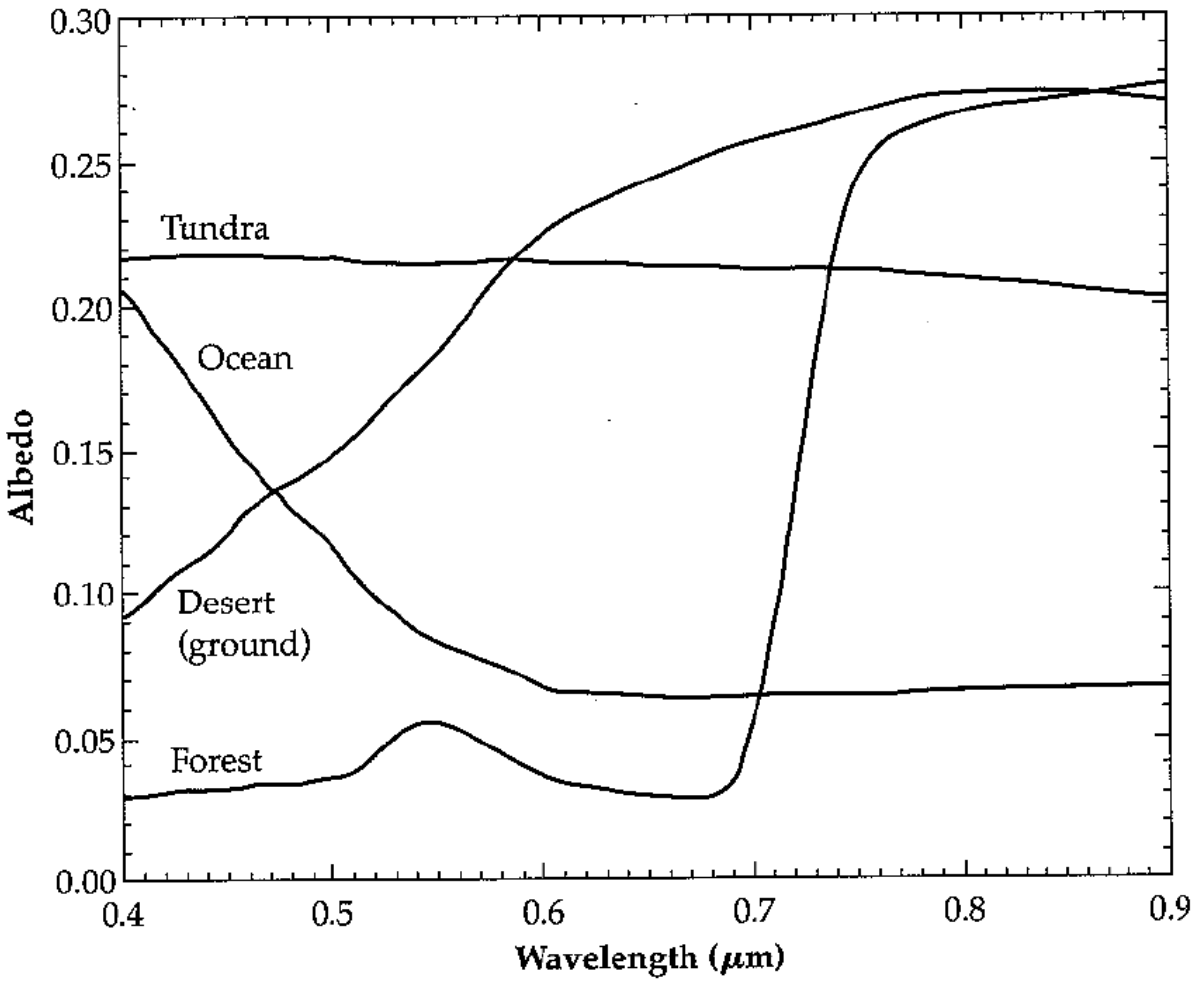
Gas	Element	Sun	Jupiter	Saturn	Uranus	Neptune	References
Major gases							
H_2	H	0.835	0.864 ± 0.006	0.963 ± 0.03	0.85 ± 0.05	0.85 ± 0.05	1, 2, 3, 4
He	He	0.195	0.157 ± 0.004	0.034 ± 0.03	0.18 ± 0.05	0.18 ± 0.05	1, 2, 3, 4
Condensable gases							
H_2O	O	1.70×10^{-3}	2.6×10^{-3}	$>1.70 \times 10^{-3}$?	$>1.70 \times 10^{-3}$?	$>1.70 \times 10^{-3}$?	5, 6
	in stratosphere		$(2–20) \times 10^{-9}$	detection	detection	detection	6, 7
	Galileo, 19 bar		$(6 \pm 3) \times 10^{-4}$				6
CH_4	C	7.94×10^{-4}	$(2.1 \pm 0.2) \times 10^{-3}$	$(4.5 \pm 2.2) \times 10^{-3}$	0.024 ± 0.01	0.035 ± 0.010	4, 8, 9, 10
NH_3	N	2.24×10^{-4}	$(2.60 \pm 0.3) \times 10^{-4}$	$(5 \pm 1) \times 10^{-4}$	$< 2.2 \times 10^{-4}$	$< 2.2 \times 10^{-4}$	6, 8
	Galileo, 8 bar		$(8 \pm 1) \times 10^{-4}$				6
H_2S	S	3.70×10^{-5}	$(2.22 \pm 0.4) \times 10^{-4}$?	$(4 \pm 1) \times 10^{-4}$?	3.7×10^{-4}?	1×10^{-3}?	6, 8
	Galileo, 16 bar		$(7.7 \pm 0.5) \times 10^{-5}$				6
Noble gases							
^{20}Ne	Ne	2.3×10^{-4}	$(2.30 \pm 0.2) \times 10^{-5}$				6
^{36}Ar	Ar	6.1×10^{-6}	$(1.5 \pm 0.3) \times 10^{-5}$				6
^{84}Kr	Kr	1.84×10^{-9}	$(5.0 \pm 1) \times 10^{-9}$				6
^{132}Xe	Xe	8.9×10^{-11}	$(2.3 \pm 0.5) \times 10^{-10}$				6
Disequilibrium species							
PH_3	P	7.50×10^{-7}	6×10^{-7}	$(7 \pm 3) \times 10^{-6}$			6
GeH_4			$(7 \pm 2) \times 10^{-10}$	$(4 \pm 4) \times 10^{-10}$			6
AsH_3			$(2.2 \pm 1.1) \times 10^{-10}$	$(3 \pm 1) \times 10^{-9}$			6
CO			$\sim 2 \times 10^{-9}$	$(1 \pm 0.3) \times 10^{-9}$	$< 1 \times 10^{-8}$	1×10^{-6}	6, 11
CO_2			detection	3×10^{-10}		detection	6, 7
HCN					$< 1 \times 10^{-10}$	1×10^{-9}	11
Photochemical species							
C_2H_2			$(3–10) \times 10^{-8}$	$(2.1 \pm 1.4) \times 10^{-7}$	1×10^{-8}	6×10^{-8}	6, 11
C_2H_4			$(7 \pm 3) \times 10^{-9}$			detection	6, 12
C_2H_6			$(1–5) \times 10^{-6}$	$(3 \pm 1) \times 10^{-6}$	$< 1 \times 10^{-8}$	2×10^{-6}	6, 11
C_3H_4			$(2.5 \pm 2) \times 10^{-9}$				6
C_3H_8			detection				6
C_4H_2			9×10^{-11}	9×10^{-11}			6, 13
C_6H_6			$(2 \pm 2) \times 10^{-9}$	2.5×10^{-10}			6
CH_3C_2H				6×10^{-10}			13

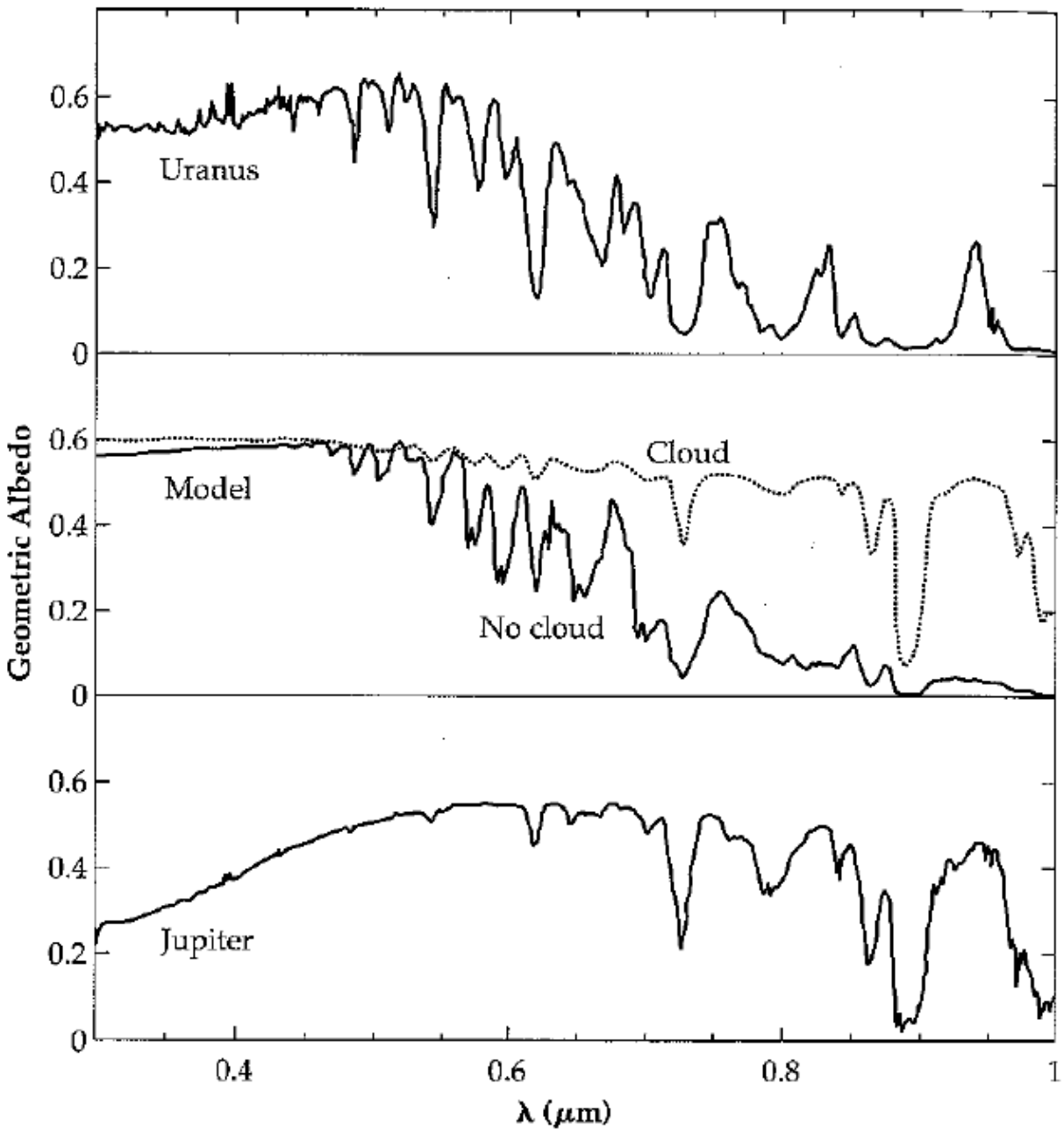
The elements O, C, N, S and P are in the form of H_2O, CH_4, NH_3, H_2S and PH_3 on the giant planets, respectively.
The abundance of H_2S is inferred rather than measured directly, except for the second value for Jupiter, which was measured directly by the Galileo probe.

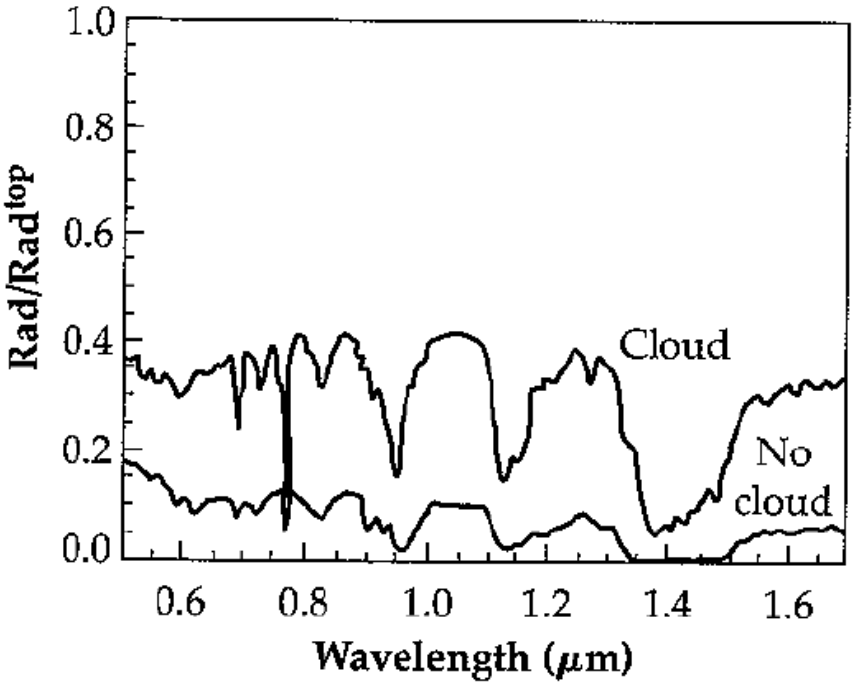


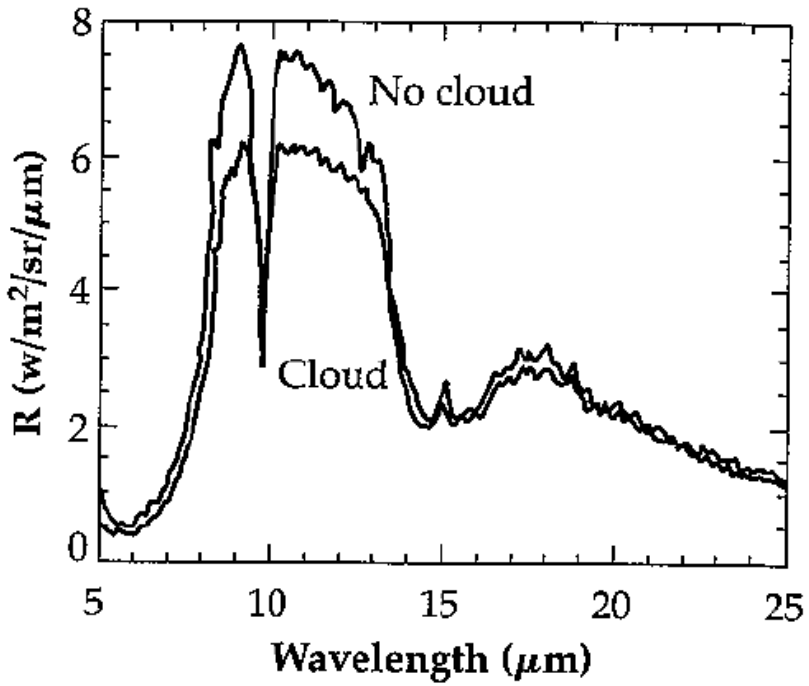
The approximate spectra (in units of 10^{-26} W m^{-2} Hz^{-1}) of some solar system bodies as seen from a distance of 33 light years. The Sun is represented by a black body of 5750 K. The planets Jupiter, Venus, Earth, and Mars are shown and are labeled with their first initial. A representative hot Jupiter exoplanet is also shown.

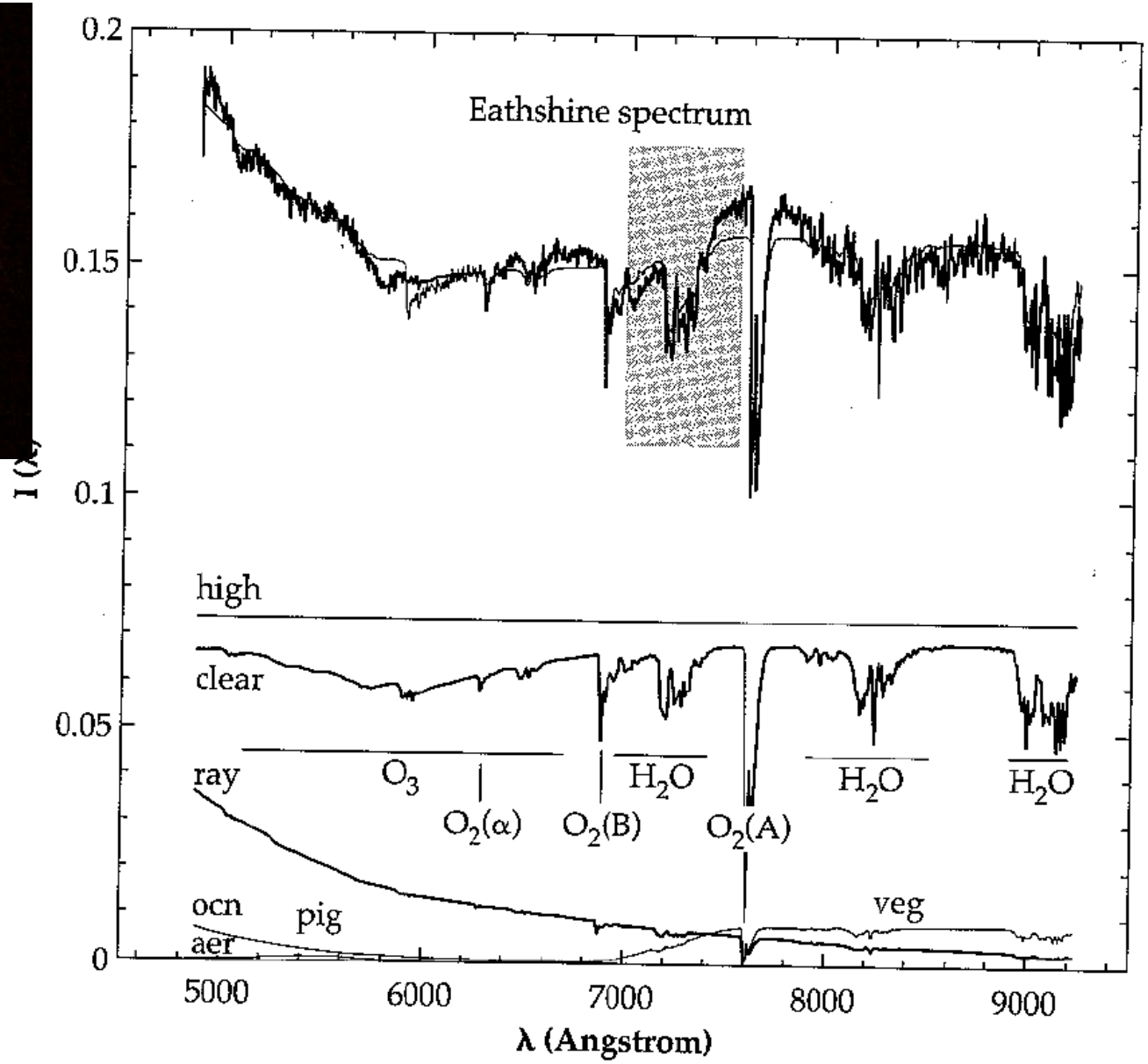

Absorption lines/bands
from atmospheric gases
Broad absorption from
minerals on surface
Absorption and
emission lies
I(λ)
Reflected
Emitted
uv/optical
λ
Far infrared


0.30
0.25
0.20
0.15
0.10
0.05
0.00
Albedo
Tundra
Ocean
Desert
(ground)
Forest
0.4
0.5
0.6
0.7
0.8
0.9
Wavelength (μm)


Uranus
Model
Cloud
No cloud
Jupiter
Geometric Albedo
0.6
0.4
0.2
0
0.4
0.6
0.8
1
λ (μm)


1.0
0.8
0.6
0.4
0.2
0.0
Rad/Rad^top
Cloud
No
cloud
0.6
0.8
1.0
1.2
1.4
1.6
Wavelength (μm)


8
6
4
2
0
R (w/m²/sr/μm)
No cloud
Cloud
5
10
15
20
25
Wavelength (μm)


Eathshine spectrum
high
clear
ray
O3
O2(α)
O2(B)
O2(A)
H2O
H2O
H2O
ocn
aer
pig
veg
0.2
0.15
0.1
0.05
0
5000
6000
7000
8000
9000
λ (Angstrom)

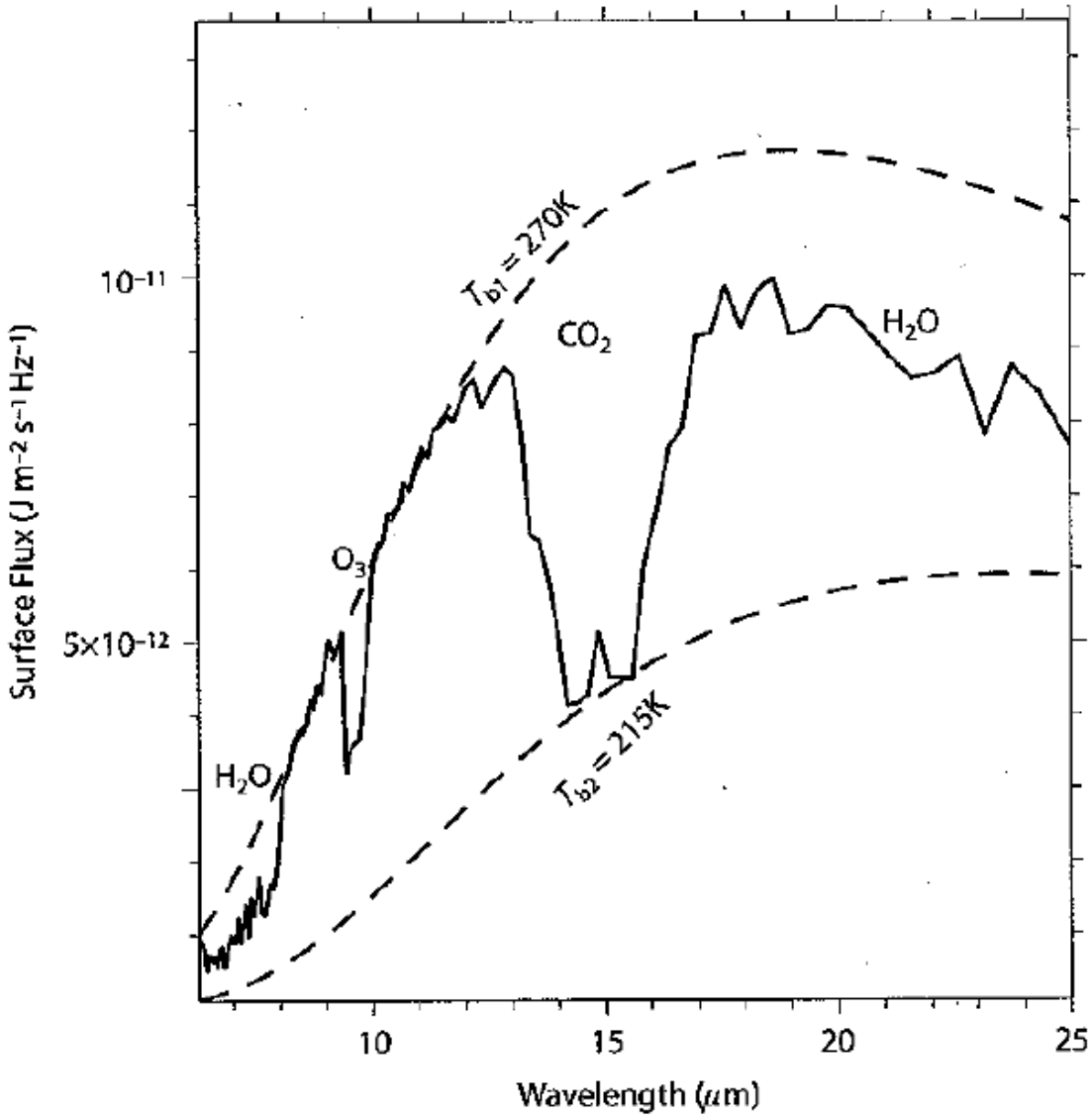
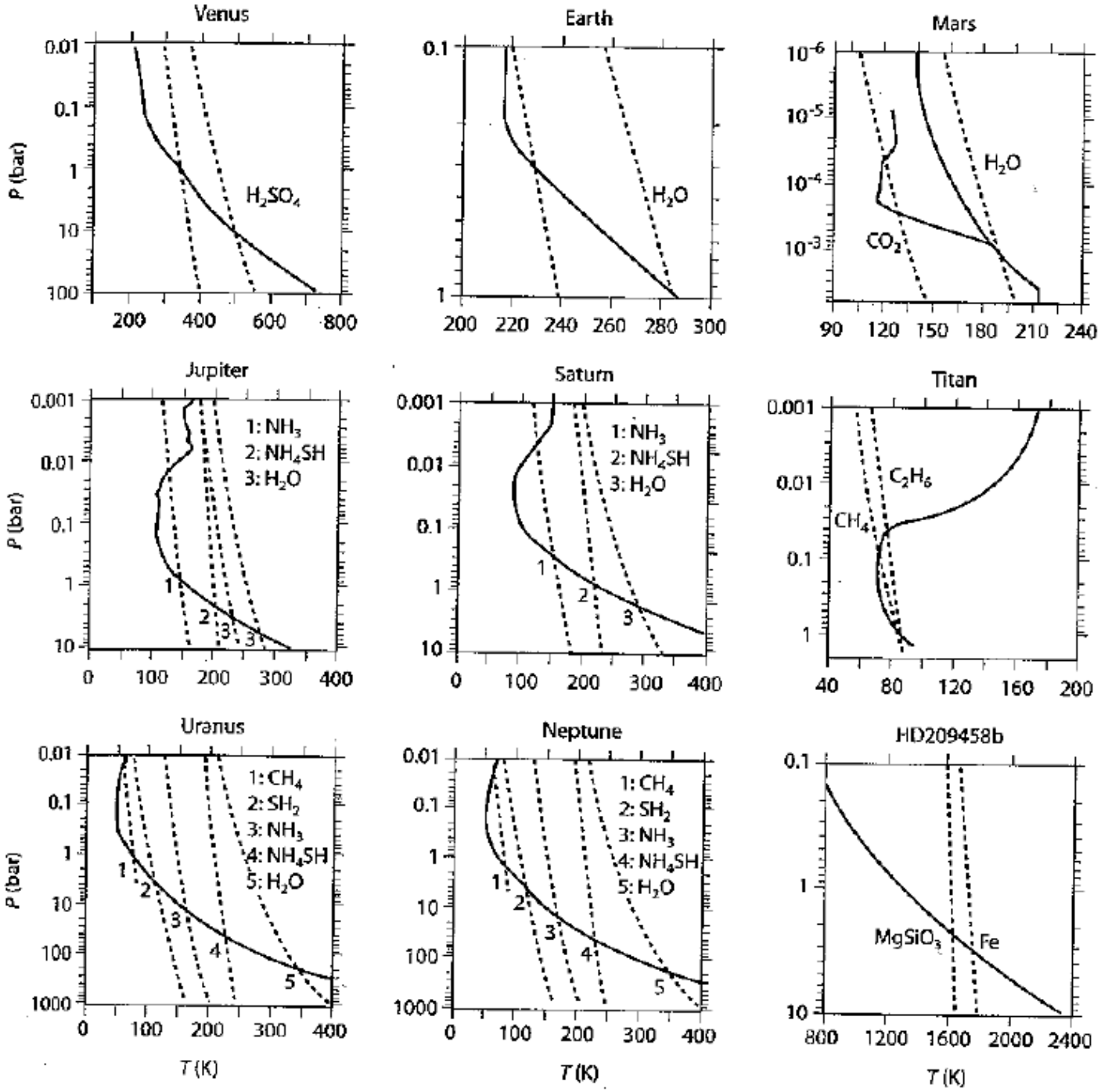
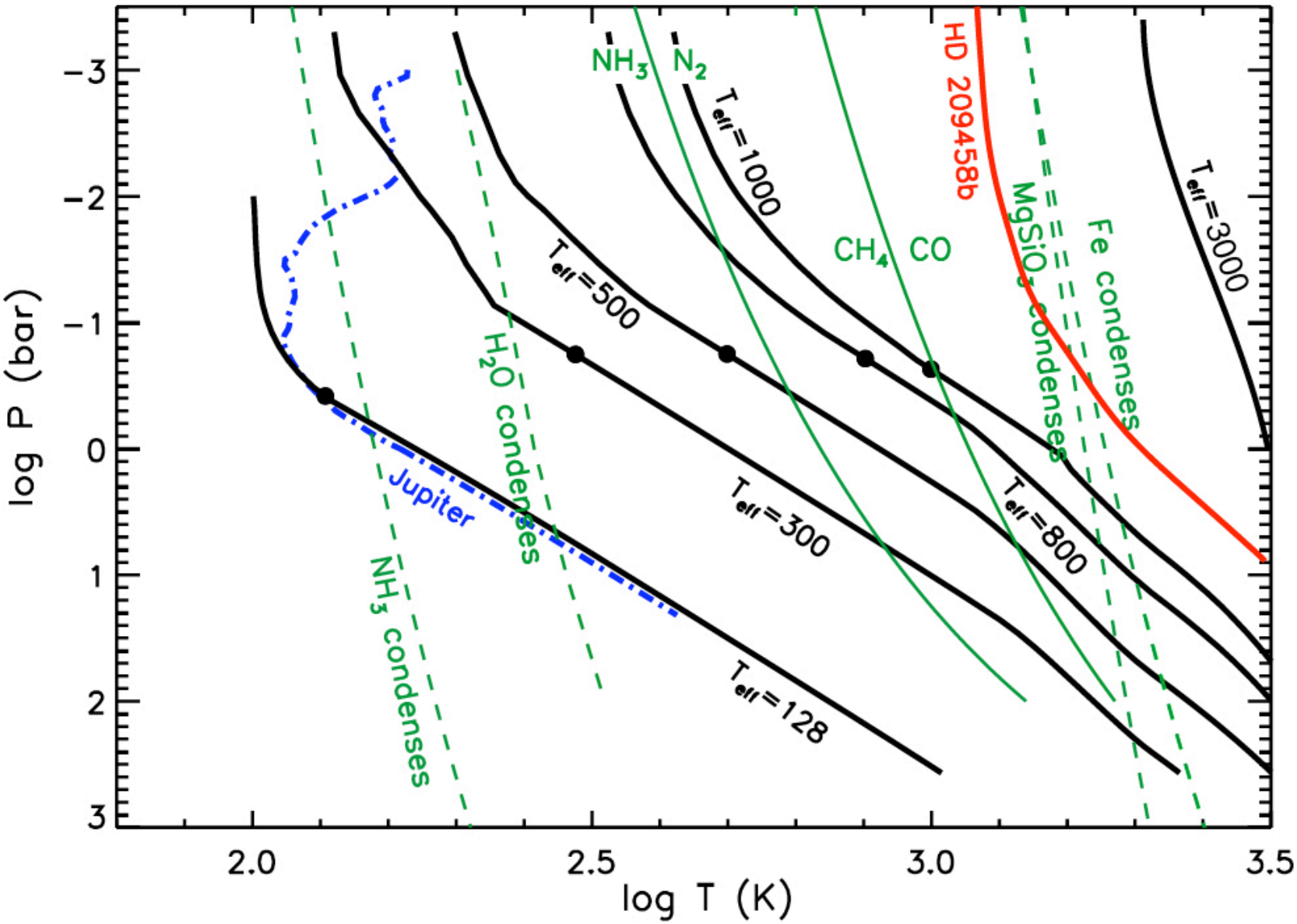
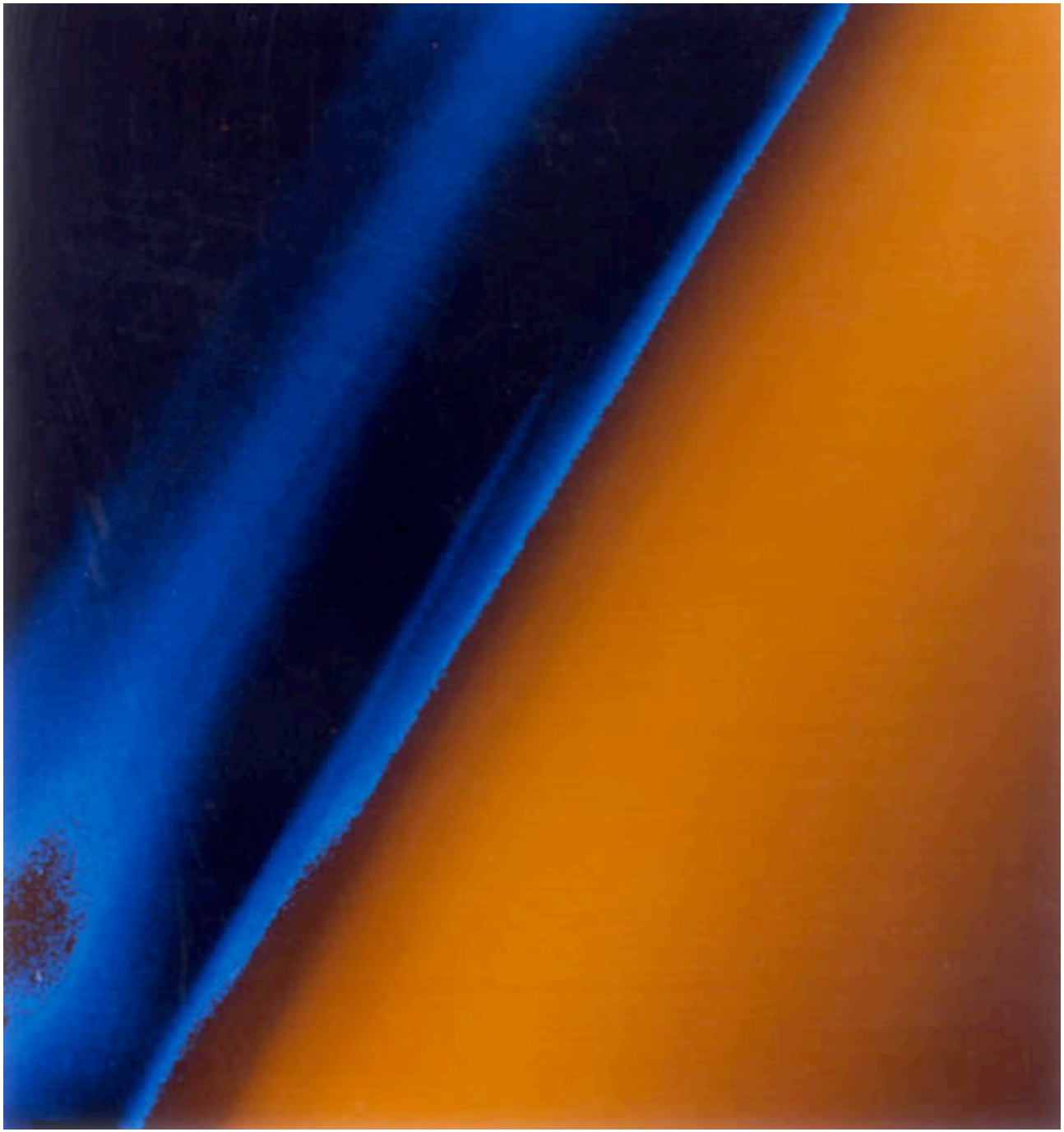
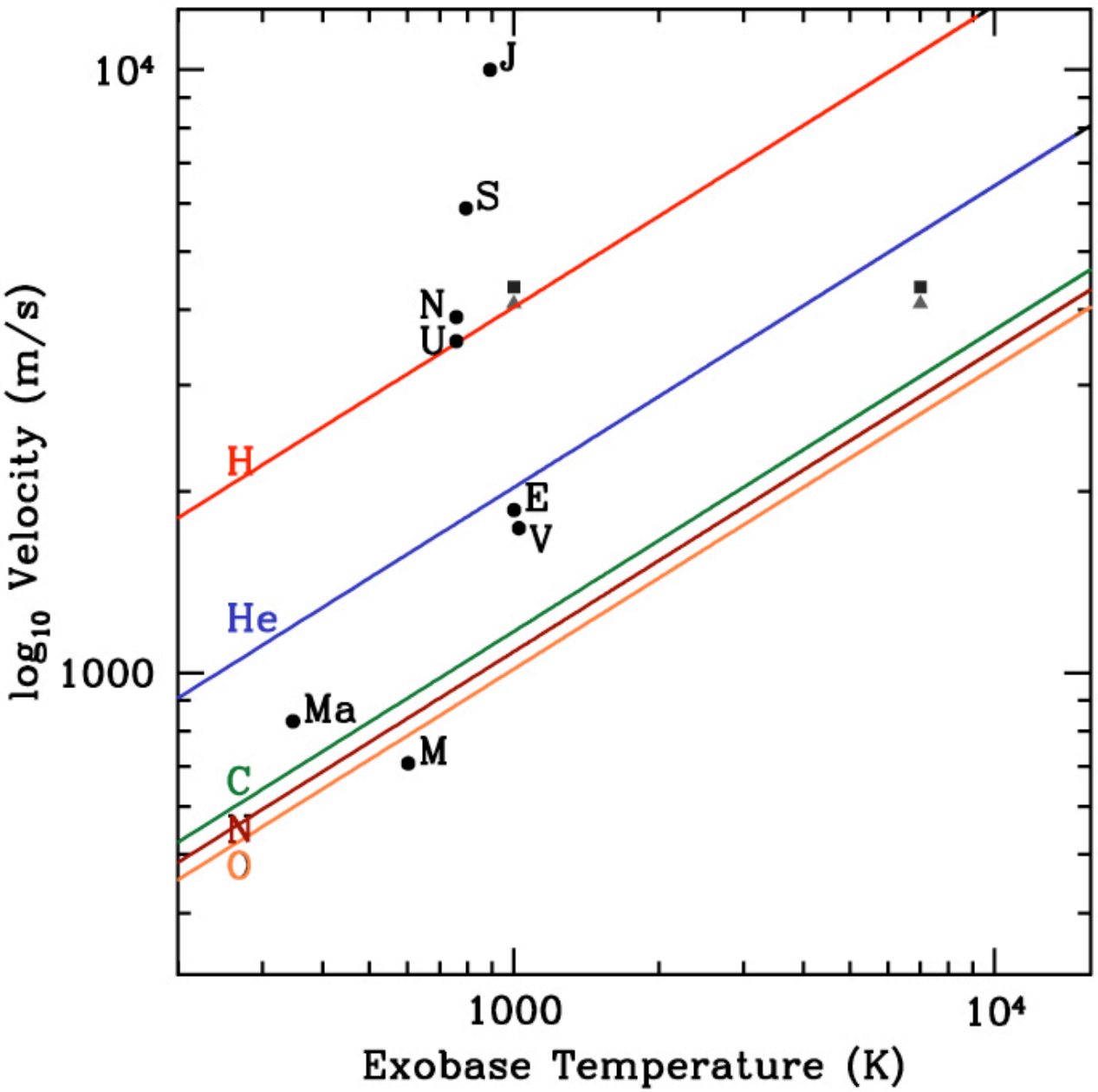


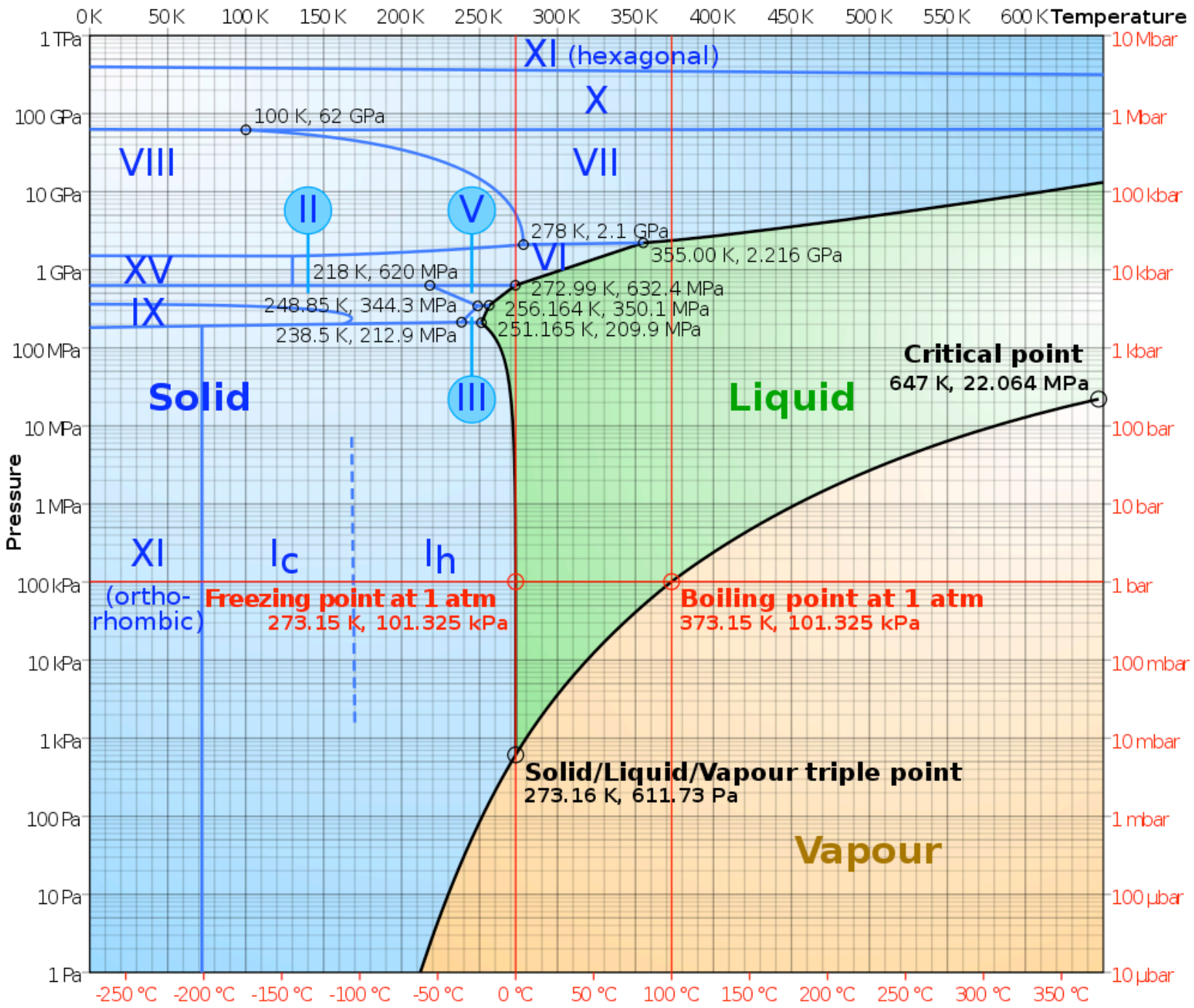
Illustration of the brightness temperature definition. The solid curve is Earth's surface flux as measured by the *Mars Global Surveyor* [2]. The dashed curves are black body fluxes with different temperatures, showing that the brightness temperature T_b can vary with wavelength or frequency. From Earth's spectrum we see that $T_b(12\ \mu m) \simeq 270$ K, in contrast to $T_b(14.2\ \mu m) \simeq 215$ K.

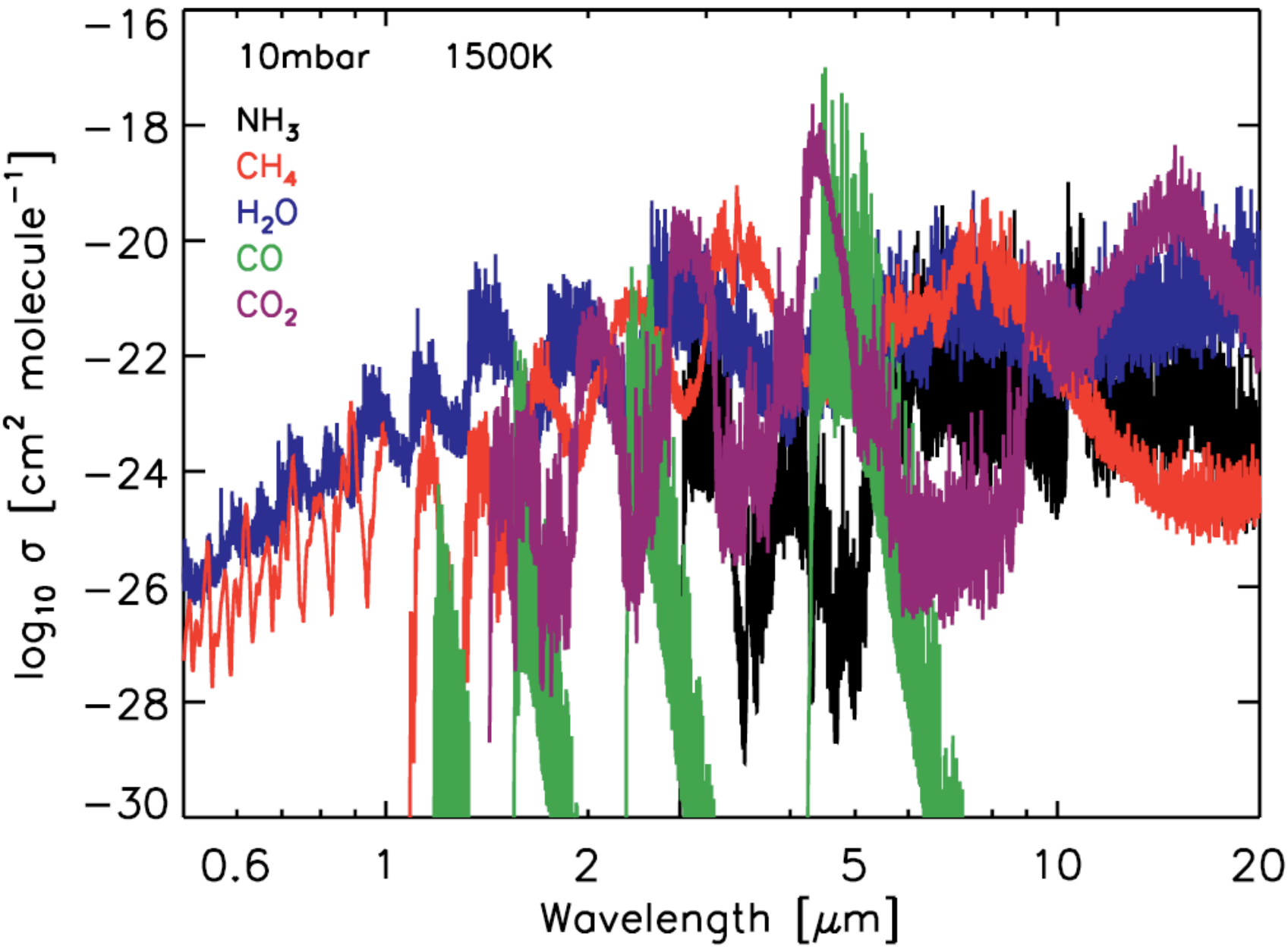

Venus
Earth
Mars
Jupiter
Saturn
Titan
Uranus
Neptune
HD209458b
P (bar)
T (K)
H2SO4
H2O
CO2
1: NH3
2: NH4SH
3: H2O
C2H6
CH4
1: CH4
2: SH2
3: NH3
4: NH4SH
5: H2O
MgSiO3
Fe

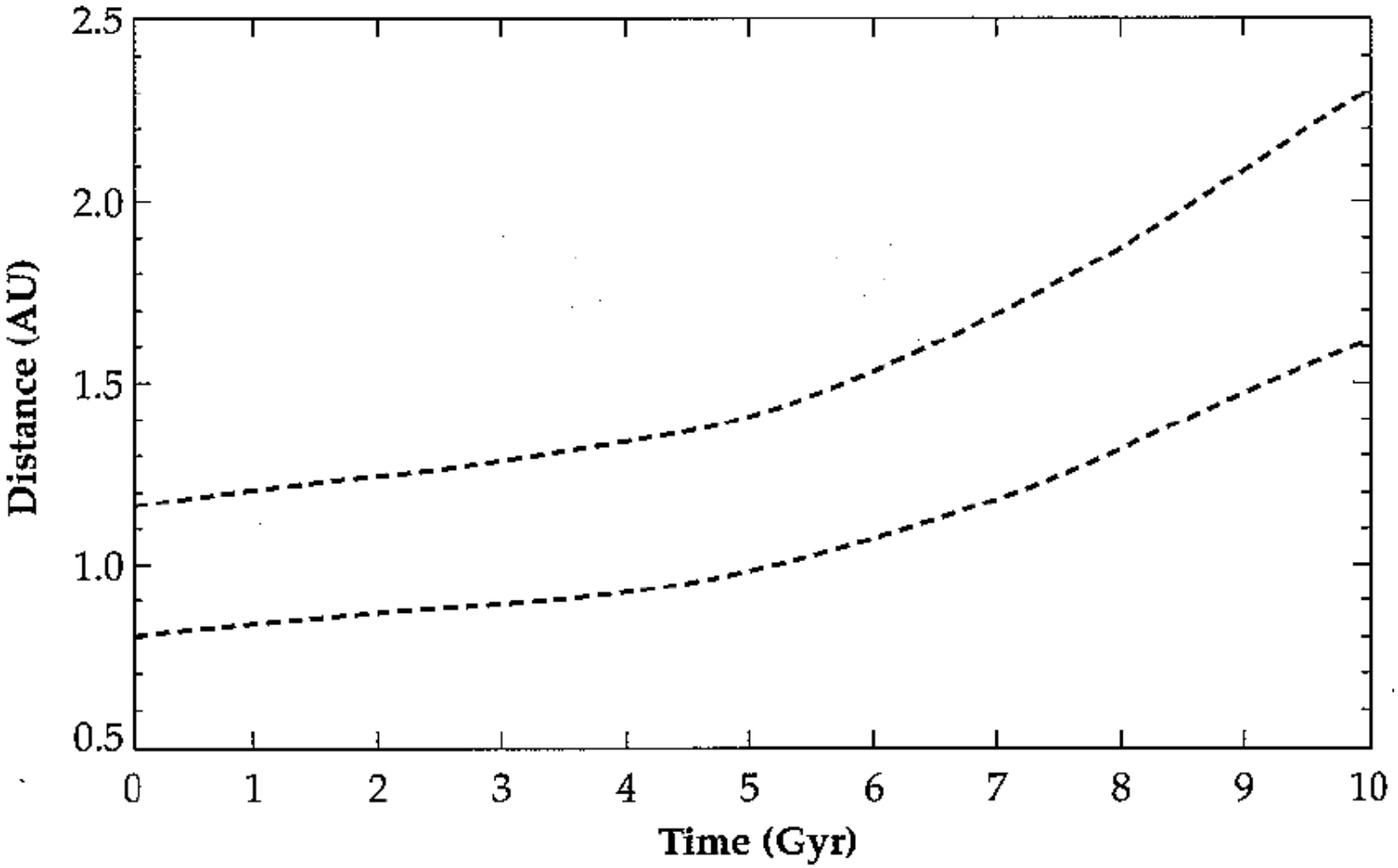

log P (bar)
log T (K)
2.0
2.5
3.0
3.5
−3
−2
−1
0
1
2
3
T_{eff}=3000
T_{eff}=1000
T_{eff}=800
T_{eff}=500
T_{eff}=300
T_{eff}=128
NH_3
N_2
CH_4
CO
HD 209458b
$MgSiO_3$ condenses
Fe condenses
H_2O condenses
NH_3 condenses
Jupiter

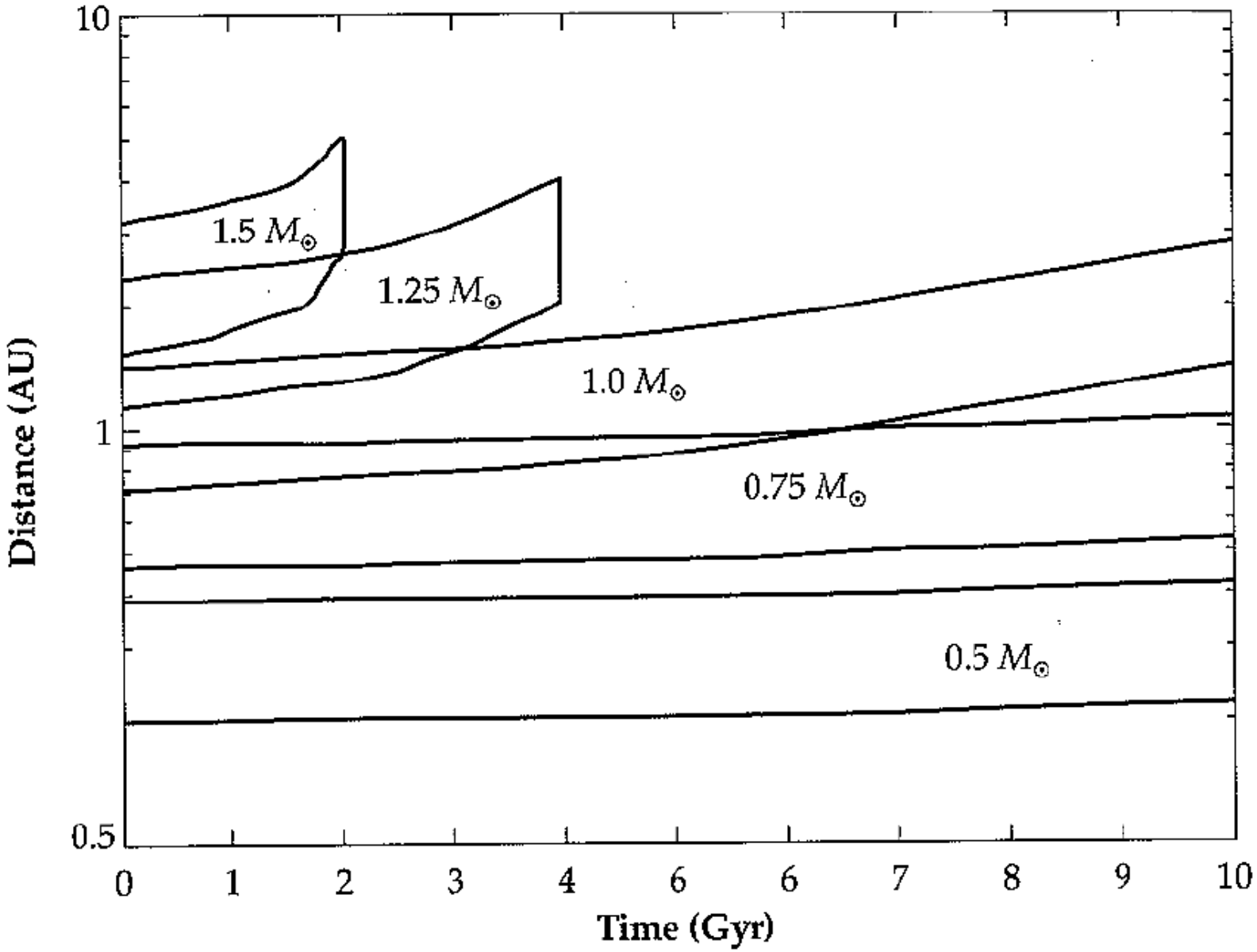


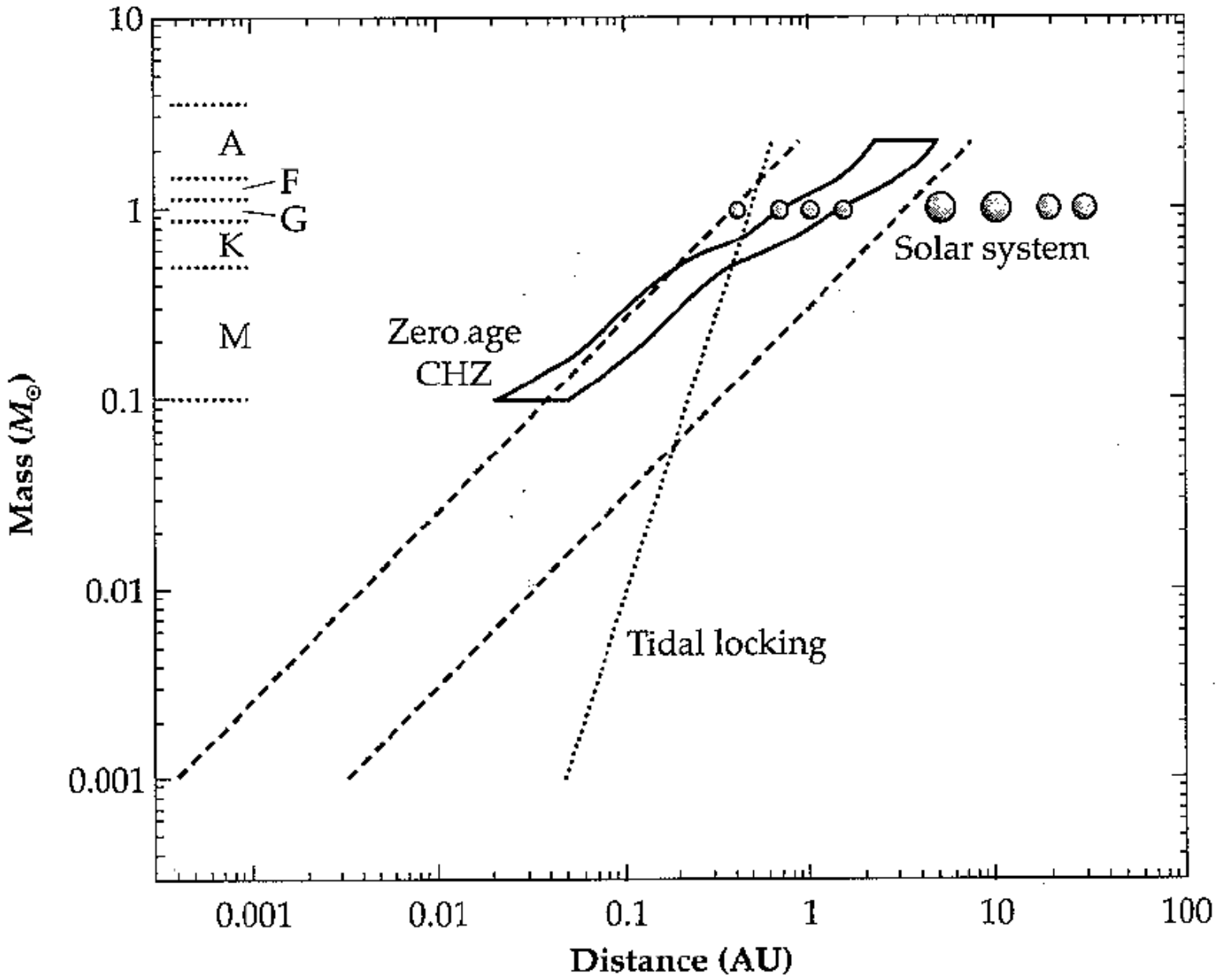

10⁴
1000
log₁₀ Velocity (m/s)
1000
10⁴
Exobase Temperature (K)
J
S
N
U
E
V
Ma
M
H
He
C
N
O


0 K
50 K
100 K
150 K
200 K
250 K
300 K
350 K
400 K
450 K
500 K
550 K
600 K
Temperature
1 TPa
100 GPa
10 GPa
1 GPa
100 MPa
10 MPa
1 MPa
100 kPa
10 kPa
1 kPa
100 Pa
10 Pa
1 Pa
Pressure
10 Mbar
1 Mbar
100 kbar
10 kbar
1 kbar
100 bar
10 bar
1 bar
100 mbar
10 mbar
1 mbar
100 µbar
10 µbar
-250 °C
-200 °C
-150 °C
-100 °C
-50 °C
0 °C
50 °C
100 °C
150 °C
200 °C
250 °C
300 °C
350 °C
XI (hexagonal)
X
VIII
VII
II
V
VI
XV
IX
III
100 K, 62 GPa
278 K, 2.1 GPa
355.00 K, 2.216 GPa
218 K, 620 MPa
272.99 K, 632.4 MPa
248.85 K, 344.3 MPa
256.164 K, 350.1 MPa
238.5 K, 212.9 MPa
251.165 K, 209.9 MPa
Solid
Liquid
Vapour
Critical point
647 K, 22.064 MPa
XI
(ortho-
rhombic)
Ic
Ih
Freezing point at 1 atm
273.15 K, 101.325 kPa
Boiling point at 1 atm
373.15 K, 101.325 kPa
Solid/Liquid/Vapour triple point
273.16 K, 611.73 Pa


10mbar
1500K
NH3
CH4
H2O
CO
CO2
−16
−18
−20
−22
−24
−26
−28
−30
log10 σ [cm2 molecule−1]
0.6
1
2
5
10
20
Wavelength [μm]


2.5
2.0
1.5
1.0
0.5
Distance (AU)
0
1
2
3
4
5
6
7
8
9
10
Time (Gyr)


10
1
0.5
Distance (AU)
1.5 $M_\odot$
1.25 $M_\odot$
1.0 $M_\odot$
0.75 $M_\odot$
0.5 $M_\odot$
0
1
2
3
4
6
6
7
8
9
10
Time (Gyr)


10
1
0.1
0.01
0.001
A
F
G
K
M
Zero age
CHZ
Solar system
Tidal locking
Mass ($M_\odot$)
0.001
0.01
0.1
1
10
100
Distance (AU)