The Martian Atmosphere

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- The Mars atmosphere consists of a troposphere, an isothermal mesosphere, and a thermosphere where the daytime temperature at the top of the thermosphere may vary depending on the time in the solar cycle. Photochemistry occurs throughout the entire Mars atmosphere, from the top of the thermosphere to the bottom of the troposphere. The photodissociation of the major constituent carbon dioxide produces carbon monoxide and atomic oxygen. The recombination of CO and O takes place in the troposphere through catalytic reactions involving the odd-hydrogen species, H, OH and HO_2. Observational tests that confirm the general validity of the odd-hydrogen model are: (1) the observed abundances of molecular oxygen and carbon monoxide; (2) the observed seasonal variation of ozone over the polar caps of Mars; and (3) the observed density of atomic hydrogen in the thermosphere. Odd nitrogen is produced in the upper atmosphere from the reaction of N(2D) and CO2. Viking mass spectrometers have measured neutral nitric oxide molecules in the Mars atmosphere. Photochemical processes control the behavior of the ionosphere of Mars. The principal ion is O_2^+ with smaller amounts of CO_2^+ and O^+ at the ionospheric peak near 135 km. The density of the 0^+ ion becomes comparable to the density of the O_2^+ ion near the top of the atmosphere. The most intense emissions in the ultraviolet airglow of Mars are the carbon monoxide Cameron bands. Strong ultraviolet emissions from CO_2^+ are the result of photoionization of carbon dioxide. The atomic oxygen airglow at 1304 A is used to determine the density of atomic oxygen and the 1216 A Lyman α line is used to calculate the density of atomic hydrogen and, when coupled with the temperature measurement, the escape flux of atomic hydrogen. The most intense airglow is the infrared atmospheric band of O_2 at 1.27um that results from the photodissociation of ozone. The escape mechanism for atomic hydrogen is thermal, or Jeans, escape while atomic oxygen escape is caused by a nonthermal process, namely, the dissociative recombination of O_2^+. The ratio of deuterium to hydrogen is enriched by a factor of 6. This observation may be used to study the past history of water on Mars. Three-dimensional models of the Mars thermospheric circulation show that planetary rotation has a significant influence on the wind, composition and temperature structure. There is upward flow on the day side, downward flow on the night side. Observations of the thermospheric temperatures near solar minimum from Viking showed a mean dayside temperature of 195 K and near solar maximum from Mariners 6 and 7, a value of 310 K. The challenge for the future is to make observations to study the diurnal, seasonal and solar cycle changes that occur in the Mars atmosphere. **(Abstract of reference 1, Barth chapter in Mars book)**

Plan

- Summary of Atmospheric Properties
- Vertical Structure
- Further Properties
- Carbon Dioxide Cycle
- Water Cycle
- Dust Cycle
- Chemical and Isotopic Composition
- Ionosphere
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- Venus, Earth, and Mars Compared
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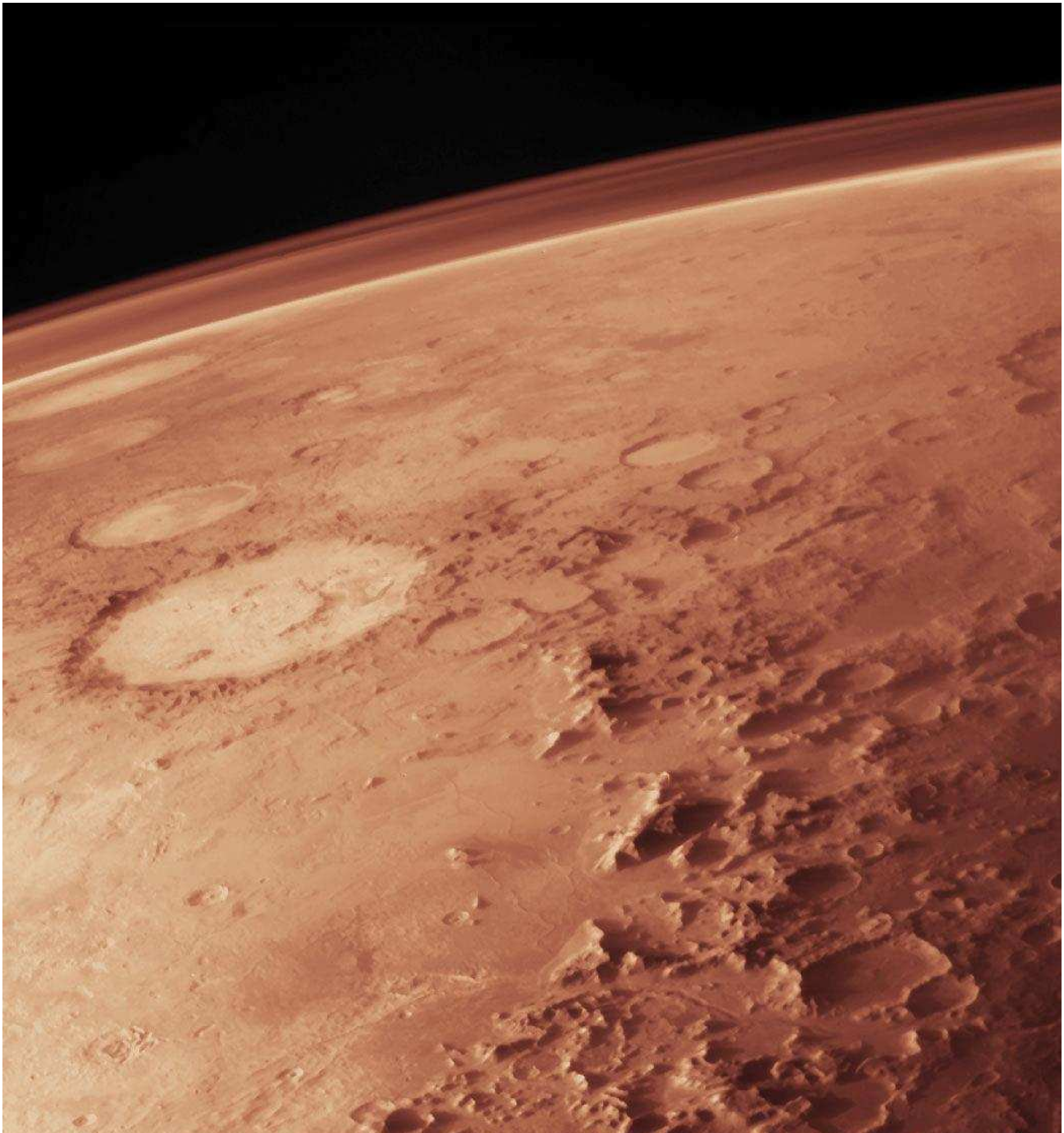
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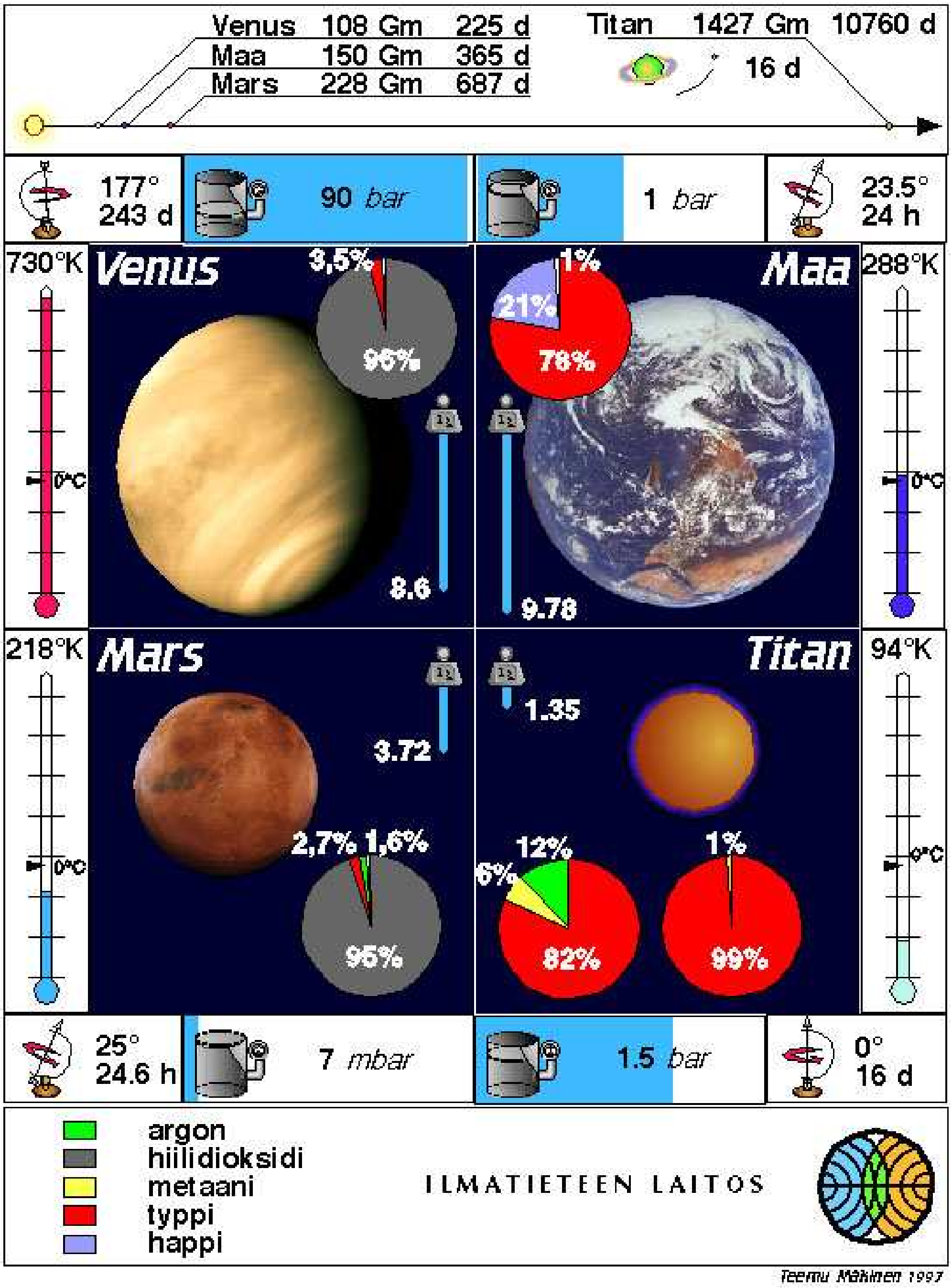
Summary of Atmospheric Properties



Teemu Makinen,
Finland

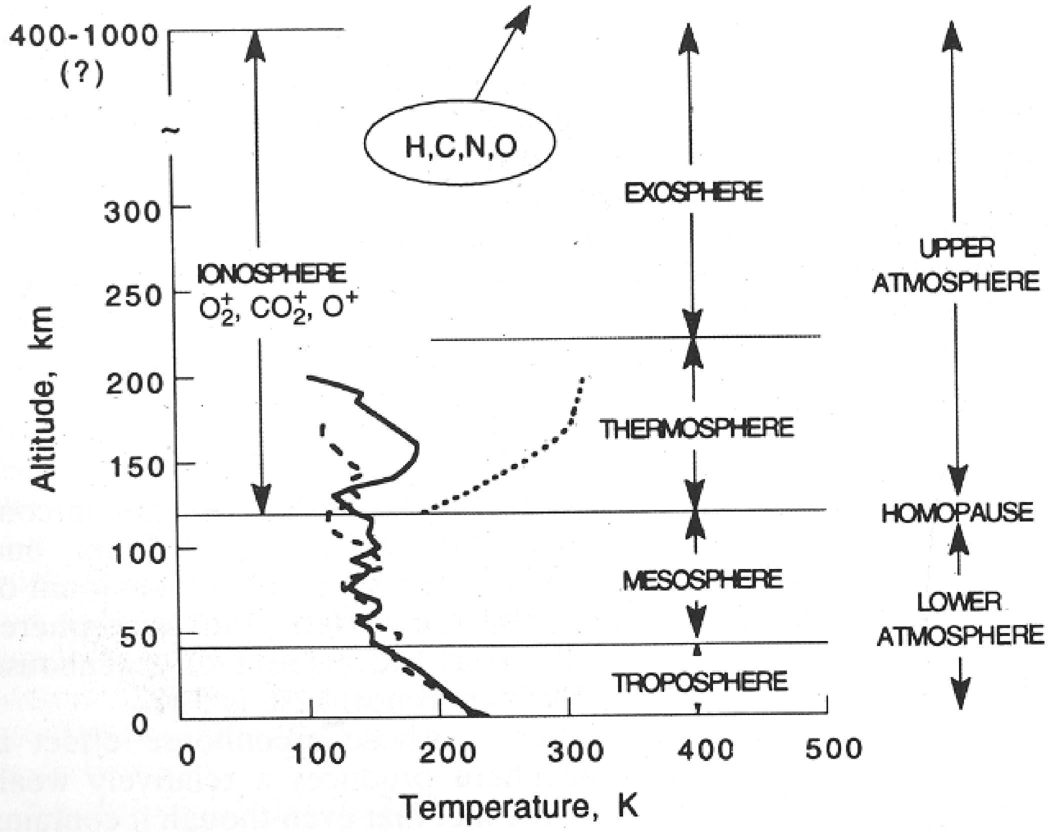


Figure M25 Vertical structure of the Martian atmosphere. Solid and dashed curves represent the temperature profiles measured by the Viking Lander 1 and 2 respectively, as they descended to the surface. Dotted curve above 120 km represents a theoretical profile consistent with Mariner 9 airglow measurements.

From reference 7, Haberle chapter in Encyclopedia

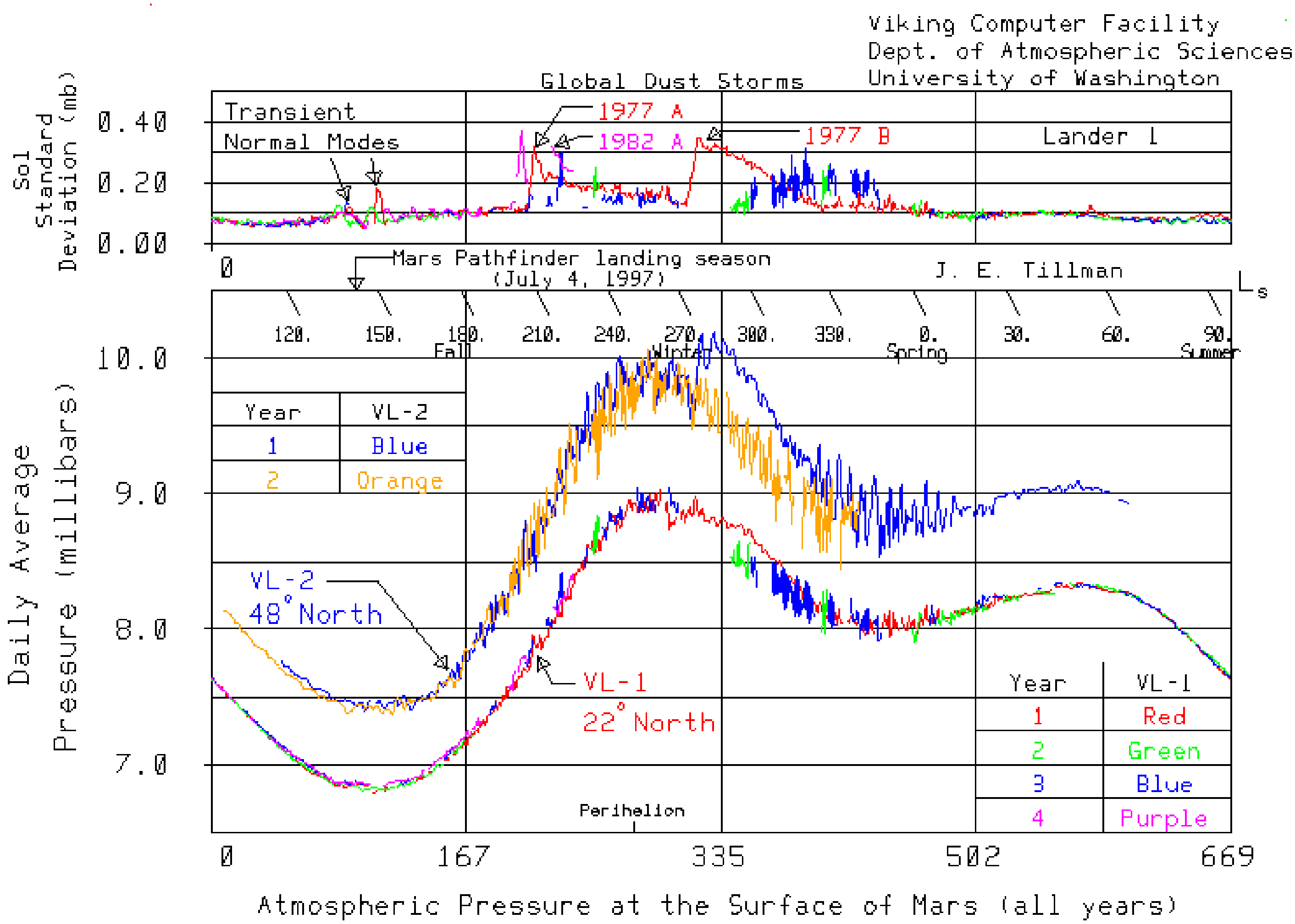
- Table 7.1 Astronomical and atmospheric data for Mars

Radius (equatorial)	3394.5 km
Mass	6.4185E23 kg
Mean density	3.9335 g cm^{-3}
Gravity (surface. equator)	3.711 m s^{-2}
Semimajor axis	1.52366 AU
Obliquity (relative to orbital plane)	25.19 degrees
Eccentricity of orbit	0.0934
Period of revolution (Earth days)	686.98
Orbital velocity	24.13 km s^{-1}
Period of rotation	24h 37m 22.663s
Atmospheric pressure at surface	5.6 mbar
Mass of atmospheric column	1.50E-2 kg cm^{-2}
Total atmospheric mass	2.17E16 kg
Equilibrium temperature	216 K
Surface temperature	220 K
Annual variation in solar insolation (a)	1.45
Atmospheric scale height (T = 210 K)	10.8 km
Adiabatic lapse rate (dry)	4.5 K km^{-1}
Atmospheric lapse rate (b)	2.5 K km^{-1}
Escape velocity	5.027 km s^{-1}

- Taken from Kieffer. H. H. et al. (1992).
- (a) Based on the ratio of aphelion to perihelion distance squared.
- (b) Mean observed value. variable.

- **Table 7.1 from reference 2, Yung and DeMore**

Carbon Dioxide Cycle



Southern winter occurs at slow, distant aphelion, so more CO2 can condense onto southern pole

Water Cycle

- Water in deep interior, shallow subsurface, polar caps, and atmosphere
- Polar caps are summertime source and wintertime sink for atmospheric water
- Surface temperatures are above 273K at noon, summer, equator, but 6 mbar surface pressure prevents stable brines or liquid water on surface
- Higher pressures at depth, liquid water?
- Atmosphere saturated with 10 pr um of H2O
- Negligible contribution to heat transport
- Past oceans, rainfall, and glaciers?

Dust Cycle

- As important as water/ozone on Earth in affecting atmospheric temperatures
- Dust in atmosphere absorbs incoming solar flux, absorbs and emits in IR, raises surface temperature
- Redistributed by small-scale dust devils and global-scale dust storms, spatially and temporally variable in atmosphere and on surface
- Global storms can obscure all surface features, lift dust 50 km above surface, often associated with strong winds coming off the southern polar cap in southern spring as frozen CO2 sublimes into atmosphere and blows northwards
- Dust trapped in CO2 frost and snow at poles, forms layers that reveal recent climate history

Table 7.2 Chemical composition of the atmosphere of Mars

Gas	Abundance	Reference and remarks
CO_2	0.9532	(1)
N_2	0.027	(1)
^{40}Ar	0.016	(1)
O_2	1.3×10^{-3}	(1)
CO	7.0×10^{-4}	(1)
H_2O	3.0×10^{-4}	(2); variable
$^{36}Ar+^{38}Ar$	5.3×10^{-6}	(1)
Ne	2.5×10^{-6}	(1)
Kr	3.0×10^{-7}	(1)
Xe	8.0×10^{-8}	(1)
O_3	3.0×10^{-8}	(3); variable

(1) Owen et al. (1977); (2) Farmer and Doms (1979); (3) Barth (1974).

Table 7.3 Isotopic composition of the atmosphere of Mars

Species	Ratio	Reference
D/H	$9 \pm 4 \times 10^{-4}$	(1)
	$7.8 \pm 0.3 \times 10^{-4}$	(2)
$^{12}C/^{13}C$	90 ± 5	(3)
$^{14}N/^{15}N$	170 ± 15	(3)
$^{16}O/^{17}O$	2655 ± 25	(2)
$^{16}O/^{18}O$	490 ± 25	(3)
	545 ± 20	(2)
$^{36}Ar/^{38}Ar$	5.5 ± 1.5	(4)
$^{40}Ar/^{36}Ar$	3000 ± 500	(5)
$^{129}Xe/^{132}Xe$	$2.5 \pm^{2}_{1}$	(5)

(1) Owen et al. (1988); (2) Bjoraker et al. (1989); (3) Nier and McElroy (1977); (4) Biemann et al. (1976).

From reference 2

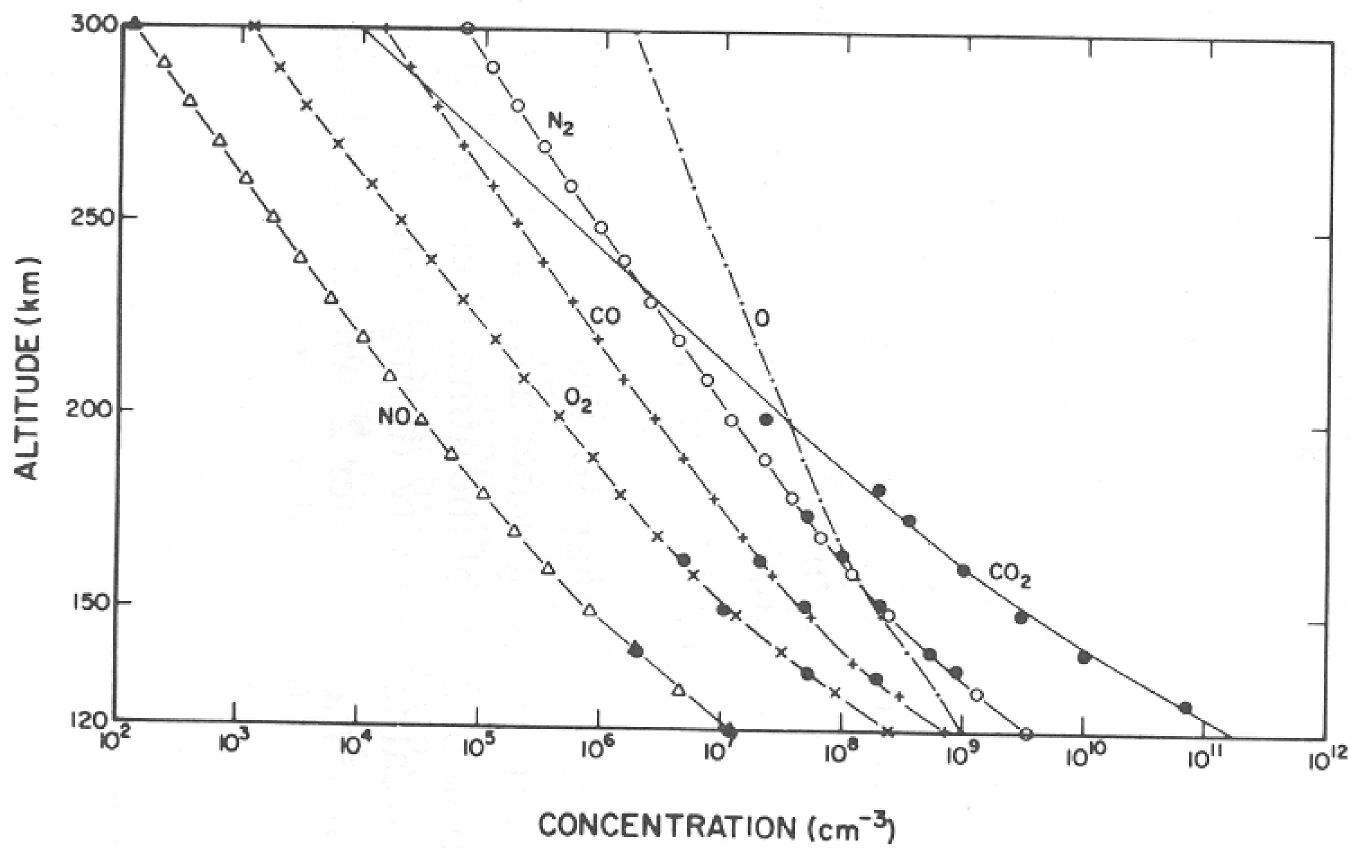


Fig 1.24 from Chamberlain and Hunten

Homopause at ~125 km

ionosphere. The predominance of O_2^+ is the result of the ion molecule reactions (1) and (2) below, which transform very rapidly the originally produced CO_2^+ and O^+ ions to O_2^+:

$$CO_2^+ + O \rightarrow O_2^+ + CO \tag{1}$$

$$O^+ + CO_2 \rightarrow O_2^+ + CO. \tag{2}$$

From reference 3

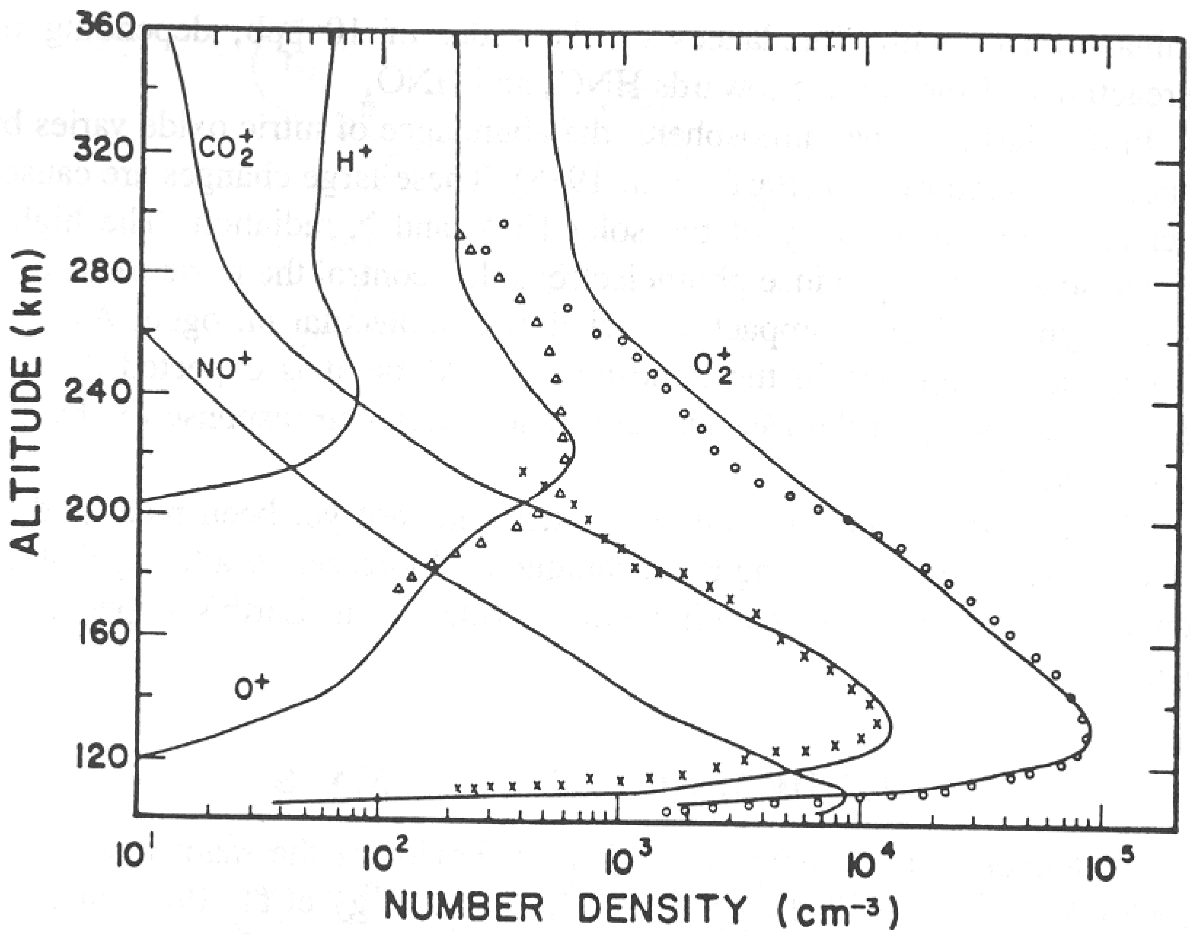


Fig.9. Ion density profiles: ion density profiles in which the solid lines are calculated profiles. The circles are O_2^+ data, the triangles are O^+ data and the crosses are CO_2^+ data; the values were by Chen et al. (1978) from the Viking 1 RPA experiment (Hanson et al. 1977) (figure from Chen et al. 1978).

Atmospheric Escape

- Affects elemental and isotopic composition over the lifetime of the solar system. Extremely uncertain.
- Light species escape easier than heavy ones, so get fractionation
- Exobase height ~ 160 km at solar max. Corona of H observed by Ly α emissions by UV spectrometers, thermal Jeans escape. Only H, He can use this mechanism. 1E26 H atoms s^{-1}.
- Low g means that escape is relatively easy. Dissociative recombination of N_2^+ and O_2^+ with an electron to form suprathermal 2N or 2O is a major current pathway.
- Current escape rates of H twice that of O, net loss of H_2O. Possibly regulated by lower atmosphere photochemistry.
- Bury CO_2 and H_2O on/below surface
- Impact erosion strips atmosphere without mass selection
- History of magnetic field is important here
- Warm, wet early Mars?
- M9 UVS, ion profiles, isotopic ratios

Table la. Terrestrial Planet Parameters

Parameter	Earth	Venus	Mars
Gravity, cm s^{-2}	982	888	373
Heliocentric distance AU	1.0	0.72	1.38-1.67
Radius, km	6371	6050	3396
Omega rad s^{-1}	7.3(-5)	3.0(-7)	7.1(-5)
Magnetic dipole moment (wrt Earth)	1.0	~4.0(-5)	~2.5(-5)
Obliquity, deg	23.5	1-3	25.0

Table lb. Implications of Parameters

Effect	Earth	Venus	Mars
Scale heights, km	10-50	4-12	8-22
Major EUV heating, km	~200-300	~140-160	120-160
	broad	narrow	intermediate
O Abundance (ion peak)	~40%	~7-20%	~1-4%
CO_2 15um cooling	</=130 km	</=160 km	</=125-130 km
Dayside thermostat	conduction	CO_2 cooling	winds/conduction
Dayside solar cycle T	900-1500 K	230-310 K	220-325 K
Rotational forces	important	negligible	important
Cryosphere	no	yes	no
Auroral/Joule heating	yes	no	no
Seasons	yes	no	yes

From reference 6

Conclusions

- Atmospheric composition and presence of volatile reservoirs affects atmospheric temperatures, atmospheric dynamics, habitability, and atmospheric escape
- Orbital distance, eccentricity, and obliquity affect mean and seasonal behaviour. Variations in obliquity over time lead to large variations in climate (ice ages)
- Basic physical principles of fluid dynamics, radiative transfer, and thermodynamics apply to all atmospheres, but local environment can cause very different results

Sources

1) Barth et al. (1992) "Aeronomy of the current martian atmosphere." In Kieffer et al. (Eds.) "Mars," pp. 1054-1089

2) Yung and DeMore (1999) "Photochemistry of Planetary Atmospheres," particularly pp. 244-281

3) Gladstone et al. (2002) "Solar System Upper Atmospheres: Photochemistry, Energetics, and Dynamics." In Mendillo et al. (Eds.) "Atmospheres in the Solar System Comparative Aeronomy," pp. 23-38

4) Nagy and Cravens (2002) "Solar System Ionospheres." In Mendillo et al. (Eds.) "Atmospheres in the Solar System Comparative Aeronomy," pp. 39-54

5) Hunten (2002) "Exospheres and Planetary Escape." In Mendillo et al. (Eds.) "Atmospheres in the Solar System Comparative Aeronomy," pp. 191-202

6) Bougher et al. (2002) "Simulations of the Upper Atmospheres of Terrestrial Planets." In Mendillo et al. (Eds.) "Atmospheres in the Solar System Comparative Aeronomy," pp. 261-288

7) Haberle (2000) "Mars: Atmosphere." In Shirley and Fairbridge (Eds.) "Encyclopedia of Planetary Sciences," pp. 432-440

8) Bougher (2000) "Thermosphere." In Shirley and Fairbridge (Eds.) "Encyclopedia of Planetary Sciences," pp. 819-825

9) Hunten (1993) "Atmospheric evolution of the terrestrial planets," Science, v259, pp. 915-920