The Martian Upper Atmosphere

- By Paul Withers, newly graduated from LPL’s PhD program
- Dissertation on “Tides in the Martian Atmosphere”
- Lecture given to Roger Yelle’s PTYS 544 class
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Plan

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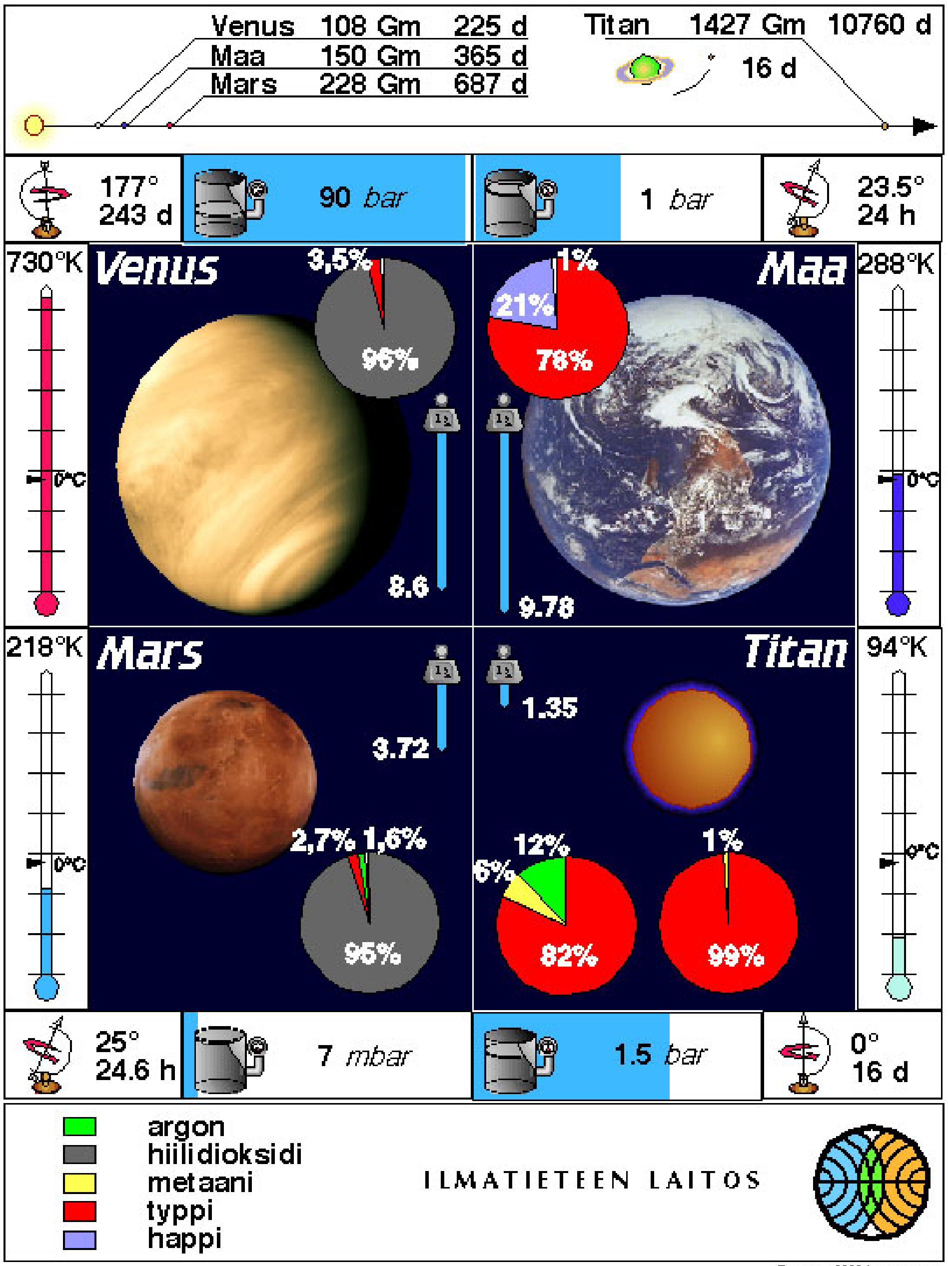
Summary of Atmospheric Properties



Teemu Makinen,
Finland

- 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 1.27μm 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)**

- 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**

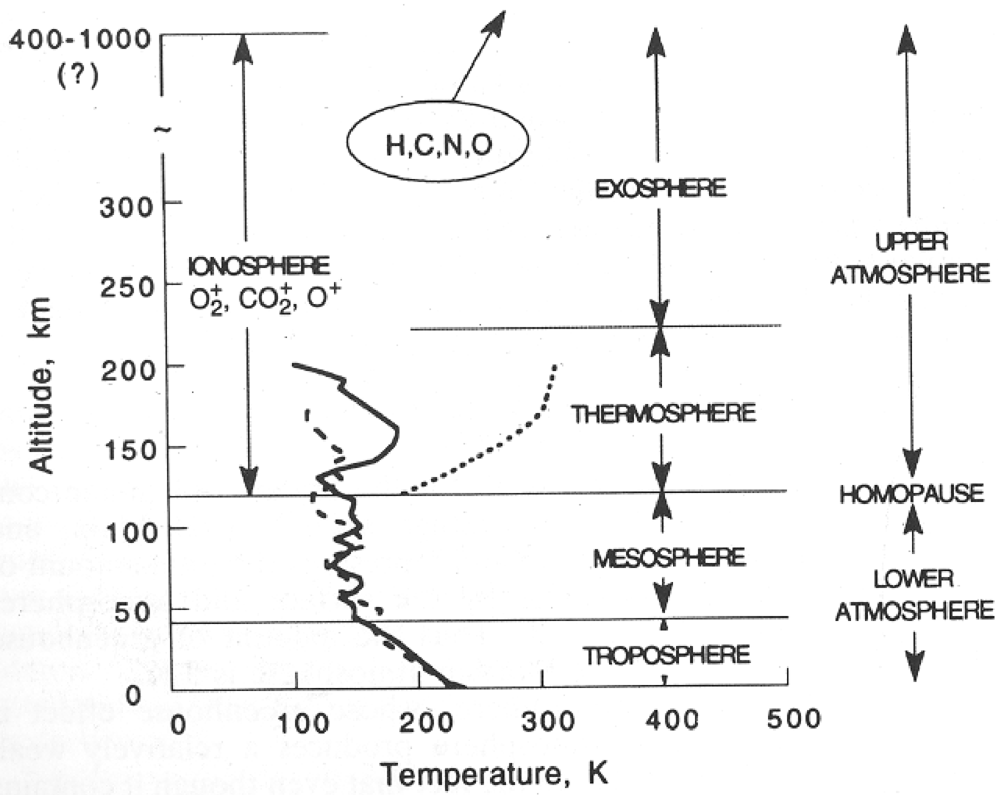


Figure M25 Vertical structure of the Martian atmosphere. Solid and dashed curves represent the temperature profiles measured by the Viking Lander 1 and 2 respectively, as they descended to the surface. Dotted curve above 120 km represents a theoretical profile consistent with Mariner 9 airglow measurements.

From reference 7, Haberle chapter in Encyclopedia

Observations from Viking lander p, T sensors, mass spectrometer; orbiting IR spectrometers and entry accelerometers for T(z)

Elemental and Isotopic Composition

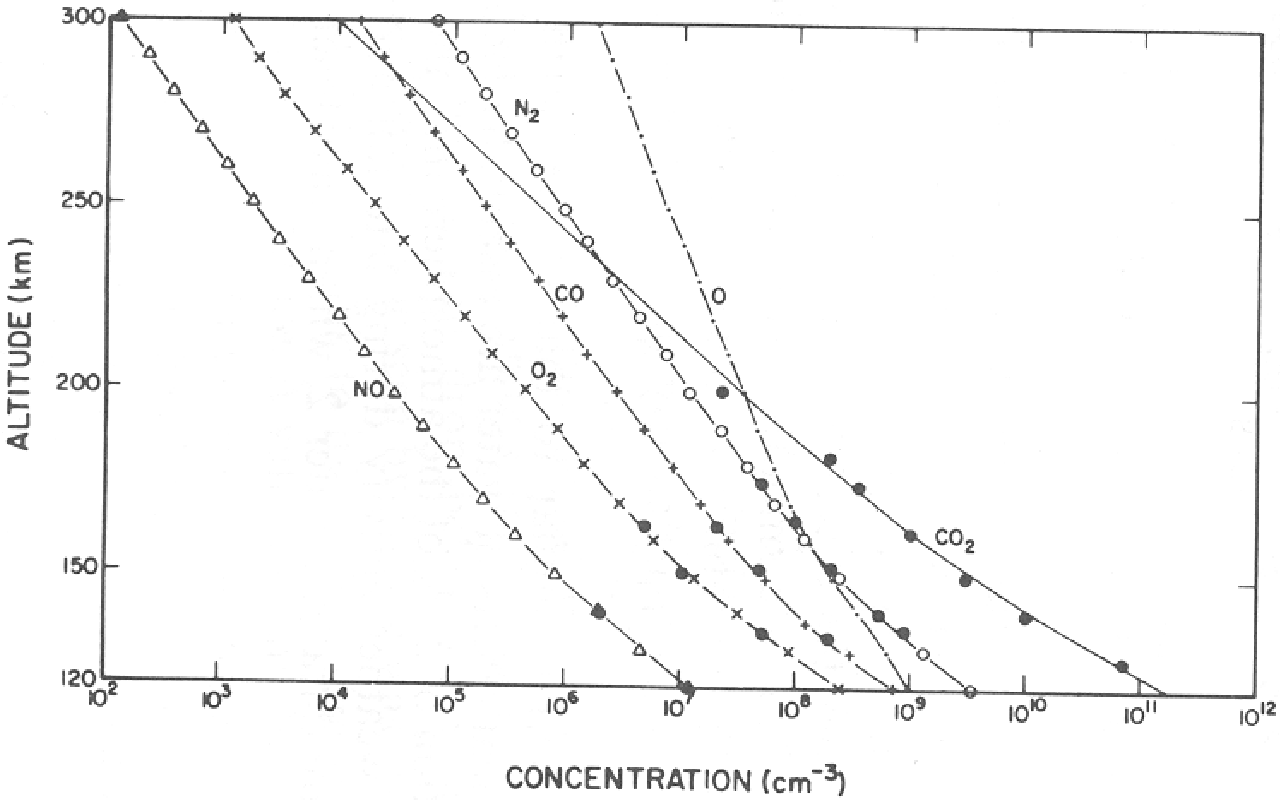


Fig 1.24 from Chamberlain and Hunten

Homopause at ~125 km

Observations from mass spectrometers during Viking entry and after landing

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

Energetics and Thermal Structure (1)

- Short (<200nm) wavelength EUV is readily absorbed by most atmospheric species to either ionize or excite the electronic state. Other wavelengths (VIS, IR) in which significant energy is radiated from the Sun are less readily absorbed.
- So upper atmosphere is dominated by absorption of UV and charged particles from the solar wind. These fluxes are very variable (factors of few to ten) over 11 year solar cycle and short-term solar flares/CMEs.
- Observations from Viking entry accelerometers, orbiting IR spectrometers, radio occultations

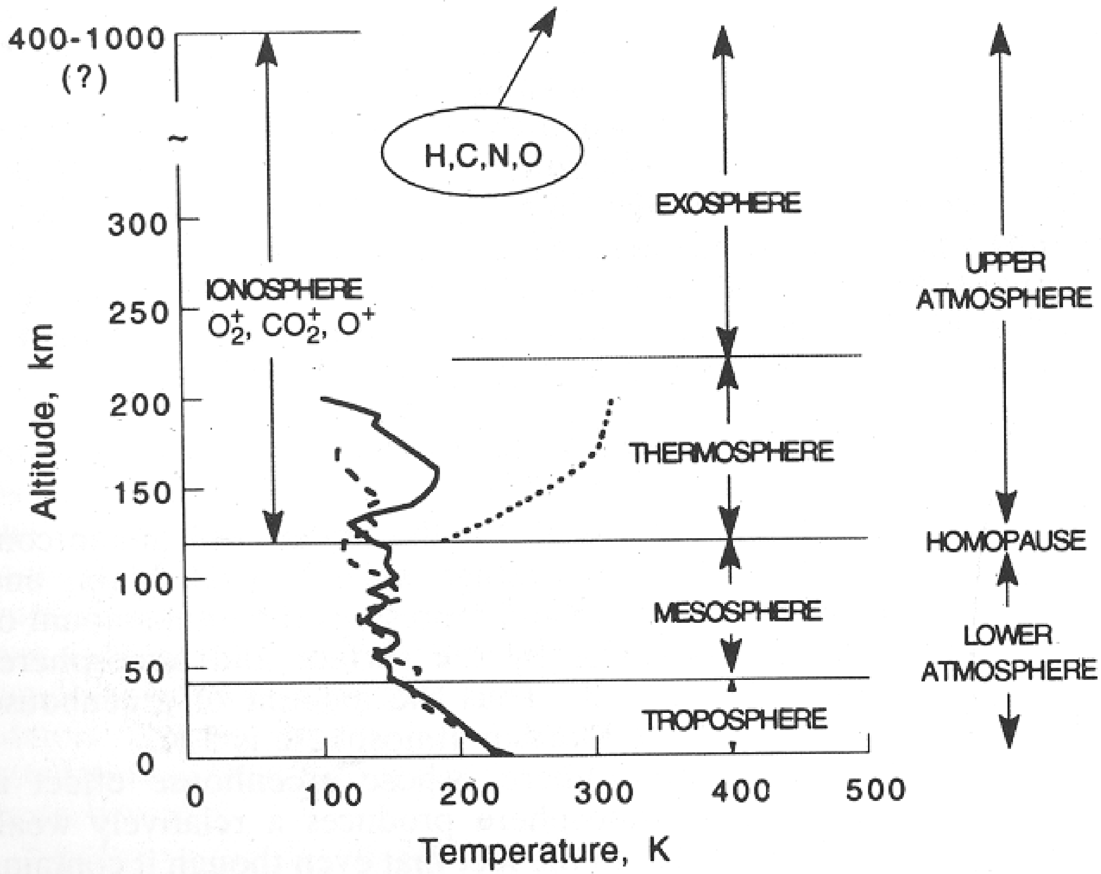


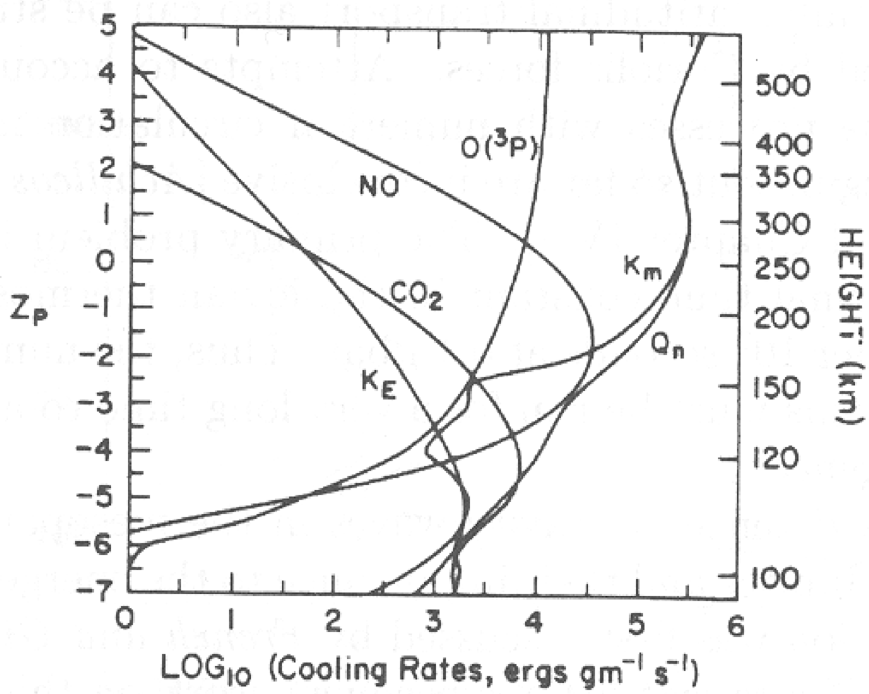
Figure M25 Vertical structure of the Martian atmosphere. Solid and dashed curves represent the temperature profiles measured by the Viking Lander 1 and 2 respectively, as they descended to the surface. Dotted curve above 120 km represents a theoretical profile consistent with Mariner 9 airglow measurements.

From reference 7, Haberle chapter in Encyclopedia

Energy also transported to upper atmosphere by upwardly-propagating tides

From reference 3…

a



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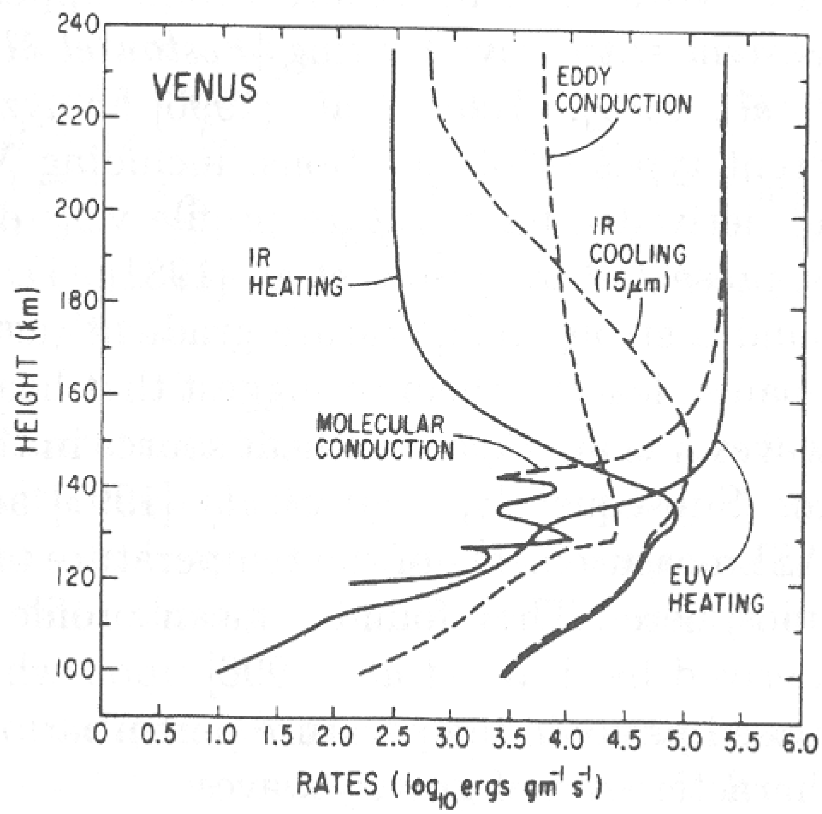

c

…From reference 3

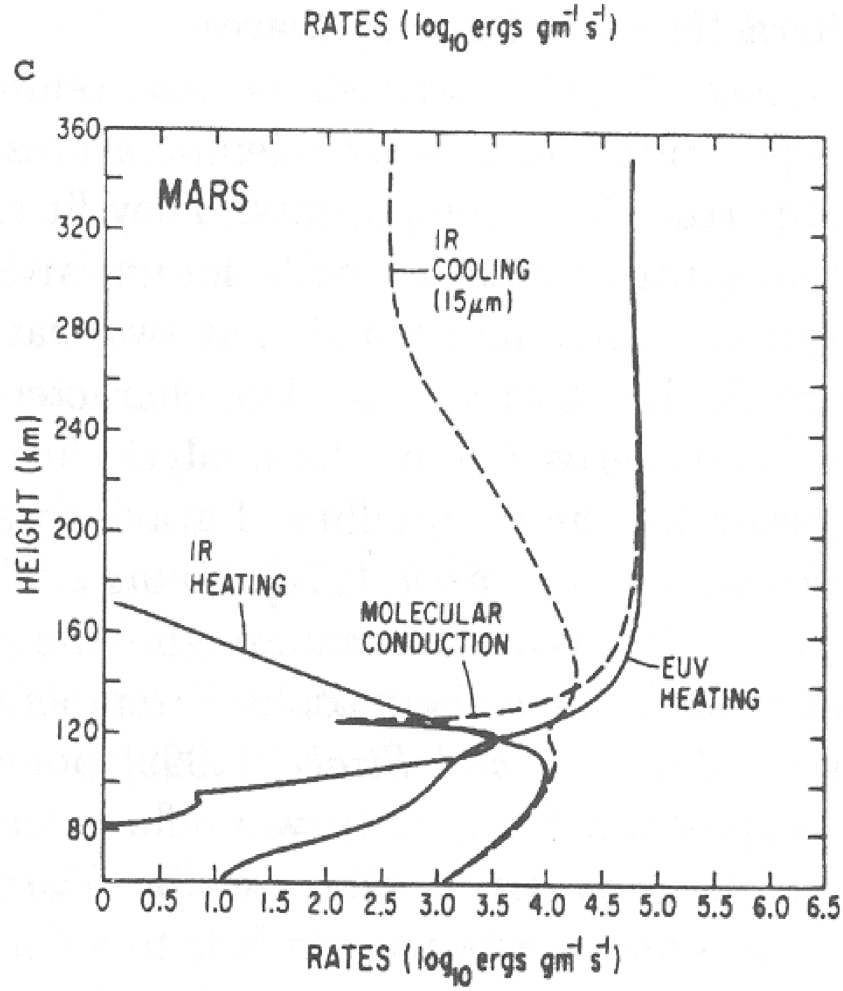

Figure 2. a) Heating and cooling rates for the Earth's upper atmosphere [*Bougher and Roble*, 1991, Fig. 3b]. b) Cooling rates in the atmosphere of Venus [*Bougher and Roble*, 1991, Fig. 3a]. K_m represents cooling by molecular conduction and K_E cooling by eddy conduction. The curves labeled by molecular formulas represent radiative cooling by the indicated species. Q_n represents the net heating rate. c) Heating and cooling rates in the upper atmosphere of Mars [*Bougher and Roble*, 1991, Fig. 3c].

Energetics and Thermal Structure (2)

- Exospheric T asymptotes to constant value since neither upwelling nor downwelling radiation fluxes change significantly when propagating through such low-density regions. Usually a relatively high value.
- Dominant mode of heat transfer at highest altitudes (exosphere and thermosphere) is molecular conduction since radiation can't carry enough of the energy. Have to conduct heat downwards, so T must decrease as z decreases. Eventually densities have increased enough to make radiative cooling viable – mesopause. Composition is important here as CO_2 has transition at 15μm that is at right wavelength for cooling. O/CO_2 collisions make 15μm cooling more efficient.

Dynamics

- Essentially unobserved – that hasn't stopped anyone from speculating
- No strong global magnetic field to confuse matters, just a weak patchy magnetic field whose effects are not really included in models yet
- Need to worry about 3D, unlike much chemistry and T(z) work
- Winds caused by variations in solar heating (daily, seasonal, annual, solar cycle) ~100 ms^{-1} plausible
- Hot dayside has $p(z_0)$ greater than cold nightside, pressure differences drive global thermospheric circulation that transports heat from dayside to nightside, rotation timescale causes a phase lag.
- Lower atmosphere influences this. Dust storms heat and inflate lower atm, change day/night gradients and winds. Also large tides propagating upwards from lower atmosphere can cause pressure gradients and winds.
- Low mass => very responsive to changes in external forcings
- MGS accelerometer might provide some observations

Chemistry

- Both lower and upper atmosphere
- Odd hydrogen species (H, OH, HO_2) derived from photolysis of H_2O catalyse the recombination of CO and O_2 into CO_2.
- H_2O and O_3 are anti-correlated. If H_2O is present, it is photolysed into odd hydrogen species and then catalyses the conversion of O_3 into O_2 and O_2 back into CO_2. If H_2O is not present, then the O_2 can be converted into O_3.
- There's some nitrogen as well
- 5 – 110 nm solar EUV changes by factors of a few over 11 yr solar cycle, might this alter the chemistry?
- Viking entry and landed mass spectrometers, VO MAWD, M9 UV Spec

From reference 2

7.2.1 Pure CO_2 atmosphere

The major constituent of the Martian atmosphere, CO_2, is readily photolyzed by solar ultraviolet radiation under 2050 Å:

$$CO_2 + h\nu \rightarrow CO + O \tag{7.1}$$

where near the threshold the O atom is in the ground state, $O(^3P)$, but at shorter wavelengths the atom could be in excited states $O(^1D)$ and $O(^1S)$. However, the primary fate of the excited atoms is quenching to the ground state by CO_2 (a small fraction of the excited atoms reacts with H_2O). Once CO_2 is converted into CO and $O(^3P)$, it is difficult to restore it. The reverse of reaction (7.1),

$$CO + O + M \rightarrow CO_2 + M \tag{7.2}$$

is spin-forbidden. The three body rate coefficient at 200 K is 3×10^{-37} cm^3 s^{-1}, a value that is many orders of magnitude smaller than the corresponding rate coefficient for a typical three-body reaction such as

$$O + O + M \rightarrow O_2 + M \tag{7.3}$$

with rate coefficient equal to 2.8×10^{-32} cm^3 s^{-1} at 200 K. Hence, the net results of CO_2 photodissociation are

$$2CO_2 \rightarrow 2CO + O_2 \tag{7.4}$$

Thus, a pure CO_2 atmosphere exposed to solar ultraviolet radiation would have large amounts of CO and O_2 at a ratio of 2 : 1. Of course, O_2 cannot build up indefinitely, and eventually it would dissociate:

$$O_2 + h\nu \rightarrow O + O \tag{7.5}$$

We can construct a self-consistent model with reactions (7.1)–(7.5), assuming that the only path for reversing the result of photodissociation (7.4) is the slow reaction (7.2), with the oxygen atoms being supplied by (7.5). Such a model predicts that the mixing ratios of CO and O_2 are 7.72×10^{-2} and 3.87×10^{-2}, respectively. However, the predictions of CO and O_2 are greater than the observed abundances summarized in table 7.2 by factors of 110 and 30, respectively. In addition, the model CO/O_2 ratio of 2 is significantly larger than the observed ratio of 0.5. It is of interest to point out that in this hypothetical model of Mars, the predicted O_3 mixing ratio at the surface is 10^{-5} and the column-integrated O_3 is 3.4×10^{18} cm^{-2} or 126 DU (1 Dobson unit = 2.69×10^{16} cm^{-2}). This amount of O_3 is sufficient for shielding the surface of Mars from harmful ultraviolet radiation.

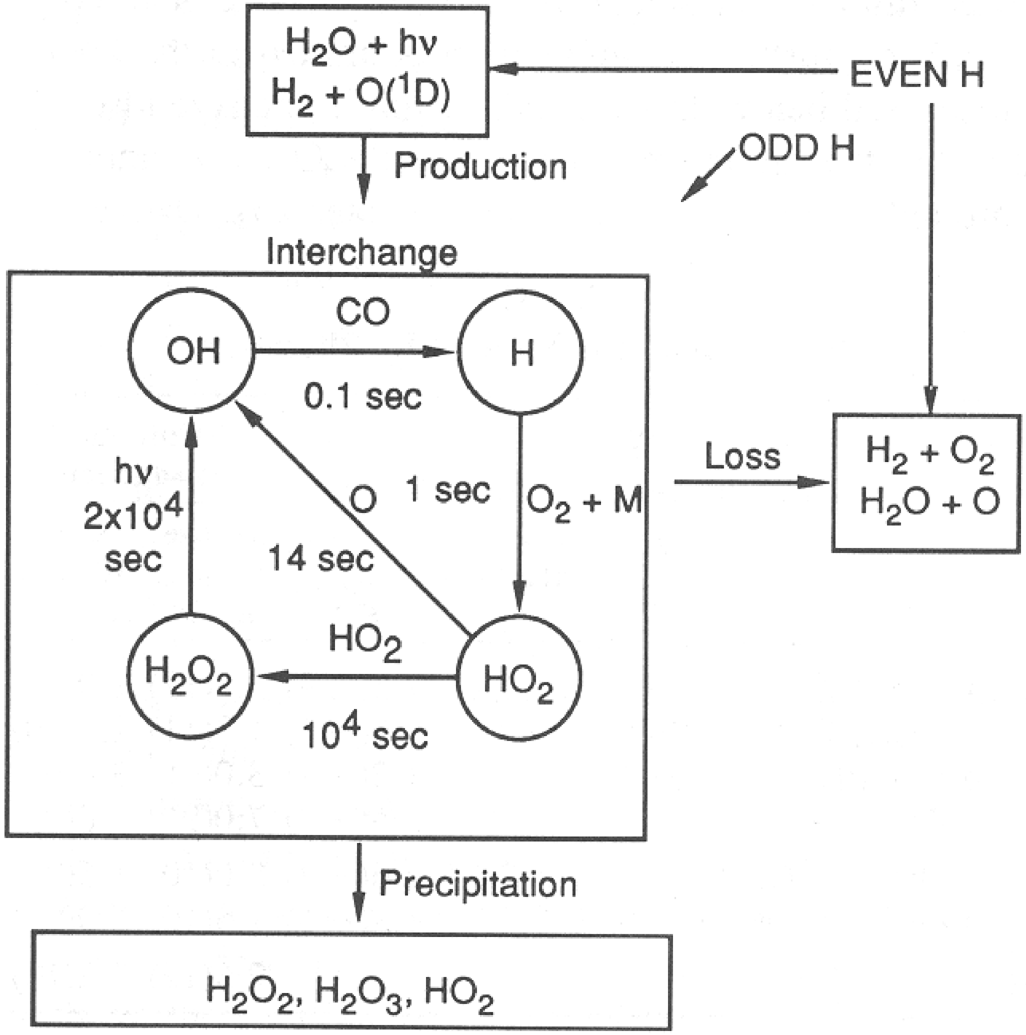

Fig.3. Odd hydrogen: flow diagram for odd hydrogen near the surface of Mars. Beside each arrow is the reaction time in seconds (figure from Chamberlain and Hunten 1987 adapted from Hunten 1979*b*).

From reference 3

From reference 2

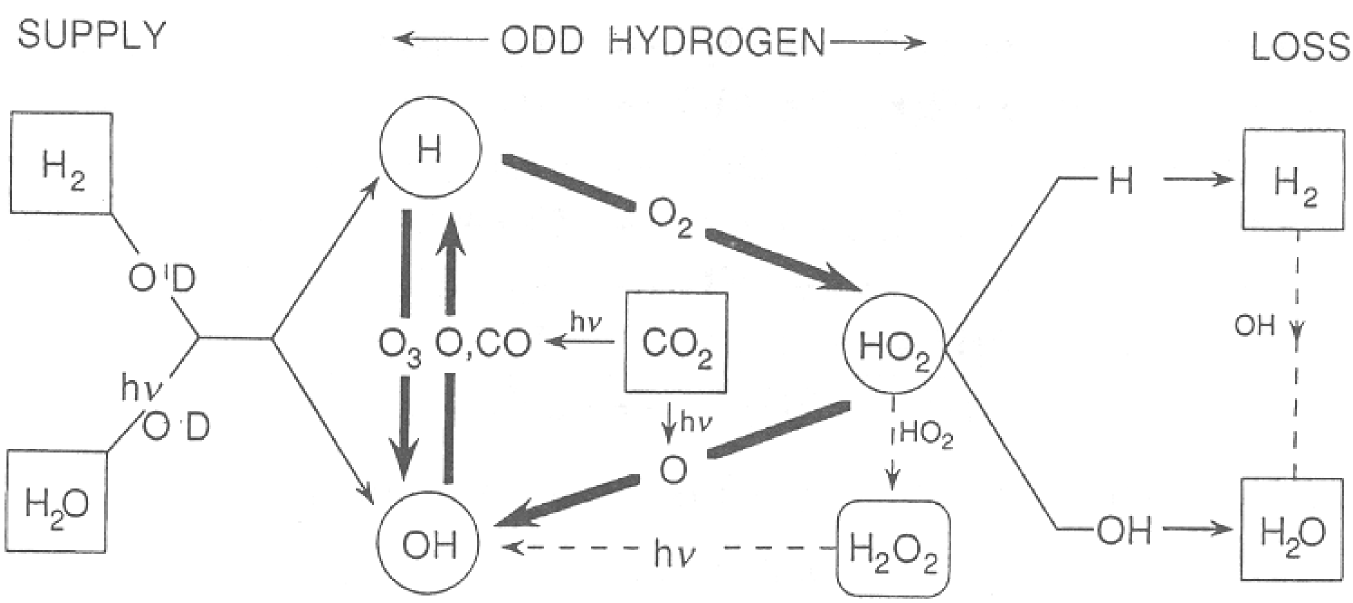

Figure 7.4 Schematic diagram showing the principal pathways for reactions involving hydrogen species. From Nair, H., Allen, M., Anbar, A. D., Yung, Y. L., and Clancy, R. T., 1994, ''A Photochemical Model of the Martian Atmosphere.'' *Icarus* **111**, 124.

From reference 3

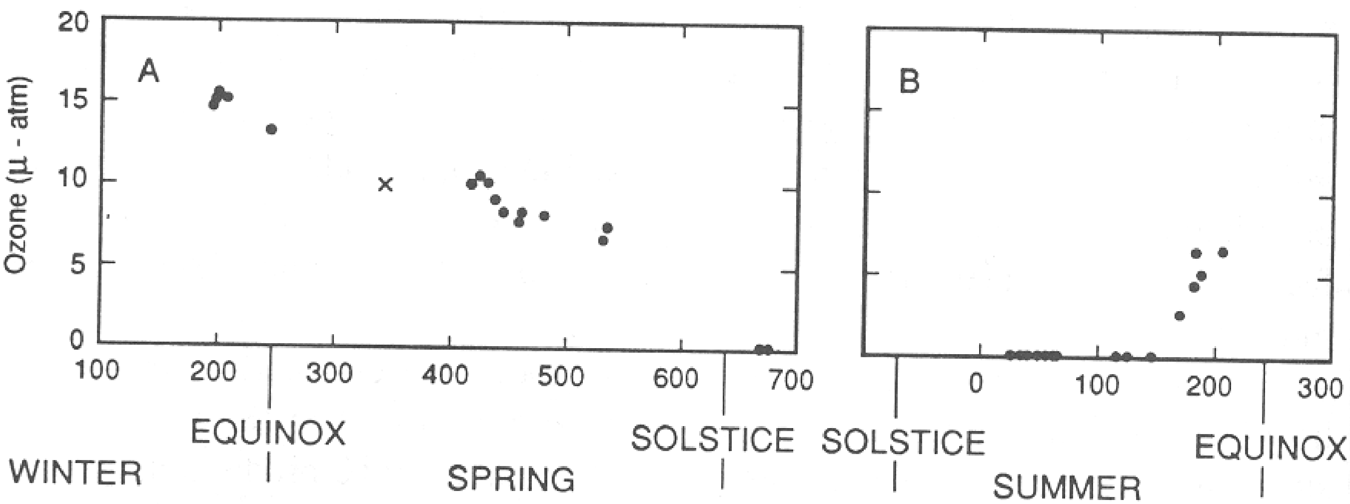

Fig.7. Mariner 9 ozone observations. (A) Amount of ozone observed over the north polar cap during the winter, spring and beginning of summer. The cross refers to the Mariner 7 measurement which was made over the south polar cap in 1969. (B) Amount of ozone observed over the south polar cap during the summer. (figure from Barth et al. 1973).

The sequence of reactions may be summarized as

From reference 2

$$\begin{array}{rrcl} & CO + OH & \rightarrow & CO_2 + H \\ & H + O_2 + M & \rightarrow & HO_2 + M \\ & O + HO_2 & \rightarrow & O_2 + OH \\ \hline \textit{net} & CO + O & \rightarrow & CO_2. \end{array}$$

The net result of chemical scheme (Ia) is the

Ionosphere

- Odd nitrogen is important here
- Photoionization of CO_2 by solar EUV
- Peak plasma density ~ 1E5 cm^{-3} and height of peak is ~ 135 km, also a secondary peak around 115 km. Primary peak is controlled by photochemistry, not dynamics.
- Patchy magnetic field has significant effects.
- Ionopause, or sharp drop in ion densities at top of ionosphere due to solar wind, at about 400 km. Need to look at a Mitchell or Acuna paper for some details here.
- Nightside very poorly constrained
- Many radio occultations of electron density, Viking entry in situ RPA identified species

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

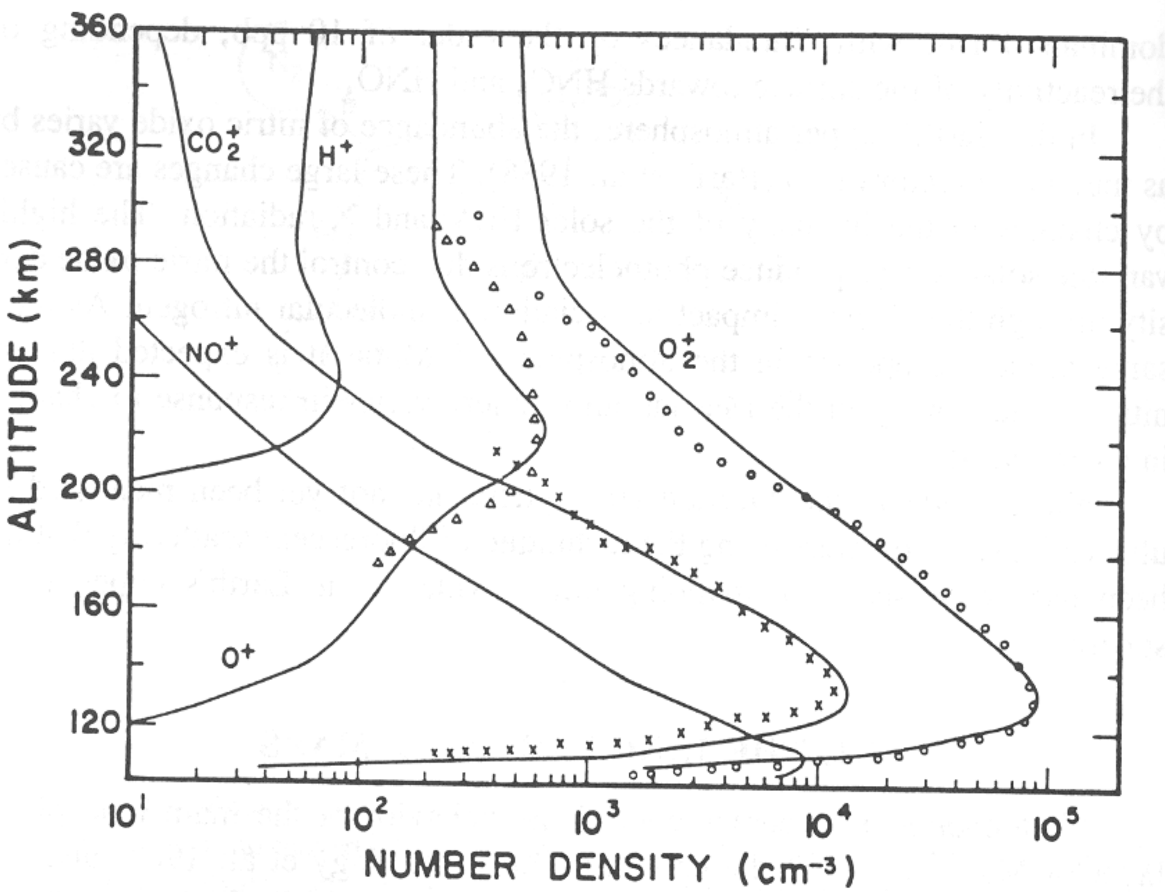

Fig.9. Ion density profiles: ion density profiles in which the solid lines are calculated profiles. The circles are O_2^+ data, the triangles are O^+ data and the crosses are CO_2^+ data; the values were by Chen et al. (1978) from the Viking 1 RPA experiment (Hanson et al. 1977) (figure from Chen et 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_20 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

Modelling Efforts

- 1D coupled chemistry and radiative transfer models. Specify composition and solar flux, model chemical reactions and transfer of energy by radiation and other processes
- 3D General Circulation Models (GCMs). Couple dynamics, chemistry, and energy. Martian upper atmosphere not constrained enough by observations for these to be verified yet.
- Past and future extrapolations of escape rates – how does orbit change, magnetic field, subsurface volatile reservoirs? Current escape processes not measured or modelled with real accuracy.

Venus, Earth, and Mars Compared

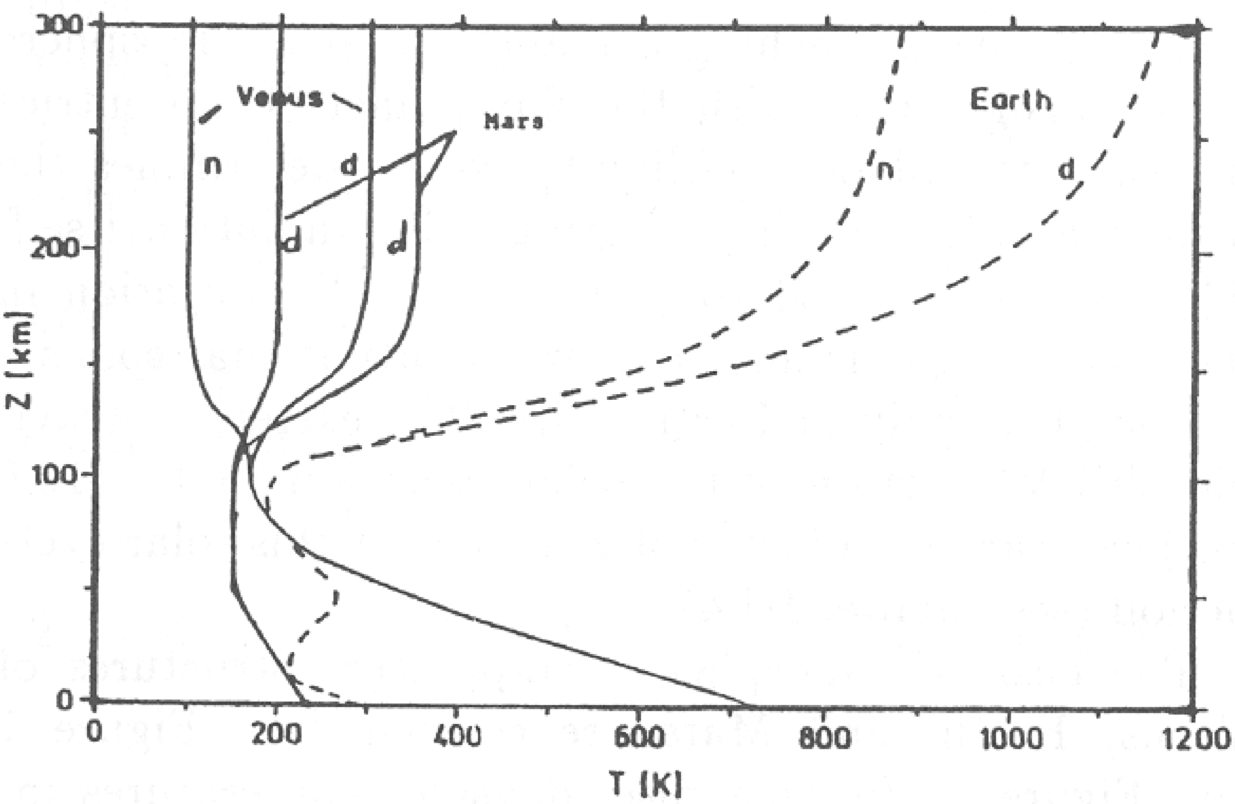

Figure 2. Temperatures of the neutral atmospheres of Earth, Venus, and Mars. Nightside temperatures of the Mars thermosphere (above 130 km) are not measured. Adapted from Fox and Bougher, [1991]

From reference 6

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
0 Abundance (ion peak)	~40%	~7-20%	~1-4%
CO_2 15μm 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

Recent and Upcoming Observations

- MGS RS, ACC, ER, MAG
- Mars Odyssey ACC
- Mars Express ASPERA will measure energetic neutrals, ions, electrons
- Mars Express PFS will measure atmospheric composition via a Fourier spectrometer
- Mars Express SPICAM will measure H_2O and O_3
- Nozomi is doomed
- Mars Reconnaissance Orbiter ACC

Mars Aeronomy Orbiter Discussion

From Belton report

Mars Upper-Atmosphere Orbiter

We include in our priority scheme an orbiter dedicated to studies of Mars' upper atmosphere and plasma environment. Interactions with the solar wind are thought to have played a significant role in the long-term evolution of the martian atmosphere, yet no measurements have been made to confirm or reject these ideas. A variety of atmospheric escape processes have been inferred from indirect measurements and/or predicted from theoretical models. This mission would provide quantitative information on the various potential escape fluxes and, thus, quantify current escape rates. Back extrapolation of such measurements might result in new understanding of the evolution of the martian atmosphere and maybe also provide important clues to atmospheric evolution on Venus and Earth. In carrying out these measurements, numerous other important questions of high scientific value associated with the middle and upper atmosphere, exosphere, ionosphere, solar wind interaction processes will also be addressed.

There are no existing plans in the current U.S. Mars Exploration Program to address any of the scientific questions identified by previous panels in this area. The Nozomi and Mars Express missions will address them to some extent, but much more data will be needed to meaningfully elucidate these issues. The measurements required for this mission could be accommodated as a science package on an international orbiter mission or as a stand-alone mission in the Scout program.

Sources

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