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Mars

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Introduction

The atmosphere of Mars is similar to Earth's; it is thin and relatively transparent to sunlight. Mars' spin rate and axial tilt are also Earthlike. Thus, the Martian atmosphere falls into the category of a rapidly rotating, differentially heated atmosphere with a solid lower boundary. However, there are also important differences. The Martian atmosphere is primarily carbon dioxide with a much lower surface pressure than Earth's; and Mars does not have an Earthlike hydrological cycle, so latent heat release is not as important as it is for Earth. It does, however, contain suspended dust particles, which provide significant diabatic heating.

Mars also appears to have experienced significant climate change. Today, Mars is cold and dry, yet spacecraft images provide tantalizing evidence that the planet's climate was different in the past. Layered terrains in the polar regions may have been created by climate change associated with astronomical variations in Mars' orbital parameters. Valley networks and degraded craters in ancient terrains may be the result of a thicker atmosphere early in Mars' history. And there is some evidence that the planet may have had an ocean at some time in its past, perhaps on several occasions. Thus, Mars is an ideal laboratory for comparative meteorological studies and it may provide insights into the mechanisms responsible for climate change here on Earth.

Composition and Mass

The composition of the Martian atmosphere was determined in the mid 1970s by the *Viking* landers. The results of their measurements are given in **Table 1**. Carbon dioxide is the principal constituent, followed by nitrogen, argon, oxygen, and carbon monoxide. Trace amounts of the noble gases are also present. Additional minor and highly variable constituents include water vapor, ozone, and dust particles. Together, these gases exert a global annually averaged surface pressure of 6.1 hPa, which corresponds to an average column mass loading of 164 kg m^{-2}.

Temperatures

Temperatures depend critically on Mars' orbital parameters (**Table 2**). The main points are that (1) Mars receives about half as much annually averaged

Table 1 Composition of the Martian lower atmosphere (<120 km)

Constituent	*Abundance*
CO_2	95.32%
N_2	2.7%
^{40}Ar	1.6%
O_2	0.13%
CO	0.07%
H_2O	0.03% (variable)
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.04–0.2 ppm (variable)
Dust	0 to $\gg$ 5 (visible optical depth)

Table 2 Orbital parameters for Mars and Earth

Property	*Mars*	*Earth*
Mass (kg)	6.46×10^{23}	5.98×10^{24}
Radius (m)	3 394	6 369
Gravity at surface ($m\,s^{-2}$)	3.72	9.81
Orbit eccentricity	0.093	0.017
Semimajor axis (AU)	1.52	1.0
Solar flux ($W\,m^{-2}$)	590	1 360
Length of year (Earth days)	687	365
Length of solar day (s)	88 775	86 400
Spin-axis inclination (°)	25.2	23.5
Longitude of perihelion (°)	250	285

sunlight as Earth; (2) its orbit is much more eccentric than Earth's; and (3) its rotation rate and obliquity are similar to Earth's. Consequently, Mars is colder, experiences a much greater seasonal change in available insolation (40% compared to 6% for Earth), has Earthlike diurnal and seasonal changes, and has a similar Coriolis parameter.

Except during very dusty periods, the atmosphere of Mars is semitransparent to solar radiation. Consequently, its temperature structure is influenced by thermal emission from the surface. The globally averaged surface temperature on Mars is approximately 215 K. However, because Mars lacks oceans, its surface temperatures undergo considerable seasonal, diurnal, and latitudinal variation.

The lowest surface temperatures (~150 K) occur in polar regions during winter and are associated with the condensation of CO_2 onto the surface. The highest surface temperatures (~300 K) occur in the southern subtropics when Mars is closest to the Sun. In these same regions, diurnal variations can exceed 100 K.

Approximately 10–20% of the radiation emitted by the surface is absorbed in the atmosphere. Some of the absorbed radiation is reradiated back to the surface, producing a modest greenhouse effect. A convenient measure of the greenhouse effect is the difference between the average surface temperature, T_s, and the planet's effective temperature, T_e. For Mars this difference is about 5 K. By comparison, the Earth's atmosphere produces a much stronger greenhouse effect ($T_s - T_e \sim 35$ K) owing to a much greater abundance of water vapor.

Dust particles in the atmosphere strongly influence the transmission of solar and infrared radiation. Based on *Pathfinder* measurements, the mean particle radius is ~1.7 μm. Particles in this size range interact efficiently with sunlight and less so with thermal radiation. During the *Viking* mission, the daily mean temperature at the *Viking Lander 1* site declined by several degrees kelvin during the passage of a dust storm. This suggests that dust particles produce a modest antigreenhouse effect; that is, they reflect more sunlight back to space then they emit to the surface.

Vertical Structure

Temperatures decrease with height in the Martian atmosphere as they do on Earth. As illustrated in **Figure 1**, the variation of temperature with height on Mars gives rise to a troposphere, a mesosphere, and a thermosphere. Mars does not have a stratosphere because it lacks an ozone layer.

The troposphere on Mars is deep by comparison to Earth. Based on *Viking* and *Pathfinder* lander entry measurements, the troposphere on Mars extends to almost 60 km with an average lapse rate of $\sim2.5\,K\,km^{-1}$. On Earth, the troposphere is about 12 km deep, and the lapse rate is $\sim6.5\,K\,km^{-1}$.

On both planets the observed lapse rates are much less than the dry adiabatic lapse rate (**Table 3**). For Earth, this is due to latent heat release associated with the condensation of water vapor. For Mars, the additional heating comes from the absorption of solar radiation by suspended dust particles. On both planets, temperatures are further stabilized by vertical heat fluxes associated with large-scale circulation systems.

Theoretical studies indicate that daytime boundary layer convection could extend to very high altitudes (~15 km) on Mars. In such regions the lapse rates should be close to the adiabatic value. Evidence for deep daytime convection on Mars can be seen in the *Viking Lander 1* entry profile (**Figure 1**), which shows a near adiabatic lapse rate between the surface and 6 km. Above 15 km, temperatures continue to decrease with height, but are controlled almost entirely by radiation rather than convection.

In the Martian mesosphere, temperatures become nearly constant. Superimposed on this structure are oscillations due to the adiabatic heating and cooling associated with vertically propagating planetary waves. These waves are associated with a global

Table 3 General circulation parameters for Mars and Earth

Property	*Mars*	*Earth*
Scale height (km)	10.2	7.6
Mean temperature of lowest scale height (K)	200	260
Dry adiabatic lapse rate ($K\,km^{-1}$)	4.3	9.8
Mean lapse rate of lowest scale height ($K\,km^{-1}$)	2.5	6.5
Brunt–Väisälä frequency ($10^{-2}\,s^{-1}$)	~0.06	1.12
Radiative damping time Earth (days)	~2	> 20
Winter westerly jet speed ($m\,s^{-1}$)	80	30
Planetary Rossby number	0.05	2.0
Rossby deformation radius (km)	920	1 150

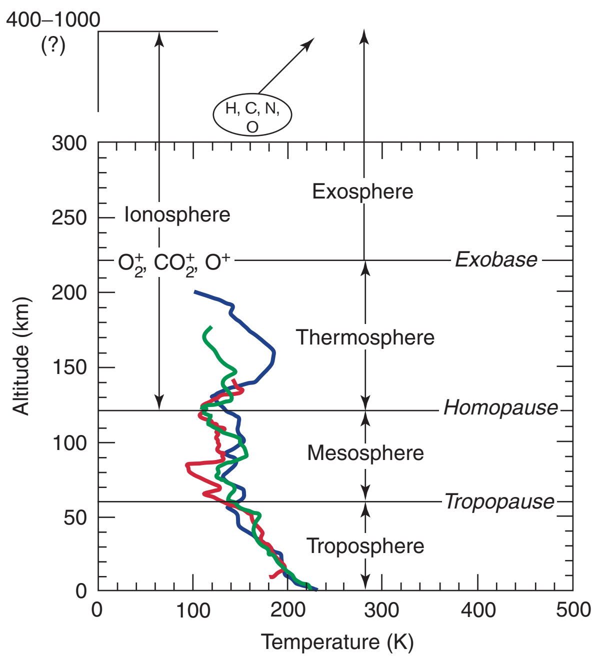

Figure 1 Vertical structure of the Martian atmosphere. Colored curves are temperatures inferred from deceleration measurements aboard the *Viking 1* (blue), *Viking 2* (green), and *Pathfinder* (red) landers.

system of thermal tides. As the tides propagate upward, their amplitude increases. Eventually, they produce superadiabatic lapse rates at which point the waves 'break' and generate local mixing. There are several locations in the *Viking* entry profiles where wave breaking is indicated.

In the thermosphere, temperatures increase because of heating due to the absorption of solar radiation in the far and extreme ultraviolet part of the spectrum. This also occurs on Earth. The base of the thermosphere is about 80 km on Earth and about 100 km on Mars.

Photochemistry

Photochemical reactions occur throughout Mars' atmosphere. Carbon dioxide, the main constituent, is readily dissociated by ultraviolet radiation (eqn [I]).

$$CO_2 + h\nu \rightarrow CO + O \qquad (\lambda < 227.5\,\text{nm}) \qquad [I]$$

However, the reverse reaction (eqn [II], where M is any nonreactive molecule) is very slow, such that the oxygen atoms tend to form O_2 and O_3 rather CO_2.

$$CO + O + M \rightarrow CO_2 + M \qquad [II]$$

The time required to convert the present CO_2 atmosphere into one composed predominantly of CO and O_2 is only several thousand years. Yet CO_2 is the dominant constituent while CO and O_2 are scarce. How CO_2 is stabilized in the Martian atmosphere is a major focus of Martian photochemical studies.

The prevailing view is that CO is oxidized by OH via one of several cycles, the most important being that shown in [III].

$$\begin{aligned} &CO + OH \rightarrow CO_2 + H \\ &H + O_2 + M \rightarrow HO_2 + M \\ &(\text{M is a neutral third body}) \\ &O + HO_2 \rightarrow O_2 + OH \qquad [III] \\ &\textit{Net}: CO + O \rightarrow CO_2 \end{aligned}$$

The OH is derived mainly from the photolysis of water vapor (eqn [IV]) with a minor contribution from reaction [V].

$$H_2O + h\nu \rightarrow H + OH \qquad [IV]$$

$$H_2O + O(^1D) \rightarrow OH + OH \qquad [V]$$

The excited oxygen atom ($O(^1D)$) is derived from the photolysis of ozone as in eqn [VI].

$$O_3 + h\nu \rightarrow O_2 + O(^1D) \qquad [VI]$$

Note that the 'odd-hydrogen' radicals in the above reactions (H, OH, HO_2) are used as catalysts in the recombination of CO and O. Thus, tiny amounts of a reactive species (water vapor) appear to control the bulk composition of the Martian atmosphere.

Although confirmatory measurements of the hydrogen-containing species have not yet been made, support for the importance of water chemistry comes from the distribution and abundance of ozone. Ozone abundances on Mars are much less than on Earth and range from below the threshold of detection in warm tropical regions to as high as 150×10^{15} molecules cm^{-2} in cold polar regions. Ozone is produced when O and O_2 combine, and is destroyed by dissociation by ultraviolet radiation. However, in the absence of additional atmospheric sinks, ozone would be much more abundant than is observed. The H and OH produced by water photolysis provide this additional sink by using the same catalytic cycle that operates in Earth's stratosphere, namely, that shown in [VII].

$$\begin{aligned} &H + O_3 \rightarrow OH + O_2 \\ &O + OH \rightarrow O_2 + H \qquad [VII] \\ &\textit{Net}: O + O_3 \rightarrow 2O_2 \end{aligned}$$

Since the source of odd hydrogen is water vapor, ozone will be depleted in regions where water vapor is abundant, and plentiful in region where it is absent. This anticorrelation between ozone and water vapor has been observed and provides support for the importance of water as a key chemical ingredient of the Martian atmosphere.

Escape Processes

Escape occurs in the exosphere, which begins on Mars at about 230 km. In the exosphere the probability of collisions is so small that particles execute ballistic trajectories, some of which carry them away from the planet. The most important gases that can escape from Mars are hydrogen, oxygen, carbon, and nitrogen.

Molecular hydrogen (H_2) is a product of series of reactions in the lower atmosphere. The net result is a conversion of water to hydrogen and oxygen (eqn [VIII]).

$$2H_2O \rightarrow 2H_2 + O_2 \qquad \text{[VIII]}$$

Most of the hydrogen produced in this manner is removed by reactions with OH and $O(^1D)$, but a small fraction ($\sim$20%) escapes destruction and is transported into the upper atmosphere where it is decomposed into H by reactions with various ionospheric species. Some of the atomic hydrogen produced in this manner has enough thermal kinetic energy to escape into space. Ultraviolet spectrometers aboard the *Mariner 9* spacecraft have detected atomic hydrogen escaping from Mars.

The escape of hydrogen implies that there must be a sink for O_2. Otherwise, the amount of O_2 would double in about 2×10^5 years. Loss of oxygen can occur through the oxidation of surface materials and/or escape to space. Loss to the surface requires the continual exposure of surface materials and is not likely to be significant on the 10^5-year time scales. On the other hand, atomic oxygen is too heavy to escape on the basis of its thermal motion alone. However, it can escape when ionized oxygen molecules (O_2^+) in the ionosphere recombine with electrons. The recombination dissociates the molecule into its constituent atoms with enough kinetic energy to escape. This nonthermal escape mechanism yields an oxygen escape flux that adjusts itself until it balances the hydrogen loss: that is, for every oxygen atom that escapes, two hydrogen atoms also escape. In effect, water is escaping the planet. If extrapolated over the 4.5 billion year age of the planet, the loss is equivalent to a layer of water covering the entire planet to a depth of about 2.5 m.

General Circulation

Although the meteorological database for Mars lacks the coverage needed to fully characterize its general circulation, much can be inferred from it, particularly in connection with general circulation models. **Figure 2** is a schematic illustration of our present understanding of the general circulation. From the data and models, the main components of the general circulation are a zonally symmetric mean meridional circulation, stationary and propagating planetary waves, thermal tides, and a mass flow associated with the seasonal cycling of CO_2 into and out of the polar regions. The latter is a unique feature of Martian meteorology.

The mean meridional circulation dominates the lower latitudes and is characterized by a deep Hadley circulation, which undergoes significant seasonal variation in structure and intensity. At the equinoxes, two roughly symmetric Hadley cells develop that share a common rising branch centered at or near the equator. At the solstices, the two Hadley cells give way to a single cross-equatorial circulation. Models indicate that the intensity of the Hadley cell mass flux varies from 10^9 kg s^{-1} at the equinoxes to 10^{10} kg s^{-1} at the solstices.

The zonal wind component of the mean meridional circulation has been inferred from temperature data through the gradient wind relationship. An illustration of winds derived in this manner is shown in **Figure 3**. Application of the gradient wind relationship to Mars indicates that easterly winds prevail in the tropics at all seasons, and in the summer hemisphere at the solstices. Westerlies prevail in the winter hemisphere at the solstices, and at middle and high latitudes during the equinoxes. If zonal winds at the surface are relatively

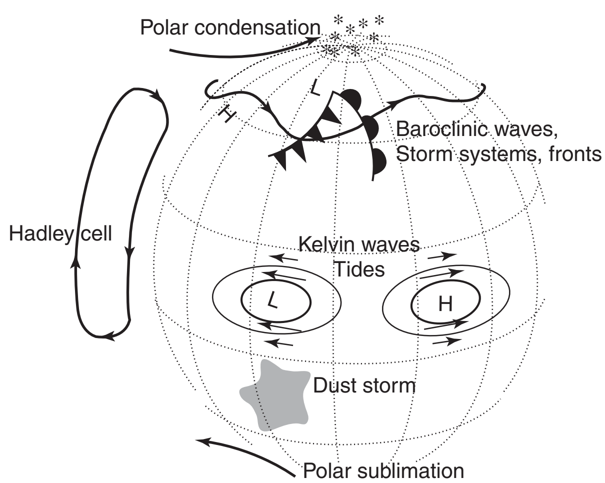

Figure 2 Schematic illustration of the general circulation on Mars.

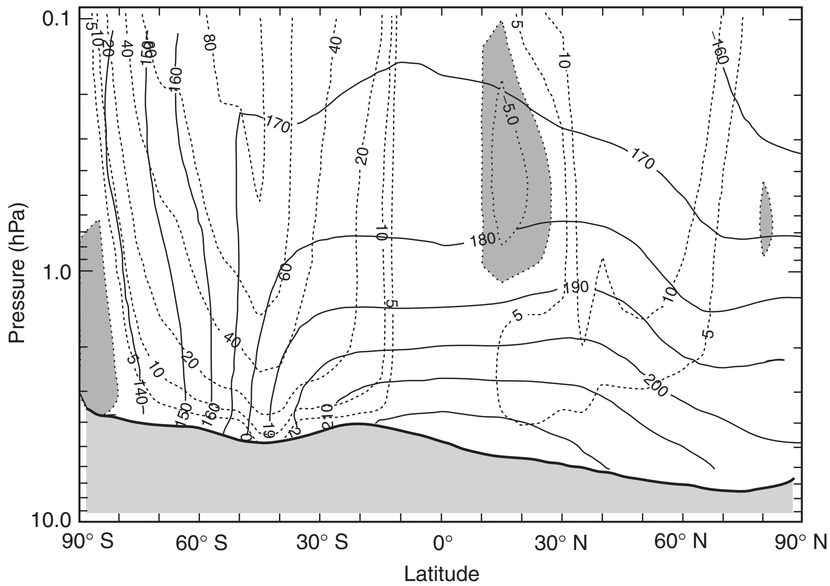

Figure 3 Zonal mean winds derived from Thermal Emission Spectrometer (TES) temperatures data using the gradient wind relationship. Data are averaged over a 30 day period during late southern winter. Solid lines are isotherms (K), dotted lines are isotachs ($m\,s^{-1}$).

weak, as was indicated by the *Viking* and *Pathfinder* landers, then the thermal data indicate that the westerly jet stream in the winter hemisphere is typically on the order of $100\,m\,s^{-1}$.

At high northern latitudes during winter, the *Viking* landers detected eastward-propagating disturbances of high- and low-pressure systems. These traveling disturbances are very similar to terrestrial 'weather' systems in that southerly (northerly) winds are generally associated with falling (rising) pressures and warm (cold) air advection. Theory suggests that the transient eddies arise from baroclinic instability. Both theory and observations indicate that the dominant zonal wavenumber of the transient eddies varies between 1 and 4, and that they propagate around latitude circles with phase speeds between 10 and $20\,m\,s^{-1}$. **Figure 4** is an example of traveling weather system on Mars.

Figure 4 Mars Orbiter Camera (MOC) image of a midsummer Martian weather system. The north polar ice cap is the white feature at the center of each frame. The time between each picture is approximately 2 h. Clouds associated with this system consist of water ice (white) and dust (brown). The distance from edge to edge is approximately 1000 km. (Credit: Malin Space Science Systems.)

Climate System

The climate of Mars is characterized in terms of the seasonal cycles of CO_2, water, and dust. Each of these cycles involves the exchange of material between surface and atmospheric reservoirs. The exchange itself is driven by daily and seasonal variations in insolation. The atmosphere plays a major role in these cycles by serving as the agent of transport. The signature of the Martian climate system is shown in **Figures 5** and **6**.

CO_2 Cycle

During winter, temperatures in the polar regions become low enough for CO_2 to condense. The condensation of CO_2 during winter and its subsequent sublimation during spring give rise to the familiar waxing and waning of the polar caps. Approximately 20% of the Martian atmosphere is cycled into and out of the polar regions each year by this process.

The waxing and waning of the polar caps leads to a pronounced semiannual variation in the daily averaged surface pressure (**Figure 5**). The variation is semiannual rather than annual because while one cap is growing the other cap is retreating. However, the variation is asymmetric, with a much deeper minimum occurring during southern winter than during northern winter. This asymmetry is a direct consequence of Mars' orbital eccentricity. Southern winters are longer than northern winters, so that much more CO_2 condenses out of the atmosphere. As a result, pressures are lowest during the middle of southern winter, and highest in late spring when the cap has disappeared.

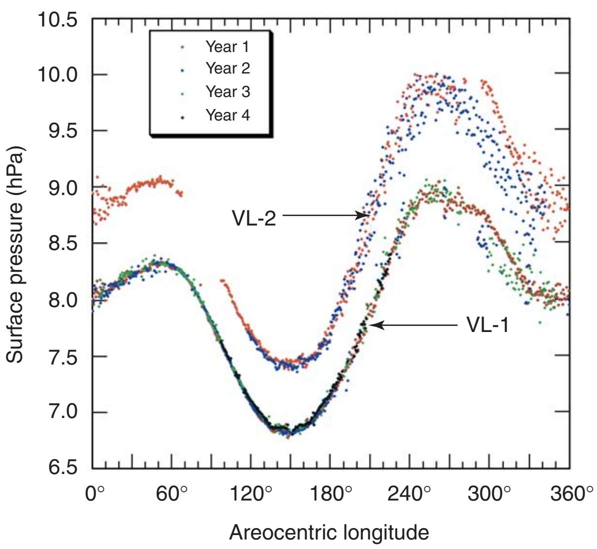

Figure 5 Seasonal variation of the daily averaged surface pressure on Mars measured by the *Viking Landers*.

At both poles, however, the caps never completely disappear during summer. At the north pole the seasonal CO_2 frost deposit completely sublimes by summer, and exposes an underlying water ice cap. At the south pole, however, CO_2 frost appears to survive all summer long. Thus, the summer caps have different compositions. The reason for this compositional asymmetry is not understood.

Water Cycle

The behavior of water vapor in the atmosphere strongly reflects the compositional asymmetry in the summer caps (**Figure 6**). When water ice is exposed at the north pole, it sublimes into the atmosphere and produces the ~100 precipitable micron (pr-μm) maximum that occurs over the north pole. (Precipitable microns refers to the equivalent depth of a column of liquid water produced by condensing out all the water vapor in the atmosphere.) Some of this water is transported equatorward by the atmosphere. In the southern hemisphere during summer, a maximum can also be seen, but it is about a factor of 2 smaller than in the north.

The minimum observed abundances are less than several pr-μm and occur over both polar regions during winter where temperatures reach 150 K (**Figure 6**). Because their temperature is fixed at the CO_2 frost point (~150 K), the seasonal CO_2 caps act as a sink for any atmospheric water vapor that is brought in contact with them. During spring, however, as the caps retreat they release water back into the atmosphere. The source for the southern hemisphere maximum in **Figure 6** may be water released by the retreating south seasonal cap. Alternatively, it may be water that is desorbing directly from the regolith.

Water vapor readily condenses in the Martian atmosphere to form clouds. However, typical cloud water contents are quite low (several pr-μm). Clouds have been observed to form as low-lying fogs, high-altitude hazes, convective clouds, and clouds associated with fronts and lee waves.

Figure 6 also shows the opacity of ice clouds as observed by the *Mars Global Surveyor* (MGS) spacecraft. They generally occur in two distinct regions: along the edge of the polar caps, and in the tropics during northern summer. The cap edge clouds are associated with what is historically referred to as the 'polar hood'. They form during winter owing to general cooling and during summer owing to the release of water from the retreating cap. The cap edge clouds in the north are more optically thick than those in the south. The northern summer tropical clouds are mostly widespread hazes. These hazes are most prevalent during northern summer because this is the

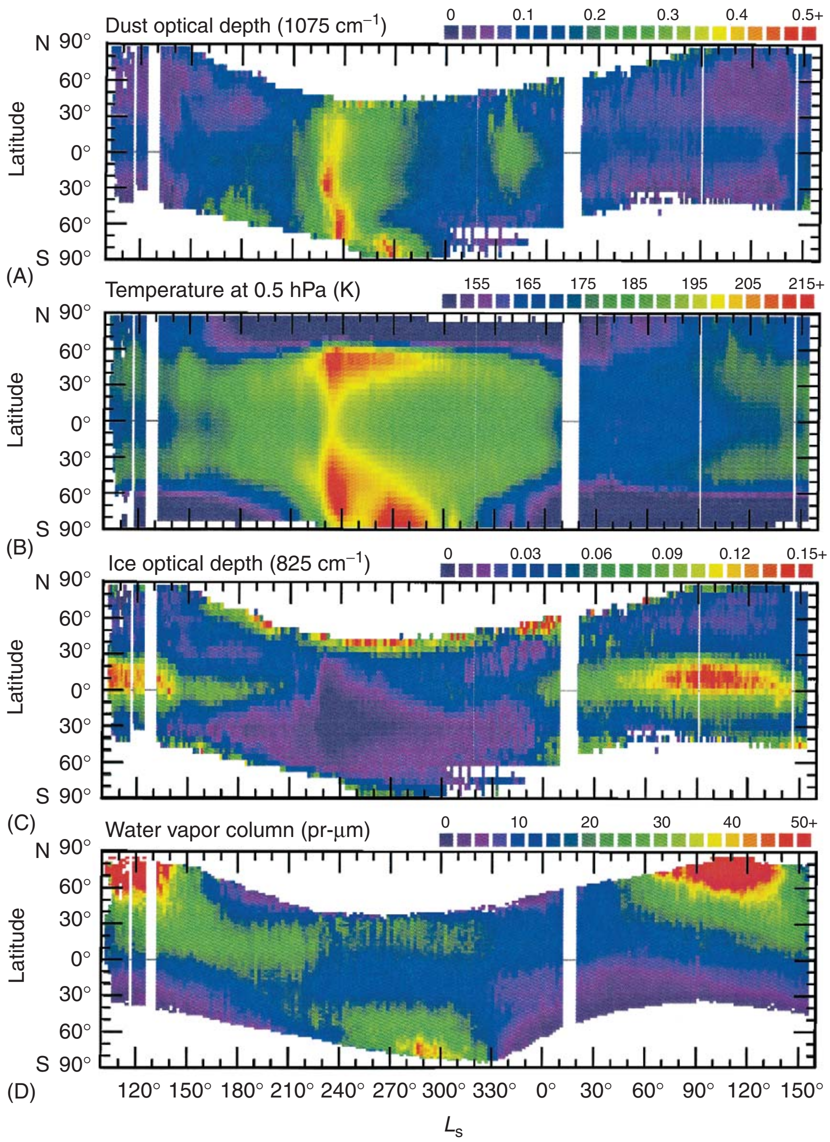

Figure 6 One Mars year of TES zonally averaged afternoon observations as a function of latitude and season. Season is expressed in terms of the areocentric longitude, L_s, which is an angular measure of the planets orbital position, $L_s = 0$ corresponds to northern spring equinox; $L_s = 90$ is northern summer solstice; $L_s = 180$ is northern fall equinox; and $L_s = 270$ is northern winter solstice. (A) 9 μm dust optical depth at 6.1 hPa. (B) Atmospheric temperatures (K) at 0.5 hPa (~25 km). (C) 12 μm water ice optical depth. (D) Water vapor column abundance in precipitable microns (the depth liquid water would have by condensing out all the water vapor in a column of air of unit cross-sectional area). White vertical stripes represent data gaps. (Credit: Michael Smith and the TES Team.)

time of year when water vapor abundances are high and tropical atmospheric temperatures are cool.

Dust Cycle

The surface of Mars is mantled with a fine dusty material that is lifted into the atmosphere when surface winds become strong enough to initiate particle motion. Because of the low density of the Martian atmosphere, dust-raising winds must be quite strong. Surface winds gusting to $30\,\mathrm{m\,s^{-1}}$ were measured by the *Viking 1 Lander* during the passage of a dust storm. Apparently, this is the minimum wind speed required to initiate lifting. However, the dust-raising process is complicated and the threshold for lifting can vary depending on surface properties and atmospheric stability.

Numerous dust storms occur each Martian year and are generally classified according to size. From the smallest to largest, they are dust devils ($<10^{-1}\,\mathrm{km}^2$), local storms ($\sim 10^3\,\mathrm{km}^2$), regional storms ($\sim 10^6\,\mathrm{km}^2$), and planet-encircling storms ($>10^6\,\mathrm{km}^2$). In general, the smaller storms have shorter lifetimes and occur much more frequently than the larger storms. Dust devils, for example, occur daily and last from minutes to hours, whereas planet-encircling storms occur quasi-annually and can last for months.

Dust devils are typically tens of meters in diameter and several kilometers tall. Some have been observed to heights of ~8 km. They generally form over smooth terrain within several hours of local noon. The *Pathfinder Lander* meteorology sensors detected 79 dust devils over a period of 83 days. From orbit these systems have been detected from the shadows they produce, and from the trails they leave on the surface (**Figure 7**). Dust devils are believed to be major contributors to the dust loading of the Martian atmosphere.

Local dust storms are also quite common. Based on recent MGS images, as many as 2000 local storms occur each Martian year. This gives a daily averaged rate of 2–3 storms per Martian day. They have typical lifetimes of less than several days. Local dust storms tend to form along the edge of the polar caps and in the mid-latitudes of both hemispheres. These systems often have a distinct convective morphology and can be quite optically thick.

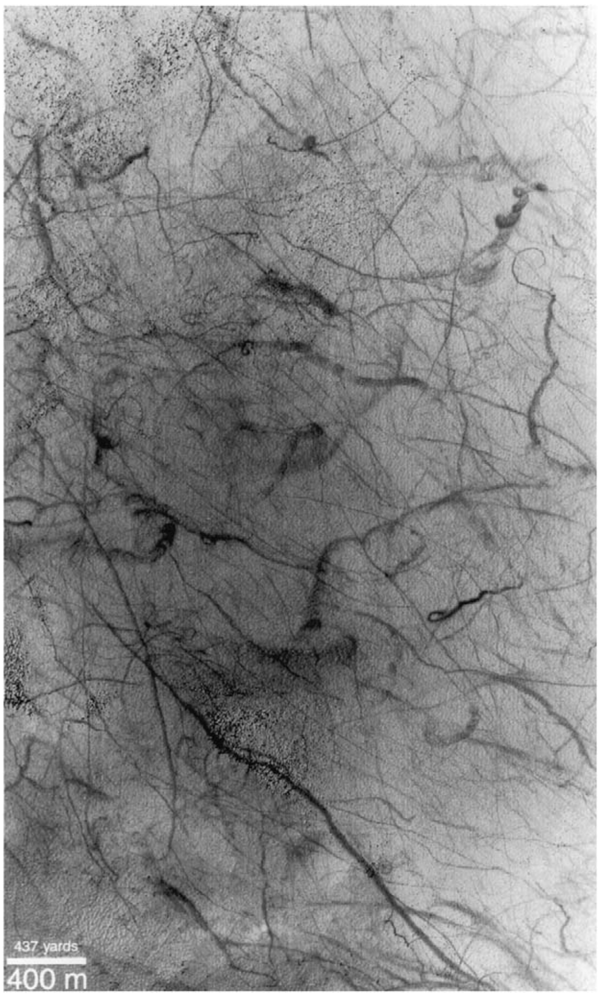

Figure 7 Dust devil trails. Dust devils remove fine, bright, sandy material from the surface and expose a darker underlying bedrock. (Credit: Malin Space Science Systems.)

Regional storms have been observed at nearly all seasons but are most frequent during southern spring and summer. Most regional storms develop within ±30° of latitude, though there is a distinct bias toward the southern hemisphere. Regional storms can last from days to weeks. These storms can drift a significant distance from their original location, and new satellite storms can develop that are quite remote from the original center. The MGS has observed two such storms. The signature of the first one can be seen in **Figure 6**.

Planet-encircling storms are the least frequent but the most spectacular of Martian dust storms. They spread dust around all longitudes and most latitudes to heights in excess of 50 km. They generally begin in the southern hemisphere during southern spring and summer. None have been observed at other seasons. They start as regional storms and then expand in longitude then in latitude. The *Viking* landers observed two planet-encircling storms during the first year of operations (**Figure 8**). To date only seven planet-encircling storms have been observed. The most recent occurred in late June 2001 and was seen from Earth and the MGS orbiter.

The mechanisms responsible for the Martian dust storms are poorly understood. Dust devils are probably related to strong daytime convective heating as they are on Earth. For the larger storms, however, feedback effects are probably important. The most important feedback is the dust heating feedback. Suspended dust particles warm the atmosphere by direct absorption of sunlight. This then intensifies the circulation, which lifts additional dust. This positive feedback continues until the dust loading is so high that the atmosphere stabilizes and further lifting is suppressed.

Quasi-Periodic Climate Change

Both polar regions on Mars are characterized by extensive layered terrains, which are among the youngest geological features on the planet. The layered structure consists of series of plates of varying thickness (~30 m) that are stacked one upon the other. The fact that they are continuous and uniform suggests they were formed by atmospheric sedimentation processes that were modulated in time.

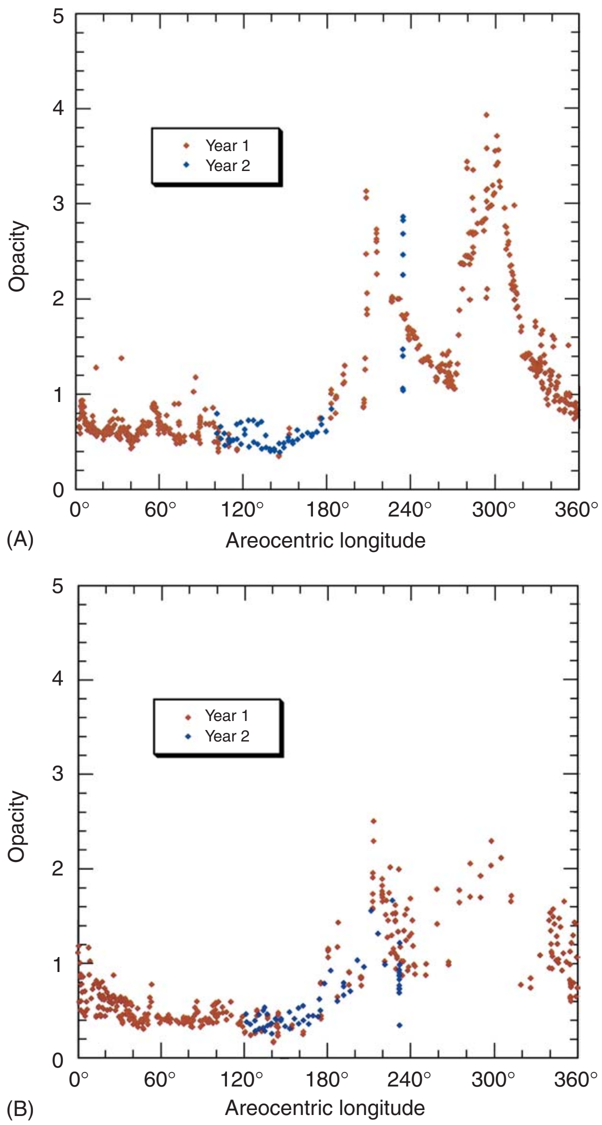

Figure 8 Seasonal variation in the visible optical depth observed by (A) *Viking Lander 1* and (B) *Viking Lander 2*. The sharp increases seen around $L_s = 210°$ and $270°$ correspond to global dust storms.

The leading theory on the origin of the layered terrains is the astronomical theory. According to this theory, Mars' orbital parameters vary in a quasi-periodic fashion and this alters the transport and subsequent sedimentation of dust and water into the polar regions. The key orbital parameters are the obliquity, eccentricity, and longitude of perihelion, which vary on time scales from 10^5 to 10^6 years.

The theory focuses mostly on the effect of changes in the obliquity. The current obliquity for Mars is 25.2°, but orbit calculations suggest it has varied from between 15° and 45° during the past 10 million years, and may have been as high as 60° before that. As the obliquity increases, the polar regions warm with respect to the equator and this has two important consequences. First, any CO_2 stored in the high-latitude regolith will be driven into the atmosphere, thereby increasing surface pressures. Higher surface pressures lead to greater dust lifting and greater dust transport into the polar regions. Second, water ice will be driven off the pole and into low-latitude reservoirs such as permafrost. Thus, polar layers forming at high obliquities would be dominated by dust.

At low obliquities the opposite occurs. The polar regions cool with respect to the equator. CO_2 migrates back into the high-latitude regolith and eventually the atmosphere freezes out, forming permanent CO_2 ice caps. The surface pressures fall so low that dust lifting ceases and there is no transport of dust into the polar regions. At the same time, water diffuses out of the low-latitude permafrost and is cold-trapped out at the poles, leading to the creation of an ice sheet whose thickness is limited by the amount of water stored as permafrost and its ability to diffuse through the soil and into the atmosphere. Thus, polar layers forming at low obliquity would be predominately water ice.

One problem with the astronomical theory is the estimated age of the layered deposits. From crater statistics, the surface of the north layered deposits appears to be $<10^5$ years old, while the south polar layered deposits appear to have been stable for at least 10^7 years. These ages are not well correlated with the time scale for orbital oscillations, so other processes must be involved. Nevertheless, orbitally induced climate change must be significant on Mars.

Origin and Evolution

There are several lines of evidence that suggest Mars began with an atmosphere much different from the one it has today. The first are geochemical in nature and are based on measurements of the isotopic abundance of various gases in the atmosphere. The second are geological in nature and are based on the morphology of the surface and its implications for fluid flow. Both lines of evidence favor an initial atmosphere containing much more CO_2, N_2, and water than it has today. However, they differ in the initial abundance of these gases; the geochemical evidence favors low initial abundances (hundreds of hPa), while the geological evidence favors high initial abundances (thousands of hPa).

There is also geological evidence for warmer and wetter conditions early in Mars' history. The evidence is based mainly on valley network systems and highly eroded craters that are found on surfaces that date back an estimated $3.5–3.8\times10^9$ y. Both these features are thought to require the action of liquid water over extended periods of time. A good example of a valley system is shown in **Figure 9**. Extensive ancient layered sedimentary deposits and the possible presence of an ocean also make the case for a warm early mars. Taken together, these observations imply that early Mars not only had a thicker atmosphere, it had a climate system capable of supporting an active hydrological cycle with precipitation and runoff.

One way to achieve warmer and wetter conditions on early Mars is through a greenhouse effect. A particularly strong greenhouse effect ($\sim$77 K) is required since the Sun was 25% less luminous 3.5–3.8 billion years ago. The most likely greenhouse gases are CO_2 and water vapor. These gases could easily have been supplied by the intense volcanic activity thought to characterize early Mars. However, climate models have not convincingly demonstrated that pure CO_2/H_2O atmospheres are sufficient. Special circumstances, such as infrared-scattering CO_2 ice clouds or additional reducing greenhouse gases such as methane, need to be invoked. Thus, the nature of the early Martian climate systems remains unknown.

Figure 9 Nanedi Vallis. This valley system ($\sim$2.5 km wide) may have been cut by the continuous flow of water very early in Mars' history (3.8 billion years ago). (Credit: Malin Space Science Systems.)

If Mars did start out with a more massive atmosphere than it has today, then how has it evolved to its present state? If a strong enough greenhouse effect did exist, then much of the original CO_2 would have been drawn out of the atmosphere and incorporated into the carbonate rock reservoir. Recycling CO_2 back into the atmosphere through volcanic activity or impact burial is not expected to have lasted very long on Mars because of its small size and subsequent rapid loss of internal heat. Thus, carbonate formation should have been largely irreversible. Yet the MGS orbiter has not detected any substantial outcrops of carbonate deposits.

Other sinks for an early thick atmosphere include impact erosion and escape. The small size of the planet makes it easier for large impactors to strip away the atmosphere. As much as 100 times the present atmospheric mass may have been lost by this process. Escape is also facilitated by the planet's small size, but for CO_2 escape is more significantly enhanced by the lack of a magnetic field. Without the protection of the magnetic field, Mars is unable to hold off the solar wind, which can energize O^+ ions in the upper atmosphere to levels sufficient to eject a CO_2 molecule directly after a collision. This process, known as sputtering, is sensitive to solar extreme ultraviolet flux, whose history is uncertain. However, conservative calculations show that several hundred hPa could have easily been lost over the history of the planet.

The Future

Mars has become a high-priority target for exploration and atmospheric science is a key objective of many of the missions to be launched. The European Space Agency will launch the Mars Express mission in 2003, which will carry a number of instruments for atmospheric studies including a visible/infrared spectrometer to map the thermal and compositional structure of the atmosphere. In 2005, the United States National Aeronautical and Space Administration plans to launch an orbiter carrying a dedicated infrared atmospheric sounder to profile temperature and water vapor. In 2007, the French space agency, Centre

National d'Etudes Spatiales, is planning a mission that would deliver an orbiter with a microwave sounder for continued atmospheric profiling, and a network of four landers to carry out seismological and meteorological measurements These missions will continue to add to our knowledge of the meteorology and climate of Mars.

See also

Aerosols: Physics and Chemistry of Aerosols. **Boundary Layers:** Neutrally Stratified Boundary Layer. **Chemistry of the Atmosphere:** Principles of Chemical Change. **Climate:** Overview. **Climate Variability:** Seasonal to Interannual Variability. **Clouds:** Climatology. **Evolution of Atmospheric Oxygen**. **Evolution of Earth's Atmosphere**. **General Circulation:** Overview. **Planetary Atmospheres:** Jupiter and the Outer Planets; Mars; Venus.

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Venus

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Introduction

Venus is the Earth's sister planet, 0.723 times as far from the Sun as is the Earth. Its radius (6052 km) and mass (4.869×10^{24} kg) are 95% and 82% of the Earth's. Thus, in size and distance from the Sun it is quite similar to Earth, but its atmosphere is strikingly different from the Earth's. The atmosphere of Venus is much more massive, with a mass per square meter of 10.8 kg m^{-2} compared to 0.1 kg m^{-2} on Earth. It is composed of carbon dioxide (96.5% mole fraction) and molecular nitrogen N_2 (3.5%) plus traces of other gases. A hydrosphere is absent on Venus. There is a very low abundance of water in any form. These compositional differences point to a drastically different evolution of the Venusian and terrestrial atmospheres through geological history.

The current state of the Venusian atmosphere also shows great differences from that of the Earth. There is a strong greenhouse effect, which raises the surface