Planetary Atmospheres: Mars

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Synopsis

The Martian atmosphere is mainly CO_2 with a mean surface pressure of 6.1 mb. Its thermal structure, wind systems, and photochemistry are similar to Earth's but with important differences. The present climate is characterized in terms of the seasonal cycles of dust, water, and CO_2. Past climates were different due to large changes in Mars' orbital characteristics, and a thicker atmosphere that existed very early in its history. Liquid water flowed on the surface at these early times, but is not stable on Mars today.

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, it falls into the category of a rapidly rotating, differentially heated atmosphere with a solid lower boundary. However, there are important differences. The Martian atmosphere is primarily carbon dioxide with a much lower surface pressure, and Mars does not have oceans and 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 do provide significant diabatic heating.

Mars also appears to have experienced significant climate change. Today, Mars is cold and dry. Yet spacecraft images provide compelling 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' orbit 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.

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 mean annual surface pressure of 6.1 mb, which corresponds to an average column mass loading of 164 kg m^{-2}. More recent measurements by the Mars Science Laboratory confirm the Viking measurements, but find equal abundances for N_2 and ^{40}Ar (both 1.9%). The change may be the result of different measurement techniques and/or an indication of time variable phenomena.

Temperatures

Temperatures depend critically on Mars' orbit parameters. These are listed in Table 2. The main points are that (1) Mars receives about half as much annually averaged 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. Models indicate that the globally averaged surface temperature on Mars is $\sim$200 K. However, because Mars lacks oceans, its surface temperatures undergo considerable seasonal, diurnal, and latitudinal variation. The lowest surface temperatures ($\sim$150 K) occur in the polar regions during winter and are associated with the condensation of CO_2 on the surface. The highest surface temperatures ($\sim$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 emission temperature T_{se} ($\sim$215 K) and the planet's effective temperature T_{eff} ($\sim$210 K). For Mars, this difference is about 5 K. By comparison, the Earth's atmosphere produces a much stronger greenhouse effect ($\sim$33 K) due to a much greater abundance of water vapor and other greenhouse gases.

Table 1 Composition of the Martian lower atmosphere (<120 km); the global mean annual surface pressure is $\sim$6.1 hPa

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)

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Table 2 Orbital parameters for Mars and Earth

Property	*Mars*	*Earth*
Mass, kg	6.46×10^{23}	5.98×10^{24}
Radius, m	3394	6369
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	1360
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

Dust particles in the atmosphere strongly influence the transmission of solar and infrared radiation. Based on lander and orbiter measurements, their mean particle radius is ~1.5 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 (i.e., they reflect more sunlight back to space than they emit in the infrared range 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,

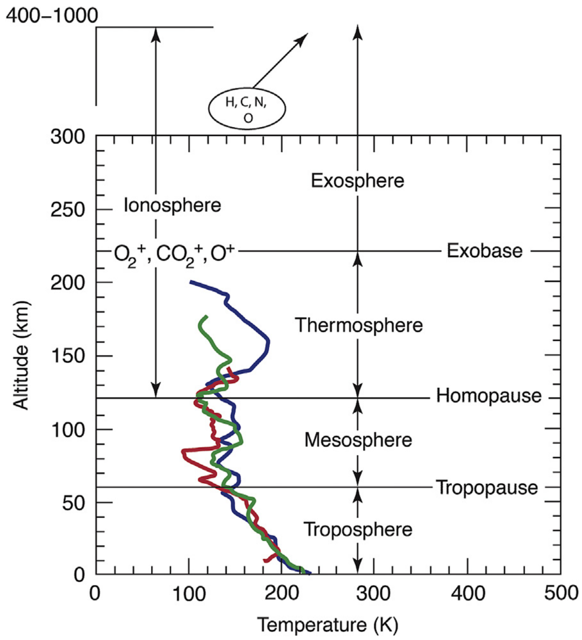

Figure 1 Vertical structure of the Martian atmosphere. Colored curves are temperatures inferred from deceleration measurements aboard the Viking 1 (blue), Viking 2 (green), and Pathfinder (red) Landers.

a mesosphere, and a thermosphere. Mars does not have a stratosphere because it lacks a significant 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 ~2.5 K km^{-1}. On Earth, the troposphere is about 12 km deep, and the lapse rate is ~6.5 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 (~10 km) on Mars. In such regions, the lapse rates should be close to the adiabatic value. Evidence for deep daytime convection on Mars was found in the Viking Lander 1 entry profile (Figure 1), which indicated 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 isothermal. 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 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 radiation in the far and extreme ultraviolet ranges. 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 the Mars atmosphere. Carbon dioxide, the main constituent, is readily dissociated by ultraviolet radiation:

$$CO_2 + h\nu \rightarrow CO + O\left(\lambda < 2275\ \text{Å}\right)$$

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, days	~2	>20
Winter westerly jet speed, m s^{-1}	80	30
Planetary Rossby number	0.05	2.0
Rossby deformation radius, km	920	1150

However, the reverse reaction

$$CO + O + M \rightarrow CO_2 + M$$

(where M is any nonreactive molecule) is very slow such that the oxygen atoms tend to form O_2 and O_3 rather than CO_2. 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

$$CO + OH \rightarrow CO_2 + H$$

The OH itself is ultimately derived from the photolysis of water vapor. Thus, even though water vapor is a minor constituent, it may play a very important role in maintaining CO_2 as the dominant constituent. Support for the importance of this water chemistry comes from the detection of molecular hydrogen (H_2) in the atmosphere and the distribution and abundance of ozone.

Ozone abundances on Mars are much less than on Earth, and they range from below the threshold of detection in warm tropical regions to as high as 150×10^{15} molecules cm^{-2} in the cold polar regions. Ozone is produced when O and O_2 combine, and is destroyed by ultraviolet dissociation. However, in the absence of additional atmospheric sinks, ozone would be much more abundant than 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

$$\begin{array}{l} H + O_3 \rightarrow OH + O_2 \\ O + OH \rightarrow O_2 + H \\ \hline \text{Net} : O + O_3 \rightarrow 2O_2 \end{array}$$

Since the source of odd hydrogen is water vapor, ozone will be depleted in regions where it 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.

During the early 2000s, methane (CH_4) was detected in the Martian atmosphere at the 10 ppb level. The detection is significant since none is expected and its presence at these levels could be the result of a biological source. However, the reported seasonal and latitudinal variability has been difficult to explain since methane is expected to have a long lifetime (200–300 years). This variability implies there are strong sources and sinks for methane, which have yet to be identified and confirmed. Furthermore, the Mars Science Laboratory did not detect any significant methane in the Martian atmosphere during its first year of operations. Thus, the validity of the earlier measurements is controversial.

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, and nitrogen.

Molecular hydrogen (H_2) is one of the products of water vapor photolysis. Below the homopause, H_2 is well mixed and has a long lifetime (10^3 years). Above the homopause, it is converted into atomic hydrogen and has enough thermal kinetic energy to escape to 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 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 – known as 'dissociative recombination' – yields an oxygen escape flux that is theoretically expected to adjust itself until it balances the hydrogen loss (i.e., for every oxygen atom that escapes, two hydrogen atoms also escape). In effect, water would be leaving the planet. However, observations suggest that the oxygen escape flux is much less than this prediction, indicating that the atmosphere is not in redox balance at the present time.

General Circulation

Although the meteorological database for Mars lacks the temporal and spatial 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.

To some extent, the Hadley cell is a mathematical construct in that the circulation is not in itself zonally uniform. In the rising branch, for instance, much of the upward motion may take place in narrow convective plumes embedded in a broader pattern of overall sinking motion. When averaged over longitude, the net result is upward flow. Thunderstorms play such a role in the Earth's tropics. While there are good theoretical reasons to expect that a similar situation exists on Mars, better observations are needed to confirm this.

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

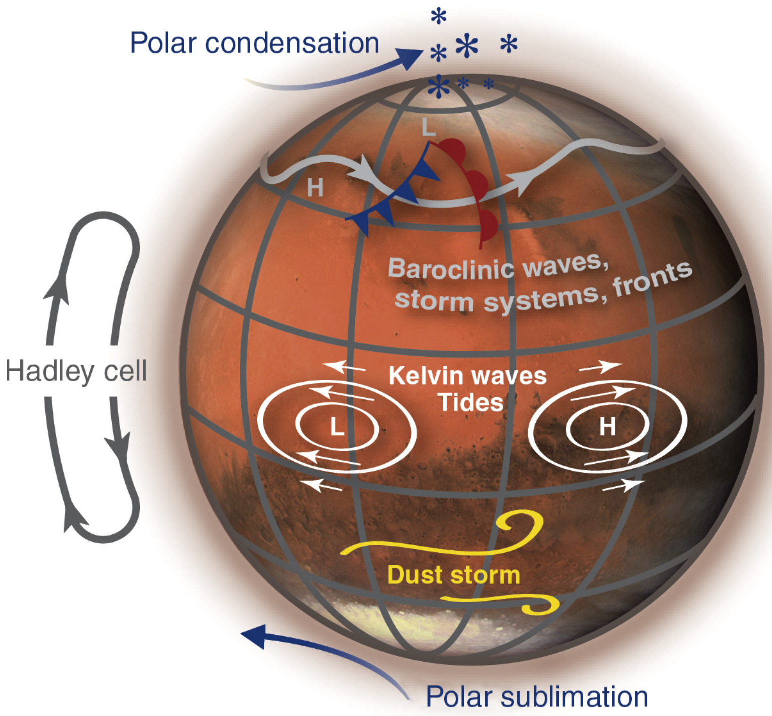

Figure 2 Schematic illustration of the general circulation on Mars.

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 weak, as was indicated by the Viking, Pathfinder, and Phoenix 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

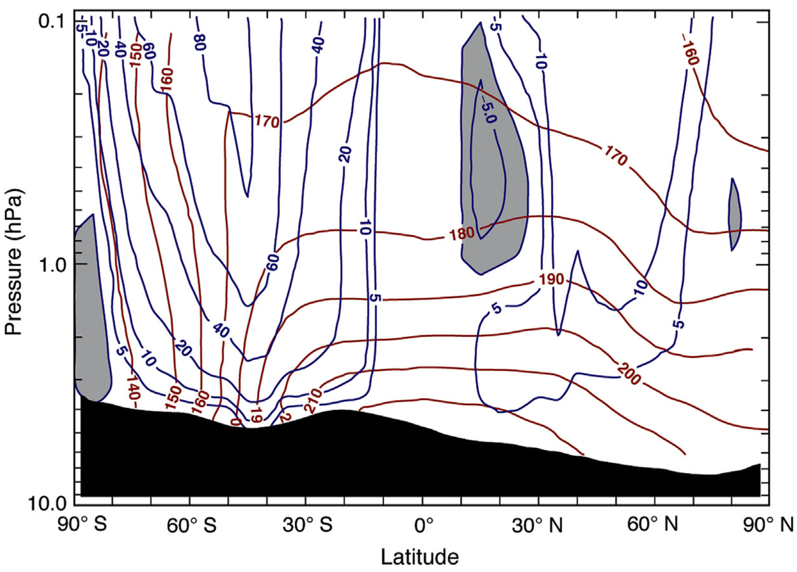

Figure 3 Time-averaged zonal mean winds as a function of latitude and pressure (altitude) for winter in the southern hemisphere. Winds are derived from thermal emission spectrometer (TES) data using the gradient wind relationship. Red-colored contours are isotherms (K); blue-colored contours are wind speed (m s^{-1}).

and warm (cold) air advection. Theory suggests that the transient eddies arise from baroclinic instability. Both theory and observations indicate that the dominant zonal wave number 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}.

Dust Storms

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. Viking Lander 1 measured surface winds gusting to 30 m s^{-1} during the passage of a dust storm, suggesting that 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 ($<10^{-1}$ km^2), local storms ($\sim 10^3$ km^2), regional storms ($\sim 10^6$ km^2), and planet-encircling storms ($>10^6$ 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 quasiannually 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 $\sim$8 km. They generally form over smooth terrain within several hours of local noon. From orbit, these systems have been detected from the shadows they produce and from the trails they leave on the surface. From the surface, they have been detected in meteorological data and camera images. Dust devils are believed to be significant contributors to Martian atmospheric dust loading.

Local dust storms are also quite common. Based on Mars Global Surveyor (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 at the midlatitudes of both hemispheres. These systems often have a distinct convective morphology and can be quite optically thick.

Regional storms have been observed at nearly all seasons, but are most frequent during southern spring and summer. Most regional storms develop within $\pm 30°$ of latitude, although 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.

Planet-encircling storms are the least frequent but the most spectacular of Martian dust storms (Figure 4). 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. To date, eight planet-encircling storms have been confirmed. The most recent occurred in late April 2009 and was observed by the Mars Reconnaissance Orbiter (MRO).

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, radiative feedback effects must be important. Suspended Martian dust particles interact efficiently with sunlight. Thus, as dust loading increases, so does the direct in situ heating of the atmosphere. This then intensifies the circulation, which lifts additional dust. This positive feedback continues until the supply of mobile dust particles on the surface is exhausted, or the dust loading becomes so high that the atmosphere stabilizes and further lifting is suppressed.

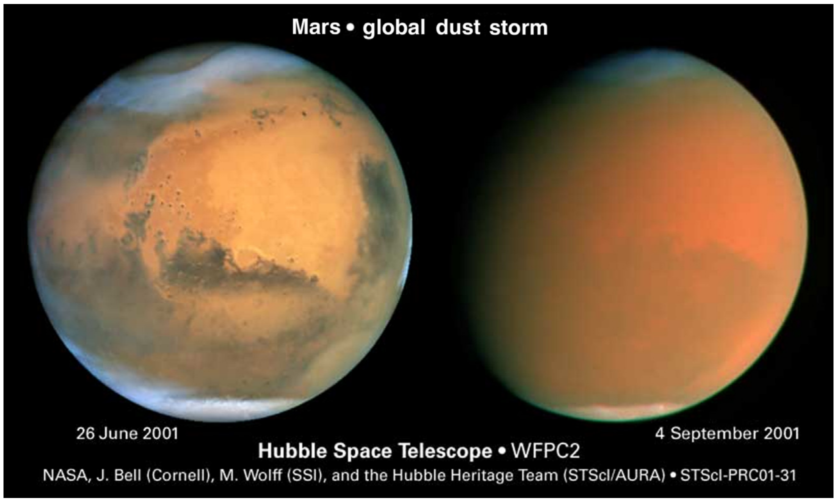

Figure 4 Hubble Space Telescope images of Mars before (left) and during (right) the 2001 global dust storm.

Clouds

Water vapor in the Martian atmosphere is controlled by saturation. Thus, water–ice clouds are fairly common. However, their water content is generally low (several pr-μm). Clouds are most prominent during northern summer in the tropics and during winter in the polar regions. The northern-summer tropical clouds are commonly referred to as the aphelion cloud belt (ACB) since Mars is near its aphelion at this season. These clouds form at altitudes above 15 km and are generally diffuse, although optically thick clouds can often be seen over the volcanoes in the Tharsis province (Figure 5). The winter polar clouds form in the lowest scale height and are called 'polar hoods.' These clouds are widespread, are optically thick, and often contain wave clouds forced by topographic obstacles such as craters. The north polar hood is more prominent than the south polar hood. In general, water ice clouds are more common in the northern hemisphere than in the southern hemisphere.

The size and shape of Martian water ice clouds are not well constrained. Retrievals from remote-sensing data indicate that their effective radii are typically in the 1–4 μm range, although light detection and ranging measurements at the Phoenix Lander site suggest sizes as large as 35 μm in clouds near the surface. Submicron-sized particles have also been inferred for thin hazes at high altitudes. These retrievals further suggest that there is very little dispersion in particle sizes and that their shapes are multifaceted and equidimensional.

While latent heat release is not important for Martian clouds, recent studies indicate that the radiative effect of clouds can significantly alter the thermal structure of the atmosphere. Clouds in the ACB warm the atmosphere by absorbing infrared radiation upwelling from the warmer surface, while clouds in the polar hoods cool the atmosphere by emission to space. Thus, cloud radiative effects tighten the equator-to-pole temperature gradient and increase the baroclinicity of the atmosphere.

Clouds of CO_2 ice also form in the Martian atmosphere. In the winter polar regions, atmospheric temperatures can reach the frost point of CO_2 (<150 K). The presence of CO_2 ice clouds in this region has been inferred from thermal emission and laser altimeter data. CO_2 ice clouds also form at very high altitudes (>50 km) in tropical regions. Like water ice clouds, the physical properties of CO_2 ice clouds are uncertain, but retrievals from remote-sensing data and theoretical microphysical studies suggest they are larger than water ice particles with effective radii up to 60 μm. Unlike water ice clouds, however, latent heat release is important for CO_2 ice clouds and may result in buoyant convection.

Climate

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 from source to sink.

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 25% of the Martian atmosphere is cycled into and out of the polar regions each year by this process. The signature of this cycling can be seen in the measurements of surface pressure by the Viking Landers (Figure 6). Recent measurements by the Mars Science Laboratory show similar trends in surface pressure.

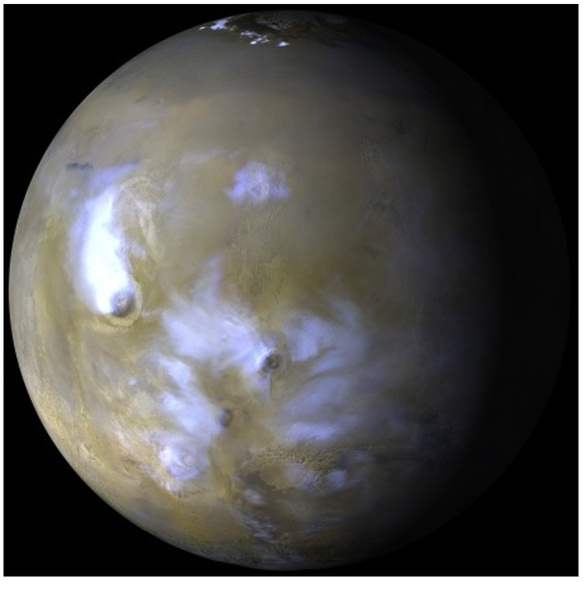

Figure 5 Clouds in the Martian atmosphere as observed by the Mars Color Imager (MARCI) on the Mars Reconnaissance Orbiter (MRO). Figure provided courtesy of Bruce Cantor of Malin Space Science Systems (MSSS): Cantor, B.A., 2007. MOC observations of the 2001 planet-encircling dust storm. Icarus 186, 60–96. http://dx.doi.org/10.1016/j.icarus.2006.08.019. Credit: NASA, JPL, and MSSS.

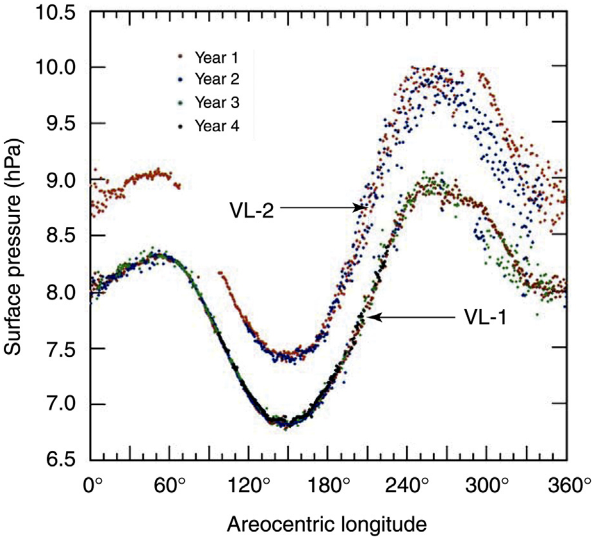

Figure 6 Seasonal variation of the daily-averaged surface pressure on Mars as measured by the Viking Landers. Season is expressed in terms of L_s, an angular measure of the planet's orbital position. $L_s = 0°$ corresponds to the northern spring equinox, $L_s = 90°$ is the summer solstice, $L_s = 180°$ is the fall equinox, and $L_s = 270°$ is the winter solstice.

At each site, there is a pronounced semiannual variation. 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 much longer than northern winters such that much more CO_2 condenses out of the atmosphere. As a result, pressures are the lowest during the middle of southern winter and highest in late spring when the cap disappears.

At both poles, however, the caps never completely disappear during summer. At the North Pole, CO_2 frost completely sublimes by summer and leaves behind an underlying water ice cap. Near the South Pole, surface CO_2 frost appears to survive all summer long. Thus, the summer caps have different compositions: CO_2 frost in the south, and water ice in the north. The reason for this compositional asymmetry is not understood. Furthermore, the year-to-year changes in the morphology of the residual south cap suggest that it may be slowly eroding and possibly disappear completely within several Mars decades since it appears to be relatively thin ($\sim$5 m thick). Thermal data show that a thin layer of water ice underlies the visible CO_2 cap. Recent radar measurements indicate that as much as 5 mb global equivalent of CO_2 ice may be buried to depths of 500 m or more below that thin layer of water ice.

When water ice is exposed at the North Pole during summer, it sublimes into the atmosphere. Winds transport this water all around the planet. The Viking, MGS, and MRO orbiters have mapped the resulting seasonal and spatial variation of atmospheric water vapor. An example is shown in Figure 7. Maximum abundances of about 60 pr-μm are found at high northern latitudes during summer. The northern-summer ice cap is therefore an important source of atmospheric water vapor. Minimum observed abundances of less than several pr-μm occurred in the polar regions during winter. Because of their low temperatures ($\sim$150 K), the seasonal CO_2 caps will act as a sink for any atmospheric water vapor that is brought in contact with them. For the current epoch, this implies that on an annual averaged basis, there is a net transfer of water from the north cap to the south cap. The Mars Express orbiter has observed water frost mixed with CO_2 frost at both poles, thus supporting this conjecture.

Climate Change

There is good evidence that Mars has experienced climate change in the recent geological past. Both polar regions are characterized by extensive layered terrains, which were likely formed by atmospheric sedimentation processes that were modulated in time. Furthermore, there are numerous nonpolar ice-related deposits that cannot be produced in today's climate such as tropical mountain glaciers, gullies, pedestal craters, polygons, and a latitude-dependent ice-rich mantle. The most widely accepted theory on the origin of these features is climate change forced by orbital variations. According to this theory, Mars' orbital parameters vary in a quasiperiodic fashion, and this alters the seasonal and latitudinal variation of zonally averaged insolation, which changes the general circulation and the dust, water, and CO_2 cycles.

The key orbital parameters are the obliquity and eccentricity. Because Mars does not have a large stabilizing moon, these parameters can vary significantly on time scales of tens to hundreds of thousands of years. Orbit models can accurately predict how these parameters have varied during the past 20 My (Figure 8). Beyond 20 My, however, the solutions

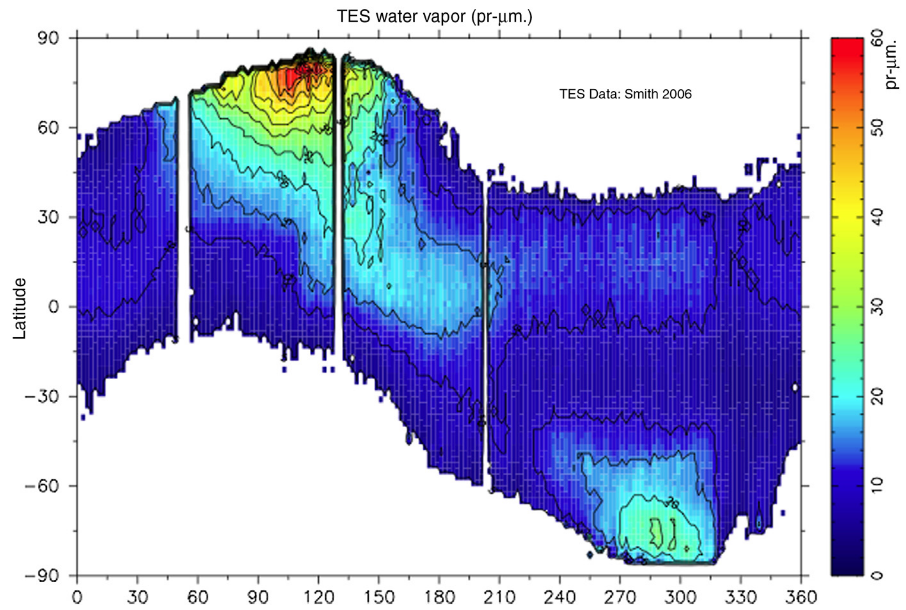

Figure 7 TES zonally averaged column water vapor abundances (pr-μm) as a function of latitude and season (expressed in terms of L_s). Data provided courtesy of Michael Smith of NASA/GSFC: Smith, M.D., 2008. Spacecraft observations of the Martian atmosphere. Annual Review of Earth and Planetary Sciences 36, 191–219.

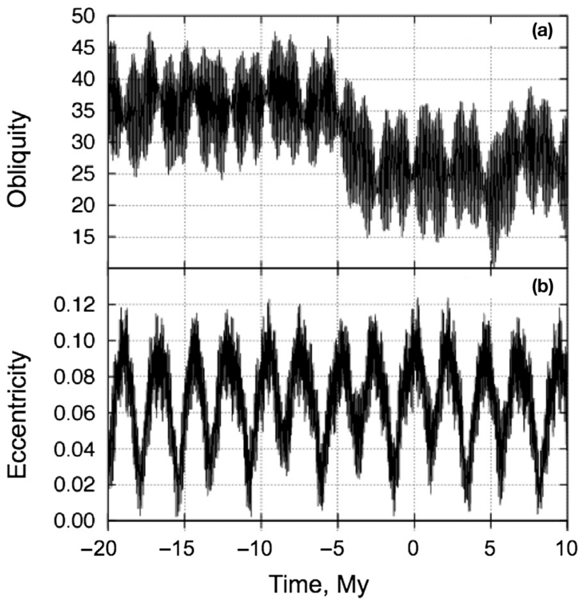

Figure 8 Variation of the (a) obliquity (top) and (b) eccentricity (bottom) of Mars for the past 20 My. Reproduced from Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., Robutel, P., 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. Icarus 170, 343–364. http://dx.doi.org/10.1016/j.icarus.2004.04.005.

become chaotic and are predictable only in a statistical sense. The obliquity is the most important parameter. The current value is 25.2°, but it has varied from between 15 and 45° during the past 20 My, and between nearly 0 and 80° over the full history of the planet. The most likely value of the obliquity is ~41°. Thus, today's obliquity is not representative of most of Mars' history.

As obliquity increases, annually averaged insolation increases at the poles and decreases at the equator. Consequently, the polar regions warm with respect to the equator. At such times, model studies indicate that water ice at the poles would be transferred to lower latitudes, which may explain some of the features mentioned in this article. Furthermore, surface pressures, and hence the atmospheric dust loading, may increase if the CO_2 ice buried at the South Pole is driven into the atmosphere. Surface pressures could also increase if any exchangeable adsorbed CO_2 is stored within the high-latitude regolith.

At low obliquities, polar regions cool and tropical regions warm. During these times, permanent CO_2 polar caps would form that would act as a sink for both CO_2 and water. Surface pressures would fall, possibly as low as 0.3 mb. Under these circumstances, dust storms would cease, the atmosphere would clear, and seasonal variations would subside. Thus, by modulating the latitudinal distribution of solar insolation, obliquity oscillations provide a mechanism to mobilize and redistribute dust, water, and CO_2 around the planet.

Early Mars

Three lines of evidence suggest that early in its history (>3.5 Gy ago), Mars had an atmosphere much different from what it has today. The first are geochemical in nature and are based on the mineralogy of surface materials. The second are isotopic in nature and are based on measurements of isotopes in the atmosphere and in the SNC meteorites. The third are geological in nature and are based on the morphology of the surface and its implications for fluid flow.

An example of a geochemical argument is the presence of phyllosilicates (clays) on ancient Martian terrains. Phyllosilicates are the end products of the aqueous weathering of basaltic materials and therefore imply that liquid water was abundant when they formed. The liquid water could be the result of an active hydrological cycle with rainfall and runoff, which implies a warm climate system. Alternatively, it could have been part of a subsurface hydrothermal system driven by internal heating, which has no implications for climate conditions. Geochemical arguments tend to be somewhat ambiguous in their implications for the early Mars climate system.

An example of an isotopic argument is the observed enrichment of N^{15} relative to N^{14}. Like oxygen, nitrogen can escape from Mars nonthermally by dissociative recombination. Above the homopause (~120 km), the heavier isotope decreases in concentration more rapidly with height than the lighter one. Consequently, at the exobase (~200 km), there are fewer N^{15} atoms available for escape. Over the lifetime of the planet, this leads to an enrichment of N^{15} relative to N^{14}. The observed value is $N^{15}/N^{14} = 0.006$, or approximately 1.6 times the terrestrial value. This implies a higher abundance of nitrogen in the past, which also implies a higher abundance of CO_2. Isotopic arguments like this generally indicate that a thicker atmosphere existed in the past.

Two features in the geologic record provide compelling evidence for a different environment on early Mars. They are the valley networks and the degraded crater rims. Both are found in terrains estimated from crater counts to be 3.5–3.8 Gy old. These terrains are found mostly in the southern hemisphere. An example is shown in Figure 9. The valley networks resemble terrestrial drainage systems and appear to have formed by erosion associated with rainfall and runoff. Such erosion can also explain the degraded crater rims. These features provide the best evidence for warmer, wetter conditions with an active hydrological cycle early in Mars' history.

The most likely way to achieve warmer and wetter conditions on early Mars is through a greenhouse effect, and the most likely greenhouse gases are CO_2 and water vapor. A strong greenhouse effect is required because the sun was 25% less luminous 3.5 Gy ago. At present, neither CO_2 nor water vapor is present in sufficient quantities to produce much greenhouse warming. However, these may have been present in ample quantities in the early Mars atmosphere. Unfortunately, climate models based on pure CO_2–H_2O atmospheres have been unable to reproduce the conditions needed for sustained rainfall and runoff. Even when supplemented with additional greenhouse gases such as SO_2 or CH_4, thicker CO_2 atmospheres are only marginally capable of significant warming. Thus, a sustained greenhouse effect capable of supporting liquid water on the surface has not yet been convincingly demonstrated for early Mars.

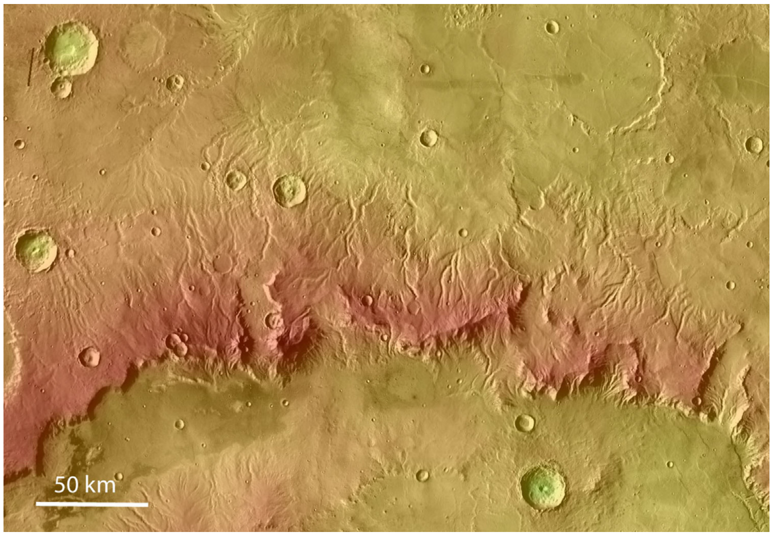

Figure 9 Huygens crater on Mars (10° S, 55° E). Valley networks drain toward the north into a depression where degraded crater rims can be seen (upper right and upper left). Figure provided courtesy of Carr, M.H., 1996. Water on Mars, Oxford University Press, New York, 229 pp. Credit: NASA, JPL.

An alternative hypothesis is that the valley networks were formed in multiple transient events associated with impacts. Meteors larger than 10 km in diameter deliver enough energy to temporarily generate a very warm and wet climate capable of providing significant rainfall for hundreds or perhaps thousands of years after the impact. This hypothesis is attractive because Mars obviously experienced a high impact rate early in its history, and we know that impacts can significantly alter the climate system on Earth. However, the predicted erosion rates of impact-generated climate change fall short of the required amount. Thus, a convincing explanation for the mineralogical, isotopic, and geological evidence about early Mars has yet to emerge.

The Future

Our knowledge of Martian atmosphere and climate has greatly benefited from a vigorous international Mars exploration program. Beginning with the MGS mission in 1996, eight spacecraft missions have successfully reached the red planet to study its mysteries from orbit and the surface (Table 4). On 5 August 2012, the Mars Science Laboratory landed the *Curiosity* rover in Gale Crater with plans to operate it for at least one Mars year. The Rover Environmental Monitoring Station on *Curiosity* gathers hourly meteorological data to extend our record of the surface environment. In late 2013, NASA will launch the Mars Atmosphere and Volatile Evolution mission to study the upper atmosphere and measure escape rates of gases and ions. The European Space Agency and the Russian Space Agency (Roscosmos) are jointly planning several missions to Mars for the 2016 and 2018 launch opportunities that will deliver a lander and an orbiter in 2016 and a rover in 2018. The 2016 lander is expected to have some meteorological instruments, and the orbiter is expected to monitor trace gases in the atmosphere. Many countries are considering missions to Mars for the decade beginning in 2020 that have atmospheric science in their payloads. A sample return mission continues to be a high priority for many space agencies, and beyond that, human missions will ultimately be attempted. Atmospheric science will benefit from these missions as well.

Table 4 Successful spacecraft missions to Mars since 1996

Mission	*Launch date*	*Type*	*Status (as of Aug. 2013)*
Mars Global Surveyor	07 Nov. 1996	Orbiter	Completed
Pathfinder	04 Dec. 1996	Lander/Rover	Completed
Mars Odyssey	07 Apr. 2001	Orbiter	Ongoing
Mars Express	02 Jun. 2003	Orbiter	Ongoing
MER: Spirit	10 Jun. 2003	Rover	Completed
MER: Opportunity	08 Jul. 2003	Rover	Ongoing
Mars Reconnaissance Orbiter	12 Aug. 2005	Orbiter	Ongoing
Phoenix	04 Aug. 2007	Lander	Completed
Mars Science Laboratory	26 Nov. 2011	Rover	Ongoing

MER, Mars Exploration Rover.

See also: **Aerosols:** Role in Radiative Transfer. **Chemistry of the Atmosphere:** Principles of Chemical Change. **Climate and Climate Change:** Greenhouse Effect; Overview. **Dynamical Meteorology:** Baroclinic Instability; Overview. **General Circulation of the Atmosphere:** Overview. **Solar System/Sun, Atmospheres, Evolution of Atmospheres:** Evolution of Earth's Atmosphere; Planetary Atmospheres: Venus.

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