PLANETARY ATMOSPHERES

Contents

Jupiter and the Outer Planets

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Introduction

The planets and satellites in the outer solar system exhibit a diverse range of atmospheres. The giant planets — Jupiter, Saturn, Uranus, and Neptune — are fluid objects whose atmospheres have compositions similar to that of the solar nebula from which our solar system formed. They are dynamically active, exhibiting behavior on time scales from hours to centuries, and have multiple zonal (east–west) jets with speeds that exceed those of Earth's atmosphere. Titan, the largest moon of Saturn, has a nitrogen atmosphere with a surface density four times that of Earth's, a global smog layer that hides the surface from view, and perhaps a surface or subsurface reservoir of liquid methane and ethane. Triton (Neptune's largest satellite) and Pluto have tenuous nitrogen atmospheres thought to be in vapor pressure equilibrium with solid nitrogen ice on their surfaces. And the Galilean satellites of Jupiter — Io, Europa, Ganymede, and Callisto — have tenuous atmospheres resulting from volcanic processes and interaction of their surfaces with energetic particles from Jupiter's magnetosphere. These atmospheres embody the same physical and chemical processes as Earth's atmosphere but, because of differing compositions, gravities, lower boundary conditions, incident solar energy fluxes, and histories, the phenomena observed there are unique. The study of these planets enriches atmospheric science by placing Earth in a broader perspective.

Jupiter, Saturn, Uranus, and Neptune

Jupiter, Saturn, Uranus, and Neptune, which respectively have diameters of 11, 9, 4, and 4 times that of Earth, greatly exceed the terrestrial planets in mass. At 318 Earth masses, Jupiter contains more mass than all the other planets in our solar system combined. Nevertheless, their internal densities are modest, and Jupiter is the only planet with a gravity substantially exceeding Earth's (**Table 1**). The dominant atmospheric constituent of all four giant planets is molecular hydrogen (H_2), followed by helium (He) and trace species composed of carbon, oxygen, nitrogen, sulfur, and other elements. The interiors are fluid, and the transition between atmosphere and interior occurs gradually. All features visible in images of the giant planets are clouds (**Figure 1**). The clouds organize into latitudinal bands that are obvious on Jupiter and Saturn and weaker, yet still persistent, on Uranus and Neptune.

Systematic observations of Jupiter began in the nineteenth century and continue to the present day, providing a ~150-year record of the planet's visual appearance. Inferences about Jupiter's composition began in the 1930s with the identification of methane (CH_4) and ammonia (NH_3) absorption features in spectra of sunlight reflected from the planet. The space age allowed a revolution in giant-planet studies. *Pioneer 10* and *Pioneer 11* flew past Jupiter in 1973 and 1974, respectively, followed by *Voyager 1* and *Voyager 2* in 1979; the latter three of these reached Saturn in 1979, 1980, and 1981, respectively. *Voyager 2* continued on to Uranus in 1986 and Neptune in 1989. The Galileo mission consisted of a Jupiter orbiter and a probe that entered Jupiter's atmosphere in 1995. Cassini flew past Jupiter in December 2000 and will enter Saturn orbit in 2004, starting a three-year mission of the ringed planet.

Composition

Unlike the terrestrial planets, the giant planets formed under conditions that allowed them to retain gas from the solar nebula (the gaseous disk from which the Sun and planets formed). The abundances of elements in the jovian atmospheres therefore resemble a

Table 1 Physical and orbital properties of the giant planets

	Jupiter	*Saturn*	*Uranus*	*Neptune*
Date of discovery	Antiquity	Antiquity	1781	1846
Mass (kg)	1.90×10^{27}	5.68×10^{26}	8.68×10^{25}	1.02×10^{26}
Mass (Earth = 1)	318	95.2	14.5	17.1
Equatorial radius[a] (10^3 km)	71.49	60.27	25.56	24.77
Polar radius[a] (10^3 km)	66.85	54.36	24.97	24.34
Mean density (g cm^{-3})	1.33	0.69	1.318	1.638
Equatorial surface gravity[a] (m s^{-2})	23.12	8.96	8.69	11.00
Rotation period[b] (h)	9.925	10.6562	17.24	16.3872
Obliquity[c]	3.12°	26.73°	97.86°	29.56°
Equatorial escape velocity (km s^{-1})	59.5	35.5	21.3	23.5
Orbital semimajor axis (AU)[d]	5.20	9.55	19.21	30.11
Orbital eccentricity	0.048	0.056	0.046	0.009
Orbital period (years)	11.856	29.424	83.747	163.723
Bond albedo	0.34 ± 0.03	0.34	0.31 ± 0.05	0.290
Geometric albedo[e]	0.52	0.47	0.51	0.41
Incident solar flux (W m^{-2})	50.5	14.90	3.71	1.51
Emitted/absorbed radiation	1.7	1.8	1.06 ± 0.08	2.6
Scale height[a] (km)	27	56	33	25
Emission pressure (bar)	0.4	0.3	0.4	0.5
Emission temperature (K)	124	95	59	59
Temperature at 1bar[f] (K)	166	134	76	72
Speed of sound[a,g] (m s^{-1})	940	840	630	620

[a]At the 1 bar level.

[b]Measured relative to the rotating magnetic field for Jupiter, Uranus, and Neptune and for the inferred magnetic-field rotation rate for Saturn.

[c]Angle between rotation axis and normal to orbital plane. Rotation axis calculated from magnetic field.

[d]1 AU = 1.496×10^8 km is the average distance between the Earth and the Sun.

[e]At visible wavelengths.

[f]Uncertainty/spatial variability is about ± 5 K.

[g]Calculated using $c = \sqrt{\gamma RT/m}$, where $\gamma = 1.4$ is the ratio of specific heats, R is universal gas constant, T is the 1bar temperature, and m is the molar mass.

Data from Beatty *et al.* (1999); Ingersoll (1990); Ingersoll (1995) in Cruikshank 1995, pp. 613–682; Hanel RA, Conrath BJ, Herath LW *et al.* (1981) Albedo, internal heat, and energy balance of Jupiter – preliminary results of the Voyager infrared investigation. *Journal of Geophysical Research* 86(A10): 8705–8712; Cox AN (ed.) (2000) *Allen's Astrophysical Quantities*. Springer-Verlag, New York.

cooled-down parcel of the Sun. In such a parcel, the dominant constituents are hydrogen (H_2) and helium (He), which together comprise 98% of the mass, followed by neon (Ne), oxygen (O), carbon (C), nitrogen (N), and sulfur (S). The chemical equilibrium forms of oxygen, carbon, nitrogen, and sulfur in the giant-planet atmospheres are H_2O, CH_4, NH_3, and H_2S.

Analysis of infrared spectra of the giant planets indicate that the C:H ratio is 2.9 times the solar value for Jupiter, about 6 times solar for Saturn, and 30–40 times solar for Uranus and Neptune. These enrichments suggest that the giant planets received solids in addition to nebular gas during their formation. The Galileo probe, which directly sampled Jupiter's atmosphere in 1995, confirmed the spectral estimate of C:H and demonstrated that the abundances of NH_3, H_2S, Ar, Kr, and Xe are all between 2.5 and 3.5 times solar (**Table 2**).

Vertical Structure and Clouds

The temperature profiles at pressures less than a few bars (1 bar = 10^5 Pa) have been measured for all four giant planets by radio occultations from the *Voyager* spacecraft and, in the case of Jupiter, by the Galileo probe to 22 bars (**Figure 2**). Each planet exhibits a temperature minimum (tropopause) near 100 mbar, with a troposphere below and a stratosphere above. The temperature gradient (lapse rate) in the troposphere approaches the dry adiabatic value at pressures exceeding about 1 bar. Galileo probe measurements indicate that Jupiter's atmosphere is close to a dry adiabat from 1 to 22 bars. All four planets also have hot thermospheres, with temperatures ranging from $\sim$600 to 1000 K at pressures of 10^{-3} μbar or less. The thermospheric temperatures are greater than can be achieved with solar energy absorption and, interestingly, do not show a systematic decrease with distance

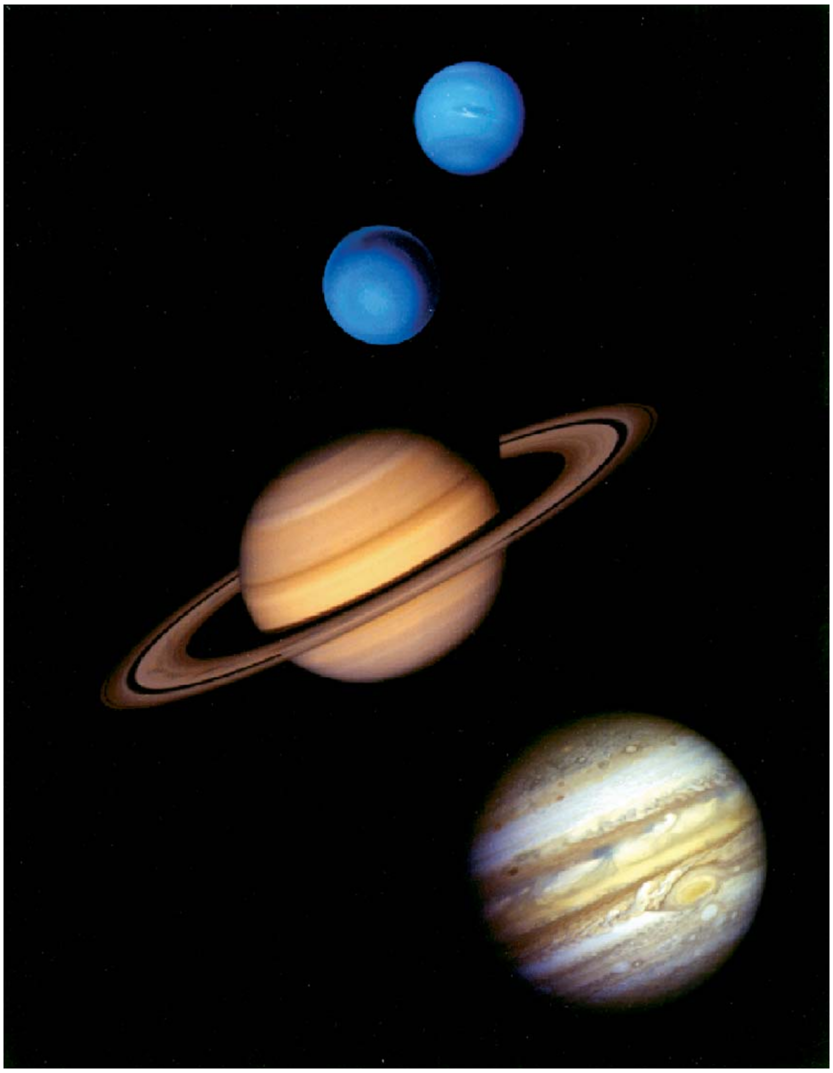


Figure 1 The giant planets Jupiter, Saturn, Uranus, and Neptune (bottom to top, respectively) shown to scale.

from the Sun. At such altitudes, thermal energy is rapidly conducted downward, so a large heat source is required. Possibilities include deposition of energy from charged particles impinging on the top of the atmosphere (most relevant to Jupiter) and dissipation of gravity or acoustic waves that propagate up from lower altitudes.

At pressures greater than about 1 bar, the giant planets' vertical heat flux is carried by convection. Infrared radiation escapes directly to space at pressures of 100 to 300 mbar.

Condensation of trace species leads to the formation of clouds at about 1–10 bars (**Table 3**). On Jupiter and Saturn, the expected condensates are, from high to low pressure, water (H_2O), ammonium hydrosulfide (NH_4SH, which condenses from gaseous NH_3 and H_2S), and ammonia (NH_3). On Uranus and Neptune, the condensates are H_2O, NH_4SH, either NH_3 or H_2S (depending on the nitrogen to sulfur ratio), and methane (CH_4).

Analyses of infrared spectra allow the actual cloud structure to be inferred. For Jupiter and Saturn, the top cloud is a global layer at pressures near 0.5–1 bar. These clouds are thought to consist of NH_3 ice from a comparison with **Table 3**. (Solid ammonia absorption features have been observed only in localized active clouds, however. Perhaps the ammonia ice across most of the planet is chemically modified or coated with impurities that mask the absorption features.) Cloud particles range from 1 to 100 μm in size. Some studies of infrared spectra suggest that on Jupiter a cloud exists at 2 bars, where NH_4SH is expected to condense. No global cloud is present at 5 bars, but sporadic local clouds have been seen with tops at pressures exceeding 4 bars, where the only possible condensate is water. On both Jupiter and Saturn, the

Table 2 Composition of Jupiter's atmosphere

Species	*Mole fraction*	*Comments*
H_2	0.86	
He	0.136	0.8 times solar
Ne	2.0×10^{-5}	0.1 times solar
Ar	1.6×10^{-5}	2.5 ± 0.5 times solar
Kr	8.0×10^{-9}	2.7 ± 0.5 times solar
Xe	7.7×10^{-10}	2.6 ± 0.5 times solar
CH_4	2×10^{-3}	2.9 times solar
H_2O (19 bars)	$<6 \times 10^{-4}$	<0.35 times solar[a,b]
H_2S (16 bars)	7×10^{-5}	2.5 times solar[a]
NH_3 (8 bars)	7×10^{-4}	3.5 times solar[a]
CH_3D	2×10^{-7}	
C_2H_6 (stratosphere)	10^{-6}–10^{-5}	[c]
C_2H_4 (stratosphere)	10^{-9}–10^{-8}	[c]
C_2H_2 (stratosphere)	10^{-8}–10^{-7}	[c]
CO	1×10^{-9}	[d]
PH_3	1×10^{-6}	[d]
AsH_3	2×10^{-10}	[d]
GeH_4	7×10^{-10}	[d]

[a]Decreases with height and varies horizontally owing to condensation and dynamics.
[b]Galileo probe measurement in a dry spot. Other studies suggest that Jupiter's deep, global-averaged water abundance is 3–10 times solar.
[c]Produced by photolysis of methane. Variable with location.
[d]A disequilibrium species in the atmosphere, but stable at great depths, so its presence provides evidence of convective transport from the deep interior.
Sources: Mahaffy PR, Niemann HB, Alpert A *et al.* (2000) Noble gas abundances and isotope ratios in the atmosphere of Jupiter from the Galileo Probe mass spectrometer. *Journal of Geophysical Research* 105: 15061–15071; Encrenaz T, Drossart P, Feuchtgruber H, *et al.* (1999) The atmospheric composition and structure of Jupiter and Saturn from ISO observations: a preliminary review. *Planetary Space Science* 47: 1225–1242; Fegley B and Lodders K (1994) Chemical models of the deep atmospheres of Jupiter and Saturn. *Icarus* 110: 117–154; Niemann HB, Atreya SK, Carignan GR, *et al.* (1998) The composition of the Jovian atmosphere as determined by the Galileo probe mass spectrometer. *Journal of Geophysical Research* 103: 22831–22845; Gladstone GR, Allen M, Yung YL (1996) Hydrocarbon photochemistry in the upper atmosphere of Jupiter. *Icarus* 119: 1–52.

0.5–1 bar cloud is overlaid by an optically thin, homogeneous haze from 0.1–0.5 bar.

On Uranus and Neptune, two tropospheric cloud layers have been observed. The lowermost cloud forms an opaque global layer with tops at 2.8 ± 0.5 and 3.8 ± 0.6 bars on Uranus and Neptune, respectively. The composition may be H_2S on the basis of a comparison with **Table 3** and observations showing that gaseous NH_3 is extremely depleted. At pressures of 1.2 and 1.5 bars on Uranus and Neptune, respectively, a patchy, methane-ice cloud with optical depths of 0.1–1 exists.

Thin haze layers are also present in the stratospheres of all four giant planets; these result from condensation of methane photolysis products such as ethane

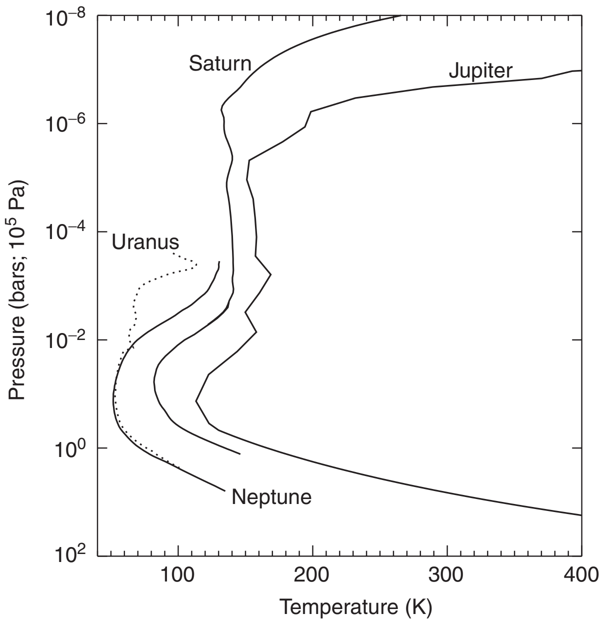


Figure 2 Temperature versus pressure on Jupiter, Saturn, Uranus, and Neptune. Uranus is shown in a dotted line to distinguish it from Neptune. Data are from Galileo probe for Jupiter and Voyager radio occultations for Saturn, Uranus, and Neptune. Saturn data at pressure less than 10^{-3} bar are from occultation of a star behind Saturn.

(C_2H_6), acetylene (C_2H_2), and higher-order organics. Vaporization (and subsequent condensation) of material from incoming interplanetary dust particles also provides a small source of upper-atmospheric aerosols.

The colors of the giant planets remain poorly understood. Ammonia ice is colorless; the earth tones exhibited by Jupiter and Saturn result from trace quantities of solid organic, sulfur, or phosphorus compounds ('chromophores') mixed in with the ammonia ice. The blue-green colors of Uranus and Neptune result from absorption of red light by gaseous methane and perhaps by particles in the global cloud near 3 bars.

Table 3 Condensation pressures on giant planets (bars)

Species	*Jupiter*	*Saturn*	*Uranus*	*Neptune*
CH_4	–	–	1.2	1.5
NH_3	0.6	1.4	3[a]	3[a]
H_2S	–	–	~5[a]	~5[a]
NH_4SH	2	4	~30[b]	~30[b]
H_2O	6	~15[b]	~300[b]	~300[b]

[a]Either NH_3 or H_2S cloud expected (depending on relative abundance of NH_3 and H_2S) but not both.
[b]Uncertain; depends on (poorly known) composition.

Dynamics

All four giant planets exhibit persistent east–west (zonal) jets at the height of the visible clouds. These winds have been measured by tracking the motion of small clouds over periods of hours (**Figure 3**). The measurements show that Jupiter and Saturn each have over ten jets, with peak speeds of 180 m s^{-1} on Jupiter and 470 m s^{-1} on Saturn. The equatorial winds are eastward. Uranus and Neptune have westward jets at the equator and broad eastward jets at high northern and southern latitudes, with peak speeds of 200 and 400 m s^{-1}, respectively. Interestingly, wind speeds do not decrease with distance from the Sun. Observations of Jupiter extending over a century reveal that significant changes in the mean jet speeds have occurred at only a few latitudes. Even Uranus and Neptune show little variation in the 15 years over which such observations have been available. Nevertheless, Voyager observations and ground-based telescope images show that enormous small-scale variability occurs over periods of hours to days.

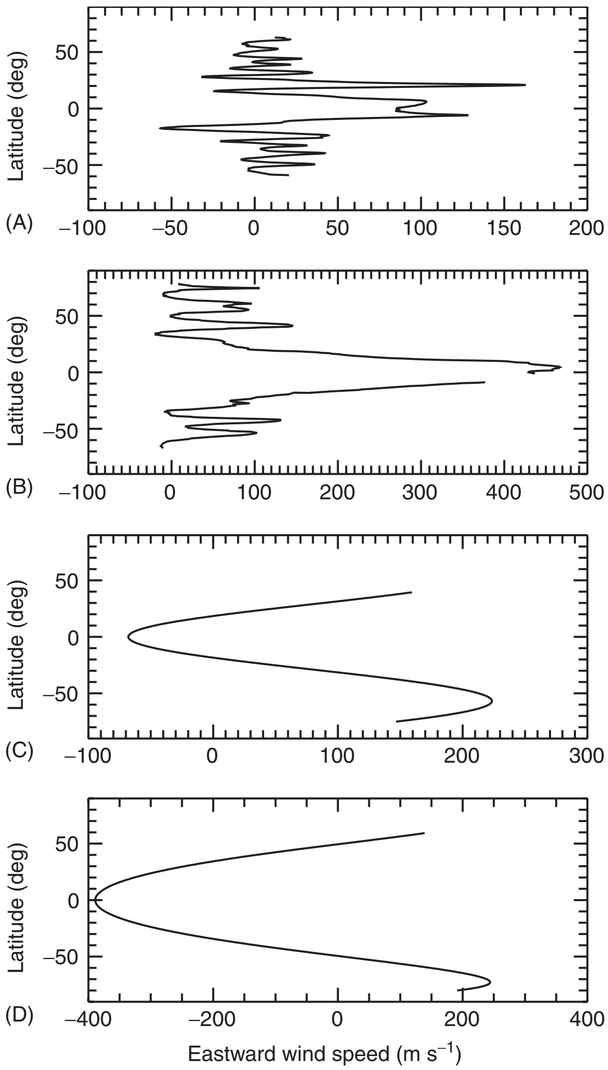


Figure 3 Longitudinally averaged eastward winds on (A) Jupiter, (B) Saturn, (C) Uranus, and (D) Neptune, obtained by tracking cloud features in Voyager and ground based telescope images. The wiggles are not noise but represent long-lived atmospheric jets analogous to the jet stream on Earth.

The rapid rotation rates and large sizes of the giant planets ensure that the large-scale winds are in geostrophic balance (a balance between horizontal pressure gradient and Coriolis accelerations).

Although discrete clouds are not normally present in the stratospheres of the giant planets, measurements of temperature at pressures less than 400 mbar imply that the jets weaken with height above the cloud deck on all four giant planets. The depth of the jets below the clouds is a major unknown. Galileo probe measurements indicate that, on Jupiter, the winds at 7° N latitude continue to at least 20bars, 150 km below the visible cloud deck (**Figure 4**). For Neptune, analysis of Voyager gravity data indicates that the strong winds seen in **Figure 3** are confined to the outermost few percent of the planet's mass.

Jupiter, Saturn, and Neptune receive more sunlight at the equator than the poles; but the spin axis of Uranus is tipped over, so that averaged over a Uranian year, Uranus receives more sunlight at the poles than the equator. During Uranus' northern summer, the Sun is overhead at the north pole and the southern hemisphere is in darkness. The reverse is true during southern summer.

Jupiter, Saturn, and Neptune radiate 1.7, 1.8, and 2.7 times more energy, respectively, than they absorb from the Sun. Unlike Earth, these planets therefore undergo net radiative cooling at all latitudes. No excess radiation has been detected from Uranus.

Measurements of temperatures above the cloud tops indicate that, although small-scale temperature variations are present, little global equator-to-pole temperature difference exists. Efficient energy transport therefore occurs within the giant planets. For Jupiter and Saturn, atmospheric transport alone is insufficient to mute the equator-to-pole temperature gradient, and the homogeneous temperatures may result from preferential escape of the internal heat at the poles. On Uranus, the minuscule internal heat flux precludes this mechanism from occurring, and atmospheric transport (e.g., by baroclinic eddies) may be sufficient.

Jupiter and Saturn exhibit a wealth of small-scale vortices, cloud streaks, and turbulent regions that evolve on time scales of days or less. On Jupiter, the Voyager, Galileo, and Cassini spacecraft imaged thousands of atmospheric vortices ranging from the Great Red Spot (spanning 20 000 km by 10 000 km in

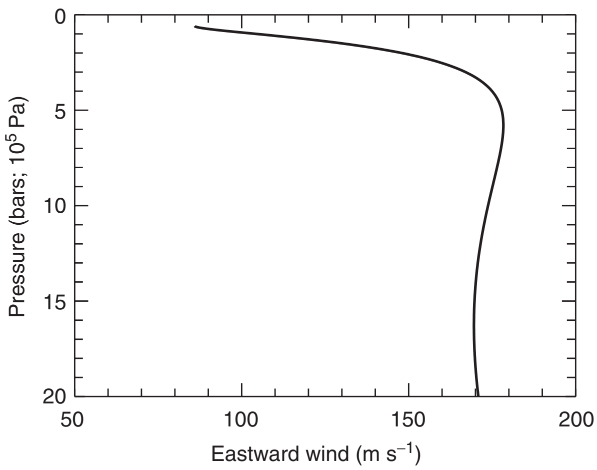


Figure 4 Eastward winds versus pressure obtained by Doppler-tracking of the Galileo probe's radio signal during its descent into Jupiter's atmosphere in December 1995.

longitude and latitude, respectively) to spots hundreds of kilometers across (**Figures 5** and **6**). On average, vortices smaller than 2000 km are circular, while larger vortices are elongated in the east–west direction. Ninety percent of the observed vortices are anticyclones and reside in anticyclonic shear zones. Cyclones, which reside in cyclonic shear zones, tend to be more turbulent and short-lived than anticyclones. When vortices collide, they merge irreversibly and sometimes eject a filament. Coherent vortices do not produce other spots — instead, small vortices are produced in turbulent 'filamentary regions' that reside in cyclonic shear zones. The band within 8° latitude of the equator contains, rather than vortices, a set of bright and dark features that are probably the upwelling (cloudy) and downwelling (cloud-free) branches, respectively, of a large-amplitude, equatorially trapped wave. The Galileo probe entered such a dark region (**Figure 7**), where it measured humidities and cloud abundances much lower than expected.

Moist convection occurs on Jupiter and may be important in driving the jets. Lightning was imaged on Jupiter's nightside by Voyager and Galileo, and Galileo showed that the lightning occurred within bright, rapidly-expanding clouds that can reach diameters of 2000 km in a few days (**Figure 8**; the small white clouds north-west of the Great Red Spot in **Figure 5** are typical of lightning-producing clouds). The buoyancy caused by latent heat release is dominated by condensation of water and can reach ~ 10 K (similar to that in terrestrial thunderstorms) for likely water abundances on Jupiter. Theoretical calculations suggest that this supplies energy to small-scale eddies that in turn

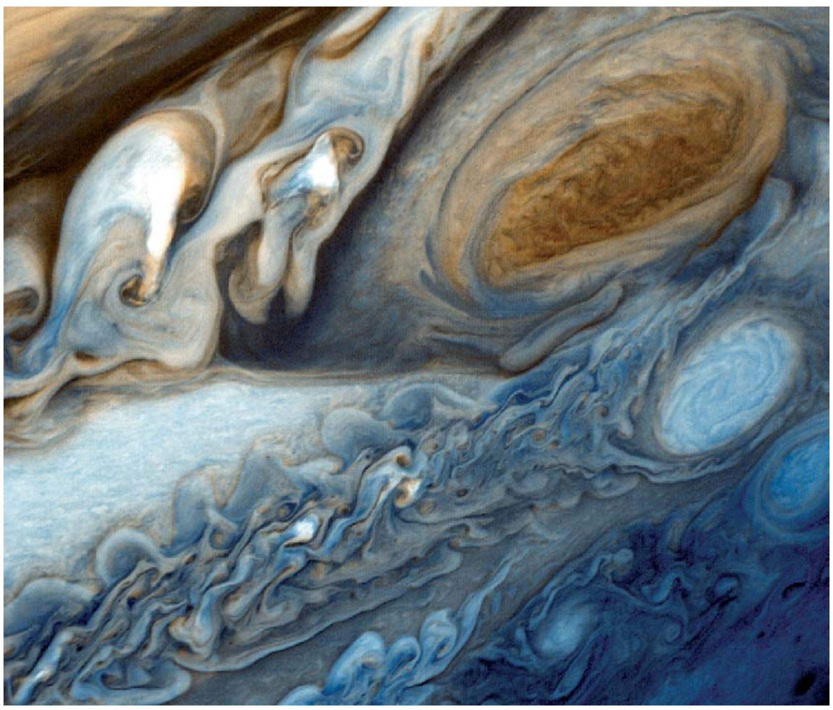


Figure 5 False-color visible-wavelength Voyager image of Jupiter's Great Red spot (GRS) (upper right) taken in 1979. The GRS is an anticyclonic vortex that rotates counterclockwise once per week. The white vortex below the GRS is also an anticyclone. The turbulent region north-west of the GRS and west of the smaller vortex have cyclonic vorticity. North is to upper left.

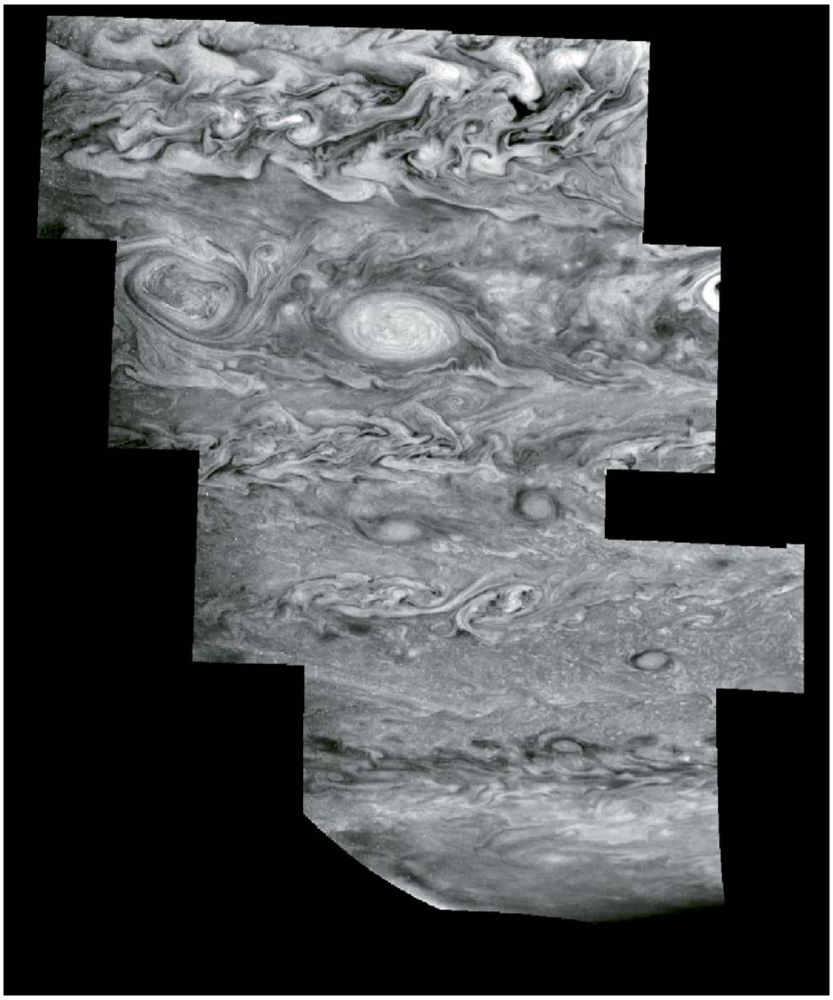


Figure 6 Near-infrared (756 nm) Galileo image showing latitudes 25° to 80° S in May 1997. North is up. The two large vortices are about 3500 km in the north–south direction. The leftmost is cyclonic (clockwise rotation) and the rightmost is anticyclonic (counterclockwise rotation).

provide their energy to the larger vortices and jets via mergers.

Saturn is less active than Jupiter. Features 1000 km across are at least ten times less abundant, turbulent regions occupy a smaller fraction of the area, and no Great Red Spot-like giant ovals exist. Nevertheless, hundreds of rapidly-evolving, small-scale streaks and spots were observed by the Voyagers (**Figure 9**). An intriguing feature dubbed the Ribbon (**Figure 10**) appears to be unique to Saturn.

Jupiter and Saturn exhibit complex long-term variability that has been documented by ground-based observers in photographs and drawings. Although Jupiter's cloud bands are stable enough to have received names, several of the bands undergo quasi-periodic disturbances every 3–5 years involving changes in color or brightness (**Figure 11**) and production of dozens of 5000 km to 10 000 km sized spots that shear apart before the band returns to its original appearance. The large vortices also evolve – the three 10 000 km long 'White Ovals' were created in 1938 from the latitudinal deflection and pinching of a zonal jet; in 1998 and 2000, these vortices underwent two separate mergers, leaving a single White Oval behind. The Great Red Spot, which is at least 130 years old and may be as old as 300 years, has been steadily shrinking in east–west dimension since the nineteenth century. On Saturn, enormous disturbances that produce 20 000 km-long bright clouds (the 'Great White Spots'), which expand around the planet in 2–3 months and decay over 1–3 years, have occurred at least six times since 1876 (**Figure 12**).

Uranus has few identifiable cloud features and appears bland in Voyager images (**Figure 13**). Nevertheless, enough discrete clouds have been observed to determine the planet's zonal wind pattern.

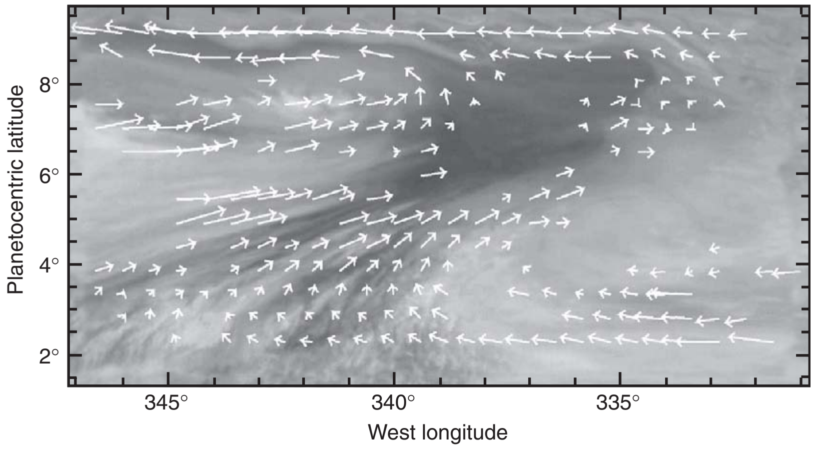


Figure 7 The dark region is one of about ten cloud-free regions that exist north of Jupiter's equator. The Galileo probe entered one in 1995, measuring extremely low humidities to depths 80 km below the expected condensation levels. The winds relative to the feature (arrows) have speeds up to 70 m s^{-1} and show that these features are not vortices. Instead, they are probably the downwelling branches of a high-amplitude Rossby wave, which pushes dry air from above the cloud tops downward by 80 km.

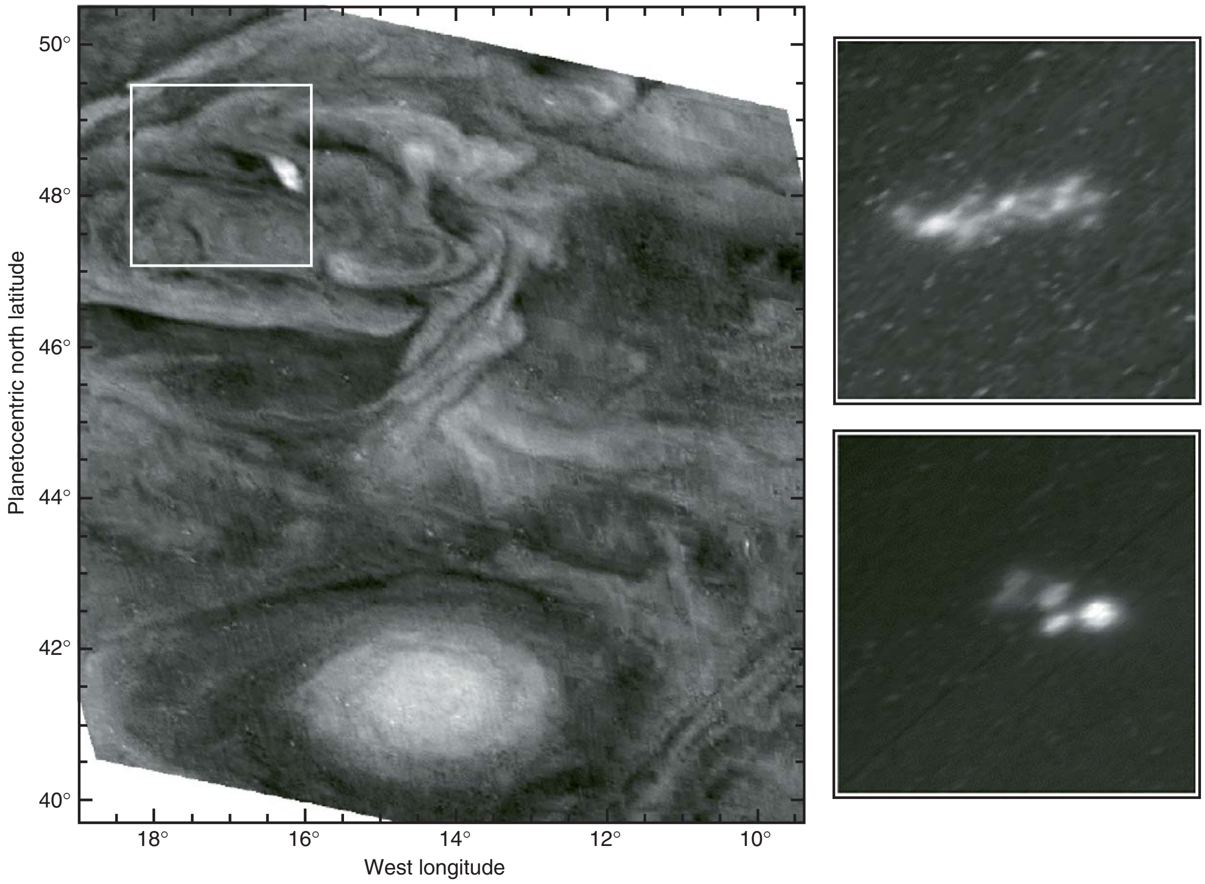


Figure 8 Galileo images of a thunderstorm on Jupiter's dayside (left) and nightside (right). The latitudes and longitudes in the white box at the upper left were imaged again 2 h later when they rotated onto the nightside (shown in right panels; they cover the same area as the white box but have been enlarged for better viewing). The bright regions in the two right panels (which were taken 3.6 min apart) show where lightning has illuminated the cloud deck from below.

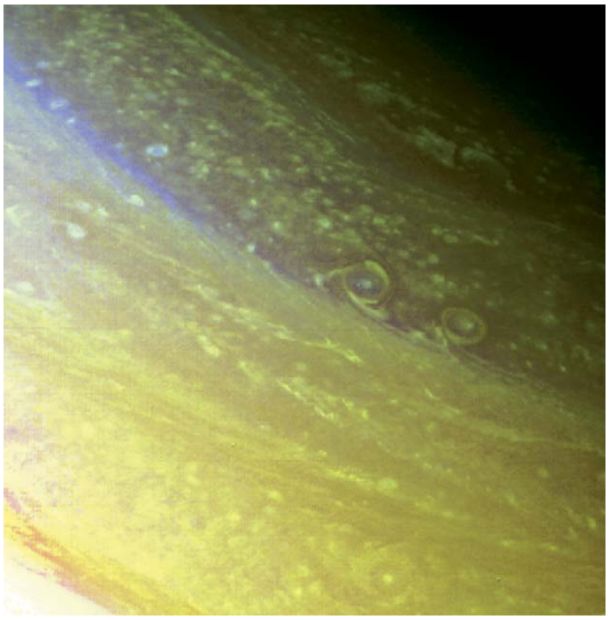


Figure 9 False-color Voyager 2 image of Saturn's north polar region taken in August 1981. The two oval cloud systems at the middle right are about 250 km across.

Neptune resembles an active version of Uranus. Although calm by comparison with Jupiter, Neptune nevertheless exhibits several active clouds (**Figure 14**). The largest feature is the Great Dark Spot (GDS), a

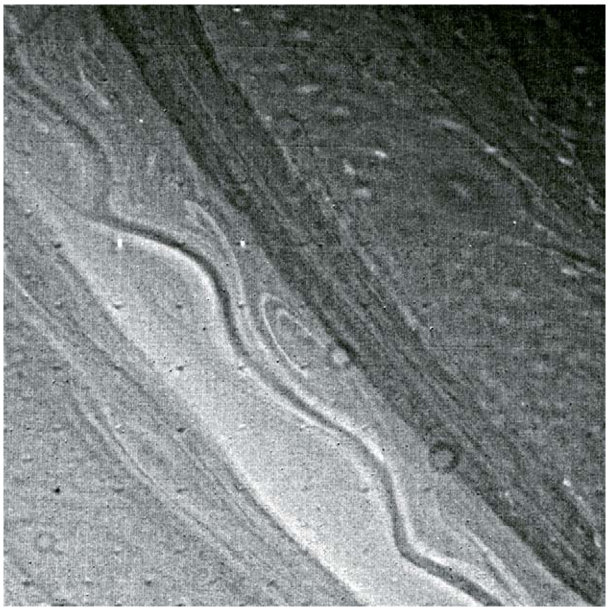
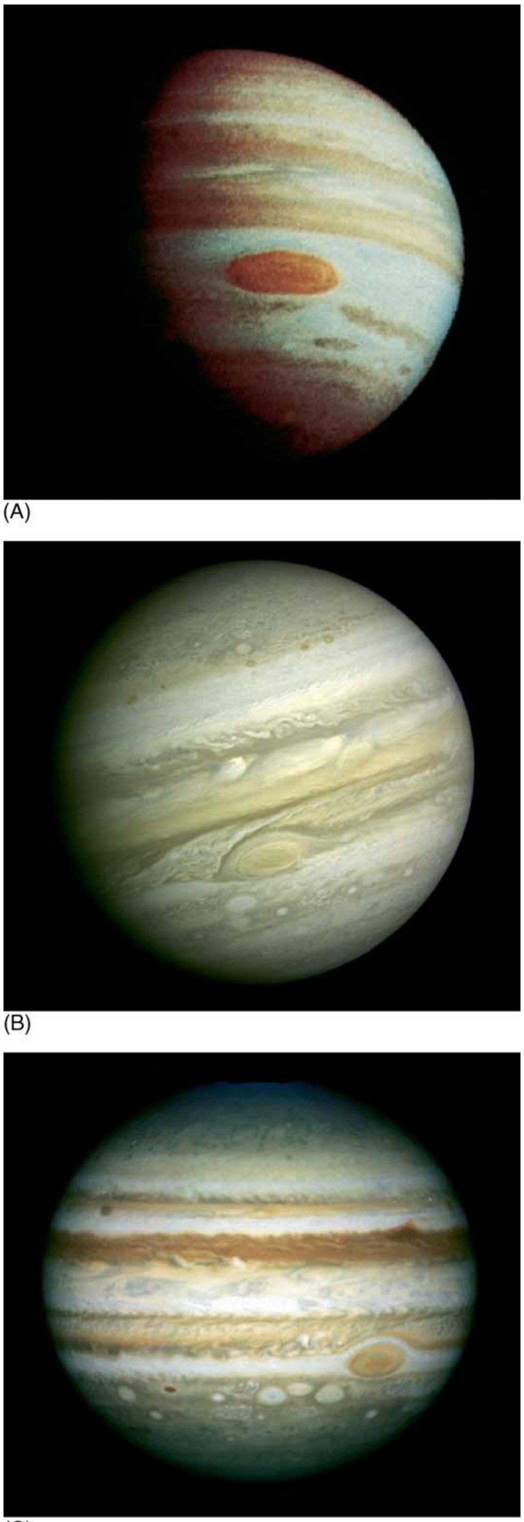


Figure 10 'The Ribbon', a wavelike feature at 46° N latitude in Saturn's atmosphere imaged by *Voyager 2* in August 1981. The Ribbon's wavelength is 10 000 km. North is to upper right, and the Ribbon moves eastward with the flow at about 150 m s^{-1}. The small black dots and dark circular annuli are camera artifacts.



(A)

(B)

(C)

Figure 11 Three views of Jupiter taken by (A) *Pioneer 11* in 1974, (B) Voyager in 1979, and (C) the Hubble Space Telescope in 1995. Notice the changes in the cloud patterns around the Great Red Spot and in the relative colors of the bands at and north of the equator.

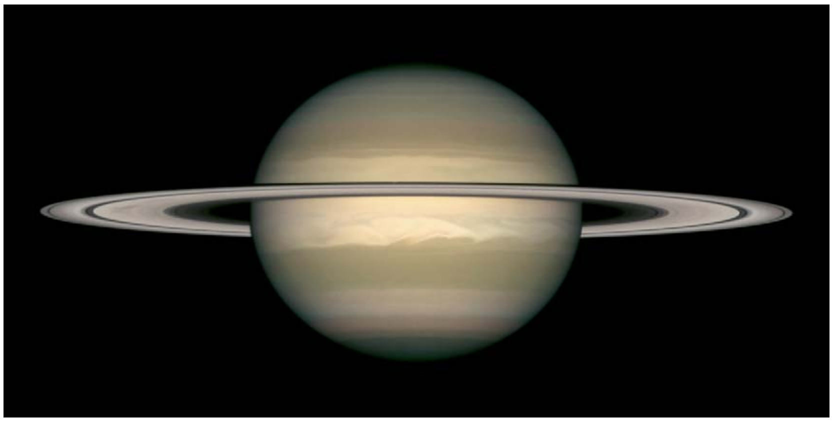


Figure 12 Hubble Space Telescope image showing Saturn's banded structure. The bright, blotchy cloud just below the rings is the decaying stage of a massive quasiperiodic outburst called a Great White Spot.

20 000 km long anticyclonic vortex observed by Voyager in Neptune's southern hemisphere. The GDS, which underwent large-amplitude week-long oscillations in shape and orientation (**Figure 15**), drifted toward the equator at 1.3° latitude per month and subsequently disappeared. A new GDS appeared in the northern hemisphere in 1994. In addition to the dark spots, bright cloud streaks also exist; some are isolated, while others are associated with features such as the GDS. In some cases they cast shadows on the blue (3.8 bar) cloud deck, indicating heights of 50–100 km (**Figure 16**). The streaks often comprise rapidly changing smaller clouds that move at speeds up to 200 m s^{-1} relative to the main streak, which suggests the presence of atmospheric waves.

Satellites and Pluto

Jupiter, Saturn, Uranus, and Neptune have 4, 6, 5, and 2 natural satellites, respectively, with diameters exceeding 400 km. The largest, and the only ones with known atmospheres, are Jupiter's moons Io, Europa, Ganymede, and Callisto (the Galilean satellites), Saturn's moon Titan, and Neptune's moon Triton (**Table 4**).

Titan

Titan, which exceeds Mercury and Pluto in diameter, is the second-largest satellite in the solar system and the only satellite with a dense atmosphere. Titan was discovered by Huygens in 1655. A controversial observation that Titan's disk is brighter at the center than at the edge suggested to Comas Sola in 1908 that Titan has an atmosphere. But the true discovery of an atmosphere around Titan occurred in 1944 when Kuiper discovered gaseous absorption lines of methane in infrared spectra of Titan. Debate existed about the surface density (and even whether methane is the dominant constituent) until the Voyager encounters, when it became clear that the surface density is four

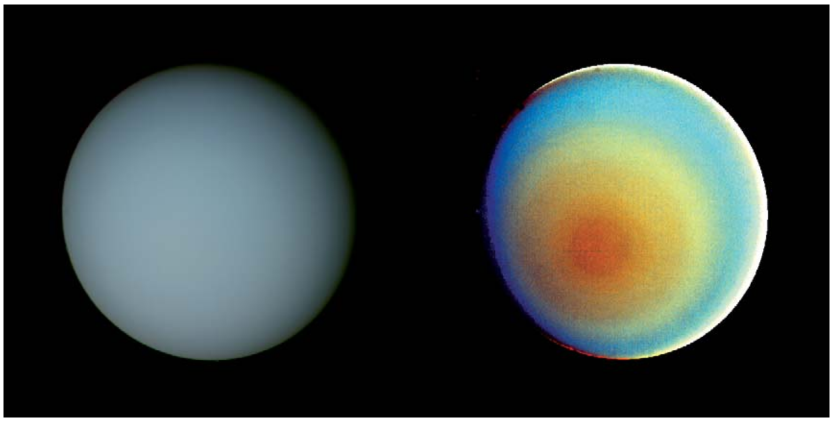


Figure 13 Southern hemisphere of Uranus in true and false color (left and right, respectively) imaged by *Voyager 2* in 1986. Few discrete clouds are visible. The south pole is slightly below and left of center. Faint banding along latitude circles is evident in the false-color image.

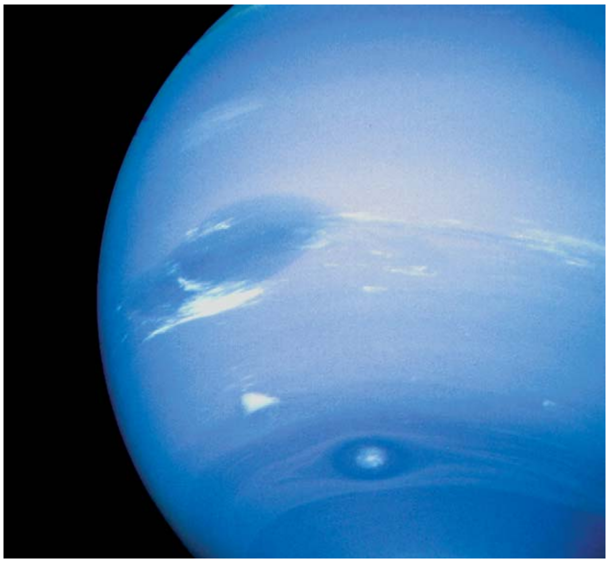


Figure 14 Neptune as imaged by *Voyager 2* in 1989. The Great Dark Spot (the large dark oval), a smaller dark vortex, and scattered, rapidly changing white clouds are visible.

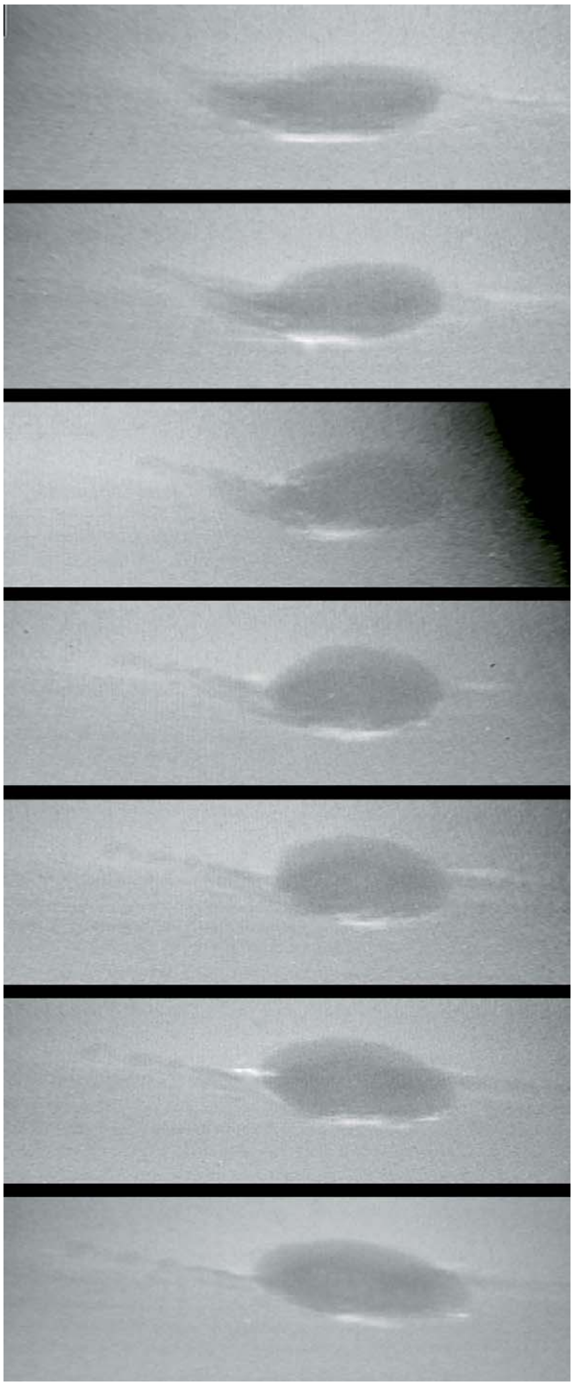


Figure 15 Time evolution of Neptune's Great Dark Spot over 4.5 Earth days. Time proceeds forward from top to bottom at 18-hour intervals.

times that of Earth (5.2 kg m^{-3} versus 1.2 kg m^{-3} for the Earth) and that the primary constituent is molecular nitrogen (N_2) (**Table 5**). Despite the great atmospheric mass, Titan's small gravity produces a surface pressure of 1.5 bars, similar to that of Earth.

Titan's temperature profile, measured by the Voyager radio occultation, shows similarities to that of Earth (**Figure 17**). The temperature reaches a broad minimum of 72 ± 2 K at 130 mbar (40 km altitude), defining a troposphere (where temperature decreases with height) and a stratosphere (where temperature increases with height). The surface temperature is 97 ± 4 K. Overlying the stratosphere are a well-defined mesosphere from 300 to 600 km (0.1 mbar–0.1 μbar), where temperature decreases with height, and a thermosphere above 600 km, where temperature increases with height.

Titan is enshrouded by an opaque global layer of orange-colored aerosols (**Figure 18**). The *Voyager 1* flyby reached a minimum distance from Titan of 4000 km, but no obvious hints of the surface were seen in Voyager images. The haze shows faint banding but no discrete clouds, preventing the precise measurements of wind. The haze resides primarily between 50 and 200 km altitude, with an overlying (detached) layer at roughly 300 km altitude.

A variety of laboratory and theoretical studies have shown that the haze is produced from photolytic and catalytic destruction of CH_4 and N_2. Photolytic breakup of methane by ultraviolet light, which occurs primarily above 700 km altitude, leads to methane radicals that react to produce ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), and numerous higher-order organics. As these gases diffuse downward to the stratosphere, where temperature is lower, they condense to form aerosols. Ices of these simple compounds are colorless, so Titan's orange hue suggests that a variety of complex compounds (such as organic

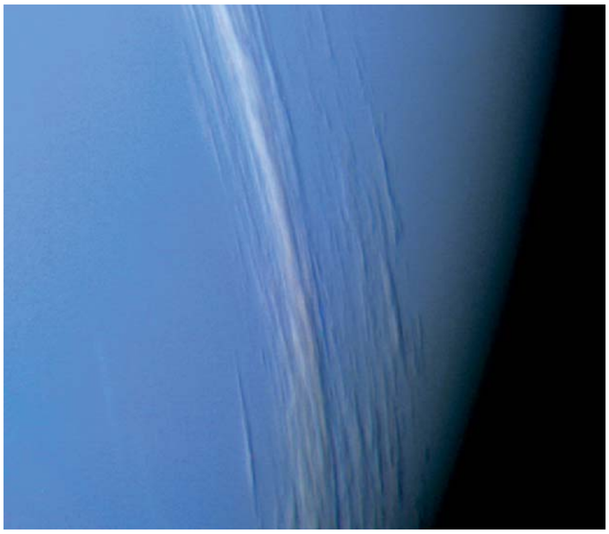


Figure 16 Clouds on Neptune at 29° N latitude. Sunlight comes from the lower left. Shadows indicate that the white clouds are ~ 50 km above the blue cloud deck.

polymers) may also result. Eventually, the haze particles presumably reach the surface, producing an organic sludge.

The destruction of methane in Titan's atmosphere is irreversible, because the hydrogen freed from the photolysis reactions escapes to space. Titan's atmospheric methane would be destroyed in 10^7 years without some means of replenishment. The most likely scenario is that a reservoir of methane exists at or below Titan's surface. (Titan's bulk density indicates that approximately half its mass consists of ice, and, while H_2O ice is expected to dominate, a substantial reservoir of methane is also plausible.) Moreover, extrapolation of current reaction rates backward in time indicates that, over the age of the solar system, a layer of organics (primarily ethane) nearly 1 km deep would have been produced. At Titan's surface conditions, ethane is a liquid, so seas of liquid ethane and dissolved methane may be present on Titan's surface.

A global ocean, however, is not allowed by present data. Radar can penetrate Titan's haze layers, and radar observations taken in 1990 indicate that Titan's reflectivity at radar wavelengths far exceeds that of liquid ethane and is more consistent with water ice. Furthermore, Titan's atmosphere is moderately transparent at several wavelengths near 1 μm and, starting in 1994, crude maps of Titan were produced at near-infrared wavelengths. These images show a heterogeneous surface with bright and dark regions; this heterogeneity is best explained by a predominantly solid surface. Nevertheless, nonglobal ethane–methane seas or lakes may still exist; another possibility is that the liquid hydrocarbons exist in pores and caverns in Titan's crust.

The temperatures in Titan's atmosphere allow condensation of methane, so Titan may have a 'hydrological' cycle in which methane plays the role that water does in Earth's atmosphere. Over the past few years, several researchers have looked for evidence of methane condensation clouds in infrared spectra of Titan. Time-variability in the infrared flux at wavelengths sensitive to the lower atmosphere suggest that such clouds (perhaps Titan's equivalent of thunderstorms) occasionally exist. The lowermost few kilometers of Titan's atmosphere appears to be subsaturated in methane, but, surprisingly, Titan's infrared spectrum is best explained by the idea that, in the mid- and upper troposphere, methane is supersaturated (with a relative humidity of 150–200%).

Table 4 Properties of satellites with atmospheres

	Io	*Europa*	*Ganymede*	*Callisto*	*Titan*	*Triton*
Primary	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Date of discovery	1610	1610	1610	1610	1655	1846
Orbital radius (10^5 km)	4.22	6.71	10.7	18.8	12.2	3.54
Orbital radius (planetary radii)	5.9	9.4	15.0	26.4	20.2	14.0
Mass (10^{23} kg)	0.893	0.480	1.482	1.076	1.346	0.215
Mass (Earth = 1)	0.0149	0.00803	0.0248	0.0180	0.0225	0.00360
Radius (km)	1818	1561	2634	2408	2575	1353
Mean density (g cm^{-3})	3.50	3.0	1.94	1.84	1.88	2.05
Surface gravity (m s^{-2})	1.80	1.31	1.42	1.24	1.35	0.78
Orbital period (days)[a]	1.77	3.55	7.16	16.689	15.945	5.877
Rotation period[b] (days)[a]	Syn	Syn	Syn	Syn	(Syn?)	Syn
Orbital inclination	0.04°	0.47°	0.21°	0.51°	0.33°	157.3°

[a]1 day = 24 hours = 86 400 s.
[b]'Syn' = synchronous rotation (i.e., rotation period equals orbital period). Titan probably rotates synchronously, but its dense cloud layer has prevented definitive measurement.
Data from Showman and Malhotra (1999); Beatty *et al.* (1999).

Table 5 Composition of Titan's atmosphere[a]

Species	*Mole fraction*	*Comments*
N_2	0.82–0.99	
Ar	0–0.06	Not yet detected, but expected
CH_4	0.01–0.12	
H_2	0.002	
C_2H_6	$1.3 \pm 0.5 \times 10^{-5}$	
C_2H_4	$8 \pm 2 \times 10^{-8}$	
C_2H_2	$1.9 \pm 0.2 \times 10^{-6}$	
C_3H_8	$5 \pm 2 \times 10^{-7}$	
C_3H_4	$8.0 \pm 1.5 \times 10^{-9}$	
C_4H_2	$1.5 \pm 0.2 \times 10^{-9}$	
C_6H_6 (benzene)	$< 6.0 \times 10^{-9}$	
HCN	$1.5 \pm 0.2 \times 10^{-7}$	
HC_3N	$< 1 \times 10^{-9}$	
C_2N_2	$< 1.5 \times 10^{-9}$	
CO	6×10^{-5}	Troposphere. Exact value debated
	$0.4–6 \times 10^{-5}$	Stratosphere
CO_2	$1.5 \pm 0.1 \times 10^{-8}$	
H_2O	$4 \pm 2 \times 10^{-10}$	

[a]Includes only gases. Particulates are of uncertain composition (see text).
Data from Taylor and Coustenis (1998); Owen (1999) in Beatty *et al.* (1999).

Nevertheless, such supersaturation is difficult to understand and a subsaturated methane profile may also explain the observations.

Titan's atmosphere exhibits an equatorial bulge, indicating that the atmosphere rotates substantially faster than the surface rotation period of 16 days. In the upper stratosphere (0.25 mbar), maintenance of this bulge requires the existence of 50–100 m s^{-1} zonal

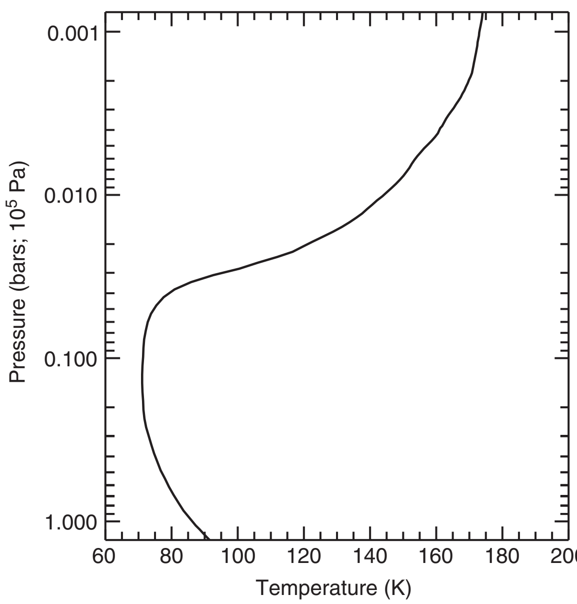


Figure 17 Temperature versus pressure on Titan as obtained by Voyager radio occultation.

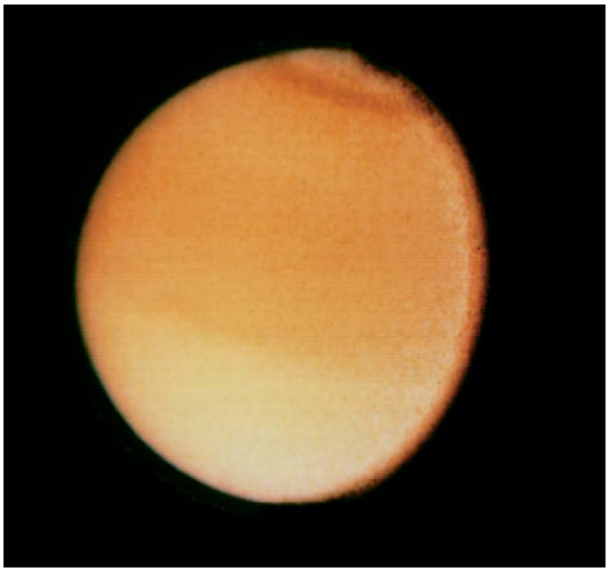


Figure 18 Saturn's moon Titan as imaged by *Voyager 2* in 1981. An orange pall of smog particles obscures the surface from view. The haze is brighter in the southern hemisphere, and a dark collar can be seen around the north pole.

winds near the equator and two broad 150 m s^{-1} jets near 60° N and S latitude. At Titan's 16-day period, the Coriolis force is weak, and the horizontal force balance is expected to be cyclostrophic (i.e., a balance between horizontal pressure-gradient and centripetal accelerations). Because of surface drag, winds in the lower atmosphere should be weak, and the implied vertical shear indicates that, at least over some range of altitudes, air should be warmer at low latitudes than at high latitudes. This is consistent with Voyager infrared data, which indicate that at pressures of about 100 and 0.3 mbar the equatorial temperature is 2 and 12 K warmer, respectively, than that at 60° latitude (the highest latitude sampled by Voyager).

These considerations do not determine whether the wind is east or west. However, winds on the edges of Titan's disk that approach or recede from Earth produce a Doppler shift that, if measured, could determine the sign of the winds. Measurements of this phenomenon in 2001 indicated with 94% confidence that the upper-stratospheric winds are eastward.

General circulation models of Titan are in their infancy. Nevertheless, they have been capable of producing a superrotation similar to that observed. Preliminary attempts to investigate the effects of a methane 'hydrological' cycle are also being undertaken.

Triton and Pluto

Triton, which is Neptune's largest moon, and Pluto, which is usually the most distant planet from the Sun, are mid-sized icy worlds with tenuous atmospheres whose main constituent, N_2, is in vapor pressure equilibrium with solid N_2 ice on the surface. The shapes of infrared spectral features in the solid N_2 on the surface indicate that the N_2 ice temperatures are 38 ± 1 K and 40 ± 2 K on Triton and Pluto, respectively. Over the past few decades, solid CH_4, CO, and H_2O as well as N_2 have been discovered on the surfaces of both bodies; solid CO_2 has been detected on Triton but not on Pluto. That N_2 dominates Triton's atmosphere is suggested by detection of gaseous N_2 absorption and emission features at ultraviolet wavelengths by the Voyager spacecraft; furthermore, the surface pressure, 14 μbar, is equal to the vapor pressure of N_2 ice at 38 K. Analysis of data obtained when a star passed behind Pluto in 1988 indicates that the molecular mass of Pluto's atmosphere is near 28, consistent with either N_2 or CO; the low vapor pressure of CO relative to N_2 suggests that CO is at most a minor constituent. Gaseous CH_4 has been detected in the atmospheres of Triton and Pluto, with mole fractions of $2\text{–}6 \times 10^{-4}$ and 0.001–0.1, respectively. The low CH_4 abundance is consistent with the lower volatility of CH_4 relative to N_2.

The *Voyager 2* flyby past Triton in 1989 showed a dynamic world with a wealth of atmospheric and surface processes (**Figure 19**). Despite the low atmospheric mass, several types of airborne particulates were observed. First was a nearly ubiquitous, and very tenuous, haze layer extending to 25 km altitude. The haze probably results from photochemical destruction of CH_4 to form C_2H_6, C_2H_4, C_2H_2, and other compounds that condense at Triton's cold temperatures. Second, isolated clouds 70–300 km in length were observed at heights of 1–3 km, which may result from condensation of N_2. Third, and most spectacular, four geysers were seen erupting at Triton's surface, sending columns of dark particles to altitudes of 8 km. These particles formed plumes that extended up to 150 km downwind (**Figure 20**). Analysis of surface wind streaks and orientations of the clouds and plumes suggests that, in Triton's southern mid-latitudes (the region best imaged by Voyager), the winds blow to the north-east at the surface, to the east at 1–3 km altitude, and to the west at 8 km altitude. This wind pattern is consistent with a polar vortex aloft (whose sign changes from east to west with increasing height, consistent with a negative equator-to-pole temperature gradient in thermal wind balance) and a frictional boundary layer at the surface. The north-eastward winds at the surface may result from flow of air away from the south polar cap (modified by the Coriolis acceleration) as N_2 ice from the cap sublimes (Note that Triton's rotation is retrograde, that is, from east to west, so the astronomically defined south pole has the same sense of rotation as Earth's north pole.)

Figure 19 Neptune's moon Triton as imaged by *Voyager 2* in 1989. Varied surface terrains indicate an active geological history. Dark streaks toward the bottom of the image may be dust deposited by geyserlike plumes.

The atmospheres of Triton and Pluto are dense enough for transport of latent heat to play an important role in the surface energy balance. Because the vapor pressure of N_2 ice depends strongly on temperature, any variation in N_2-ice temperature across the surface would cause sublimation (hence cooling) in the warm regions and condensation (hence

Figure 20 An active geyser on Triton. Comparison of stereo pairs of images shows that the dark streak curving across the rightmost two-thirds of the image is a cloud at 8 km altitude. The dark material (probably a carbon-rich dust) is ejected from the surface to 8 km altitude within the vertical column visible at the left edge of the dark streak. The material then blows downwind to the right. Sequences of images show substantial time variability in the plume.

warming) in the cool regions. This process is efficient enough to guarantee that the nitrogen ice, which covers approximately half of both bodies, maintains constant temperatures across the surface (at 38 ± 1 K on Triton and 40 ± 2 K on Pluto) despite the fact that the absorbed solar and emitted infrared fluxes usually do not balance. Regions lacking N_2 ice may attain temperatures up to 60 K.

Voyager measurements at ultraviolet wavelengths indicate that Triton's atmospheric temperature reaches 100 K at altitudes above 300 km. On the basis of the low surface temperature, the 0–300 km atmosphere must therefore contain a stably stratified layer where temperature increases with height. Sunlight is absorbed aloft and conducted down this thermal gradient toward the surface. Nevertheless, the fact that the geyser plumes rose to 8 km before spreading horizontally (**Figure 20**) indicates that the atmosphere below 8 km is almost neutrally stable (so that temperature decreases with height, perhaps following an adiabat). This is puzzling, because unlike the case in Earth's lower atmosphere, radiation cannot compete with conduction on Triton, so no troposphere (where radiative cooling forces the atmosphere toward convective instability) is expected. Triton's 'troposphere' may result instead from mechanically forced turbulence caused by air flow over rough topography.

Little is known about Pluto (**Table 6**), which has not yet been visited by spacecraft. Our knowledge of Pluto's atmosphere derives largely from the fact that Pluto passed in front of a star in 1988 (an event called a stellar occultation). The dimming of the stellar light occurred gradually rather than suddenly, proving that Pluto has an atmosphere. Analysis of these observations indicates that the surface pressure is at least 3 μbar, but could exceed 100 μbar depending on the exact temperature of the nitrogen ice at the surface. (Over the allowed range of N_2-ice surface temperatures, 38–42 K, the vapor pressure ranges from 14 to 160 μbar). Analysis of the occultation data indicates a temperature near 100 K at pressures near 1 μbar, implying that temperature increases with height between the surface and 1 μbar pressure. Pluto's eccentric orbit causes large variations in distance from the Sun over its 248-year orbit, reaching a minimum of 29.7 AU in 1990 and a maximum of 49.5 AU in 2114. Pluto's surface temperature and atmospheric pressure will therefore probably plummet over the next century, although uncertainty in surface properties precludes a firm prediction.

Table 6 Properties of Pluto

Date of discovery	1930
Mass (kg)	1.32×10^{22}
Mass (Earth = 1)	0.002
Radius (km)	1145–1200
Surface gravity (m s^{-2})	0.6
Orbital period (years)	248
Orbital semi-major axis (AU)	39
Rotation period (days)	6.387
Obliquity	120°
Orbital eccentricity	0.249

Data from Stern and Tholen (1997); Cox AN (ed.) (2000) *Allen's Astrophysical Quantities*. Springer-Verlag, New York.

The Galilean Satellites

The four Galilean satellites, Io, Europa, Ganymede, and Callisto, each have extremely tenuous atmospheres resulting from internal processes and bombardment of the surfaces by high-energy particles contained in Jupiter's magnetosphere. Io, the innermost of the four satellites, is the most volcanically active body in the solar system. Sulfur dioxide (SO_2) released from volcanic plumes forms an atmosphere with a dayside surface pressure of order 1 nanobar (10^{-9} bar). SO is probably present at mole fractions of 1–10%. SO_2 condenses at Io's surface temperatures, and evidence indicates that SO_2 frost covers parts of the surface. Unlike the case with Pluto and Triton, the atmosphere is too thin for latent heat to buffer the frosts to a single temperature. The atmosphere may be patchy rather than spatially uniform. Condensation of SO_2 on Io's nightside produces large horizontal pressure gradients that induce supersonic flow from dayside to nightside. The surface pressure, areal extent, and vertical structure of the atmosphere remain poorly characterized.

Europa, Ganymede, and Callisto have surfaces dominated by water ice. Detection of atomic oxygen airglow in Hubble Space Telescope ultraviolet spectra of Europa and Ganymede implies the presence of tenuous molecular oxygen atmospheres with column densities of 10^{14}–10^{15} cm^{-2} and scale heights of 300 km or less on both satellites. The oxygen is probably produced by destruction of water molecules by impacting ions and electrons, followed by escape of the hydrogen to space. Ground-based observations of Europa indicate an even more tenuous sodium and potassium atmosphere extending to 25 Europan radii. Galileo spacecraft observations show a faint absorption line of CO_2 within 100 km of Callisto's surface, which provides evidence for a CO_2 atmosphere with surface pressure of 10^{-11} bar.

See also

Evolution of Atmospheric Oxygen. **Evolution of Earth's Atmosphere**. **Planetary Atmospheres:** Mars; Venus.

Further Reading

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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)