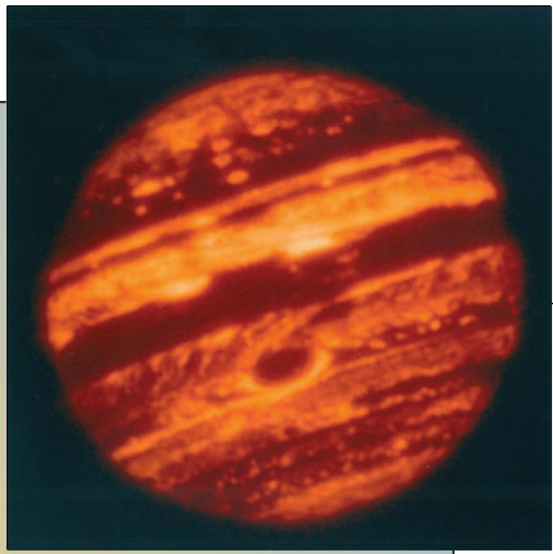
Atmospheres of the Giant Planets

Robert A. West

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



CHAPTER 20

The atmospheres of the giant planets—Jupiter, Saturn, Uranus, and Neptune—are very unlike those of the Earth, Mars, and Venus. They are composed mainly of hydrogen and helium, with some trace species, the most abundant of which are water, methane, and ammonia. They are cold enough to form clouds of ammonia and hydrocarbon ices, which extend deep into the interior of the planet, and indeed a significant fraction of the planet's mass may be responsible for the near-surface winds. The winds are primarily east–west (zonal) jets that alternate with latitude. Superimposed on the jets are spots of all sizes up to about three Earth diameters. Some of them, like Jupiter's Great Red Spot, are remarkably long-lived. At the highest altitudes, powerful **auroras**, as well as some still mysterious processes, heat the atmospheres to temperatures higher than current models can explain.

1. Introduction

To be an astronaut explorer in Jupiter's atmosphere would be strange and disorienting. There is no solid ground to stand on. The temperature would be comfortable at an altitude where the pressure is eight times that of Earth's surface, but it would be perpetually hazy overhead, with variable conditions (dry or wet, cloudy or not) to the east, west, north, and south. One would need to carry oxygen as there is no free oxygen, and to wear special clothing to protect the skin against exposure to ammonia, hydrogen sulfide, and ammonium hydrosulfide gases, which form clouds and haze layers higher in the atmosphere. A trip to high latitudes would offer an opportunity to watch the most powerful, vibrant, and continuous auroral displays in the solar system. On the way, one might pass through individual storm systems the size of Earth or larger and be buffeted by strong winds alternately from the east and west. One might be sucked into a dry downwelling sinkhole like the environment explored by the *Galileo* probe. The probe fell to depths where the temperature is hot enough to vaporize metal and rock. It is now a part of Jupiter's atmosphere.

Although the atmospheres of the giant planets share many common attributes, they are at the same time very diverse. The roots of this diversity can be traced to a set of basic properties, and ultimately to the origins of the planets. The most important properties that influence atmospheric behavior are listed in Table 1. The distance from the Sun determines how much sunlight is available to heat the upper atmosphere. The minimum temperature for all of these atmospheres occurs near the 100 mbar level and ranges from 110 K at Jupiter to 50 K at Neptune. The distance from the Sun and the total mass of the planet are the primary influences on the bulk composition. All the giant planets are enriched in heavy elements, relative to their solar abundances, by factors ranging from about 3 for Jupiter to 1000 for Uranus and Neptune. The latter two planets are sometimes called the ice giants because they have a large

TABLE 1 **Physical Properties of the Giant Planets**

Property	Jupiter	Saturn	Uranus	Neptune
Distance from the Sun (Earth distance = 1[a])	5.2	9.6	19.2	30.1
Equatorial radius (Earth radius = 1[b])	11.3	9.4	4.1	3.9
Planet total mass (Earth mass = 1[c])	318.1	95.1	14.6	17.2
Mass of gas component (Earth mass = 1)	254–292	72–79	1.3–3.6	0.7–3.2
Orbital period (years)	11.9	29.6	84.0	164.8
Length of day (hours, for a point rotating with the interior	9.9	10.7	17.4	16.2
Axial inclination (degrees from normal to orbit plane)	3.1	26.7	97.9	28.8
Surface gravity (equator–pole, m s^{-2})	(22.5–26.3)	(8.4–11.6)	(8.2–8.8)	(10.8–11.0)
Ratio of emitted thermal energy to absorbed solar energy	1.7	1.8	~1	2.6
Temperature at the 100-mbar level (K)	110	82	54	50

[a]Earth distance = 1.5×10^8 km.
[b]Earth radius = 6378 km.
[c]Earth mass = 6×10^{24} kg.

fraction of elements (O, C, N, and S) that were the primary constituents of ices in the early solar nebula.

The orbital period, axial tilt, and distance from the Sun determine the magnitude of seasonal temperature variations in the high atmosphere. Jupiter has weak seasonal variations; those of Saturn are much stronger. Uranus is tipped such that its poles are nearly in the orbital plane, leading to more solar heating at the poles than at the equator when averaged over an orbit. The ratio of radiated thermal energy to absorbed solar energy is diagnostic of how rapidly convection is bringing internal heat to the surface, which in turn influences the abundance of trace constituents and the morphology of eddies in the upper atmosphere. Vigorous convection from the deeper interior is responsible for unexpectedly high abundances of several trace species on Jupiter, Saturn, and Neptune, but convection on Uranus is sluggish. All these subjects are treated in more detail in the sections that follow.

2. Chemical Composition

This section is concerned with chemical abundances in the observable part of the atmosphere, a relatively thin layer of gas near the top (where pressures are between about 5 bar and a fraction of a microbar). To place the subject in context, some mention will be made of the composition of the interior. [*See* INTERIORS OF THE GIANT PLANETS.]

The bulk composition of a planet cannot be directly observed, but must be inferred from information on its mean density, its gravity field, and the abundances of constituents that are observed in the outer layers. The more massive planets were better able to retain the light elements during their formation, and so the bulk composition of Jupiter resembles that of the Sun. When the giant planets formed, they incorporated relatively more rock and ice fractions than a pure solar composition would allow, and the fractional amounts of rocky and icy materials increase from Jupiter through Neptune. [*See* THE ORIGIN OF THE SOLAR SYSTEM.] Most of the mass of the heavy elements is sequestered in the deep interior. The principal effects of this layered structure on the observable outer layers can be summarized as follows.

On Jupiter the gas layer (a fluid molecular envelope) extends down to about 40% of the planet's radius, where a phase transition to liquid metallic hydrogen occurs. Fluid motions that produce the alternating jets and vertically mix gas parcels may fill the molecular envelope but probably do not extend into the metallic region. Thus, the radius of the phase transition provides a natural boundary that may be manifest in the latitudinal extent of the zonal jets (see Section 4), whereas vertical mixing may extend to levels where the temperature is quite high. These same characteristics are found on Saturn, with the additional possibility that a separation of helium from hydrogen is occurring in the metallic hydrogen region, leading to enrichment of helium in the deep interior and depletion of helium in the upper atmosphere.

Uranus and Neptune contain much larger fractions of ice- and rock-forming constituents than do Jupiter and Saturn. A large water ocean may be present in the interiors of these planets. Aqueous chemistry in the ocean can have a profound influence on the abundances of trace species observed in the high atmosphere.

In the observable upper layers, the main constituents are molecular hydrogen and atomic helium, which are well mixed, up to the **homopause** level, where the mean free path for collisions becomes large enough that the lighter constituents are able to diffuse upward more readily than heavier ones. Other constituents are significantly less abundant than hydrogen and helium, and many of them condense in the coldest regions of the atmosphere. Figure 1 shows how temperature varies with altitude and pressure, and the locations of the methane, ammonia, and water cloud layers.

The giant planets have retained much of the heat generated by their initial collapse from the solar nebula. They cool by emitting thermal infrared radiation to space. Thermal radiation is emitted near the top of the atmosphere, where the opacity is low enough to allow infrared photons to escape to space. In the deeper atmosphere, heat is transported by convective fluid motions from the deep, hot interior to the colder outer layers. In this region, upwelling gas parcels expand and subsiding parcels contract adiabatically (e.g., with negligible transport of heat through their boundaries by radiation or conduction). Therefore temperature depends on altitude according to the adiabatic law $T = T_0 + C(z - z_0)$, where T_0 is the temperature at some reference altitude z_0, C is a constant (the adiabatic lapse rate) that depends on the gas composition, and z is altitude. The adiabatic lapse rate for dry hydrogen and helium on Jupiter is −2.2 K/km. On Uranus it is −0.8 K/km. The adiabatic lapse rate is different in regions where a gas is condensing or where heat is released as *ortho*-hydrogen and is converted to *para*-hydrogen. Both of these processes are important in the giant planet atmospheres at pressures between about 30 and 0.1 bar.

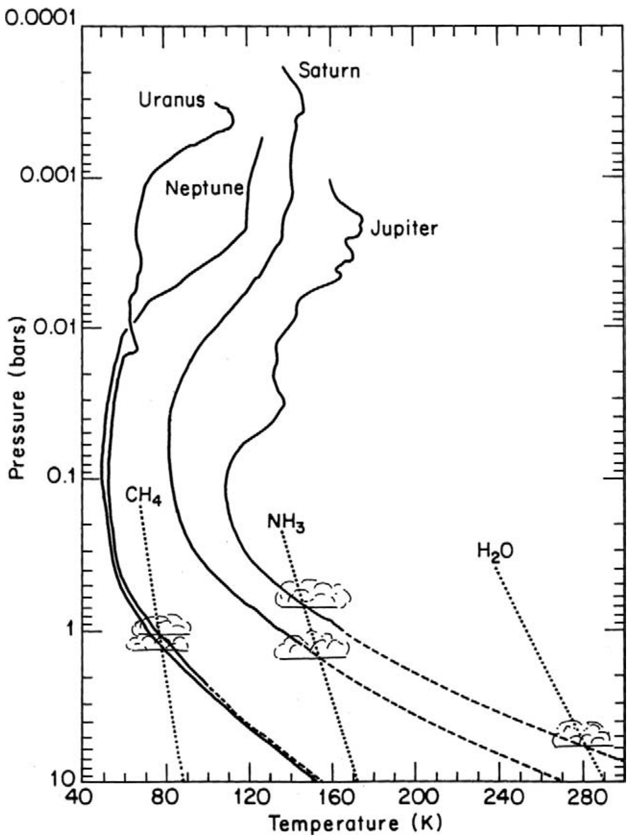


FIGURE 1 Profiles of temperature as a function of pressure in the outer planet atmospheres derived from measurements by the Voyager Radio Sciences experiment (solid curves). The dashed parts of the temperature profiles are extrapolations using the adiabatic lapse rate. At high altitudes (not shown), temperatures rise to about 1200 K for Jupiter, 800 K for Saturn and Uranus, and 300 K for Neptune. The dotted lines show vapor pressure curves divided by observed mixing ratios for water, ammonia, and methane. Condensate clouds are located where the solid and dotted curves cross. (From Gierasch and B. Conrath, 1993, *J. Geophys. Res.* **98**, 5459–5469. Copyright American Geophysical Union.)

Hydrogen is the main constituent in the observable part of the giant planet atmospheres, but not until recently was it recognized as especially important for thermodynamics. The hydrogen molecule has two ground-state configurations for its two electrons. The electrons can have their spins either parallel or antiparallel, depending on whether the spins of the nuclei are parallel or antiparallel. These states are called the ortho and para states. Transitions between ortho and para states are slow because, unlike most molecules, the nuclear spin must change when the electron spin changes. At high temperature (about 270 K or higher), the ortho:para relative abundance is 3:1. At lower temperature, a larger fraction is converted to the para state. Heat release from conversion of *ortho*- to *para*-hydrogen can act in the same way as **latent heat** release from condensation. The relative fractions of *ortho*- and *para*-hydrogen are observed to be close to thermal equilibrium values in the giant planet atmospheres, leading to the question of how equilibrium is achieved. Catalytic reactions on the surfaces of **aerosol** particles are thought to be important in equilibrating the ortho and para states.

Temperature follows the adiabatic law at pressures deeper than about 2 bar. The atmospheric temperature would drop at the adiabatic rate to near absolute zero at the top of the atmosphere were it not for sunlight, which heats the upper atmosphere. Sunlight penetrates to pressure levels near 20 bar, depending on how much overlying cloud and haze opacity is present. The competition between convective cooling and solar heating produces a temperature minimum near the 100 mbar level (the tropopause). At pressures between about 100 and 0.1 mbar, the temperature is determined primarily by equilibrium between thermal radiative cooling and solar heating. At even lower pressures, other processes, including auroral heating, dump energy into the atmosphere and produce higher temperatures. More will be said about this in Section 5.

The current inventory of observed gaseous species is listed in Table 2. Molecular hydrogen and helium are the most abundant. Helium is in its ground state in the **troposphere** and **stratosphere** and therefore does not

TABLE 2 **Abundances of Observed Species in the Atmospheres of the Giant Planets**

	Peak mixing ratio (by number) or upper limit			
Constituent	**Jupiter**	**Saturn**	**Uranus**	**Neptune**
Species with constant mixing ratio below the homopause				
H_2	0.86	0.90	0.82	0.79
HD	4×10^{-5}	4×10^{-5}		
He	0.14	0.10	0.15	0.18
CH_4	2×10^{-3}	2×10^{-3}		
CH_3D	3.5×10^{-7}	2×10^{-7}		
^{20}Ne	2×10^{-5}			
^{36}Ar	1×10^{-5}			
Condensable species (estimated or measured below the condensation region)				
NH_3	2.5×10^{-4}	2×10^{-4}		
H_2S	7×10^{-5}			
H_2O	6×10^{-4}			
CH_4			0.025	0.02–0.03
CH_3D			2×10^{-5}	2×10^{-5}
Disequilibrium species in the troposphere				
PH_3	5×10^{-7}	2×10^{-6}		
GeH_4	7×10^{-10}	4×10^{-10}		
AsH_3	2.4×10^{-9}	3×10^{-9}		
CO	2×10^{-9}	$1–25 \times 10^{-9}$	$<1 \times 10^{-8}$	1×10^{-6}
HCN			$<1 \times 10^{-10}$	1×10^{-9}
Photochemical species (peak values)				
C_2H_2	1×10^{-7}	3×10^{-7}	1×10^{-8}	6×10^{-8}
C_2H_4	7×10^{-9}			
C_2H_6	7×10^{-6}	7×10^{-6}	$<1 \times 10^{-8}$	2×10^{-6}
C_3H_4	2.5×10^{-9}			
C_6H_6	2×10^{-9}			

produce spectral lines from which its abundance can be determined. The mixing ratio for Saturn, Uranus, and Neptune is inferred from its influence on the broad collision-induced hydrogen lines near the 45 μm wavelength, and from a combined analysis of the infrared spectrum and refractivity profiles retrieved from spacecraft radio occultation measurements. Helium on Jupiter is accurately known from measurements made by the *Galileo* probe, which descended through the atmosphere. It is a little smaller than the mixing ratio inferred for the primitive solar nebula from which the planets formed. Helium is substantially depleted in Saturn's upper atmosphere, consistent with the idea that helium is precipitating out in the metallic hydrogen region. For Uranus and Neptune, the helium mixing ratio is close to the mixing ratio (0.16) in the primitive solar nebula. There is still some uncertainty in the helium mixing ratio for Uranus, Neptune, and Saturn because additional factors, such as aerosol opacity and molecular nitrogen abundance, affect the shapes of the collision-induced spectral features, and we do not have a completely consistent set of values for all these parameters.

Mixing ratios of **deuterated** hydrogen and methane (HD and CH_3D) also provide information on the formation of the planets. **Deuterium**, which once existed in the Sun, has been destroyed in the solar atmosphere, and the best information on its abundance in the primitive solar nebula comes from measurements of the giant planet atmospheres. On Jupiter, the deuterium mixing ratio is thought to be close to that of the primitive solar nebula. On Uranus and Neptune, it is enhanced because those planets incorporated relatively more condensed material on which deuterium preferentially accumulated through isotopic fractionation. Isotopic fractionation (the enhancement of the heavier isotope over the lighter isotope during condensation) occurs because the heavier isotope has a lower energy than the lighter isotope in the condensed phase.

The elements oxygen, carbon, nitrogen, and sulfur are the most abundant molecule-forming elements in the Sun (after hydrogen), and all are observed in the atmospheres of the giant planets, mostly as H_2O, CH_4, NH_3, and (for Jupiter) H_2S. Water condenses even in Jupiter's atmosphere, at levels that are difficult to probe with infrared radiation (6 bars or deeper). A straightforward interpretation of Jupiter's spectrum indicated its abundance to be about a hundred times less than what is expected from solar composition. The *Galileo* probe measurements indicated that water was depleted relative to solar abundance by roughly a factor of two at the deepest level measured (near 20 bars of pressure) and even more depleted at higher altitude. However, the probe descended in a relatively dry region of the atmosphere, analogous to a desert on Earth, and the bulk water abundance on Jupiter may well be close to the solar abundance. Water is not observed on any of the other giant planets because of the optically thick overlying clouds and haze layers. It is thought to form a massive global ocean on Uranus and Neptune based on the densities and gravity fields of those planets, coupled with theories of their formation.

Methane is well mixed, up to the homopause level, in the atmospheres of Jupiter and Saturn, but it condenses as ice in the atmospheres of Uranus and Neptune. Its mixing ratio below the condensation level is enhanced over that expected for a solar-composition atmosphere by factors of 2.6, 5.1, 35, and 40 for Jupiter, Saturn, Uranus, and Neptune, respectively. These enhancements are consistent with ideas about the amounts of icy materials that were incorporated into the planets as they formed. The stratospheres of Uranus and Neptune form a cold trap, where methane ice condenses into ice crystals that fall out, making it difficult for methane to mix to higher levels. Nevertheless, the methane abundance in Neptune's stratosphere appears to be significantly higher than its vapor pressure at the temperature than the tropopause would allow (and also higher than the abundance in the stratosphere of Uranus), suggesting some mechanism such as convective penetration of the cold trap by rapidly rising parcels of gas. This mechanism does not appear to be operating on Uranus, and this difference between Uranus and Neptune is symptomatic of the underlying difference in internal heat that is available to drive convection on Neptune but not on Uranus.

Ammonia is observed on Jupiter and Saturn, but not on Uranus or Neptune. Ammonia condenses as an ammonia ice cloud near 0.6 bar on Jupiter and at higher pressures on the colder outer planets. Ammonia and H_2S in solar abundance would combine to form a cloud of NH_4SH (ammonium hydrosulfide) near the 2 bar level in Jupiter's atmosphere and at deeper levels in the colder atmospheres of the other giant planets. Hydrogen sulfide was observed in Jupiter's atmosphere by the mass spectrometer instrument on the *Galileo* probe. Another instrument (the nephelometer) on the probe detected cloud particles in the vicinity of the 1.6 bar pressure level, which would be consistent with the predicted ammonium hydrosulfide cloud. Evidence from thermal emission at radio wavelengths has been used to infer that H_2S is abundant on Uranus and Neptune. Ammonia condenses at relatively deep levels in the atmospheres of Uranus and Neptune and has not been spectroscopically detected. A dense cloud is evident at the level expected for ammonia condensation (2–3 bar) in near-infrared spectroscopic observations, but the microwave spectra of those planets are more consistent with a strong depletion of ammonia at those levels. An enhancement of H_2S relative to NH_3 could act to deplete ammonia by the formation of ammonium hydrosulfide in the deeper atmosphere. In that case, H_2S ice is the most likely candidate for the cloud near 3 bars.

Water, methane, and ammonia are in thermochemical equilibrium in the upper troposphere. Their abundances at altitudes higher than (and temperatures colder than) their condensation level are determined by temperature (according to the vapor–pressure law) and by meteorology, as is water in Earth's atmosphere. Some species (PH_3, GeH_4, and CO) are not in thermochemical equilibrium in the upper troposphere. At temperatures less than 1000 K, PH_3 would react with H_2O to form P_4O_6 if allowed to proceed to thermochemical equilibrium. Apparently the time scale for this reaction (about 10^7 s) is longer than the time to convect material from the 1000 K level to the tropopause. A similar process explains the detections of GeH_4. Yet another phenomenon (impact of a comet within the past 200 years) probably accounts for the detection of CO in the stratosphere.

Ammonia and phosphine are present in the stratospheres of Jupiter and Saturn, and methane is present in the stratospheres of all the giant planets. These species are destroyed at high altitudes by ultraviolet sunlight and by charged particles in auroras, producing N, P, and C, which can react to form other compounds. Ammonia photochemistry leads to formation of hydrazine (N_2H_4), and phosphine photochemistry leads to diphosphine (P_2H_4). These constituents condense in the cold tropospheres of Jupiter and Saturn and may be responsible for much of the ultraviolet-absorbing haze seen at low latitudes. Nitrogen gas and solid P are other by-products of ammonia and phosphine chemistry. Solid phosphorus is sometimes red and has been proposed as the constituent responsible for the red color of Jupiter's Great Red Spot. That suggestion (one of several) has not been confirmed, and neither N_2H_4 nor P_2H_4 has been observed spectroscopically.

Organic compounds derived from dissociation of methane are present in the stratospheres of all the giant planets. The photochemical cycle leading to stable C_2H_2 (acetylene), C_2H_4 (ethylene), C_2H_6 (ethane), and C_4H_2 (diacetylene) is shown schematically in Fig. 2. The chain may progress further to produce polyacetylenes ($C_{2n}H_2$). These species form condensate haze layers in the cold stratospheres of Uranus and Neptune. More complex hydrocarbon species (C_3H_8, C_3H_4) are observed in Jupiter's atmosphere primarily in close proximity to high-latitude regions, where auroral heating is significant. The abundant polar aerosols in the atmospheres of Jupiter and Saturn

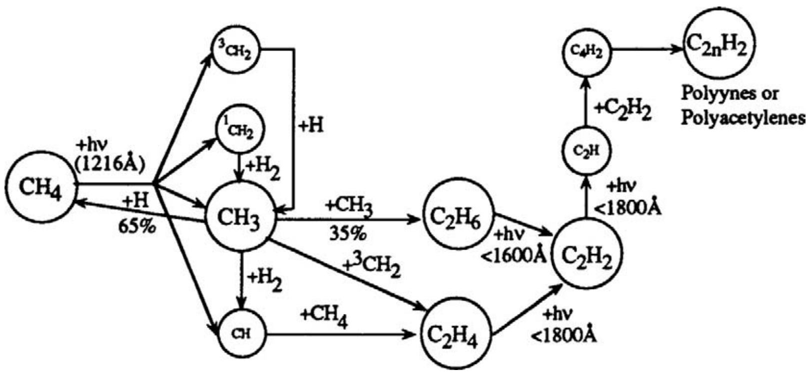


FIGURE 2 Summary of CH_4 (methane) photochemical processes in the stratospheres of the giant planets. Photodissociation by ultraviolet light is indicated by $+h\nu$ at the indicated wavelength. Methane photodissociation is the starting point in the production of a host of other hydrocarbons. (Revised by S. K. Atreya from Fig. 5-3 from J. B. Pollack and S. K. Atreya, 1992, in "Exobiology in Solar System Exploration" (G. Carle et al., eds.), NASA-SP 512, pp. 82–101.)

may owe their existence to the ions created by auroras in the upper atmosphere.

As instruments become more sensitive, new species are detected. These include C_2H_4, C_3H_4, and C_6H_6 in the atmospheres of Jupiter and Saturn, and C_3H_8 for Saturn. The methyl radical CH_3 (an unstable transition molecule in the reaction chain) has been detected on Jupiter, Saturn, and Neptune.

Hydrogen cyanide (HCN) is present in the stratospheres of Jupiter and Neptune, but for two very different reasons. On Jupiter, HCN was emplaced high in the stratosphere as a result of the 1994 impacts of comet Shoemaker–Levy 9. During the 3 years after the impacts, it was observed to spread north of the impact latitude (near 45°S), eventually to be globally distributed. It is expected to dissipate over the span of a decade or so. Cometary impact may also be responsible for HCN in Neptune's stratosphere.

Quantitative thermochemical and photochemical models are available for many of the observed constituents and provide predictions for many others that are not yet observed. These models solve a set of coupled equations that describe the balance between the abundances of species that interact and include important physical processes such as ultraviolet **photolysis**, condensation/sublimation, and vertical transport. Current models heuristically lump all the transport processes into an effective eddy mixing coefficient, and the value of that coefficient is derived as part of the solution of the set of equations. As we gain more detailed observations and more comprehensive laboratory measurements of reaction rates, we will be able to develop more sophisticated models. Some models are beginning to incorporate transport by vertical and horizontal winds. Figures 3 and 4 show vertical profiles calculated from models for a number of photochemically produced species.

3. Clouds and Aerosols

The appearance of the giant planets is determined by the distribution and optical properties of cloud and aerosol haze particles in the upper troposphere and stratosphere. Cameras on the *Voyager* spacecraft provided detailed views of all the giant planets, whose general appearances can be compared in Fig. 5. Their atmospheres show a banded structure (which is difficult to see on Uranus) of color and shading parallel to latitude lines. These were historically named belts and zones on Jupiter and Saturn, with belts being relatively dark and zones relatively bright. Specific belts and zones were named in accordance with their approximate latitudinal location (Equatorial Belt, North and South Tropical Zones near latitudes ±20°, North and South Temperate Zones and Belts near ±35°, and polar regions).

The nomenclature should not be construed to mean that low latitudes are relatively warmer than high latitudes, as they are on Earth and Mars. Nor is it true that the reflectivities of these features remain constant with time. Some features on Jupiter, such as the North and South

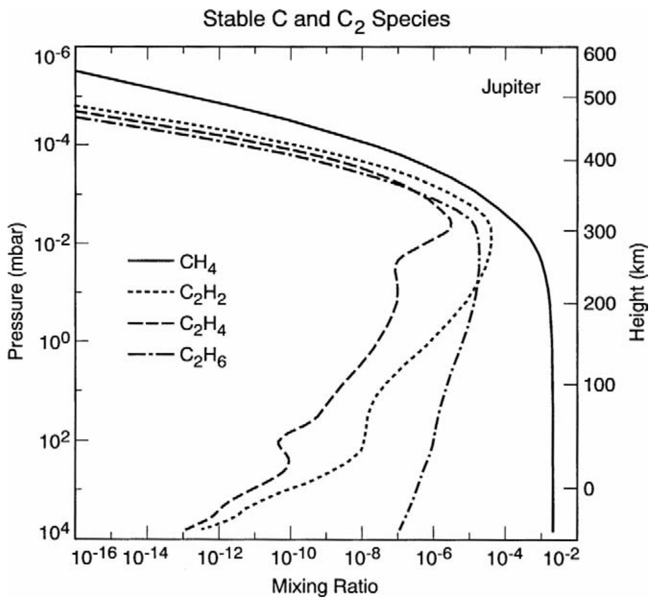


FIGURE 3 Vertical profiles of some photochemical species in Jupiter's stratosphere. The mixing ratios (horizontal axis) are plotted as a function of pressure. (From G. R. Gladstone et al., 1996, *Icarus* **119,** 1–52. Copyright Academic Press.)

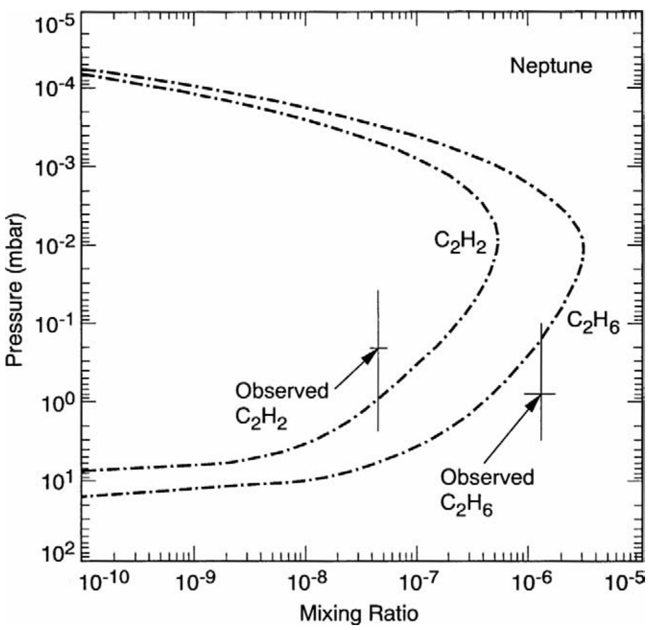


FIGURE 4 Vertical profiles of photochemical species in the Neptunian stratosphere. (From P. Romani et al., 1993, *Icarus* **106**, 442–462. Copyright by Academic Press.)

Tropical Zones, are persistently bright, whereas others, like the South Equatorial Belt, are sometimes bright and sometimes dark. On Jupiter, there is a correlation between visible albedo and temperature, such that bright zones are usually cool regions and dark belts are usually warm near the tropopause. Cool temperatures are associated with adiabatic cooling of upwelling gas, and the correlation of cool temperatures with bright clouds points to enhanced condensation of ice particles as condensable gases flow upward and cool. This correlation does not hold completely on Jupiter and almost not at all on the other giant planets. The mechanisms responsible for producing reflectivity contrasts and color remain largely mysterious, although a number of proposals have been advanced. These will be discussed in more detail.

Our understanding of aerosols and clouds is rooted in thermochemical equilibrium models that predict the temperature (and hence pressure and altitude) of the bases of condensate clouds. The cloud base occurs where the vapor pressure of a condensable gas equals its partial pressure. Model predictions for the four giant planets are shown in Fig. 6. The deepest cloud to form is a solution of water and ammonia on Jupiter and Saturn, with dissolved H_2S as well on Uranus and Neptune. At higher altitudes, an ammonium hydrosulfide cloud forms, and its mass depends on both the amounts of H_2S and NH_3 available and the ratio of S to N. At still higher altitudes, an ammonia or hydrogen sulfide cloud can form if the S/N ratio is less than or greater than 1, respectively. If the ratio is greater than 1, all the N will be taken up as NH_4SH, with the remaining sulfur available to condense at higher altitudes. This seems to be the situation on Uranus and Neptune, but the reverse is true for Jupiter and Saturn. Only the atmospheres of Uranus

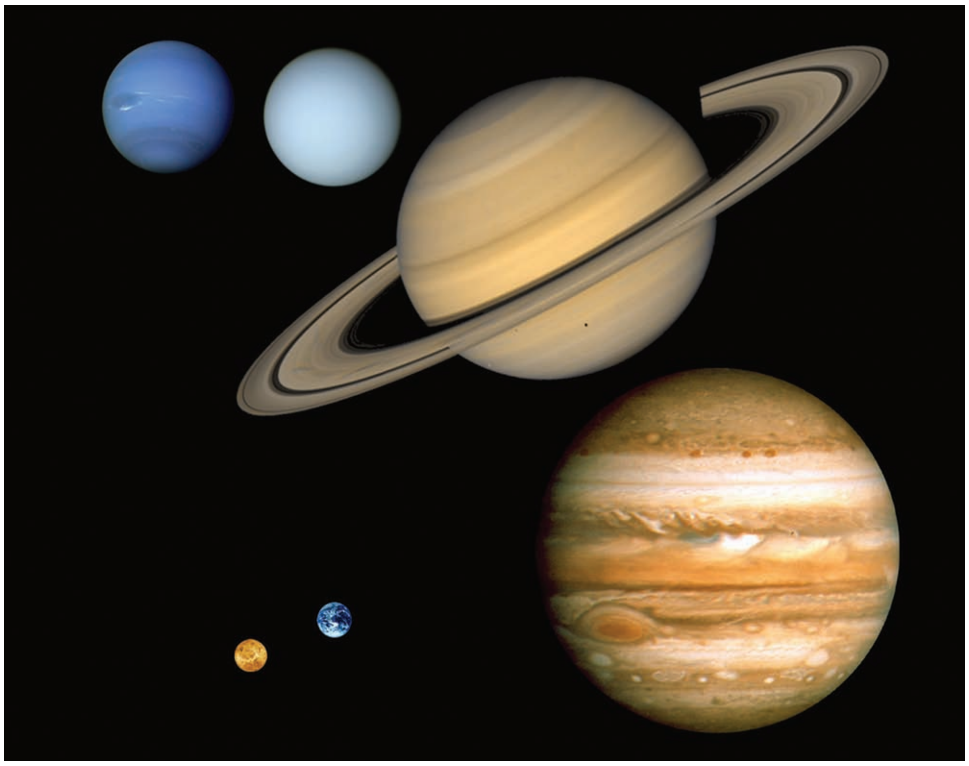


FIGURE 5 *Voyager* images of Jupiter, Saturn, Uranus, and Neptune, scaled to their relative sizes. Earth and Venus are also sown scaled to their relative sizes.

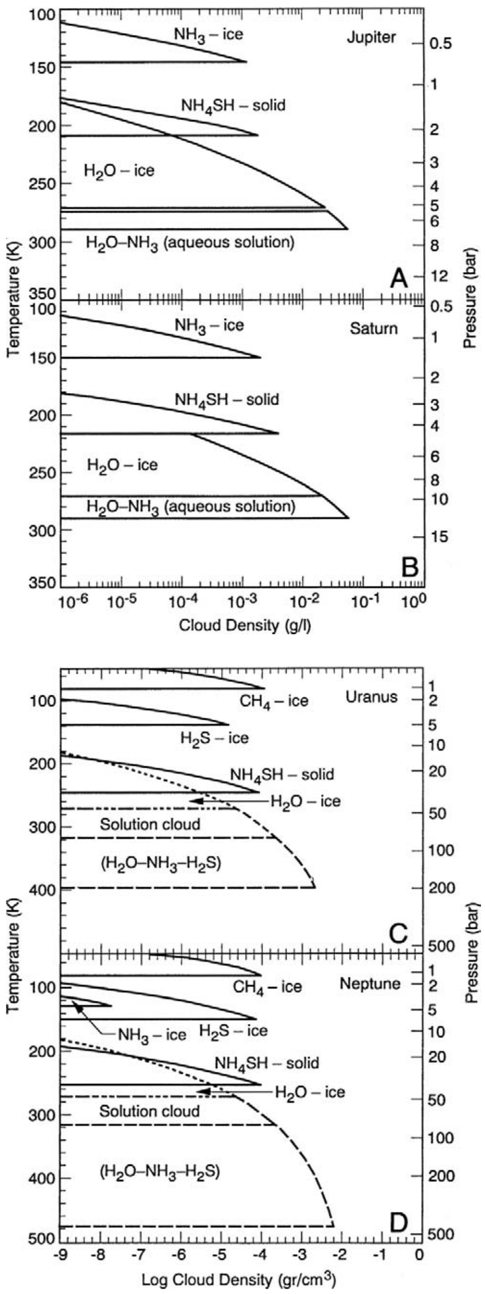


FIGURE 6 The diagrams in the four panels show the locations of condensate cloud layers on Jupiter, Saturn, Uranus, and Neptune. These figures indicate how much cloud material would condense at various temperatures (corresponding to altitude) if there were no advective motions in the atmosphere to move vapor and clouds. They are based on simple thermochemical equilibrium calculations, which assume, for Jupiter and Saturn, that the condensable species have mixing ratios equal to those for a solar composition atmosphere. (Figures for Jupiter and Saturn were constructed from models by S. K. Atreya and M. Wong, based on S. K. Atreya and P. N. Romani, 1985, in "Planetary Meteorology" (G. E. Hunt, ed.), pp. 17–68, Cambridge Univ. Press, Cambridge, United Kingdom. Those for Uranus and Neptune were first published by I. de Pater et al., 1991, *Icarus* **91**, 220–233. Copyright by Academic Press.)

and Neptune are cold enough to condense methane, which occurs at 1.3 bar in Uranus and about 2 bar in Neptune. It is predominantly the uppermost clouds that we see at visible wavelengths.

Observational evidence to support the cloud stratigraphy shown in Fig. 6 is mixed. The *Galileo* probe detected cloud particles near 1.6-bar pressure and sensed cloud opacity at higher altitudes corresponding to the ammonia cloud. With data only from remote-sensing experiments, it is difficult to probe to levels below the top cloud, and the evidence we have for deeper clouds comes from careful analyses of radio occultations and of gaseous absorption lines in the visible and near infrared, and from thermal emission at 5, 8.5, and 45 μm. Contrary to expectation, spectra of the planets show features due to ice in only a small fraction of the cloudy area. The *Voyager* radio occultation data showed strong refractivity gradients at locations predicted for methane ice clouds on Uranus and Neptune, essentially confirming their existence and providing accurate information on the altitude of the cloud base. Ammonia gas is observed spectroscopically in Jupiter's upper troposphere, and its abundance decreases with altitude above its cloud base in accordance with expectation. There is no doubt that ammonia ice is the major component of the visible clouds on Jupiter and Saturn, but it cannot be the only component and is not responsible for the colors (pure ammonia ice is white). In fact, all the ices shown in Fig. 6 are white at visible wavelengths. The colored material must be produced by some disequilibrium process like photochemistry or bombardment by energetic particles from the magnetosphere.

Colors on Jupiter are close to white in the brightest zones, gray yellow to light brown in the belts, and orange or red in some of the spots. The colors in Fig. 5 are slightly and unintentionally exaggerated owing to the difficulty of achieving accurate color reproduction on the printed page. Colors on Saturn are more subdued. Uranus and Neptune are gray-green. Neptune has a number of dark spots and white patchy clouds. Part of the green tint on Uranus and Neptune is caused by strong methane gas absorption at red wavelengths, and part is due to aerosols that also absorb preferentially at wavelengths longer than 0.6 μm.

Candidate materials for the **chromophore** material in outer planet atmospheres are summarized in Table 3. All candidate materials are thought to form by some nonequilibrium process such as photolysis or decomposition by protons or ions in auroras, which acts on methane, ammonia, or ammonium hydrosulfide. Methane is present in the stratospheres of all the giant planets. Ammonia is present in the stratosphere of Jupiter. Ammonium hydrosulfide is thought to reside near the 2-bar level and deeper in Jupiter's atmosphere, which is too deep for ultraviolet photons to penetrate.

There are two major problems in understanding which, if any, of the proposed candidate chromophores are

TABLE 3 Candidate Chromophore Materials in the Atmospheres of the Giant Planets

Material	Formation mechanism
Sulfur	Photochemical products of H_2S and NH_4SH. Red allotropes are unstable.
H_2S_x, $(NH_4)_2S_x$, $N_2H_4S_x$	Photochemical products of H_2S and NH_4SH.
N_2H_4	Hydrazine, a photochemical product of ammonia, a candidate for Jupiter's stratospheric haze.
Phosphorus (P_4)	Photochemical product of PH_3.
P_2H_4	Diphosphine, a photochemical product of phosphine, a candidate for Saturn's stratospheric haze.
Products of photo- or charged-particle decomposition of CH_4	Includes acetylene photopolymers (C_xH_2), proton-irradiated methane, and organics with some nitrogen and/or sulfur. Confined to stratospheric levels where ultraviolet photons and auroral protons or ions penetrate.

responsible for the observed colors. First, no features have been identified in spectra of the planets that uniquely identify a single candidate material. Spectra show broad slopes, with more absorption at blue wavelengths on Jupiter and Saturn and at red wavelengths on Uranus and Neptune. All the candidates listed in Table 3 produce broad blue absorption. None of them can account for the red and near-infrared absorption in the spectra of Uranus and Neptune. Second, our understanding of the detailed processes that lead to the formation of chromophores is inadequate. Gas-phase photochemical theory cannot account for the abundance of chromophore material. It is likely that ultraviolet photons or charged-particle bombardment of solid, initially colorless particles like acetylene and ethane ice in the stratospheres of Uranus and Neptune or ammonium hydrosulfide in Jupiter's atmosphere breaks chemical bonds in the solid state, paving a path to formation of more complex hydrocarbons or inorganic materials that seem to be required. Additional laboratory studies are needed to address these questions. [*See* THE SOLAR SYSTEM AT ULTRAVIOLET WAVELENGTHS.]

Haze particles are present in the stratospheres of all the giant planets, but their chemical and physical properties and spatial distributions are quite different. Jupiter and Saturn have ultraviolet (UV)-absorbing aerosols abundant at high latitudes and high altitudes (corresponding to pressures ranging from a fraction of a millibar to a few tens of millibars). The stratospheric aerosols on Uranus and Neptune do not absorb much in the UV and are not concentrated at high latitude. The polar concentration of UV-absorbing aerosols on Jupiter and Saturn suggests that their formation may be due to chemistry in auroral regions, where protons and/or ions from the magnetosphere penetrate the upper atmosphere and deposit energy. Association with auroral processes may help explain why UV absorbers are abundant poleward of about 70° latitude on Saturn, extend to somewhat lower latitudes on Jupiter, and show a hemispheric asymmetry in Jupiter's atmosphere. Saturn's magnetic dipole is nearly centered and parallel to Saturn's spin axis, but Jupiter's magnetic dipole is both significantly offset and tilted with respect to its spin axis, producing asymmetric auroras at lower latitudes than on Saturn. Other processes, such as the **meridional circulation**, also influence the latitudinal distribution of aerosols, so more work needs to be done to establish the role of auroras in aerosol formation.

Photochemistry is responsible for the formation of diacetylene, acetylene, and ethane hazes in the stratospheres of Uranus and Neptune. The main steps in the life cycle of stratospheric aerosols are shown in Fig. 7. Methane gas mixes upward to the high stratosphere, where it is photolyzed by ultraviolet light. Diacetylene, acetylene, and ethane form from gas-phase photochemistry and diffuse downward. Temperature decreases downward in the stratosphere, so ice particles form when the vapor pressure equals the partial pressure of the gas. On Uranus, diacetylene ice forms at 0.1 mbar, acetylene at 2.5 mbar, and ethane at 14 mbar. The ice particles sediment to deeper levels on a time scale of years and evaporate in the upper troposphere at 600 mbar and deeper. Polymers that form from solid-state photochemistry in the ice particles are probably responsible for the little ultraviolet absorption that does occur. They are less volatile than the pure ices and probably mix down to the methane cloud and below.

Photochemical models predict formation of hydrazine in Jupiter's stratosphere and diphosphine in Saturn's atmosphere. If these are the only stratospheric haze constituents, it is not apparent why the ultraviolet absorbers are concentrated at high latitude. As discussed earlier, auroral bombardment of methane provides an attractive candidate

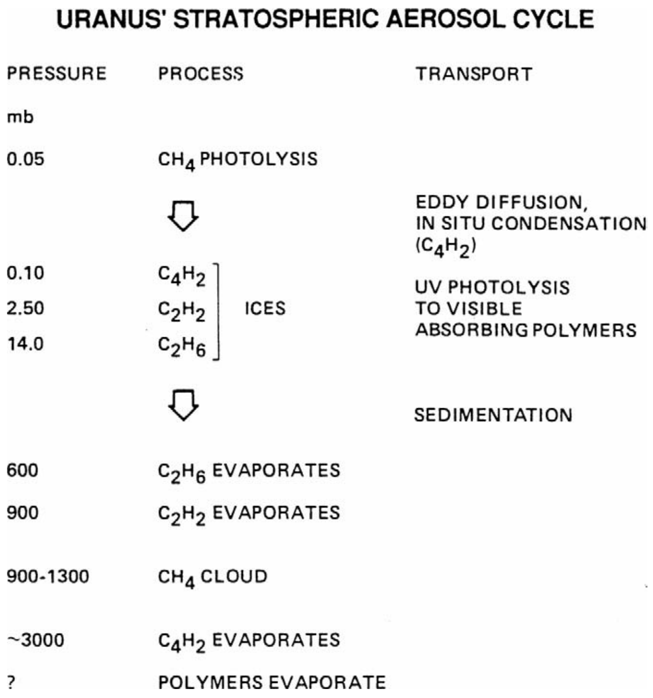


FIGURE 7 Life cycle for stratospheric aerosols on Uranus. (From J. Pollack et al., 1987, *J. Geophys. Res.* **92**, 15,037–15,066. Copyright American Geophysical Union.)

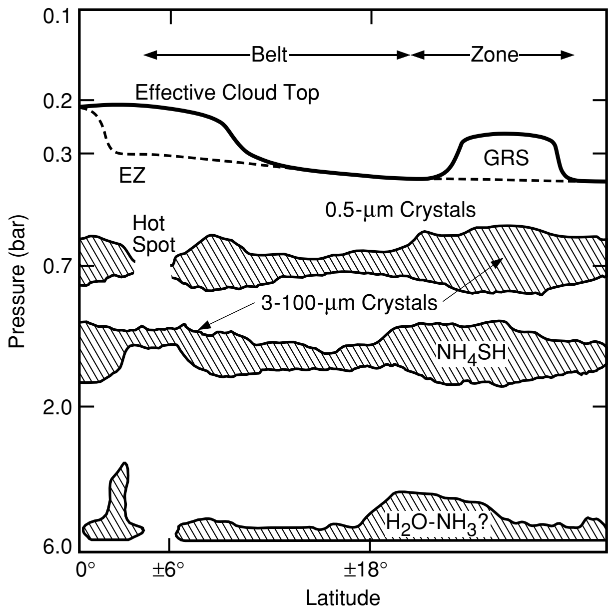


FIGURE 8 Observations of Jupiter at wavelengths that sense clouds lead to a picture of the jovian cloud stratigraphy shown here. There has been no direct evidence for a water–ammonia cloud near the 6 bar pressure level, but it is likely that such a cloud exists from indirect evidence. The hot spots are named from their visual appearance at a wavelength of 5 µm. They are not physically much warmer than their surroundings, but they are deficient in cloudy material (see Fig. 9). (From R. West et al., 2004, in "Jupiter: The Planet, Satellites and Magnetosphere" (F. Bagenal, T. Dowling, and W. McKinnon, eds.), pp. 79–104, Cambridge Univ. Press, Cambridge, United Kingdom.)

process for the abundant high-latitude aerosols on Jupiter and Saturn. However, we do not know enough to formulate a detailed chemical model of this process.

Thermochemical equilibrium theory serves as a guide to the location of the bases of tropospheric clouds, but meteorology and cloud microphysical processes determine the vertical and horizontal distribution of cloud material. These processes are too complex to let us predict to what altitudes clouds should extend, and so we must rely on observations. Several diagnostics are available to measure cloud and haze vertical locations. At short wavelengths, gas molecules limit the depth to which we can see. In the visible and near infrared are methane and hydrogen absorption bands, which can be used to probe a variety of depths depending on the absorption coefficient of the gas. There are a few window regions in the thermal infrared where cloud opacity determines the outgoing radiance. The deepest probing wavelength is 5 µm. At that wavelength, thermal emission from the water-cloud region near the 5 bar pressure level provides sounding for all the main clouds in Jupiter's atmosphere. [*See* Infrared Views of the Solar System from Space.]

The results of cloud stratigraphy studies for Jupiter's atmosphere are summarized in Fig. 8. There is spectroscopic evidence for the two highest tropospheric layers in Jupiter's atmosphere. There is also considerable controversy surrounding the existence of the water-ammonia cloud on Jupiter. The *Galileo* probe descended into a dry region of the atmosphere and did not find a water cloud, but water clouds may be present in moister regions of the atmosphere that are obscured by overlying clouds. There is evidence for a large range of particle sizes. Small particles (less than about 1 µm radius) provide most of the cloud opacity in the visible. They cover belts and zones, although their optical thickness in belts is sometimes less than in zones. Most of the contrast between belts and zones in the visible comes from enhanced abundance or greater visibility of chromophore material, which seems to be vertically, but not horizontally, well mixed in the ammonia cloud. The top of this small-particle layer extends up to about 200 mbar, depending on latitude. Jupiter's Great Red Spot is a location of relatively high-altitude aerosols, consistent with the idea that it is a region of upwelling gas.

Larger particles (mean radius near 6 µm) are also present, mostly in zones. This large-particle component appears to respond to rapid changes in the meteorology. It is highly variable in space and time and is responsible, together with the deeper clouds, for the richly textured appearance of the planet at 5 µm wavelength (Fig. 9). Some of the brightest regions seen in Fig. 9 are called 5 µm hot

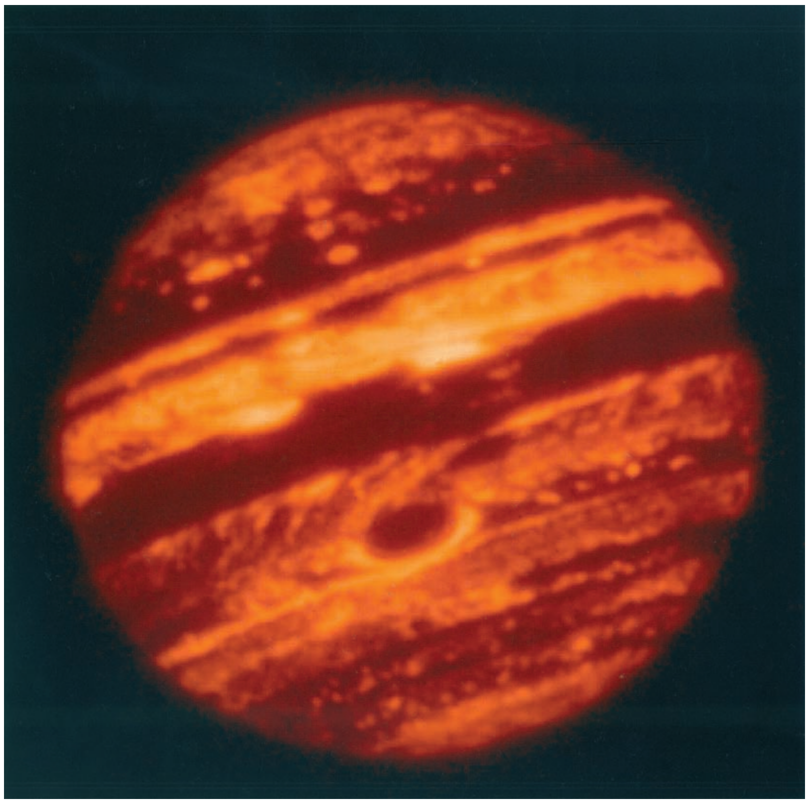


FIGURE 9 At a wavelength of 5 μm, most of the light from Jupiter is thermal radiation emitted near the 6 bar pressure level below the visible cloud. Places where the clouds are thin permit the deep radiation to escape from space, making these regions appear bright. Thicker clouds block the radiation and these appear dark. Jupiter's Great Red Spot is the dark oval just below the center. This image was taken with the NASA Infrared Telescope Facility. (Courtesy of J. Spencer.)

spots, not because they are warmer than their surroundings but because thermal radiation from the 5 bar region emerges with little attenuation from higher clouds. The *Galileo* probe sampled one of these regions. The dark regions in the image are caused by optically thick clouds in the NH_4SH and NH_3 cloud regions. The thickest clouds are generally associated with upwelling, bright (at visible wavelengths) zones, but many exceptions to this rule are observed. Until we understand the chemistry and physics of chromophores, we should not expect to understand why or how well albedo is correlated with other meteorological parameters.

Most of Jupiter's spots are at nearly the same altitude. Some notable exceptions are the Great Red Spot (GRS), the three white ovals just south of the GRS, and some smaller ovals at other latitudes. These anticyclonic features extend to higher altitudes, probably up to the 200 mbar level, compared to a pressure level of about 300 mbar for the surrounding clouds. Some of the anticyclonic spots have remarkably long lifetimes compared to the terrestrial norm. The GRS was recorded in drawings in 1879, and reports of red spots extend back to the 17th century. The three white ovals in a latitude band south of the GRS formed from a bright cloud band that split into three segments in 1939. The segments shrunk in longitude over the course of a year, until the region (the South Temperate Belt) was mostly dark except for three high-albedo spots that remain to the present. Whereas anticyclonic ovals tend to be stable and long-lived, cyclonic regions constantly change.

Similar features are observed in Saturn's atmosphere, although the color is much subdued compared to Jupiter, and Saturn has nothing that is as large or as long-lived as the GRS. The reduced contrast may be related to Saturn's colder tropopause temperature. The distance between the base of the ammonia cloud and the top of the troposphere (where the atmosphere becomes stable against convection) is greater on Saturn than on Jupiter. The ammonia-ice cloud on Saturn is both physically and optically thicker than it is on Jupiter. Occasionally (about two or three times each century), a large, bright cloud forms near Saturn's equator. One well-observed event occurred in 1990, but its cause is unknown. It appears to be a parcel of gas that erupts from deeper levels, bringing fresh condensate material to near the top of the troposphere. It becomes sheared out in the wind shear and dissipates over the course of a year.

Uranus as seen by *Voyager* was even more bland than Saturn, but recent images from the *Hubble Space Telescope* and from the ground show a much richer population of small clouds (see Fig. 10). Midlatitude regions on Uranus and Neptune are cool near the tropopause, indicating upwelling. But cloud optical thickness may be lower there than at other latitudes. The relation between cloud optical thickness and vertical motion is more complicated than the simple condensation model would predict.

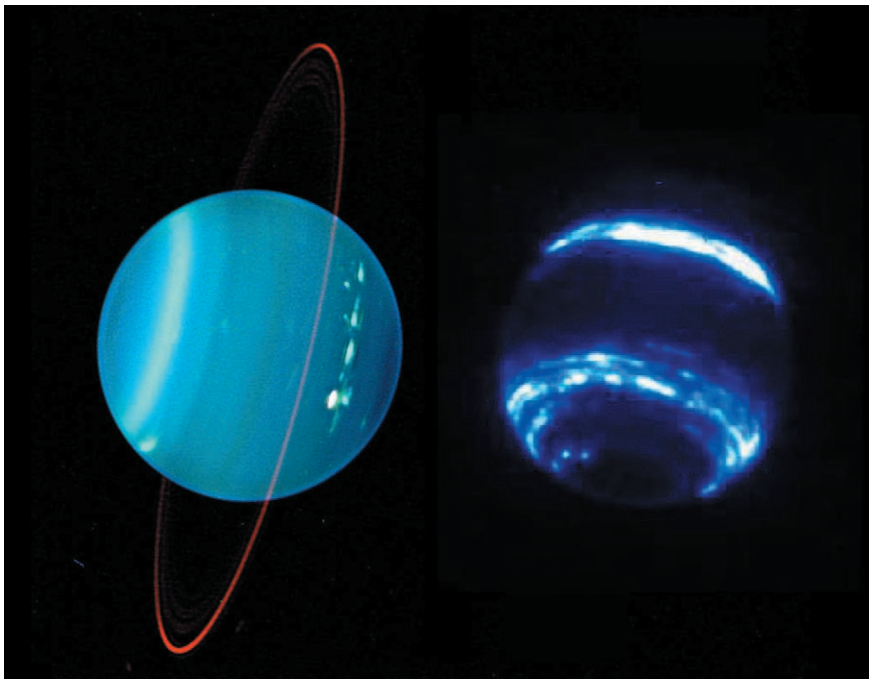


FIGURE 10 Images of Uranus (left) and Neptune (right) taken in 2004 and 2000, respectively. Both were obtained at the Keck telescope with filters in the near-infrared. Many cloud features that were not seen during the *Voyager* flyby can be seen. The Uranus ring can also be seen (a red ellipse in this false-color representation). The Uranus image appeared on the cover of *Icarus* (December 15, 2005, issue) and was provided by L. Sromovsky. The Neptune image is from I. de Pater et al. (2005, *Icarus* **174**, 263–373. Copyright Academic Press).

Neptune's clouds are unique among the outer planet atmospheres. *Voyager* observed four large cloud features that persisted for the duration of the *Voyager* observations (months). The largest of these is the Great Dark Spot (GDS) and its white companion. Because of its size and shape, the GDS might be similar to Jupiter's Great Red Spot, but the GDS had a short life compared to the GRS.

There is no explanation yet of what makes the dark spot dark. The deepest cloud (near the 3 bar level) is probably H_2S ice, since ammonia is apparently depleted and NH_4SH would be sequestered at a deeper level. At higher altitudes there is an optically thin methane haze (near 2 bar) and stratospheric hazes of ethane, acetylene, and diacetylene. At high spatial resolution, the wispy white clouds associated with the companion to the GDS and found elsewhere on the planet form and dissipate in a matter of hours. It was difficult to estimate winds from these features because of their transitory nature. Individual wisps moved at a different speed than the GDS and its companion, suggesting that these features form and then evaporate high above the GDS as they pass through a local pressure anomaly, perhaps a standing wave caused by flow around the GDS. Cloud shadows were seen in some places, a surprise after none was seen on the other giant planets. The clouds casting the shadows are about 100 km higher than the lower cloud deck, suggesting that the lower cloud is near 3 bar and the shadowing clouds near 1 bar, in the methane condensation region. More recent Hubble and ground-based images show clouds not seen in *Voyager* images (Fig. 10).

4. Dynamical Meteorology of the Troposphere and Stratosphere

Our understanding of giant planet meteorology comes mostly from *Voyager* observations, with observations from *Galileo*, *Cassini*, the *Hubble Space Telescope*, and ground-based data adding to the picture. Although we have theories and models for many of the dynamical features, the fundamental nature of the dynamical meteorology on the giant planets remains puzzling chiefly because of our inability to probe to depths greater than a few bars in atmospheres that go to kilobar pressures and because of limitations in spatial and time sampling, which may improve with future missions to the planets.

Thermodynamic properties of atmospheres are at the heart of a variety of meteorological phenomena. In the terrestrial atmosphere, condensation, evaporation, and transport of water redistribute energy in the form of latent heat. The same is true for the outer planet atmospheres, where condensation of water, ammonia, ammonium hydrosulfide, hydrogen sulfide, and methane takes place. Condensables also influence the dynamics through their effects on density gradients. In the terrestrial atmosphere, moist air is less dense than dry air at the same temperature because the molecular weight of water vapor is smaller than that of the dry air. Because of this fact, and also because moist air condenses and releases latent heat as it rises, there can be a growing instability leading to the formation of convective plumes, thunderstorms, and anvil clouds at high altitudes. On the giant planets, water vapor is significantly heavier than the dry atmosphere and so the same type of instability will not occur unless a strongly upwelling parcel is already present. Some researchers proposed that the Equatorial Plumes on Jupiter and the elongated clouds on Uranus are the outer planet analogs to terrestrial anvil clouds.

Terrestrial lightning occurs most frequently over tropical oceans and over a fraction of the land surface. Its distribution in latitude, longitude, and season is indicative of certain properties of the atmosphere, especially the availability of liquid water. Lightning has been observed on the giant planets as well, either from imaging on the night side (Jupiter) or from signals recorded by plasma wave instruments. A somewhat mysterious radio emission from Saturn (the so-called Saturn Electrostatic Discharge events) has been interpreted as a lightning signature. Combined imaging and plasma wave observations from *Cassini* in 2004 revealed a large cloud complex associated with this source. The intensity and size of the lightning spots in the images imply that they are much more energetic than the average lightning bolt in the terrestrial atmosphere, and they occur in the water–ammonia cloud region as expected. The *Galileo* probe did not detect lightning in Jupiter's atmosphere within a range of about 10,000 km from its location at latitude 6.5°N. [*See* THE SOLAR SYSTEM AT RADIO WAVELENGTHS.]

The heat capacity of hydrogen, and therefore the dry adiabatic lapse rate of the convective part of the atmosphere, depends on the degree to which the ortho/para states equilibrate. The lapse rate is steepest when equilibration is operative. The observed lapse rate for Uranus, as measured by the *Voyager* radio occultation experiment, is close to the "frozen" lapse rate—the rate when the relative fractions of ortho and para hydrogen are fixed. How can the observed relative fractions be near equilibrium when the lapse rate points to nonequilibrium? One suggestion is that the atmosphere is layered. Each layer is separated from the next by an interface that is stable and that is thin compared to the layer thickness. The air within each layer mixes rapidly compared to the time for equilibration, but the exchange rate between layers is slow or comparable to the timescale for conversion of ortho to para and back.

How can layers be maintained in a convective atmosphere? In the terrestrial ocean, two factors influence buoyancy: temperature and salinity. If the water is warmer at depth, or if the convective amplitude is large, the different timescales for diffusion of heat and salinity lead to layering. In the atmospheres of the outer planets, the higher molecular weight of condensables acts much as salinity in ocean water. Layering can be established even without molecular weight gradients. Layering in the terrestrial stratosphere and mesosphere has been observed. Layers of rapidly convecting gas occur where gravity waves break or where other types of wave instabilities dump energy. Between layers of rapid stirring are stably stratified layers with transport by diffusion rather than convection.

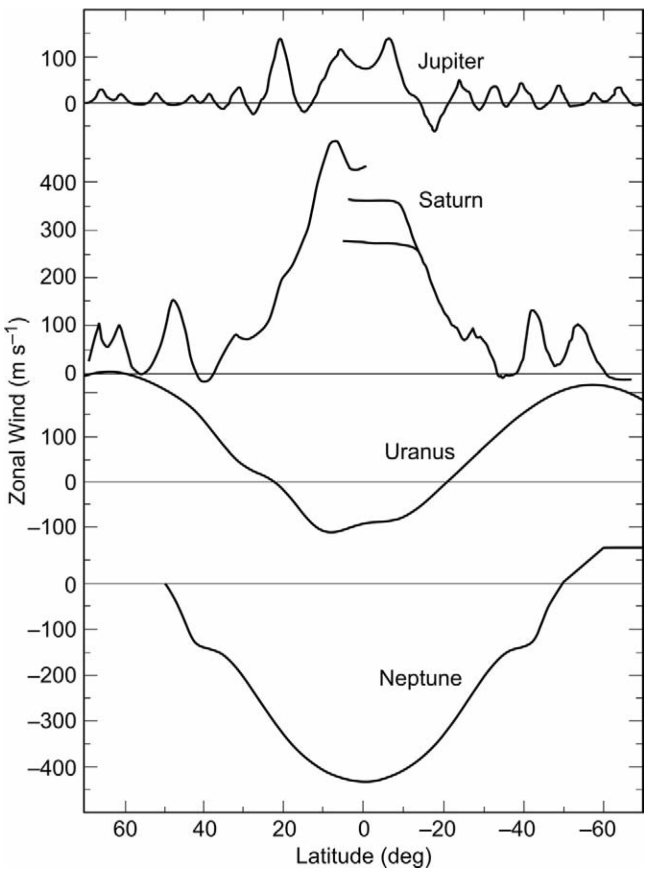


FIGURE 11 Zonal (east–west) wind velocity for the giant planets as a function of latitude. For Jupiter, the data are from Porco et al. (2003, *Science* **299**, 1541–1547. Copyright American Association for the Advancement of Science). For Saturn's northern hemisphere, the data are from P. Gierasch and B. Conrath (1993, *J. Geophys. Res*. **98**, 5459–5469. Copyright American Geophysical Union). For Saturn's southern hemisphere, data are from Porco et al. (2005, *Science* **307**, 1243–1247. Copyright American Association for the Advancement of Science). Two branches are shown for the southern low latitudes. Both are from *Cassini* observations, with similar values from *Hubble Space Telescope* images. The higher wind speeds were observed for deepest clouds, while the lower winds were observed for higher clouds. Both branches are moving more slowly than clouds at similar latitudes in the north observed by *Voyager*. This apparent change in the wind speed must have involved a large energy exchange. Data for Uranus and Neptune are mostly from analyses of Hubble and Keck data (L. Sromovsky and P. Fry, 2005, *Icarus* **179**, 459–484. Copyright Academic Press. L. Sromovsky et al., 2001, *Icarus* **150**, 244–260. Copyright Academic Press.)

Some of the variety of the giant planet meteorology, as well as our difficulty to understand it, is nicely illustrated by observations of the wind field at the cloud tops. Wind vectors of all the giant planet atmospheres are predominantly in the east–west (zonal) direction (Fig. 11). These are determined by tracking visible cloud features over hours, days, and months. Jupiter has an abundance of small features and the zonal winds are well mapped. Saturn has fewer features, and they are of less contrast than those on Jupiter, but there is still a large enough number to provide detail in the wind field. Only a few features were seen in *Voyager* images of the Uranus atmosphere, and all but one of these were between latitudes 20°S and 40°S. More recent images from the *Hubble Space Telescope* show new features at many other latitudes. The *Voyager 2* radio occultation provided an additional estimate for wind speed at the equator. Neptune has more visible features than Uranus, but most of them are transitory and difficult to follow long enough to gauge wind speed.

Figure 11 reveals a great diversity in the zonal flow among the giant planet atmospheres. Wind speed is relative to the rotation rate of the deep interior as revealed by the magnetic field and radio emissions. Jupiter has a series of jets that oscillate with latitude and are greatest in the prograde direction at latitude 23°N, and near ±10°. The pattern of east–west winds is approximately symmetric about the equator except at high latitude. Saturn has a very strong prograde jet at low latitudes (within the region ±15°). It also has alternating but mostly prograde jets at higher latitudes, with the scale of latitudinal variation being about 10°. Uranus appears to have a single prograde maximum near 60°S, and the equatorial region is retrograde. Neptune has an enormous differential rotation, mostly retrograde except at high latitude. Various theories have been advanced to explain the pattern of zonal jets. None of them can account for the great variety among the four planets.

The zonal jets are stable over long time periods (observations span many decades for Jupiter and Saturn), despite the many small-scale features that evolve with much shorter life times. An interesting exception to this rule occurred at equatorial latitudes on Saturn between the time of the *Voyager* observations (around 1981) and observations in the 1990s and later by the *Hubble Space Telescope* and beginning in 2004 by the *Cassini* cameras. Current equatorial jet speeds are significantly less than those measured on Saturn by *Voyager*. It is difficult to understand how such a large change of momentum could occur, and another explanation has been sought. Possibly the equatorial atmosphere was clearer (less haze) during the *Voyager* epoch, permitting observations to deeper levels where the wind speed is higher. Detailed analyses of haze altitudes show that the haze is thicker and higher in more recent times than it was in 1981, but probably not enough to account for the difference in wind speed.

Some of the key observations that any dynamical theory must address include: (1) the magnitude, direction, and latitudinal scale of the jets; (2) the stability of the jets, at least for Jupiter and Saturn, where observations over long periods show little or no change except for Saturn's equatorial jet, which was mentioned earlier; (3) the magnitude and latitudinal gradients of heat flux; and (4) the interactions of the mean zonal flow with small spots and eddies. One of the controversies during the past two decades concerns how deep the flow extends into the atmosphere. It is possible to construct shallow-atmosphere models that have approximately correct jet scales and magnitudes. A shallow-atmosphere model is one in which the jets extend to relatively shallow levels (100 bar or less), and the deeper interior rotates as a solid body, or at least as one whose latitudinal wind shear is not correlated with the wind shear of the jets. The facts that the jets and some spots on Jupiter are very stable, that there is approximate hemispheric symmetry in the zonal wind pattern between latitudes ±60°, and that the Jovian interior has no density discontinuities down to kilobar levels suggested to some investigators that the jets extend deep into the atmosphere. A natural architecture for the flow in a rotating sphere with no density discontinuities is one in which the flow is organized on rotating cylinders (Fig. 12).

Apart from the stability and symmetry noted here, there is little evidence to suggest that the zonal wind pattern really does extend to the deep interior. The conductivity of Jupiter's atmosphere at depth is probably too high to allow the type of structure depicted in Fig. 12 to exist. The strength of the zonal jet at the location where the *Galileo* probe entered (6.5°N) increased with depth, consistent with the idea of a deeply rooted zonal wind field on Jupiter. One way to test that hypothesis is to make highly precise measurements of the gravity field close to the planet. There are density gradients associated with the winds, and these produce features in the gravity field close to the planet. The largest signature is produced by Neptune's remarkable differential rotation. The *Voyager 2* spacecraft flew just above Neptune's atmosphere and provided the first evidence that the differential rotation cannot extend deep into the atmosphere. Gravity-field tests of the deep-wind hypothesis for the other giant planets are more difficult because the differential rotation is much weaker. No spacecraft have come close enough to make the measurements but one is planned for Jupiter

What process maintains the zonal wind pattern? *Voyager* measurements shed some light on this question, but provided some puzzles as well. The ultimate energy source for maintaining atmospheric motions is the combination of internal thermal and solar energy absorbed by the atmosphere. Jupiter, Saturn, and Neptune all have significant internal energy sources, whereas Uranus has little or none. A measure of the amount of energy available for driving winds is the escaping radiative energy per square meter of surface area. Twenty times as much energy per unit area is radiated from Jupiter's atmosphere as from Neptune's, yet the wind speeds (measured relative to the interior as determined from the magnetic field rotation rate) on Neptune are about three times higher than those on Jupiter. Rather than driving zonal winds, the excess internal energy may go

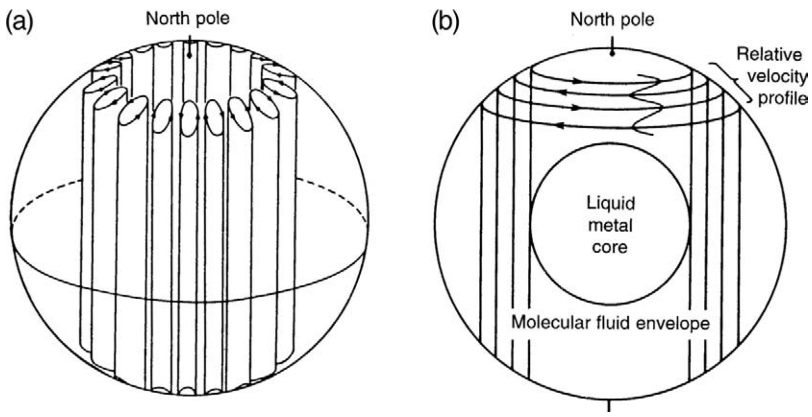


FIGURE 12 One model for the zonal wind fields of the giant planets has differential rotation organized on cylinders (a), exploiting the natural symmetry of a rotating deep fluid (b). (From F. Busse, 1976, *Icarus* **29**, 255–260. Copyright by Academic Press.)

into driving smaller scale eddies, which are most abundant to Jupiter.

What influence does the absorbed solar radiation have? Most planets receive more solar radiation at their equator than at their poles. For Uranus, the reverse is true. Yet the upper tropospheric and stratospheric temperatures on Uranus and Neptune are nearly identical, and the winds for both planets (as for Earth) are retrograde at the equator. According to one theory, deposition of solar energy may account for the fact that Uranus possesses very little internal energy today. Otherwise, it is hard to see how solar energy can be important for the tropospheric circulation of the giant planets.

What role do eddies have in maintaining the flow? Measurements of the small spots on Jupiter and Saturn have allowed an estimate of the energy flow between the mean zonal wind and the eddy motions. For Jupiter, the eddies at the cloud top appear to be pumping energy into the mean zonal flow, although that conclusion has been challenged on the grounds that the sampling may be biased. If further observation and analysis confirm the initial result, we need to explain why the jets are so stable when there is apparently enough energy in eddy motions to significantly modify the jovian wind field. At the same time, other observations imply dissipation and decay of zonal winds at altitudes just above the cloud tops.

The relationship known to atmospheric physicists as the thermal wind equation provides a means of estimating the rate of change of zonal wind with height (which is usually impossible to measure remotely) from observations of the latitudinal gradient of temperature (which is usually easy to measure). One of the common features of all the outer planet atmospheres is a decay of zonal wind with height in the stratosphere, tending toward solid-body rotation at high altitudes. The decay of wind velocity with height could be driven by eddy motions or by gravity wave breaking, which effectively acts as friction on the zonal flow.

Thermal contrasts on Jupiter are correlated with the horizontal shear and with cloud opacity as indicated by 5 μm images (see Fig. 9). Cool temperatures at the tropopause level (near 100 mbar) are associated with upwelling and anticyclonic motion, and warmer temperatures are associated with subsidence. Jupiter's Great Red Spot is an anticyclonic oval with cool tropospheric temperatures, upwelling flow, and aerosols extending to relatively high altitudes. Enhanced cloud opacity and ammonia abundance in cooler anticyclonic latitudes (mostly the high-albedo zones on Jupiter) are predicted in upwelling regions. The correlation is best with cloud opacity in the 5 μm region. At shorter wavelengths (in the visible and near infrared), there is a weaker correlation between cloud opacity and **vorticity**. Perhaps the small aerosols near the top of the troposphere, sensed by the shorter wavelengths but not at 5 μm, are transported horizontally from zone to belt on a time scale that is short compared to their rainout time (several months).

The transport of heat may well be more complicated than the previous paragraph implies. There may be at least two regions, an upper troposphere where heat transport is determined by slow, large-scale motions as previously depicted, and a lower troposphere at pressures between 2 and 10 bar, where heat is transported upward mostly in the belts, by small convective storms which are seen in the belts. There is evidence from the *Galileo* and *Cassini* observations that this is the case.

The upwelling/subsidence pattern at the jet scale in the upper troposphere penetrates into the lower stratosphere. We have relatively little information on the stratospheric circulation for the giant planets. Most of it is based on the observed thermal contrasts and the idea that friction is a dominant driver for stratospheric dynamics. We are beginning to appreciate the role of forcing by gravity or other dissipative waves. A model for the Uranus stratospheric circulation is based on the frictional damping and the observed thermal contrast as a function of latitude. The coldest temperatures in the lower stratosphere are at midlatitudes, indicating upwelling there and subsidence at the equator and poles. A different pattern is expected if the deposition of solar energy controlled the circulation. Momentum forcing by vertically propagating waves from the deeper atmosphere is apparently more important than solar energy deposition.

The mean meridional circulation in Jupiter's stratosphere differs from that predicted by the frictional damping model at pressure levels less than about 80 mbar. The zonal pattern of upwelling/sinking extends to about 100 mbar, giving way at higher altitude to a two-cell structure with cross-equatorial flow. There is also a hemispheric asymmetry. The high latitudes (poleward of 60°S and 40°N) are regions of sinking motion at the tropopause. Recent analysis of images from the *Hubble Space Telescope* indicate that the optical depth of the ammonia cloud decreases rapidly with latitude poleward of 60°S and 40°N and is well correlated with the estimated downward velocity. The descending dry air inhibits cloud formation. To produce that circulation, there must be momentum forcing in the latitude range 40°S to 80°S and 30°N to 80°N at pressures between 2 and 8 mbar. Dissipation of gravity waves propagating from the deep interior is the most likely source of momentum forcing.

Superimposed on the long-term mean are much faster processes such as horizontal eddy mixing, which can transport material in the north–south direction in days or weeks. The impacts of comet Shoemaker–Levy 9 on Jupiter in 1994 provided a rare opportunity to see the effects of eddy transport on small dust particles and trace chemical constituents deposited in the stratosphere immediately after impact. Particles spread rapidly from the impact latitude (45°S) to latitude 20°S, but there has been almost no transport farther toward the equator. Trace constituents at higher altitude such as HCN were observed to move across the equator into the northern hemisphere. [*See* PHYSICS AND CHEMISTRY OF COMETS.]

Long-term monitoring of the jovian stratosphere has yielded some interesting observations of an oscillating temperature cycle at low latitudes. At pressures between 10 and 20 mbar, the equator and latitudes ±20° cool and warm alternately on timescales of 2–4 years. The equator was relatively (1–2 K above the average 147 K) warm and latitudes ±20° were relatively (1–2 K below average) cool in 1984 and 1990. The reverse was true in 1986 and 1987. Changes in temperature must be accompanied by changes in the wind field, and these must be generated by stresses induced by wave forcing or convection. The similarities of the jovian temperature oscillations to low-latitude temperature oscillations in the terrestrial atmosphere led some researchers to propose that the responsible mechanism is similar to that driving the quasi-biennial oscillation (QBO) on Earth: forcing by vertically propagating waves. The period of the oscillation is about 4 (Earth) years and so the phenomenon has been called the quasi-quadrennial oscillation or QQO.

The *Voyager* cameras and more recently *Hubble* and ground-based images provided much information about the shapes, motions, colors, and lifetimes of small features in the atmospheres of the giant planets. In terms of the number of features and their contrast, a progression is evident from Jupiter, with thousands of visible spots, to Uranus, with only a few. Neptune has a few large spots that were seen for weeks and an abundance of small ephemeral white patches at a few latitudes. We do not have a good explanation for the contrasts and color because the thermochemical equilibrium ices that form these clouds (NH_3, NH_4SH, H_2O, CH_4, and H_2S) are colorless. We need to know more about the composition, origin, and location of the colored material before we can understand how the contrasts are produced.

Fortunately, it is not necessary to understand how the contrasts are produced to study the meteorology of these features. One of the striking attributes of some of the clouds is their longevity. Jupiter's Great Red Spot has been observed since 1879 and may have existed much earlier. A little to the south of the GRS are three white ovals, each about one third the diameter of the GRS. These formed in 1939–1940, beginning as three very elongated clouds (extending 90° in longitude) and rapidly shrinking in longitude. They survived as three distinct ovals until 1998 when two of them merged. In the year 2000, the remaining two merged, leaving one. There are many smaller, stable ovals at some other jovian latitudes. All these ovals are anticyclonic and reside in anticyclonic shear zones. Because they are anticyclonic features, there is upwelling and associated high and thick clouds, and cool temperatures at the tropopause. Sinking motion takes place in a thin boundary region at the periphery of the clouds. The boundary regions are bright at 5 μm wavelength, consistent with relatively cloud-free regions of sinking. The Great Red Spot as revealed by *Galileo* instruments is actually much more complex, with cyclonic flow and small regions of enhanced 5 μm emission (indicating reduced cloudiness) in its interior.

Another attribute of many of the ovals is the oscillatory nature of their positions and sometimes shape. The most striking example is Neptune's Great Dark Spot, whose aspect ratio (ratio of shortest to longest dimension) varied by more than 20% with a period of about 200 hours, with a corresponding oscillation in orientation angle. Neptune's Dark Spot 2 drifted in latitude and longitude, following a sinusoidal law with amplitude 5° in latitude (between 50°S and 55°S) and 90° (peak to peak) in longitude. Other spots on Neptune and Jupiter, including the GRS, show sinusoidal oscillations in position. The jovian spots largely remain at a fixed mean latitude, but the mean latitude of the GDS on Neptune drifted from 26°S to 17°S during the 5000 hours of observations by the *Voyager 2* camera. Ground-based observations in 1993 did not show a bright region at methane absorption wavelengths in the southern hemisphere, unlike the period during the *Voyager* encounter when the high-altitude white companion clouds were visible from Earth. The GDS may have drifted to the northern hemisphere and/or may have disappeared. *Hubble Space Telescope* images and ground-based images since the *Voyager* encounter show new spots at new latitudes.

Jupiter's Great Red Spot is often and incorrectly said to be the jovian analog of a terrestrial hurricane. Hurricanes are cyclonic vortices. The GRS and other stable ovals are anticyclones. Hurricanes owe their (relatively brief) stability to energy generated from latent heating (condensation) over a warm ocean surface, where water vapor is abundant. Upwelling occurs in a broad circular region, and subsidence is confined to a narrow core (the eye). The opposite is true for anticyclonic spots in the giant planet atmospheres, where subsidence takes pace in a narrow ring on the perimeter of the oval. The key to their stability is the long-lived, deep-seated background latitudinal shear of the jets. The stable shear in the jets provides an environment that is able to support the local vortices. Latent heat, so important for a terrestrial hurricane, seems to play no role. However, the ephemeral bright small clouds seen in some locations may be places where strong upwelling is reinforced by release of latent heat analogous to a terrestrian thunderstorm.

5. Energetic Processes in the High Atmosphere

At low pressure (less than about 50 μbar), the mean free path for collisions becomes sufficiently large that lighter molecules diffusively separate from heavier ones. The level where this occurs is called the homopause. The outer planet atmospheres are predominantly composed of H_2 and He, with molecular hydrogen dissociating to atomic hydrogen, which becomes the dominant constituent at the exobase (the level where the hottest atoms can escape to space). This is also the region where solar EUV (extreme ultraviolet) radiation can dissociate molecules and ionize molecules and atoms. Ion chemistry becomes increasingly important at high altitudes. Some reactions can proceed at a rapid rate compared to neutral chemistry. Ion chemistry may be responsible for the abundant UV-absorbing haze particles (probably hydrocarbons) in the polar stratospheres of Jupiter and Saturn.

The high atmospheres of the giant planets are hot (400–800 K for Jupiter to 300 K for Uranus and Neptune), much hotter than predicted on the assumption that EUV radiation is the primary energy source. Estimates prior to the *Voyager* observations predicted high-altitude temperatures closer to 250 K or less. One of the challenges of the post–*Voyager* era is to account for the energy balance of the high atmosphere. Possible sources of energy in addition to EUV radiation include (1) Joule heating, (2) currents induced by a planetary dynamo mechanism, (3) electron precipitation from the magnetosphere (and also proton and S and O ion precipitation in the jovian auroral region), and (4) breaking inertia-gravity waves.

Joule heating requires electric currents in the ionosphere that accelerate electrons and protons. It is a major source of heating in the terrestrial thermosphere. We do not have enough information on the magnetosphere to know how important this process or the others mentioned are for the giant planet atmospheres. The planetary dynamo current theory postulates that currents are established when electrons and ions embedded in the neutral atmosphere move through the magnetic field, forced by the neutral wind tied to the deeper atmosphere. Electric fields aligned with the magnetic field are generated by this motion and accelerate high-energy photoelectrons that collide with neutrals or induce plasma instabilities and dissipate energy. Similar mechanisms are believed to be important in the terrestrial atmosphere.

Electron precipitation in the high atmosphere was one of the first mechanisms proposed to account for bright molecular hydrogen UV emissions. There is recent evidence for supersonic pole-to-equator winds in the very high atmosphere on Jupiter driven by auroral energy. These winds collide at low latitudes, producing supersonic turbulence and heating. Electron and ion precipitation outside of the auroral regions undoubtedly contributes to the heating, but the details remain unclear. The possible contribution from breaking planetary waves is difficult to estimate, but *Galileo* probe measurements, details of the radio occultation profiles, and less direct lines of evidence point to a significant energy density in the form of inertia-gravity waves in the stratosphere and higher. How much of that is dissipated at pressures less than 50 μbar is unknown but could be significant to the energy budget of the high atmosphere.

The giant planets have extensive ionospheres. Like the neutral high atmospheres, they are hotter than predicted prior to the *Voyager* encounters. As for Earth, the ionospheres are highly structured, having a number of high-density layers. Layering in the terrestrial ionosphere is partially due to the deposition of metals from meteor ablation. The same mechanism is thought to be operative in the giant planet ionospheres. The Jupiter and Saturn ionospheres are dominated by the H_3^+ion, whereas those of Uranus and Neptune are dominated by H^+.

Auroras are present on all the giant planets. Auroras on Earth (the only other planet in the solar system known to have auroras) are caused by energetic charged particles streaming down the high-latitude magnetic field lines. The most intense auroras on Earth occur when a solar flare disturbs the solar wind, producing a transient in the flow that acts on Earth's magnetosphere through ram pressure. As the magnetosphere responds to the solar wind forcing, plasma instabilities in the tail region accelerate particles along the high-latitude field lines.

The configuration of the magnetic field is one of the key parameters that determines the location of auroras. Jupiter's magnetosphere is enormous compared to Earth's. If its magnetosphere could be seen by the naked eye from Earth, it would appear to be the size of the Moon (about 30 arc minutes), whereas Jupiter's diameter is less than 1 arc minute.

TABLE 4 Magnetic Field Parameters (Offset Tilted Dipole Approximation)

	Earth	Jupiter	Saturn	Uranus	Neptune
Tilt (degrees)	11.2	9.4	0.0	58.6	46.9
Offset (planetary radius)	0.076	0.119	0.038	0.352	0.485

To a first approximation, the magnetic fields of Earth and the giant planets can be described as tilted dipoles, offset from the planet center. Table 4 lists the strength, tilt, and radial offsets for each of these planets. Earth and Jupiter have relatively modest tilts and offsets, Saturn has virtually no tilt and almost no offset, whereas Uranus and Neptune have very large tilts and offsets. Such diversity presents a challenge to planetary dynamo modelers. [*See* PLANETARY MAGNETOSPHERES.]

The mapping of the magnetic fields onto the upper atmosphere determines where auroral particles intercept the atmosphere. Maps for Jupiter, Uranus, and Neptune are shown in Fig. 13, along with locations of field lines connected to the orbits of some satellites that may be important for auroral formation. The configuration for Saturn is not shown because contours of constant magnetic field magnitude are concentric with latitude circles owing to the field symmetry. Because of the large tilts and offsets for Uranus and Neptune, auroras on those planets occur far from the poles.

The jovian aurora is the most intense and has received the most scrutiny. The remainder of this section will focus on what is known about it. It has been observed over a remarkable range of wavelengths, from X-rays to the infrared, and possibly in the radio spectrum as well. Energetic electrons from the magnetosphere dominate the energy input, but protons and S and O ions contribute as well. Sulfur and oxygen k-shell emission seems to be the most plausible explanation for the X-rays. Models of energetic electrons impacting on molecular hydrogen provide a good fit to the observed molecular hydrogen emission spectra. Secondary electrons as well as UV photons are emitted when the primary impacting electrons dissociate the molecules, and these secondaries also contribute to the UV emissions. Some of the UV-emitted radiation is reabsorbed by other hydrogen molecules, and some is absorbed by methane molecules near the top of the homopause. From the detailed shape of the spectrum, it is possible to infer the depth of penetration of electrons into the upper atmosphere. In the near infrared (2–4 μm), emissions from the H_3^+ ion are prominent. Attempts to account for all the observations call for more than one type of precipitating particle and more than one type of aurora.

Ultraviolet auroras from atomic and molecular hydrogen emissions are brightest within an oval that is approximately bounded by the closed field lines connected to the middle magnetosphere (corresponding to a region some 10–30 Jupiter radii from the planet) rather than the orbit of Io or open field lines connected to the tail. Weaker diffuse and highly variable UV emissions appear closer to the pole. They are produced by precipitation of energetic particles originating from more distant regions in the magnetosphere. There is also an auroral hot spot at the location where magnetic field lines passing through Io enter the atmosphere (the Io flux tube footprint). All these features are evident in Fig. 14.

Io is a significant source of sulfur and oxygen, which come off its surface. The satellite and magnetosphere produce hot and cold plasma regions near the Io orbit, which may stimulate plasma instabilities. High spatial resolution, near-infrared H_3^+ images show emission from a region that maps to the last closed field lines far out in the magnetosphere (Fig. 15). This and evidence for auroral response to fluctuations in solar wind ram pressure indicate that at least some of the emission is caused by processes that are familiar to modelers of the terrestrial aurora. [*See* IO: THE VOLCANIC MOON.]

Auroral emission is strongest over a small range of longitudes. In the north, longitudes near 180°, System III coordinates (which rotate with the magnetic field) show enhanced emission in the UV and also in the thermal infrared. The spectrum of the aurora in the UV resembles electron impact on molecular hydrogen, except the shortest wavelengths are deficient. This deficit can be accounted for if the emission is occurring at some depth in the atmosphere (near 10 μbar) below the region where methane and acetylene absorb UV photons. By contrast, the Uranian high atmosphere is depleted in hydrocarbons and does not produce an emission deficit.

Energy deposition at depth is also required to explain the warm stratospheric temperatures seen in the 7.8 μm methane band. At 10 μbar of pressure, the hot spot region near longitude 180° appears to be 60–140 K warmer than the surrounding region, which is near 160 K. Undoubtedly such temperature contrasts drive the circulation of the high atmosphere. Auroral energy also contributes to anomalous chemistry. An enhancement is seen in acetylene emission in the hot spot region, whereas ethane emission decreases there. A significant part of the acetylene enhancement could be due simply to the higher emission from a warmer

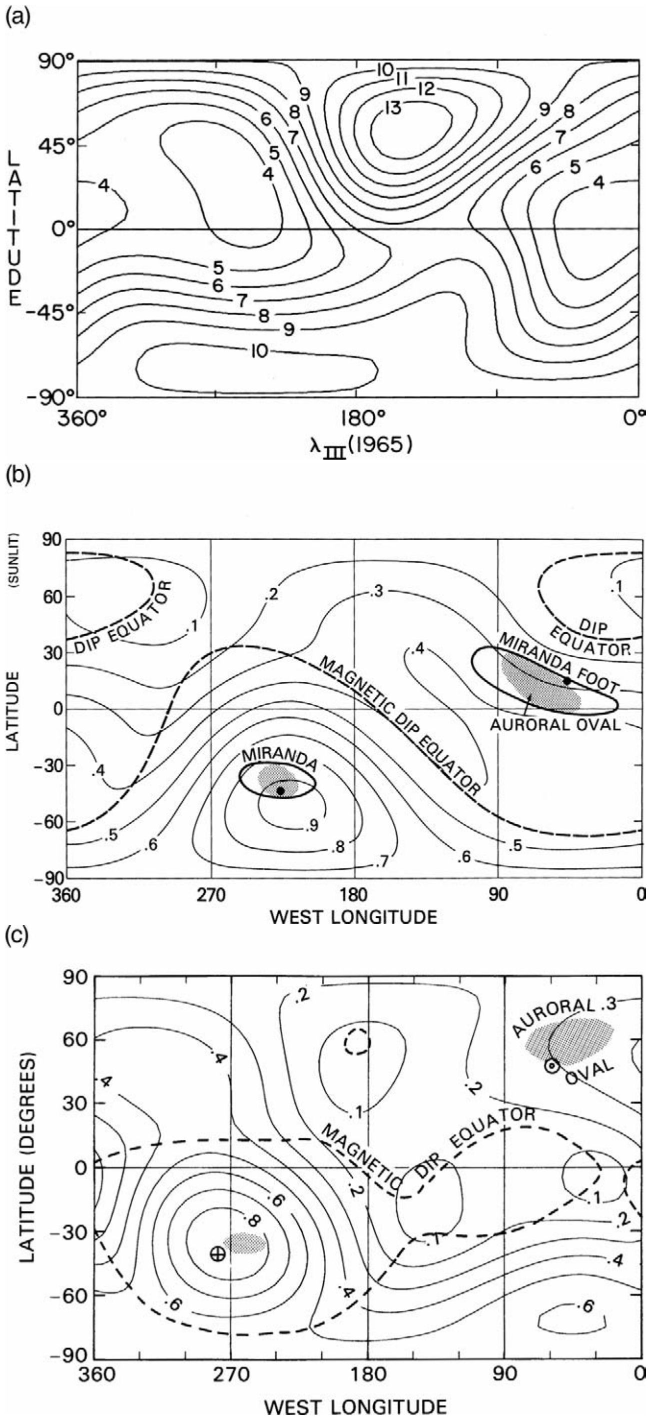


FIGURE 13 (a) Contours of magnetic field magnitude (gauss) on the surface of Jupiter (using the GSFC Model D_4). (b) Contours of constant magnetic field on the upper atmosphere of Uranus, along with the location of the auroral oval and the lines connected to the orbit of the satellite Miranda (Model Q_3). The magnetic dip equator is the location where the field lines are tangent to the surface. (c) Contours of constant magnetic field magnitude and pole locations (circled cross and dot) for Neptune (Model O_8). (From J. Connerney, 1993, *J. Geophys. Res.* **98**, 18,659–18,679. Copyright American Geophysical Union.)

FIGURE 14 (Top) Image of Jupiter at ultraviolet wavelengths taken with the Wide Field and Planetary Camera 2 on the *Hubble Space Telescope*. Bright auroral ovals can be seen against the dark UV-absorbing haze and in the polar regions. Jupiter's north magnetic pole is tilted toward Earth, making it easier to see the northern auroral oval as well as some diffuse emission inside the oval. Small bright spots just outside the oval in both hemispheres are at the location of the magnetic field lines connecting to Io, depicted by a blue curve. Io is dark at UV wavelengths. (Bottom) Image taken a few minutes after the one above in a filter that samples the violet part of the spectrum just within the range that the human eye can detect. The Great Red Spot appears dark at this wavelength and can just be seen in the top image as well. Io's small disk appears here along the blue curve, which traces the magnetic field lines in which it is embedded. (Courtesy of J. Trauger and J. Clarke.)

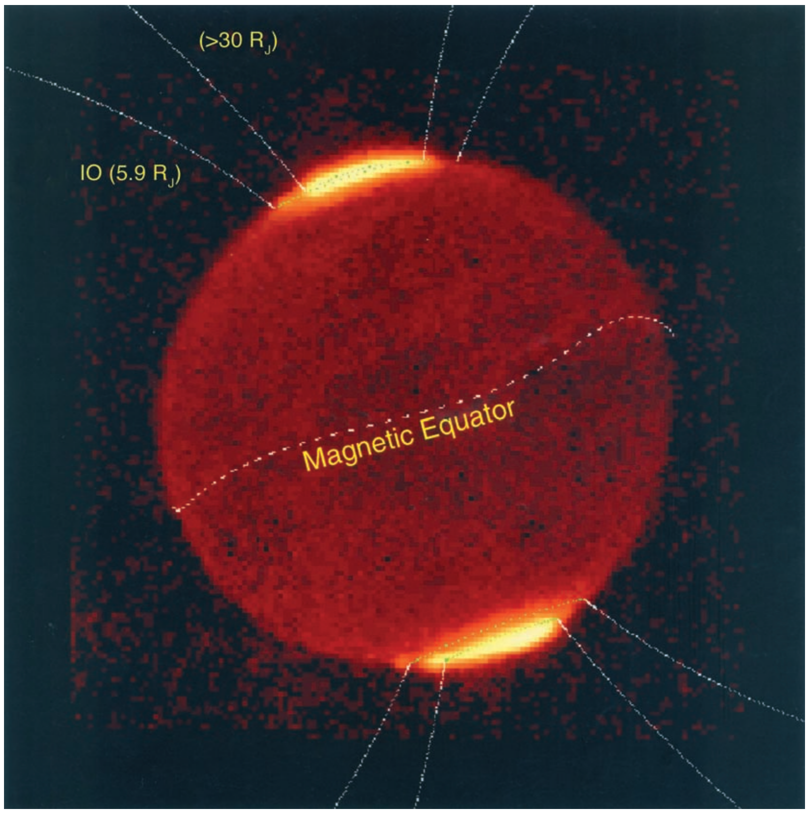


FIGURE 15 Auroral regions are bright in this image at wavelength 3.4 μm, where the H^{3+} ion emits light. Magnetic field lines connecting to Io and to the 30-Jupiter-radius equator crossing are shown. The brightest emissions are poleward of the $30R_j$ field line, which means the precipitating particles responsible for this emission come from more distant regions on the magnetosphere. (Reprinted with permission from J. Connerney et al., 1993, *Science* **262**, 1035–1038. Copyright 1993 American Association for the Advancement of Science.)

stratosphere, but a decrease in ethane requires a smaller ethane mole fraction.

Future work on the auroras of Jupiter and the other giant planets will focus on which types of particles are responsible for the emissions, the regions of the magnetosphere or torus from which they originate, the acceleration mechanisms, and how the deposited energy drives circulation and chemistry in the high atmosphere.

Bibliography

Atreya, S. K., Pollack, J. B., and Matthews, M. S., eds. (1989). "Origin and Evolution of Planetary and Satellite Atmospheres." Univ. Arizona Press, Tucson.

Bagenal, F., Dowling, T., and McKinnon, W., eds. (2004). "Jupiter: The Planet, Satellites and Magnetosphere" Cambridge Univ. Press, Cambridge, United Kingdom.

Beatty, J. K., and Chaikin, A., eds. (1990). "The New Solar System," 3rd Ed. Sky Publishing, Cambridge, Massachusetts.

Beebe, R. (1994). "Jupiter: The Giant Planet." Smithsonian Institution Press, Washington, D.C.

Bergstralh, J. T., Miner, E. D., and Matthews, M. S., eds. (1991). "Uranus." Univ. Arizona Press, Tucson.

Chamberlain, J. W., and Hunten, D. M. (1987). "Theory of Planetary Atmospheres: An Introduction to Their Physics and Chemistry," 2nd Ed. Academic Press, Orlando, Florida/San Diego.

Cruikshank, D. P., ed. (1995). "Neptune." Univ. Arizona Press, Tucson.

Gehrels, T., and Matthews, M. S., eds. (1984). "Saturn." Univ. Arizona Press, Tucson.

Rogers, J. H. (1995). "The Planet Jupiter." Cambridge Univ. Press, Cambridge, United Kingdom.