Impacts with objects as small as 2 km in diameter, which occur every several hundred thousand years (or one chance in a few thousand during the next century), could produce global climatic effects that might threaten civilization as we know it. The dramatic impact of fragments of Comet Shoemaker-Levy 9 into Jupiter in July 1994 provided ample warning: the larger comet fragments struck Jupiter with energies equivalent to an object of 2 km striking Earth, and the resulting firestorms and subsequent year-long blackened regions of Jupiter's atmosphere were as large as our entire planet.

An international "Spaceguard Survey" has been proposed to find the 90 percent of the NEO population that remains undiscovered and to learn if any particular one happens to be headed our way. A by-product of such a search, besides rich scientific rewards, would be discovery of hundreds of objects that would be easier for an astronaut (or would-be miner) to get to than the Moon. Earth-approaching asteroids may yet become astronauts' stepping stones to more distant worlds, such as Mars.

Bibliography

BINZEL, R. P., T. GEHRELS, and M. S. MATTHEWS, eds. *Asteroids II.* Tucson, AZ, 1989.

CHAPMAN, C. R., and D. MORRISON. *Cosmic Catastrophes.* New York, 1989.

MCSWEEN, H. Y., JR. *Meteorites and Their Parent Planets.* Cambridge, Eng., 1987.

CLARK R. CHAPMAN

ASTRONAUTS

See Apollo Astronauts

ATMOSPHERES, PLANETARY

All nine planets, four moons, and most comets have atmospheres. These gaseous envelopes are remarkably diverse, although they are made largely from the same six elements—hydrogen (H), helium (He), oxygen (O), carbon (C), nitrogen (N), and sulfur (S). These are the most abundant elements in the Sun and stars. And with the exception of helium, they are the main elements in living things.

Atmospheres differ in composition, mass, temperature, and degree of interaction with the underlying planet. At one extreme, the atmospheres of the four giant planets merge imperceptibly with the planetary interiors, which are made of the same gaseous mixtures as the atmospheres. Pressures in the interiors of these fluid planets reach millions of bars—millions of times the sea level pressure on Earth. At the other extreme, the atmospheres of the Moon and Mercury consist of individual molecules hopping around the surface, never colliding with each other because the density is too low. The intermediate cases are Venus, Earth, Mars, Pluto, Io (a satellite of Jupiter), Titan (a satellite of Saturn), and Triton (a satellite of Neptune). These atmospheres rest on solid or liquid surfaces and interact chemically with the solid planet on a variety of timescales.

This article is organized around two main themes—chemistry and dynamics. The former involves composition and how it has evolved. The latter involves weather and climate. Table 1 gives the general properties of atmospheres around solar system objects.

Chemical Composition and Evolution

Hydrogen and helium are the most abundant elements in the giant planet atmospheres. Chemically reactive elements like oxygen, carbon, and nitrogen exist mainly in combination with hydrogen in compounds such as water (H_2O), methane (CH_4), and ammonia (NH_3). The latter three compounds are gases in the warm interiors of the giant planets, but they condense in the cooler atmospheres. Temperatures on Jupiter and Saturn are too high to allow methane condensation, and the visible clouds are made of ammonia. On Uranus and Neptune the high-altitude clouds are methane ice; the deeper clouds are ammonia and possibly hydrogen sulfide. The giant planets resemble the Sun in overall elemental abundances, but with varying degrees of enrichment of heavy elements relative to hydrogen and helium (*see* PLANETOLOGY, COMPARATIVE).

Carbon dioxide is the most abundant constituent in the atmospheres of Venus and Mars, and

Table 1. General Properties of the Atmospheres around Solar System Objects

Classes of Atmospheres	*Solar System Object*	*Composition—Main Components*	*P, T*[a] *at Base or Visible Cloud and T in Thermosphere*	*Nature of Upper Cloud Deck*	*Typical Flow Speed*	*Typical Temperature Contrasts*
H_2-He atmospheres of the giant planets	Jupiter	H_2, He, CH_4, NH_3[b], . . .	0.5 bar, 150 K, 1000 K	NH_3	100 m/s	5 K
	Saturn	H_2, He, CH_4, NH_3[b], . . .	1 bar, 160 K, 400 K	NH_3	400 m/s	5 K
	Uranus	H_2, He, CH_4[b], . . .	1 bar, 80 K, 870 K	CH_4	200 m/s	2 K
	Neptune	H_2, He, CH_4[b], . . .	1 bar, 80 K, 600 K	CH_4	400 m/s	2 K
Terrestrial CO_2 atmospheres	Venus	CO_2, N_2, SO_2[b], H_2SO_4[b], . . .	90 bar, 730 K, 200 K	H_2SO_4	100 m/s	5 K
	Mars	CO_2,[b] N_2, H_2O[b], . . .	7 mbar, 200 K, 400 K	H_2O	40 m/s	40 K
N_2 atmospheres	Titan	N_2[b], CH_4[b], . . .	1.5 bar, 90 K, 180 K	CH_4	?	5 K
	Earth	N_2, O_2, Ar, H_2O[b], . . .	1 bar, 280 K, 1000 K	H_2O	20 m/s	40 K
	Pluto	N_2[b], CO[b], CH_4[b], . . .	3–600 μbar?, 35–45 K?, ?	N_2	?	<20 K
	Triton	N_2[b], CO[b], CH_4[b], . . .	14 μbar, 38 K, 100 K	N_2	?	?
Volcanic	Io	SO_2[b]	0.1–10 nbar,[c] 120 K, 600 K	SO_2	200 m/s	?
Exospheres	Moon	Na, K, . . .	?	—	?	—
	Mercury	Na, K, . . .	?	—	?	—
Unknown	Charon	?	?	?	?	?
Comae	Comets	H_2O, CH_4, CO, CO_2, CH_3OH	—	—	—	—
	Chiron	CO?, ?	?	?	?	?

[a] P, pressure; T, temperature.
[b] A condensing, time-variable constituent.
[c] Time variable.
From Table 4.2 of *An Integrated Strategy for the Planetary Sciences: 1995–2010* (1994).

might have been the most abundant constituent in the atmosphere of Earth. On our planet, carbon dioxide from the atmosphere has reacted with the rocks to form calcium carbonate—limestone. This reaction takes place in solution, and therefore requires liquid water. It is estimated that Earth's limestone deposits are equivalent to an amount of carbon dioxide that is 40–100 times the mass of Earth's current atmosphere, including all constituents. Without liquid water, this CO_2 would reside in the atmosphere. Venus, which lacks oceans and liquid water, has a dense CO_2 atmosphere whose surface pressure is ninety times that on Earth. Thus Earth and Venus have roughly the same total inventory of CO_2. The CO_2 inventory on Mars is largely unknown, since large amounts of CO_2 might lie buried in polar ice deposits and carbonate rocks. The atmospheric pressure of Mars is only 0.7 percent that of Earth, and is controlled by equilibrium with frozen CO_2 at the poles.

Molecular nitrogen (N_2) is the most abundant constituent in the atmospheres of Earth, Titan, Triton, and Pluto. As with CO_2 on Mars, the N_2 in the atmosphere on Triton and Pluto is in equilibrium with N_2 frost on the ground. As the frost heats up or cools off in response to seasonal changes, the atmosphere expands or contracts. The surface pressure of Mars varies by 30 percent during the martian year. The thinner atmospheres of Triton and Pluto vary by orders of magnitude. This control by N_2 frost is only possible at the low temperatures of the outer solar system.

Oxygen (O_2) is the second most abundant constituent in Earth's atmosphere, constituting 20 percent of the molecules in dry air. Oxygen is produced during photosynthesis from CO_2 and H_2O, and is consumed during respiration and decay. Without life, our planet would have little or no O_2 in its atmosphere. Ozone (O_3), atomic oxygen (O), and O_2 are trace constituents in the atmospheres of Mars and Venus, where they are produced by photodissociation—the destruction of CO_2 molecules by sunlight.

Water is not the major constituent of any planetary atmosphere, although it is the most abundant volatile compound on Earth. The ocean is 300 times as massive as the atmosphere, but Earth temperatures are too low to vaporize more than 0.002 percent of it. Venus contains almost no water, although traces of hydrogen are found in the clouds, which are concentrated solutions of sulfuric acid (H_2SO_4). The hydrogen on Venus tells an interesting story. The proportion of deuterium, the heavy isotope of hydrogen, is 100 times greater than on Earth. Such enrichment comes about when the lighter isotope of hydrogen escapes, suggesting that Venus lost massive amounts of water. Instead of oceans, Venus may have formed with a massive water vapor atmosphere maintained by its own "runaway greenhouse" and greater energy from the Sun. Once up in the atmosphere, water was destroyed by photodissociation, and the lighter hydrogen was lost to space. These processes occurred in the inner solar system, where temperatures are high. On Mars, water is mostly frozen in polar and subsurface ice. On the surfaces of the satellites of the giant planets, water is as hard as rock.

Hydrocarbons in Titan's atmosphere also tell an interesting story. The satellite is not massive enough to hold onto hydrogen over the age of the solar system, so photodissociation of hydrogen-bearing compounds like CH_4 and NH_3 leads to hydrogen escape. The remaining carbon atoms bind to themselves to form compounds like ethane (C_2H_6), acetylene (C_2H_2), and higher hydrocarbons. The result is a photochemical smog that hides the surface and may have condensed out in sufficient quantities to form lakes or oceans.

Sulfur dioxide (SO_2) is the dominant constituent in the atmosphere of Io. The surface of the satellite is cold enough to freeze out all but trace amounts of the gas, especially on the nightside. But a detectable atmosphere is present above the volcanic vents and above the warm patches of frost on the dayside. Maximum surface pressures never exceed 10^{-7} Earth atmospheres, and the pressure away from the vents is several orders of magnitude less. The winds away from the vents rise to supersonic speeds as the thin atmosphere flows out over the cold surface and disappears into a vacuum. Io's atmosphere is patchy.

Sodium and potassium atoms have been detected above the surfaces of Earth, Io, Mercury, and the Moon. These volatile elements scatter sunlight effectively, and so are easy to detect. On the Moon and Mercury, the density is so low that the molecules collide only with the surface and not with each other. On Earth, the collisionless region where the atmosphere merges with the vacuum of space is termed the "exosphere." On Mercury and the Moon, the exosphere extends down to the surface. Sodium and potassium atoms are released from surface rocks through impact by high-energy particles in a process called sputtering. Both Mercury and the Moon may have ice deposits in the permanently shaded craters at the north and south poles. With no sunlight and no atmosphere to transport heat from the hot equator, these regions are as cold as Triton and Pluto. The ice comes from comets that crash onto the surface: Water molecules from the comet hop randomly around until they are destroyed by sunlight or find a safe haven in one of the permanently shaded cold traps.

The noble gases—helium, neon (Ne), argon (Ar), krypton (Kr), and xenon (Xe)—are rare on the terrestrial planets but are abundant on the Sun and the giant planets. The later objects incorporated both gas and dust from the solar nebula—the cloud of material out of which the solar system formed. The noble gases were incorporated along with hydrogen. Objects in the inner solar system incorporated only dust. Their atmospheres come from outgassing—release of material that was chemically bound to the dust—and from comets, which deliver ice from the outer solar system.

Weather and Climate

Atmospheres move because they are heated, and because the heat sources are in different locations than the heat sinks. Sunlight is the main energy source for most planetary atmospheres. The Sun heats only the dayside and heats the equator more than the poles. Internal heat is comparable to sunlight for the giant planets and Io. Convection currents from the warm tropics and the warm interior carry heat poleward and upward. The energy reaches altitudes where the atmosphere is transparent, at which point the energy is radiated to space. On most planets that altitude is near the 100 mbar level—the altitude where the pressure is 0.1 times Earth's sea-level pressure.

Figure 1 shows the mean temperature profiles for the major planet atmospheres. Temperature falls off rapidly with altitude in the troposphere and less rapidly in the stratosphere. The boundary between the two regions, the tropopause, is near 100 mbar for all planets except Mars and Pluto, whose atmospheres end at the 6 mbar and 3 microbar levels, respectively.

Convection is usually a small-scale process consisting of cool downdrafts and warm updrafts that carry heat from where the sunlight is absorbed and the internal heat is stored to where energy is radiated to space. Shimmering of air over the desert, cumulus clouds, dust devils, and thunderstorms are all examples of small-scale convection. Convection can be either moist or dry. In moist convection, the condensable vapor rises, releases its latent heat, and then falls out as rain or snow. Tornadoes and hurricanes are intense forms of moist convection on small and intermediate scales, respectively.

Large-scale motions transport heat laterally. On Earth the Hadley circulation—the slow overturning of the tropical troposphere—transports heat from the equator out to 30° latitude. Extratropical cyclones and anticyclones—rotating masses of air thousands of kilometers across—transport heat beyond 30° to the polar regions. These huge vortices develop from waves on the jet stream, which is an eastward-moving current of air at midlatitude in each hemisphere.

These same weather elements are present in other planetary atmospheres, but there are differences. Wind speeds are generally larger than on Earth, even in the outer solar system where sunlight is hundreds of times weaker. Storms last much longer: The Great Red Spot on Jupiter was discovered three hundred years ago shortly after the invention of the telescope. It is a huge vortex whose spiraling winds bring up compounds that form the red clouds. The cloud patterns and wind directions vary widely. Venus, Titan, and the giant planets have banded, axisymmetric features—cloud patterns and jet streams that circle the planet on lines of constant latitude. Io, Triton, and Pluto have winds that always blow toward the dark side. Earth and Mars are intermediate cases in which axisymmetric features—Hadley cells and jet streams—coexist with large-scale cyclones and waves.

Paradoxically, wind speeds do not decrease as one moves out in the solar system. Although the power per unit area emitted by Neptune is only one twentieth that at Jupiter and one four hundredth that at Earth, Neptune's large-scale wind speeds reach 400 m/s, while Jupiter's reach 160 m/s and Earth's only reach 50 m/s. The explanation may lie in the role of small-scale convective motions, which provide dissipation for the large-scale flow. As one moves outward from the Sun in the solar system, the small-scale motions decrease, allowing the large-scale motions to build up. At Neptune these large-scale motions are coasting along with almost no dissipation. On Earth, where small-scale convection is more vigorous, the large-scale winds are weaker. Low dissipation may also

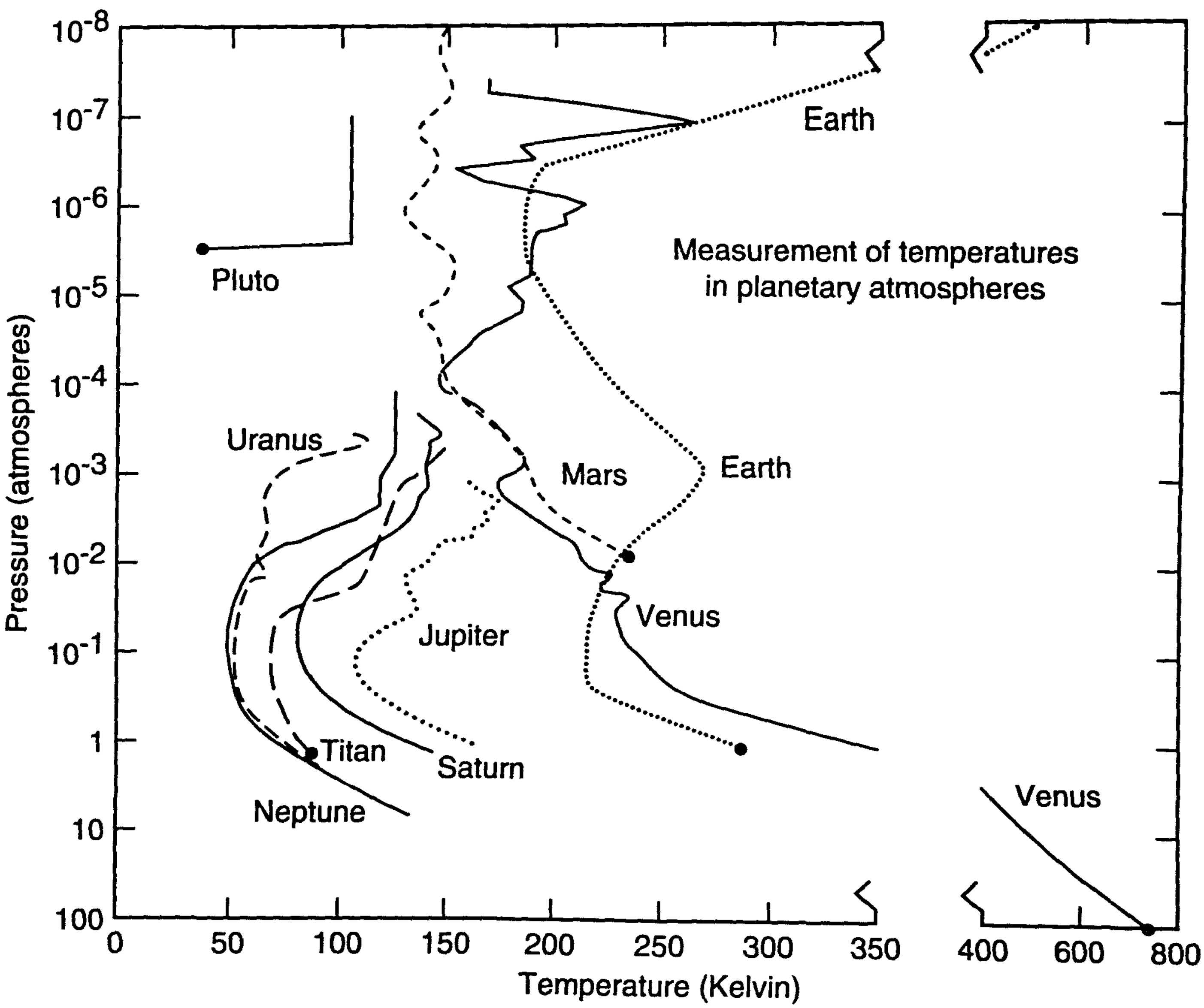

Figure 1. Temperature profiles of major planetary atmospheres. For the giant planets, the base of the profile is the deepest point sampled, so the base pressure has no special significance. For the other planets and Titan, the base pressure is the surface pressure and is indicated by a solid circle. Reproduced from Figure 4.4 of *An Integrated Strategy for the Planetary Sciences: 1995–2010.*

explain the longevity of the large vortices in the giant planet atmospheres. Numerical models show that these vortices arise spontaneously and are stable at the interfaces between the eastward- and westward-flowing jet streams, provided the dissipation is low.

Venus presents a number of questions: Why is Venus so dry? Why is the surface so hot? What makes the atmosphere rotate fifty times faster than the solid planet? As discussed earlier, Venus may have lost an amount of water equal to Earth's oceans. The high surface temperatures reflect the greenhouse effect of the massive CO_2 atmosphere: Enough sunlight diffuses down to the surface to provide an energy source, but the heat cannot readily escape because the infrared bands are blocked by atmospheric gases. The superrotation of the atmosphere is strange because friction tends to make all layers spin with the solid planet. The explanation involves waves, which can propagate vertically in planetary atmospheres. The waves carry momentum and energy, and could balance the effects of friction. Thus far, however, the waves responsible for the superrotation of Venus have not been identified.

Mars offers interesting examples of climate change. Although the surface now is cold and dry, flowing water carved enormous channels early in the planet's history. The questions are: What caused the climate to change so drastically? And, is the water now frozen in the substrate and at the poles? Layered deposits in the polar regions may provide the answers, but so far the layers have been observed only from orbiting spacecraft and not from the ground. Because Mars is so dry, dust builds up in the atmosphere and creates enormous changes in the weather. The global dust storms are unpredictable and seem to occur every few years. High wind speeds are required, but the mechanism that triggers a global dust storm is unknown.

Earth's climate has also changed drastically over geologic time. The early Earth was warm, despite less output from the early Sun. The present ice sheets in Greenland and Antarctica only appeared a few million years ago. Every hundred thousand years the ice sheets advanced down to about the latitude of New York City and then retreated abruptly. As on Mars, changes in Earth's spin in relation to its orbit may account at least partly for the ice ages—the advances and retreats of the glaciers. The atmosphere was dustier during the cold dry periods. As on Venus, changes in the amount of carbon dioxide may account for the high temperatures of the early Earth. The mystery is how the rather small changes in the orbit could have caused the ice ages, and why the CO_2 should have changed at all. Studying planets does not provide all the answers, but it does reveal some of the extreme possibilities.

Bibliography

ATREYA, S. K., J. B. POLLACK, and M. S. MATTHEWS, eds. *Origin and Evolution of Planetary and Satellite Atmospheres.* Tucson, AZ, 1989.

BEATTY, J. K., and A. CHAIKIN, eds. *The New Solar System,* 3d ed. New York, 1990.

CHAMBERLAIN, J. W., and D. M. HUNTEN. *Theory of Planetary Atmospheres.* Orlando, FL, 1987.

COMMITTEE ON PLANETARY AND LUNAR EXPLORATION 1994. *An Integrated Strategy for the Planetary Sciences: 1995–2010.* Space Studies Board, National Research Council. Washington, DC, 1994.

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AURORAS

At their simplest, auroras appear to be hanging curtains of light in an otherwise dark nighttime sky. The light is created by the discharge of electricity in Earth's upper atmosphere. The electricity is generated as an electromagnetic storm from the Sun as it sweeps past Earth.

In general, auroras occur in narrow oval belts displaced away from, but surrounding, Earth's magnetic poles. Nearly identical auroras occur simultaneously in the Northern and Southern Hemispheres—the Aurora Borealis in the north and the Aurora Australis in the south. Satellite-borne electronic images show Earth's auroras occurring all the time.

The vertical striations that appear in the hanging curtains of light are similar to the streaks of light that often precede sunrise. In 1621 the French scientist Pierre Gassendi was the first to call them "aurora" after the Greek goddess Aurora, who, according to myth, was responsible for the "rosy fingers of dawn." The striations result from the alignment of electrical discharges on the normally invisible lines of Earth's magnetic field. Light-producing electrical discharges start occurring around 250 kilometers above Earth and continue growing brighter until they are extinguished near 115 kilometers. On rare occasions auroras extend thousands of kilometers high. More rarely the sky will be partially covered with a blood red glow that is a high-altitude, low-energy aurora.

The colors of auroras are indicative of the types of elemental gases in Earth's atmosphere where the electrical discharges are taking place. At the altitudes of the auroras, nitrogen and oxygen exist in both their atomic and molecular forms. Electrical discharges in each create a unique discontinuous spread of colors. Electrical discharges in atomic oxygen produce the greenish-white and deep-red colors, while those in singly ionized molecular nitrogen produce blue colors.

A low-level flow of energy from the Sun creates a low level of continuous aurora that is confined to regions near Earth's magnetic poles. Observations of the Sun have revealed that, in general, a high level of aurora activity follows an approximate eleven-year cycle. Specific high-energy storms that create dramatic displays are unpredictable. The flow of energy from a typical solar storm takes approximately forty-eight hours to reach Earth.