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Jupiter and Saturn

Competing models seek to describe the sun's two giant companions. In one model the winds are confined to a thin layer at the surface; in another the winds extend through the fluid depths of each planet

by Andrew P. Ingersoll

There were many exciting moments during the encounters of the Voyager spacecraft with Jupiter in 1979 and with Saturn in 1980 and 1981, but to me the most memorable ones came early in the first encounter, when we viewed the time-lapse images of Jupiter's swirling clouds made by *Voyager 1* on its long approach to the planet. The sequence compressed a 30-day history of the Jovian weather into a one-minute motion picture. As a scientist who studies the atmospheres of the planets, I was familiar with Jupiter's brown belts and white zones: the colored cloud bands some thousands of kilometers wide that circle the planet at constant latitude. And I had come to accept the hypothesis that Jupiter's Great Red Spot is a storm as large as the earth that has lasted for centuries.

I was not prepared, however, for the intricate motions revealed in the time-lapse sequence. The sequence was synchronized to the rotation of Jupiter, so that the Great Red Spot appeared to be stationary, with the adjacent atmosphere swirling around it. Bright, small-scale features appeared and then were torn apart, all in a few days. Small spots encountering the Red Spot from the east seemed to be drawn into its counterclockwise, rotatory flow, to circle it in one or two weeks and then to divide, a part of each one merging with the spot and the other part returning eastward. Elsewhere spots were forming, merging and dividing every few days. On scales less than 1,000 kilometers everything seemed to be chaos. How the larger structures could endure and retain their distinct colorations in such a well-mixed atmosphere was more of a mystery than it had been before the spacecraft arrived.

It is still a mystery today. Nevertheless, an analysis of the images made by *Voyager 1* and *Voyager 2* reveals order in the chaos. Indeed, it shows that many aspects of the atmospheric circulation on Jupiter and Saturn resemble patterns in the atmosphere and oceans of the earth. A number of theoretical models and laboratory experiments are now invoked to explain the circulation. The models differ in their assumptions about a basic unanswered question. Are the motions in the atmosphere of Jupiter and Saturn confined to a thin sunlit layer 100 or 200 kilometers thick where clouds form and the atmospheric pressure is only a few times the sea-level pressure on the earth? Or do the motions extend tens of thousands of kilometers down to the top of a metallic hydrogen zone where the pressure is three million times the earth's sea-level pressure?

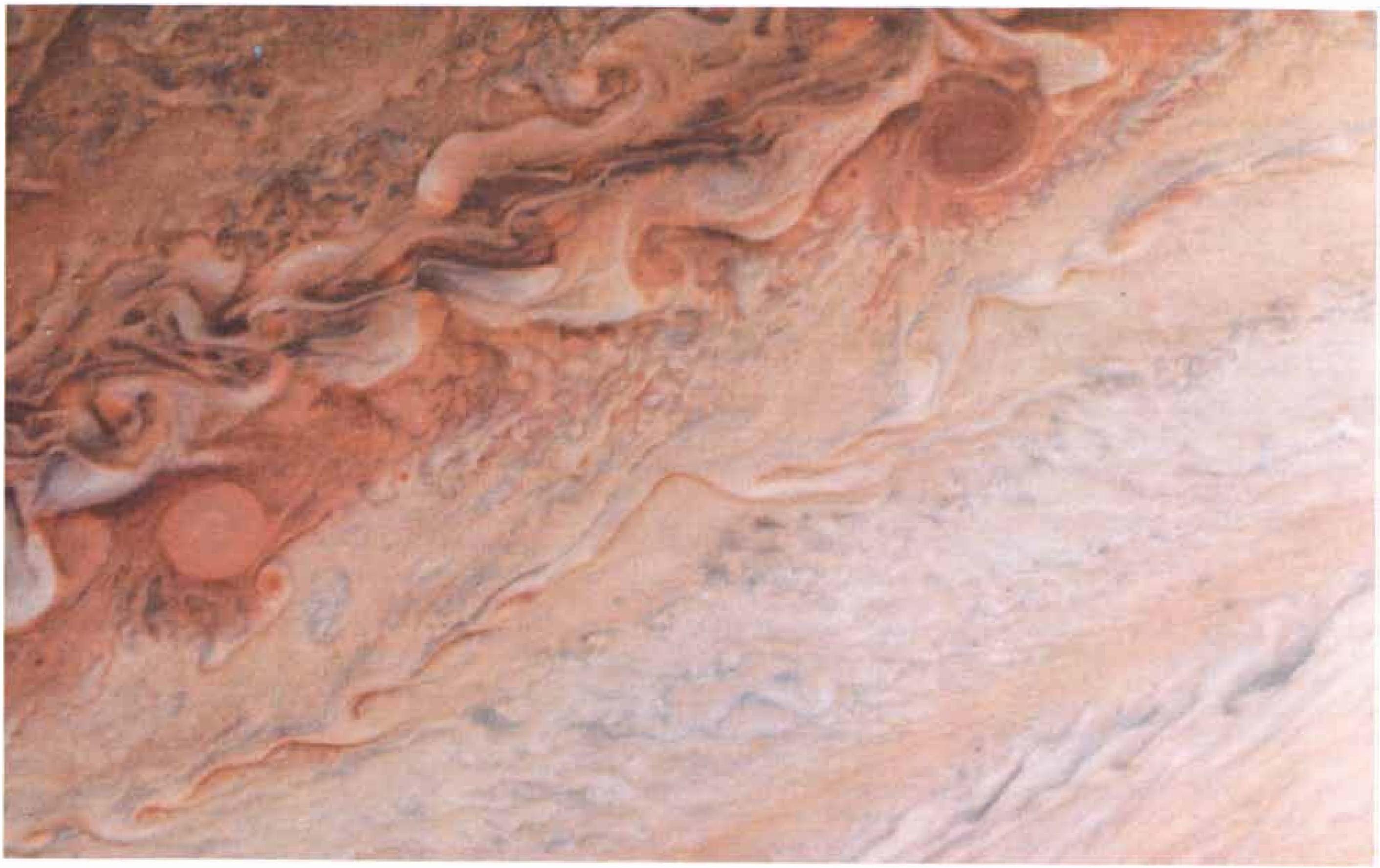
In considering these questions I shall focus on Jupiter and Saturn themselves, to the exclusion of their moons and rings. I shall begin with bulk planetary properties: the mass, the density and the composition of Jupiter and Saturn. This leads to a discussion of the internal structure of each planet and of the origin of the internal heat each is radiating into space. Next I shall describe the structure and chemistry of the atmosphere of Jupiter and Saturn. Alternative explanations of the dynamics of the atmosphere I shall take up last. Here the challenge is to find out why features of atmospheric flow can persist for decades or centuries on Jupiter and Saturn and only for days or weeks on the earth.

Mass, Density and Internal Structure

No theory is available that accounts precisely for the mass of the sun's two principal companions. The mass of Jupiter is 318 times the mass of the earth, or about a thousandth the mass of the sun. The mass of Saturn is 95 times the mass of the earth. Presumably these values reflect the amount of matter left in orbit around the sun soon after it formed. Moreover, no theory is available that accounts precisely for the relative abundances of the various chemical elements constituting Jupiter and Saturn. The abundances do, however, resemble those in the sun. Specifically, Jupiter and Saturn are the only planets in the solar system that consist mostly of hydrogen and helium. No other substances could give Jupiter its bulk density of only 1.33 grams per cubic centimeter at the pressures and temperatures that characterize the planet. The density of Saturn is even less—.69 gram per cubic centimeter—because Saturn's smaller mass entails a lesser degree of gravitational self-compression.

Mercury, Venus, the earth and Mars are made of heavier stuff: their densities are from 3.9 to 5.5 grams per cubic centimeter, or several times the density of Saturn. In general they are made of rocks: the most abundant metals and their oxides. The densities of Uranus and Neptune are twice as great as Saturn's, although their self-compression is less. Their most likely constituent elements are therefore oxygen, carbon and nitrogen: the third, fourth and fifth most abundant elements in the solar system. (The first two are hydrogen and helium.) At the temperatures that characterize the outer solar system oxygen, carbon and nitrogen should combine with the available hydrogen to form water, methane (CH_4) and ammonia (NH_3). On the surface of Uranus and Neptune these compounds are ices; in the interior they are liquids. The enrichment of ices with respect to hydrogen and helium on the planets beyond Saturn is hard to explain. The depletion of gases and ices in the inner solar system probably reflects the high temperatures close to the sun in the early life of the solar system.

Given the mass and composition of a planet such as Jupiter or Saturn one may seek to infer its internal structure. The size and density of the planet adjust themselves so that the outward pressure of the compressed material exactly balances the inward pull of gravity at any given place in the planet's interior. The result is a state of hydrostatic equilibrium. If the planet is rotating, a further force enters the balance. It is the outward centrifugal force that results from the planet's rotation. The outward force on a rotating mass is proportional to the square of the distance of the mass from the axis of rotation. Hence a rotating planet is flattened: its polar radius is less than its equatorial radius. The degree of flattening will depend on the internal distribution of mass. For example,

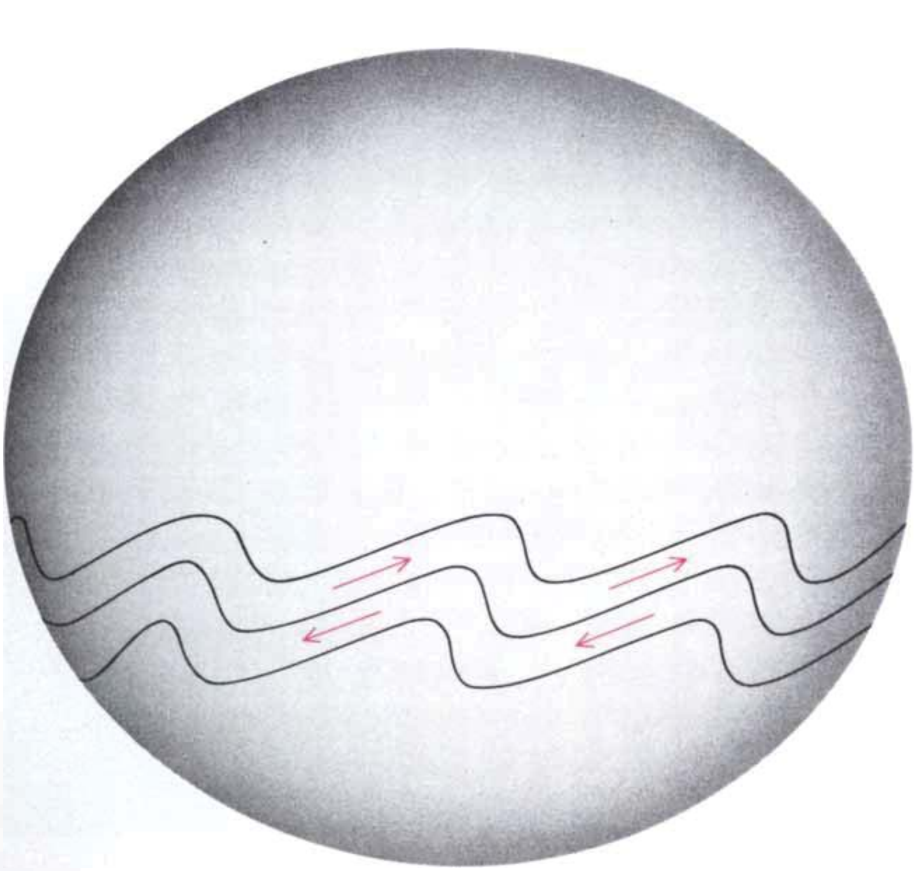


EDDY CURRENTS in the atmosphere of Jupiter and Saturn are deviations in patterns of flow that otherwise consist of sustained, alternating ribbons of eastward and westward wind. The northern mid-latitudes of Jupiter (*top*) were photographed in exaggerated color by the spacecraft *Voyager 1* on March 2, 1979. The orange ribbon cutting diagonally across the bottom right corner represents a steady eastward wind whose speed is some 130 meters per second. The sinuous lines toward the top represent eddies whose speeds are about 30 meters per second with respect to the steadier currents. The northern mid-latitudes of Saturn (*bottom*) were photographed in exaggerated color by *Voyager 2* on August 19 of this year. The sinuous line inside the light blue ribbon is a pattern moving eastward at 150 meters per second. The dark oval and the puffy white features below it are eddies drifting westward at speeds as high as 20 meters per second.

two planets of the same mass and rate of rotation will differ in the degree to which they are flattened if matter is concentrated near the center in one and farther from the center in the other. The latter will be the more flattened of the two. Clearly the degree of flattening is a sensitive probe of a rotating planet's internal structure.

Both Jupiter and Saturn have a rotational period of about 10 hours. Moreover, both planets are somewhat flattened. Jupiter's equatorial radius is 6.5 percent greater than its polar radius; Saturn's is 9.6 percent greater. Measurements of the planets' gravitational field imply a corresponding degree of concentration of mass toward the equatorial plane. An incorporation of the measurements into models of the internal structure of Jupiter and Saturn have led William B. Hubbard, Jr., of the University of Arizona and V. Zharkov and V. Trubitsyn of the Institute of the Physics of the Earth in Moscow to a further conclusion. Both Jupiter and Saturn have a dense core that cannot consist of compressed hydrogen and helium. The pressure inside each planet is simply not great enough to produce the required central densities from a mixture of those two elements. Apparently Jupiter has a core of rock and ice that constitutes about 4 percent of its mass, and Saturn has a similar core that constitutes about 25 percent of its mass. Each core may be the "seed" on which the rest of the planet condensed from gases when the solar system formed. Or perhaps the cores formed later as the result of a redistribution of matter inside the planets.

Knowledge of the internal structure of Jupiter and Saturn also comes from the quantum-mechanical description of how atoms and molecules behave as they are compressed. According to the exclusion principle of modern physics, the electrons bound to protons in a compressed assemblage of hydrogen molecules can occupy the same shrinking volume only by climbing to higher levels of energy. At a certain compression (and thus a certain amount of energy) they are no longer bound to individual protons but become free to wander in an electrically neutral mixture of protons and electrons. The hydrogen then becomes a metal. Calculations made by Edwin E. Salpeter of Cornell University and David J. Stevenson, who is now at the California Institute of Technology, show that the transition from molecular hydrogen to metallic hydrogen comes at nearly the same critical pressure (three million earth atmospheres) on both Jupiter and Saturn. Since Jupiter is more massive than Saturn, the critical pressure is attained closer to the surface. On Jupiter the distance from the center of the planet to the metallic-molecular transition is in the range of .75 to .80 times the distance from the center to the surface. On Saturn it is .45 to .50.



TRANSFER OF MOMENTUM from eddy currents to sustained eastward and westward winds was documented for the earth by Victor P. Starr and his colleagues at the Massachusetts Institute of Technology; the Voyager images suggest that similar transfers feed momentum into the east-west winds on Jupiter and Saturn. In the illustration eddies on a model planet are shown to feed eastward momentum toward the north and westward momentum toward the south. This augments the velocity difference between the planet's mean east-west currents.

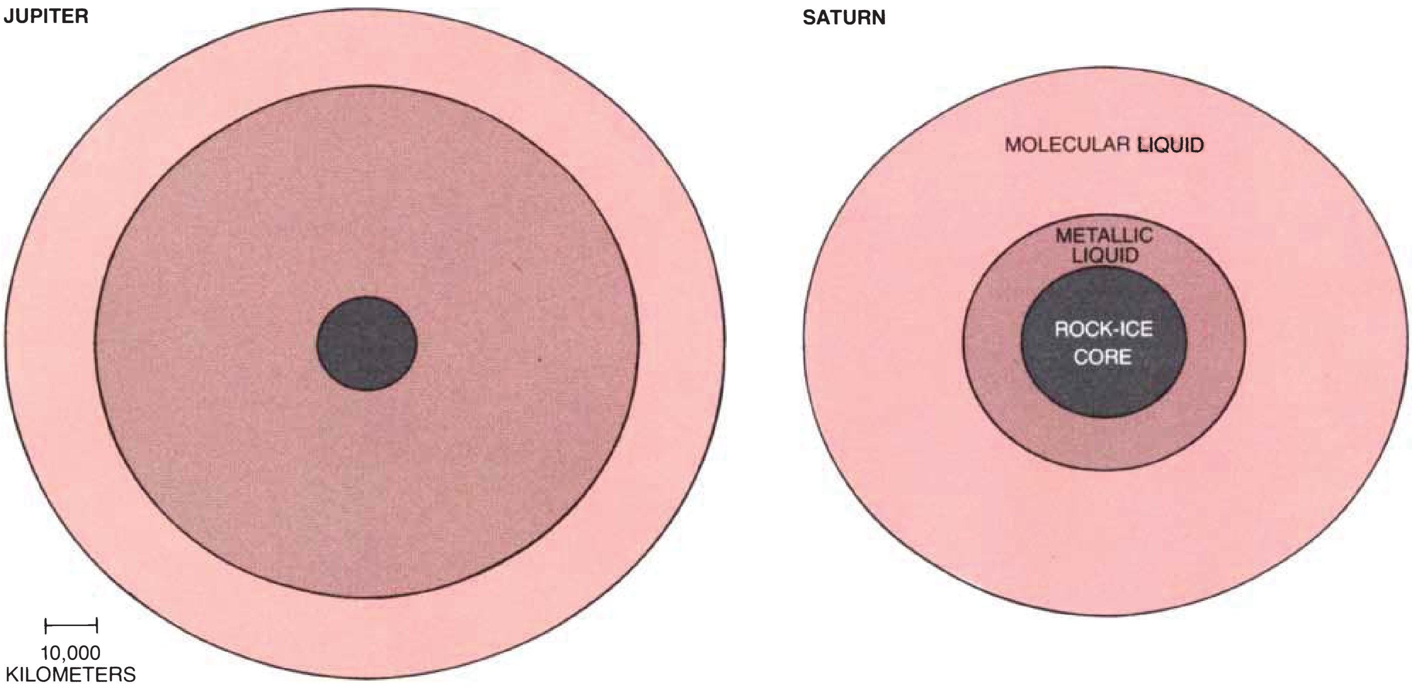
Sources of Internal Heat

Measurements made by instruments on the Voyager spacecraft, and also the Pioneer spacecraft that reached Jupiter as early as 1973, imply that the power Jupiter gives off (as infrared radiation) is 1.5 to 2.0 times the amount it absorbs (as sunlight). The power Saturn gives off is 2.0 to 3.0 times the amount it absorbs. Hence both Jupiter and Saturn have internal sources of heat. Yet neither planet is massive enough for gravitational self-compression to have initiated nuclear fusion. In short, neither planet is a star. Instead their internal heat must represent the conversion of the gravitational potential energy that became available as each planet contracted from a cloud of gas beginning some 4.6 billion years ago. James B. Pollack and his colleagues at the Ames Research Center of the National Aeronautics and Space Administration have developed models of the history of the giant planets and conclude that the interior of Jupiter and Saturn is still hot today.

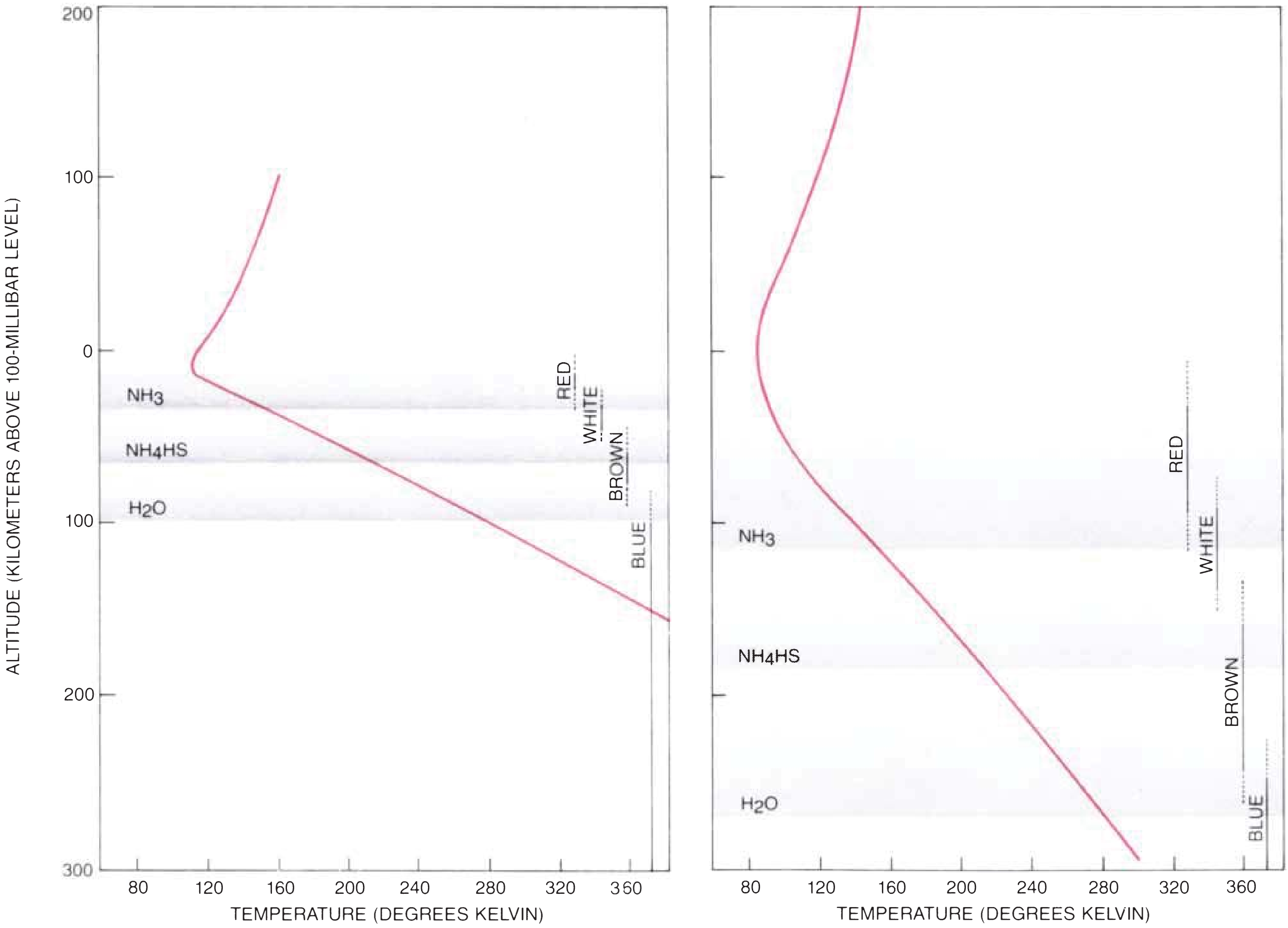
How hot? The answer follows from the thermodynamic law that heat flows from warmer places to colder. Specifically, a mixture of hydrogen and helium in Jupiter or Saturn (even a metallic mixture) cannot conduct heat away from the center of the planet unless the rate of temperature decrease with distance from the center is significant. The rate of decrease is limited, however, by convection: the overturning of a fluid in which warm parcels of the fluid rise and cooler parcels sink.

Briefly, convection mixes a fluid until its temperature decrease with altitude matches the adiabatic lapse rate: the rate at which a rising fluid parcel will cool when no heat is exchanged with its surroundings. Instead of losing energy by heat flow the parcel loses energy by pushing on its surroundings as it expands. On this basis it can be shown that the temperature gradient in Jupiter and Saturn's interior is close to adiabatic and that the central temperatures are in a range of 20,000 to 30,000 degrees Kelvin. At such temperatures a mixture of hydrogen and helium does not solidify. Thus the metallic hydrogen inside Jupiter and Saturn is liquid. At an intermediate level, where the pressure is three million earth atmospheres, the metallic liquid abruptly gives way to a molecular liquid. At still higher levels the molecular liquid gradually gives way to a molecular gas: the atmosphere of Jupiter and Saturn.

Models of the cooling of Jupiter over



INTERIOR of Jupiter (*left*) and Saturn (*right*) consists of three layers. The outermost layer is a liquid mixture of hydrogen and helium; the hydrogen is molecular. The innermost layer is a core of rock and ice. In the middle layer a pressure in excess of three million earth atmospheres transforms the hydrogen into a liquid mixture of protons and wandering electrons. Thus the hydrogen in the middle layer is a metal. The rotation of each planet makes it somewhat flattened toward the poles. The degree of flattening is greater on Saturn.



ATMOSPHERE of Jupiter (*left*) and Saturn (*right*) is assumed to have proportions of the various chemical elements much like the proportions in the sun; on that basis each atmosphere can be assumed to include stratified clouds of ammonia (NH_3), ammonium hydrosulfide (NH_4HS) and water. These compounds all form white particles; hence the colors in each atmosphere must have other causes, which have yet to be identified. In the charts each color is assigned a range of altitudes in accord with measurements of cloud-top temperatures. Red clouds, for example, are the coldest and therefore the highest. The cloud tops on each planet lie no higher than the level at which the temperature (*colored curves*) begins to increase with altitude, so that convection currents no longer carry solid (or liquid) particles upward.

the history of the solar system account for all the power that Jupiter is radiating today in excess of the amount it absorbs. Similar models fail, however, to account for about a third of the excess that Saturn radiates. Apparently Saturn has a source of internal heat not included in the calculations, a source Jupiter lacks. In the mid-1970's Salpeter and Stevenson proposed an explanation that is now supported by the Voyager data. A planet incorporating a mixture of hydrogen and helium has two types of energy: thermal and gravitational. If the mixing ratio (that is, the ratio of hydrogen to helium) is constant throughout the mixture, the two types of energy are released together in constant proportions. As the planet cools it contracts. If, however, the mixing ratio changes (for example, if the helium falls through the hydrogen), an additional quantity of gravitational energy is released. Such a process is likely on Saturn because the planet has already cooled to the extent that helium is precipitating at the top of the metallic hydrogen zone.

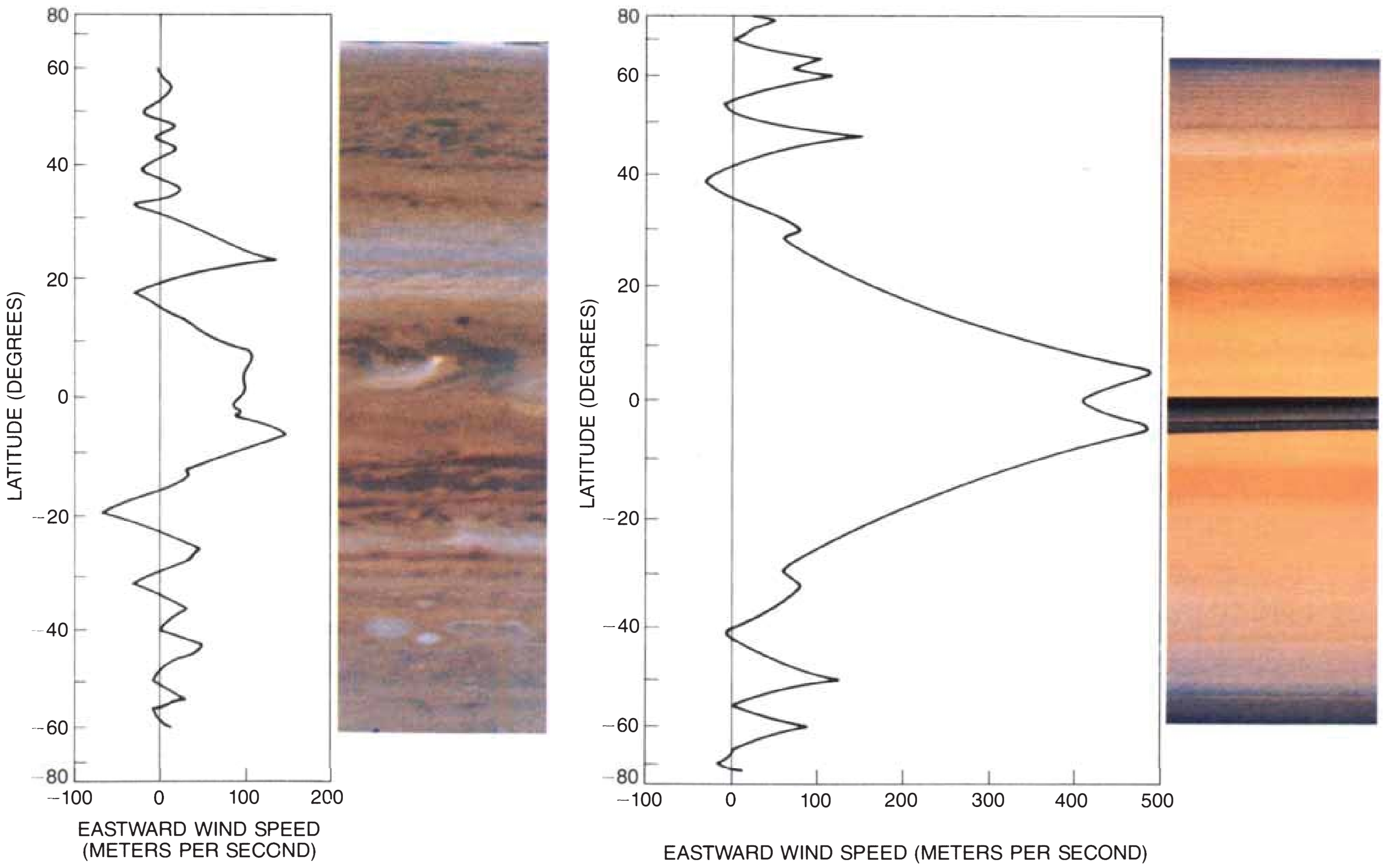
According to Salpeter and Stevenson, the process is much like ordinary rainfall. When a parcel of the earth's atmosphere is cooled below its saturation point, water condenses and raindrops fall. The condensation releases the heat that had been added to the water to make it a vapor, and the rate of atmospheric cooling slows. On Saturn the raindrops are helium, and energy is released as the raindrops rub against the hydrogen fluid through which they fall. The process began on Saturn some two billion years ago. Jupiter, being more massive, has not yet cooled to a point where the planet at any level is saturated with helium. Perhaps it is just now reaching that point.

Evidence in support of the hypothesis that helium rain releases energy on Saturn has come from measurements of the atmospheric helium abundance. It is not an easy measurement to make. Helium does not absorb radiation in the infrared, and so the spectrum of the radiation emitted by Jupiter and Saturn does not reveal helium directly. The presence of helium does, however, affect the absorption of infrared radiation by hydrogen. By this means a group led by Rudolph A. Hanel of the Goddard Space Flight Center of NASA and Daniel Gautier of the University of Paris has determined the relative numbers of helium atoms and hydrogen molecules from measurements made by the Voyager spacecraft.

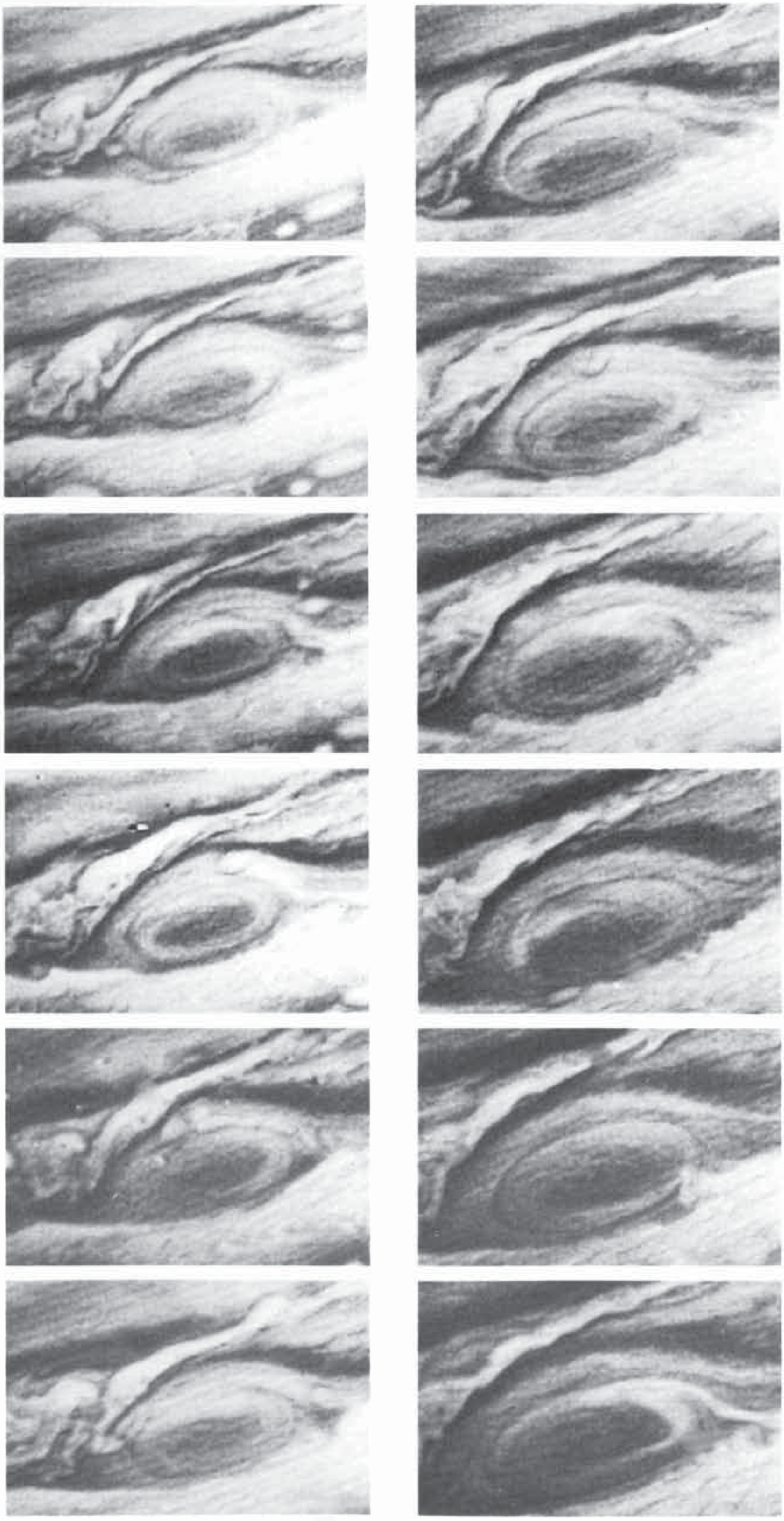
Above the zone of metallic hydrogen Jupiter turns out to be 10 percent helium, a value not significantly different from the 11 percent of helium in the sun. Saturn turns out to be less than 6 percent helium. If the missing helium has rained downward from the molecular zone to deep in the metallic zone, the heat that would have been released could indeed have maintained Saturn's internal heat source at its present value for the past two billion years. Thus the various inferences about the bulk composition, the internal structure and the history of the cooling of the giant planets all seem to hold together.

Atmospheric Chemistry

As early as the 1930's investigators were identifying lines in the spectrum of sunlight reflected from Jupiter due to the absorption of light by gaseous methane and ammonia. The hydrogen molecule has only weak absorption lines; hence its presence was confirmed only some 30 years later even though its abundance was then inferred to be 1,000 times greater than that of methane and ammonia. The calculated abundances of hydrogen, carbon and nitrogen in the atmosphere of Jupiter and Saturn support the hypothesis that the giant planets



MEAN WIND SPEEDS on Jupiter (*left*) and Saturn (*right*) are compared with images of each planet. Positive numbers are eastward velocities; negative numbers are westward ones. The numbers are wind speeds with respect to the speed of the planet's rotation; they were measured by tracking the motion of cloud features in successive images of each planet made by *Voyager 2*. It emerges from the measurements that each hemisphere of Jupiter has several alternations of eastward and westward currents. Saturn's pattern is simpler but the currents are stronger; in the atmosphere of Saturn 500 meters per second is two-thirds the speed of sound. Eighty years of observations from the earth and recent observations from spacecraft suggest that the cloud colorations at any latitude are changeable but that the winds are much more persistent. The dark band across the equator of Saturn is the ring system of the planet and its shadow on the surface.



GREAT RED SPOT of Jupiter is shown in a sequence of images made by *Voyager 1* every fourth rotation of the planet, or about once every 40 hours. The spot itself has been observed for three centuries from the earth. It rolls counterclockwise between a westward current to its north and an eastward current to its south. It is some 25,000 kilometers long. In the Voyager sequence structure on a scale of 1,000 kilometers is revealed. Small clouds approach the spot from the east. They circle the spot in six to 10 days. They are partially swallowed. Smaller spots return to the east. In addition to the Great Red Spot, Jupiter has several white ovals.

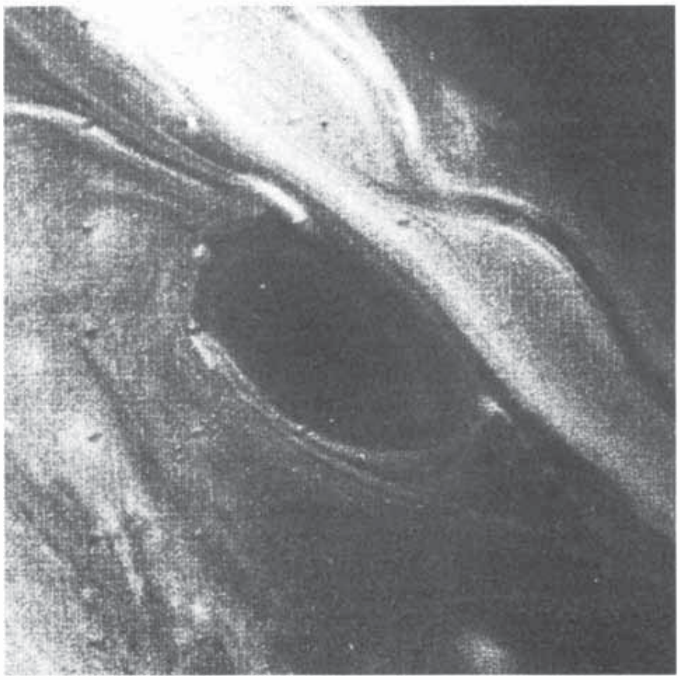
are composed of material much like that which condensed to form the sun.

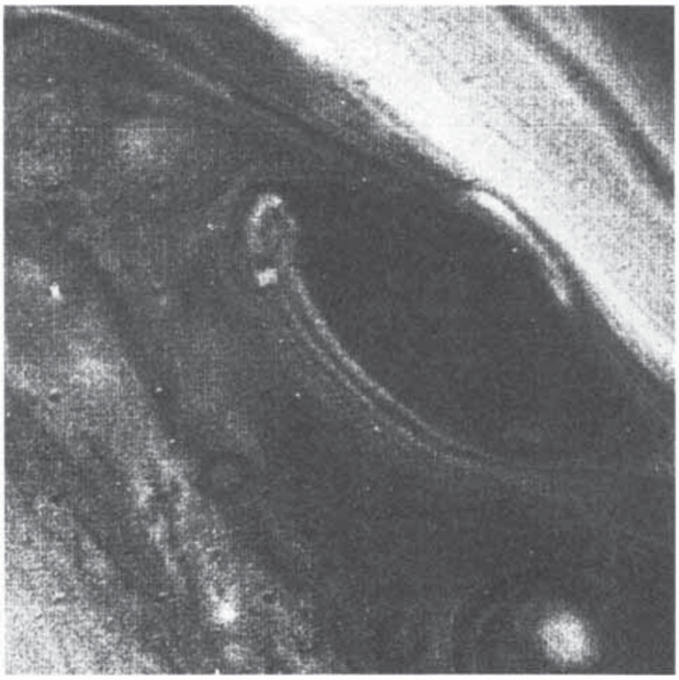
Other gases, however, should also be detected in a mixture of solar composition. Notable among them are water vapor and hydrogen sulfide (H_2S). In the 1970's spectral lines due to the absorption of infrared radiation by water vapor on Jupiter were detected by Harold P. Larson and Uwe Fink of the University of Arizona. Such lines have not been detected on Saturn. Moreover, hydrogen sulfide has escaped detection on both Jupiter and Saturn. Still, both water vapor and hydrogen sulfide gas must have a rather low concentration at the top of the clouds on Jupiter and Saturn, where the temperature is 150 degrees K. (−123 degrees Celsius) or less. Ultimately the vapors may turn out to be present in solar abundances at levels below the clouds.

The infrared spectra of Jupiter's hot spots (holes in the clouds) reveal a rich chemical mixture. In addition to water vapor, phosphine (PH_3), germane (GeH_4), hydrogen cyanide (HCN) and carbon monoxide (CO) have all been detected, and so has heavy methane, that is, methane molecules incorporating the heavy isotope of either hydrogen (hydrogen 2, called deuterium) or carbon (carbon 13). Moreover, ethane (C_2H_6) and acetylene (C_2H_2) have been detected all over the disk of Jupiter and on Saturn as well. Most of these compounds would not be present in an atmosphere rich in hydrogen if the atmosphere were in chemical equilibrium. For example, the various carbon compounds would revert to methane, and the nitrogen would form ammonia.

The obvious source of the chemical disequilibrium is the sun. Specifically, the sun's ultraviolet radiation can break down the dominant chemical species such as methane and liberate free radicals such as CH_2 and CH_3. Lightning in the clouds of Jupiter and Saturn and the impact of electrically charged particles can have the same effect. (The charged particles rain down into the atmosphere from the magnetosphere, the zone above the planet where they are confined by the planet's magnetic field.) The radicals can react with methane molecules to form ethane and acetylene and liberate hydrogen. The composition of the atmosphere of Jupiter therefore reflects a balance between the production and the breakdown of these higher hydrocarbons.

The presence of carbon monoxide in Jupiter's hot spots is more problematic, since water, the potential source of oxygen, is scarce above the clouds, where ultraviolet photons (quanta of ultraviolet radiation) are plentiful. On the other hand, water may be abundant below the clouds, and there it may combine with methane to form carbon monoxide. The conditions of temperature and pressure well below the clouds favor such a reac-





LONG-LIVED SPOT ON SATURN is a brown oval in the northern hemisphere that was photographed on August 23 (*left*) and one rotation of the planet (10 hours) later (*right*) by *Voyager 2*. It is a fourth the size of the Great Red Spot. Its rotation is clockwise.

tion. Another possibility is that the oxygen above the cloud tops comes not from Jupiter but from sulfur dioxide ejected from the volcanoes of Jupiter's satellite Io, whose activity was revealed in images made by *Voyager 1*.

The solid and liquid particles that constitute the clouds of Jupiter and Saturn give further evidence of chemical disequilibrium. The most abundant condensable vapors in a mixture of solar composition are water, ammonia and hydrogen sulfide. At chemical equilibrium they form crystals of water ice, of ammonia and of ammonium hydrosulfide (NH_4HS). Liquid drops of water and of ammonia-water solutions are also conceivable, as John S. Lewis and his colleagues at the Massachusetts Institute of Technology have noted. The problem is that all these condensates are white, whereas the clouds of Jupiter and Saturn are colored.

Ronald G. Prinn of M.I.T. has suggested some possible coloring agents. For one thing, molecular sulfur (S_n, where n can take several values greater than 1) forms brown and yellow particles. It therefore becomes all the more vexing that hydrogen sulfide, the parent molecule of the elemental sulfur, has not yet been detected. The challenge for theorists championing sulfur as a coloring agent is to hide the hydrogen sulfide in the clouds from spectroscopic view but still expose enough of it to solar photons so that S_n can form. Prinn notes that elemental phosphorus has a red color resembling that of the Great Red Spot, and it could be formed when ultraviolet photons strike molecules of phosphine gas. Given the affinity of carbon atoms for one another, complex organic compounds are also a possible source of color. Unfortunately the spectroscopic identification of compounds in the solid state is difficult because the pattern of vibrations (and the associated absorption of certain wavelengths of light) by the molecules in a solid is blurred by the collisions between neighboring molecules. Hence the sources of color on Jupiter and Saturn remain uncertain.

It can be said, however, that clouds of differing color on Jupiter and Saturn are associated with different levels in the atmosphere. A comparison of images made in visible light and in infrared radiation reveals this correlation. The visible images show the colors; the infrared images distinguish cool (and therefore high) clouds from warm (and therefore low) ones. On Jupiter the highest cloud tops are red; the next-highest are white, the ones lower than that are brown and the lowest ones (or perhaps the atmosphere below the clouds) are blue. Presumably the various compounds responsible for these colors form at different levels in response to different temperatures and amounts of sunlight. The white particles that form the major constituents of the clouds should also be layered. Ammonia should be uppermost, then ammonium hydrosulfide and finally water.

Atmospheric Circulation

In the atmosphere of the earth horizontal gradients of temperature are the reservoir from which the winds get their energy. The gradients arise because the sun heats the Tropics more than the poles; then the warm tropical air slides over the colder polar air. This converts gravitational potential energy into kinetic energy and also transports heat upward and poleward.

On Jupiter and Saturn horizontal temperature gradients may be less important than they are on the earth. First of all, the gradient of temperature from the equator to the pole is small on Jupiter and Saturn, at least at the cloud-top levels where the Pioneer and Voyager spacecraft could measure it. On Jupiter, for example, the difference in temperature between the equator and the pole is less than three degrees C. On the earth the difference is 10 times greater, and it is compressed into a distance from the Equator to the pole that is 10 times smaller.

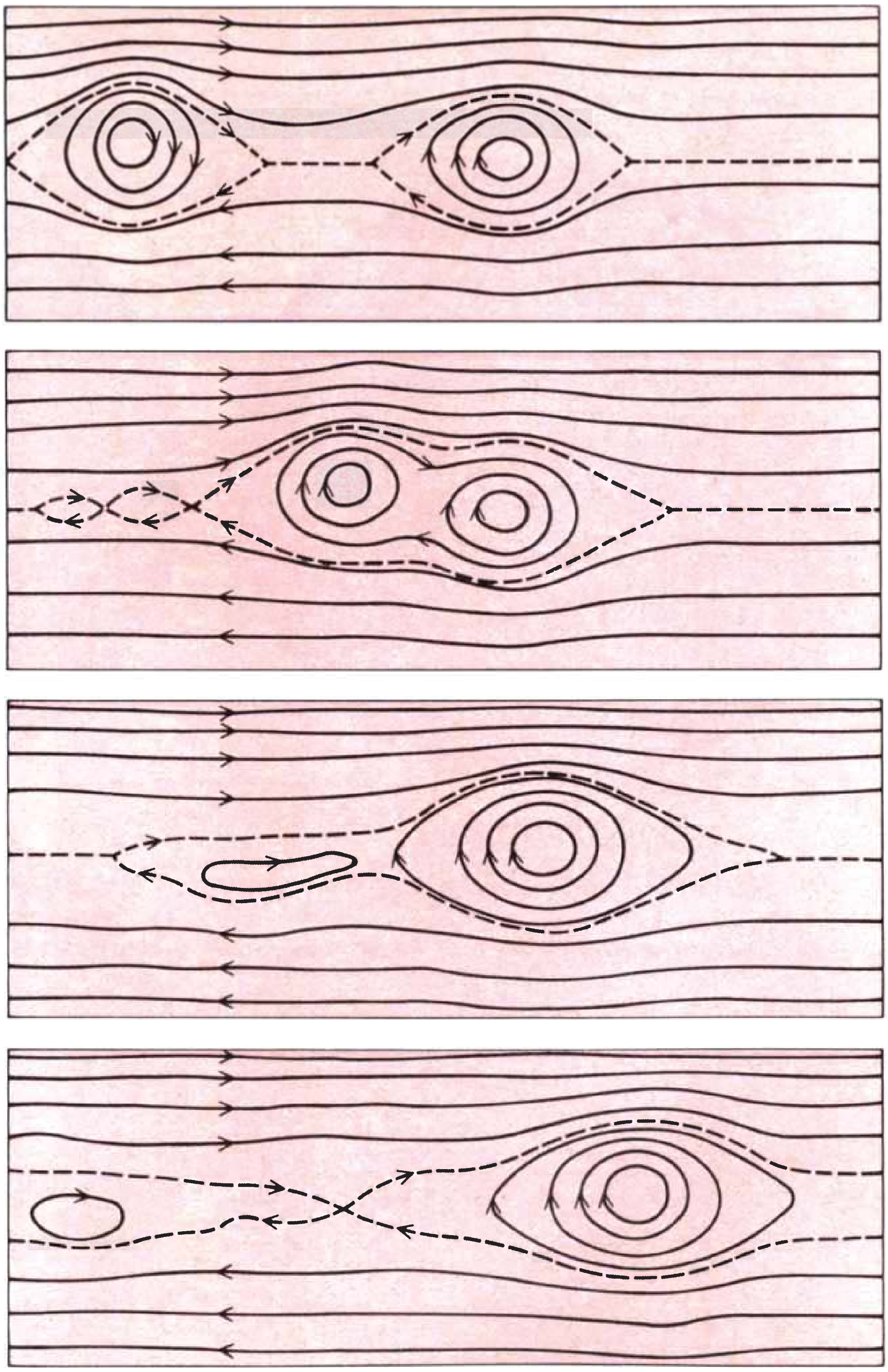
In the second place the atmosphere of Jupiter and Saturn gets half or more of its heat from the interior of the planet. In that regard Jupiter and Saturn resemble stars more than they resemble the earth. According to theories of convection employed in stellar models, an internal heat source should produce an adiabatic temperature gradient that is the same along any radius from the center of the planet to a point on its surface. Moreover, since the part of the atmosphere of Jupiter or Saturn receiving sunlight has only a millionth the mass (and therefore a millionth the heat-carrying capacity) of the planet's interior, one can expect the atmosphere to be in essence short-circuited by the interior. It is as if all points on the surface of the planet were wired to the center by strong conductors, and weak conductors connected points on the surface to each other. On this reasoning horizontal temperature gradients should be small.

Still, more sunlight is deposited at the surface of Jupiter and Saturn than at the poles, and measurements made by the Pioneer and Voyager spacecraft show that the rate of infrared emission is roughly independent of latitude and is greater than the rate of absorption of sunlight at all latitudes. Heat is therefore transported poleward. The argument that the interior of each planet is in effect a strong conductor implies that the entire fluid interior of each planet is involved in the poleward transport. A computer model that I and Carolyn Porco have devised at Cal Tech suggests how the transport is maintained. In response to the uneven distribution of sunlight at the surface of the planet small differences in temperature develop in the interior. The differences modulate the rate at which internal heat arrives from below. According to the model, the poleward decrease in the solar heating of the thin sunlit layer is offset by a poleward increase in the upwelling of internal heat. Poleward heat transport in the thin sunlit layer is negligible.

A model based on entirely different assumptions has been published by Gareth P. Williams of the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration at Princeton University. Williams began with a mathematical formalism employed in predicting the weather on the earth. The mathematics describes the motions that arise in a fluid atmosphere much thinner than the planet's radius in accord with physical laws such as the conservation of momentum and energy. Williams scaled the radius and the rotation rate of the model planet so that they would characterize Jupiter or Saturn, and he reduced what are called the dissipation parameters, which represent the rate at which an atmosphere loses heat and momentum because of forces such as friction. The reduction of the parameters can be justified on the ground that Jupiter and Saturn have no solid surfaces that winds can rub against. Moreover, a deep, cold atmosphere loses heat extremely slowly, as Peter J. Gierasch, now at Cornell, and Richard Goody of Harvard University pointed out 15 years ago.

Williams also assumed that the atmosphere below the level to which sunlight penetrates on Jupiter or Saturn has negligible effects on the circulation above. In other words, the upwelling of heat from the interior was neglected or assumed to be independent of latitude. In addition the lower boundary of the sunlit layer was assumed to act like a solid surface in that it is undeformable and impermeable. This assumption would be justified if the density of the sunlit layer were substantially less than that of the layer below it. Such a decrease is found between the warm water at the surface of the earth's oceans and the cooler water below it. The decrease is less likely to be found, however, in a fluid that is convecting heat upward from below.

In short, Williams' model of the atmosphere of Jupiter or Saturn resembles in many ways a model of the atmosphere of the earth. Yet his model proves able to generate the most notable feature of the meteorology of Jupiter or Saturn: an alternating pattern of east and west winds. Indeed, the model entails a prediction of how the winds are maintained. In the atmosphere of the earth the sustained low-latitude winds blow to the west and the sustained middle-latitude winds blow to the east. Both are maintained by large-scale eddies that transport eastward momentum away from the equatorial latitudes. The eddies include the cyclones and anticyclones that give rise to much of the



MERGING OF SPOTS on Jupiter and Saturn was simulated with a computer by the author and Pham Giem Cuong at the California Institute of Technology. They propose that each spot is a more or less permanent vortex above an underlying pattern of east-west flow. On their hypothesis the small transient spots on Jupiter and Saturn are buoyant; thus the small spots store gravitational potential energy. The large spots are maintained by swallowing the small ones. The broken lines mark boundaries between each vortex and the atmosphere's laminar flow.

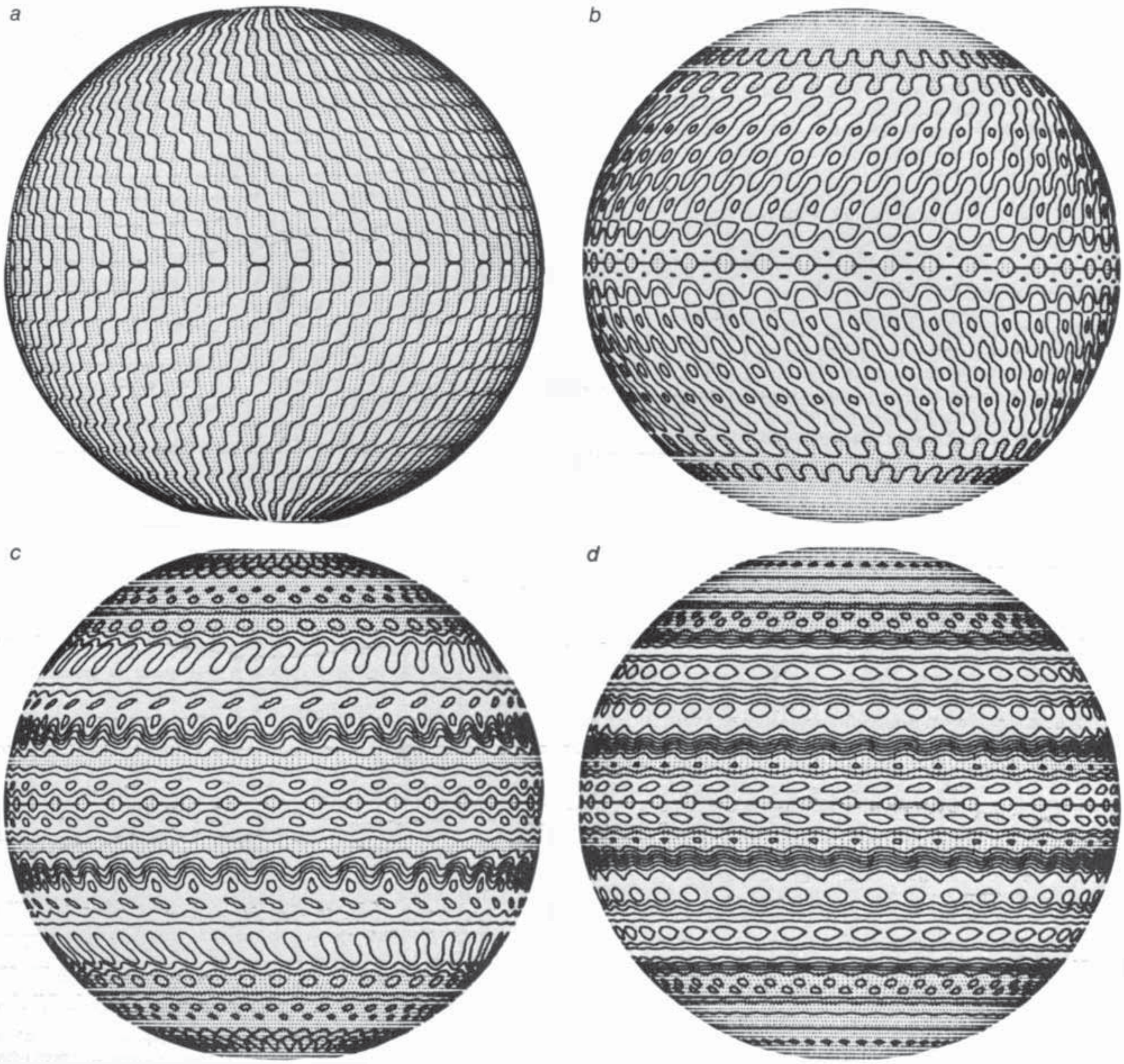
earth's weather. On Jupiter and Saturn the bands of alternating winds are more numerous. Nevertheless, in Williams' model it is eddies that put energy into the east-west winds. Furthermore, the energy driving the eddies on Jupiter, Saturn and the earth comes ultimately (Williams proposes) from the same source: the temperature gradient from the equator to the poles that is maintained by solar heating.

Voyager Measurements

The best measurements of the winds on Jupiter and Saturn come from tracking the position of cloud features in successive images made by the Voyager spacecraft. The investigators responsible for making these measurements included Reta Beebe, Garry E. Hunt, Jim L. Mitchell and me. For Jupiter our first goal was to define the mean wind velocity at each degree of latitude by averaging the velocities of all the features we could identify at that latitude. At most latitudes 50 to 100 high-contrast features could be tracked. Saturn has fewer such features and so fewer measurements could be made.

One remarkable result was the agreement between the measurements based on the Voyager images of Jupiter and the measurements based on some 80 years of observations from the earth. The changes over the 80 years seem to have been mostly in the coloration of the clouds at given latitudes. At times the east-west winds were unobservable from the earth, but apparently they did not change.

A second result has to do with how the winds deviate from their mean velocity at a given latitude. On Jupiter the mean eastward velocities are no greater than 130 meters per second. The deviations from this mean, which correspond to eddies, are typically 20 meters per second. The deviations have a systematic tilt. For example, at places where the mean eastward velocity increases with lati-



PLANETARY MODEL proposed by Gareth P. Williams of the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration assumes that the processes shaping the weather on the earth also shape the weather on Jupiter and Saturn. Specifically the uneven distribution of solar radiation across the disk of the planet entails eddy currents in a thin sunlit layer of the atmosphere. The momentum of the eddies then fuels eastward and westward currents. Trains of spots arise in the model but isolated ovals do not. The illustration shows the state of Williams' computer simulation after 4.6 days (*a*), 23 days (*b*), 46 days (*c*) and 73.3 days (*d*).

tude, the vectors that represent the velocity (and therefore the momentum) of the deviations tend to be tilted toward the northeast. Hence they feed velocity and momentum northward into latitudes where the mean velocity and momentum are already greater. This is precisely the mechanism by which eddies sustain the mean winds on the earth, and it is also the mechanism that underlies Williams' model. Jupiter's seemingly chaotic eddies have more order than one might suspect.

There are nonetheless some important quantitative differences between Jupiter and the earth. On the one hand, the mean velocities of the winds and the velocities of the eddies are greater on Jupiter. Indeed, the rate at which kinetic energy is transferred from eddies to sustained east-west winds is 10 times greater on Jupiter than it is on the earth per unit area on the surface of the planet. On the other hand, the rate at which thermal energy is made available to the atmosphere of Jupiter for possible conversion into kinetic energy of winds is 20 times less than it is on the earth, again per unit area, because Jupiter is cooler. Thus the efficiency with which the atmosphere converts thermal energy into kinetic energy seems to be much greater on Jupiter than on the earth.

And yet one must be careful in making any general conclusion about the efficiency of Jupiter or Saturn's energy cycle because these cycles involve transformations of energy that have not yet been measured. For example, a mass of cold air above a mass of warm air represents a certain amount of gravitational potential energy, which is released when the cold air sinks. Such releases occur inside the clouds of Jupiter and Saturn, and thus they are hidden from view. On the earth the net efficiency of the atmosphere's energy cycle is about 1 percent. That is, about 1 percent of the solar power absorbed by the earth fuels the large-scale motions of the atmosphere before friction in the atmosphere converts it back into heat that the earth radiates into space. The rest is radiated into space without ever being converted into kinetic energy. The net efficiency of Jupiter and Saturn is unknown.

Coaxial Cylinders

I myself suspect that the great depth of the fluid interior cannot be neglected in modeling the atmospheric dynamics of Jupiter or Saturn. Laboratory experiments, including those done by Geoffrey I. Taylor at the University of Cambridge in the 1920's and those being done by F. H. Busse at the University of California at Los Angeles today, show that small-scale turbulent motions (that is, eddies) in a rapidly rotating fluid align themselves in columns parallel to the axis of rotation. At any level in each column the motion in a plane perpendicular to the axis is the same. The columns span their container and resist stretching or compression along the axis. Therefore if the container is spherical, each column remains at a fixed distance from the axis of rotation. Busse's experiments and calculations suggest that a sustained pattern of flow develops in the fluid as a result of the columns. In a liquid of constant density and low viscosity the pattern turns out to be one in which coaxial cylinders of fluid rotate at different velocities about their common axis, which is the axis of the fluid's mean rotation. In a liquid of greater viscosity or stratification into layers of varying density other patterns are possible.

The relevance of these laboratory experiments to Jupiter and Saturn depends, then, on the distribution of density in each of the planets. A marked increase in density below the sunlit layer of the atmosphere, as postulated by Williams, implies that each planet is the large-scale analogue of a stratified laboratory fluid. Columns of the type found by Taylor and Busse do not cross the interface between two layers of differing density, and so the sunlit layer can be decoupled from the interior. On the other hand, the convection of heat in the interior of Jupiter and Saturn should lead to an adiabatic gradient of temperature and a well-mixed interior. This implies that each planet is the analogue of a laboratory fluid of constant density.

According to most models of Jupiter and Saturn's interior, the adiabatic zone ends in the clouds. Hence the steady eastward and westward winds we have measured in the clouds of Jupiter and Saturn may turn out to be the visible sign of the motion of coaxial cylinders that extend all the way through each planet's fluid interior. To be sure, the winds might get their energy from eddies, as is suggested by Williams' model and supported by data from the Voyager spacecraft. If the winds do represent the motion of cylinders, however, the inertia that supports the winds would be immense. Once the coaxial cylinders are set in motion they might well remain in undisturbed rotation throughout the 80 years of observations made first by earth-based astronomers and then by the Voyager instruments.

The coaxial cylinders do imply that the profiles of wind velocity v. latitude in the northern and southern hemispheres of Jupiter and Saturn should be symmetrical about the equator. The symmetries need not, however, extend to high latitudes, because the jump in density at the interface between molecular and metallic hydrogen inside each planet decouples the inner coaxial cylinders. For Jupiter the decoupling should affect latitudes greater than 40 to 45 degrees North and South. For Saturn it should affect latitudes greater than about 65 degrees. In profiles produced from Voyager data the requisite symmetries are present: the northern and southern hemispheres of Jupiter and Saturn each show about three complete cycles of alternating eastward and westward winds between the equator and the latitudes affected by decoupled cylinders. Small departures from symmetry, such as the ones at 25 degrees north and south on Jupiter, where eastward jets are found, may be due to a nonadiabatic temperature gradient in the cloud layers. Larger departures would imply a nonadiabatic interior and would constitute a disproof of the hypothesis.

It is difficult at present to choose between a model of Jupiter and Saturn in which the great depth of the fluid interior is immaterial and one in which the depths are crucial. After all, even the data recorded by the Voyager spacecraft pertain only to the cloud tops. The spacecraft *Galileo,* which is scheduled for launching in the late 1980's, will probe the atmosphere of Jupiter more deeply. It is hoped the probe will measure winds at the level of the cloud bases and will determine if the adiabatic zone extends that high. Meanwhile some indirect strategies may prove useful.

One such strategy exploits the differences between Jupiter and Saturn. In particular, the winds at the cloud tops on Saturn are three to four times stronger than the winds on Jupiter. (The eastward wind speeds at the equator of Saturn are almost 500 meters per second, or more than 1,000 miles per hour.) The eastward and westward currents are broader than on Jupiter, and fewer large oval structures are found. The possible causes of these differences cannot be many. Perhaps, for example, it is significant that the zone of metallic hydrogen lies much deeper in Saturn than in Jupiter. The corresponding increase in the depth of the molecular hydrogen zone might give coaxial cylinders that rotate in opposite directions a greater spacing and greater relative velocities. On the surface of Saturn (as compared with the surface of Jupiter) gravity is weaker, the flux of heat is lower and seasonal changes are greater. (The last follows because Saturn's axis of rotation is more inclined than Jupiter's with respect to the plane of its orbit around the sun and because the rings of Saturn cast a shadow on the surface that changes its position seasonally.) As a result of the weaker gravity Saturn's clouds are thicker and as a result of the lower flux of heat the small-scale convective motions of the atmosphere might be weaker. The implications of the differences at the surface of each planet for large-scale motions in the atmosphere are, however, unclear.

Long-lived Ovals

Another strategy is to examine Jupiter and Saturn's atmospheric flow patterns other than the eastward and westward winds and see what assumptions about the deep interior are compatible with the observations. In particular, the Great Red Spot of Jupiter and other long-lasting ovals on Jupiter and Saturn are a unique and possibly diagnostic feature of the giant planets. The ovals themselves are relatively slow-moving. For example, the Great Red Spot moves westward only a few meters per second, although the winds around it reach speeds of 100 meters per second. In fact, all the ovals on Jupiter and Saturn seem to rotate like ball bearings between adjacent eastward and westward currents. Each rotation takes only a few days.

The ovals are also enduring: they can last for decades and even centuries. The eddies in the oceans and the atmosphere of the earth are less enduring by orders of magnitude. For example, the eddies in the Atlantic tend to drift westward until they merge with the Gulf Stream off the east coast of North America. Their lifetimes are measured in months and sometimes years. The eddies in the atmosphere of the earth are of several types. The most enduring ones seem to be trapped in place near features of the surface such as mountain chains or boundaries between a continent and an ocean. On Jupiter and Saturn there is no such topography.

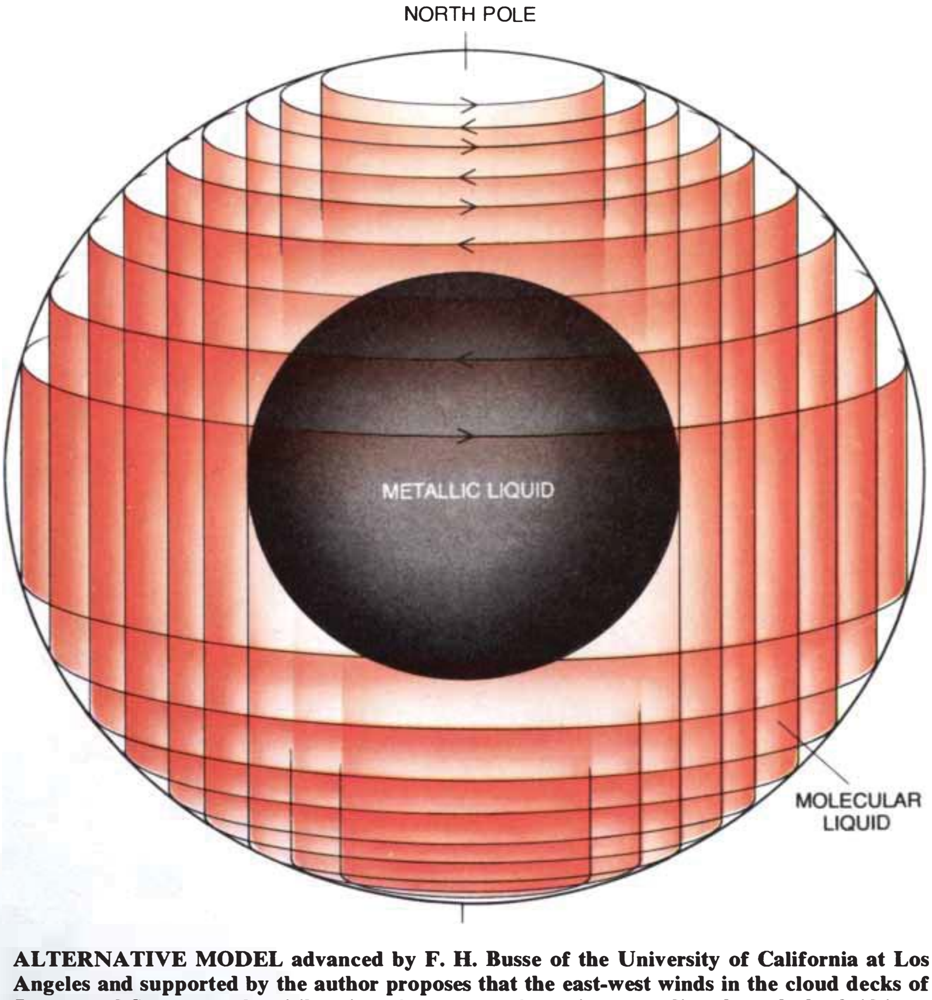
At least two proposals have been put forward that account for many of the properties of the ovals. Each proposal seeks only to show how an isolated vortex can endure in the midst of a pattern of alternating eastward and westward currents. It seeks, in other words, to show that the configuration is stable even if small perturbations of the configuration occur. The proposals do not account for how the vortexes arise.

Tony Maxworthy and Larry G. Redekopp of the University of Southern California have proposed that a long-lived oval represents a "solitary wave," that is, a self-sustaining wave with a single crest instead of a train of crests and troughs. Such a wave is a fluid-dynamical curiosity dating back to the 19th century; in Maxworthy and Redekopp's hypothesis it is a single north-south displacement of flow lines that otherwise lie east-west. The models Maxworthy and Redekopp have published often bear a striking resemblance to the Great Red Spot. Moreover, those models imply that a planetary solitary wave can exist only in a pattern of east-west flow that is unstable to certain perturbations. This may explain why isolated ovals do not spontaneously appear in Williams' models, in which the east-west flows are not unstable. In Williams' models the closest analogues to isolated ovals are trains of spots strung out at constant latitude. Such patterns do appear on Jupiter, but they are distinct from the large, isolated ovals. When two solitary waves meet, however, they simply pass through each other. When two ovals meet on Jupiter or Saturn, they sometimes merge.

The second proposal, made by me and Pham Giem Cuong of Cal Tech, depends on assuming that the east-west pattern of flow in the clouds is part of a much deeper pattern, perhaps one of rotating coaxial cylinders. On that hypothesis it can be shown that stable vortexes can exist in an east-west flow that is also stable. According to this proposal, such a vortex extends downward only to the top of the adiabatic zone, wherever that may lie. We tested the stability of the ovals in our computer model by introducing large and small perturbations, by forcing two ovals to collide and by feeding small ovals to the larger ones. Given the right east-west flow under them, the ovals are quite robust: they survive rather large perturbations. Moreover, the large spots can grow by consuming the smaller spots. It is likely that on Jupiter and Saturn the smaller, transient spots derive energy from their buoyancy.

So far Williams' model of Jupiter and Saturn, which derives from models of the earth, is the only proposal that is complete, in the sense that it has sources and sinks of energy and the eastward and westward currents arise spontaneously. To varying degrees the other models take much of the pattern as presupposed. For example, the models of the long-lived ovals presuppose the basic east-west flows.

The fundamental issues remain unresolved. How deep do the visible patterns of flow on Jupiter and Saturn extend? How important is solar heating of the atmosphere, as opposed to internal heating? How is the density of the atmosphere stratified below the cloud tops? The issues are particularly challenging because an all-encompassing computer model of Jupiter or Saturn is impractical. One simply cannot incorporate into the same mathematical description of a planet the small, transient atmospheric eddies that are crucial in Williams' hypothesis and the slow, large-scale internal responses to uneven solar heating that occur in the hypothesis advanced by Porco and me. The scales of size and time for the two phenomena are just too different. Computer models will be important, but as we come to understand the giant planets clever thinking and insight will be needed even more.



ALTERNATIVE MODEL advanced by F. H. Busse of the University of California at Los Angeles and supported by the author proposes that the east-west winds in the cloud decks of Jupiter and Saturn are the visible sign of a pattern of rotation extending through the fluid interior of each planet. The model is based on the experiments of Geoffrey I. Taylor at the University of Cambridge and those of Busse, which suggest that in a rotating fluid planet that has been well mixed by convection the sustained motions are those of nested fluid cylinders. A discontinuity in the density of the planet's interior at the top of the zone of metallic hydrogen interrupts the innermost cylinders. The small asymmetries between the northern and southern hemispheres in the wind profiles shown on page 96 are not inconsistent with the model.