The Meteorology of Jupiter

The visible features of the giant planet reflect the circulation of its atmosphere. A model reproducing those features should apply to other planetary atmospheres, including the earth's

by Andrew P. Ingersoll

Every feature that is visible in a picture of the planet Jupiter is a cloud: the dark belts, the light-colored zones and the Great Red Spot. The solid surface, if indeed there is one, lies many thousands of kilometers below the visible surface. Yet most of the atmospheric features of Jupiter have an extremely long lifetime and an organized structure that is unknown in atmospheric features of the earth. Those differences, and the fact that atmospheric features are easy to observe on Jupiter, make the giant planet a laboratory where terrestrial meteorologists can test theories about atmospheric dynamics in ways not possible on the earth.

Jupiter's diameter is 11 times larger than the earth's; its surface gravity is 2.4 times stronger; it rotates on its axis 2.4 times faster (once every 10 hours). There is little or no change of season on Jupiter because the axis of the planet's rotation is nearly parallel to the axis of its orbit around the sun.

Jupiter's atmosphere and interior are mostly hydrogen, with other elements such as helium, carbon, oxygen and nitrogen mixed with the hydrogen in the same proportions as they are in the sun. Because that mixture does not solidify at the temperatures and pressures that have been calculated to exist on Jupiter, the planet is probably gaseous or liquid throughout its interior. The mixture is gently stirred at all depths by convection currents that carry heat from the interior to the surface. Theoretical calculations indicate that the internal heat is most likely left over from Jupiter's initial gravitational contraction, when it condensed out of the nebula that also gave rise to the sun and the other planets. The amount of internal energy Jupiter releases at present is approximately equal to the amount of energy it absorbs from the sun.

From the point of view of meteorology the most important differences between Jupiter and the earth lie in the fact that Jupiter has an appreciable internal energy source and probably lacks a solid surface. The other differences—in radius, gravity, rate of rotation and so on—are mainly differences of degree. Even the chemical composition of Jupiter's atmosphere is similar to the chemical composition of the earth's as far as its effect on meteorology is concerned. The atmospheres of the two planets consist chiefly of noncondensable gases: hydrogen and helium on Jupiter, nitrogen and oxygen on the earth; mixed in are small amounts of water vapor and other gases that do condense, forming clouds. In terms of the temperature changes that would occur on the two planets if the condensable vapors were entirely converted into liquid or solid form, thus releasing all their latent heat, Jupiter's atmosphere would be somewhat less affected by condensation than the earth's. Clouds, condensation and precipitation are nonetheless important in the dynamics of both atmospheres.

Our picture of the average composition and vertical structure of the Jovian atmosphere is based partly on observation and partly on theory. Spectroscopic studies from the earth have established that the atmosphere is mostly molecular hydrogen (H_2), with smaller amounts of methane (CH_4), ammonia (NH_3) and a growing list of other gases. In those studies absorption features in the infrared spectrum of Jupiter are compared with absorption features in the spectrum of gases in the laboratory. Since each gas has characteristic wavelengths at which it absorbs radiation, absorption spectra of the Jovian atmosphere make it possible to positively identify most of the gases in it even in very small concentrations. The exception is helium, which absorbs radiation only in the ultraviolet region of the spectrum at wavelengths that cannot be observed through the earth's atmosphere. Helium was recently detected, however, by an ultraviolet spectrometer on the spacecraft *Pioneer 10,* and the effect of the helium on the infrared spectra of other gases in the Jovian atmosphere has also been observed.

From the relative strengths of the absorption spectra of hydrogen, methane and ammonia the relative abundances of those gases can be determined. On Jupiter the ratio of the number of carbon atoms to hydrogen atoms is about 1 : 3,000 and the ratio of nitrogen atoms to hydrogen atoms is 1 : 10,000. Those abundances are close to the abundances of the same elements in the sun. Within wide limits the ratio of helium to hydrogen in Jupiter is consistent with the inferred ratio of helium to hydrogen in the sun (1 : 15). It is the abundance ratios, together with the low density of Jupiter as a whole, that suggest that the planet is very much like the sun in its composition.

The amount of heat Jupiter radiates implies that the interior of the planet is hot. If it were cold, there would not be enough heat in the interior to have lasted until the present time. A consequence of the hot-interior model of Jupiter is that solids cannot form in it. According to current thinking, the planet is mostly liquid, with a gradual transition to a gaseous atmosphere in the outermost few thousand kilometers.

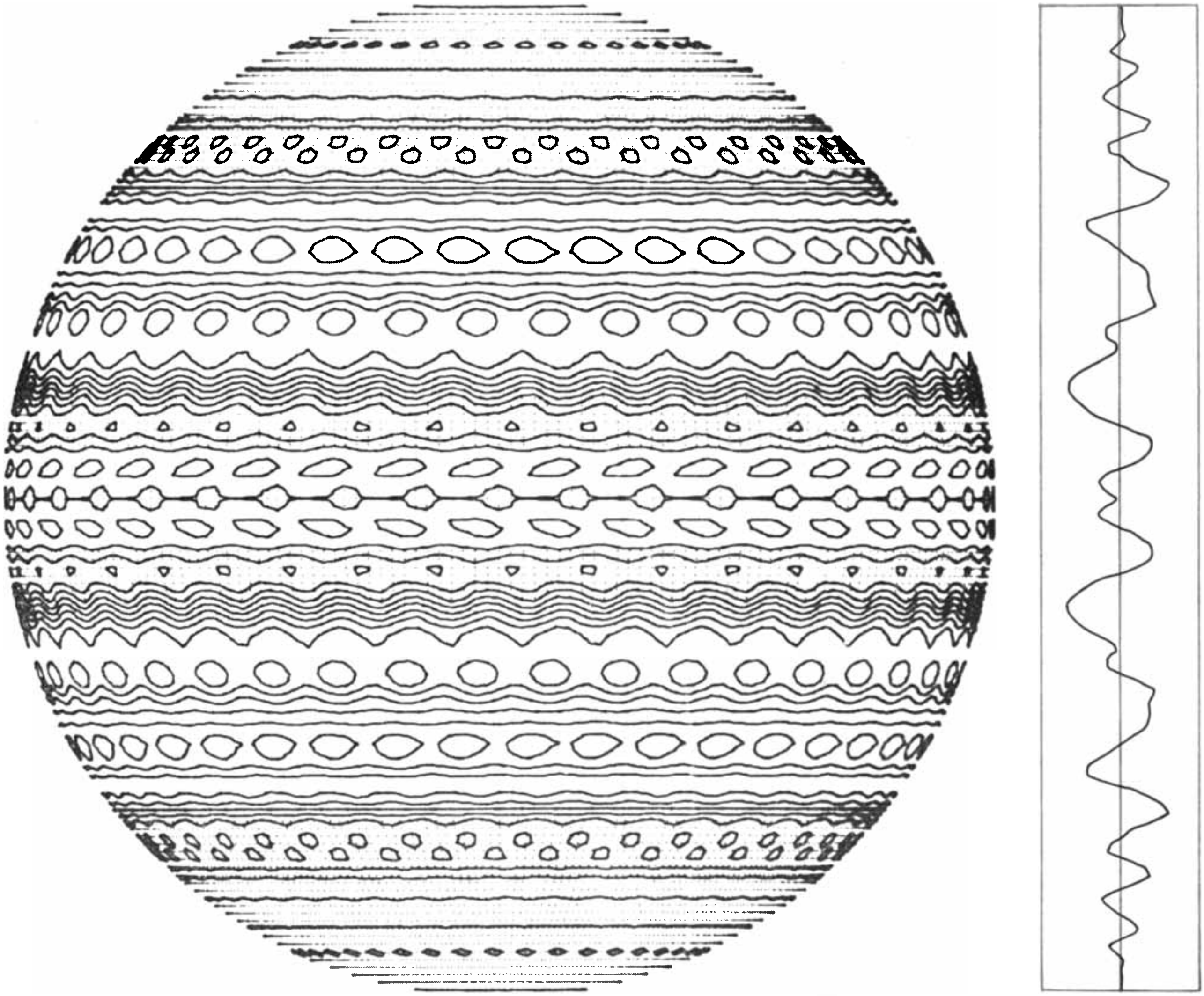
Spectroscopic data at infrared and radio wavelengths also yield information about the temperature and pressure in the Jovian atmosphere. At the deepest levels the temperature decreases with altitude at the rate of some two degrees Celsius per kilometer. That rate is close to the adiabatic lapse rate, which is the value of the temperature gradient in a well-mixed atmosphere. In such an adiabatic atmosphere parcels of gas move vertically without exchanging heat with neighboring parcels. They get cooler or warmer, but they do so only because their pressure changes as they ascend or descend. Neighboring parcels at the same level in the atmosphere are indistinguishable from one another. An adiabatic temperature gradient also usually implies that the atmosphere is stirred by convection.

The temperature in Jupiter's atmosphere is 165 degrees Kelvin (degrees C. above absolute zero) at the level where the pressure is one atmosphere (the pressure of the earth's atmosphere at sea level). The temperature continues to decrease with height until it reaches a minimum value of 105 degrees K. at the level where the pressure is .1 atmosphere. At that point it begins to rise slightly once again. By analogy with the earth's atmosphere this minimum marks the beginning of the Jovian stratosphere. In that layer of the Jovian atmosphere the temperature is controlled largely by radiation rather than by convection.

There are thin clouds on Jupiter as high as the base of the stratosphere. Broken thick clouds, with holes opening into deeper levels, begin to be present where the pressure is between .6 and one atmosphere. The pressure at the cloud tops on Jupiter is thus similar to the pressure at the cloud tops on the earth. The temperatures at those levels on Jupiter are much lower, however, since Jupiter is five times farther from the sun than the earth is.

The composition of the Jovian cloud particles and the nature of the material that endows them with their remarkable colors cannot be determined from spectroscopy alone. Here theoretical calculations by John S. Lewis of the Massachusetts Institute of Technology have been useful. Lewis began by assuming that Jupiter's atmosphere has the same composition as the sun's at the ranges of temperature and pressure observed on the planet, and that all its constituents are at chemical equilibrium. He then calculated the amount of solid and liquid matter in the atmosphere as a function of height above an arbitrary base level. His calculations show that the deepest and thickest clouds are condensed water, since both oxygen and hydrogen are abundant in the atmosphere. Above those clouds are clouds of ammonium hydrosulfide (NH_4SH) and above those in turn are clouds of pure ammonia (NH_3). The level of each cloud depends on the vapor pressure of the particular condensate, which is a strong function of temperature. The less volatile substances such as water condense at higher temperatures (deeper in the atmosphere) than the more volatile substances such as ammonia. The relatively low vapor pressure of water at the temperatures characteristic of the Jovian cloud tops also explains why water vapor was found there only recently: water cannot be detected spectroscopically unless it is in the form of a vapor. In 1974 Harold P. Larson and his co-workers at the University of Arizona detected water on Jupiter for the first time by observing radiation that emerged through holes in the upper cloud layers from water molecules at deeper levels.

Lewis' model, which assumes that all the substances are at chemical equilibrium at each level, cannot account for the colors of the clouds. The cloud particles in that model are white, whereas the Jovian clouds are subtle shades of red, brown, white and blue. With convection bringing up exotic material from deeper levels, however, and with ultraviolet radiation from the sun energizing chemical reactions at the top of the atmosphere, it is not surprising that portions of Jupiter's atmosphere do depart from local chemical equilibrium. Only small amounts of coloring material are needed to explain the observations, and an atmosphere with the same composition as the

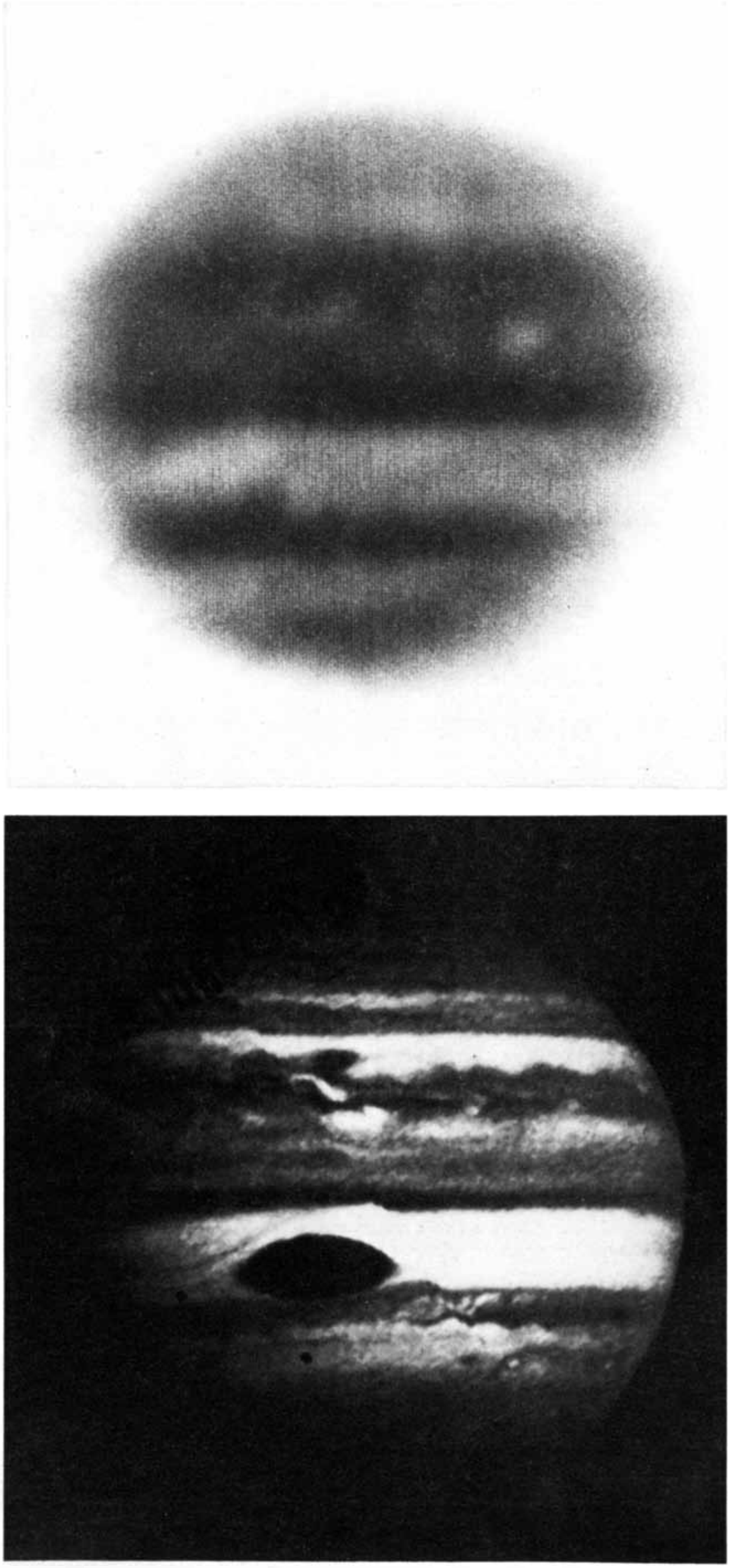


TURBULENCE OF JOVIAN ATMOSPHERE is depicted in a computer simulation devised by Gareth P. Williams of Princeton University, who used one model that attempts to account for Jupiter's east-west bands. The lines plotted are streamlines along which the atmosphere flows. Flow is fastest where the lines are closest together. The relative direction of the flow is indicated by the graph at the far right. Where the curve travels to the right of the vertical line the net flow is eastward, or faster than the planet's mean rotational velocity. Where the curve travels to the left of the vertical line the net flow is westward, or slower than the mean rotational velocity. The relative velocity of the flow, which is up to 50 meters per second, is indicated by the magnitude of the deviation of curve from vertical line.

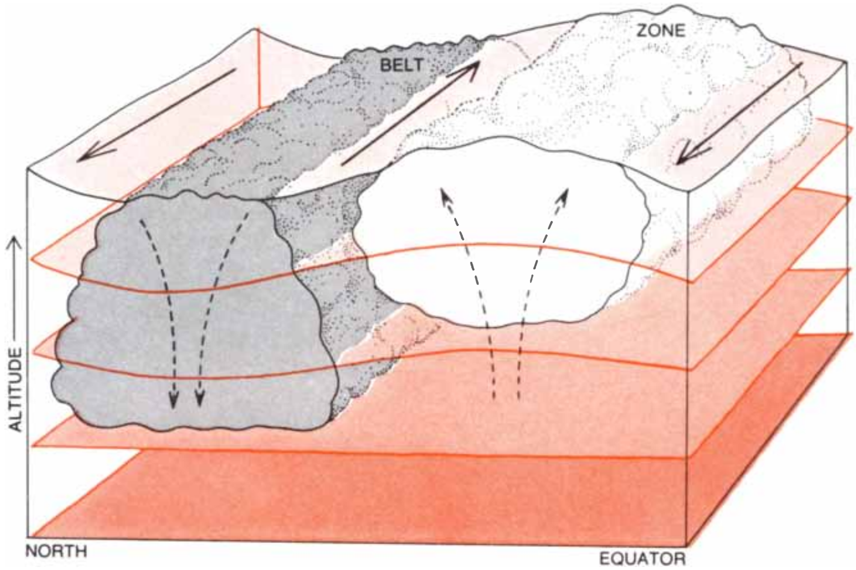
sun's would contain all the necessary elements in a wide variety of compounds. It is currently believed that the clouds are basically as Lewis has predicted, with the colors explained by the addition of small amounts of sulfur, red phosphorus and complex organic molecules.

Data on the horizontal structure and motions of the Jovian atmosphere are obtained mainly from photographs at visible wavelengths. The data include ground-based observations beginning at the end of the 19th century, together with the high-resolution images made from the spacecraft *Pioneer 10* and *Pioneer 11*. The ground-based observations before 1955 are summarized by B. M. Peek in his classic work *The Planet Jupiter*. It is evident from surveying these observations that most of the principal features of Jupiter's atmosphere have existed for decades or longer. Such longevity of cloud patterns is remarkable by terrestrial standards. On the earth cloud patterns rarely last longer than one or two weeks, unless they are directly connected with underlying topography such as mountain ranges. On Jupiter there is no underlying topography as far as anyone knows. Hence it would be of great interest to know why the Jovian cloud patterns are so long-lived.

Perhaps the simplest and most direct explanation of the longevity of Jupiter's clouds is one provided by Peter J. Gierasch, who is now at Cornell University, and Richard M. Goody of Harvard University. Gierasch and Goody point out that on Jupiter the radiative time constant is extremely long. The radiative time constant is the time it takes for a mass of air to warm up or cool off by radiating in the infrared portion of the spectrum. On the earth the radiative time constant is a few weeks, which is comparable to the lifetime of flow features in the atmosphere. On Jupiter the radiative time constant is longer than a year. The differ-



INFRARED FEATURES of the atmosphere of Jupiter (*top*) photographed from the spacecraft *Pioneer 10* reveal the distribution of the temperature at the cloud tops. Light areas are regions of low infrared emission and are evidence of thick, high clouds. Dark areas are regions of high infrared emission and are evidence for holes in upper cloud layer exposing warmer layers below. When infrared image is compared with an image made in visible light (*bottom*), it is evident that the regions of high clouds correspond to the light-colored "zones" and that the regions of few clouds correspond to the dark-colored "belts." Since clouds usually form on warm, rising currents in an atmosphere and disperse on cooler, sinking currents, the zones must correspond to regions of warm rising gas and the belts to cooler sinking gas. Great Red Spot can be seen at the lower left in both images; it is an area of particularly low infrared emission and resembles the zones more closely than the belts. On image made in visible light the comblike feature at top left, two square black dots near Great Red Spot and apparent discontinuity running across photograph are artifacts of way in which picture was made.



REGIONS OF HIGH AND LOW PRESSURE on Jupiter are compared in a cross section of the atmosphere made along a meridian of longitude. Atmospheric pressure increases toward the center of the planet. At great depths, where the atmosphere rotates uniformly with planet's mean rotation period, "surfaces" of constant pressure (*darker colors*) in the atmosphere are horizontal. At intermediate depths the higher temperatures of the zones cause the surfaces of constant pressure (*lighter colors*) to bulge upward, creating higher pressures in the zones (*right*) than in the belts (*left*). Coriolis forces generated by the rotation of the planet then cause the atmosphere to flow in a direction out of the page (westward) along the equatorward edges of the zones, and into the page (eastward) along poleward edges of zones. Slower, secondary circulation is produced in atmosphere as warmer gas rises in zones and cooler gas sinks in belts.

ence is the result of the lower temperatures in Jupiter's atmosphere, the smaller amount of heat the planet receives from the sun (only 4 percent of the amount the earth receives) and the fact that the gases of Jupiter's atmosphere emit less infrared radiation than the gases of the earth's atmosphere. Furthermore, if the masses of gas in the Jovian atmosphere store their heat at altitudes as low as the base of the clouds, then the radiative time constant may be even longer than a year because of the large volume of gas that must be heated or cooled. Thus the long lifetime of atmospheric phenomena on Jupiter could be largely due to the low rate at which temperature differences are radiated away.

An equally remarkable aspect of Jovian cloud features is their organization and spatial regularity. At any one time there are usually at least 10 bands, the belts and the zones, each circling the planet on a line of constant latitude. Such a high degree of symmetry around the axis of rotation does not appear in satellite photographs of terrestrial clouds.

The belts are either brown or brown tinged with blue, and the zones are either white or white tinged with red. The reddest features, such as the Great Red Spot and smaller spots, are usually located in the zones. Infrared observations that measure the temperature of the cloud tops suggest that there is a basic difference between the zones and the red spots on the one hand and the belts on the other.

On Jupiter, as on the earth, the most dramatic differences in temperature within a limited area are found between one level of the atmosphere and another. Since in general temperature decreases with altitude, a high infrared temperature indicates that at high altitudes there are only thin, transparent clouds or no clouds at all, and a low infrared temperature indicates that at high altitudes there are relatively thick, opaque clouds. On the earth weather satellites utilize that principle for photographing clouds both in the daytime and at night at infrared wavelengths: a convective storm such as a hurricane always appears as a region of low infrared temperature because of its extensive cover of high clouds.

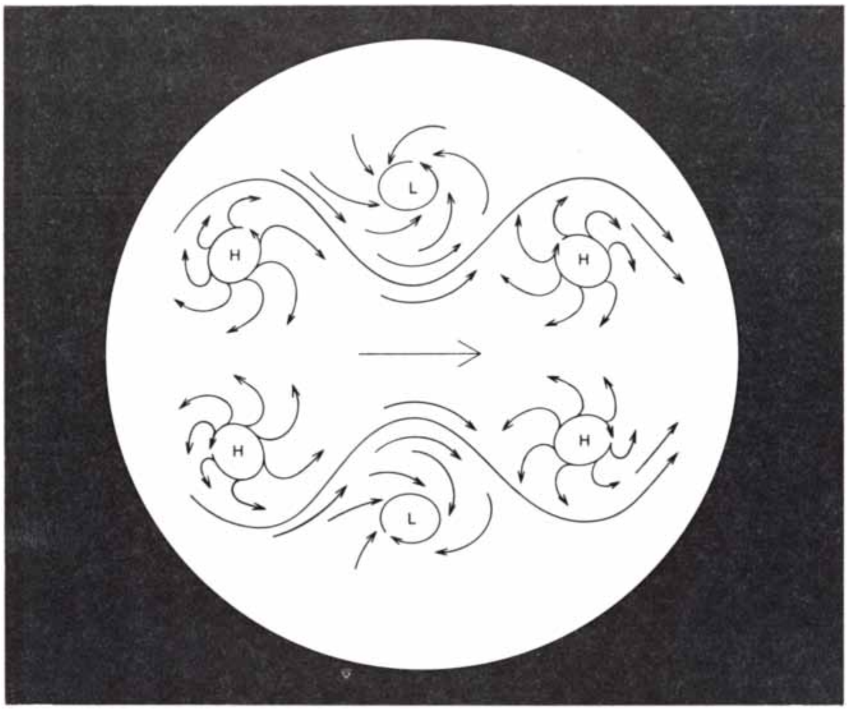
Pioneer 10 made two infrared images as it sped past Jupiter on December 3, 1973. *Pioneer 11* made four infrared images a year later. A comparison of one of the infrared images with a similar image made in the visible region of the spectrum reveals that the zones are regions of low infrared temperature and the belts are regions of high infrared temperature. The Great Red Spot has a particularly low infrared temperature, and therefore it is similar to the zones rather than to the belts. Hence by analogy with the earth one can infer that the red spots and white zones are regions of active convection and rising motion in the atmosphere, whereas the brown belts are regions of cloud dispersal and sinking motion.

Although the infrared observations help to classify Jupiter's atmospheric features, they do not answer the more basic question of why such features exist. Some clues to the answer to that question are provided by observing the motions of the clouds. From the earth observers can chart the position of small spots with respect to the belts and zones and other large features. Photographic records of the features go back about 100 years. The smallest spots that can be seen from the earth are about 3,000 kilometers in diameter, which is about a fiftieth the diameter of Jupiter or approximately the diameter of a large storm system on the earth. Such storm systems on the earth generally move with the mean wind direction; for example, in North America they move from west to east. As the storm systems evolve and decay, however, their apparent motion with respect to the mean motion of the wind sometimes changes. Hence there are problems in using cloud features to track winds on a large scale. Such features are nonetheless the best wind data we have for Jupiter at present.

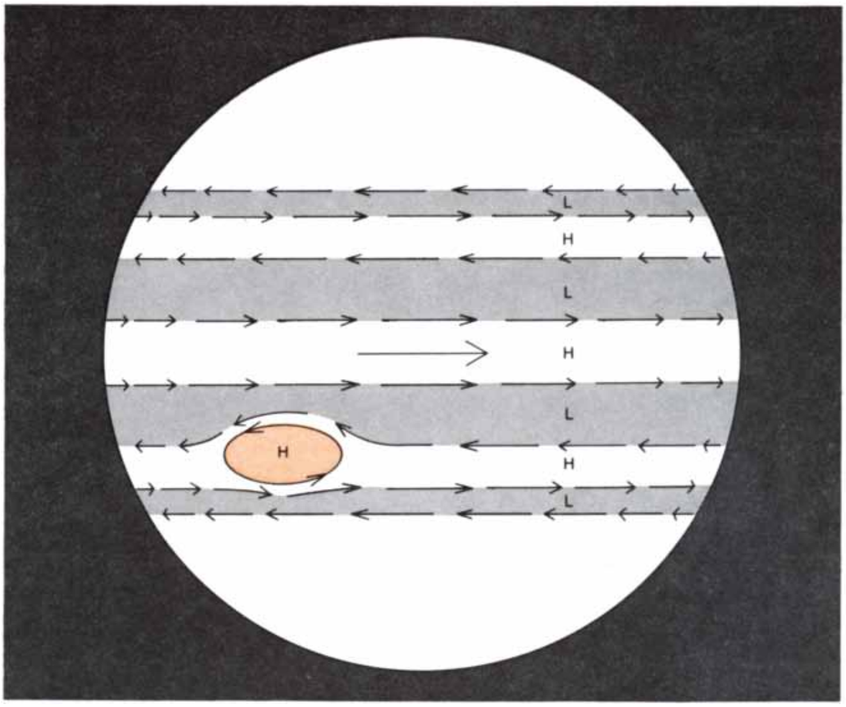
Observed over a period of a few weeks the smaller spots around the Great Red Spot always move counterclockwise; therefore the winds around the Great Red Spot probably blow in that direction. Moreover, the direction and magnitude of the winds are typical of those observed in the same region decades earlier. Elsewhere on Jupiter the wind blows along lines of constant latitude; the largest relative velocities are at the boundaries between belts and zones.

As on the earth, the relative velocities are small compared with the mean velocity of the atmosphere associated with the planet's rotation. The rotation of Jupiter's interior can be determined from the rotation of the planet's magnetic field, which has a period of nine hours 55 minutes 29.7 seconds. The same rotation period is typical of the clouds in Jupiter's middle latitudes, although the winds at the edges of belts and zones cause small regions to depart from the mean rotation period by as much as five minutes. Within a band of latitudes extending some eight degrees on each side of the Jovian equator the rotation period of the atmosphere is about five minutes shorter than the rotation period of the magnetic field. The shortest rotation period of all is found away from the equatorial region. It is associated with the boundary between a prominent belt and a zone in the northern hemisphere. There the winds complete a circuit of the planet once every nine hours 49 minutes. At that boundary the velocity of the clouds relative to the velocity of Jupiter's rotating interior is about 120 meters per second, or more than 270 miles per hour.

Whenever atmospheric motions persist for intervals that are long compared with a planet's period of rotation, the Coriolis force must play an important role in the dynamics of the atmosphere. In the northern hemisphere of Jupiter or the earth the Coriolis force acts to the right of the direction of motion. In order to balance the force there must be a pressure force to the left, that is, there must be a high-pressure area to the right of the flow direction. Thus on the earth the wind blows counterclockwise around a low-pressure center (forming a cyclone) in the Northern Hemisphere and clockwise around a high-pressure center



EARTH'S ATMOSPHERE IS BAROCLINIC on a global scale, that is, there are large horizontal temperature differences between the Equator and the poles. As a result of the differences a longitudinal wave forms in the atmosphere in both hemispheres, traveling from west (*left*) to east (*right*) and transporting heat from the Equator to the poles. The troughs (equatorward excursions) of the wave are associated with low-pressure regions (*L*) and the crests (poleward excursions) of the wave are associated with high-pressure regions (*H*). The flow of air around low-pressure regions is cyclonic and flow of air around high-pressure regions is anticyclonic.



JUPITER'S ATMOSPHERE IS BAROTROPIC on a global scale, that is, there is very little horizontal temperature difference between the equator and the poles. Regions of high pressure (*H*) and low pressure (*L*) are linear features along parallels of latitude: the zones (*white*) and the belts (*gray*). High-speed winds flow at the boundaries between the bands; where relative wind motion is westward (*toward the left*) the winds are known as retrograde jets. Above a latitude of 45 degrees in both hemispheres banded pattern breaks down (*see illustration on page 54*). Color oval in southern hemisphere is Great Red Spot. Winds around it are anticyclonic.

(forming an anticyclone). The pattern is reversed in the Southern Hemisphere. For winds moving in latitudinal zones (as at the boundaries between Jupiter's belts and zones) the highs and lows are found in bands between the regions of maximum and minimum zonal velocity.

On Jupiter the zones and the Great Red Spot are high-pressure regions (anticyclonic) and the belts are low-pressure regions (cyclonic). That was first pointed out in 1951 by Seymour L. Hess of Florida State University and Hans A. Panofsky of New York University. Hence the zones and the Great Red Spot seem to be fundamentally different from terrestrial storms, which are usually cyclonic at sea level. The difference is not, however, as fundamental as it seems. Since clouds tend to form in rising air, and since rising air tends to be warm, it is reasonable to assume that the zones and the Great Red Spot are warmer than their surroundings at any particular level within the clouds. In that respect they resemble tropical cyclones (hurricanes) and mature extratropical cyclones on the earth, most of which are also warm. The resemblance is significant because terrestrial air masses that are warm tend to have high-pressure centers and anticyclonic circulation at high altitudes, the altitudes to which the Jovian observations refer.

The reason that such storms are anticyclonic at great heights is that the pressure drop with altitude in a warm air mass is less than the pressure drop with altitude in a cold one. This fact is a consequence of the hydrostatic relation between pressure change and density: when the density is low, as it is when the air is warm, the pressure drop with altitude is also low. Thus a warm air mass tends to become a high-pressure (anticyclonic) region with increasing altitude. If the pressure is very much lower than the surroundings at low altitudes, as it is with a terrestrial cyclonic storm, the transition to anticyclonic circulation may not arise. In general, terrestrial hurricanes are strongly cyclonic at sea level and weakly anticylonic at high altitudes. In other words, the observed anticyclonic circulation of the Jovian zones and the Great Red Spot is consistent with the evidence from infrared observations that they are warm centers of rising motion. Hence in one way they are similar to warm convective storms on the earth.

As we have seen, however, there is a fundamental difference between the earth and Jupiter in that the earth's atmosphere is bounded at the bottom by a relatively undeformable surface of water and land. The surface can support large differences in air pressure at sea level from one place to another, and so there can be strong winds close to the ground. We have little information about the atmosphere below the visible clouds on Jupiter, but it is reasonable to assume that below some level it rotates uniformly with a period equal to the rotation period of the magnetic field. The situation is equivalent to saying that the atmosphere

FEATURE	INFRARED MEASUREMENTS	CLOUD HEIGHT	VORTICITY	PRESSURE	TEMPERATURE	VERTICAL VELOCITY	EXPECTED CLOUDS	COLOR
BELT	HOT	LOW	CYCLONIC	LOW	COLD	DOWN	LOW, THIN	DARK
ZONE	COLD	HIGH	ANTICYCLONIC	HIGH	HOT	UP	HIGH, THICK	LIGHT
GREAT RED SPOT	COLD	HIGH	ANTICYCLONIC	HIGH	HOT	UP	HIGH, THICK	ORANGE

CHARACTERISTICS OF FEATURES in the Jovian atmosphere are summarized. The zones and the Great Red Spot are similar in all important respects except shape. The belts are the reverse of the zones in all respects. Taken together the data suggest that all the features are not different and isolated phenomena, and that they all must be linked together as part of one global weather pattern.

has a fluid lower boundary that deforms easily when pressure is applied from above. The deformation prevents the buildup of pressure differences at deep levels and therefore keeps the circulation at those levels weak. Thus whereas a warm air mass on the earth can have either cyclonic or anticyclonic circulation at low altitudes, on Jupiter the low-altitude circulation must be zero. In that respect the circulation on Jupiter may resemble currents in the earth's oceans more closely than currents in its atmosphere. Ocean currents tend to be weak at great depths and are always anticyclonic near the surface if the water between the two levels is warm.

There have been several attempts to put these arguments on a quantitative basis. In 1969 Jeffrey Cuzzi, who was then a graduate student at the California Institute of Technology, and I decided to study the observed zonal wind patterns on Jupiter. We first rediscovered the qualitative relation discussed by Hess and Panofsky in 1951. We then made a rough estimate of how great a difference in temperature between zones and belts would be needed to account for the observed winds. Actually the quantity one wants to determine is not the temperature difference alone but rather the product of the average temperature difference and the depth to which the difference extends. If the observed zonal motions refer to the tops of the ammonia clouds in Lewis' model of the Jovian atmosphere, then the depth must be measured downward from that level.

On the basis of the observed Jovian winds the value of the product of the temperature difference and the depth is about 150 kilometer-degrees. In other words, the actual depth over which there are appreciable temperature differences between the zones and the belts is unknown, but if the depth were 15, 150 or 1,500 kilometers, the temperature difference at those depths would have to be respectively 10 degrees, 1 or .1 degree C. in order to account for the observed winds. The magnitude of the temperature difference is related to the heat sources and heat sinks that are maintaining the atmospheric circulation. The critical depth is the thickness of the source-sink region. To discuss the situation further we need to consider the source-sink mechanism.

In 1971 Gierasch, who was then at Florida State University, and Albert I. Barcilon suggested that Jupiter's atmosphere is similar to the earth's atmosphere over the Tropics. There the sun heats the surface of the ocean, causing the water to evaporate. The moist air close to the surface becomes unstable, leading to convection and the formation of cumulus clouds. Large-scale, organized motions are present over the Tropics because the small-scale cumulus convection, which is the principal means by which heat is transferred from the ocean to the atmosphere, varies in response to the large-scale motions. The maximum horizontal temperature difference from one place to another in the Tropics is found between air that has been heated by condensation and air that has not.

According to Gierasch and Barcilon, the temperature difference between the zones and the belts on Jupiter is due to the release of latent heat, as are the temperature differences over the earth's Tropics. Lewis' model of the clouds is assumed to apply to the Jovian zones; the belts are assumed to be dry, without any condensable vapors. The zones are then about two degrees hotter than the belts at all levels above the level where water vapor condenses. (Compared with the clouds composed of water, the clouds of ammonium hydrosulfide and of ammonia have only a small effect on the temperature.) Thus a temperature difference of about two degrees extends over a depth of about 75 kilometers, which is the total thickness of the water-ammonia cloud system. Moreover, the product of the temperature difference and the depth agrees with the 150 kilometer-degrees deduced from the wind observations.

Gierasch and Barcilon did not offer a mechanism by which condensable vapors remain concentrated in the zones. In a tropical hurricane on the earth the cyclonic winds exert a cyclonic stress (force per unit area) on the ocean surface. That stress, interacting with the Coriolis force, causes air to flow inward toward the low-pressure center of the hurricane just above the surface and causes water to flow outward just below the surface. On the earth the flow in the ocean can be ignored, but the convergence of moist air toward the center of the hurricane renews the hurricane's supply of latent heat and maintains its circulation.

On Jupiter the cloudy regions are anticyclonic and rotate in a direction opposite to that of cloudy regions on the earth. There is no ocean; the lower fluid is simply the atmosphere below the clouds. An anticyclonic stress from above on the lower fluid causes the lower fluid to flow inward and the upper atmosphere to flow outward. Here, however, it is the convergence of the lower fluid toward the center that matters. The convergence occurs below the base of the clouds, at levels where precipitation is evaporating. It is this convergence that continuously resupplies the zones with condensable vapor. Such a process is one possible mechanism by which the temperature difference between zones and belts is maintained.

So far I have said nothing about the circulation of the atmosphere in middle latitudes on Jupiter and on the earth. On the earth the basic energy source of the atmosphere at middle latitudes is the horizontal temperature gradient. The gradient arises because the sun heats the Equator far more than it heats the poles. An atmosphere with such horizontal temperature differences at any given altitude is said to be baroclinic. It is usually unstable. The instability manifests itself as a wavelike pattern in the basic eastward flow of the atmosphere. Each trough of the wave is the point where the air makes its maximum excursion toward the Equator and each crest is where it makes its maximum excursion toward the poles. The wave transports heat both upward in the atmosphere and toward the poles. The upward heat transport, in which hot air rises and cold air sinks, tends to lower the center of mass of the atmosphere, since a given volume of cold air is denser and therefore heavier than the same volume of hot air. The heat transport thereby releases gravitational potential energy. The troughs and crests of the baroclinic wave are respectively the cyclones and anticyclones that dominate the earth's weather at the middle latitudes.

An important question is whether or not such baroclinic waves are present on Jupiter. If the heat flux from Jupiter's interior were uniform from the equator to the poles, the total heat supplied to the atmosphere from both the sun and the interior would still be twice as great at the equator as at the poles, because of the difference in the degree to which those regions are heated by the sun. Such a difference in heating could cause a considerable amount of baroclinic instability if Jupiter were like the earth at middle latitudes.

The axially symmetrical, banded appearance of Jupiter suggests, however, that Jupiter must be quite different from the earth at those latitudes. Mixing across circles of latitude is an essential aspect of baroclinic instability. And although there are some disturbances resembling baroclinic waves on Jupiter, they are confined to narrow bands of latitude and do not seem to give rise to large-scale mixing between one band and another. In addition, if heat transport toward the poles by baroclinic instability were the only means of balancing the extra amount of solar heating at Jupiter's equator, an appreciable temperature difference between the equator and the poles would develop.

Peter H. Stone of M.I.T. has a general theory of baroclinic instability in any planetary atmosphere. For Jupiter he estimates that the equator would be 30 degrees hotter than the poles if the solar heat were transported poleward by baroclinic instability alone. His estimate was recently tested when the infrared radiometers on *Pioneer 10* and *Pioneer 11* obtained the first good heat measurements of the Jovian poles.

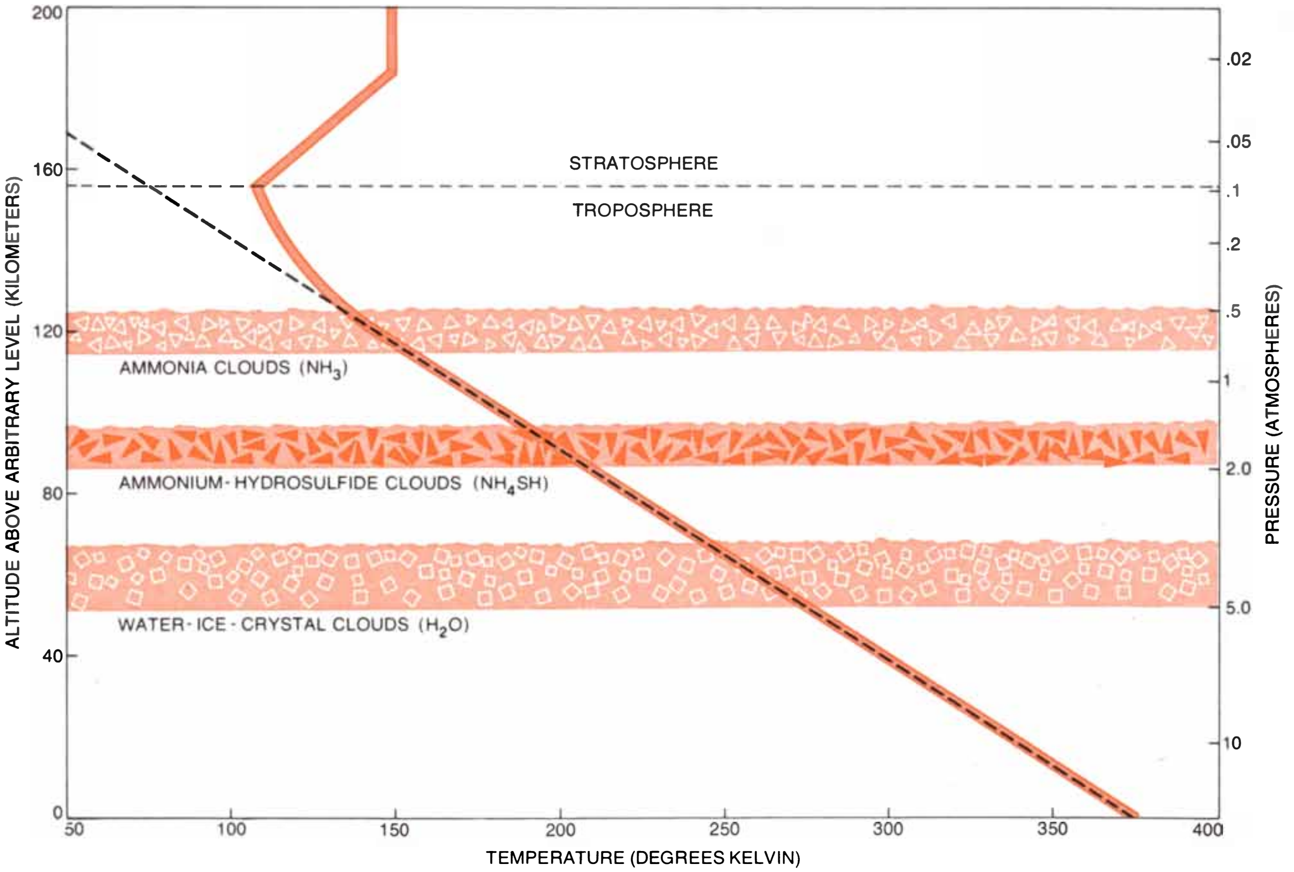
The measurements showed that the heat emitted by Jupiter is about the same over both the poles and the equator. This implies that the poles are at about the same temperature as the equator at the same levels of pressure in the atmosphere. In fact, the observed temperature difference is no greater than three degrees, as compared with the value of 30 degrees predicted by Stone's baroclinic-instability model. The implication is that Jupiter is not like the earth at middle latitudes, and that the transport of heat in the Jovian atmosphere by baroclinic instabilities is insignificant.

If that is the case, the difference in solar heating between the equator and the poles of Jupiter must be balanced by heat from the planet's interior. Recently I suggested a mechanism whereby the difference could be equalized by the convective flow of the internal heat. The mechanism works like a thermostat. Where the actual vertical temperature gradient in the atmosphere is equal to the adiabatic value the convective heat flux is zero. Where the temperature falls with altitude at a rate slightly higher than the adiabatic rate, however, the convective heat flux is large. Thus a slight cooling of the poles relative to the equator because of the difference in amount of solar energy absorbed soon leads to a large increase in the convective heat flux to the poles relative to the flux to the equator. The convective thermostat ensures that Jupiter is very nearly adiabatic throughout. Hence the relation between temperature and pressure at both the equator and the poles must be very nearly equal. The possibility that there is greater convective flow of internal heat at the Jovian poles seems to be confirmed by the appearance of convectionlike patterns north of a latitude of about 45 degrees.

The internal heat source might also play a role in supplying energy for the circulation observed within the Jovian belts and zones. It has been suggested that the belts and zones are simply surface manifestations of giant convection cells. The giant cells might be as deep as they are wide, and therefore they might extend an appreciable fraction of Jupiter's radius downward toward the center of the planet.

There are several arguments against the convection-cell hypothesis, although none of them is conclusive. First, if Jupiter's atmosphere is indeed analogous to the earth's tropical atmosphere, it does not need a deep, large-scale circulation below the clouds. Condensable vapor could be concentrated in the zones and dispersed in the belts in a shallow layer just below the base of the clouds. The temperature differences arising from the condensation within the clouds seem fully capable of accounting for the observed winds. Therefore the belts and zones could well be a superficial phenomenon, extending only slightly deeper than the base of the deepest clouds.

Second, if the belts and zones were associated with the large-scale convection of internal heat, one would expect that the infrared emission from Jupiter would be strongest in the zones, since the zones are the site



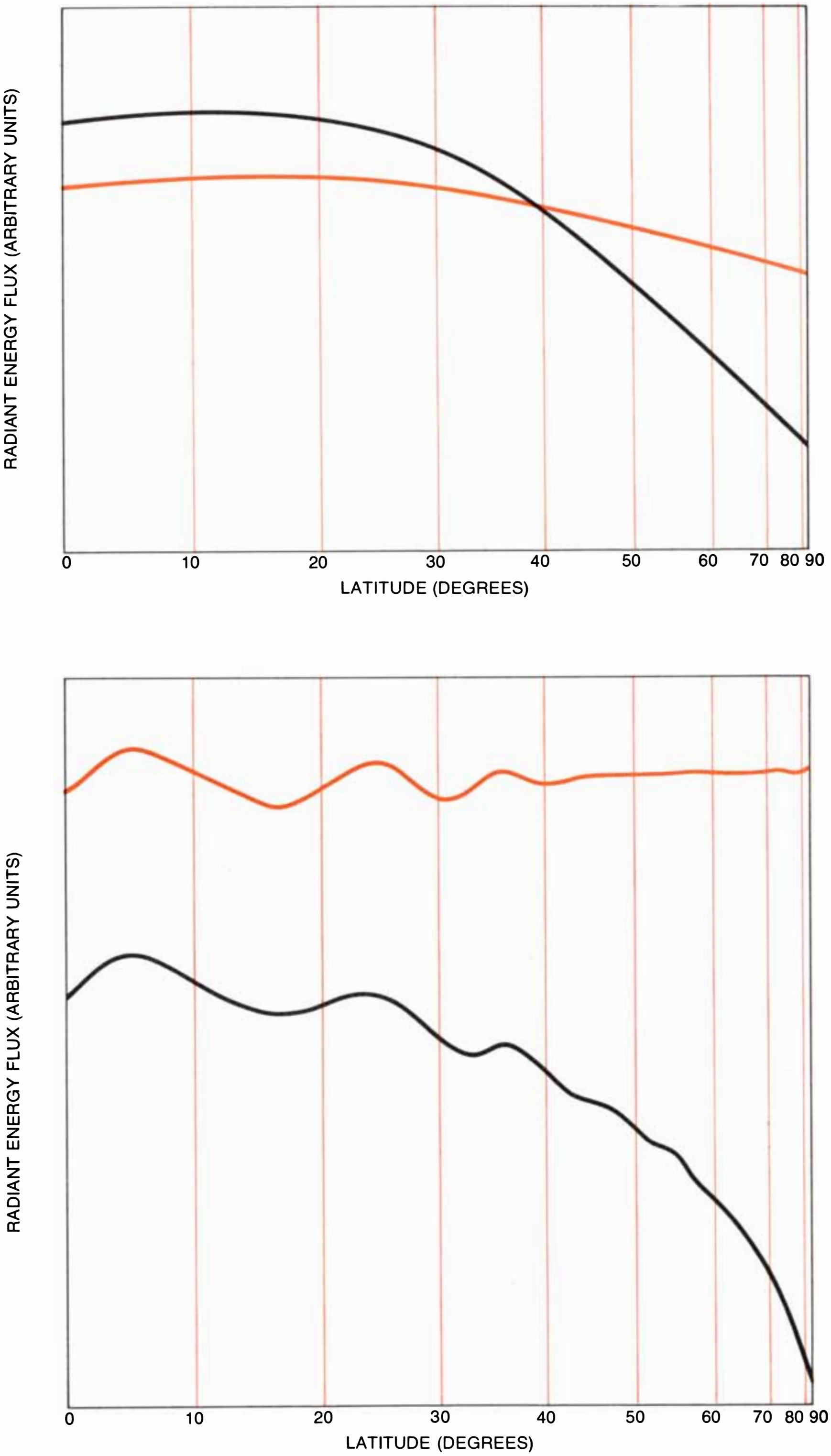
VERTICAL CLOUD STRUCTURE of the atmosphere of Jupiter has been computed from a theoretical model devised by John S. Lewis of the Massachusetts Institute of Technology. In an atmosphere composed primarily of the noncondensable gases hydrogen and helium there are distinct layers of clouds. The color line indicates the temperature of the atmosphere at various depths and pressures; it is based on an analysis of infrared data made by Glenn S. Orton of the Jet Propulsion Laboratory of the California Institute of Technology. The black broken line indicates the theoretical temperature of the atmosphere at the same depths and pressures if the atmosphere were perfectly adiabatic (completely mixed by convection). The planet's atmosphere is nearly adiabatic except at uppermost levels.

of rising motion. It is true that we can observe the heat flux only at the top of the atmosphere; nevertheless, the zones do not seem to be the principal regions of infrared emission. In fact, it is the belts that both emit the greater amount of infrared energy and absorb the greater amount of solar energy. On the other hand, the net flux, that is, the difference between the amount of energy emitted and the amount absorbed, is about equal in the zones and the belts. This equality implies that the internal heat flux at the base of the clouds is the same in the belts and the zones, provided that there is no latitudinal heat transport within the clouds. The point is that the radiative-flux data provide no evidence to support the convection-cell hypothesis, even though they do not rule it out.

Third, the convection-cell hypothesis has more than its share of theoretical difficulties. Convection is typically a small-scale phenomenon. In the sun or in the earth's atmosphere the size of the dominant energy-carrying cells is on the order of one scale height, that is, the vertical distance in which the density and the pressure increase by a factor of *e*, or 2.718. On Jupiter the scale height is a few tens of kilometers, and the belts and zones are some 10,000 kilometers wide. Moreover, on a rotating body convection patterns tend to develop a longitudinal structure, just the opposite of what is observed on Jupiter. Such arguments suggest that small-scale convection is the dominant mode of heat transfer, at least below the clouds, where radiation and condensation are unimportant.

There are other ways, however, in which Jupiter's belts and zones might be part of a deep pattern of convection extending down a significant fraction of the planet's radius. Several theoretical and laboratory studies have shown that convection in a rotating sphere usually takes the form of long, thin columns, the axes of which are parallel to the axis of rotation. The two ends of each column intersect the visible surface of the sphere at opposite latitudes in the northern and southern hemispheres. Friedrich H. Busse of the University of California at Los Angeles has suggested that the belts and zones are the surface manifestation of such long, thin columns. So far the columns have been shown to exist only in laboratory experiments with comparatively viscous liquids. Extending the hypothesis to cover the compressible gases on a rotating sphere the size of Jupiter is therefore somewhat speculative.

Whether the belts and zones are a shallow phenomenon confined to the cloud layers or are part of a deep convection pattern, there is still no satisfactory explanation of why they are oriented in the east-west direction. The earth's tropical atmosphere also is banded, with a cloudy zone around the Equator and clear belts to the north and south. The equatorial intertropical convergence zone is a band of cumulus clouds and thunderstorms that generally occupies a strip some five to 10 degrees north of the



RADIATION BALANCE in the atmosphere of the earth (*top*) and of Jupiter (*bottom*) shows dramatic differences between the planets. For both planets the amount of thermal radiation emitted (*color*) is nearly independent of latitude, whereas the amount of sunlight absorbed (*black*) is strongly affected by the oblique angle of the sun at the poles. The earth has a negligible source of internal heat, and so the areas under the two curves for the earth are equal. The excess amount of solar heating at the earth's Equator is carried poleward by currents in the atmosphere and ocean. Jupiter has an appreciable source of internal heat: it emits 1.9 times as much energy as it receives from the sun. Thus the area under the color curve for Jupiter is 1.9 times larger than the area under the black curve. In addition very little heat is carried poleward by currents in Jupiter's atmosphere. Hence Jupiter's internal heat must reach the surface preferentially at the poles. The smaller bumps in the curves for Jupiter are created by the belts and zones; more thermal radiation is emitted and more sunlight is absorbed in the belts than in the zones. Curves for both planets are averaged relative to longitude, time of day and season.

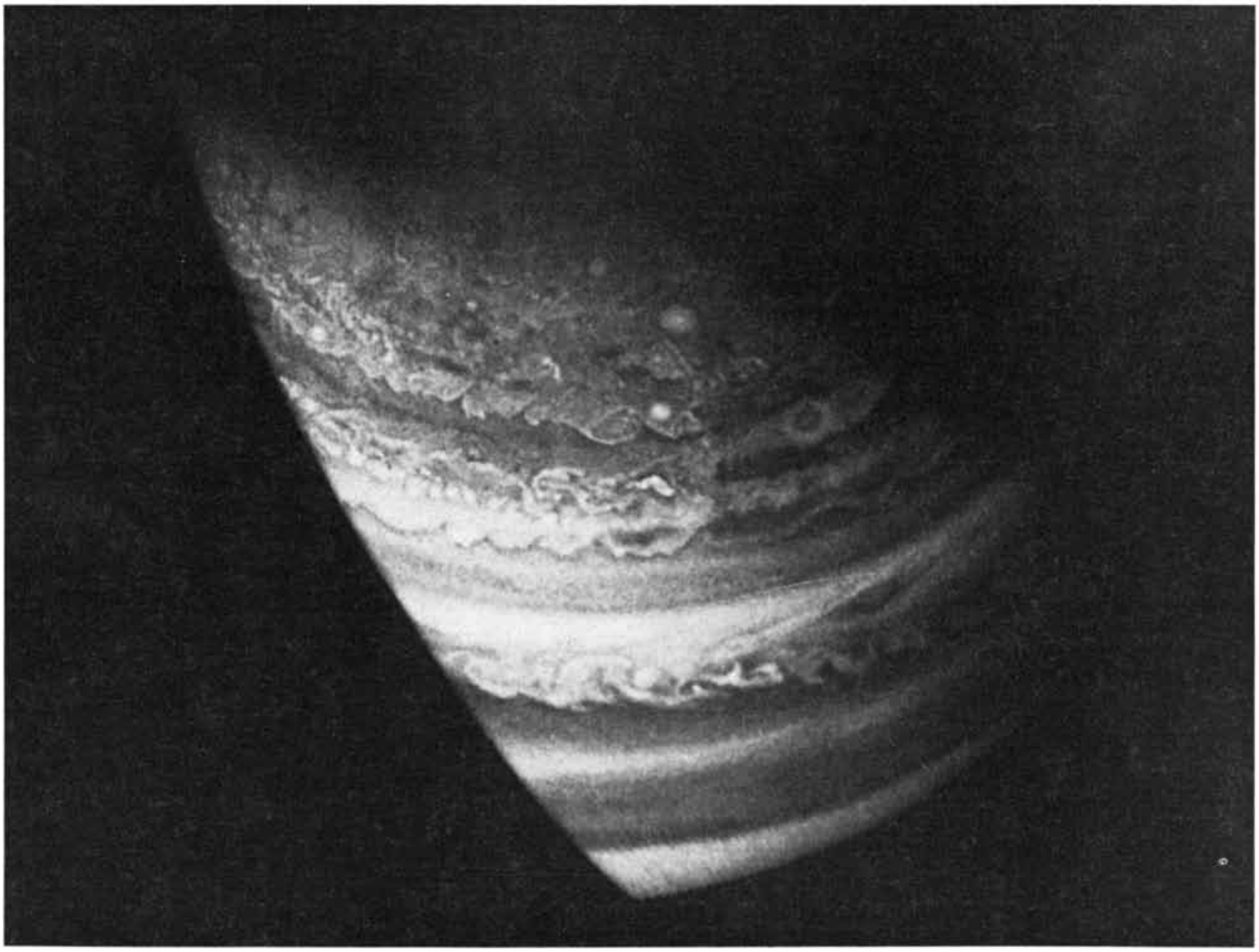
Equator. It is a region of net upwelling in the atmosphere, even though heat is carried upward to the base of the stratosphere by a system of both updrafts and downdrafts. On each side of the intertropical convergence zone there is a dry belt extending to 30 degrees north and south of the Equator. There the motion is almost everywhere downward; updrafts are confined to a thin layer close to the ground. The skies are generally clear and heat is transferred vertically mainly by infrared radiation. The northward offset of the intertropical convergence zone is apparently due to the fact that the continents and oceans are distributed differently in the Northern and Southern hemispheres.

The difference between Jupiter and the earth seems to come at higher latitudes. On Jupiter the banded pattern repeats itself several more times; on the earth the pattern breaks up into baroclinic instabilities. The difference may be due to the thermostatic effect of the internal heat source on Jupiter. On the earth baroclinic instabilities provide the only way for the atmosphere to balance the solar heating: the air over the Equator heats up relative to the air over the poles, instabilities develop and soon the middle-latitude circulation is dominated by cyclones and anticyclones. On Jupiter the equatorial regions heat up only slightly relative to the polar regions, and the internal heat flux readjusts itself by an amount that is sufficient to balance the difference in the solar heating.

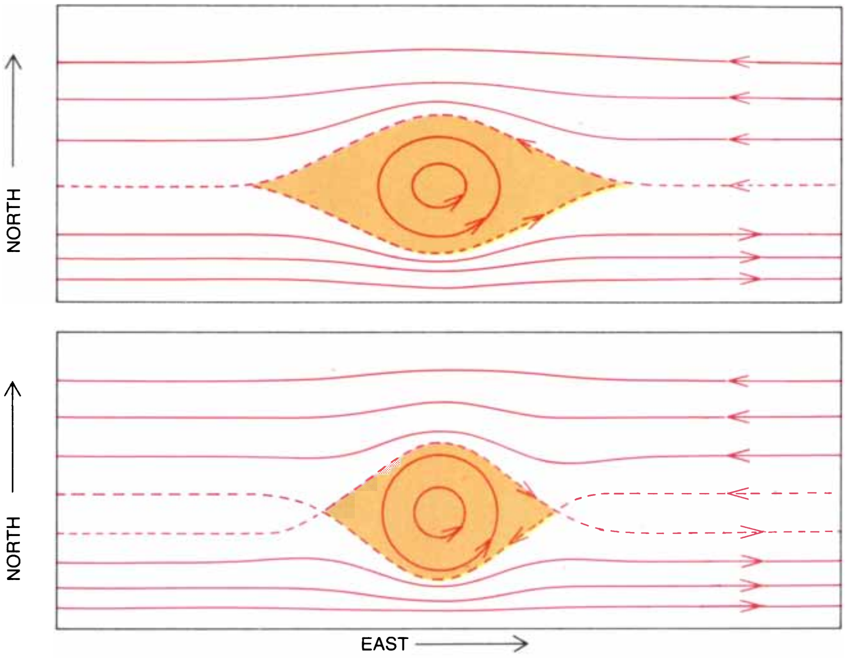
The instability of the belts and zones is an interesting question in its own right. Any equilibrium state of an atmosphere, except the state of uniform rotation, has kinetic energy and gravitational potential energy. A small-amplitude disturbance may be able to extract some of that energy and grow at the expense of the basic state. The basic state is stable only if all the disturbances remain small. It is unstable if there is at least one kind of disturbance that continues to grow. In any real situation all kinds of disturbances are always present to some extent, so that an unstable basic state always breaks up or evolves in a finite time.

The simplest basic state is one in which an atmosphere flows strictly from west to east and the wind velocity varies only with latitude. Superficially that is the case on Jupiter, although it may not be valid to neglect the dependence of velocity on altitude. The only available energy in that basic state is kinetic, and it is associated with the different velocities at the different latitudes. There are no horizontal temperature gradients from one place to another at the same level. The atmosphere is said to be barotropic, as opposed to baroclinic, where the available energy is mainly gravitational and is associated with horizontal temperature gradients.

The different velocities of the eastward winds can be plotted with respect to latitude to yield a velocity profile. For a barotropic atmosphere an instability is possible only when the curvature of the velocity profile exceeds a certain critical value. That value is equal to twice the cosine of the latitude times the planet's rotation rate divided by the radius. In 1969 Cuzzi and I applied the stability criterion to Peek's long-term data on Jupiter's rotation period with respect to latitude. We found that according to this criterion there are only a few latitudes on Jupiter where an instability is even marginally possible. The instabilities are found at the center of retrograde jets in



PATTERN OF BANDS BREAKS DOWN at high latitudes on Jupiter, as is shown by this high-resolution image of the planet's northern hemisphere made from *Pioneer 11*. The equator is the second light zone from the bottom. The disturbed region to the north is at a latitude where the basic flow between a belt and a zone is theoretically expected to be unstable. Farther north such an instability dominates at all latitudes. Borders of picture are distorted because of rotation of planet and motion of spacecraft during time picture was made.



COMPUTER MODEL OF GREAT RED SPOT (*top*) **in Jupiter's atmosphere duplicates several of the atmospheric flow features that are observed. It shows the counterclockwise winds around the spot and the proper directions of the east-west flow of the gas north and south of the spot. Moreover, it shows pointed tips at the east and west edges of the spot. A variation of the model** (*bottom*) **shows how smaller dark spots that occasionally approach the Great Red Spot can sometimes suddenly change latitude and begin to recede, carried by a current of gas back in the direction from which they came. In both versions of the model the horizontal scale of the diagram has been compressed by a factor of three with respect to the vertical scale.**

Jupiter's atmosphere: latitudes where the rotation period is the longest. The disturbance that grows the fastest is a longitudinally oscillating wave. Thus we expect the basic east-west flow to break up into a wavy pattern in the vicinity of the retrograde jets whenever the stability criterion is exceeded. When the stability criterion is not exceeded, the east-west flow pattern remains constant in time.

A confirmation of sorts was provided by *Pioneer 11* in its closeup pictures of the Jovian northern hemisphere. The pictures show several bands where a wavelike pattern suggests the location of an instability. The most prominent patterns are seen on the equatorward edges of zones (the poleward edges of belts). According to Peek's data, those same positions are the location of the retrograde jets. In other words, the instability seems to be developing where the barotropic-stability criterion says it should.

The *Pioneer 11* pictures also suggest that the parallel flow of the belts and the zones breaks down entirely at latitudes higher than about 45 degrees. That is at least qualitatively consistent with the barotropic-stability criterion, because the critical value of the curvature is proportional to the cosine of the latitude, and the cosine of the latitude drops to zero at the poles. Hence according to the stability criterion, a pattern of east-west bands at the poles would be unstable, and therefore such a pattern could not be a permanent atmospheric feature.

A north-south pattern is different. The most general north-south pattern is a mixture of waves that also propagate westward at various speeds. The difference between the north-south flow patterns and the east-west ones seems to explain the recent computer results of Gareth P. Williams of the Geophysical Fluid Dynamics Laboratory at Princeton University. He began with the barotropic model of Jupiter's atmosphere and introduced into the equations a term that described a randomly varying force and a term that described the dissipation of energy attributable to the viscosity of the atmosphere. He found that initially both the east-west and the north-south motions appeared in his model. Later the north-south motions continued to form and decay, whereas the east-west pattern grew slowly to the limiting amplitude imposed by the stability criterion. By adjusting the balance between the randomly-varying-force term and the dissipation term, Williams was able to produce a quite realistic-looking computer model of Jupiter [*see illustration on page 47*].

It is still hard to understand why the barotropic model should be so successful in explaining Jupiter's atmospheric features. The deep atmosphere must rotate with the interior, so that the speed of the currents at the boundaries of the belts and the zones must vary with depth. Associated with such a variation with depth there must be temperature differences between the belts and the zones on horizontal surfaces. In other words, the Jovian atmosphere should be baroclinic, not barotropic. The barotropic model would still be a valid approximation if the actual lapse rate were very much less than the adiabatic lapse rate, or if temperature increased with altitude. Those, however, are unlikely possibilities; both theory and observation suggest that the actual lapse rate is close to the adiabatic lapse rate except in the stratosphere, which is above the region of cloud motions. Perhaps the success of the barotropic model is due to our overzealous efforts to match the observational data with a theory that is based on terrestrial experience. The real mechanisms at work on Jupiter might still be eluding us.

Let us now turn to the Great Red Spot and similar spots in Jupiter's atmosphere. For a number of years the only theory that seemed capable of explaining the Great Red Spot was the Taylor-column hypothesis put forward by Raymond Hide, who was then at M.I.T. [see "Jupiter's Great Red Spot," by Raymond Hide; SCIENTIFIC AMERICAN, February, 1968]. Because of the Great Red Spot's long lifetime, its constancy in latitude and its uniqueness it seemed that it must be connected with an underlying solid object or topographic feature that was giving rise directly to the flow patterns at the visible surface. A Taylor column is the cylinder of stagnant fluid that was believed to join the solid object to the red cloud we see at the top of the Jovian atmosphere.

Since it now seems likely that Jupiter has no solid surface at any depth, the Taylor-column hypothesis is not as compelling. Moreover, the recent observations have brought out the similarity between the Great Red Spot and the zones. In fact, the spot's long lifetime and its constancy in latitude are no more unique than the long lifetime and the constancy of latitude of the zone in which it is embedded. The Great Red Spot also drifts irregularly westward relative to Jupiter's magnetic field, which would presumably be rooted in the solid surface of the planet if there were one. Finally, other zones seem to have their own red spots, suggesting that the Great Red Spot is not unique.

The prevailing view now is that all the red spots, like the zones, are basically a meteorological phenomenon. Since the Great Red Spot has higher clouds and a more strongly anticyclonic circulation than any of the zones, it could be called a superzone. If the zones and red spots are driven by the latent heat of condensation, then it could also be called a Jovian hurricane.

As with a terrestrial hurricane, there is probably a net rising motion within the Great Red Spot and a relatively uniform sinking motion in the regions immediately outside it. By far the highest velocities, however, are associated with the horizontal flow around the spot; the vertical motion of the atmosphere and its associated spreading motion at the cloud tops are too small to be measured. Perhaps the vertical heat transfer and energy release, and the energy dissipation as well, are small. Therefore to a first approximation one might neglect all the dissipative processes and ask whether there is an adequate model of the horizontal flow

SMALLER RED SPOT resembling the Great Red Spot is shown in this image made from *Pioneer 10.* Such spots, lasting for about two years, are not uncommon and are usually found in the zones. Their similarity to the Great Red Spot suggests that all such features are purely long-lived meteorological phenomena and are not associated with any solid feature within Jupiter.

GREAT RED SPOT, photographed from *Pioneer 11,* is now believed to resemble a terrestrial hurricane. The observed flow of the atmosphere in the zone and around the spot is anticyclonic, implying that the pressure within the spot is high. The flow near the top of a terrestrial hurricane is also anticyclonic, implying that it too is a high-pressure region at high altitudes. The Great Red Spot has been a feature on Jupiter for some three centuries. Hydrodynamic models of the spot show that in the absence of the dissipation of energy such a flow feature could in principle last forever. Even a small amount of dissipation will not affect it appreciably, and on Jupiter the energy that would need to be dissipated could be completely provided by the release of latent heat from the rising gas within the zone condensing to form clouds.

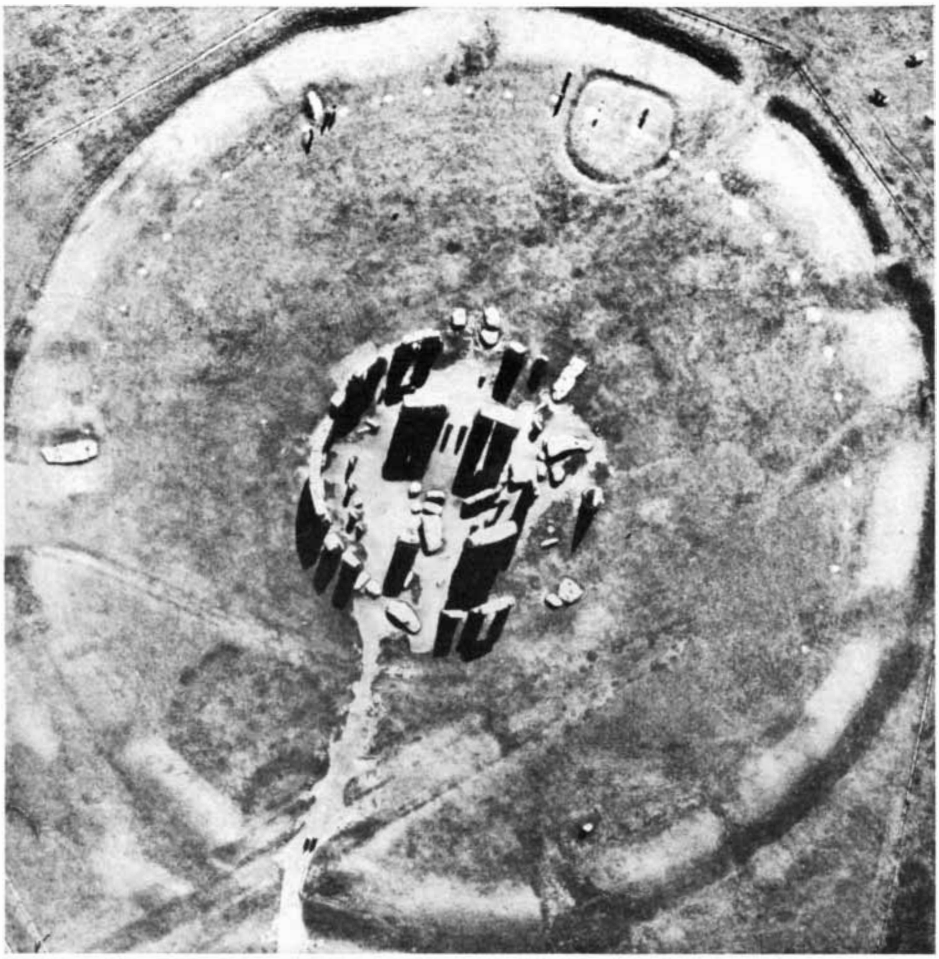
around the spot. Once again the simplest case is for a barotropic atmosphere. The aim of such a study would be to see if there are any special conditions under which red spots can or cannot exist, and to see if the model can predict any details of the flow pattern of such spots that can be compared with observation.

The Great Red Spot is embedded in a zone in the Jovian southern hemisphere, and it rotates counterclockwise like a wheel between two oppositely moving surfaces. Northward (equatorward) of the spot, along the northern edge of the zone, the flow is to the west. Southward (poleward) of it the flow is to the east. In 1970, working with a computer model, I found that the rolling-wheel configuration was the only one that gave a steady (time-independent) configuration of flow. The configuration shows that anticyclonic spots such as the Great Red Spot can exist only in an anticyclonic linear feature such as a zone. That aspect of the computer model is confirmed in the association between red spots and zones in both the northern and the southern hemisphere. The computer model also predicts that the Great Red Spot should have pointed tips at its east and west ends where the opposing wind currents of the zone divide. That aspect is confirmed in the closeup pictures of the spot, where the pointed tips are clearly visible. Recently Tony Maxworthy and Larry G. Redekopp of the University of Southern California have duplicated additional features of the flow around the Great Red Spot, including the interaction of other large spots with it over a long period of time. The basic flow is assumed to be barotropic, so that this model suffers from the weakness common to barotropic models: the actual lapse rate must differ from the adiabatic lapse rate by an amount that is inconsistent with other data on Jupiter's atmosphere.

All the studies of the Great Red Spot demonstrate that such flow features are possible in a steady state without a solid surface to define the shape of the pattern. In the absence of energy dissipation such a flow feature will last forever. Introducing a small amount of dissipation, as is appropriate for Jupiter, will not change the flow patterns appreciably. The energy that would need to be dissipated might be completely provided by the convergence between moist and dry gas and the release of latent heat.

Someday I should like to develop a computer model that works for both Jupiter and the earth. With the appropriate energy sources and sinks, with more stringent boundary conditions, with allowances made for Jupiter's internal heat source and so on the model should realistically predict the behavior of the atmosphere of either planet. Having such a model would mean that we understood terrestrial meteorology at a much deeper level, since the universality of the principles involved would have been tested by their applicability in two independent atmospheric systems.

We want to be useful...and even interesting

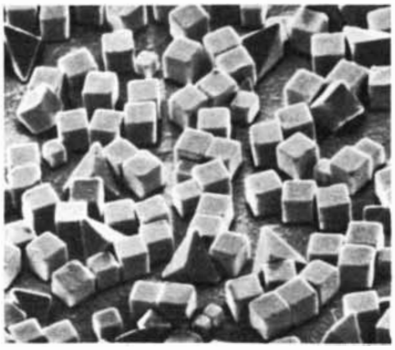


Kenting Earth Sciences Limited, Ottawa, Canada

Silver halide imagery, among other uses, illuminates mankind's path from its past towards its future. Few traces of our forebears are as obvious as Stonehenge. Nor does aerial photography merely lead the ethnographers and archaeologists to interesting sites. They need it as much to see why the sites were chosen. Their disciplines are useful, with pertinence to any regional planning commission caught between the environmentalists and the booster types.

Homo sapiens uses grass fires or nuclear fission, a lichen uses rock-dissolving acids, and both organisms change the surface of Earth in pursuing their respective needs. Seeking a longer perspective and better guide to understanding human needs than the bottom line on an accountant's balance sheet, scholars study photographs of our old planet's surface for subtle clues left in geologically recent times by our kind. The aerial camera is the tool for surface study, just as the shovel and brush are for vertical exploration, but the price of air-survey contracts sometimes frustrates scholars when dealing with people interested in balance sheets.

Let them take heart. All existing aerial photography has not yet been drained of ethnographic excitement. For the sparks to fly, the photography and a specific conceptual framework must strike together. If you've got the concepts, we may have hints on where to find the photography. Just please don't explain the concepts. Our mind is on a balance sheet. State question to E. G. Tibbils, Aerial Mapping Markets, Kodak, Rochester, N.Y. 14650.



Silver halide itself is to colloid science and surface chemistry almost what the colon bacillus and the fruit fly are to genetics. For doing science, a dispersion like this of near-perfect AgBr cubes—ranging narrowly in edge length size around 4 micrometers—has come a long way from the wild type of AgX crystal on which practical photography based itself until rather recently. This is quite aside from the uniquely retentive memory that such a crystal has for a few photons of light. The practical consequences thereof have kept numerous scientists the world around in meat and potatoes. So intensely has interest been focused on this stuff that scientists pursuing pure, fundamental studies in adsorption phenomena, dielectric loss, electrophoresis, light scatter, etc. like to work with silver halide and its extensive literature. If you want the name of someone whose interests run in that direction, try Dr. A. H. Herz, Kodak Research Laboratories, Rochester, N.Y. 14650.

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