GREAT RED SPOT appears somewhat orange in this remarkably detailed photograph made at the Lunar and Planetary Laboratory of the University of Arizona. During the century or so that Jupiter's great red spot has been closely observed its color has reportedly ranged from "full gray" and "pinkish" to "brick red" and "carmine." The photograph was made on December 23, 1966, by Alika Herring and John Fountain, who used a 61-inch reflecting telescope. The exposure was one second on High Speed Ektachrome.

JUPITER'S GREAT RED SPOT

There is evidence to suggest that this peculiar marking is the top of a "Taylor column": a stagnant region above a bump or depression at the bottom of a circulating fluid

by Raymond Hide

The surface markings of the planets have always had a special fascination, and no single marking has been more fascinating and puzzling than the great red spot of Jupiter. Unlike the elusive "canals" of Mars, the red spot unmistakably exists. Although it has been known to fade and change color, it has never entirely disappeared in the 130 years it has been regularly observed. The red spot appears to be embedded in the banded clouds of Jupiter's atmosphere, and its period of rotation about the axis of the planet undergoes slight but persistent fluctuations. For this reason astronomers have generally thought that the spot could not be attached to the solid planet (assuming Jupiter has a solid surface underlying its atmosphere) and that it must be a solid object rather like a huge raft floating in the atmosphere.

An alternative suggestion was put forward in 1961: I proposed that the great red spot might be visible evidence of a hydrodynamic phenomenon essentially similar to a "Taylor column." This is a more or less stagnant cylinder that can be produced in a rotating fluid by either a protuberance or a depression at the base of the fluid. Such columns, which tend to be parallel to the axis of rotation of the fluid, are named for their first investigator, Sir Geoffrey Taylor of the University of Cambridge. According to my hypothesis, the presence of even a shallow topographical feature on the surface of the solid planet, if indeed it be solid, would give rise to a pronounced disturbance in the atmosphere because the planet is rotating so rapidly (one revolution in less than 10 hours). This hypothetical disturbance could well give rise to a permanent marking, such as the red spot, at the top of the cloud layer, where it would be visible to outside observers.

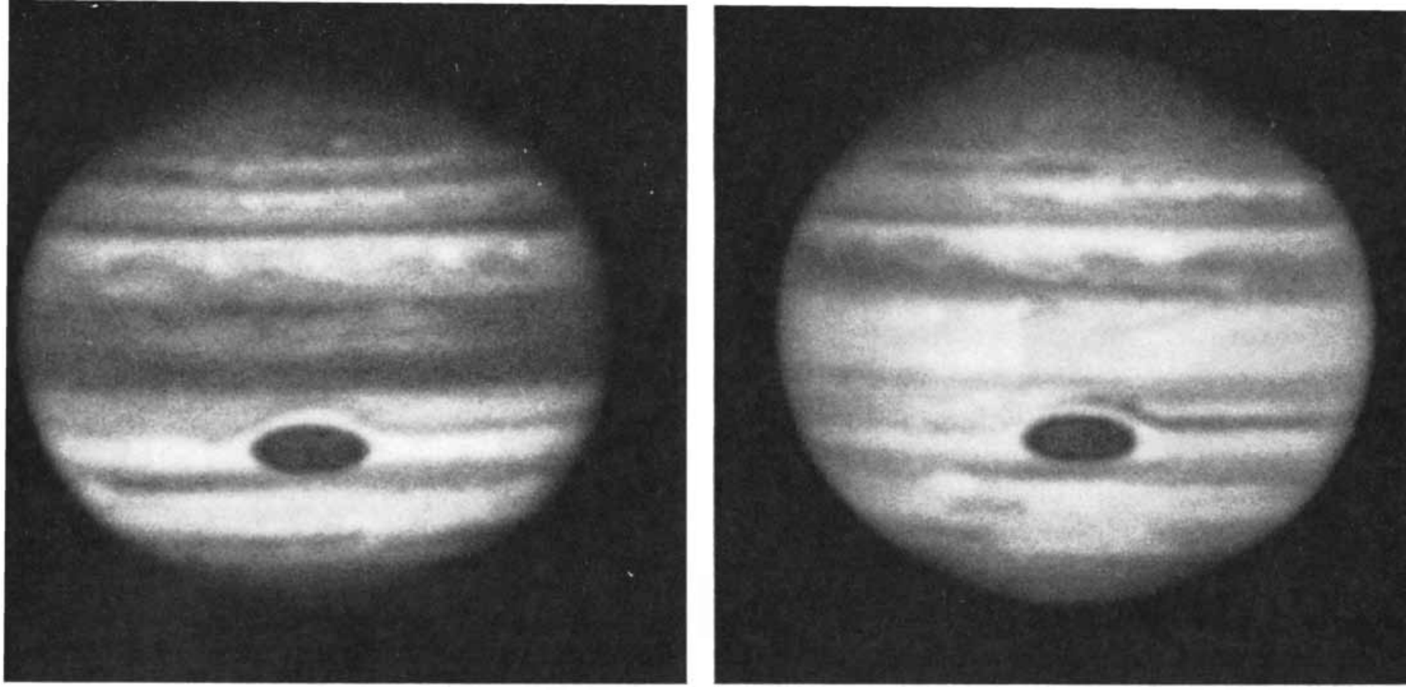
To explain the fluctuations in the red spot's period of rotation one must assume that there are forces acting on the solid planet capable of causing an equivalent change in its rotation period. In other words, the fluctuations in the rotation period of the red spot are to be regarded as a true reflection of the rotation period of the planet itself. Theoretical studies suggest that the fluid regions of Jupiter —its atmosphere and its fluid core, assuming there is one—are together sufficiently massive and well agitated to create the forces needed to alter the planet's speed of rotation. At the same time the topographical feature responsible for the red spot would be kept from wandering in latitude because of the planet's great gyroscopic stability. Indeed, one of the principal objections to the "raft hypothesis" is its apparent inability to explain why the latitude of the spot has remained fixed.

Fifth in order of distance from the sun, Jupiter is a giant among the planets. Its diameter is some 138,000 kilometers (about 86,000 miles), or roughly 11 times the diameter of the earth. Jupiter circles the sun once every 11.8 years. It can be observed profitably for about 10 months out of every 13; the rest of the time it is on the far side of the sun from the earth and its apparent diameter is much reduced. At opposition, when both planets are in line with the sun on the same side of it, Jupiter is twice as bright as Sirius, the brightest star, and its apparent diameter reaches 50 seconds of arc. This corresponds to a 33rd of the diameter of the moon. Among the planets only Venus and occasionally Mars exceed Jupiter in brilliance.

Studies of various kinds indicate that the visible surface of Jupiter is made up of clouds of ammonia and ammonia crystals suspended in an atmosphere that is mainly hydrogen admixed with water and perhaps methane and helium. Other lines of evidence, particularly the fact that Jupiter's density is only 1.3 times the density of water, suggest that the main constituents of the planet are hydrogen and helium. It was once conjectured that Jupiter had a metallic core similar to the core of the earth, jacketed by a thick mantle of ice. Ideas changed in 1951 when William H. Ramsey, then at the University of Manchester, pointed out that the high pressures prevailing deep inside the planet would have the effect of converting hydrogen from its ordinary liquid or solid form into a metallic, electrically conducting form.

Theoretical models of Jupiter's structure based on Ramsey's ideas have since been constructed by a number of workers. Although these models give a fairly complete description of the distribution of density and pressure within the planet, they do not lead to predictions about such important properties as temperature, thermal and electrical conductivity, viscosity and mechanical strength. Moreover, they cannot predict whether the material at the base of the atmosphere is a solid or a liquid. Thus for all anyone knows Jupiter could be fluid throughout [*see illustration on page 79*].

In 1610 Galileo turned his primitive telescope on Jupiter and discovered the four largest of the planet's 13 satellites. Twenty years later Nicolas Zucchi and Daniel Bartoli observed and recorded the large-scale features of Jupiter's visible disk. The most prominent are a series of bright and dark bands, numbering 14 or more, that run parallel to the planet's equator. The bright bands are usually called zones, the dark ones belts [*see top illustration on page*



JUPITER THROUGH BLUE FILTER confirms the visual impression that the light reflected by the great red spot is primarily yellow to red. The equatorial zone brightened markedly in blue light between October 23, 1964 (*left*), and December 12, 1965 (*right*). Photographs on these two pages were taken at New Mexico State University Observatory with either a 12-inch or a 24-inch telescope.

78]. Because the zones and belts present a continually changing pattern it is obvious that they are cloudlike structures in a fluid atmosphere, not markings on the surface of a solid planet. Isolated dark spots and brilliant white areas frequently appear in the zones. At other times an entire belt or a large portion of it will disappear from view and reappear after several weeks or months.

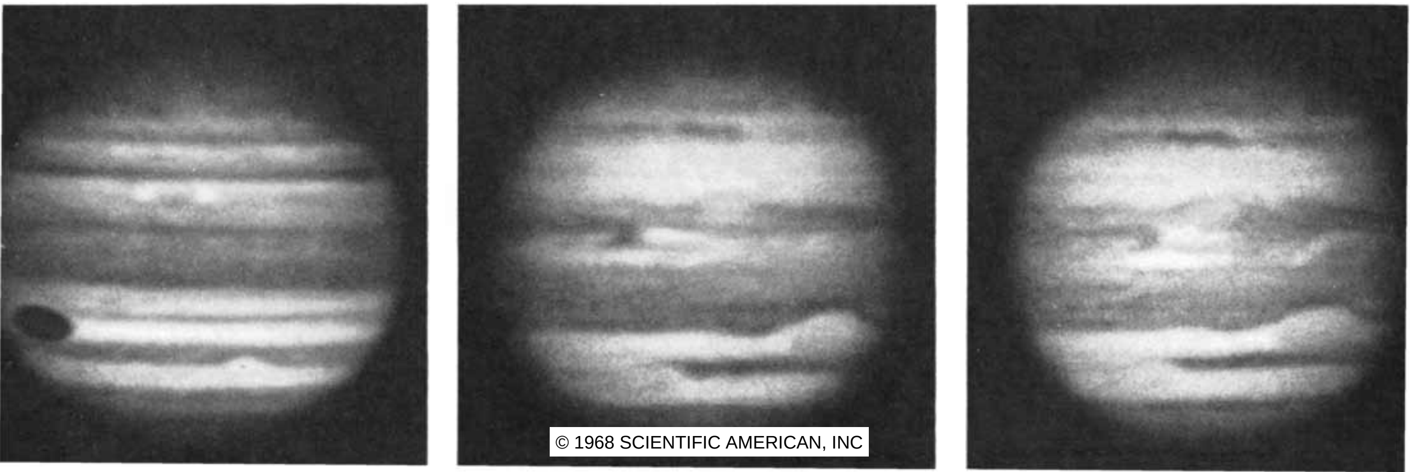
The great red spot was probably first observed in 1664 by Robert Hooke. That same year Giovanni Cassini made drawings of the spot and began recording its period of rotation. He found that it speeded up slightly between 1664 and 1672, when its rotation period, originally nine hours 55 minutes 59 seconds, decreased by five seconds. "Hooke's spot," as it was later called, was observed intermittently until 1713.

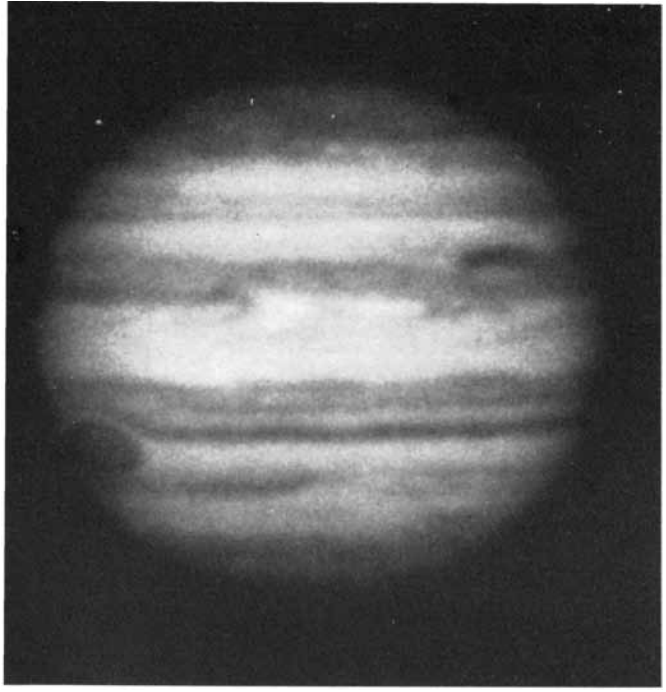
The next known record of the spot is a drawing made in 1831 by Heinrich Samuel Schwabe, the German apothecary who is best known for his discovery that sunspots wax and wane on a cycle of roughly 11 years. Drawings of Jupiter showing the spot were made in 1857 by William Rutter Dawes, an English clergyman, in 1870 by Alfred M. Mayer, an astronomer at Lehigh University [*see bottom illustration on page* 78] and thereafter by many other observers.

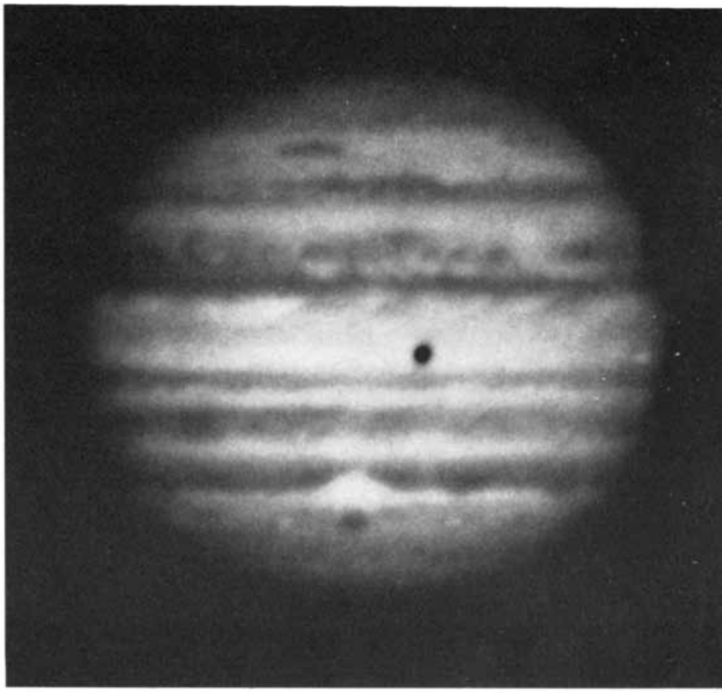
Mayer described his observation of Jupiter with a 15-centimeter refracting telescope in January, 1870, as follows: "I was struck with the beautiful definition and steady sharpness of outline of the details of [Jupiter's] disk, and especially was my attention riveted on a ruddy elliptical line lying just below the South Equatorial belt.... This form was so remarkable that I was at first distrustful of my observation; but...I perceived that the ellipse became more and more distinct as it advanced toward the centre of the disk." Mayer believed the feature he was recording had "never before been noticed."

The great red spot became so conspicuous in 1879 that it was widely publicized; it was then that the spot received its present name. In 1882 the spot began to fade. Its decline was so steady that by 1890 astronomers believed it would eventually disappear. By 1891, however, the fading had halted and was

TWO-COLOR SERIES taken on November 8 and 9, 1964, makes it possible to compare the markings on Jupiter as seen in blue light (*left*) and in red light (*middle and right*). The two photographs at the right, which were taken only 30 hours apart, show how cloudlike structures in the equatorial zone can change quite considerably in the time required for the planet to make only three rotations.







JUPITER THROUGH GREEN FILTER shows the planet with the red spot visible (*left*) and out of sight on the far side of the planet (*right*). Extensive changes in band structure took place between October 29, 1965 (*left*), and March 2, 1967 (*right*). The dark spot near the equator at right is the shadow of Jupiter's third largest satellite Io, which is a barely visible white spot near the right limb.

soon reversed. Although the spot has varied since then, it has never disappeared from view.

Any acceptable theory of the great red spot must account for its principal properties without being at variance with what is known about the planet as a whole. These properties can be listed as follows.

First, the spot has a specific size, position and form. It is an ellipse about 40,000 kilometers long and 13,000 kilometers wide, centered on about 22 degrees south latitude. The spot is roughly equal in area to the entire surface of the earth. Its shape, size and orientation undergo slight fluctuations.

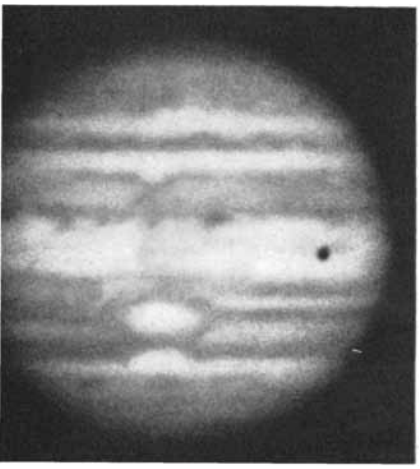
Second, the spot has a rotation period that fluctuates by more than 10 seconds [*see top illustration on page 80*]. These fluctuations, when plotted as variations in longitude with respect to a mean period, show that the spot has at times advanced or fallen back as much as 500 degrees. Significant accelerations of this motion occurred in 1880, 1910, 1926 and 1936, years when the spot was also very conspicuous.

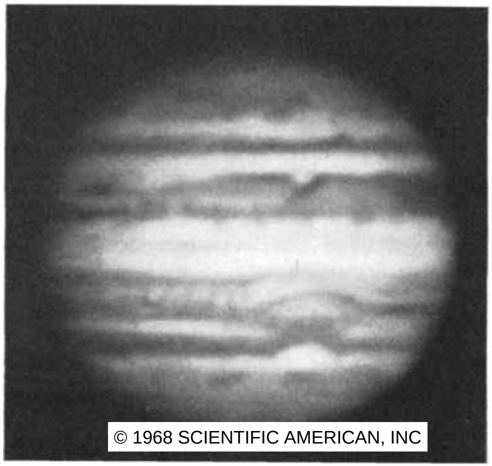
Third, the spot exhibits only slight excursions in latitude. In fact, variations in the latitude of the center of the spot have never exceeded the probable error of measurement.

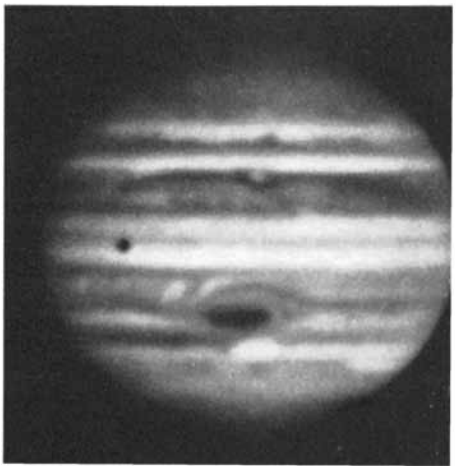
Fourth, the spot is associated with a persistent indentation, known as the red spot hollow, in the southern boundary of the south equatorial belt. On no occasion have the hollow and the spot been simultaneously absent.

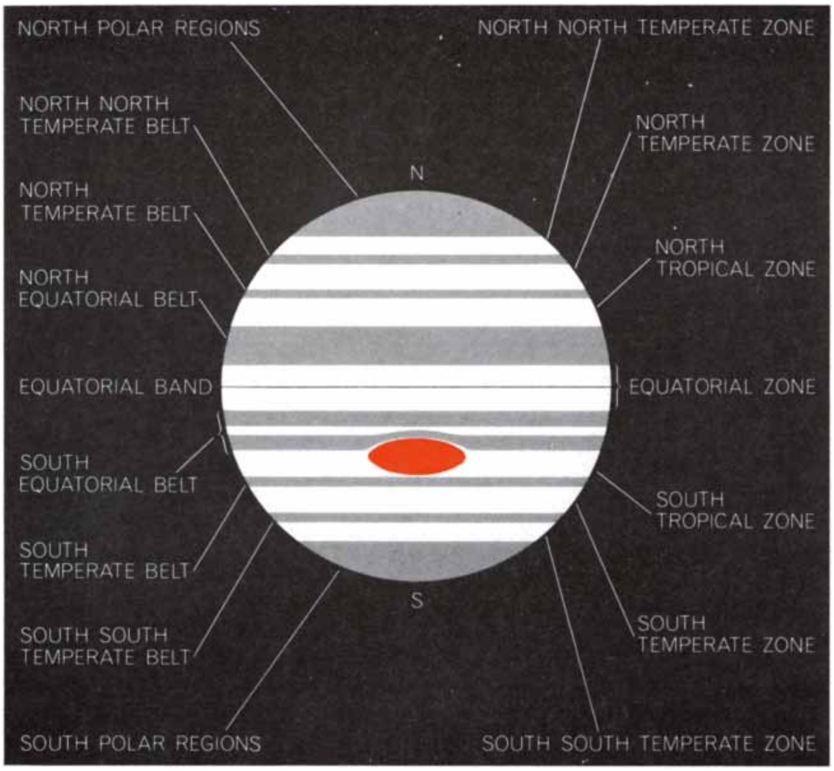
Fifth, the spot has interacted in a specific way with a phenomenon called the south tropical disturbance. The disturbance made its appearance in 1901 as a short dark streak in the south tropical zone some distance from the red spot. Eventually it grew in length until it stretched nearly two-thirds of the way around the planet. In 1939 the disturbance vanished, seeming to give way to three "bright ovals" that can still be seen in the belt just south of the red spot. The rotation period of the disturbance was somewhat less than that of the red spot, and the two features came in contact on nine occasions. The most remarkable behavior at these conjunctions was

THREE-COLOR SERIES was made in March, 1967. The red-light view (*left*) was taken on March 4, only 32 minutes before the green-light view (*middle*). The elliptical shape below the great red spot is one of three "bright ovals" in the south temperate belt. The blue-light view (*right*), taken 17 rotations after the green-light view, shows that the ovals travel slightly faster than the spot.

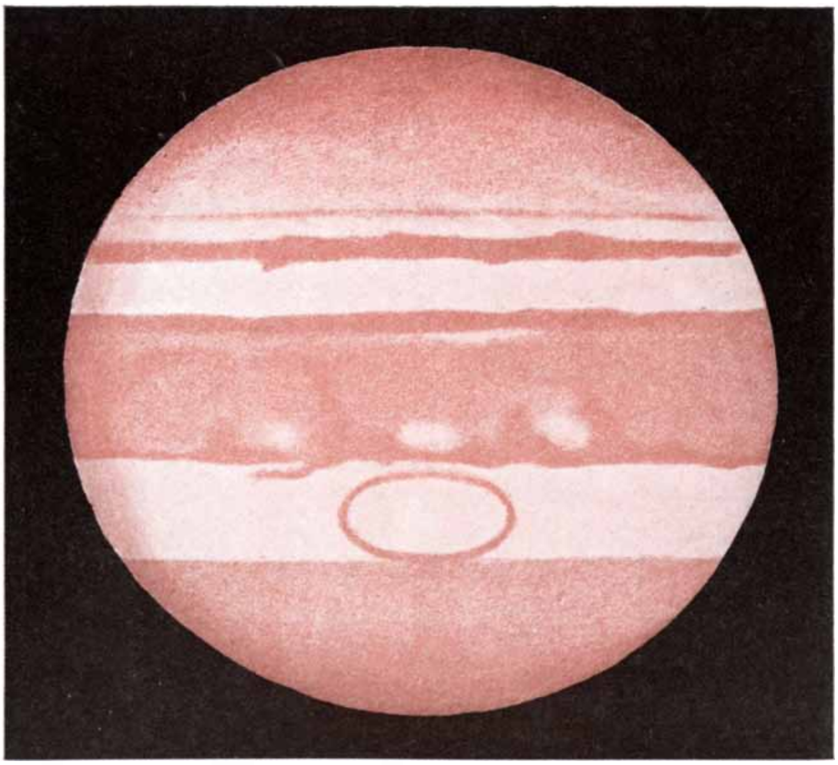








JUPITER'S BANDS are commonly called zones if they are bright and belts if they are dark. At any given time some of the bands may be indistinct or even absent. Nevertheless, most of the zones and belts shown here can be identified in the photographs on the preceding pages.



THE RED SPOT IN 1870 was drawn by Alfred M. Mayer of Lehigh University and published in a paper titled "Observations of the Planet Jupiter." A feature now believed to be the red spot was first reported in 1664 by Robert Hooke. For more than 200 years the spot had attracted so little attention that Mayer wrote in his account that the "ruddy elliptical [feature] lying just below the South Equatorial belt...has never before been noticed."

the tendency for the disturbance to skirt around the edge of the red spot at about 10 times the speed with which it approached the spot and receded from it.

Sixth, the color of the spot seems to fluctuate, although the changes are hard to measure. At its faintest the spot has been described as "full gray" and "pinkish" and at its most prominent as "brick red" and "carmine." In black-and-white photographs made through colored filters the spot usually shows up very dark when the filter is blue and is almost invisible when the filter transmits only red or infrared. In 1963, using the 200-inch telescope on Palomar Mountain, Bruce C. Murray and his colleagues at the California Institute of Technology compared the infrared emission of the spot with the emission of surrounding areas. They found that the temperature of the spot was about 127 degrees Kelvin (degrees centigrade above absolute zero), or about two degrees cooler than the adjacent regions.

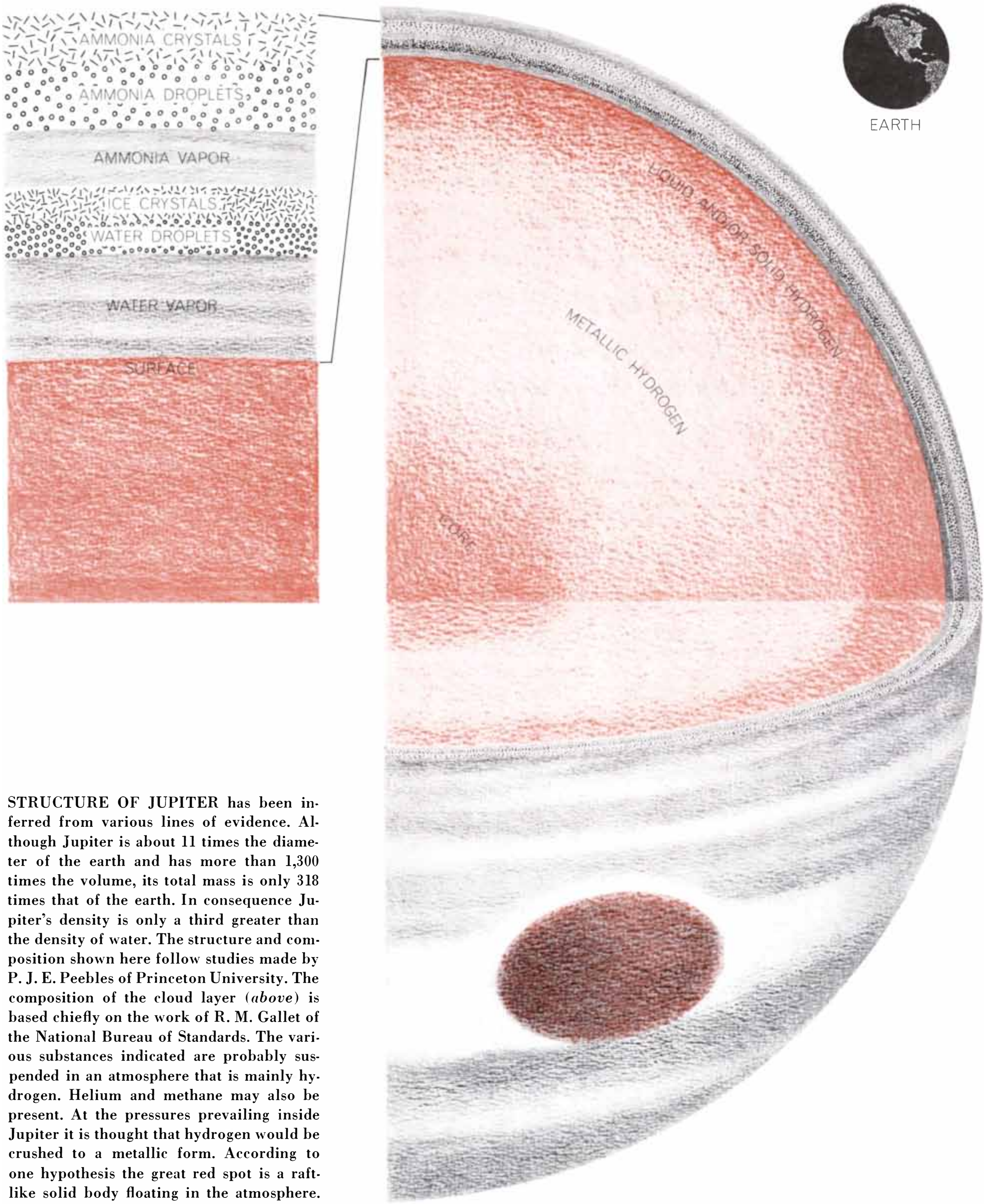
Finally, a truly satisfactory theory of the great red spot should be able to explain its uniqueness. Why are there not several spots of various sizes? Until evidence to the contrary is provided, the theorist must also assume that the red spot is a permanent feature that has existed for thousands or millions of years.

The great red spot is such a weird phenomenon that few serious attempts have been made to account for it. The raft hypothesis seems to have been first proposed in 1881 by G. W. Hough in his annual report for the Dearborn Observatory. One of its strongest advocates was Bertrand M. Peek, an amateur astronomer whose book *The Planet Jupiter* contains a valuable collection of visual observations of the planet. He proposed that the raft was mainly made up of several solid forms of water that have been produced in the laboratory at high pressures. Peek suggested that the fluctuations in the red spot's rotation period might be due to slow variations in the depth at which the raft floated in the planet's atmosphere. He also proposed that as the raft rose and fell one form of ice would change into another form with a consequent absorption or release of heat that might account for the variations in the appearance of the spot.

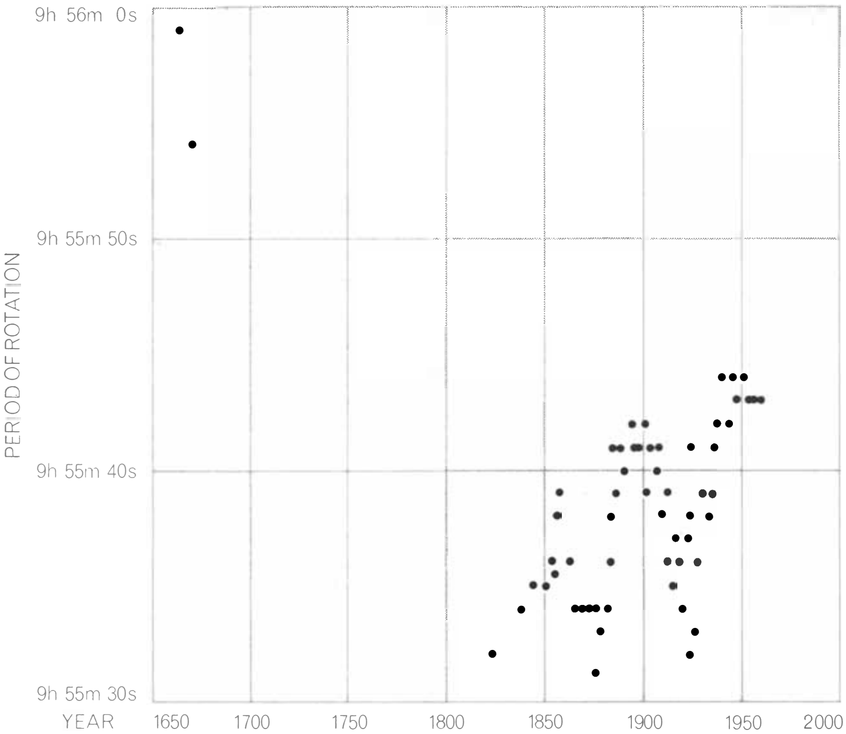
In a recent appraisal of the raft hypothesis Wendell C. DeMarcus of the University of Kentucky and Rupert Wildt of the Yale University Observatory said: "It has proved difficult to conceive of an object able to float in a surfaceless ocean of... hydrogen gas." They assert, however, that in principle the red spot could be a solid object with the same density as the fluid surrounding it and having the same constituents but in different proportions.

When the hypothesis has been fully tested against observation and when its other consequences have been carefully examined, it may well look more attractive than it does now. For example, Robert H. Dicke of Princeton University has suggested that Jupiter's atmospheric winds, being strongly channeled in zones parallel to the equator, might inhibit any tendency for a raft to drift in latitude. If this is so, one of the strongest objections to the raft hypothesis would be removed. One would still be puzzled, however, as to why Jupiter's atmosphere contains only one such object and how it resists disruptive forces.

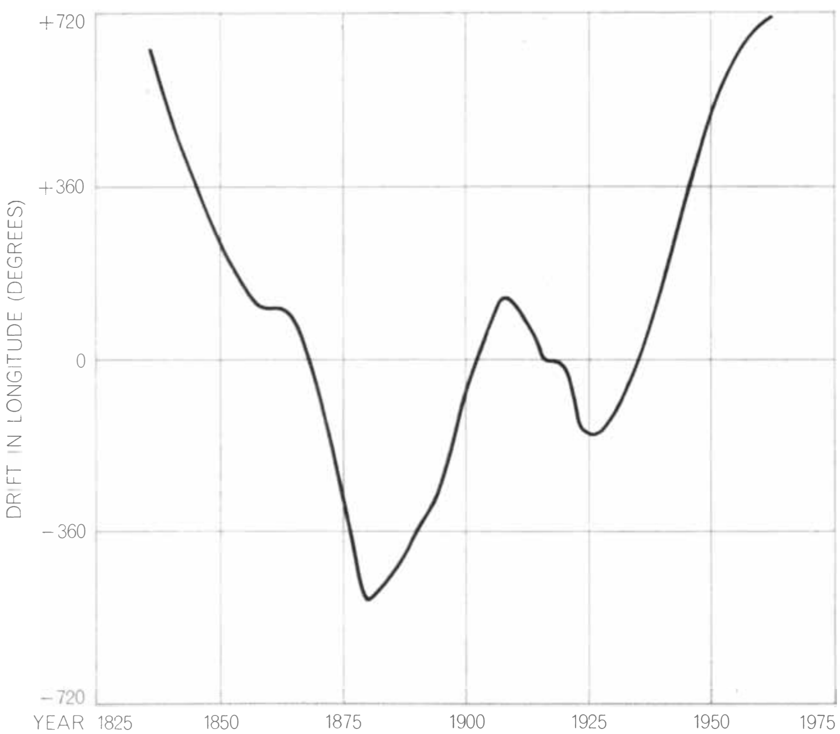
The Taylor-column hypothesis avoids many of the problems that beset the raft hypothesis. I should point out, however, that a raft could also give rise to a Taylor column. In what follows, therefore, I shall use "Taylor-column hypoth-



STRUCTURE OF JUPITER has been inferred from various lines of evidence. Although Jupiter is about 11 times the diameter of the earth and has more than 1,300 times the volume, its total mass is only 318 times that of the earth. In consequence Jupiter's density is only a third greater than the density of water. The structure and composition shown here follow studies made by P. J. E. Peebles of Princeton University. The composition of the cloud layer (*above*) is based chiefly on the work of R. M. Gallet of the National Bureau of Standards. The various substances indicated are probably suspended in an atmosphere that is mainly hydrogen. Helium and methane may also be present. At the pressures prevailing inside Jupiter it is thought that hydrogen would be crushed to a metallic form. According to one hypothesis the great red spot is a raftlike solid body floating in the atmosphere.



ROTATION PERIOD OF GREAT RED SPOT has varied considerably in the 135 years since it has been recorded with care. The variation is even greater if the earliest observations of Giovanni Cassini, made between 1664 and 1672, are regarded as accurate. It was long thought that a feature with such a variable period could not be connected in any way with the surface of the "solid" planet below, which one would expect to rotate with great constancy. But if the author's hypothesis is correct, the red spot is produced by a surface feature, either a raised area or a depression, and the planet's rotation rate is indeed variable.



LONGITUDINAL WANDERING OF RED SPOT can be visualized by defining a mean period of rotation and plotting in degrees how much the spot advances or retreats with respect to the mean. The diagram is based on one in *The Planet Jupiter*, by Bertrand M. Peek.

esis" to mean a hydrodynamic phenomenon caused by an irregularity on the surface underlying Jupiter's atmosphere.

In the simplest conceivable fluid system, in which the fluid has uniform density and zero viscosity, the effects of rapid rotation on hydrodynamical flow can be expressed in terms of a theorem first proposed in 1916 by James Proudman of the University of Liverpool. This theorem simply states that the flow must be the same in planes perpendicular to the axis of rotation.

In 1921 Sir Geoffrey Taylor recognized, and verified by experiment, an important implication of Proudman's theorem: If a solid object were to be moved slowly through a rotating tank of fluid, the object would carry with it a relatively stagnant column of fluid aligned parallel to the axis of rotation. Taylor columns can also be created by irregularities such as bumps and corrugations at the bottom of a rigid container when the fluid is in motion with respect to the container.

In considering whether a topographical feature on the surface of Jupiter might give rise to a Taylor column it is important to know how high (or alternatively how deep) the feature must be to be effective. It turns out that the height (h) must exceed a value determined by a relation involving the total depth of the fluid (D), the horizontal dimension of the topographical feature (L), the speed of the fluid over the feature (U) and finally the angular speed of rotation of the entire system (Ω). Specifically, the value of h must exceed $D(U/2L\Omega)$, all expressed in appropriate units.

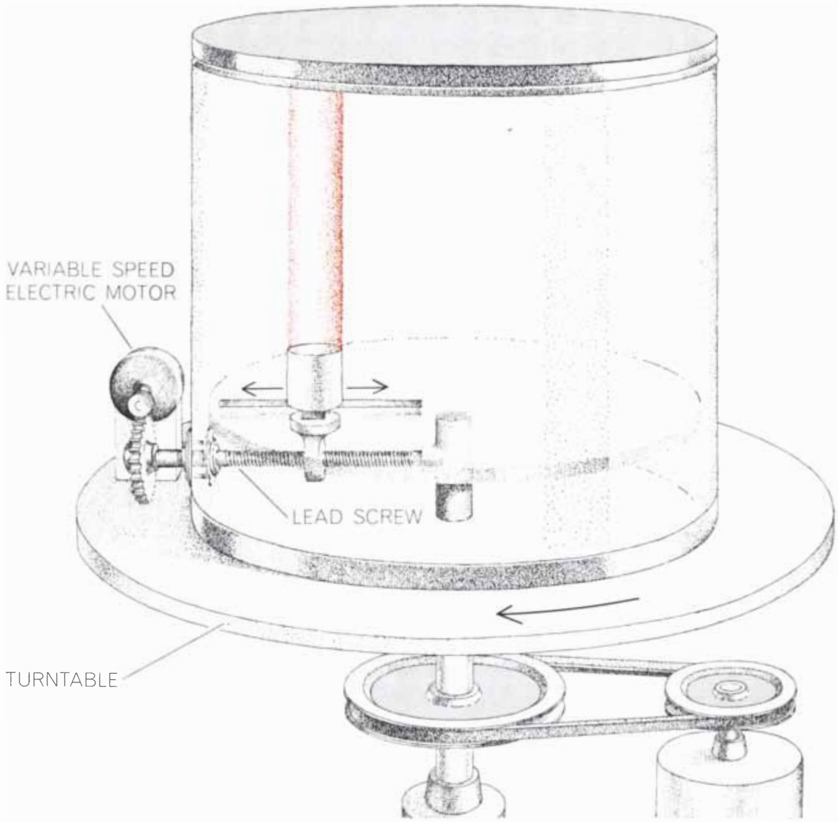
To investigate this relation, one of my students, Alan Ibbetson, and I conducted a series of laboratory experiments [*see illustrations on opposite page*]. In addition to confirming the relation, we found that some of the details of the flow patterns we observed have their counterparts in the theoretical studies of Taylor columns in fluids of zero viscosity conducted by Keith Stewartson of University College London and by Michael J. Lighthill of the Imperial College of Science and Technology. Nevertheless, certain questions concerning Taylor columns remain unanswered; both theoretical and experimental work are being continued.

The extent to which a planet's rotation influences the flow of its atmosphere depends chiefly on its size and rotation speed. The linear speed of Jupiter's surface owing to the planet's rotation is more than 25 times that of the earth. Consequently Jupiter's rotation dominates the winds in its atmosphere even more effectively than the earth's rotation dominates terrestrial winds. A measure of this "domination" is the Rossby number (R), named for the Swedish meteorologist Carl-Gustaf Rossby. This number is equal to $U/2L\Omega$, which is the factor multiplied by D in the equation given above. The smaller the Rossby number, the larger the dominance of rotation. R for large-scale motions in the earth's atmosphere is about .1. The corresponding value of R for Jupiter's atmosphere is .0002 (except near the equator, where R is .01).

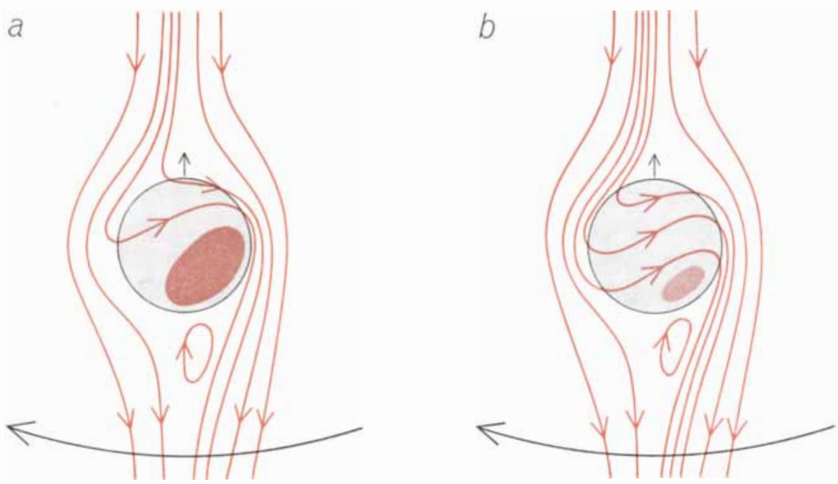
Any realistic discussion of Jupiter's meteorology would have to take account of many complicating factors, such as the nonuniform density of the planet's atmosphere and the possible effects of magnetic fields. In a first approximation, however, the complicating effects are not expected to vitiate the essential idea behind the Taylor-column hypothesis. In any case, the banded appearance of Jupiter makes it clear that large-scale winds on Jupiter must blow mainly parallel to the equator along circles of latitude, showing that the rotation of the planet indeed dominates the motions of the atmosphere.

In order to estimate the height (or depth) of a topographical feature capable of creating a Taylor column in Jupiter's atmosphere, we proceed as follows. We begin with the assumption that the atmosphere is underlain by a material of such high viscosity that it flows very much more slowly than the atmosphere; this material is the "solid" planet.

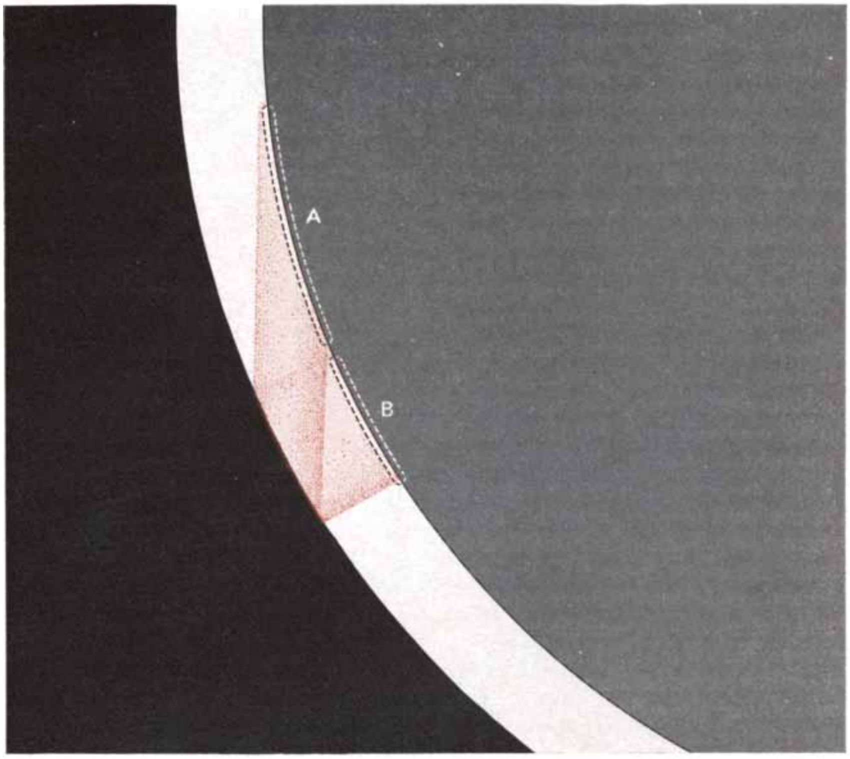
For the sake of carrying out a fairly definite calculation let us make the innocuous assumption that the depth (D) of Jupiter's atmosphere is 3,000 kilometers. Since the red spot itself is about 40,000 kilometers long let us use this as the value of L, the major horizontal dimension of the topographical feature. A plausible value for the velocity (U) of the wind passing over the surface might be two meters per second, or about four miles per hour. For this value of U the Rossby number is .0004. If one inserts these values into the preceding equation, one finds that a Taylor column will be produced if the height (or depth) of the topographical feature exceeds only one kilometer. By earth standards this is a very modest dimension, but until more is known about the mechanical properties of the "solid" part of Jupiter one cannot be sure that a topographical feature one kilometer high could in fact be supported against gravitational forces nearly three times those on the earth. The Tay-



TAYLOR-COLUMN EXPERIMENT was carried out by the author and Alan Ibbetson, using the apparatus diagrammed here. A liquid, usually water, was rotated at a uniform speed in a cylindrical tank 12.2 centimeters deep and 14.5 centimeters in radius. A short cylindrical obstacle of variable height was mounted so that it could be driven slowly across the radius of the rotating tank. The author and his colleague established the conditions under which a stagnant column of liquid, a Taylor column, would form above the obstacle.



FLOW PATTERNS OVER OBSTACLE in the experimental tank were drawn by the author and Ibbetson, who observed the streaks made by a dye tracer about 10 centimeters above the obstacle, which projected about two centimeters from the base of the tank. The obstacle was moved toward the center of the tank at various speeds while the tank and liquid rotated at about 40 r.p.m. A Taylor column formed (*colored ellipse in "a"*) when the obstacle was moved at 1.2 centimeters per minute. When the rate was increased to nine centimeters per minute (*b*), flow was diverted but no pronounced Taylor column was visible.



TAYLOR COLUMN ON JUPITER, which the author believes accounts for the great red spot, might assume various orientations with respect to either a plateau or a depression on the surface of the planet. In the simplest theoretical case (*A*) the axis of the column would be parallel to the planet's axis of rotation. But depending on the characteristics of the planet's atmosphere and other variables, the Taylor column might rise more or less vertically (*B*) above the surface feature. The depth of the atmosphere is unknown, hence not to scale.

lor column would not necessarily rise vertically over the surface feature. In the simplest case the column would have its axis parallel to the axis of rotation of the planet [*see illustration above*].

Perhaps the most obvious weakness of the Taylor-column hypothesis is one it shares with the raft hypothesis: Why should there be only one such feature or object? There is, however, a lead toward an explanation of the uniqueness of the Taylor column in Jupiter's atmosphere that has no ready analogy in the case of a raft. The conditions for creating a Taylor column discussed above show that for a given wind speed a column would not form over a topographical feature of a kilometer in height if its horizontal dimensions happened to be much less than 40,000 kilometers.

If, however, Jupiter's atmospheric winds are sufficiently variable and occasionally shift from one semistable pattern to another, it should be possible for such topographical features to give rise temporarily to Taylor columns. Clark Chapman, working in my former laboratory at the Massachusetts Institute of Technology, recently made a search for such columns, using a large amount of observational data supplied mainly by Bradford A. Smith and his colleagues at New Mexico State University. He found none. However, J. H. Focas of the Meudon Observatory in France has reported seeing "false red spots" in various locations not far from the red spot itself. Conceivably these are eddies in the downstream wake produced by the Taylor column underlying the red spot.

The other properties of the great red spot are in principle readily accounted for by the Taylor-column hypothesis. For example, the variable rotation rate of the red spot must reflect the variable rotation rate of the main mass of Jupiter. This may seem difficult to accept, involving as it does huge changes in the planet's angular momentum, but a variable rotation rate is by no means inconceivable. Since Jupiter does not rotate as a solid body, it must be constantly agitated by some energy source or other. Various lines of evidence suggest that Jupiter may still be contracting. Although the contraction would be much too slow for verification by direct observation, it could still convert gravitational energy into internal heat energy at a significant rate (a rate comparable, in fact, with the amount of solar energy received by the planet).

If the changes in the rotational energy of Jupiter were brought about entirely by frictional processes, the associated dissipation of heat would be quite excessive. The mechanical coupling between different parts of the planet need not, however, be due only to friction. The electrical conductivity of most of Jupiter's interior and lower atmosphere should be high enough for the internal magnetic field of the planet to contribute significantly to mechanical coupling. In contrast to frictional coupling, which transforms rotational energy irreversibly into heat, magnetic coupling transforms rotational energy reversibly into magnetic energy. The magnetic field involved will be mainly of the toroidal type, with a strength probably exceeding 1,000 gauss.

Observations of the intense bursts of radio emission from Jupiter provide information about the part of the magnetic field whose lines of force pass through the surface of the planet and out into surrounding space. This part of the magnetic field (the "poloidal" part) is probably much weaker than the internal toroidal field. The significance of the external field for this discussion is that the pattern of radio emission associated with it has its own period of rotation, which differs slightly from the rotation period of the great red spot. This difference, which amounts to several seconds, is expected on the Taylor-column hypothesis because the red spot motion is the motion of the "solid" planet, whereas the radio emission is related to the motion of the fluid parts of the planet where the magnetic field originates.

It will be interesting and most important, therefore, to compare future observations of the radio period with those of the red spot period, with the expectation of learning more about the dynamics and magnetohydrodynamics of Jupiter's interior. As one investigator has remarked: "This is the first instance in astronomy [where] the distribution of angular momentum within a rotating body... manifests itself in observational effects measurable within a short time scale." Meanwhile observers will continue to find the red spot a fascinating object. Their studies can hardly fail to turn up evidence that will help to support either the raft hypothesis or the Taylor-column hypothesis. And, of course, there is always the chance that someone will have a still better idea.

Statue of Benjamin Franklin by James Earle Fraser in The Franklin Institute, Philadelphia

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