Jupiter's Atmosphere

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Why do we study the atmospheres of other planets? The earth's atmosphere is easier to observe. It has more relevance to our lives. And we already know a good deal about it. Routine weather forecasts are now reasonably useful for two days after the forecast is made. Long-term forecasting of average conditions for a month or more may soon become useful. And meteorologists are trying to forecast the climate over periods of hundreds or thousands of years. But there is a basic problem: We have only one earth, and we have only studied it under one set of external conditions. We can't change the earth's orbital position, or its spin rate, or the composition of its atmosphere, and therefore we don't have a complete understanding of how the system would behave under different conditions.

This is where the planets come in. Studying the planets gives us a chance to test our theories in a broader context. Among other things, this testing should give us a better idea of the range of possible climates for the earth and how the earth's atmosphere might respond to changes in some of the external conditions.

Consider Jupiter's atmosphere. Mars and Venus might make equally interesting stories, but cloud patterns on Jupiter are easier to observe than on other planets, and some striking comparisons with the earth can be made. First, there are linear features, the dark belts and light zones that circle the planet on lines of constant latitude. Such a high degree of axisymmetry is not observed on the earth. Second, there are giant circular or elliptical features, like the Great Red Spot, whose lifetimes are tens or hundreds of years. On the earth, the lifetimes of similar features are one or two weeks.

Other differences between the earth and Jupiter that are relevant to atmospheric studies include the immense scale of phenomena on Jupiter—the diameter of the Red Spot is greater than that of the earth, for example; the rapid rotation of the planet—about 10 hours for Jupiter vs. 24 hours for the earth; the probable absence of any solid surface except perhaps at the planet's central core; and the presence of an internal heat source whose integrated intensity may be as much as twice that of the sunlight absorbed by Jupiter. These differences, and others we may not have thought of, are all connected in some way, but the entire puzzle has not yet been assembled.

Part of the work involves building theoretical models, and here it is important to have a good set of criteria for testing such models. First, the theory must be consistent with all reliable observations of the planet. Second, it must be consistent with basic physics—thermodynamics and fluid dynamics as applied to the earth's atmosphere, for instance.

Theories that satisfy these constraints can then be tested in several ways. If the theory is a dynamical one, the resulting flow patterns must be dynamically stable. For example, I once ran some simulations of the Great Red Spot on the computer, and found that the initial elliptical flow pattern quickly broke up into a complicated pattern of waves and eddies. That model was soon discarded.

It is also desirable to have a theory that ties together two or more different types of observations that previously had no logical connection. For instance, from the trajectories of small spots in and around the belts, zones, and the Great Red Spot, it is possible to infer where rising motion is occurring. This inference is made with the help of a theoretical model. The model can then be tested using infrared observations which indicate cloud heights, since high clouds are a sign of rising motion.

Several outcomes are possible: Either high clouds are observed where rising motion is expected, or they are observed where sinking motion is expected, or else there is no correlation. (In fact, the correlation is strong and positive.) Such tests are useful for eliminating theories, and when enough tests are applied together, they can help identify the correct theory.

One test is to consider the long lifetimes of atmospheric features on Jupiter. The only permanent features in the earth's atmosphere are associated with topography—the distribution of continents and oceans. However, most models of the interior of Jupiter—which are based on the inferred properties of hydrogen and helium at high pressures and the observed mass, radius, and moment of inertia of Jupiter—indicate that the interior is too hot for solids to form. This leaves us with the difficulty of explaining how the belts and zones, the Great Red Spot, and other atmospheric features could have existed for so long without any solid structures to hold them together.

Basically, there are two ways an atmospheric flow feature might cease to exist. It might become hydrodynamically unstable and break up into waves and eddies. Or it might simply run down due to loss of energy by mechanical friction or thermal radiation. The stability question is now being studied. There are various possible modes of instability, and thus far it has always been possible to adjust the model so that the flow remains stable when a new mode is introduced. However, an important fact suggests that radiative decay of thermal energy is the ultimate limiting process.

On the earth, the adjustment time for an air mass to reach thermal equilibrium in a new environment is about two weeks. On Jupiter, this time is on the order of 100 years. The difference is due to the large mass and large heat capacity of the cloudy part of Jupiter's atmosphere, as well as the low temperatures and low radiative fluxes. The important fact is that these thermal lifetimes are about equal to the actual lifetimes of atmospheric features on these two planets. Apparently thermal processes, which provide the basic energy source for atmospheric motions, also provide the ultimate mechanism for decay of such motions.

Is the Great Red Spot governed by the same mechanism that governs other flow features in Jupiter's atmosphere? Close-up images of Jupiter taken recently by the Pioneer 10 spacecraft show at least one other spot, about one-third the size of the Red Spot, with a similar appearance. This second red spot is located in the most prominent zone of the northern hemisphere, exactly where one would expect it to be by analogy with the Great Red Spot, which is in the most prominent zone of the southern hemisphere. This observation lends support to the idea that such spots are controlled by and are part of the general atmospheric circulation.

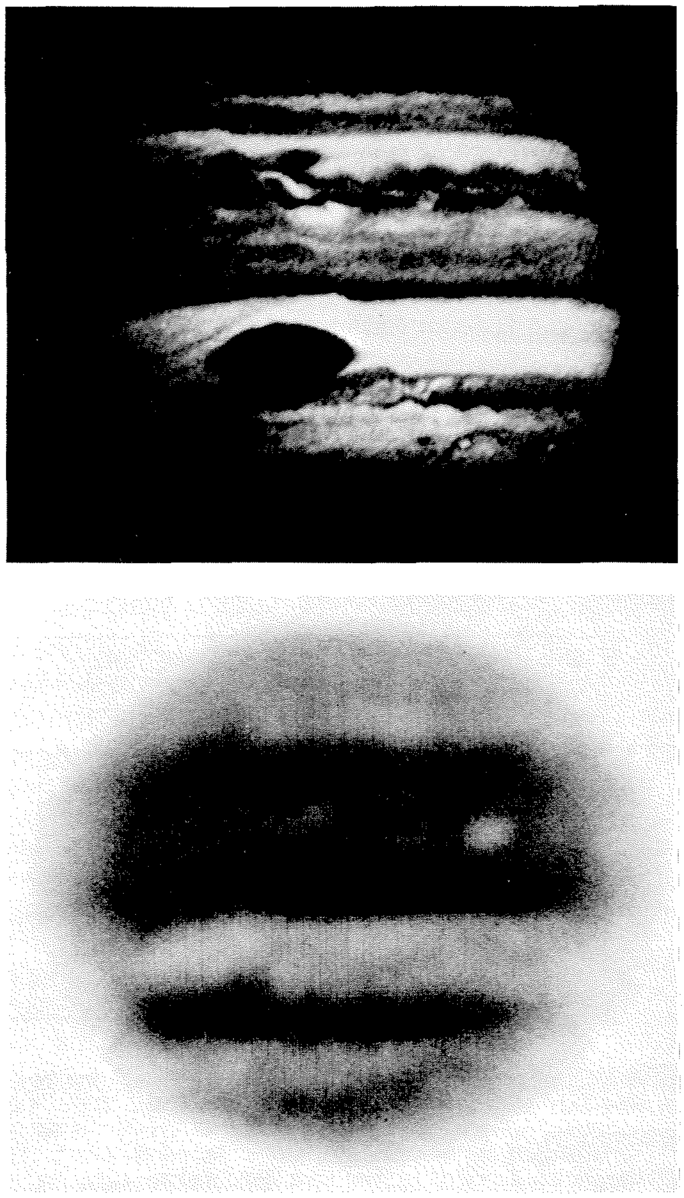
The same conclusion is reached if one compares the Great Red Spot with the belts and zones as in the table below. The zones and the Red Spot are similar in all important respects except for their shape. The belts are the reverse of the zones in all respects. Taken together, these data suggest that the belts, zones, and Great Red Spot are all part of the same phenomenon.

Infrared observations (Column 2), including James Westphal's observations at 5-micron wavelength (page 41), and Pioneer 10 observations at longer wavelengths (lower right), indicate that the infrared emission tempera-

CLASSIFICATION OF JOVIAN ATMOSPHERIC FEATURES

1. Feature	2. Infrared	3. Cloud height	4. Vorticity	5. Pressure	6. Temperature	7. Vertical velocity	8. Expected cloud	9. Color
Belt	Hot	Low	Cyclonic	Low	Cold	Down	Low, thin	Dark
Zone / Red Spot	Cold	High	Anticyclonic	High	Hot	Up	High, thick	White, orange

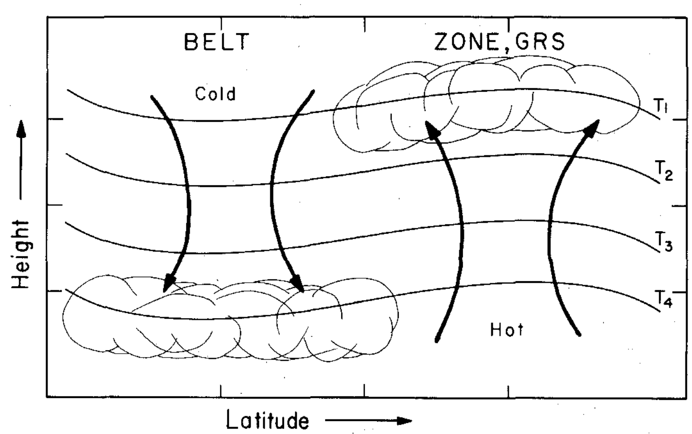
Studying the atmospheres of other planets gives us a better idea of how the earth's atmosphere might respond to changes in external conditions



Two images of the same side of Jupiter, taken by the Pioneer 10 spacecraft. At the top is a photograph in visible light (reflected sunlight). The belts and zones are the dark and bright linear features, respectively. In color photographs, the Great Red Spot has a distinct red color which distinguishes it from the belts. The lower picture is an image in the far infrared (thermal emission) at 40-micron wavelength. The belts are darker than the zones or the Red Spot, indicating higher emission temperatures. The Red Spot is light, indicating a particularly low emission temperature.

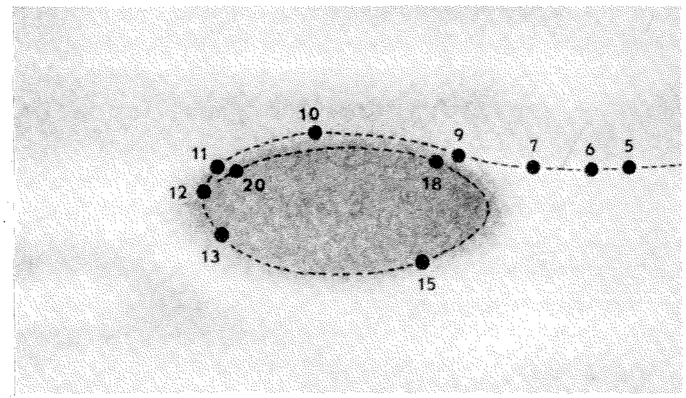
tures are higher in the belts than in the zones or the Red Spot. This could be due either to the belts being hotter at the same level in the atmosphere, or to our seeing to a deeper, hotter level in the belts than elsewhere. The former possibility can be ruled out on the basis of observed winds in Jupiter's atmosphere, since winds are associated with temperature differences at the same level, and observed infrared temperature differences are much too large to be consistent with observed winds. Thus we are seeing two different levels, which implies high thick clouds in the zones and Red Spot, and low transparent clouds in the belts (Column 3 of table on page 35). The situation is illustrated schematically below.

A separate line of reasoning proceeds from the observed motions of small spots in Jupiter's atmosphere (right). The relative rotation, or vorticity, is always anticyclonic (clockwise in the northern hemisphere, counterclockwise in the southern hemisphere) for the zones and Great Red



A schematic cross-section of a belt-zone pair or a belt and the Great Red Spot (GRS). Heavy curved lines show vertical motion. Quasi-horizontal, wavy lines show the location of constant-temperature surfaces, and are labeled at the right of the figure with $T_n > T_{n-1}$. Clouds are indicated by light lines. Note that the zones and GRS are warmer than the belts at the same height in the atmosphere, although cloud-top temperatures are greater in the belts.

Spot, and is always cyclonic for the belts (table, Column 4). And because of Coriolis forces due to the planet's rotation, this implies that the zones and Red Spot are high-pressure regions, whereas the belts are low-pressure regions (Column 5)—at least at the level we observe, near the cloud tops. However, high pressures at the cloud tops imply high temperatures inside the cloud, because hot air columns expand upward. (The deep atmosphere below the clouds prevents air columns from expanding downward.) So, from the observed winds, we infer that the zones and Red Spot



The motion of a small spot in the vicinity of the Great Red Spot in 1968. The numbers refer to successive earth days on which the spot was observed. South is at the top. Typical velocities are about 50 m/s. (Courtesy of New Mexico State University Observatory.)

have higher temperatures than the belts at the same altitudes inside the cloud (Column 6). But high temperatures in this sense imply upward motion (Column 7), and upward motion implies clouds (Column 8), which agrees with the infrared observations showing that clouds are indeed more abundant in the zones and Red Spot than in the belts (Column 3).

The colors of Jovian atmospheric features are perhaps the most difficult to explain (Column 9). The principal condensable vapor, ammonia, forms a white frost. However, a variety of colors are possible if the vapor includes complex carbon compounds and elements such as sulfur and phosphorus, which have not yet been detected in Jupiter's atmosphere but which are inferred to be present. If they are present, pressure and temperature changes associated with vertical displacement could then account for differences in color from one region to the next. Generally, a bright white or red color is associated with zones and the Great Red Spot, whereas the belts are always darker and more blue.

All of these arguments suggest that the Red Spot and zones are regions of well-developed clouds, anticyclonic vorticity, and rising motion, whereas the belts are regions of depressed clouds, cyclonic vorticity, and sinking motion. In many respects, the zones and the Red Spot resemble a terrestrial hurricane viewed from outside the atmosphere. Both have low infrared temperatures due to their high clouds, in spite of their warm interiors. And both have anticyclonic circulation at upper levels, in spite of the different conditions at the lower boundaries. The lower boundary is important, however, because a terrestrial hurricane receives its energy from condensing water vapor evaporated off the warm ocean surface. It is not yet clear whether Jupiter's deep atmosphere can supply energy to the Red Spot and zones in an analogous way, from condensation of ammonia and water vapor.

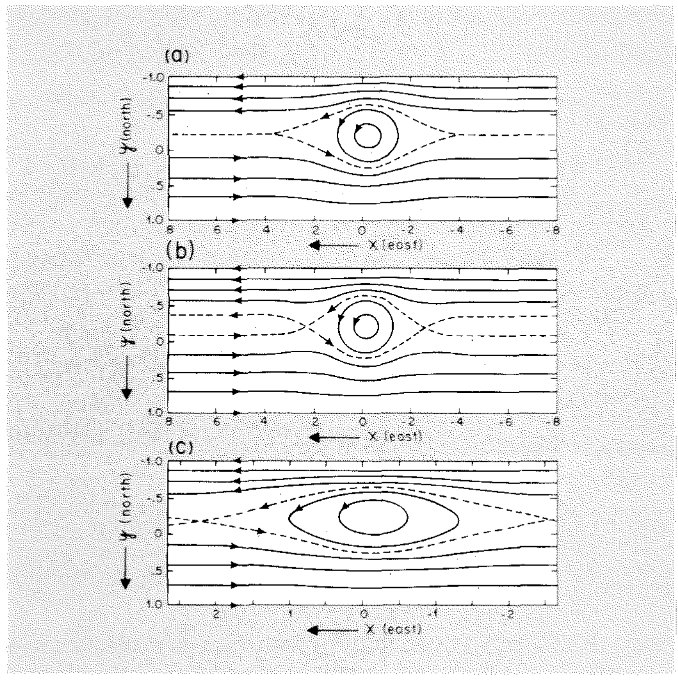
One energy source that can be assessed with data currently available is the radiative exchange at the top of the atmosphere. Because of their extra cloudiness, the zones and the Red Spot lose heat to space at a lower rate than the belts, causing them to accumulate heat inside the cloud. (We assume that heat is supplied from below at a uniform rate.) This interior heat then leads to rising motion and further cloudiness. The belts behave in the opposite way, but they can derive energy from the same process: Depression of the cloud tops leads to an increased rate of cooling, which leads to lower temperatures inside the cloud, sinking motion, and further depression of the cloud top. Thus we have a self-sustaining process, capable of maintaining the flow against dissipation. This process could also be important for terrestrial storms.

To assess this energy source quantitatively, we need a map of the net radiative flux at the top of the atmosphere as a function of latitude and longitude on Jupiter. Net radiative flux includes the infrared emission of the planet—integrated over all wavelengths—minus the absorbed fraction of the incident sunlight. Weather satellites have been making such maps for the earth for more than a decade, but now such a map is possible for Jupiter as a result of the Pioneer 10 flyby (lower photo, page 35). At present, one of my major research activities, and that of graduate students Glenn Orton and David Diner, is the processing and interpretation of the infrared radiometer data from Pioneer 10 with Drs. Guido Münch and Gerry Neugebauer.

The aim of a study of some hydrodynamic models of the Red Spot and the surrounding currents was to see under what conditions such an elliptical feature—with anticyclonic vorticity—could remain stationary and stable in the presence of linear features like the belts and zones. Dissipation, or slow thermal adjustment by radiation, was neglected. No interaction with a solid lower surface was allowed; the motions were introduced as part of the initial conditions and then allowed to evolve freely on the computer. One aim was simply to counter the widespread assumption that you need a solid body at depth to sustain the Red Spot. That aim was satisfied. Stationary flow patterns were obtained, but only if the anticyclonic vortex was imbedded in an anticyclonic linear feature like a zone.

Fortunately, this is consistent with the observed location of both the Great Red Spot and the smaller northern spot in relation to nearby belts and zones. In other words, the model says that only certain locations are permitted for anticyclonic vortices like the Red Spot, and these locations appear to be the ones where such features are observed.

Steady hydrodynamic models of the Great Red Spot and neighboring currents. Arrows show the direction of flow. In (a) and (b) the x axis is compressed by a factor of 3. In (c) the central portion of (b) is shown on an uncompressed scale. The model illustrates a free atmospheric flow; no interaction with a solid lower surface is assumed.



Another model (above) was set up in a frank attempt to duplicate as many features as possible of the observed motion of small spots in the vicinity of the Great Red Spot (page 36). Some interesting features of the model that are observed around the Red Spot are: the cusped tips at the leading and trailing edges (a) and the streamline (b) which crosses itself, enabling small spots approaching the Red Spot to change latitude and recede away in the opposite direction. In a numerical check of this model, if we choose the length scale of the features to fit the observations and use the radius and rotation rate of Jupiter, we obtain velocities for the currents which are also in agreement with observation.

With other theoretical models, my colleagues and I are trying to account for the observed widths of the belts and zones, as well as their observed east-west orientation. Some of these models have been successful; in fact, there are now several competing models, each of which depends on some parameters that have not yet or cannot yet be measured. The greatest uncertainties are associated with conditions below the clouds. What is the temperature profile at depth? Are there significant large-scale motions? Is there a solid surface at some level? These and other questions will be answered in the coming years. With the answers, we will better be able to understand Jupiter, and thereby to put the earth in a broader perspective. □