Jupiter's Great Red Spot: A Free Atmospheric Vortex?

Abstract. *A simple hydrodynamic model yields steady-state solutions with many of the properties of the Great Red Spot and the neighboring belts and zones of Jupiter. No special forcing mechanism is necessary to maintain the circulation of the Spot. This is consistent with observations which indicate that the Great Red Spot and the zones have similar dynamic properties.*

The Great Red Spot (GRS), like all other visible features on Jupiter, is a large cloud system (*1, 2*). On the earth, such cloud systems are either migrating weather systems whose lifetime is 1 or 2 weeks or quasi-permanent features directly forced by the distribution of continents and oceans. Since the GRS has existed for at least 100 years, it is tempting to assume that it also is directly forced by an underlying solid surface (*3, 4*). However, there are difficulties with this explanation. First, Jupiter may not have a solid surface; any solid surface must be thousands of kilometers below the visible clouds, and it is not clear that atmospheric motions can couple over such a great range of depth. Second, the rotation rate of the GRS is less than that of the magnetic field, which might be expected to rotate with the solid planet. Moreover, the rotation rate of the GRS varies erratically on a long time scale, while that of the magnetic field appears to be constant. While these difficulties are not insurmountable, they lead one to consider models in which there is no interaction with the solid parts of Jupiter (*5, 6*). I shall call these free or unforced flows, as opposed to forced or driven flows.

The new result presented here is that free, steady-state solutions of the governing hydrodynamic equations exist with many of the flow features of the GRS and the neighboring currents. If, as assumed here, the GRS does not have a special forcing mechanism, it should have many dynamic properties in common with other major flow features in Jupiter's atmosphere. Accordingly, in the first part of this report I discuss the observations which bear on this question, and show that the GRS is dynamically similar to the zones, which, together with the darker belts, comprise Jupiter's axisymmetric banded structure.

Table 1 summarizes the observational classification of Jovian atmospheric features. The infrared emission temperatures (column 2), especially in the 5-μm band, are perhaps the most useful. Absolute temperatures differing by factors of 2 are common. The dark belts always have the higher temperatures (*7*), whereas the zones and the GRS have relatively low temperatures (*8*). The only acceptable interpretation is that the clouds are less well developed in the belts (column 4), which enables emission from deeper, hotter atmospheric layers to reach the surface. The possibility that the infrared observations reflect horizontal temperature differences can be discounted, because the huge winds which would accompany such differences are not observed. In fact, horizontal temperature differences (temperature differences on constant pressure surfaces: column 7) can be inferred from the direction of circulation of flow patterns, and are opposite to the infrared temperatures (*9, 10*).

This inference is made as follows: by definition, the direction of circulation is cyclonic or anticyclonic depending on whether the vertical component of vorticity $\vec{\nabla} \times \vec{v}$ is parallel to or opposite to the vertical component of the planet's rotation vector (here $\vec{v}$ is the velocity of fluid elements in a reference frame rotating uniformly with the average angular velocity of the atmosphere). Because of the Coriolis force, a region of anticyclonic vorticity is a region of high pressure, relative to other points on the same horizontal surface. On Jupiter, both the zones and the GRS are anticyclonic, and are therefore high-pressure regions (columns 5 and 6). These relations refer to the level of observation, which in this case is near the cloud tops of Jupiter. At great depths, we assume that pressure is constant on horizontal surfaces, corresponding to a state of no motion. High pressures at the cloud tops must then be associated with vertical expansion of atmospheric columns, that is, with high temperatures on constant pressure surfaces (column 7). These arguments have traditionally been used in studying ocean surface currents, although recent measurements indicate that appreciable velocities sometimes occur at depth in the oceans (*11*).

Using these relations, we can infer that the mean vertical velocity is positive in the zones and the GRS (column 8), where the atmospheric temperature is relatively high, and is negative in the belts, where the temperature is relatively low. Thus we would expect active, well-developed clouds in the zones and the GRS, compared with those in the belts, since clouds tend to form in regions of low-level convergence and positive vertical velocity (column 9). This inference is consistent with the cloud structure (column 4) which we have inferred from the infrared emission observations.

Further support is provided by observations in the ultraviolet and in the near-infrared absorption bands of methane (*1, 5, 6, 12*), which also indicate that the GRS and the zones are regions of well-developed clouds. Finally, although the origin of Jovian colors is uncertain, again the GRS resembles the zones rather than the belts (column 3): that is, the colors of both the GRS and the zones vary from white through red, whereas the belts are always darker and more blue (*1, 2, 5, 13*).

To summarize the results of Table 1: the GRS and the 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. Thus, it is reasonable to investigate models in which the GRS and the zones are steady-state solutions of the same hydrodynamic equations with the same degree of forcing by the solid planet.

If we ignore dissipation, any axisymmetric, zonal (east-west) flow is a steady-state solution of the equations of motion without forcing. It is not equally

Table 1. Classification of Jovian atmospheric features. Abbreviations: GRS, Great Red Spot; $P(z)$, pressure variation on horizontal surfaces; $T(P)$, temperature variations on constant pressure surfaces.

1. Feature	2. Infra-red	3. Color	4. Cloud height	5. Vorticity	6. $P(z)$	7. $T(P)$	8. Vertical velocity	9. Expected cloud
Belt	Hot	Dark	Low	Cyclonic	Low	Cold	Down	Low, thin
Zone, GRS	Cold	White, orange	High	Anti-cyclonic	High	Hot	Up	High, thick

obvious that an elliptical streamline pattern such as the GRS is also a steady-state solution unless it is forced by some external mechanism (for example, by a solid topographic feature). I have investigated this question by using a simple hydrodynamic model, namely, the barotropic vorticity equation

$$\nabla^2 \frac{\partial \Psi}{\partial t} + J(\Psi, \nabla^2 \Psi + \beta y) = 0 \qquad (1)$$

Here $\Psi(x,y,t)$ is the stream function, t is the time, x and y are the eastward and northward coordinates, $-\partial\Psi/\partial y$ and $\partial\Psi/\partial x$ are the corresponding velocity components, ∇^2 is the horizontal Laplacian operator, J is the Jacobian, and $\beta = df/dy$, where $f = 2\Omega \sin \lambda$ is the Coriolis parameter, Ω is the planetary rotation rate, and λ is the latitude. Equation 1 is valid for flows which satisfy the condition $B \ll 1$, where

$$B = \frac{H^2}{f^2 L^2} \frac{g}{T} \left(\frac{dT}{dz} + \Gamma_a \right) \qquad (2)$$

Here H and L are the vertical and horizontal scales of the flow, g is the gravitational acceleration, z is the vertical coordinate, T is the temperature, and Γ_a is the adiabatic lapse rate. Unless the temperature gradient dT/dz is positive, which is highly unlikely, the condition $B \ll 1$ is satisfied for flows whose horizontal scale is equal to or greater than that of the GRS or the belt-zone spacing (*4*).

Equation 1 describes a free atmospheric flow. There is no driving mechanism, and solutions depend only on the initial conditions. Steady solutions may be obtained from the first integrals of Eq. 1

$$\nabla^2 \Psi + \beta y = F(\Psi) \qquad (3)$$

where $F(\Psi)$ is to be regarded as a function of integration. The form of the solution depends entirely on the function $F(\Psi)$. My aim is to show that there exist solutions of Eq. 3 which have streamline patterns similar to those observed around the GRS, and thus to show that the GRS might be a free atmospheric vortex.

Figure 1 shows two such solutions. These were obtained numerically, by iteration, by using a finite-difference approximation in x and y. The function Ψ was assumed to vanish at $y = \pm L$ and to be periodic in x with period $16L$. Starting with an initial $\Psi(x,y)$, the computer first located critical streamlines bordering the closed-streamline regions. The function $F(\Psi)$ was prescribed at the center of each closed-streamline region, at the critical streamlines, and at the streamlines $\Psi = 0$ at $y = \pm L$. In the interior regions $F(\Psi)$ was either set equal to a constant or allowed to vary linearly between the prescribed values on the edges. The computer then evaluated $F(\Psi) - \beta y$, and inverted the Laplacian $\nabla^2\Psi$ to get a new Ψ. Six-figure repeatability was obtained after about 30 such iterations.

Since the GRS is in Jupiter's southern hemisphere, Fig. 1 is shown with south at the top and east to the left. Outside the closed-streamline regions, the patterns resemble the north and south branches of the Circulating Current, which flow westward and eastward, respectively. The closed-streamline region in the center resembles the GRS. The latitude band containing the GRS resembles the South Tropical Zone, being a region of small velocity and large anticyclonic vorticity. Note that Fig. 1a and Fig. 1b are drawn with the x axis compressed by a factor of 3. In Fig. 1b, a second closed-streamline region has been added in order to model the observation that smaller spots occasionally change from one branch of the Circulating Current to the other near the leading and trailing edges of the GRS. Figure 1c shows the region around the GRS, with the x and y axes drawn to the same scale, for the solution shown in Fig. 1b. As a crude numerical check, if we choose $2L$, the total width of each figure, to be 1.1×10^4 km, and use other parameters appropriate to Jupiter, we obtain maximum velocities of about 65 and 35 m/sec for the south and north branches of the Circulating Current. All of these features compare reasonably well with observed features of the GRS (*2*, *14*).

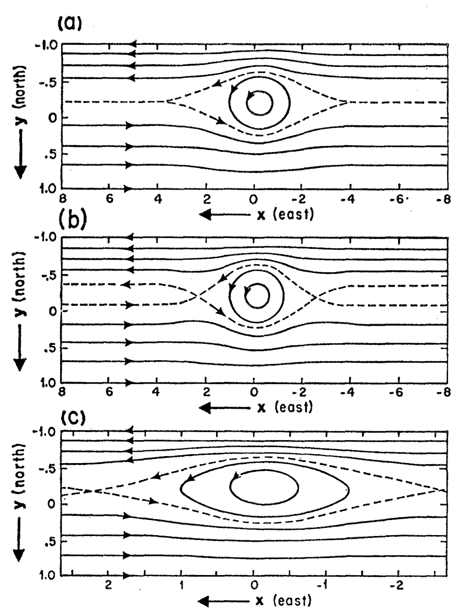

Fig. 1. Steady barotropic models of the GRS and the Circulating Current. The stream function Ψ is defined in the intervals $-1 \leq y \leq 1$ and $-8 \leq x \leq 8$, with $\Psi = 0$ at $y = \pm 1$, and Ψ periodic in x. In (a) and (b) the scale of x is compressed by a factor of 3. In (c) the scale is uncompressed, but only one-third of the region $-8 \leq x \leq 8$ is shown. Vorticity is determined by the condition $\beta y = \pm 3$ at $y = \pm 1$. The solid lines show contours of Ψ in steps of 0.2. The dashed lines show the critical streamline Ψ_c. The arrows show the direction of flow: Ψ decreases to the left of the flow direction, and has a minimum value Ψ_m at the center of the closed-streamline region. In (a) $F(\Psi)$ is 1.5 at $\Psi = 0$ (northern boundary), 1.5 at $\Psi = \Psi_c$, -4.5 at $\Psi = 0$ (southern boundary), and 6.0 at $\Psi = \Psi_m$. In (b) a second, weaker closed-streamline region has been added, within which $F(\Psi) = 1.8$; also, $F(\Psi)$ has been changed to 7.0 at $\Psi = \Psi_m$. In (c) the central portion of (b) is shown on an uncompressed scale.

Dissipation is neglected in the flows considered here. Since dissipative processes (such as radiative heat exchange) are very weak on Jupiter, only a weak energy source is needed to maintain the flows. One such source is the difference in radiative cooling rates of high and low clouds: high clouds radiate at a lower temperature, hence they remain hotter. This mechanism can explain how the zones and the GRS remain hotter than the belts on constant pressure surfaces (see Table 1), and can account for the observed width of belts and zones (*15*). The long time constant (tens or hundreds of years) associated with dissipative processes on Jupiter also qualitatively explains the long lifetime of features such as the GRS.

The question of the stability of these flows is still unanswered. Flows driven by horizontal temperature differences (baroclinic flows) are unstable in the earth's atmosphere. The length scale L of the fastest growing baroclinic disturbances is such that $B \approx 1$ in Eq. 2. On Jupiter, this scale is at or below the resolution of ground-based observations, depending on how closely the atmosphere follows the adiabatic lapse rate. It is possible that on Jupiter, unlike the earth, baroclinic instabilities take the form of axisymmetric disturbances (*16*), or that baroclinic instabilities are suppressed on Jupiter (*17*).

For disturbances of large horizontal scale, equal to or greater than the GRS or the belt-zone spacing, we can investigate stability by using the barotropic vorticity equation, Eq. 1. Jupiter's axisymmetric zonal flow has been shown to be marginally stable, according to the barotropic stability criterion (*10*). The closed-streamline flows represented in Fig. 1 are also barotropically stable, but the proof of stability depends on the presence of boundaries at $y = \pm L$. The stability question needs to be investigated further.

To summarize, it is possible to formulate a hydrodynamic model of the GRS which is consistent with most observations, and which does not require a special forcing mechanism. The fact that both the zones and the GRS are anticyclonic regions with well-developed clouds is an important part of the model. The difference between the closed-streamline pattern of the GRS and the parallel-streamline pattern of the zones may be simply part of the initial conditions of the system coupled with the extremely long time constant of Jupiter's atmosphere.

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18. Partly supported by NASA grant NGL 05-002-003 to the California Institute of Technology, and partly by NSF grant GA-37116X for summer study of geophysical fluid dynamics at the Woods Hole Oceanographic Institution. I wish to thank A. Arakawa, H. Huppert, P. Steinhardt, and G. Veronis for help in various aspects of this project.

10 September 1973

Io-Accelerated Electrons: Predictions for Pioneer 10 and Pioneer 11

Abstract. *Based on a model in which electrons are accelerated to energies of 100 kiloelectron volts through sheaths associated with Io, predictions are made about energetic electrons to be observed by Pioneer 10 and Pioneer 11 in the Jovian magnetosphere. This energetic electron source may be distinguishable from the solar wind diffusion source by the radial flux profile and by the characteristic electron energies.*

The Io sheath model in which electrons can be accelerated to energies of several hundred kiloelectron volts across sheaths in the vicinity of Io was first proposed by Gurnett (*1*). The sheath model requires that Io have a sufficiently good conductivity to act as a unipolar generator. The accelerating potential in this model is the motional electromotive force developed across Io (approximately 670 kv) due to its motion through the Jovian magnetosphere. The sheath model has been developed by Shawhan *et al.* (*2*), Hubbard (*3*), and Hubbard *et al.* (*4*) in order to further understand the detailed character of Io's interaction with the Jovian magnetosphere and atmosphere. Shawhan (*5*) has considered the consequences of 100-kev Io-accelerated electrons for decametric and decimetric radio emissions, x-ray emission, optical emissions, atmospheric ionization, and atmospheric heating. With the encounters of Jupiter by Pioneer 10 in December 1973 and Pioneer 11 about a year later, we wish to make specific predictions based on the Io sheath model which can be tested by experiments on these spacecraft. Also, these predictions may aid in interpreting the experimental results from the Pioneer/Jupiter program.

Sampling the energetic particle environment of Jupiter is one of the primary scientific goals of the Pioneer/Jupiter program, and the results may be used to ascertain the existence and significance of Io-accelerated electrons. Based on the assumptions of the Io sheath model and the expected range of physical parameters in the Jovian magnetosphere, several populations of Io-accelerated electrons are expected (*4*). Descriptions of these populations and their location, flux, and characteristic pitch angles, are given in Table 1. The precipitating electrons originate as photoelectrons from the side of Io facing Jupiter and are accelerated through a Debye sheath to energies up to 600 kev. The pitch angles (α) of these electrons lie well within the Jovian atmospheric loss cone ($\alpha < 3°$). If this beam does precipitate into the Jovian atmosphere, a backscattered population is also expected. If the beam is broken up by an instability along the field line, a significant fraction of backscattered electrons is still expected. Because of the motion of Io and the repelling force of the electric field in the Debye sheath, most of these backscattered electrons do not return to Io and are injected into trapped orbits in the Jovian magnetosphere. Because of the large electric fields and field gradients near the equatorial regions of Io, it is expected that a significant fraction of the photoelectrons emitted from these regions could attain large perpendicular energies. These electrons are also trapped and, with the backscattered electrons, make up a population of trapped electrons which can diffuse inward into the Jovian magnetosphere. It is our prediction that the inward diffusion of these electrons is sufficient to account for the primary energetic electron population in the Jovian radiation belt at $L \sim 2$ (synchrotron emitting region). (The magnetic shell parameter L is equal to R_J, Jupiter radii from the center of the planet, in the equatorial plane; however, the spacecraft frequently departs from the equatorial plane.)

In order to complete the current balance at Io, thermal plasma electrons from the vicinity of the satellite must be accelerated toward its surface. These electrons can attain energies of several hundred kiloelectron volts and are expected to produce intense x-ray emissions from the surface of Io (*5*). The Io sheath model does not treat protons explicitly. If Io has a tenuous atmosphere, then because of current balance conditions, protons and other atmospheric ions may also be accelerated to energies of several hundred kiloelectron volts.

Much consideration has been given to the problem of populating the radiation belts with high energy electrons and possibly protons (*6*). It is generally assumed that solar wind particles enter