A Truth Table Analysis of Models of Jupiter's Great Red Spot

There are a number of cases in planetary physics where we are simultaneously presented with a range of observations and a range of mutually exclusive models which purport to explain those observations. I have argued[1–3] that a simple truth table analysis from propositional calculus can be very useful in such a circumstance, and, at least for the question of the origin of the Venus microwave emission, the technique has proved very successful.[1,2]

The Great Red Spot (GRS) of Jupiter is one of the oldest planetary features known, probably being first observed by Hooke and Cassini around 1664–1667.[4] Its dimensions are enormous and somewhat variable; recent characteristic lateral dimensions are calculated to be about 28 000 × 14 000 km, while in 1878 its length was estimated to be 38 500 km.[5] The xenographic south latitude of the GRS has remained close to 22° for as long as accurate measurements have been made; in contrast, it exhibits a marked drift in longitude, e.g., drifting with respect to adjacent features all of three revolutions between the years 1831 and 1955.[6] Corresponding mean drifts in longitude of a few degrees per year are characteristic of Red Spot motions at the present time.[5] Superimposed on the slow longitude drift are a 3-month longitude oscillation of amplitude about 1° and an 8-year longitude oscillation with an amplitude of perhaps 10°.[7] Changes in the coloration of the Spot, from brick red to salmon to orange, have been reported on several occasions; such changes may have been influenced by the varying opacity of overlying white clouds. A comprehensive discussion of early observations on the coloration and motion in the vicinity of the GRS can be found in the compilation by Peek.[6] At times the GRS is white, but this is probably because it is covered by white clouds; however, at other times it is entirely clear that the Red Spot itself is missing. Nevertheless, whether the GRS is present or absent, a depression called the Red Spot Hollow, can easily be discerned in the South Temperate Belt near which the Great Red Spot resides. Material overtaking the Red Spot or the Red Spot Hollow accelerates around the Hollow. The fastest accelerations observed are $\sim 10^{-3}$ m sec^{-2} or larger.[5]

Vortical motions within the GRS, corresponding to counter-clockwise flows of roughly 10^{-2}–10^{-1} km sec^{-1} are known.[8] The exchange of material between the GRS and its surroundings is also well-documented.[9,5]

There are several reasons to believe that the GRS, whatever it is, penetrates to great altitudes: (a) The GRS remains dark to 3250 Å. Mie scattering by GRS absorbers is dominating Rayleigh scattering from the underlying atmosphere[10]; (b) Ammonia absorption over the Red Spot is significantly less than over zones and belts at corresponding latitudes[11]; (c) In strong bands methane absorption is also less over the GRS, corresponding to an altitude difference of 18 km[10]; (d) The 8 to 13 μ brightness temperature of the Red Spot is slightly lower than the brightness temperature of its surroundings.[12] Westphal[13] finds that the infrared brightness temperatures of the North Equatorial Belt, which is similar in coloration to (although darker than) the GRS, are quite high; they approach 300 °K, or more than twice the 10-μ brightness temperature of the greater part of Jupiter. It would be very interesting to know whether the GRS when not cloud-covered is also hot at 5 μ, which is a spectral region where ammonia and methane are transparent—unlike the 10-μ region which is in the middle of an ammonia fundamental.

High-dispersion visible spectra of the GRS show no characteristic absorption features, except a general albedo decline towards short wavelengths consistent with the fact that the GRS is red.[14] The most fashionable molecules invoked to explain the red coloration of the GRS are organic compounds.[15–17] Organic chromophores, which might explain the GRS coloration, are known to be produced by a variety of energy sources in the Jovian atmosphere, including charged particles, ultraviolet light, and, most likely, shock waves.[18] Most recently an orangish-brown polymeric material was made in ultraviolet photolytic simulations of conditions above the hypothesized NH_4OH clouds of Jupiter.[19] The main problem of explaining the coloration of the GRS is in preferentially producing or transporting the appropriate chromophores in or to the GRS.

The critical observations to test models of the GRS against are then:

(1) The uniqueness of the Red Spot. Why is there only one Red Spot? There are features with lifetimes of decades and dimensions of about one tenth that of the Red Spot[20]; but they are not red, and they do not share the color or the lifetime of the GRS.

(2) The coloration of the Red Spot. Why is the GRS red?

(3) Its motions, particularly its large excursions in longitude and extremely limited excursions in latitude.

(4) Its lifetime. It is at least several centuries old, possibly very much older.

(5) Its stability. It does not, for example, fragment or tend to be torn apart by shear forces, or vary its oval shape.
(6) Its vorticity.
(7) The exchange of materials between the GRS and its surroundings.
(8) The evidence that the GRS propagates high into the Jovian atmosphere.

In the accompanying truth table these observables are run against some of the more widely advertised models. In the raft model of the GRS, discussed in some detail by Peek,[6] the Red Spot is imagined to be a sort of floating island immersed in the Jovian atmosphere. If we suppose that the GRS has a vertical dimension very much smaller than its lateral dimensions, and therefore floating at some large fraction of Jupiter's radius from the planetary center, it is difficult to understand what it is that is floating in what: The outer atmosphere is composed primarily of hydrogen. In addition such a "pancake" model seems very unphysical. If we make the vertical dimensions comparable to the lateral dimensions, we then reach depths where there are probable phase transitions. From calculations of de Marcus[21] it follows that the pressures at depths comparable to the lateral dimensions of the GRS are approximately several megabars. At approximately the 0.1-Mbar level, there may be a hydrogen-rich solid phase which can float in a fluid of hydrogen slightly enriched in helium.[22] By approximately the 10-Mbar level, phase transitions to metallic hydrogen have occurred, and there is no problem of what is floating in what. However, at such levels, there are serious problems with the stability of the raft. The tensile and yield strengths of the strongest plausible materials tend to be a few times 10^9 dyne cm^{-2}. The raft might be barely stable against stresses at the 10^{-2}-Mbar level, but surely not at the 0.1–10-Mbar level. It is by no means clear why there should be only one such raft, even if it were stable, or why it should be colored red. Vorticity within and the exchange of material from such a fluid raft seem very strange, and there are serious difficulties in understanding the motions in longitude but not in latitude of such a raft.[15] The long lifetime poses no problem and the vertical extent may possibly pose no problem, but the overall prognosis for this model is distinctly negative.

An alternative nonmeteorological GRS model could be suggested. To the best of my knowledge it has never been formally proposed in the literature, but it is an obvious one and is included here for completeness. In this model, the GRS is induced by precipitation of charged particles from the Jovian radiation belts. This provides a natural explanation for the coloration of the Red Spot: Some organic compounds produced by charged particle bombardment of simulated Jovian atmospheres are red. The uniqueness of the GRS can be understood in this model if the Jovian magnetic field is an off-center dipole with an axis inclined to the rotation axis, as was once proposed by

Warwick[23] to explain some features of the decameter emission. Then one of the mirror points of the radiation belt will be much deeper in the atmosphere than the other, and the production of organic chromophores will occur preferentially in one region of the planet. The model of an eccentric off-center dipole is no longer required,[24] although it is still possible that the dipole is sufficiently off-center (0.1–0.3 Jovian radii) for this model to work. There is no problem with the lifetime or the stability of the GRS in this model. It provides a natural explanation for the great vertical extent of the Spot, and exchange of material produced below the mirror points with surrounding atmospheric regions is to be expected. The variability of the coloration of the Red Spot could even be understood in such a model, because, as terrestrial auroral activity indicates, such precipitation is strongly time-variable. And there may be no difficulty with the observed vorticity, although it does not seem to be an immediate consequence of the model. However, the model appears to be fatally flawed on two scores: First, there is a clearly observed relative motion between the GRS and System III, which, being tied to the decameter emission, must represent the motion of the Jovian radiation belts; second, the position of the mirror points in the Jovian radiation belts does not appear to be even approximately near the position of the low latitude GRS. But, as untenable as this model is, it is curious that, although it matches the observations rather better than the raft model, it has never before been proposed.

Moving on to meteorological models, we first consider the Taylor column model, as first proposed by Hide.[25–27] According to the Taylor–Proudman theorem, such a column will arise in a homogeneous fluid when fluid flows over a surface obstacle, either a depression or an elevation. The theorem can easily be generalized to a barotropic fluid (where the pressure is a function of the density only, and not of the temperature). The surface discontinuity needs only to be larger than the vertical scale of the viscous boundary layer. This model provides a natural explanation of, for example, the existence of the GRS Hollow and the acceleration of spots upon overtaking the GRS. It is conceivable that at least in the deep atmosphere, where solar radiation does not penetrate, the atmosphere may be barotropic, and the temperature gradient plays no role in driving the circulation. In this case there is a possible explanation of the uniqueness of the GRS. For the Taylor column to exist, the Rossby number must be less than unity, $\mathrm{Ro} = U/(2\Omega L) < 1$, where U is the mean velocity, Ω is the angular frequency of rotation of the planet, and L is the mean dimension of the obstacle producing the Taylor column manifested as the Red Spot in this model. For an obstacle with characteristic lateral dimensions of a few tens of thousands of kilometers, a mean wind of a few hundred meters per second is required so that the Rossby number is not much less than unity. Such winds are probably not out of the question, and a vorticity $\sim U/L \sim 10^{-5}\ \mathrm{sec}^{-1}$ has been deduced at the *top* of the GRS by

Hess[28] from the observations of Reese and Smith.[8] In this case, all surface obstacles with smaller values of L will have larger Rossby numbers, and will not produce Taylor columns. Thus the uniqueness of the GRS may be due only to the coincidence that the largest "surface" feature is the only one in the distribution function able to bring $Ro < 1$. A related idea is mentioned by Hide.[26] The purely barotropic Taylor column also provides a ready explanation of the large vertical extent of the GRS.

But a purely barotropic Taylor column is absolutely stagnant, and therefore is directly contradicted by the observations of vorticity and exchange, and provides no ready explanation of the coloration. In addition, the surface obstacle must very likely be at pressure levels ~ 0.1 Mbar or greater, and therefore the model suffers the same embarrassment concerning the strengths of materials that the deep raft model suffers. (This problem is not alleviated if we imagine the Taylor column riding over a deep floating raft, as suggested by Streett.[22]) The shear stresses in the vicinity of the obstacle would be a serious source of instability to the discontinuity producing the GRS. While the long lifetime of the GRS poses no difficulty in this interpretation the observed motions present an awkward problem. In the most straightforward interpretation, the GRS is tied to the "surface" of the planet, to which the magnetic field is also tied. The relative motion of the GRS and System III is not readily explicable, and we cannot imagine that a Taylor column has wrapped itself three times around the planet in a century. It is perhaps not altogether out of the question that there exists a slippage between the magnetic field of Jupiter and its solid body. Jupiter can perhaps be considered as intermediate between the Earth, where there are complete field reversals every 10^6 years or so, and the Sun, where there is a field reversal every 11 years or so. However, Parker[29] stresses that the field reversals for the Sun and the Earth may proceed from very different causes.

The problem of the motions appears to be a difficulty with the model, although perhaps not in itself a fatal one. In response to such criticisms about the motions of the GRS, Hide[30] (and references given there; also private communication, 1970) has proposed that the discontinuity may not be topographic, but may be rather a "heat source," or a "magnetic current loop." It is difficult to pursue this point until it is developed further. In any case, it still leaves serious problems with vorticity, exchange, color, uniqueness, and the like. In both the raft model and the Taylor column models above a surface discontinuity, the questions of motions and stability may be related to questions of motions and stability of the terrestrial continents, which are in some sense floating in the denser mantle.

However it is unclear that a purely barotropic Taylor column is required. Since the observations clearly show motion within the Red Spot and between it and its surroundings, it is natural to modify the Taylor column idea, so its two-dimensional character can be retained, but some internal motion can also be accommodated.[15] Also, since we know there is sunlight reaching at least the top of the column, and since we believe Jupiter to have internal energy sources of its own, it is by no means out of the question that the atmosphere in the vicinity of the GRS might be at least slightly baroclinic. The derivation of a relation analogous to the Taylor–Proudman theorem for a system in which the barotropic assumption is not made is, of course, difficult; and yet such a modified Taylor column seems to be much more in line with what the observations require. Some of the debate on the Taylor column idea[31,32] seems to arise out of the desire by proponents of the idea to depart from the assumptions in the initial derivation of the Taylor column without departing from the essence of the Taylor column. If we admit the possibility of a slightly baroclinic Taylor column, the problems of color, vorticity, and exchange disappear; the coloration in particular now arises by the GRS presenting to view organic compounds produced deeper in the interior of the planet.[15] There remains, however, a stability problem: The obstacle producing the column must interact with the fluid flow at very high pressures, and the obstacle appears to be unstable to shear forces.

As we back off from the idea of the purely barotropic Taylor column, we find ourselves edging towards the concept of the Great Red Spot as a long-lived atmospheric eddy. Golitsyn[33] in his similarity theory of Jovian circulation, and Smoluchowski,[34] in an application of the Turcotte–Oxburgh theory of continental drift to the Jovian Red Spot, have both recently proposed that the GRS is a large, stable atmospheric eddy. The circulation times, which both Golitsyn and Smoluchowski derive by quite different techniques, are extremely slow—of the order of a few thousand km vertical turnover in $\sim 10^6$ years. As a massive weather system, high propagation is reasonable. There is no problem of lifetime or of stability for such an eddy. On the question of uniqueness, an argument quite similar to the Rossby number argument invoked above for the Taylor column can be invoked, although it does not, in this incarnation, depend on a surface obstacle. Unlike the purely barotropic Taylor column situation, we have vertical transport of material, and the coloration of the GRS can again be understood naturally in terms of deep chromophores being carried into view. Exchange of material with the surroundings appears to be a ready consequence of the model. Motions of such an eddy on a rapidly rotating planet may be compatible with the observations, including the short period oscillations in longitude, although more work is clearly needed.

The foregoing discussion is summarized in Table 1. Of the models discussed, it appears that the eddy model is the one most free from serious difficulties, although much more work on it obviously needs to be performed. Extensive high spatial resolution optical studies of the GRS (e.g., for vorticity and

TABLE 1. Truth table analysis of models of the Great Red Spot.

Model / Observable	Nonmeteorological: Raft	Nonmeteorological: Radiation belt precipitation	Meteorological: Pure barotropic Taylor column	Meteorological: Slightly baroclinic Taylor column	Eddy
(1) Uniqueness	No	No	Yes	Yes	?
(2) Color	No	Yes	No	Yes	Yes
(3) Motions	No	No	?	?	?
(4) Lifetime	Yes	Yes	Yes	Yes	Yes
(5) Stability	No	Yes	No	No	Yes
(6) Vorticity	No	?	No	Yes	Yes
(7) Exchange	No	Yes	No	Yes	Yes
(8) Vertical extent	?	Yes	Yes	Yes	Yes

[a] No = Obvious difficulty if ad hoc assumptions are not introduced.
[b] Yes = No obvious contradiction.

exchange), would be very useful in further winnowing the models. If chromophores are not pouring into the GRS from its periphery and are not raining down from above, they must be welling up from below, which suggests that the GRS coloration is typical of that of the inaccessible lower clouds of Jupiter. If permitted and pressure-induced transitions of ammonia and hydrogen make the Jovian atmosphere above the 1-bar level entirely opaque between 8 and 50 μ, as has been recently suggested,[35] observations of the GRS may be the only method of acquiring infrared spectral signatures in this wavelength range of molecules produced in the lower clouds of Jupiter.

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