Geophysical Fluid Dynamics with a twist: in honour of Raymond Hide

Dynamical processes in Jupiter's atmosphere: from the laboratory to Juno and Cassini

Peter Read (University of Oxford)

Raymond Hide

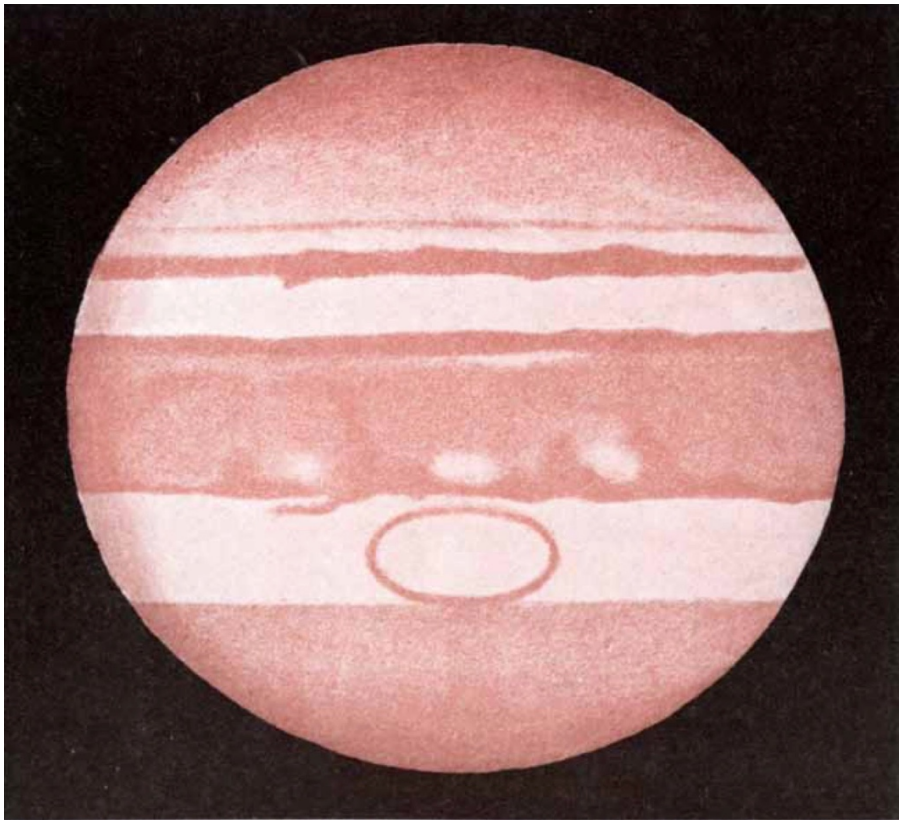
- Degrees from Manchester (B.Sc., Physics - 1950) and Cambridge (Ph.D., Geophysics - 1953)
- Research Associate in Astrophysics, Chicago (1953-4)
- Senior Research Fellow, AERE Harwell (1954-7)
- Lecturer in Physics, King's Coll. Durham (Newcastle upon Tyne) (1957-61)
- Professor of Geophysics & Physics, MIT (1961-7)
- Chief Scientific Officer (IM), Met. Office (1967-90)
- Emeritus Professor of Physics, Oxford (1994-2016)
- Senior Research Investigator, Imperial College, London (2000-2016)

[from Who's Who 2009]

Raymond Hide & Jupiter

- Great Red Spot
  - Taylor columns [Kings Coll., Newcastle]
  - Sloping convection [Met Office]
- Banded structure of winds and clouds
- Equatorial Jet
  - Hide's theorem
- Magnetic field and dynamo

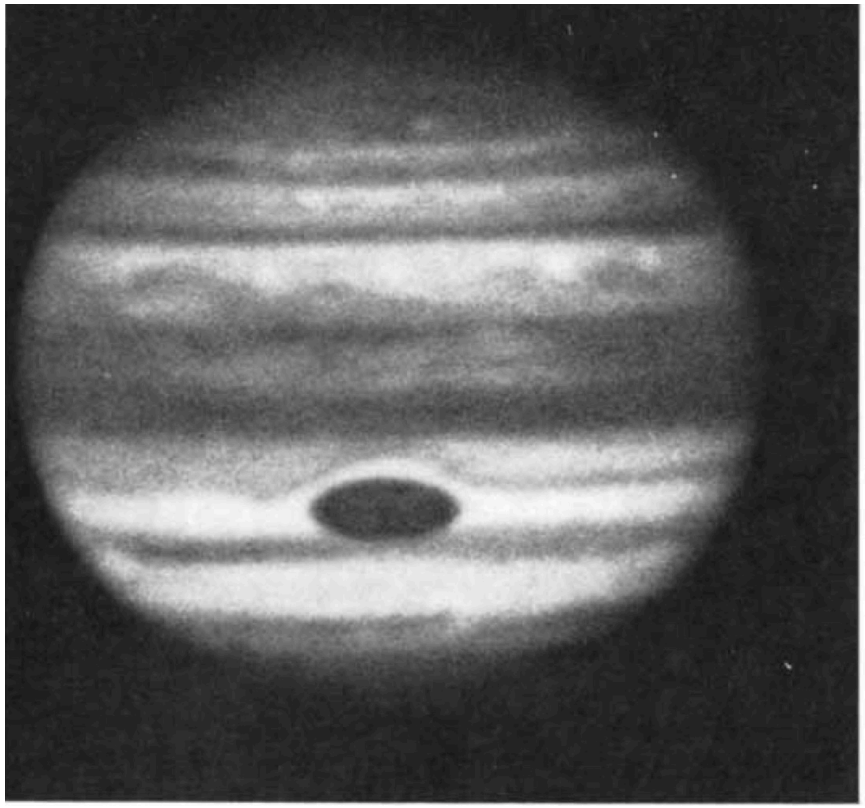
Jupiter: pre-1970

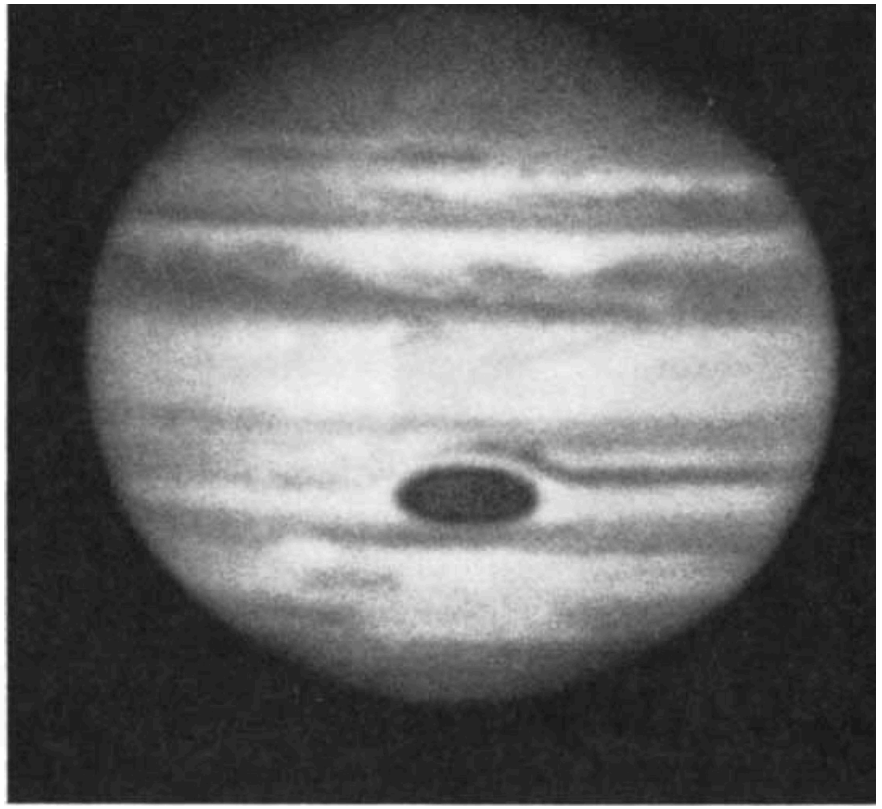


A. M. Meyer 1870

[LPL/Univ. Arizona]
December 1966

Jupiter pre-1970





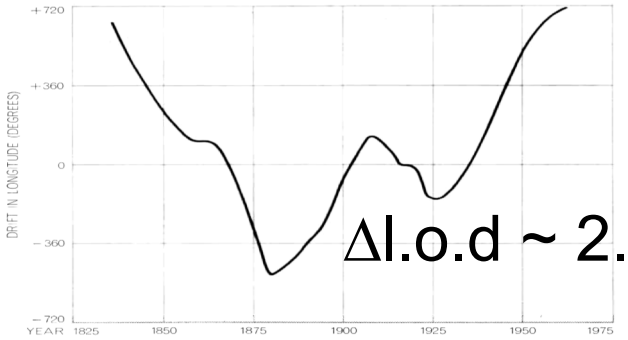
October 1964 December 1965

[New Mexico State Univ. Observatory]

Jupiter: pre-1970

Images from Hide [1968]

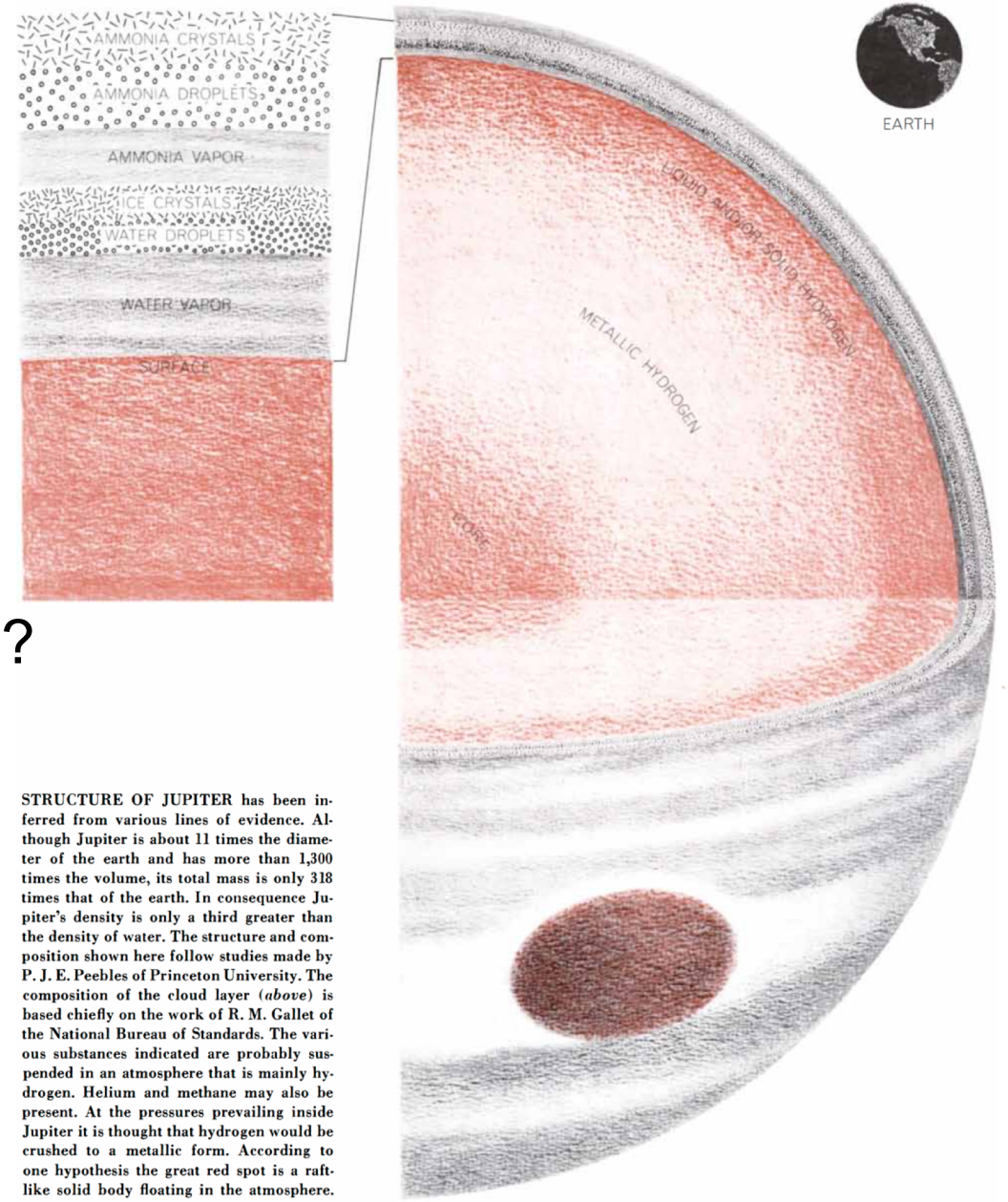
- GRS “unique”?
  - Solid or fluid?
  - Slow drift in longitude



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.

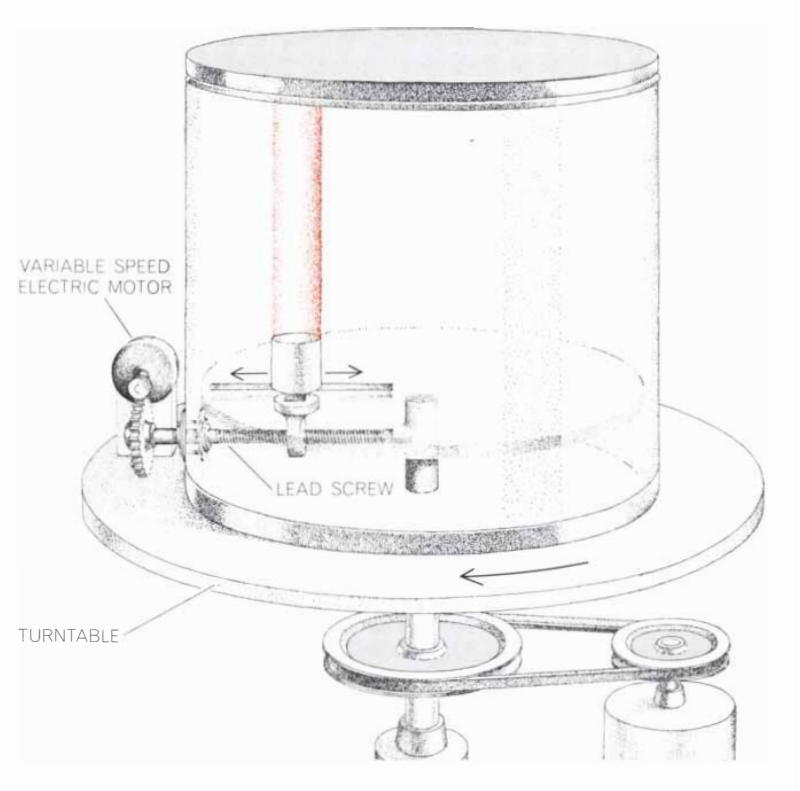
Δl.o.d ~ 2.5 s?

- Clouds of NH_3 and H_2O…
- H_2 solidifies ~few hundred km below clouds?
- Magnetic field generated in metallic hydrogen mantle?



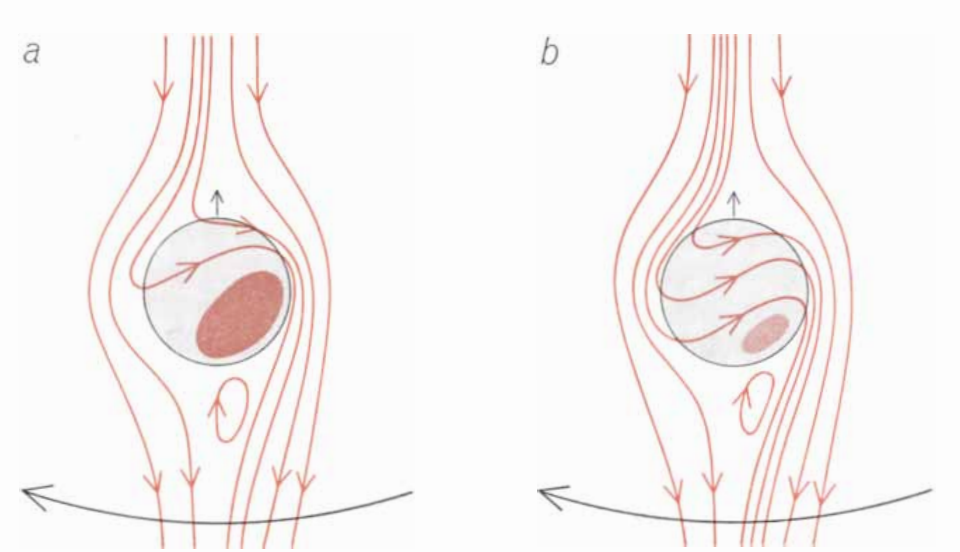
STRUCTURE OF JUPITER has been inferred from various lines of evidence. Although Jupiter is about 11 times the diameter of the earth and has more than 1,300 times the volume, its total mass is only 318 times that of the earth. In consequence Jupiter's density is only a third greater than the density of 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 raft-like solid body floating in the atmosphere.

Taylor columns
(Hide 1961; Hide & Ibbotsen 1968)

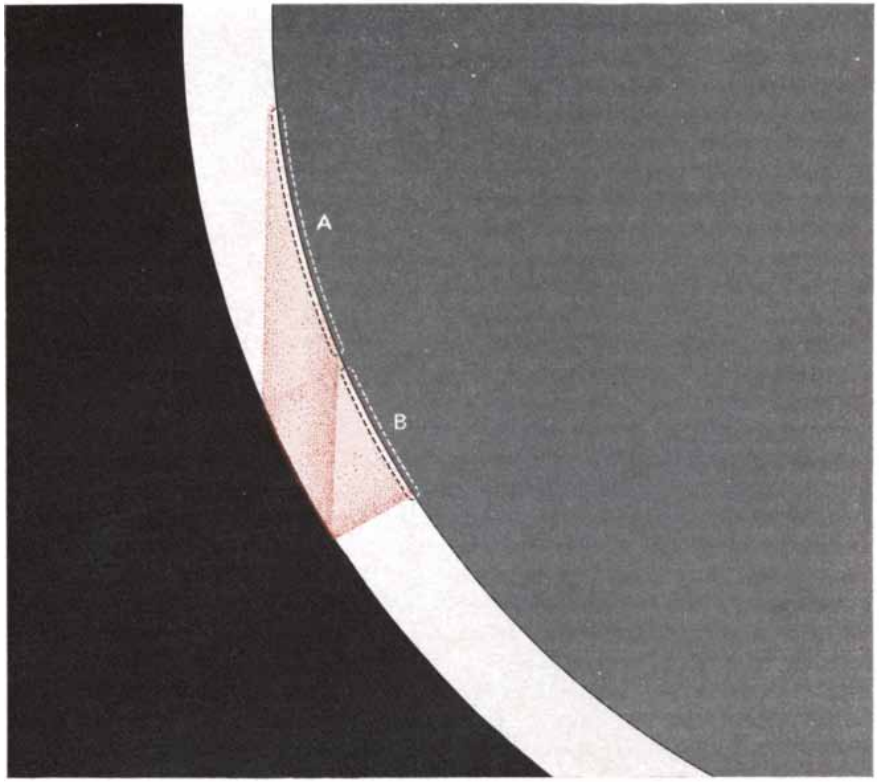


- Taylor-Proudman theorem
- $(2\boldsymbol{\Omega}.\boldsymbol{\nabla})\boldsymbol{u} = 0$
  - Coherent motion parallel to the axis of rotation
  - Apparent obstacle at all heights above a “bump”
- Hide’s theory:
  - Need an obstacle to satisfy H/L ≥ Ro to form a Taylor column

Taylor columns (Hide 1961)

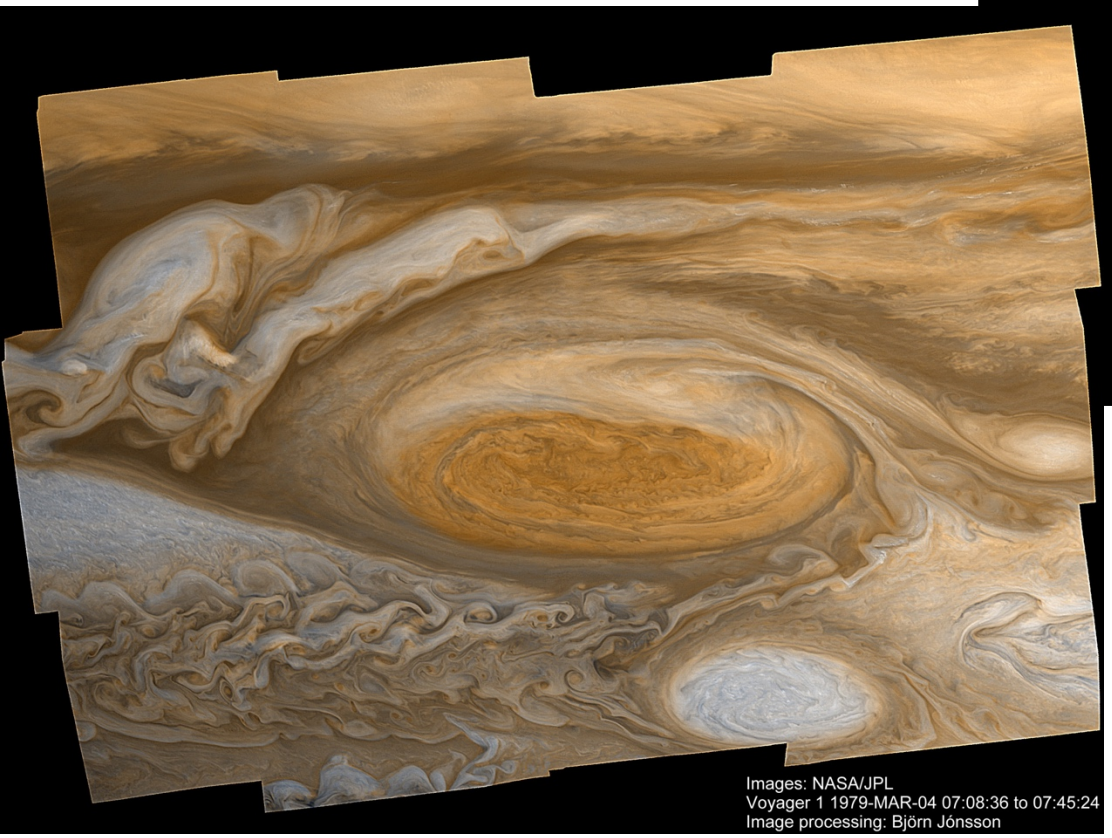


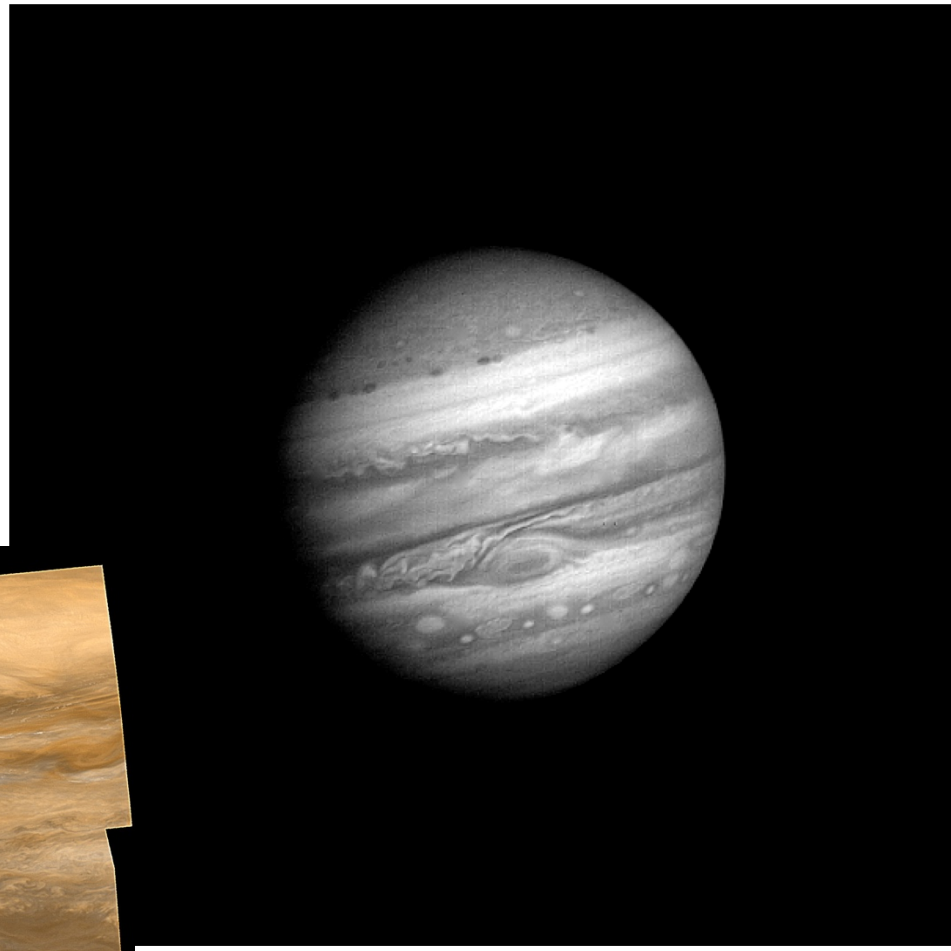
FLOW PATTERNS OVER OBSTACLE in the experimental tank were drawn by the author and Ibbetson, who observed the streaks made by a dye tracer about 10 centimeters above the obstacle, which projected about two centimeters from the base of the tank. The obstacle was moved toward the center of the tank at various 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.

Jupiter from Voyager (1979)

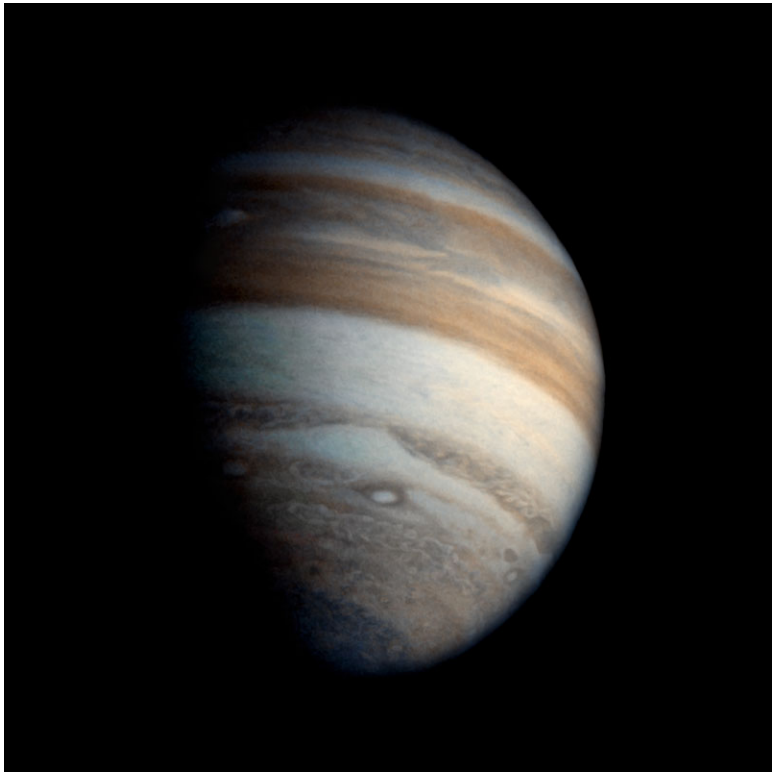




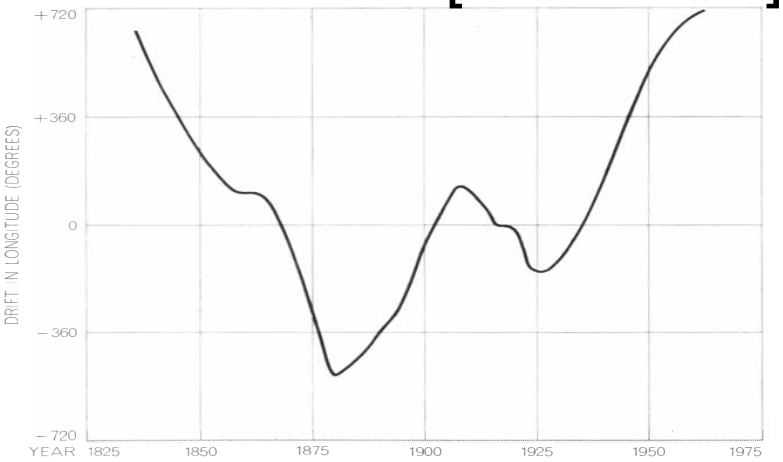
Voyager “blue movie”
[NASA/JPL]

Jupiter after Pioneer 10 & 11 (1973) and Voyager 1 & 2 (1979)

- GRS not unique but simply largest member of a family of long-lived ovals
- GRS a “free vortex”
  - Free to drift in longitude…
- Magnetic field -> interior rotation
  - **Different** from motion of GRS
- No solid H surface!
  - **No Taylor columns…?**



Pioneer 11 [NASA/JPL]



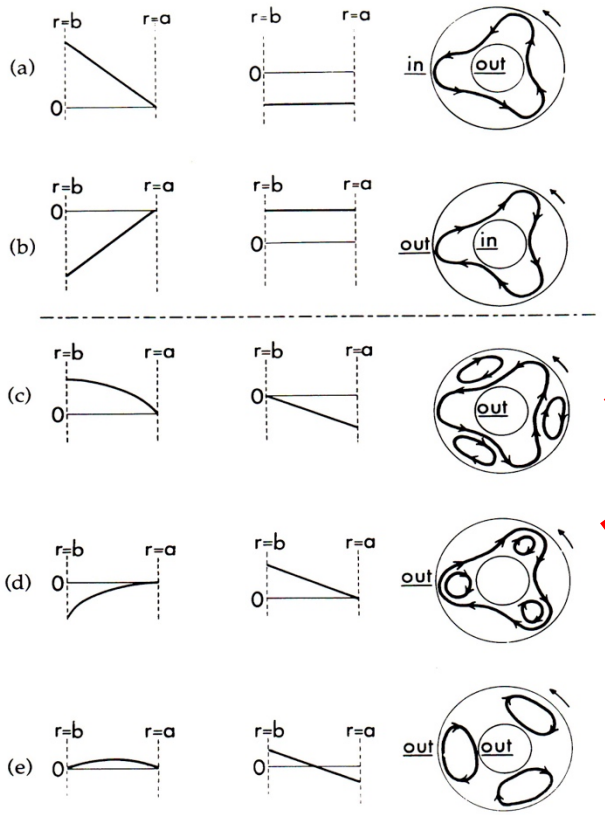
LONGITUDINAL WANDERING OF RED SPOT can be visualized by defining a mean period of rotation and plotting in degrees how much the spot advances or retreats with respect to the mean. The diagram is based on one in *The Planet Jupiter*, by Bertrand M. Peek.

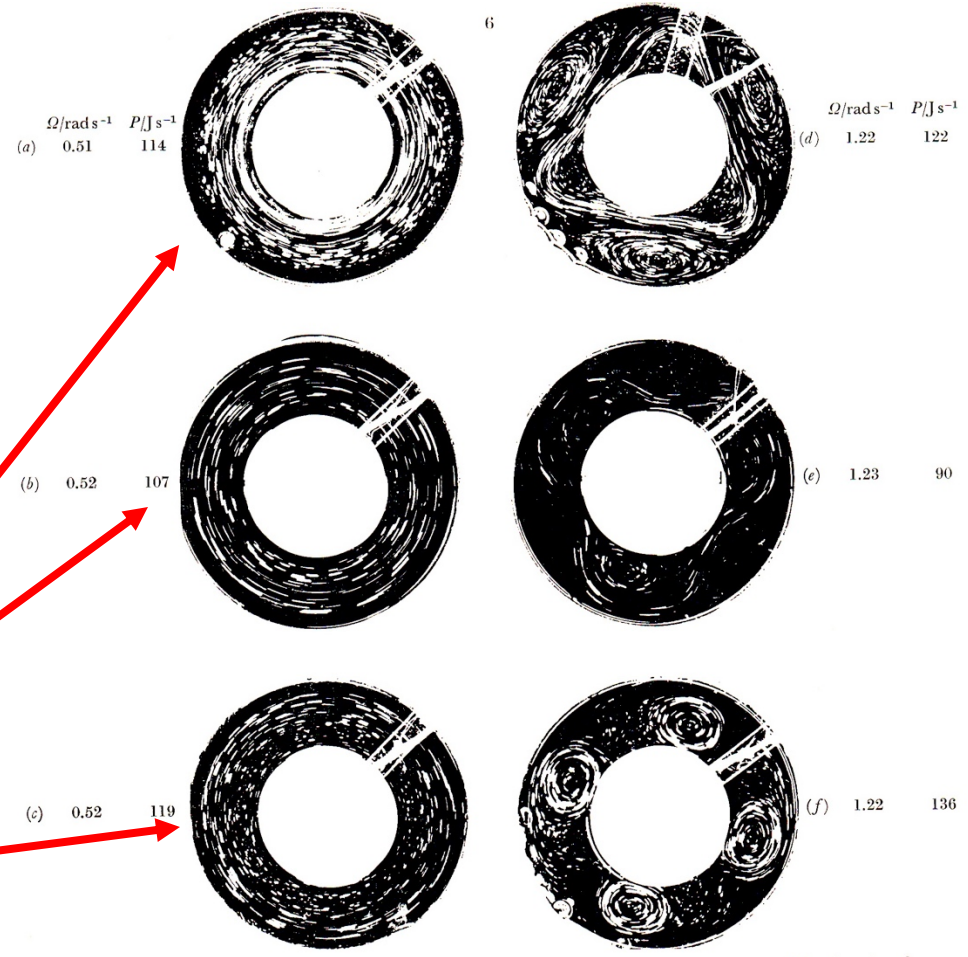
Sloping convection and baroclinic ovals?

(Hide & Mason 1970)

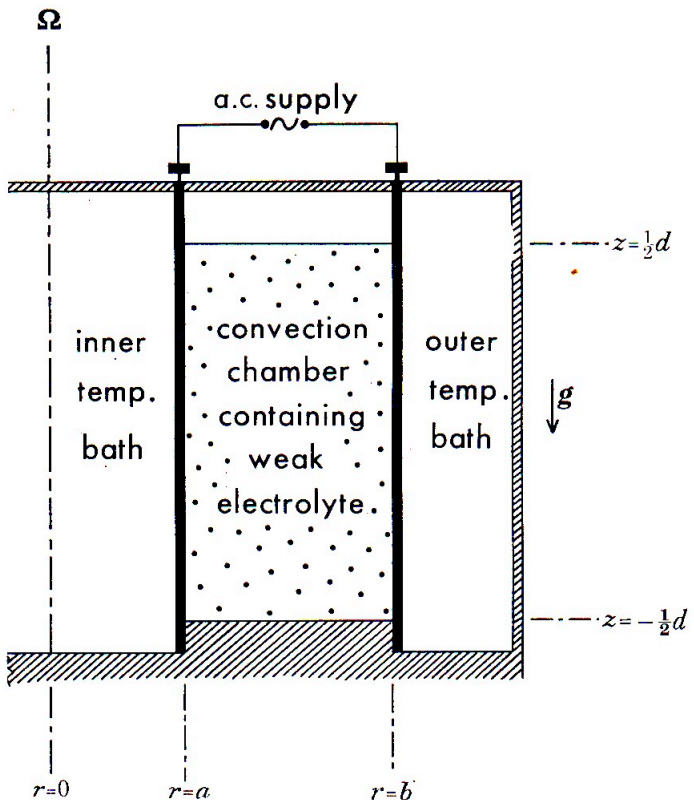
$$\mathcal{H}(r) = \iint -\kappa \frac{\partial T}{\partial r} + u(T - \bar{T}) dz d\varphi = -K \oint v(r, \varphi) d\varphi$$

Impressed T(r) v



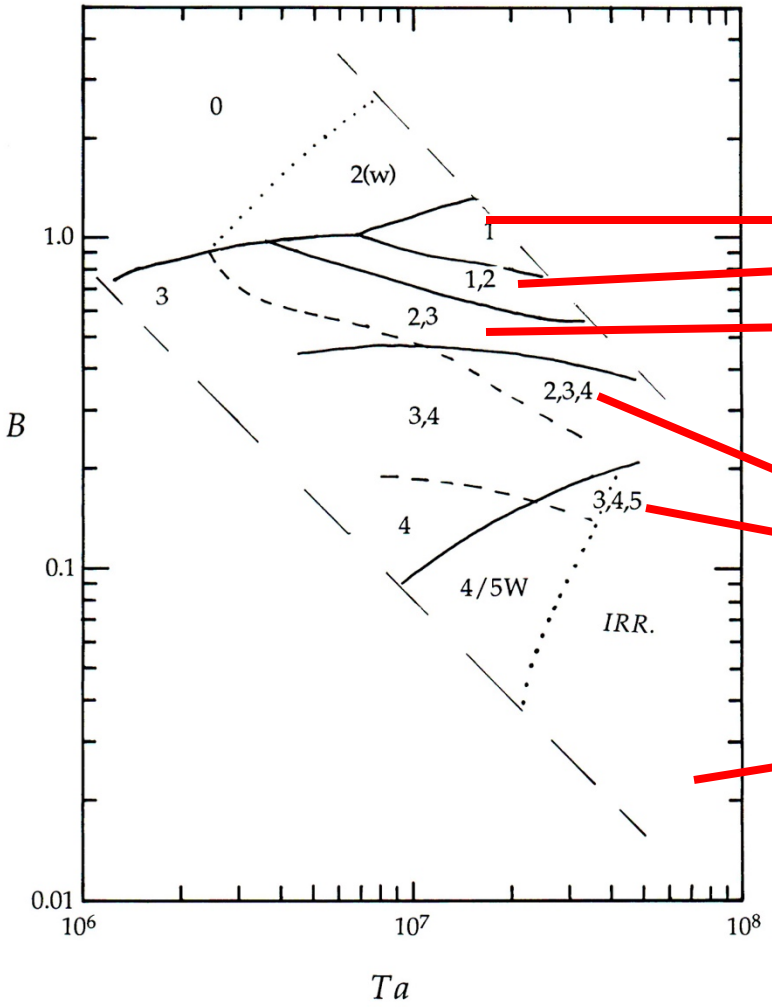


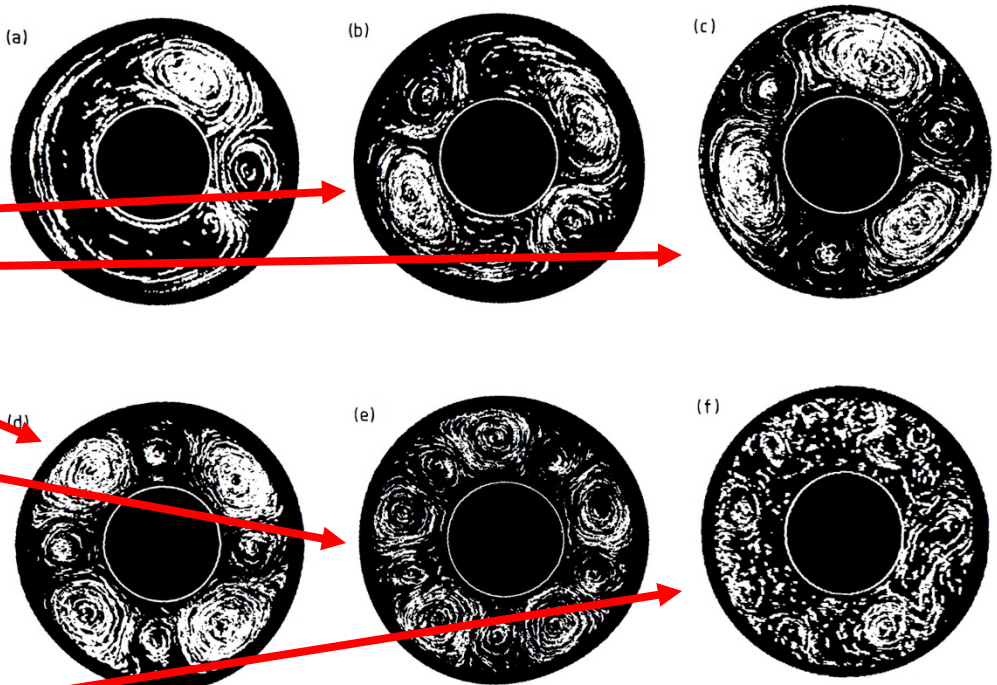
Hide & Mason (1970) experiments



- Rotating annulus experiments which combine sidewall heating/cooling and internal (ohmic) heating
- Special case of internal heating + cooling at BOTH sidewalls
- Emulates thermal structure of a Jovian zone?

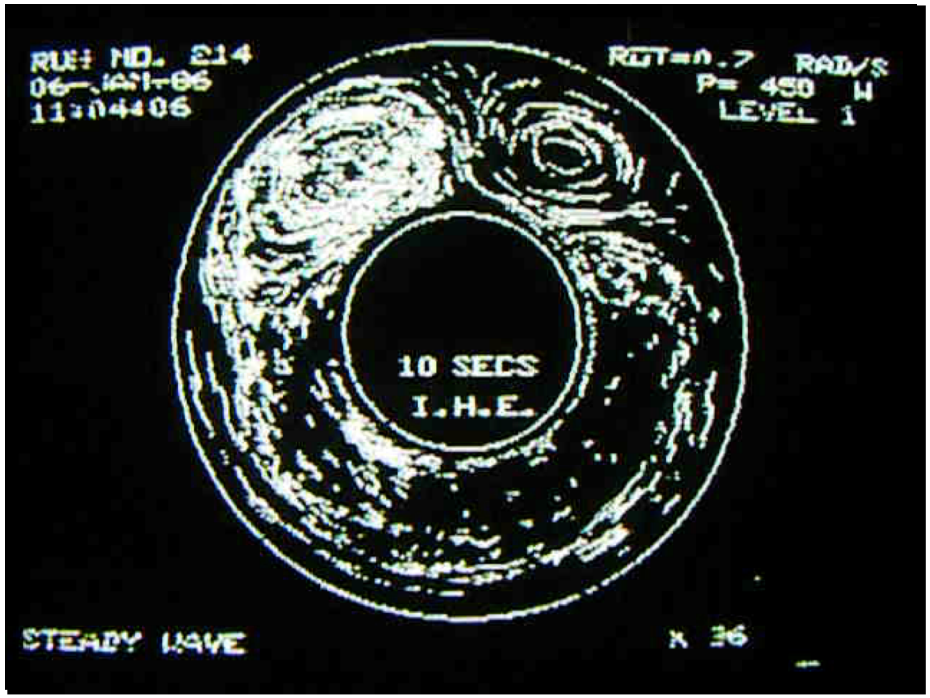
Read & Hide (1983,1984)





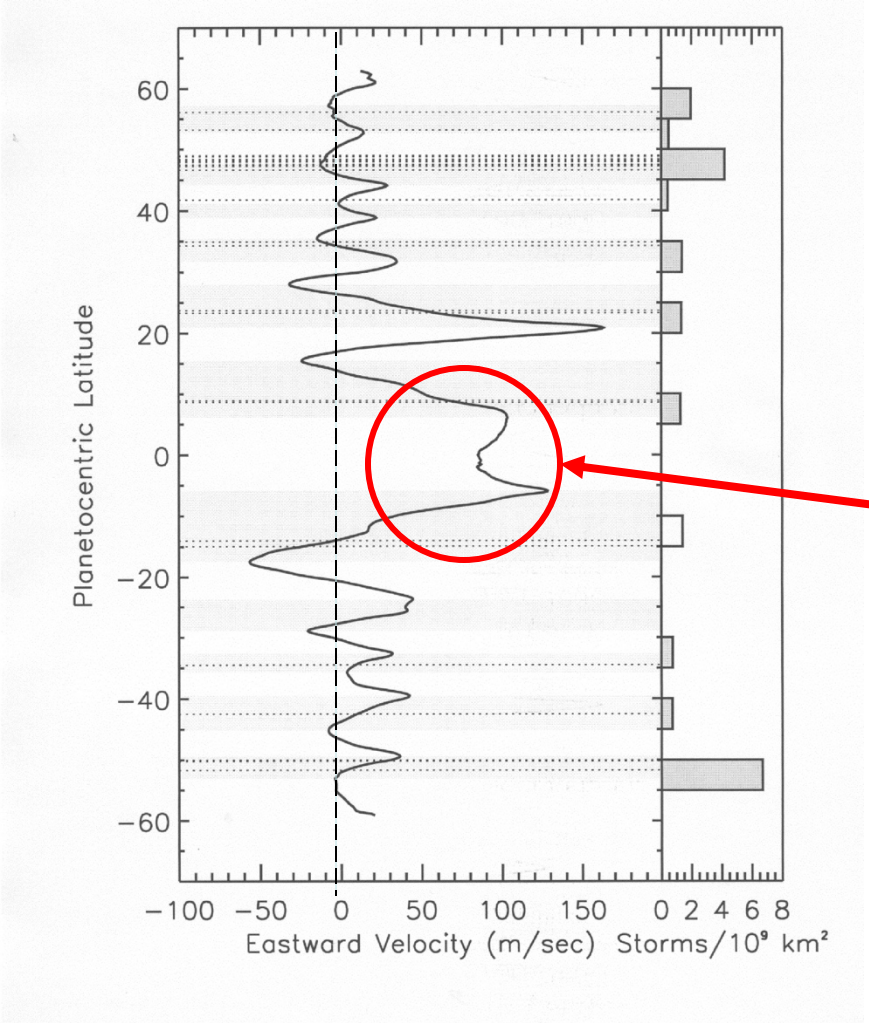
Single, isolated oval vortex (Read & Hide 1984)

- Formation of m=1 at large Θ
- Steepened isolated anticyclone in anticyclonic shear flow with strong heating
- Analogue of GRS…??



Recorded using PDP11/34 image Analysis system on mag video tape!

Jupiter's banded structure and equatorial jet



- Alternating eastward & westward zonal jets
  - What sets their separation?
- 100 m s^{-1} prograde equatorial jet
  - Source of angular momentum?

Jet separation (Hide 1969)

If the reasonable assumption is made that the essential vorticity balance is between horizontal advection of relative vorticity and effects due to the variation of Coriolis parameter with latitude, then $(UR/2\Omega)^{\frac{1}{2}}$ is an approximate expression for the latitudinal width of a jet of typical flow speed U relative to a rotating planet of radius R; the expression agrees satisfactorily with observations (Hide, 1966a).

- Identification of $(U/\beta)^{1/2}$ as relevant scale [- Rhines scale?]
- Cf Rhines (1975)

Equatorial jets: Gierasch & Stone (1968)

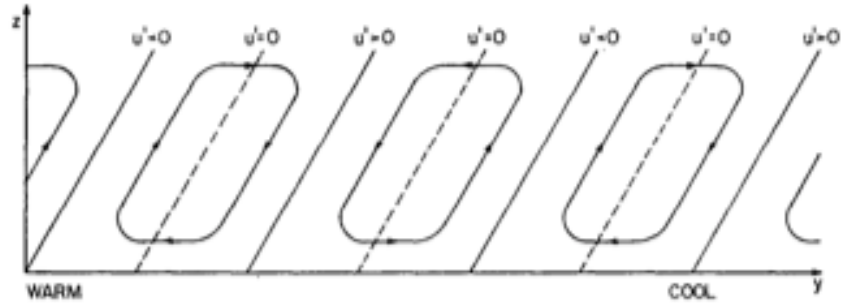


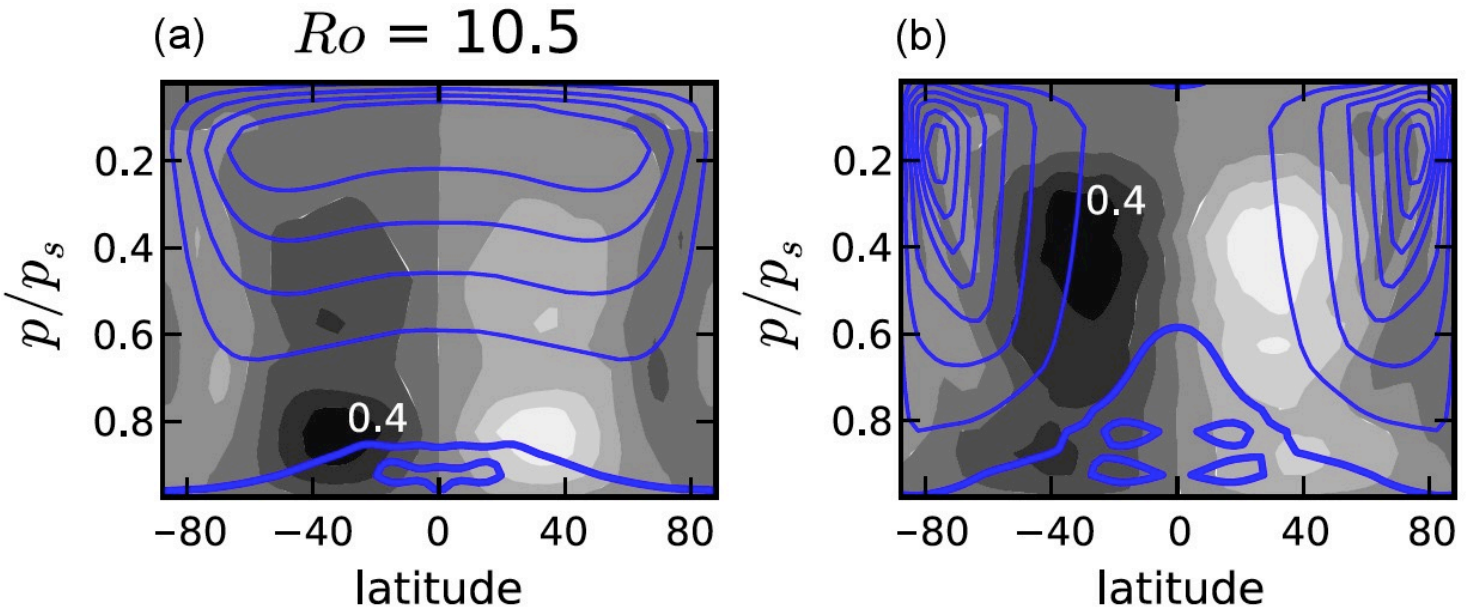
FIG. 1. Schematic cross section of the meridional stream lines of the most unstable symmetric perturbations. The sign of the perturbation zonal velocity in the different parts of the meridional cells is indicated.

- What process drives Jupiter's equatorial jet?
- Symmetric baroclinic instability (slantwise convection: Stone 1966)??
  - Axisymmetric rolls
  - Dominant for $0.25 < Ri < 1$
  - Plausible for Jupiter's troposphere?

Hide's theorem (Hide 1969)

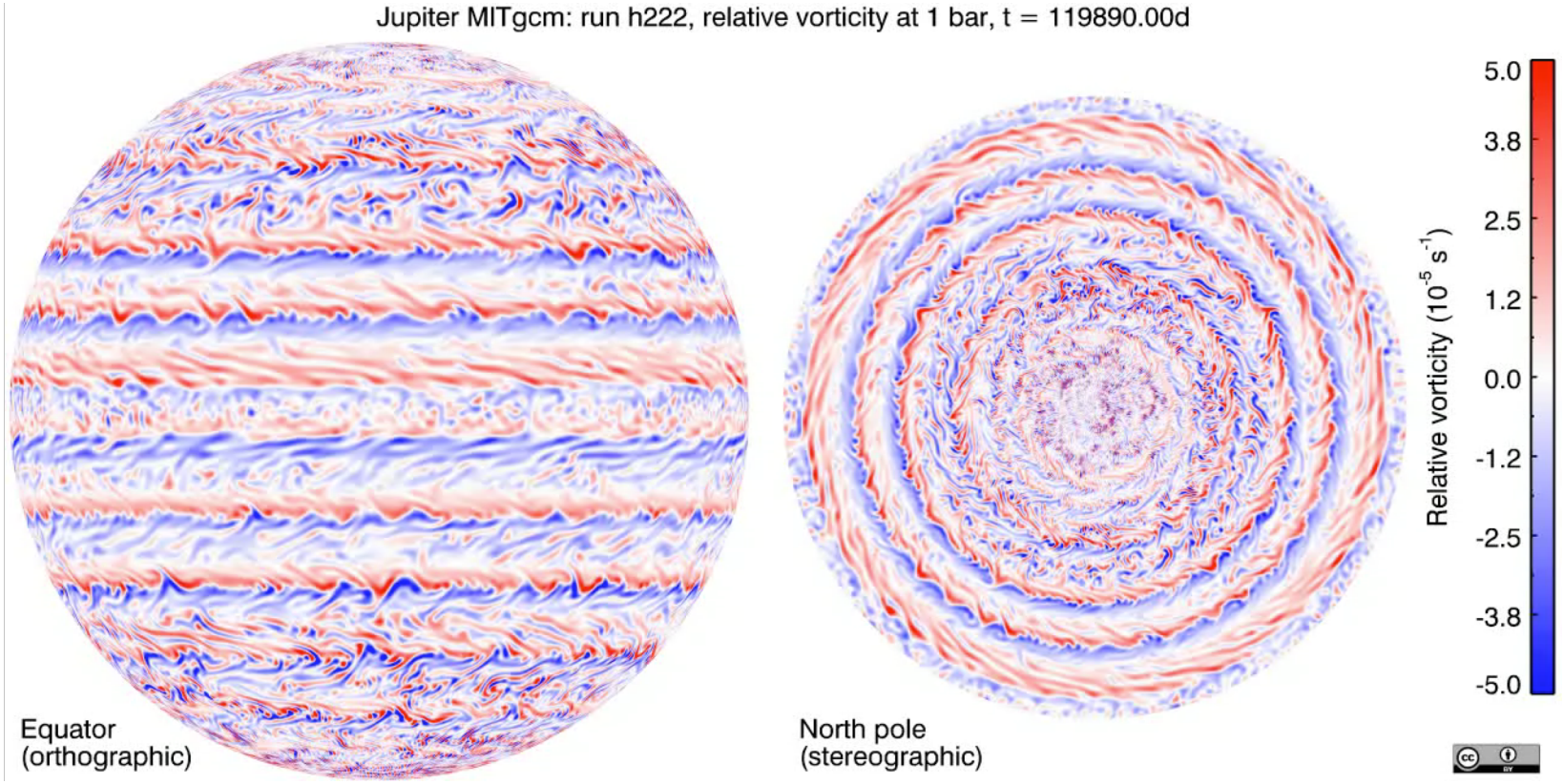
With eddies No eddies

[Mitchell & Vallis 2010]



- Axisymmetric flow cannot alter angular momentum of a ring of fluid
- Cannot accelerate zonal flow on the equator
- Cannot support a prograde zonal jet!

Models of Jupiter's weather layer

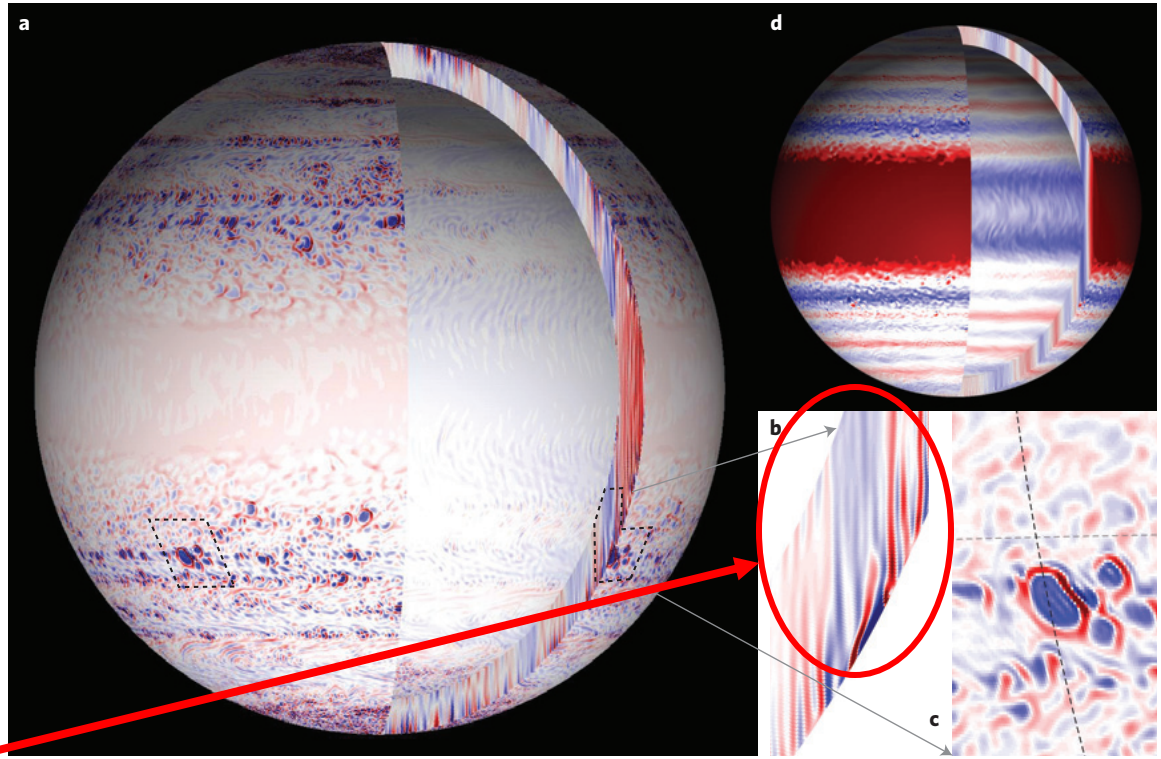


Young & Read [2018]

- Good simulation of jets
- **BUT** No large oval eddies….? [yet!]

Weather layers with deep convection?

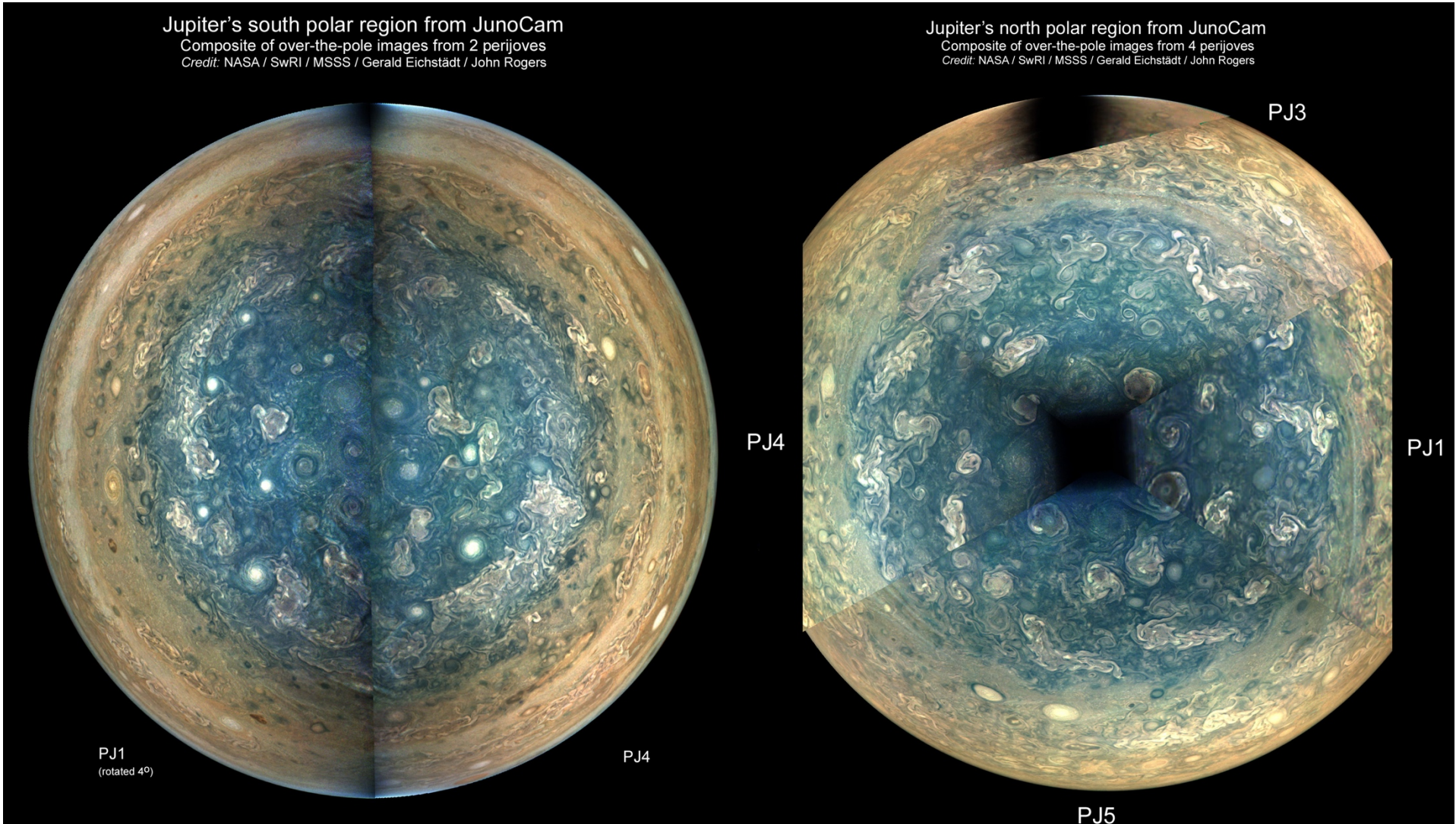
- Deep convection in a spherical shell
  - [e.g. Heimpel et al 2015]
- Large oval eddies associated with local convective hot spot?
  - Cf Taylor column…?



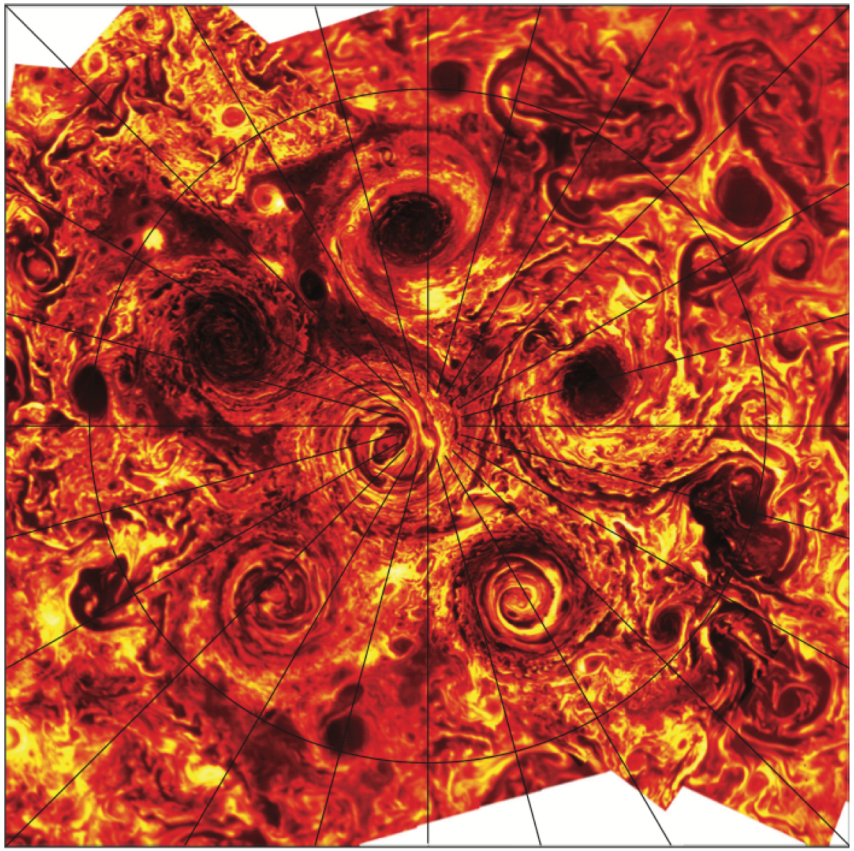
Jupiter’s magnetic field

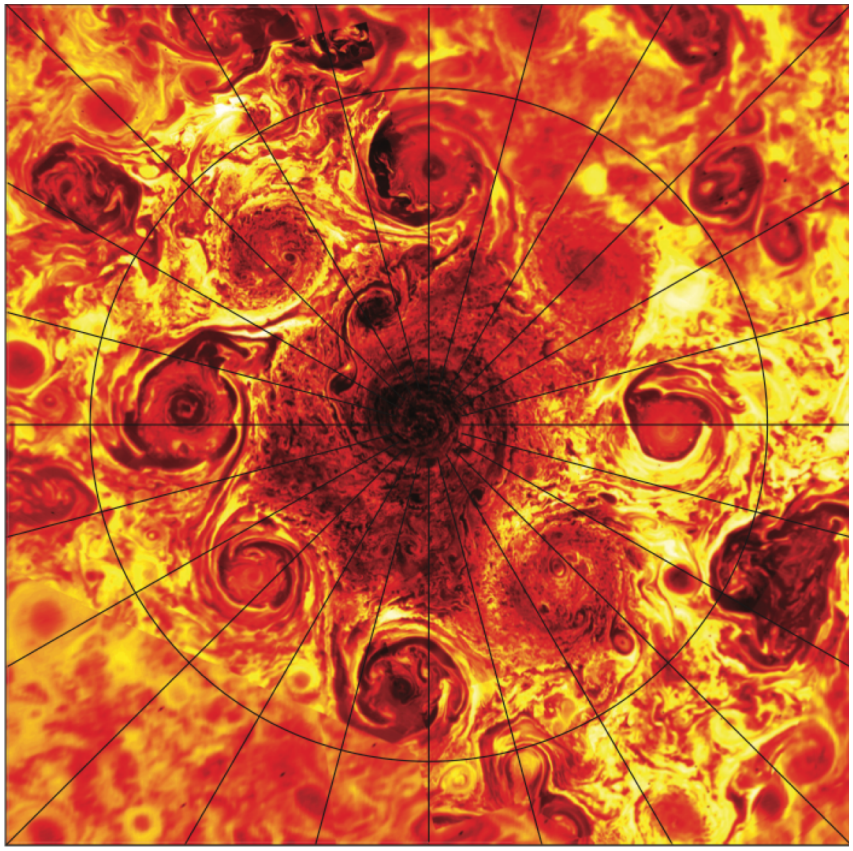
- Jupiter’s interior becomes electrically conducting only a few thousand km below visible cloud tops [Hide 1969]
- Dynamo likely to be operating well outside solid core?
- Magnetic field strongly non-dipolar?
- Jupiter's magnetic field from Juno

Jupiter's polar vortices from Junocam, MWR and JIRAM



Jupiter's polar vortices from Junocam, MWR and JIRAM [Adriani et al. 2018]





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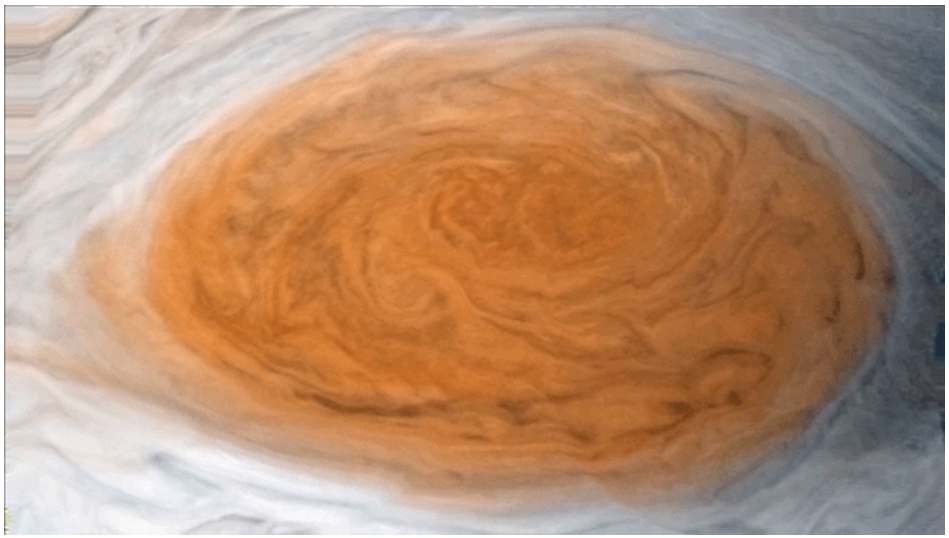

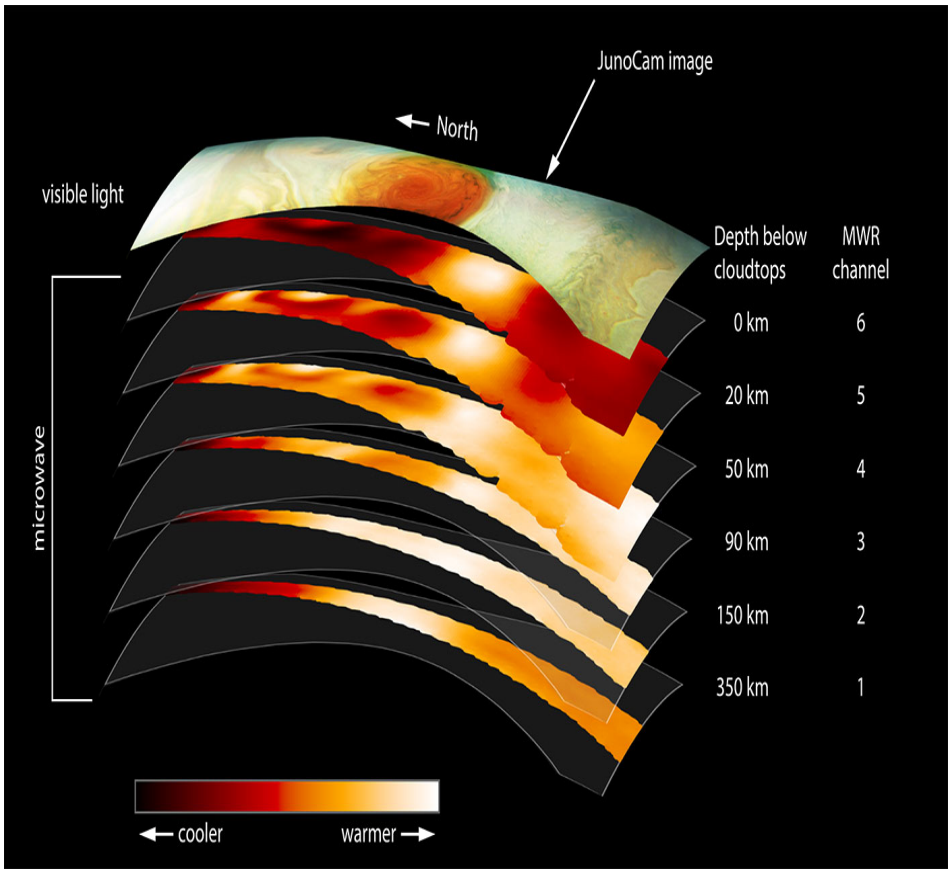

- **What would RH have made of these new results…..?**