Modeling Deep Convective Zonal Flows on the Giant Planets

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Cassini Image

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  - Max Plank Institute for Aeronomy
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Today's Seminar

- **A new model of zonal flow dynamics on the Giant Planets**
  1. **Observations**
  2. **Shallow Layer Models**
  3. **Deep Convection Models**
  4. **Yano's Shallow Model**
  5. **Deep Jovian Convection Model**
  6. **Deep Convection Model for the Ice Giants**

1. Observations of The Giant Planets

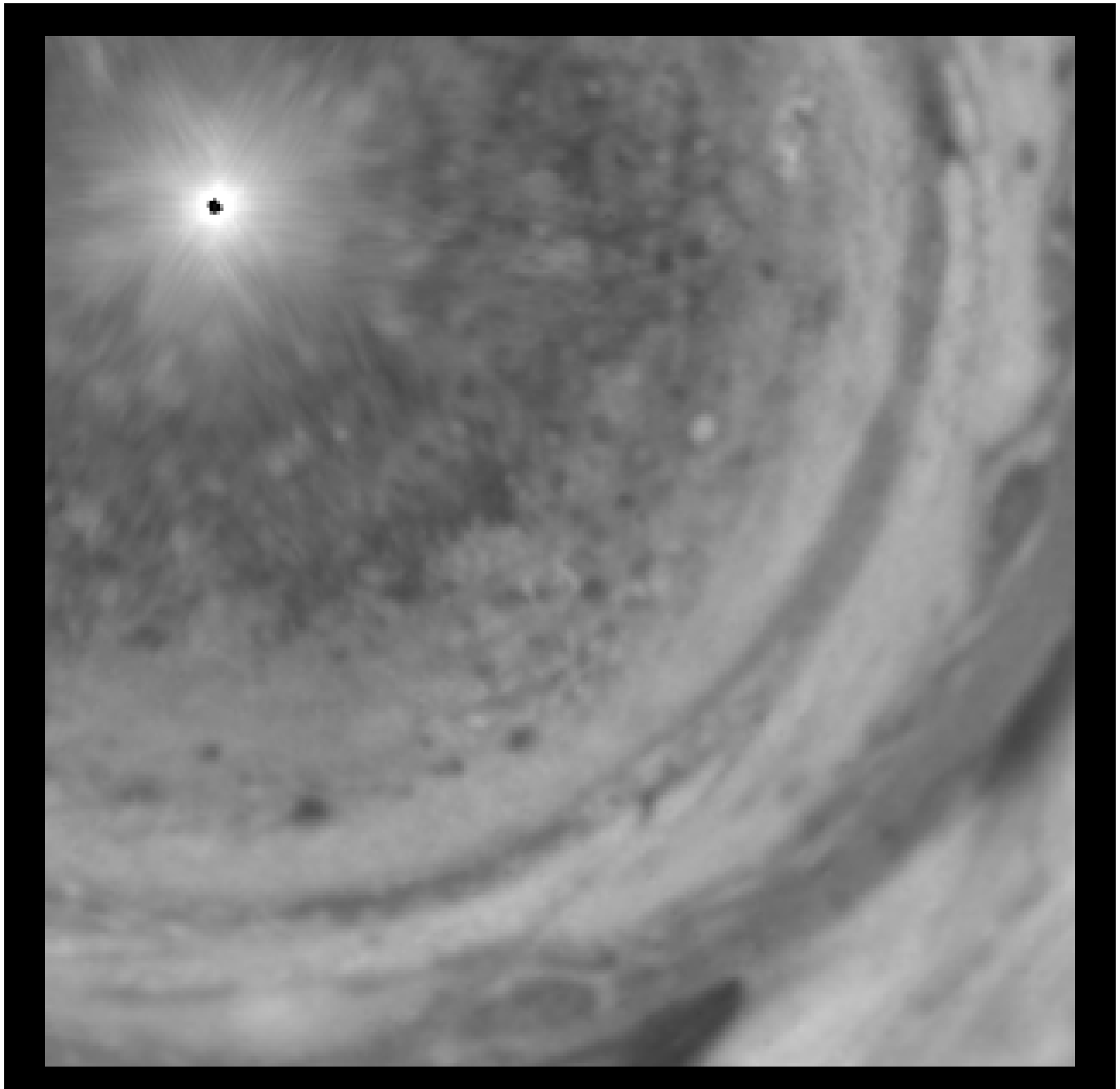
Jovian Zonal Wind Observations

- Jovian winds movie from Cassini:

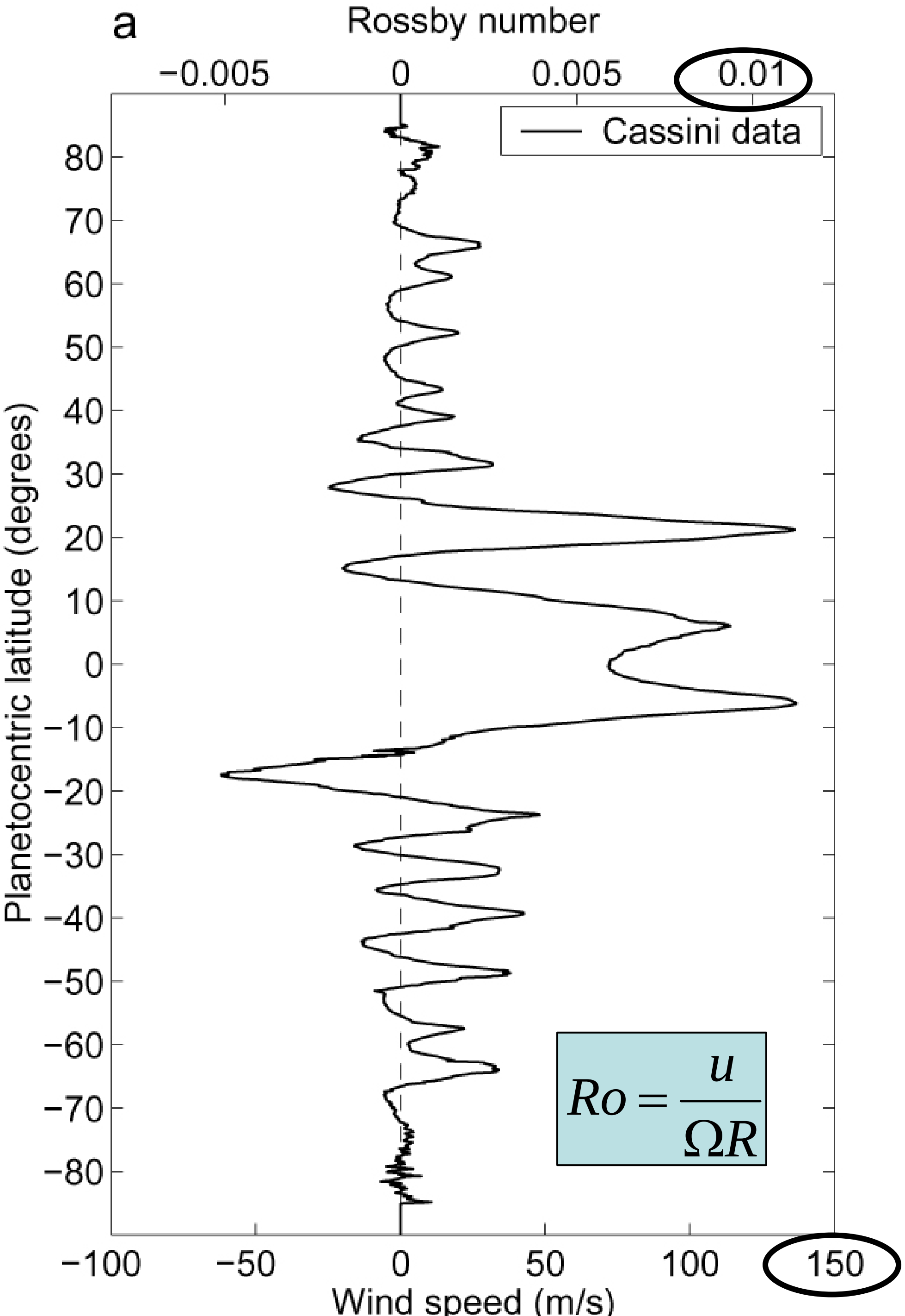
Cassini Website

Jovian Zonal Wind Observations

- Polar winds movie from Cassini:



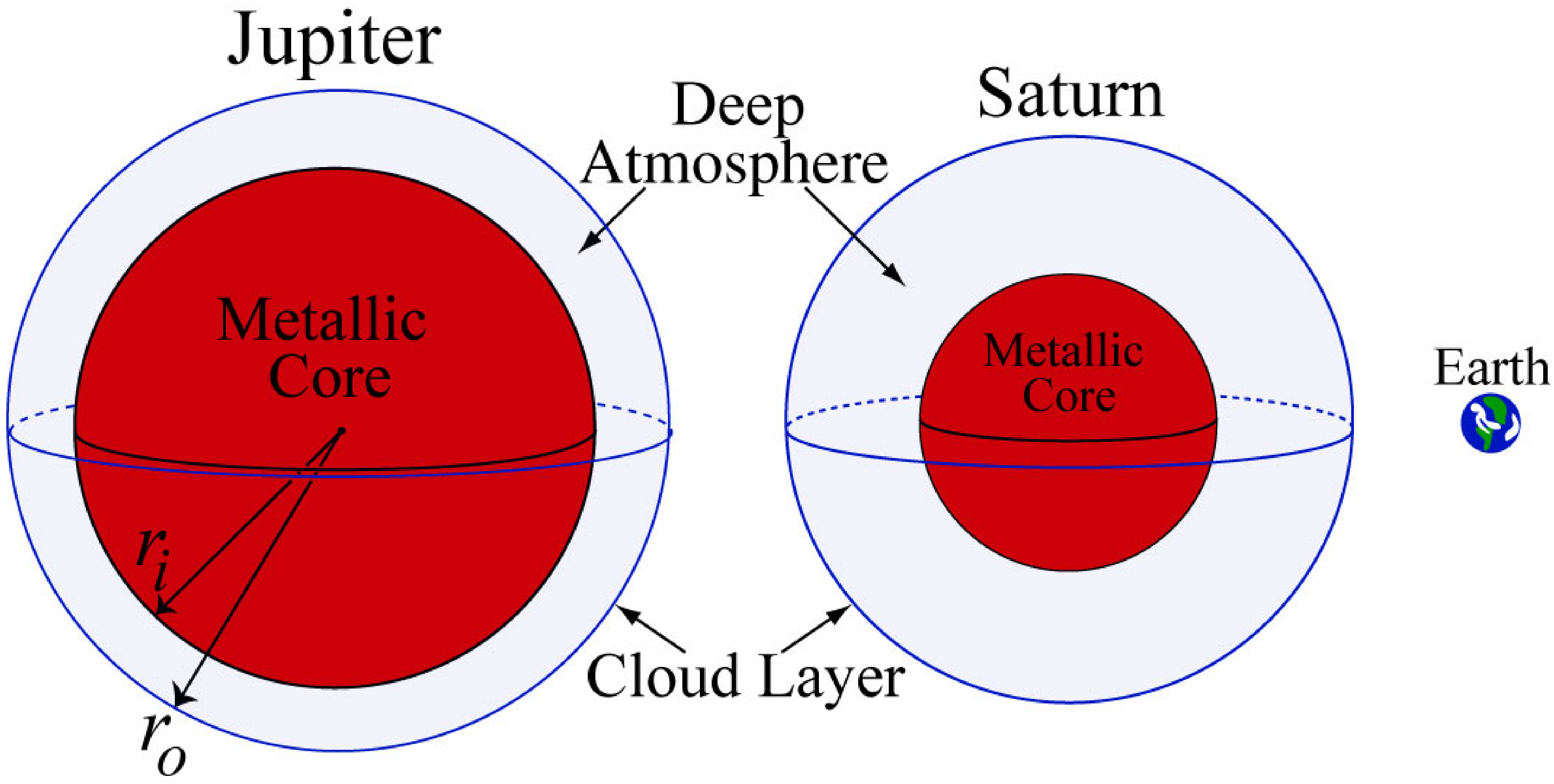
A. Vasavada



Jovian Wind Observations

- East-west velocities w/r/t ***B***-field frame
- Powerful prograde equatorial jet
- Smaller wavelength higher latitude jets
- Fine scale jets near poles
- Net prograde winds

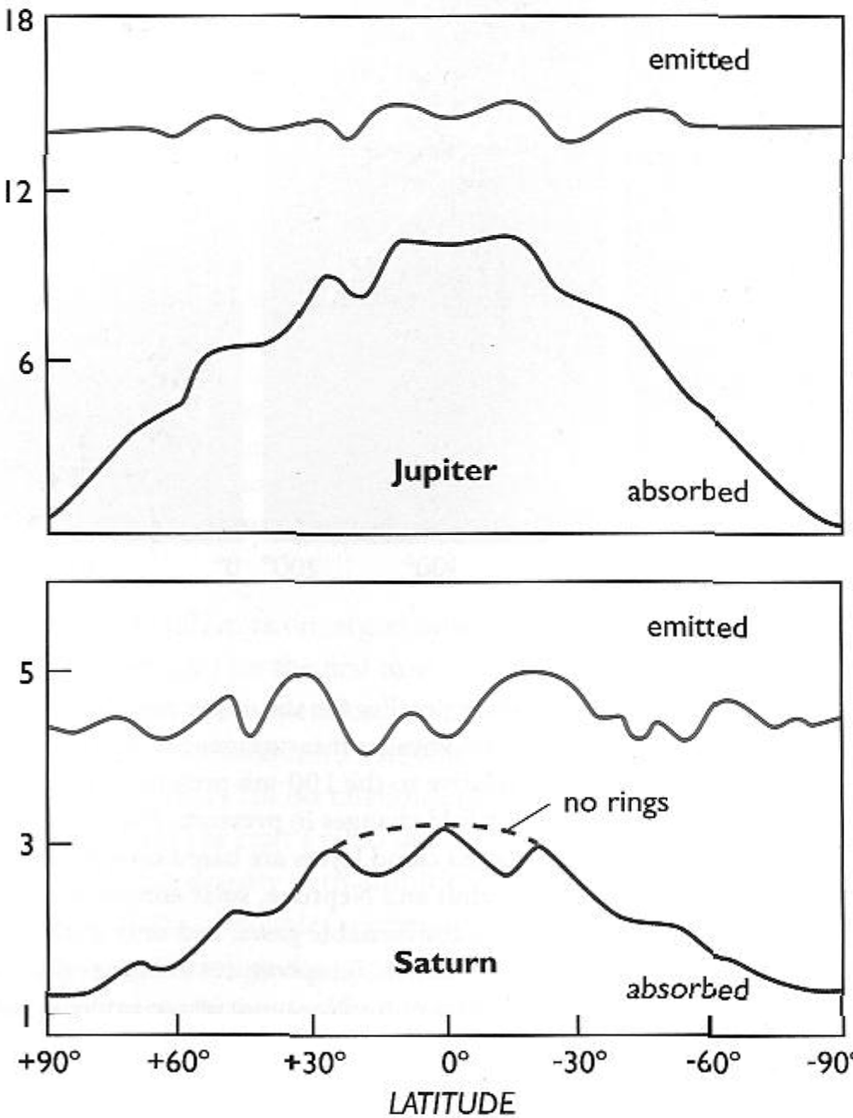
Giant Planet Atmospheres



- Deep atmospheric shell aspect ratios ($\chi = r_i/r_o$)
  - Jupiter: χ = **0.75 ~ 0.95**, Saturn: χ = **0.4 ~ 0.8**

Thermal Emission

- Jupiter and Saturn's thermal emission ~ twice solar insolation
- Neptune's ~ 3 times solar insolation
- Uranus is anomalous
  - *Zonal winds could be due to either shallow or deep energy sources*



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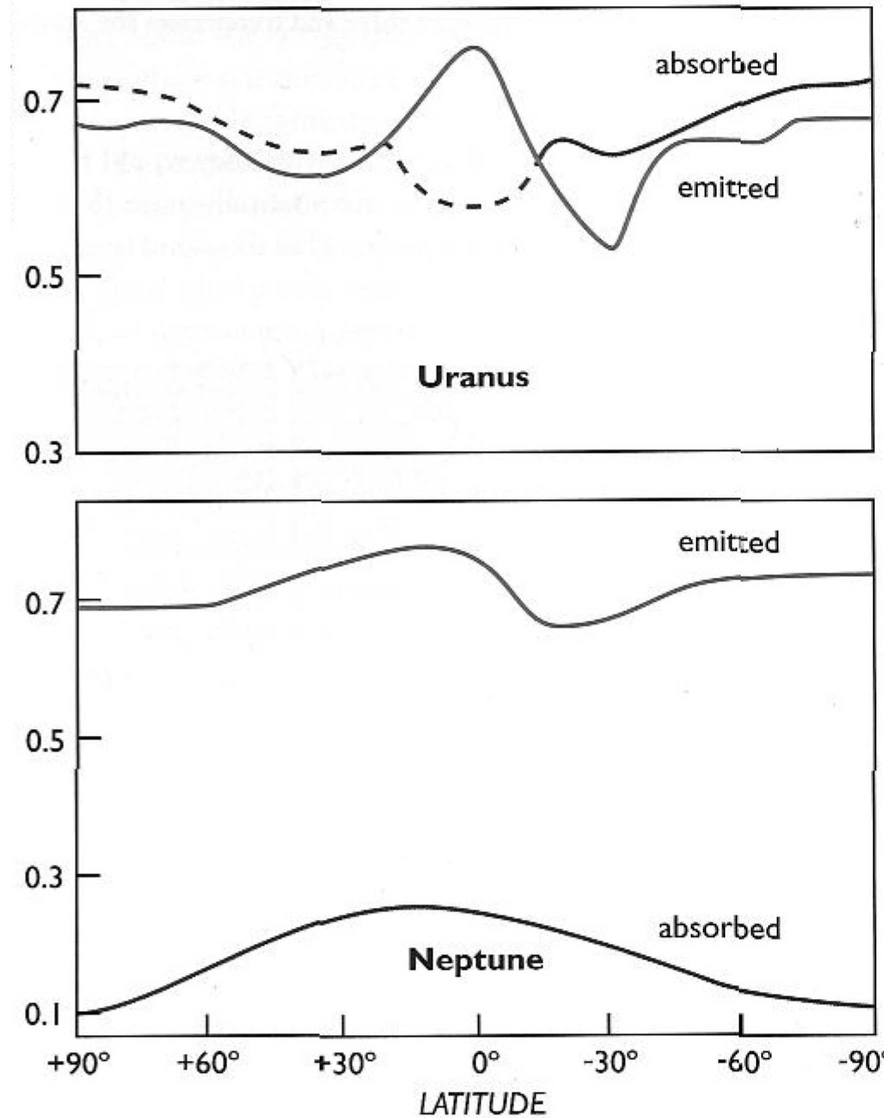


Zonal Wind Models

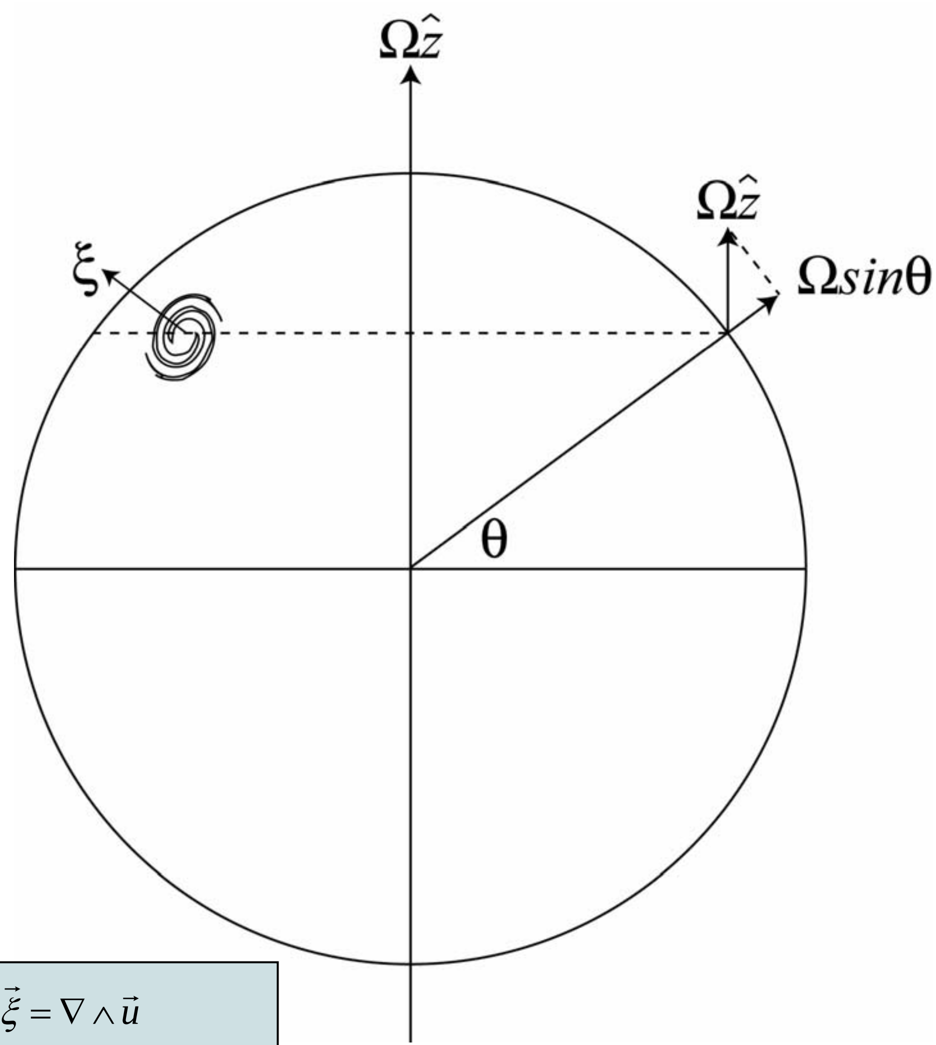
- Shallow layer models
- Deep Convection models

  – Both models are able to generate aspects of the observed zonal winds

2. Shallow Layer Models

Shallow Layer Models

- Turbulent flow on a rotating spherical surface of radius r_o
- No convection
- Simulates dynamics of outer weather layer



local vorticity: $\vec{\xi} = \nabla \wedge \vec{u}$

planetary vorticity: $\vec{f} = 2\Omega\sin\theta\hat{r}$

fluid layer depth: h

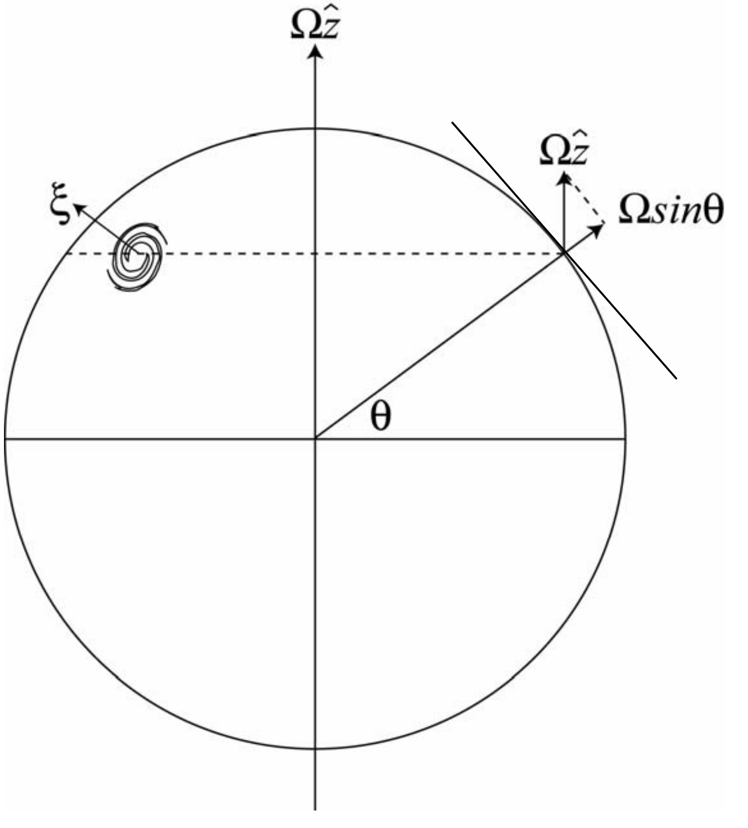
Turbulence

- 3D Turbulence: Energy cascades from injection scale eddies down to dissipation scale eddies
- 2D Turbulence: “Inverse Cascade” of energy; eddies tend to grow to domain size

Potential Vorticity Conservation

- In an inviscid shallow layer, potential vorticity (PV), *q*, is conserved:

$$\frac{dq}{dt} = \frac{d}{dt}\left(\frac{\xi + f}{h}\right) = 0$$



local vorticity: $\vec{\xi} = \nabla \wedge \vec{u}$

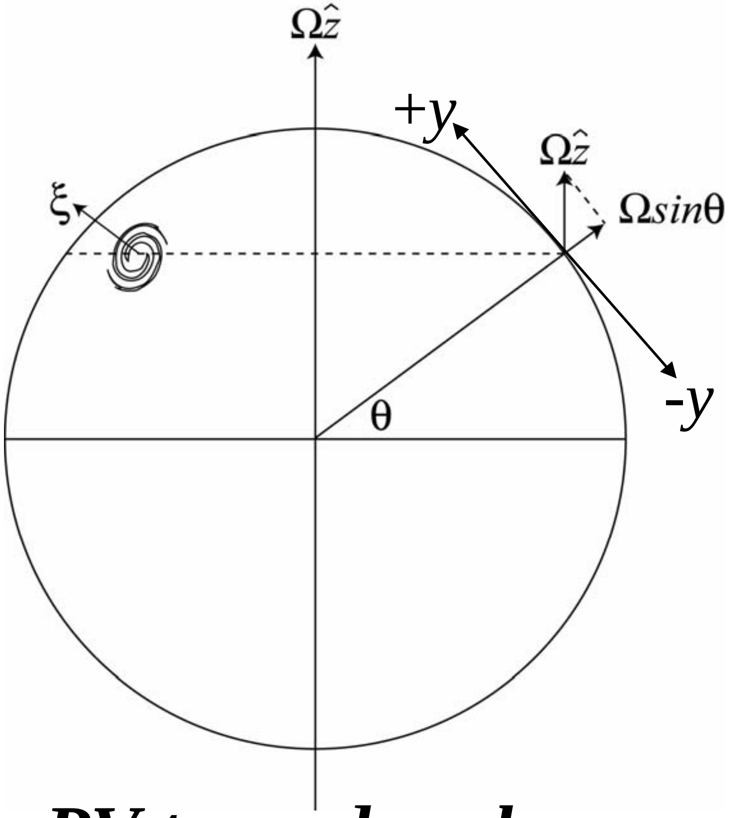
planetary vorticity: $\vec{f} = 2\Omega\sin\theta\,\hat{r}$

fluid layer depth: h

β - Plane Approximation

- Taylor expand planetary vorticity, f:

$$f(\theta) = 2\Omega \sin\theta$$
$$\approx f_o + (\nabla f)y$$
$$= f_o + \beta y$$



- On a spherical surface

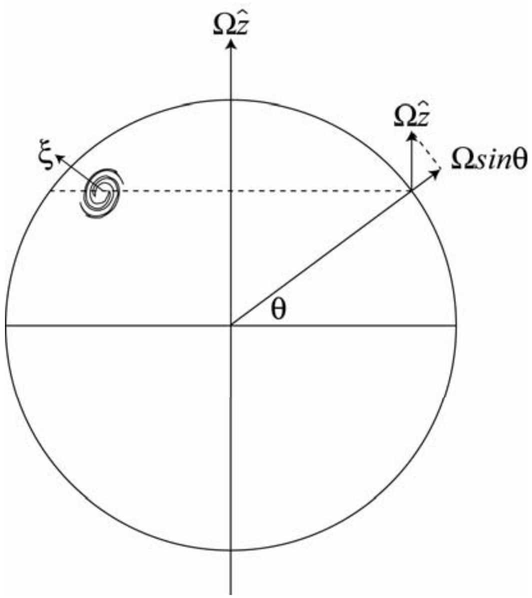
$$\beta = 2\Omega \cos\theta / r_o$$

- ***Ambient PV gradient: Increasing PV towards poles***

Potential Vorticity Conservation

- For inviscid 2D flow on the β-plane:

$$\frac{d}{dt}\left(\frac{\xi + f}{h}\right) = \frac{d}{dt}\left(\frac{\xi + f_o + \beta y}{h}\right) = 0$$



$$(\xi + \beta y) = const.$$

$$(U/L + \beta L) \sim const.$$

- For sufficiently large L :

$$U/L \sim \beta L \Rightarrow L \sim \sqrt{\frac{U}{\beta}}$$

local vorticity: $\vec{\xi} = \nabla \wedge \vec{u}$

planetary vorticity: $\vec{f} = 2\Omega \sin\theta \hat{z}$

fluid layer depth: h

Shallow Layer Rhines Length

- Rhines, *JFM*, 1975
- Rhines scale, L_R, where curvature effects truncate 2D inverse cascade:

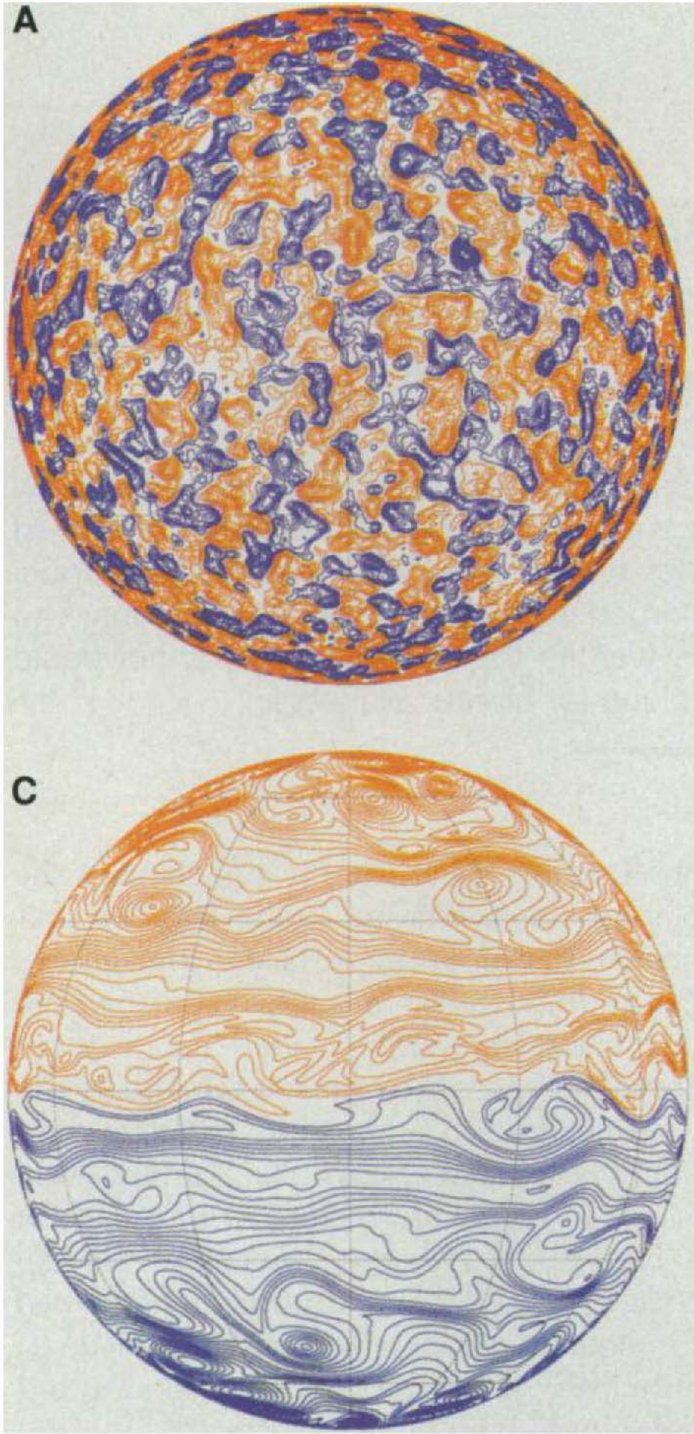
$$L_R \sim \sqrt{\frac{U}{\beta}}$$

- At L_R, turbulent eddies cease to grow
- Energy gets transferred into zonal motions
  - Scale of zonal jets

Shallow Layer Models

- Shallow layer turbulence evolves into:
  - **Large-scale zonal flows**
  - **Alternating bands**
  - **Coherent vortices**

Cho & Polvani, *Science*, 1996



Shallow Layer Models

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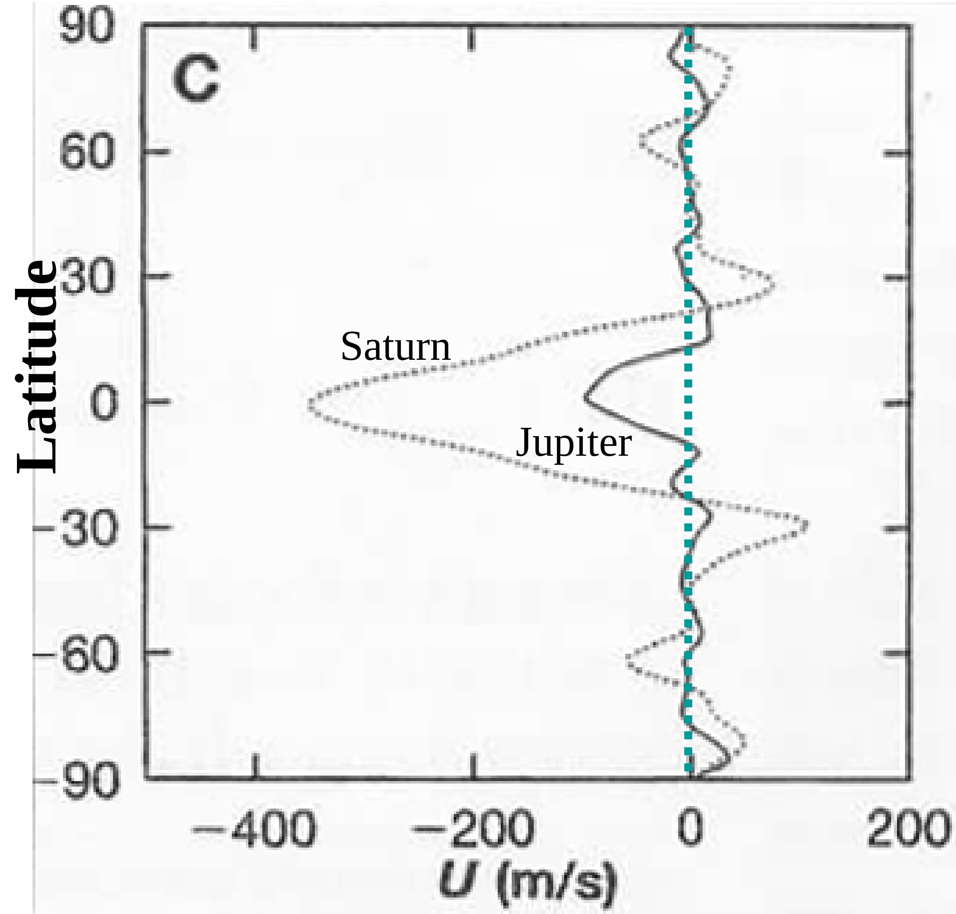
  - **Large-scale zonal flows**
  - **Alternating bands**
  - **Coherent vortices**

Equatorial jets are westward



Cho & Polvani, *Science*, 1996

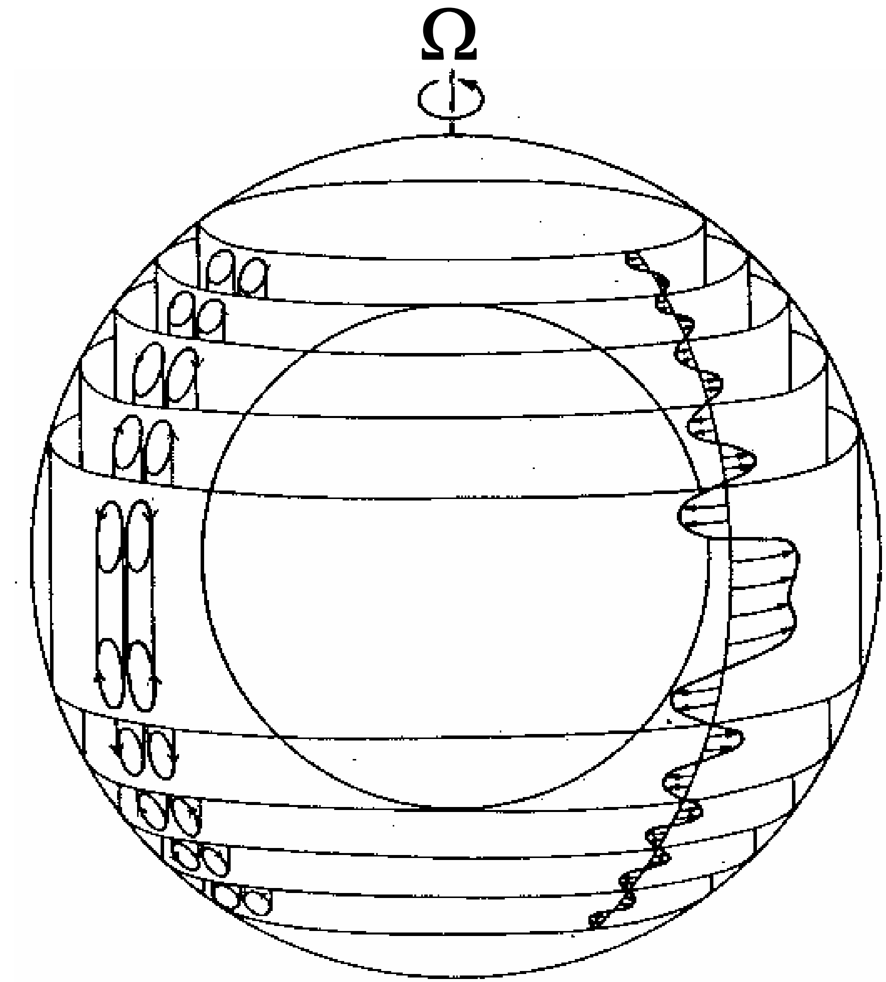
Shallow Layer Models

- 2D turbulence evolves into Rhines scale zonal jets
- Shallow layer β-effect
  - Potential vorticity increases towards poles
  - Gives retrograde equatorial jets
    - Iacono et al., 1999; Vasavada & Showman, 2005

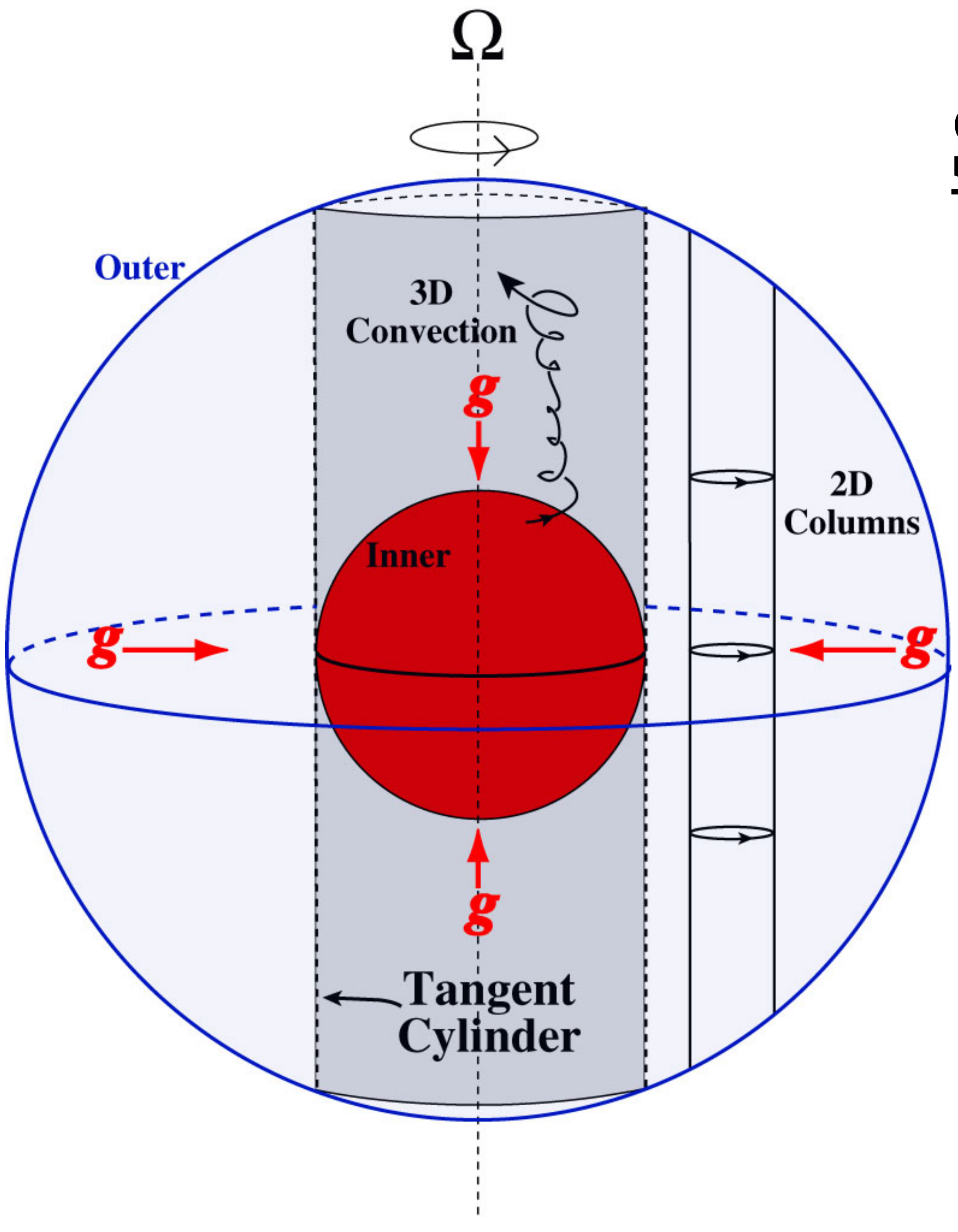
3. Deep Models

Deep Layer Models

- Busse, 1976
  - Deep spherical shell dynamics
  - Multiple jets require nested cylinders of convection columns
    - And even then…



Busse, *Icarus*, 1976



Rotating Spherical Shell Dynamics

- Geostrophic quasi-2D dynamics
  - Axial flow structures
- Tangent cylinder (TC) flow barrier

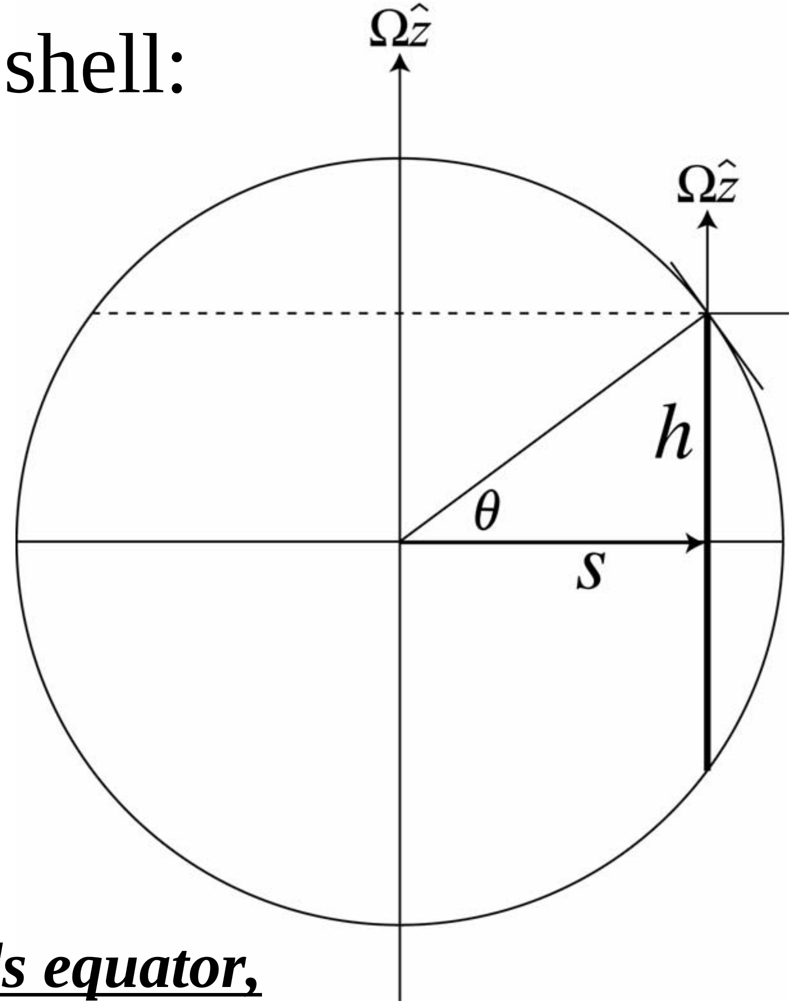
The *Topographic β*-effect

- PV Conservation in a deep shell:

$$\frac{d}{dt}\left(\frac{\xi + f_o}{h_o(1+(\frac{dh}{ds})s)}\right) = 0$$

$$(\xi - \beta_t s) = const.$$

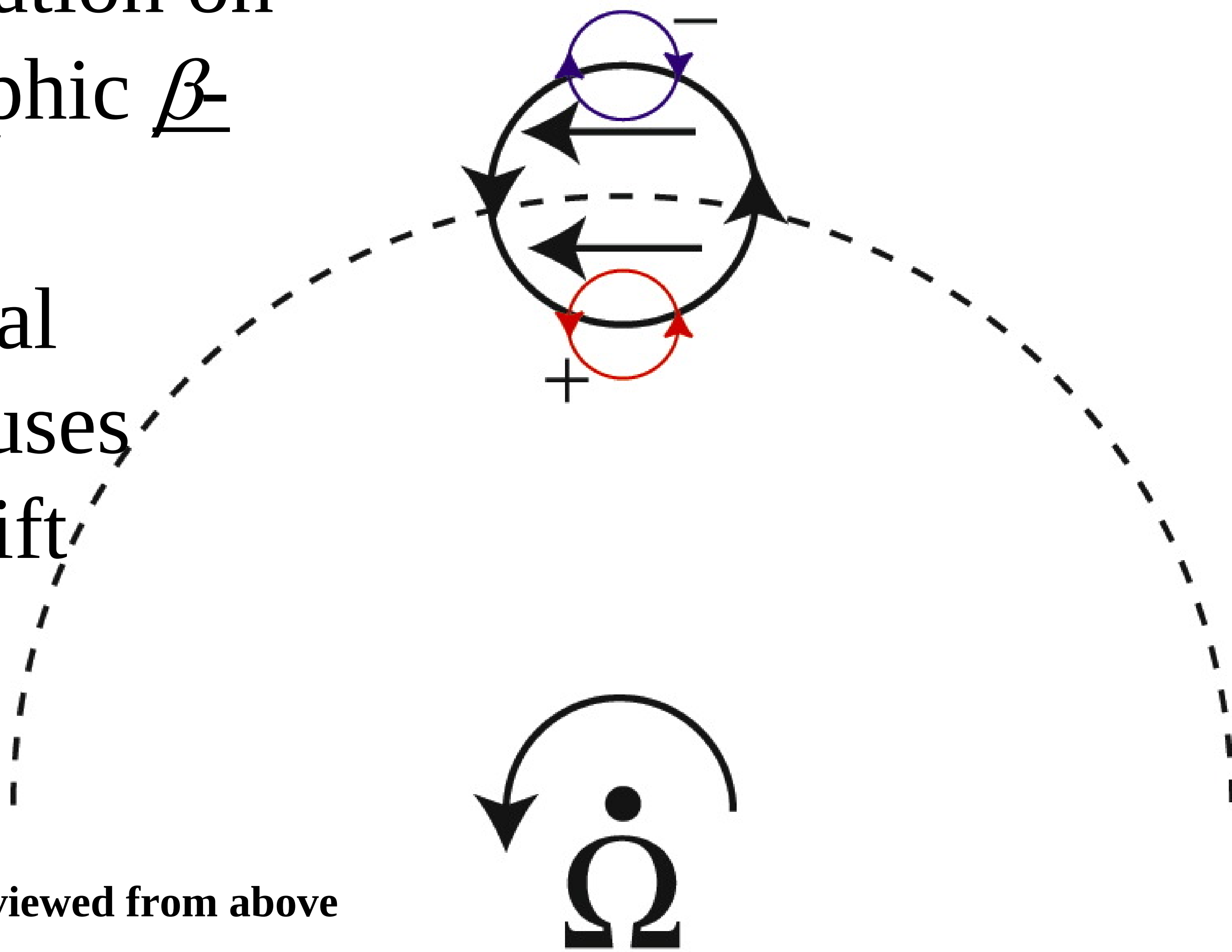
where $\beta_t = \dfrac{f_o}{h_o}\dfrac{dh}{ds}$



- ***PV gradient: Increasing PV towards equator, opposite the shallow layer case***

The *Topographic β*-effect

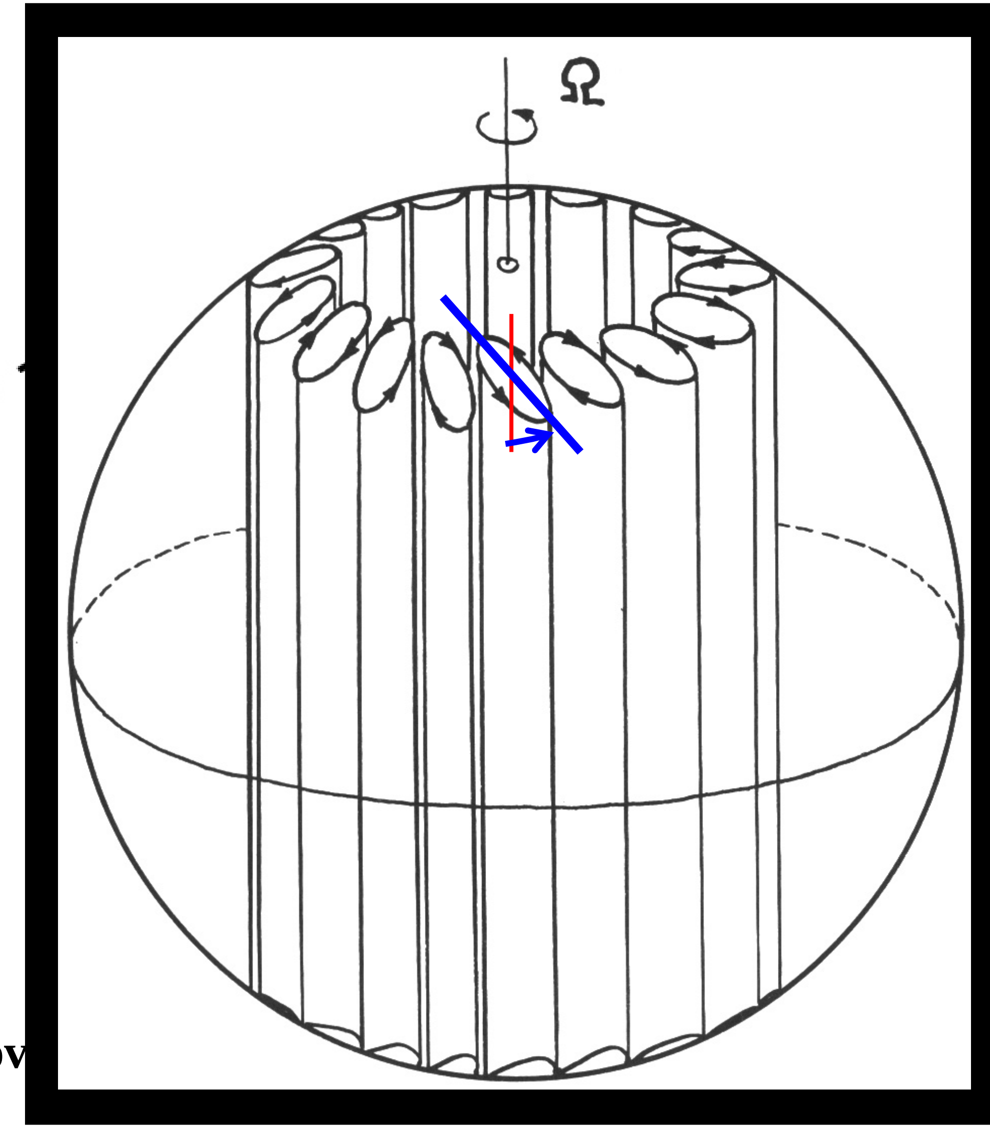
- PV conservation on the topographic *β-plane*
- Induced local vorticity causes eastward drift



Equatorial plane, viewed from above

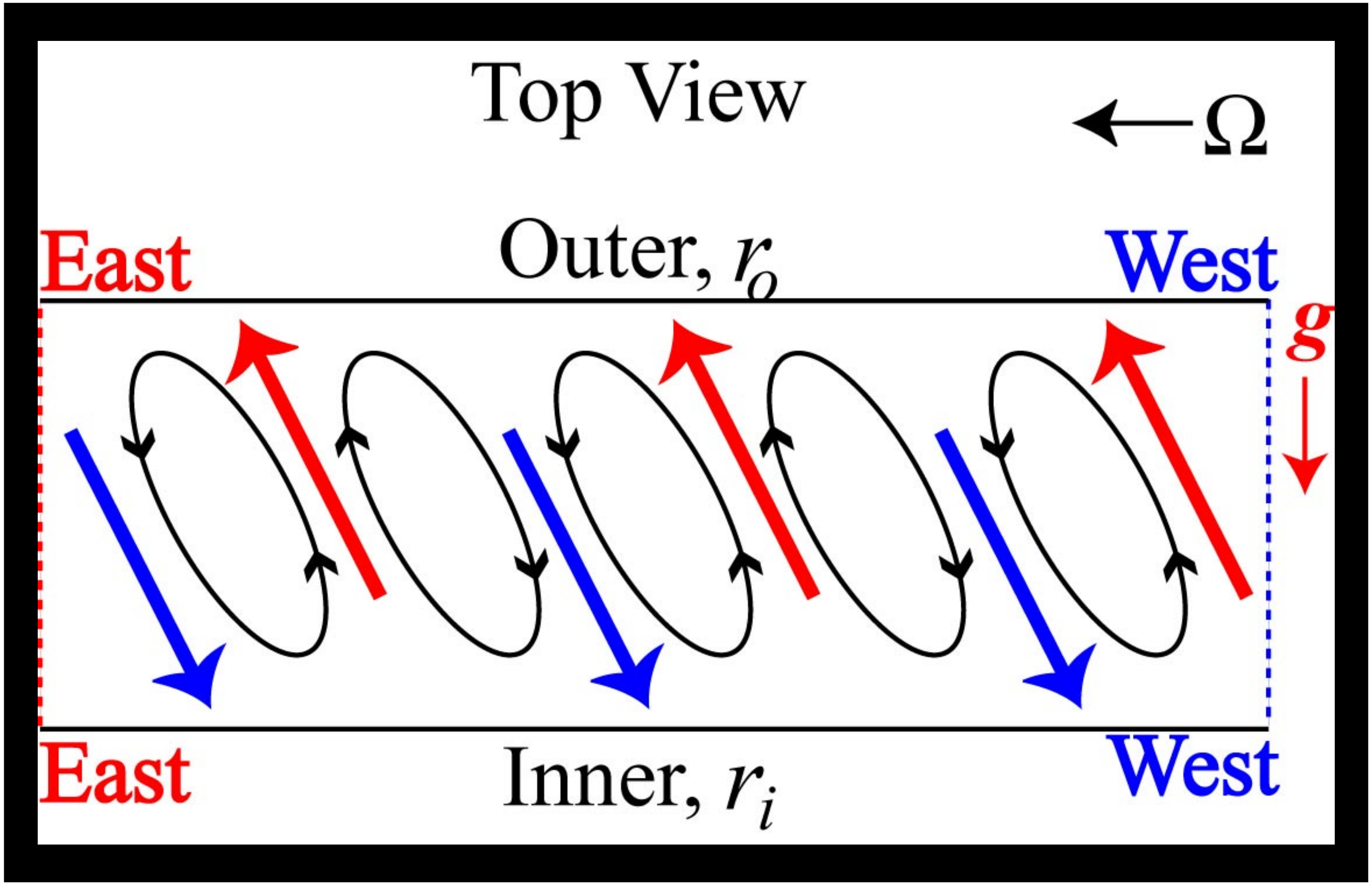
The *Topographic β*-effect

- PV conservation on *spherical boundary* causes latitudinally-varying drift rate & tilted columns



Equatorial plane, viewed from abov

Reynolds Stresses



Equatorial plane, viewed from above

Quasi-laminar Deep Convection Models

Tangent Cylinder

QuickTime?and a
YUV420 codec decompressor
are needed to see this picture.

QuickTime?and a
YUV420 codec decompressor
are needed to see this picture.

North pole view of
equatorial plane
isotherms

Outer boundary heat
flux from 20^{o}N lat

Aurnou & Olson, *GRL*, 2001

Shallow vs. Deep Model Comparison

- **Shallow Layer:**
  - **Imposed turbulence on a spherical shell**
  - **Increasing PV with latitude**
    - ***Retrograde equatorial jet***
  - **Higher latitude Rhines scale jets**
- **Deep Convection:**
  - **Quasi-laminar, QG convection**
  - **Decreasing PV with latitude**
    - **Prograde equatorial jet**
  - ***No higher latitude alternating jets***

Yano's Shallow Layer Model

Yano et al., *Nature* (2003)

Yano's Shallow Layer Model

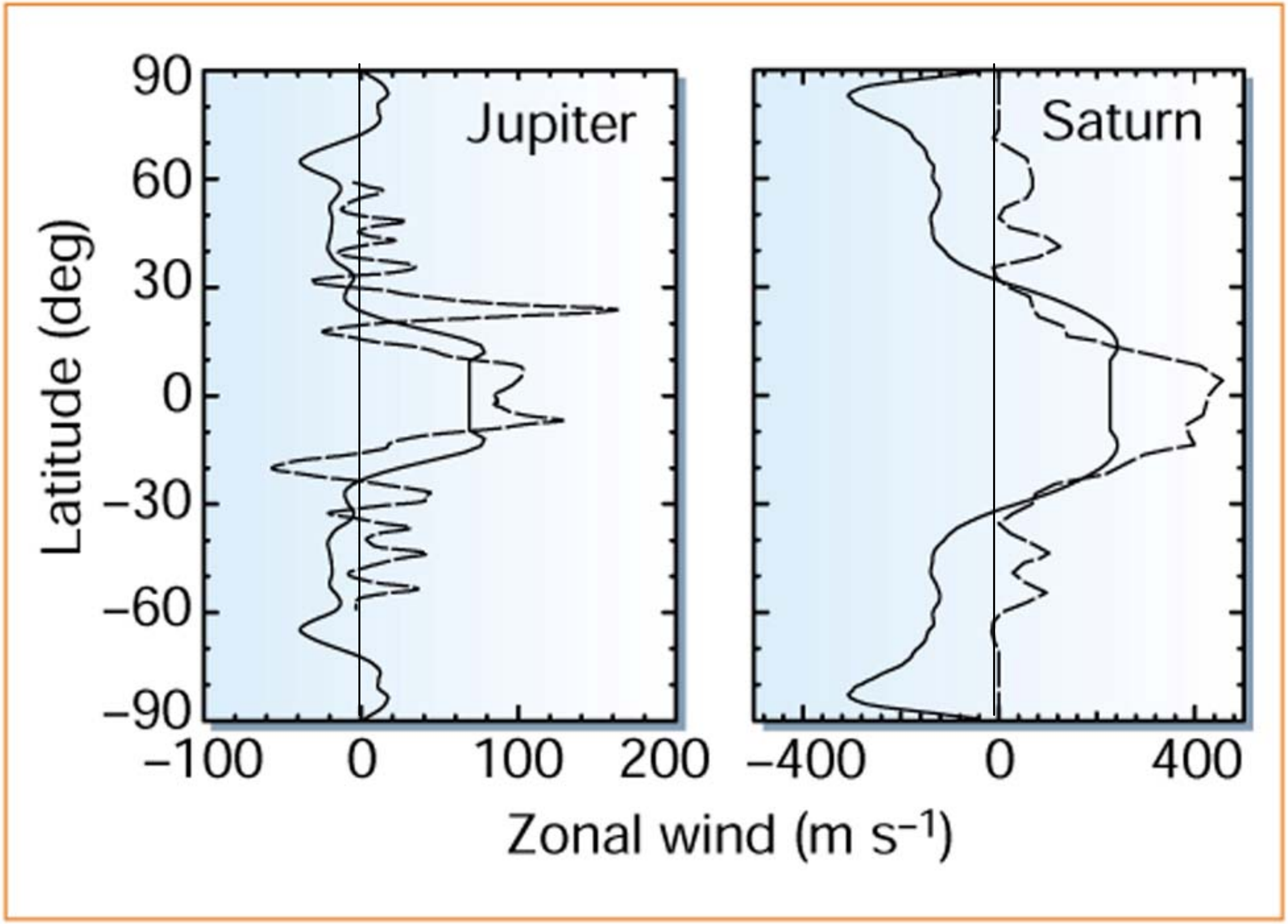
- Yano et al., 2003
  - 2D shallow layer turbulence model
  - ***Chooses*** **a different function for** β
    - **Full sphere** ***topographic*** β **parameter**
      - Opposite sign as shallow layer β
  - Simulates geostrophic turbulence in a sphere using the 2D shallow layer equations

Yano's Shallow Layer Model

- Prograde equatorial jet
- Broad Rhines scale high latitude jets

Solid Lines: Model

Dashed Lines: Observed



Yano et al., *Nature*, 2003

Yano's Shallow Layer Model

- Sign of β controls direction of equatorial jet
- Broad high latitude jets do not resemble Jovian observations

- Suggests that Rhines scale jets can form from quasigeostrophic (~2D) convective turbulence in a deep 3D model

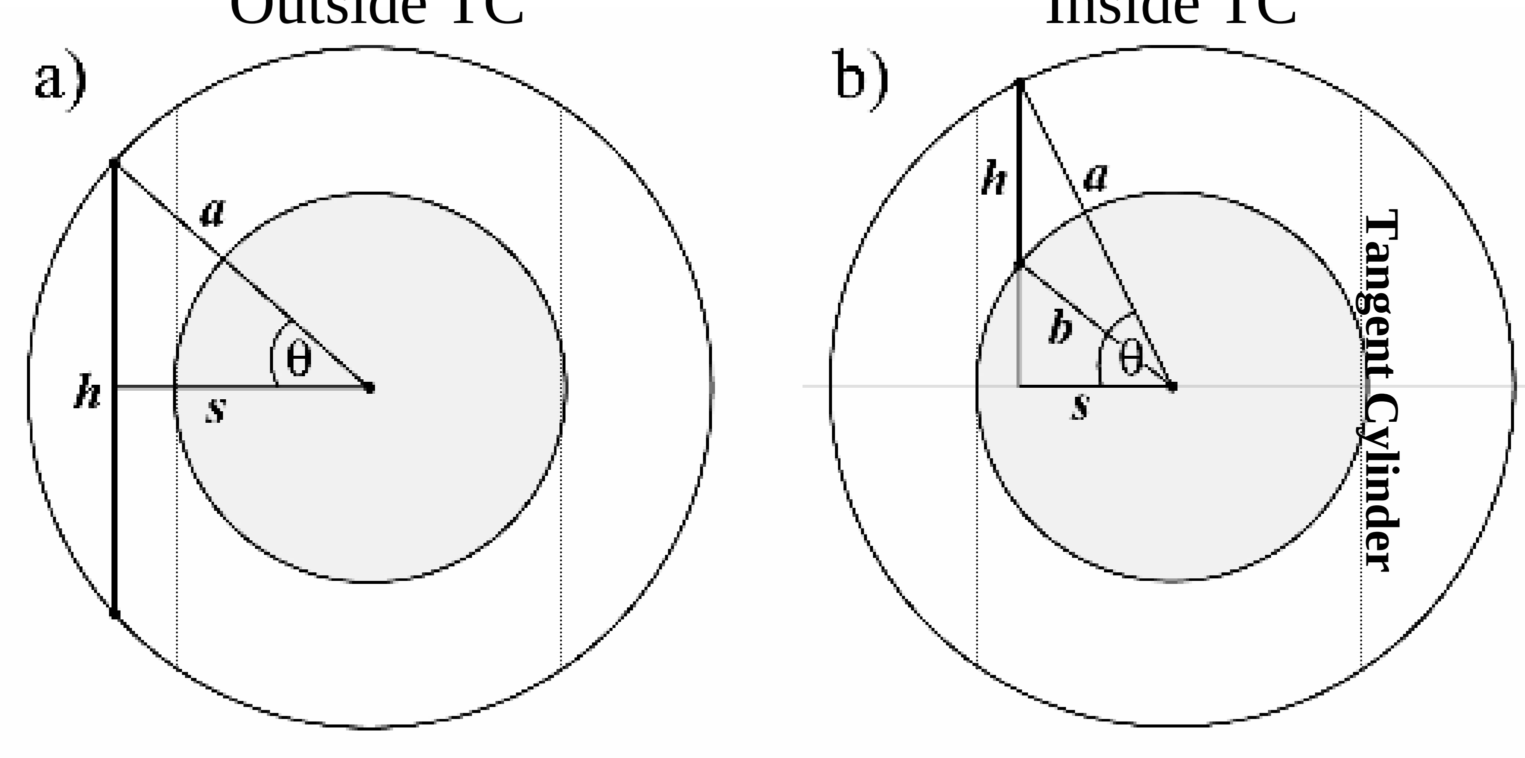
4. New Deep Convection Model

Heimpel, Aurnou & Wicht, *Nature*,

438: 193-196 (2005)

Spherical Shell Rhines Scale

Outside TC　　　　Inside TC



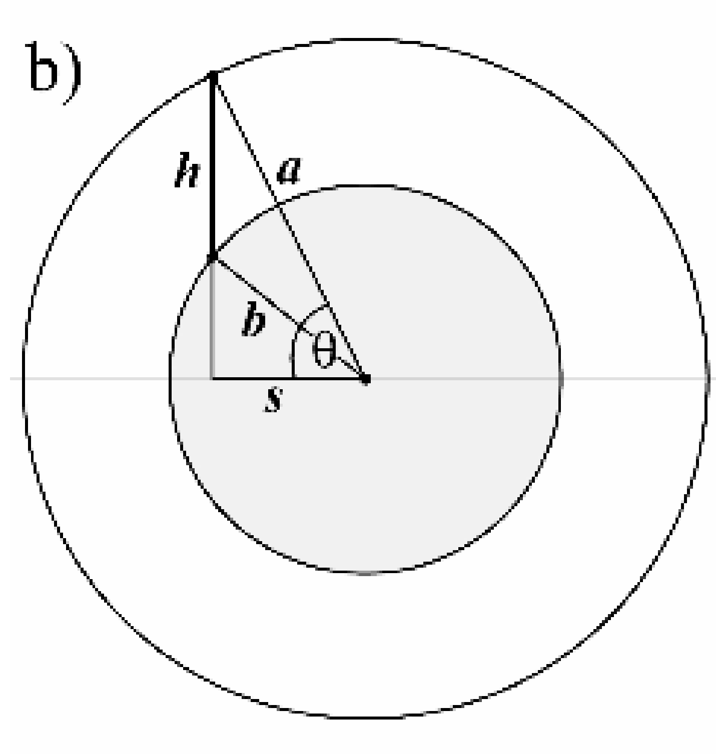
$$\frac{1}{h}\left|\frac{dh}{ds}\right| = \frac{1}{r_o}\frac{\cos\theta}{\sin^2\theta}$$

$$\frac{1}{h}\left|\frac{dh}{ds}\right| = \frac{1}{r_o}\frac{\cot\theta}{\sqrt{\chi^2 - \cos^2\theta}}$$

(Scaling discontinuity across TC)

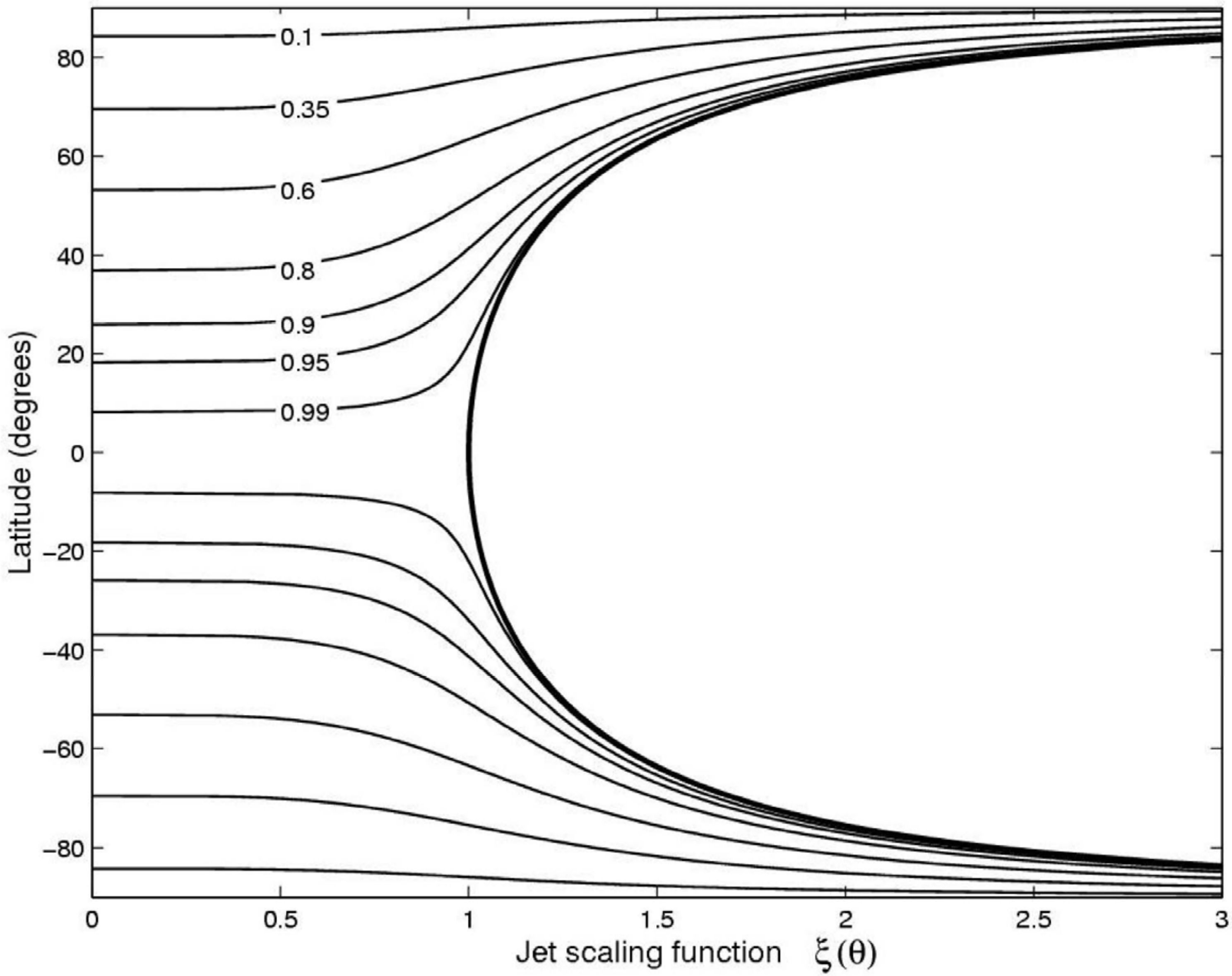
Spherical Shell Rhines Scale

- The Rhines scale is **discontinuous** across the tangent cylinder
- In thin shells:
  - The β_t parameter becomes larger inside the tangent cylinder
  - L_R becomes smaller



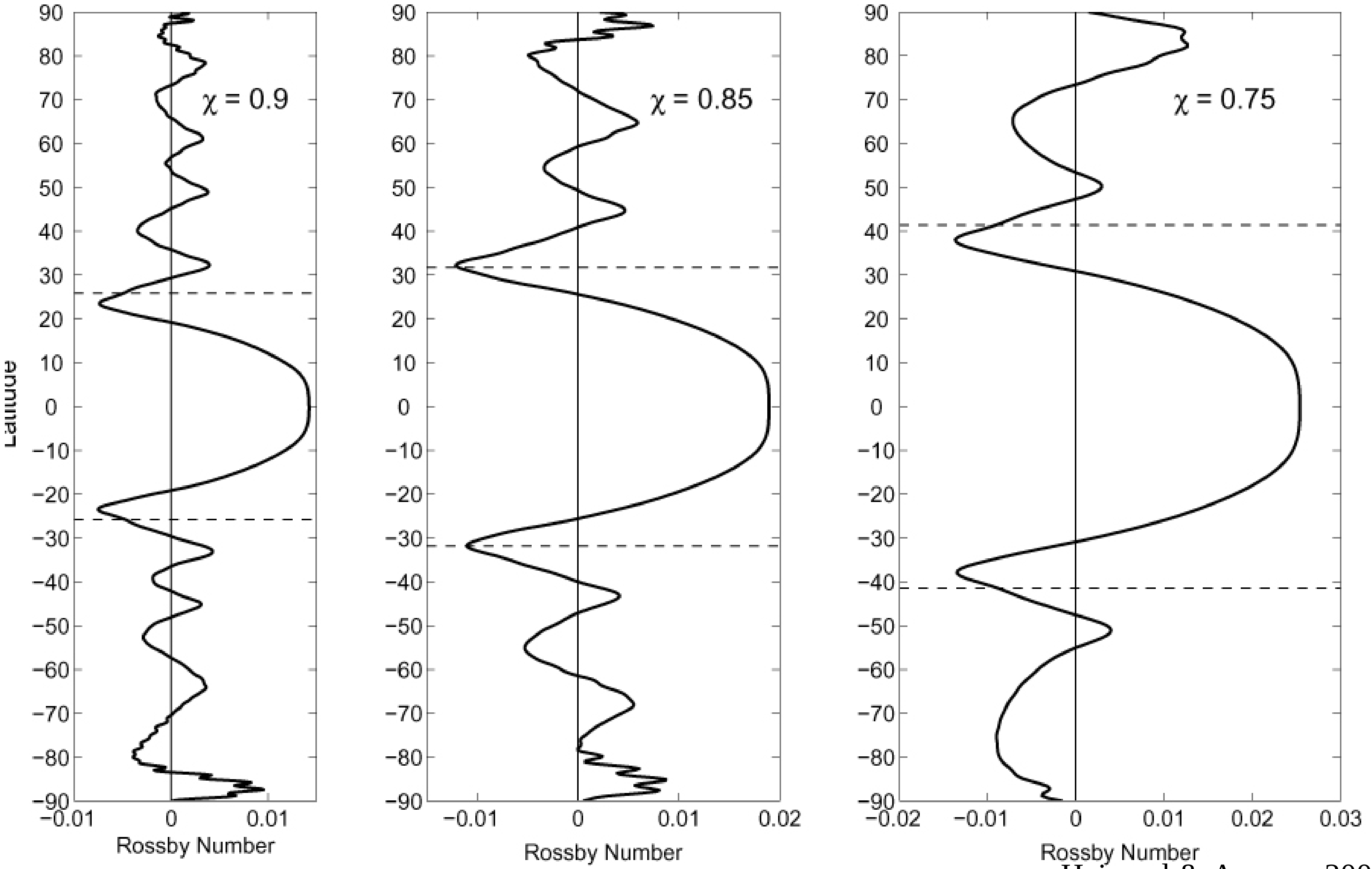
$$L_R \sim \sqrt{\frac{U}{\beta}}$$

Geometric Scaling Function



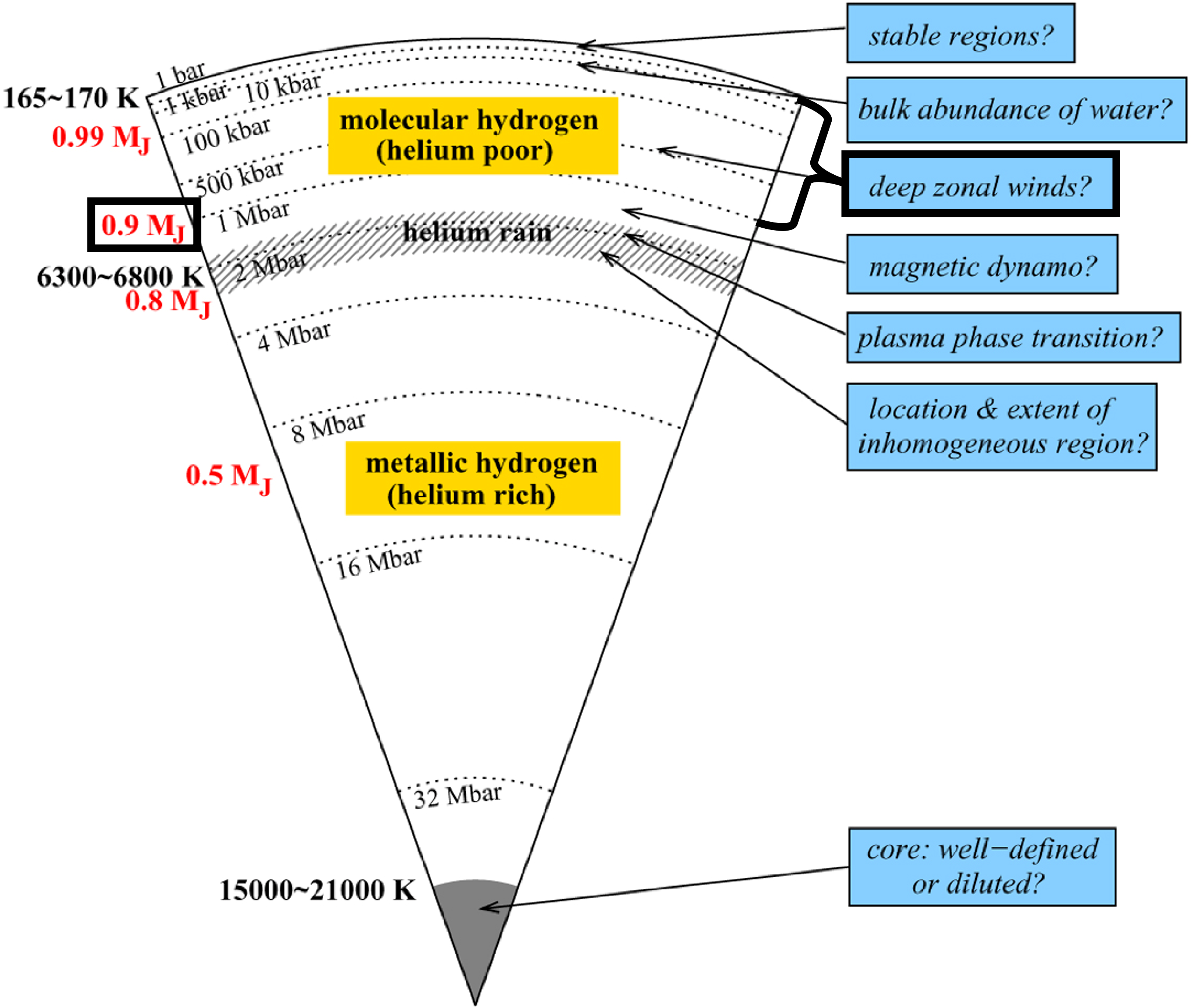
Heimpel & Aurnou, 2006

Zonal Winds vs. Radius Ratio Tests



Heimpel & Aurnou, 2006

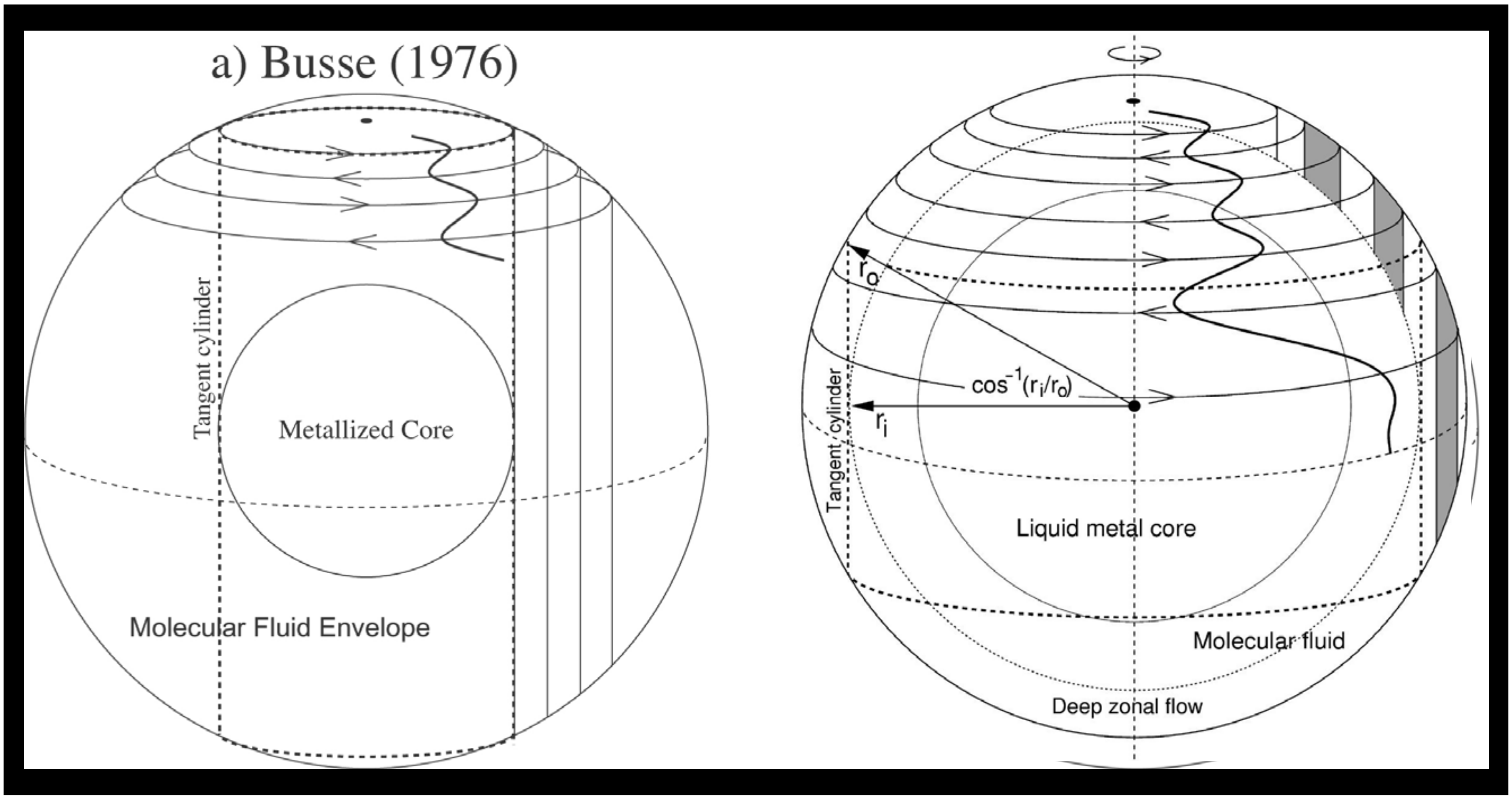
Recent Jovian Interior Models



Guillot et al., 2004

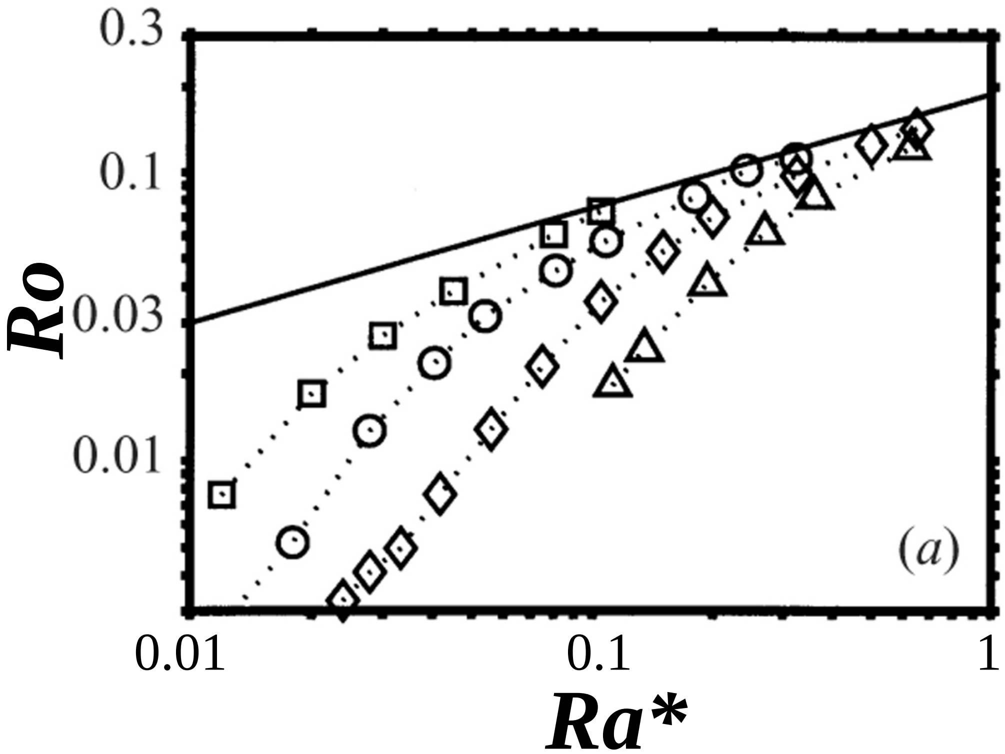
New Deep Convection Model

- **Rapidly-rotating, turbulent** convection
- **Thin shell geometry** (χ = 0.90; *7000 km deep*)



χ=0.35 Rotating Convection Studies

- Christensen, 2002
  - Zonal flow from fully-developed, quasigeostrophic turbulence
  - Asymptotic regime



Christensen, *JFM*, 2002

New Deep Convection Model

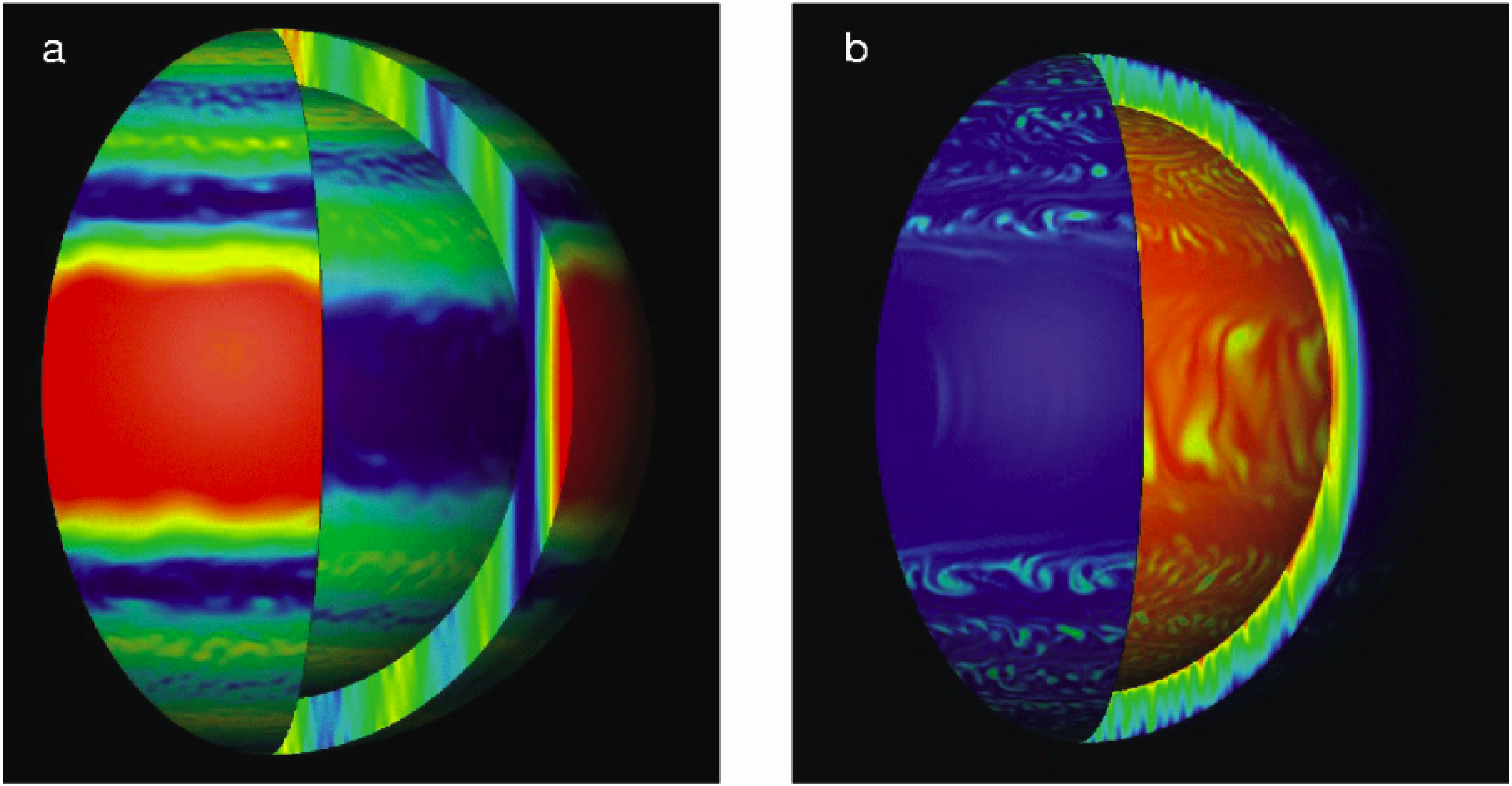
- Solve Navier-Stokes equation
- Energy equation
- Boussinesq (*incompressible*) fluid

- Wicht's MagIC2 spectral transform code
  - Spherical harmonics in lat. & long.
    - Difficulties in resolving flows near poles
  - Chebyschev in radius
  - Courant time-step using grid representation

New Deep Convection Model

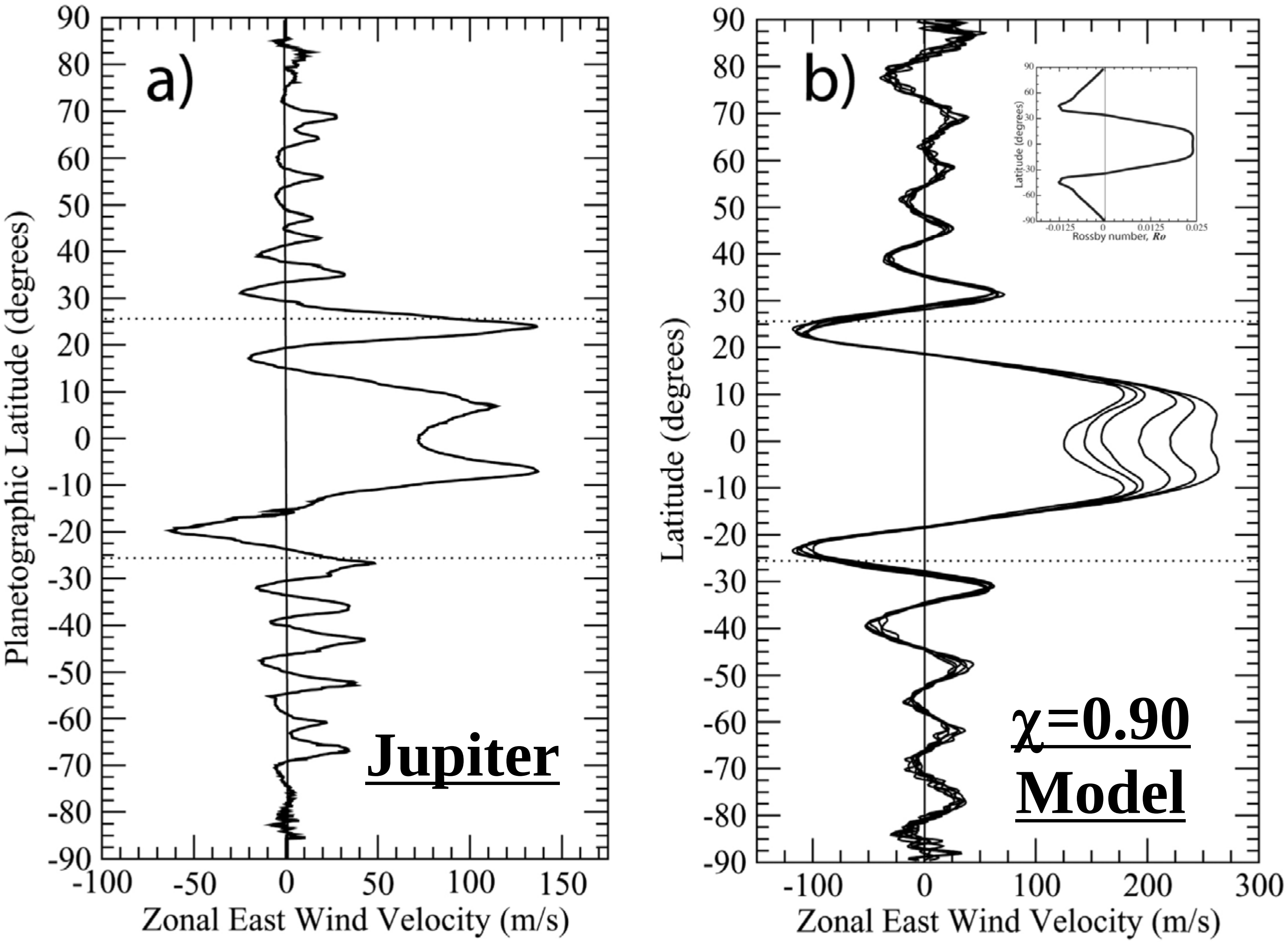
- Input Parameters:
  - $Ra = 1.67 \times 10^{10}$
  - $E = 3 \times 10^{-6}$
  - $Pr = 0.1$
    - $Ra^* = RaE^2/Pr = 0.15$
  - $r_i/r_o = \chi = 0.90$
- Output Parameters:
  - $Re \sim 5 \times 10^4$
  - $Ro \sim 0.01$
- Resolution
  - $L_{\mathrm{max}} = 512$, grid: ϕ 768, θ 192, r 65
  - Hyperdiffusion and 8-fold ϕ-symmetry

χ=0.90 Model Results



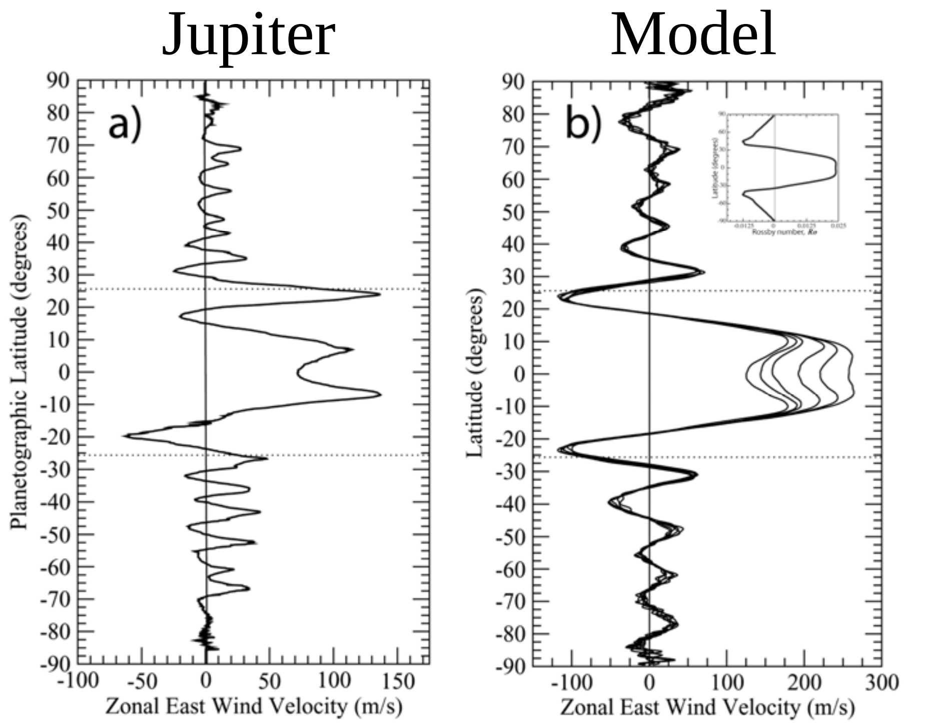
Azimuthal Velocity   Temperature

Zonal Wind Profiles



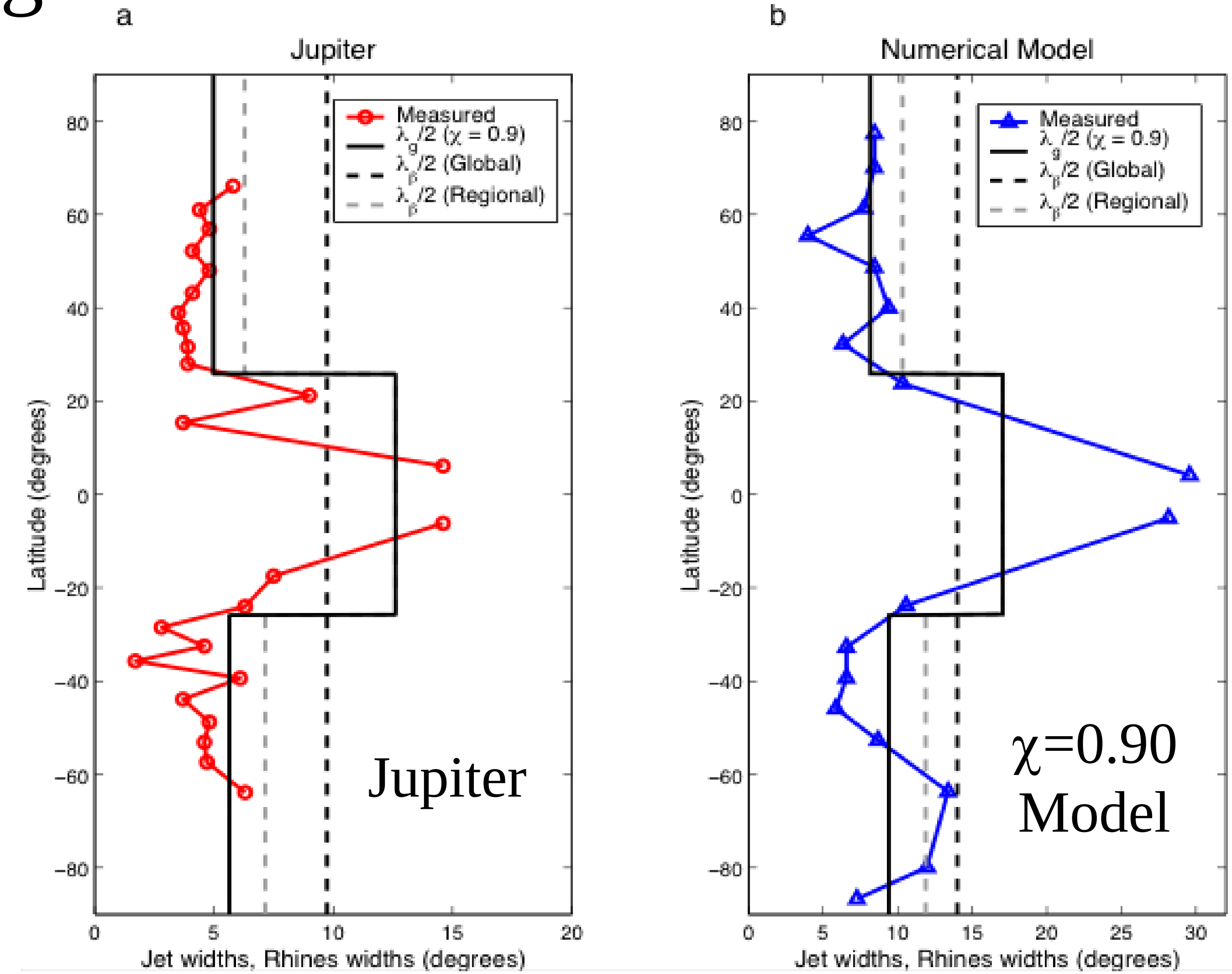
The “Tuning” Question

- We have chosen
  - – the radius ratio
  - – The lowest Ekman number feasible
    - i.e., Fastest rotation rate
  - – A Rayleigh number such that our *peak* *Ro* is similar to Jupiter’s
    - Close to asymptotic regime of Christensen, 2002



3D Spherical Shell Rhines Scale

- “Regional” 3D shell Rhines scale



New Deep Convection Model

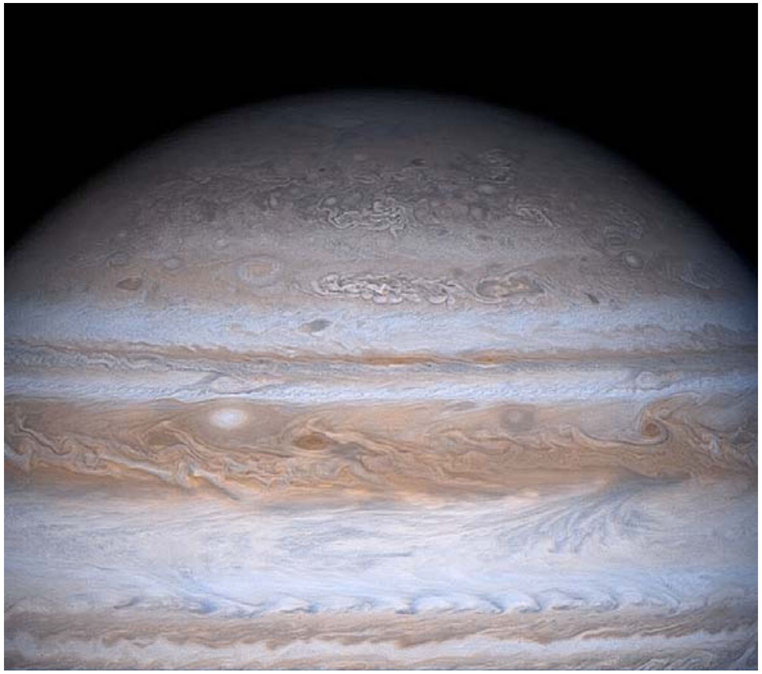
- Quasigeostrophic convective turbulence in a relatively thin spherical shell
- Generates **coexisting** prograde equatorial jets & alternating higher latitude jets
- Model (& Jovian observations) follows Rhines scaling for a 3D shell
  - Scaling **discontinuity** across the tangent cylinder
  - Smaller-scale jets inside tangent cylinder

Following Work 1

- Why do we need “regional” Rhines fits?
  - Expensive to test with full 3D models
    - 2D quasigeostrophic mechanical models
    - 2D quasigeostrophic convection models

Following Work 2

- How do we model high latitude fine scale jets?
  - Due to odd “plane layer” mode (Roberts, 1968)?
  - Local models or non-SH global models



QuickTime?and a
DV - NTSC decompressor
are needed to see this picture.

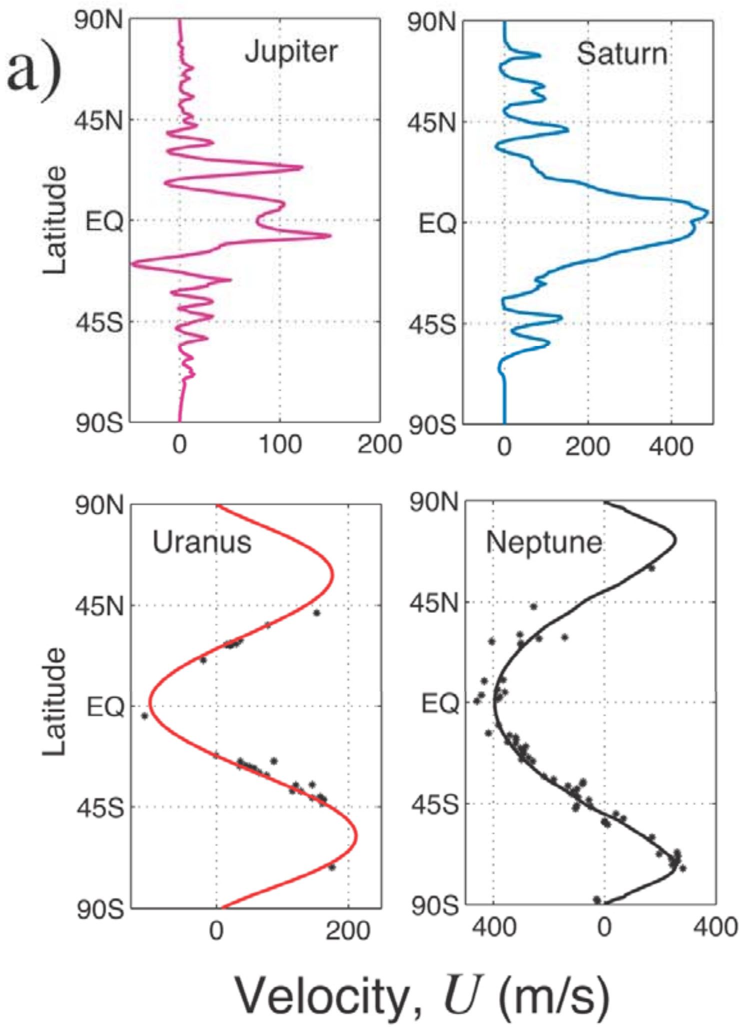
Following Work 3

- Assumed zonal flow truncation at depth due to electromagnetic braking
  - Simple 2D EM braking model
- Assumed Boussinesq fluid
  - How does compressibility change Boussinesq Rhines scaling?

5. Modeling Zonal Flows on the Ice Giants

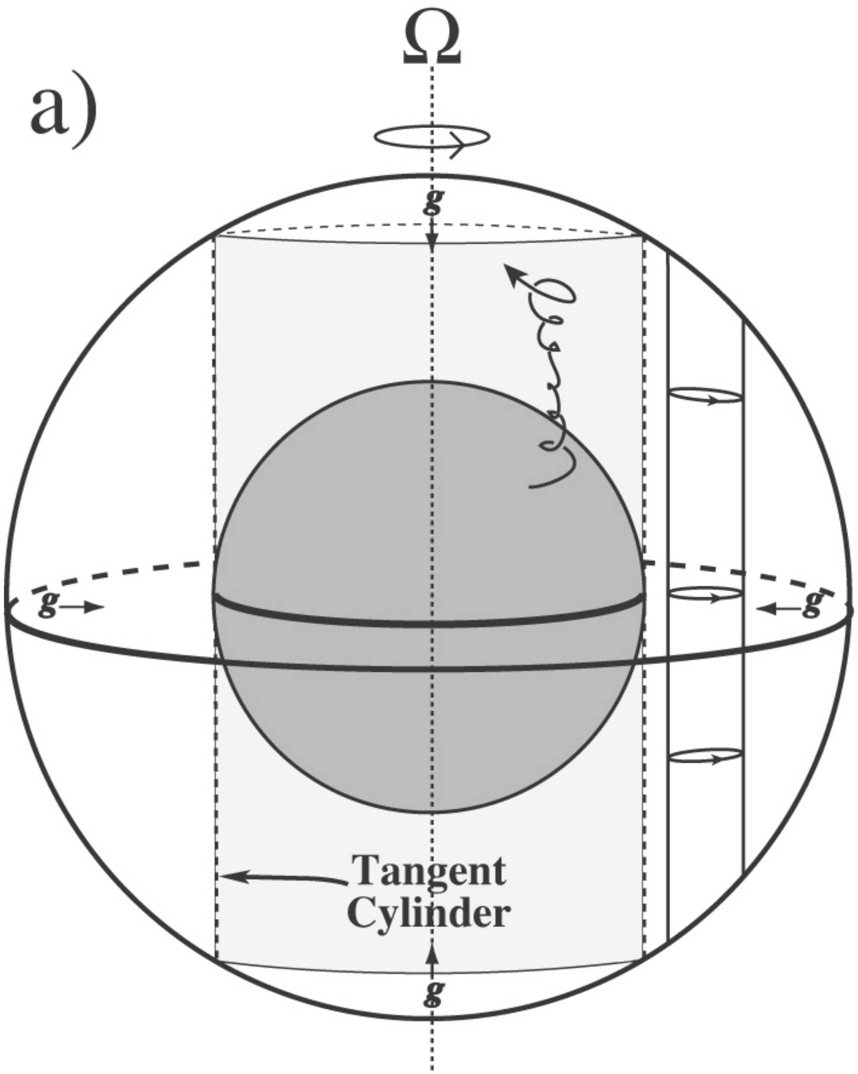
Aurnou, Heimpel & Wicht, submitted to *Icarus* (2006)

Giant Planet Zonal Wind Profiles



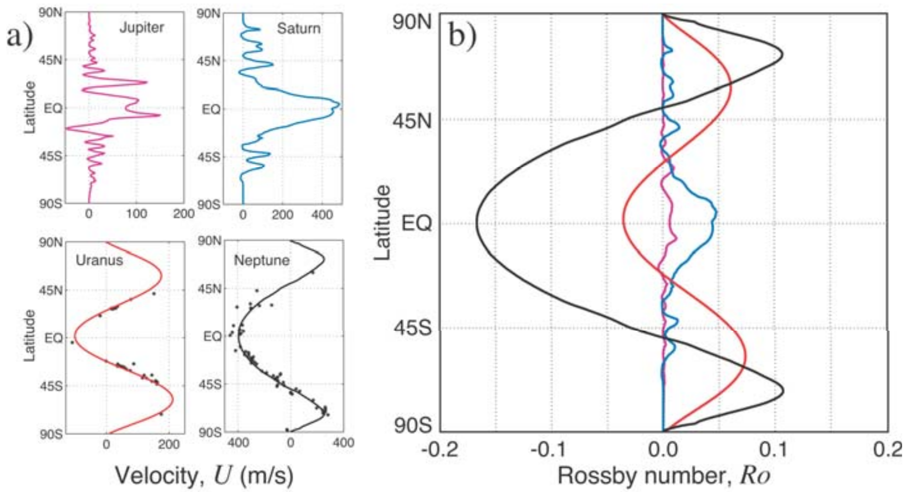
Adapted from Sukoriansky et al., 2002

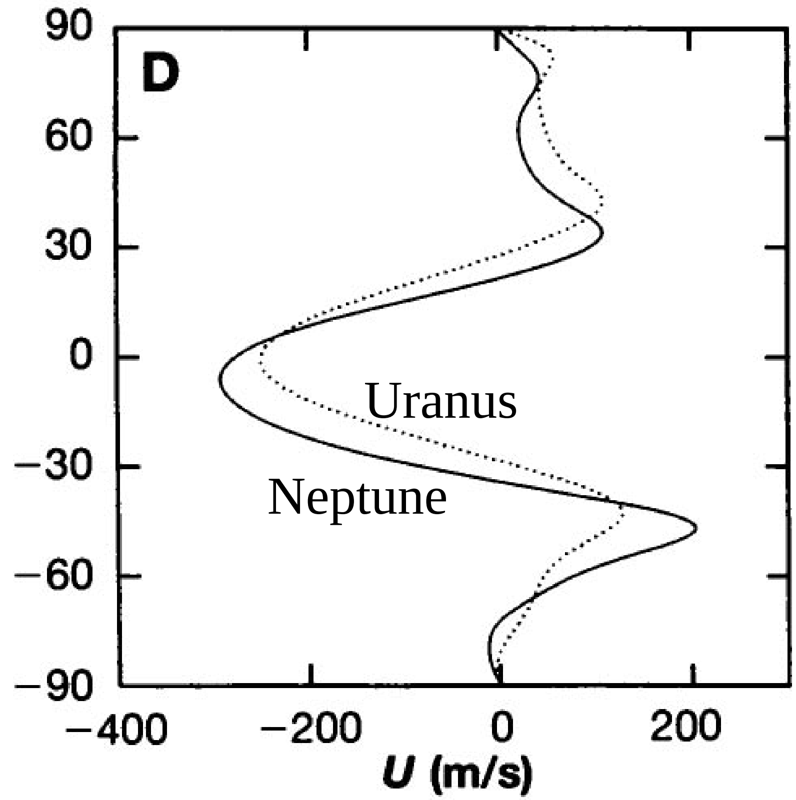
Angular Momentum in Deep Shells



Rotation >> Buoyancy

Shallow Layer Models

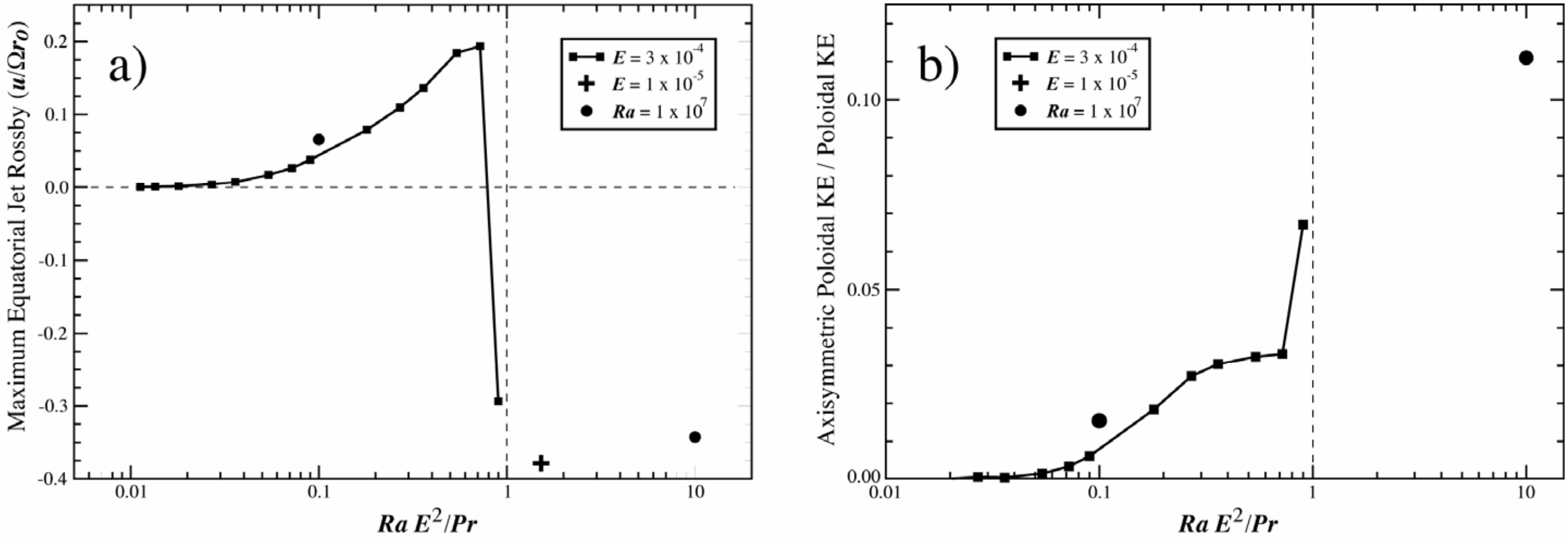




- Shallow layer turbulence naturally evolve to:
  - **Large-scale zonal flows**
  - **Retrograde equatorial jets**

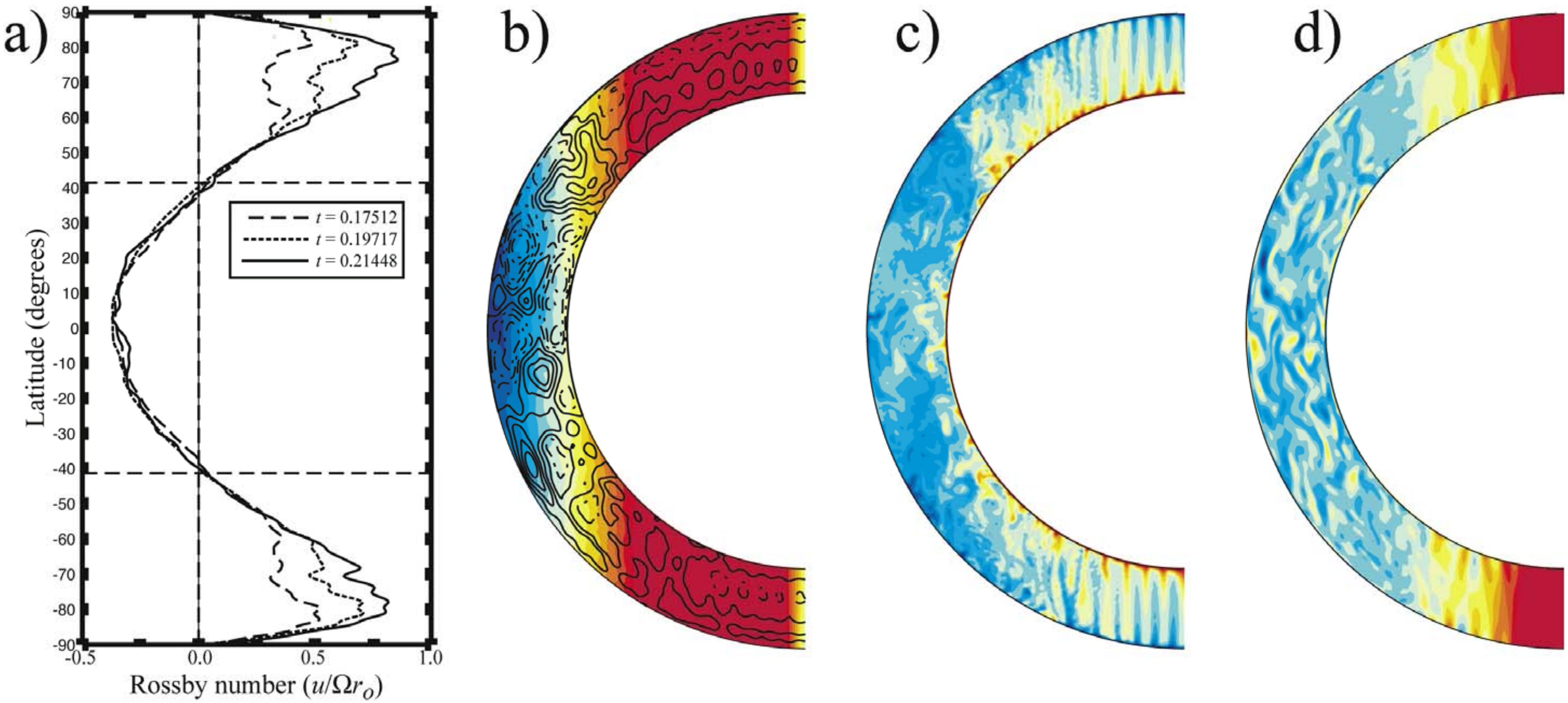
Cho & Polvani, *Science*, 1996

Deep Convection Model (χ = 0.75)



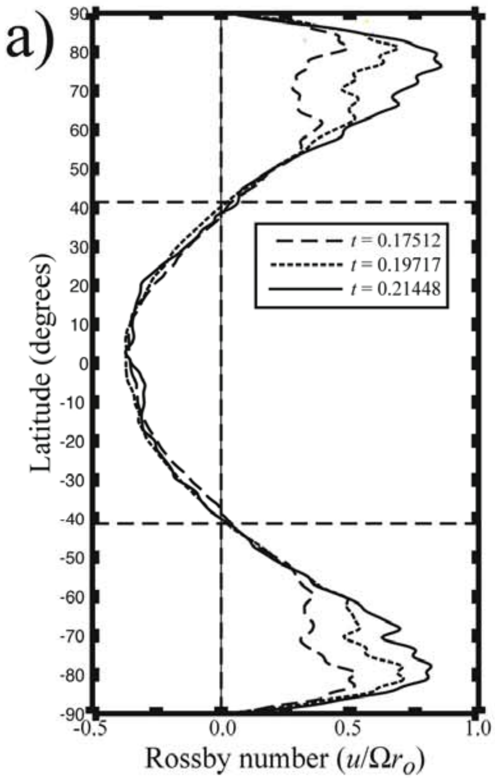
- a) Equatorial Jet vs. *Ra**
  - Ra* = Buoyancy / Coriolis
- b) Axisym. poloidal KE fraction vs. *Ra**

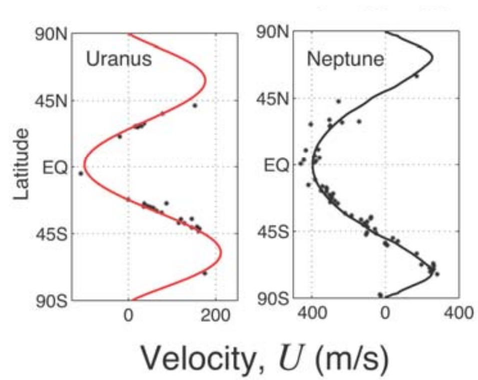
Deep Convection Model ($\chi = 0.75$)

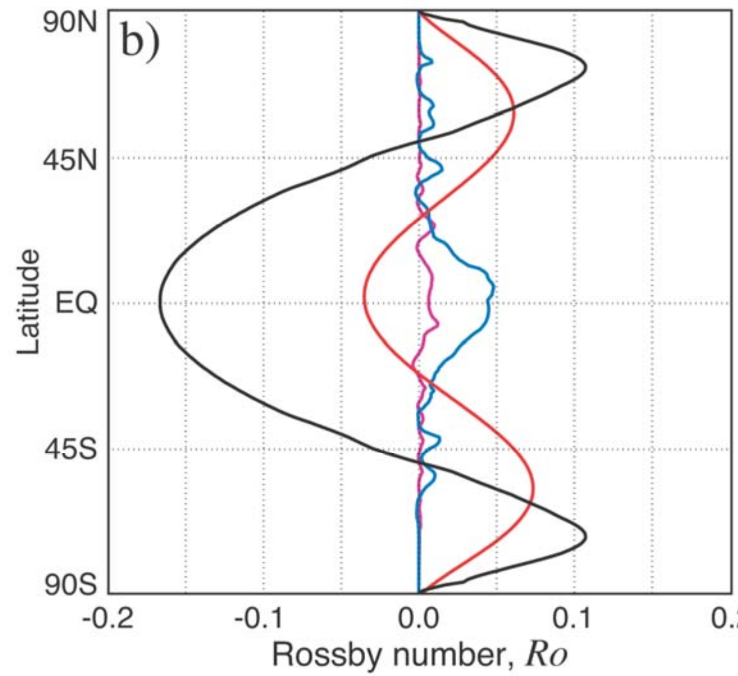


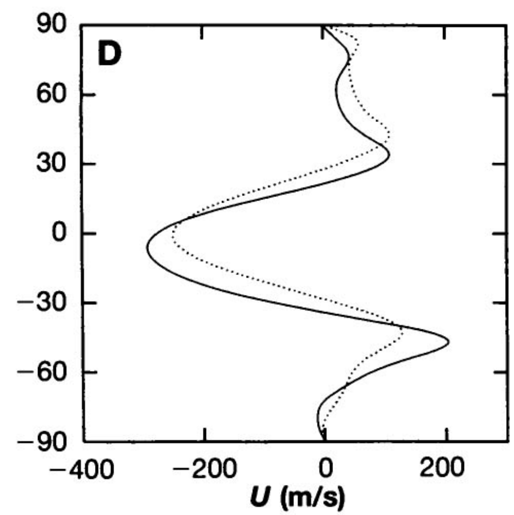
- Retrograde jet case with $Ra^* = 1.5$
  - $Ra = 1.5 \times 10^9$; $E = 10^{-5}$; $Pr = 0.1$

Deep Convection Model (χ = 0.75)









Ice Giants Work

- Deep convection model for the Ice Giants
- Can deep models explain the thermal emissions of U vs. N?
  - Modeling
  - Subaru Observations

QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

http://www.solarviews.com/raw/nep/neptri.gif

Questions?