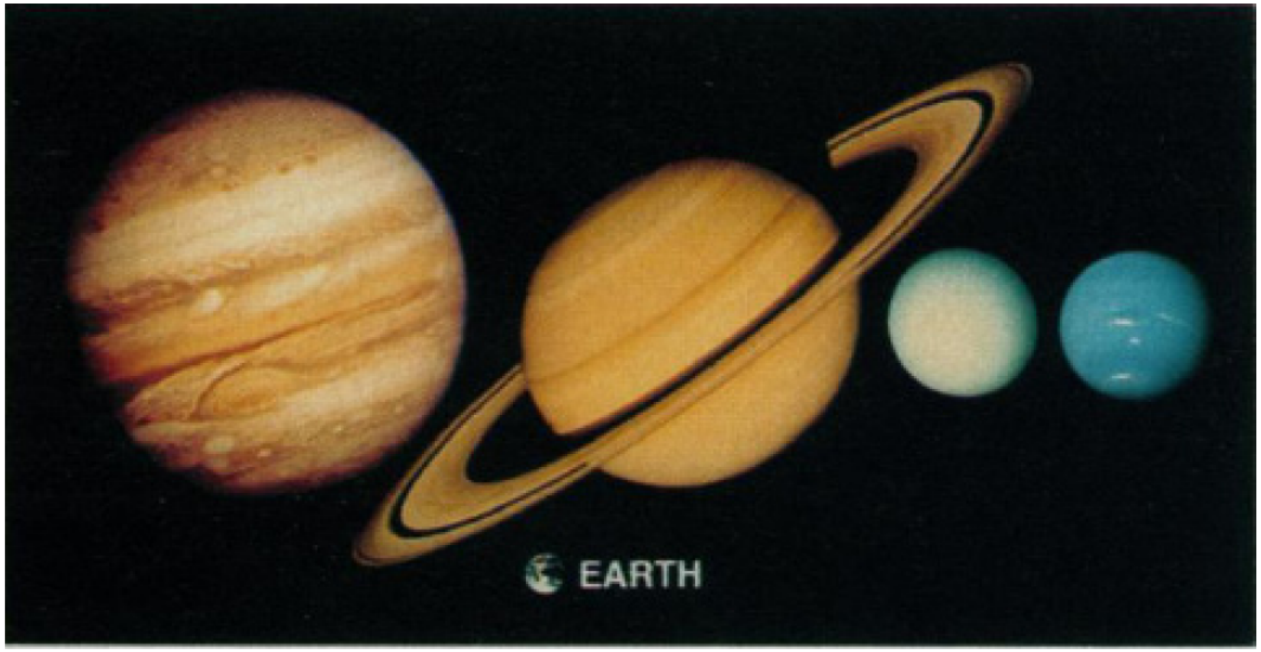
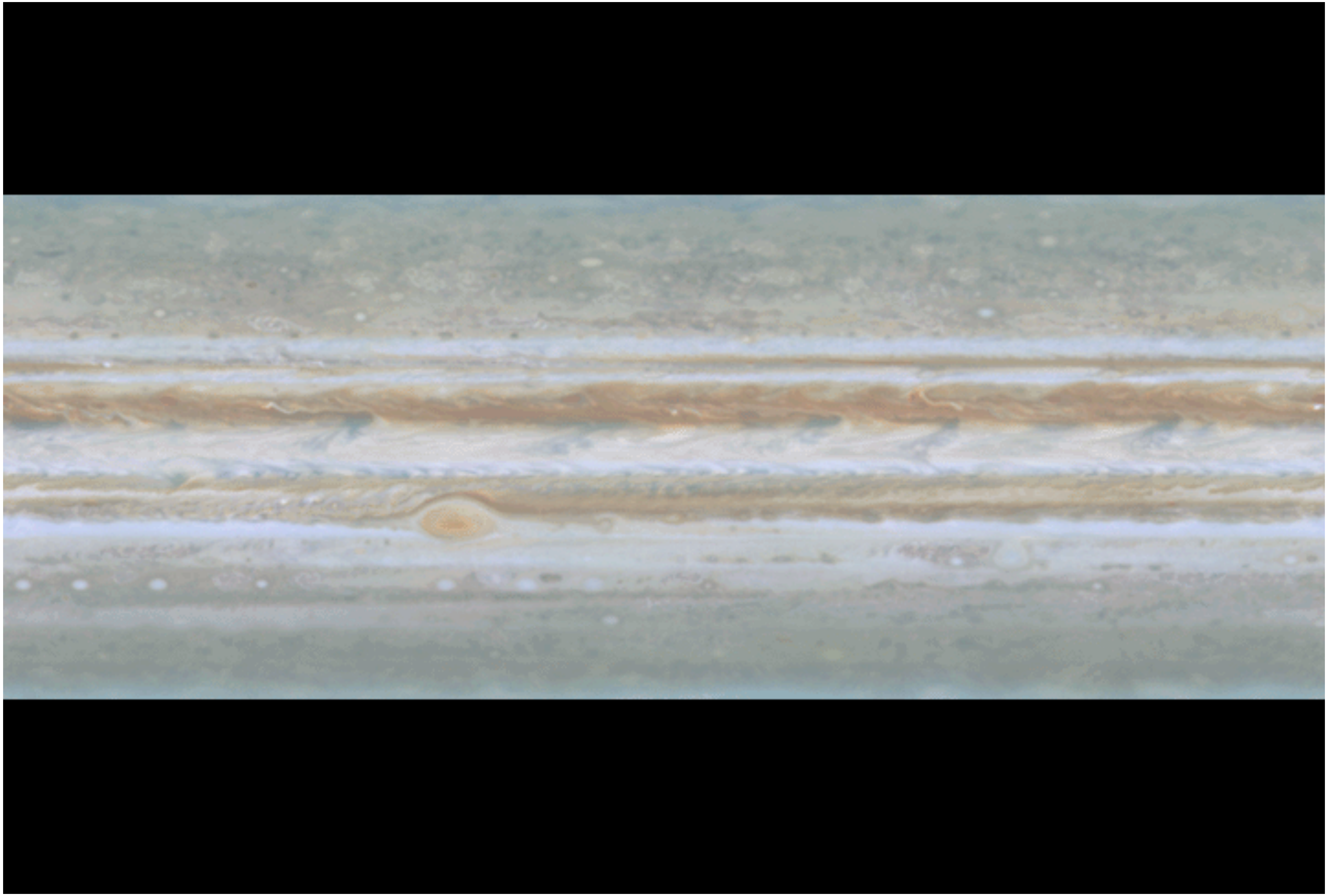
Dynamics of Giant Planet Atmospheres



Tapio Schneider (with Junjun Liu)

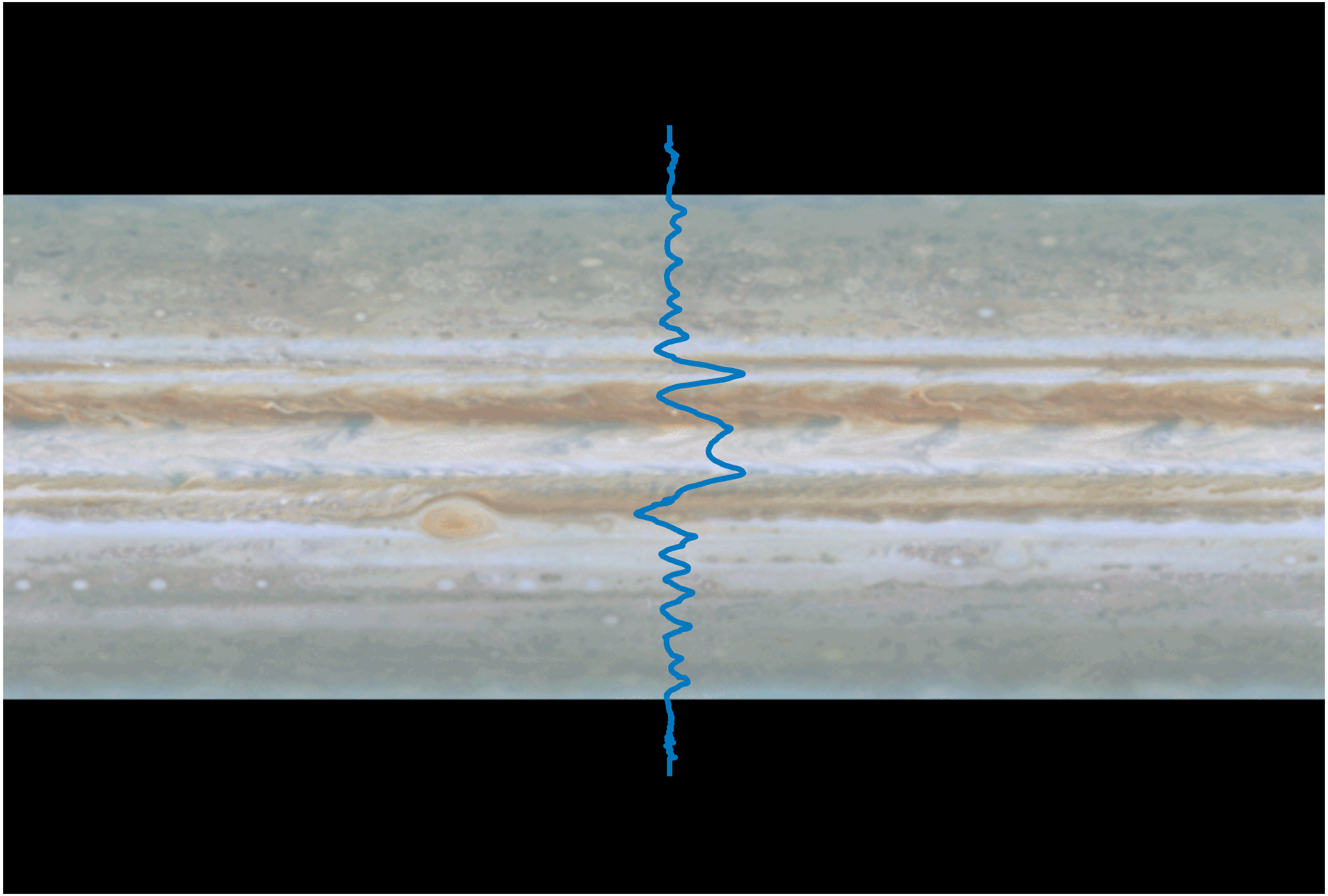
California Institute of Technology

Jupiter from *Cassini*



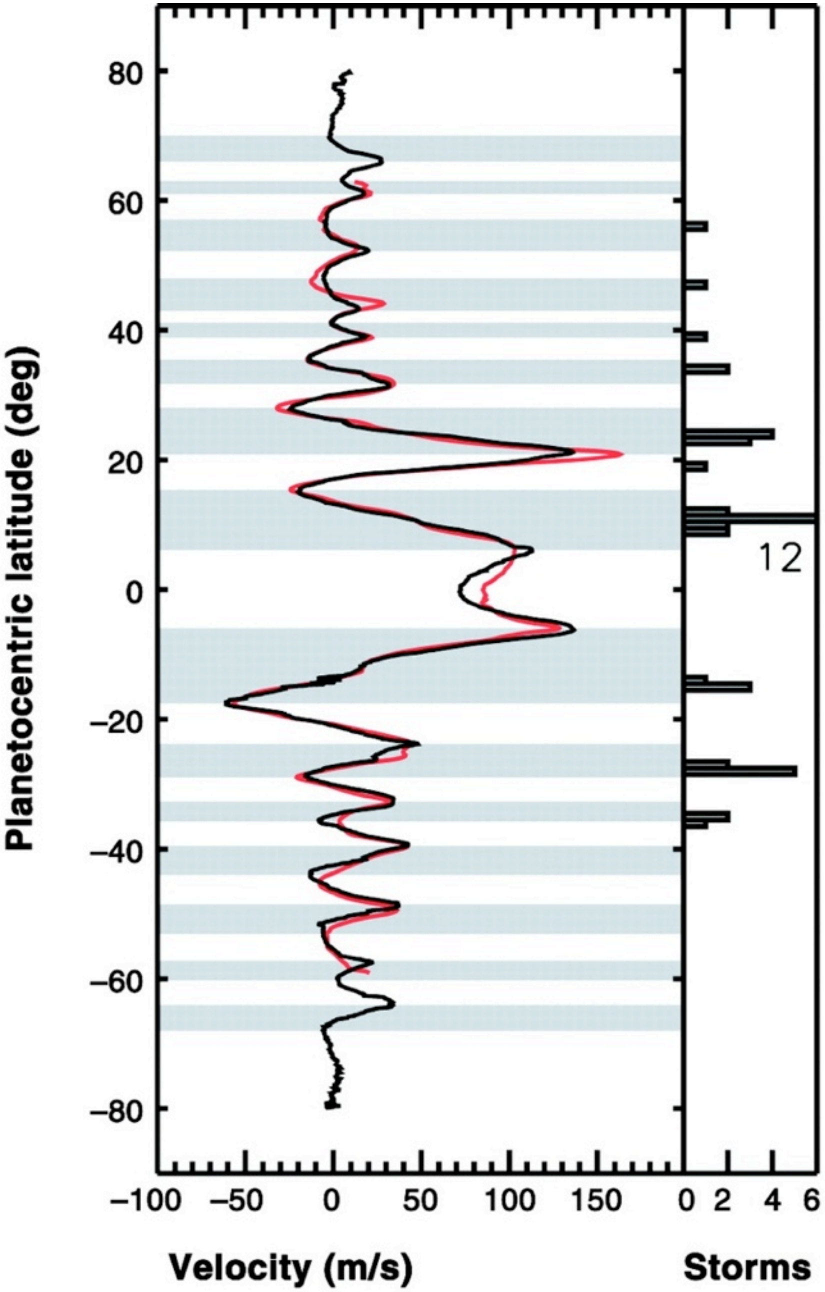
(Cassini Imaging Team 2000)

Jupiter from *Cassini*



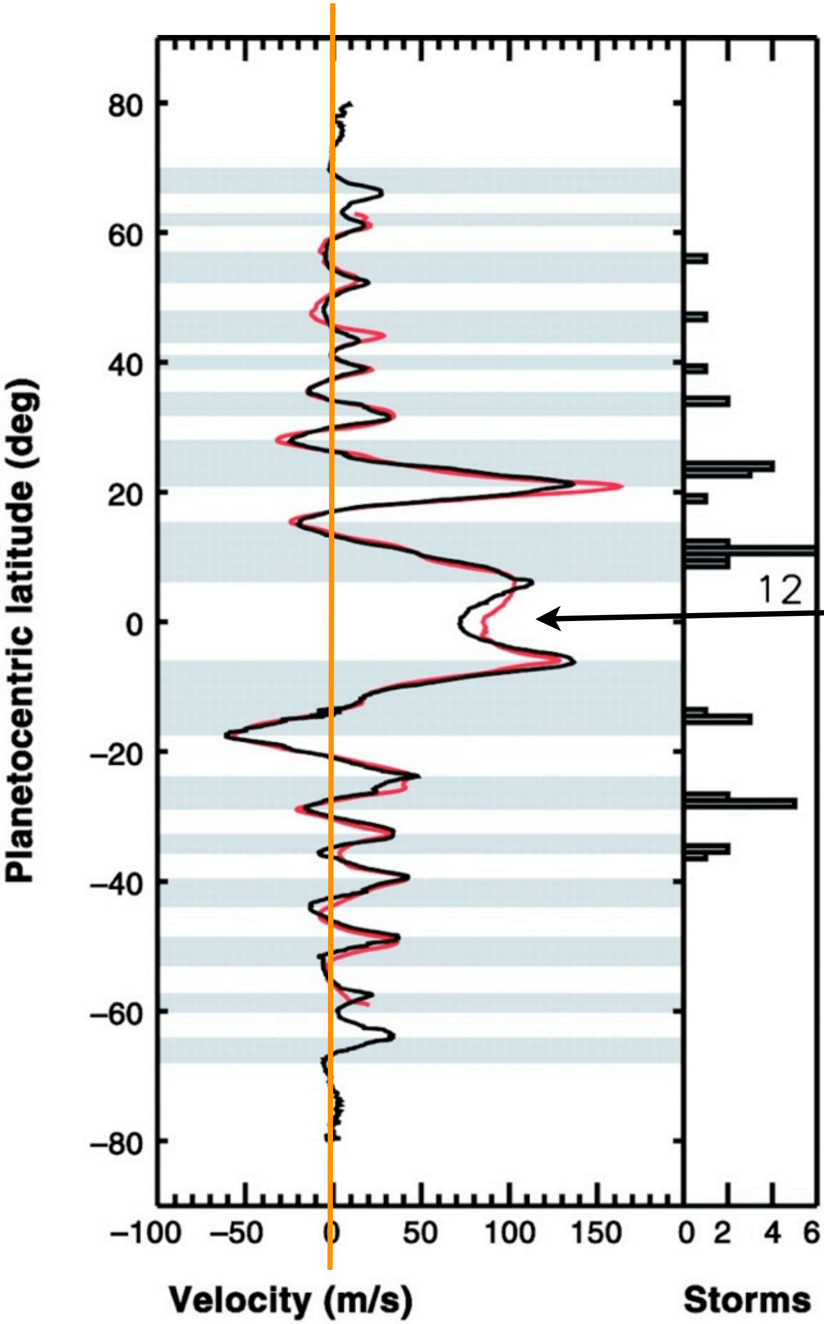
(Cassini Imaging Team 2000)

Jupiter zonal wind



(Porco et al. 2003)

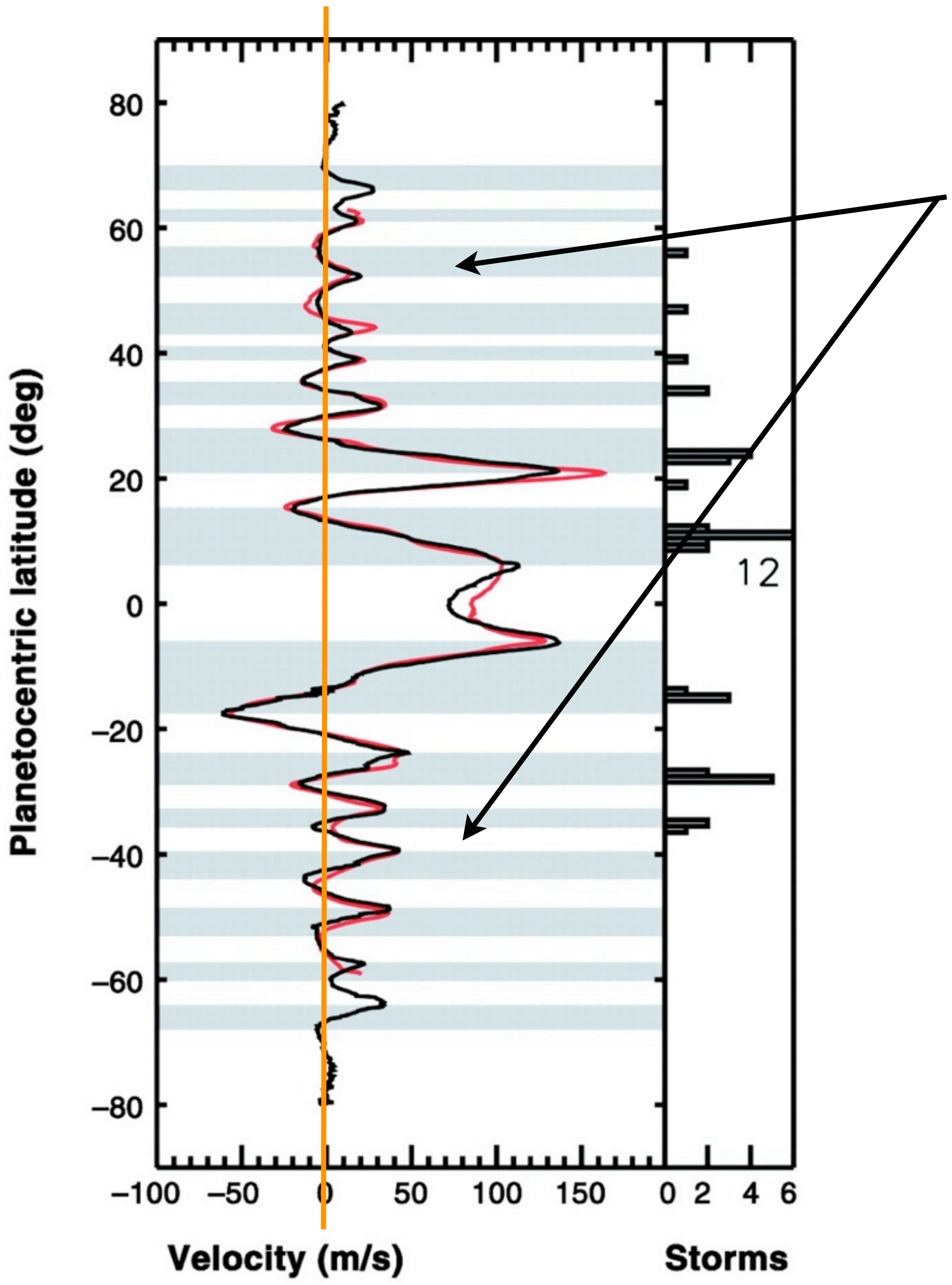
Jupiter zonal wind



Equatorial
superrotation
(~12°N/S)

(Porco et al. 2003)

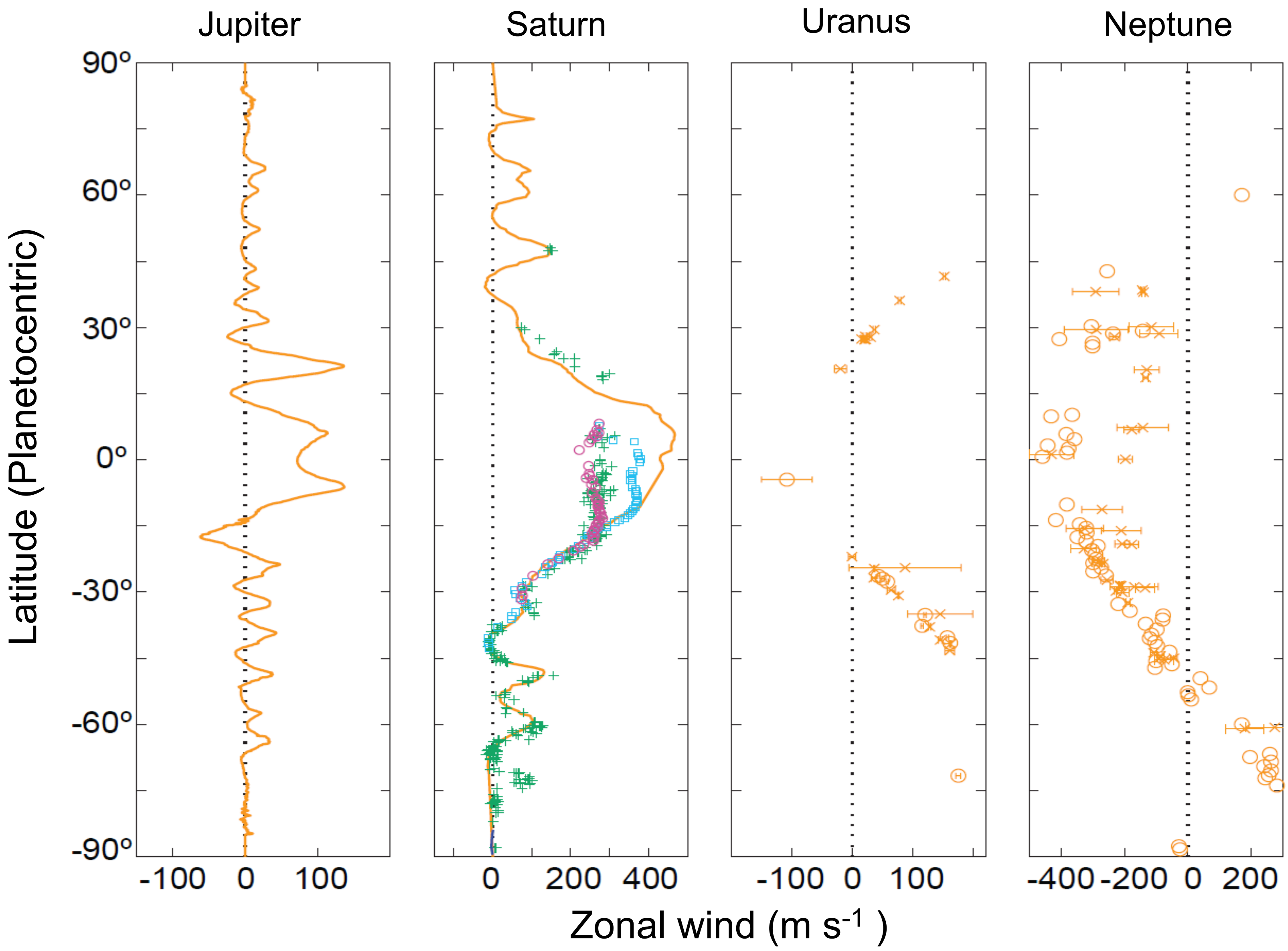
Jupiter zonal wind



Extratropical jets
(~8° spacing)

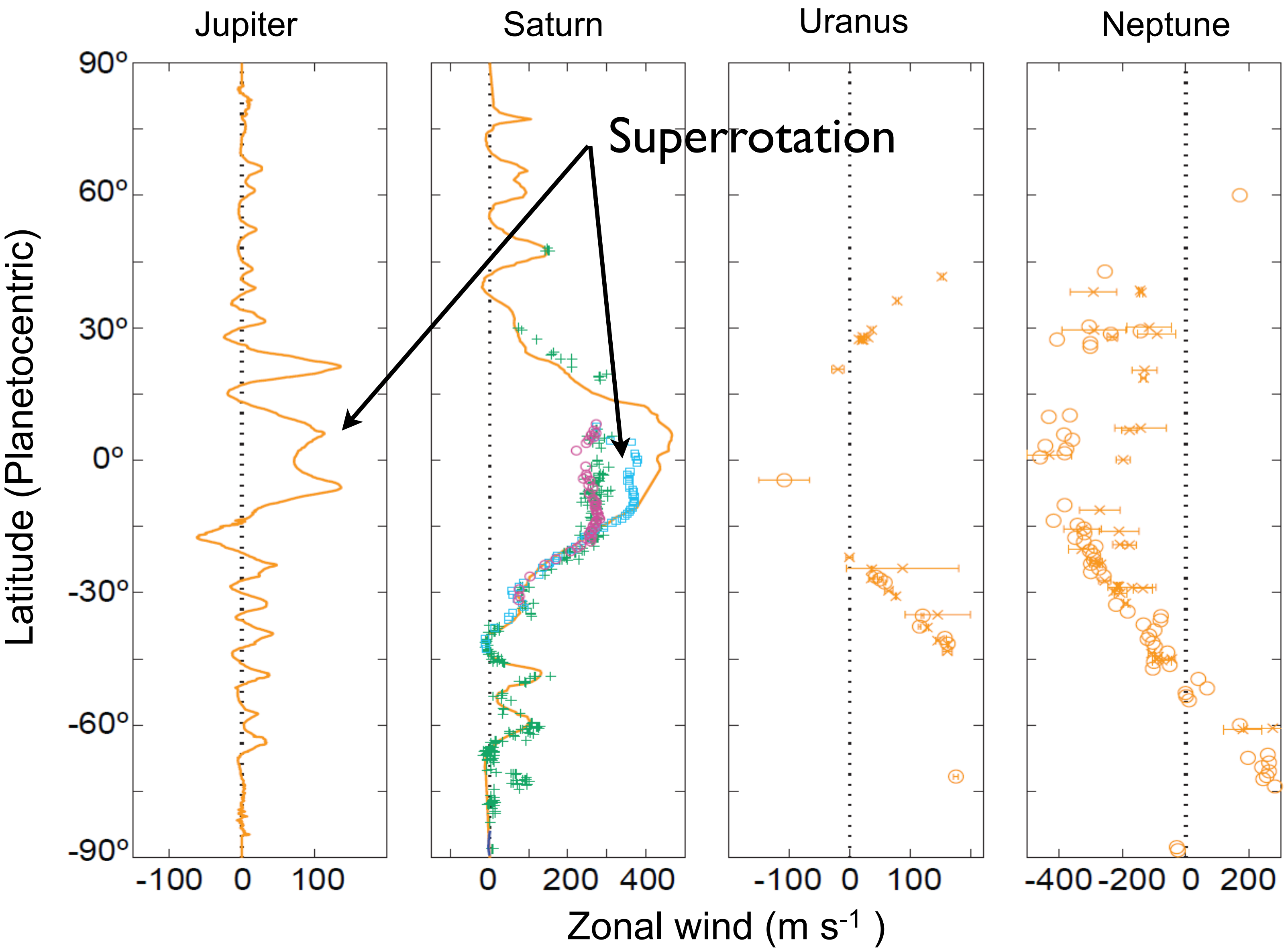
(Porco et al. 2003)

Zonal wind on all giant planets



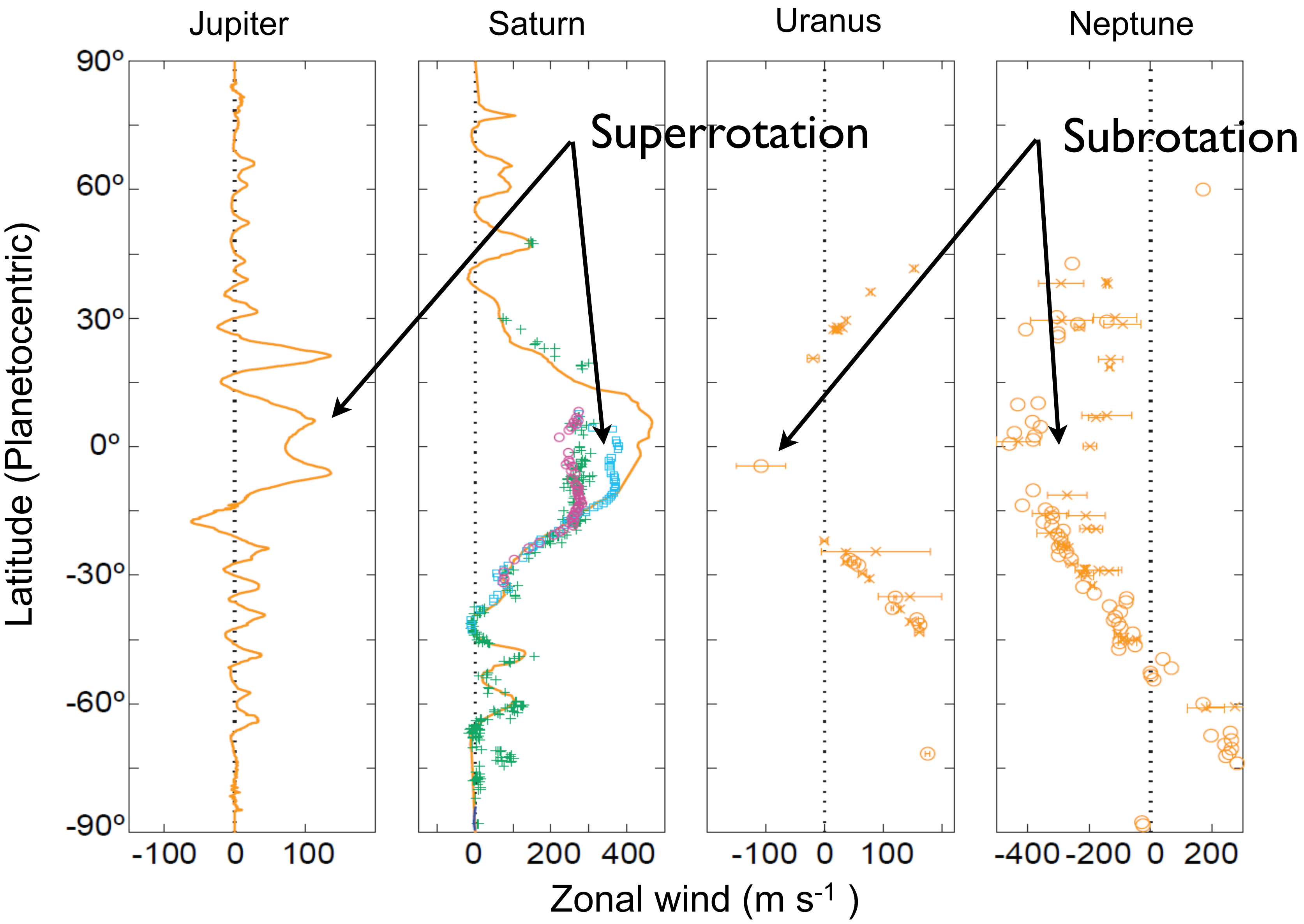
(Porco et al. 2003; Sanchez-Lavega et al. 2001; Hammel et al. 2001; Sromovsky et al. 2001)

Zonal wind on all giant planets



(Porco et al. 2003; Sanchez-Lavega et al. 2001; Hammel et al. 2001; Sromovsky et al. 2001)

Zonal wind on all giant planets



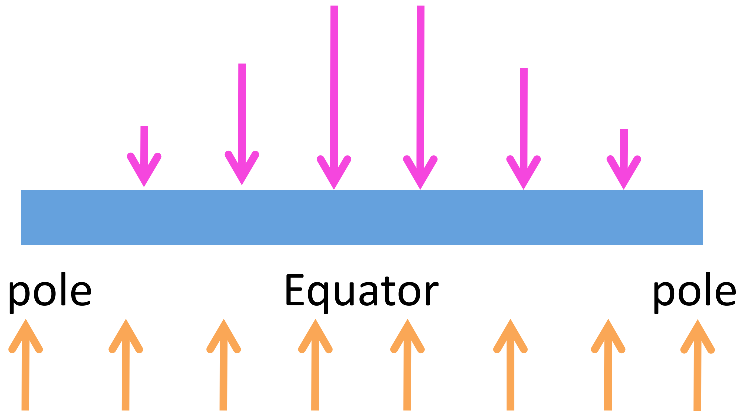
(Porco et al. 2003; Sanchez-Lavega et al. 2001; Hammel et al. 2001; Sromovsky et al. 2001)

Energy budget of giant planets

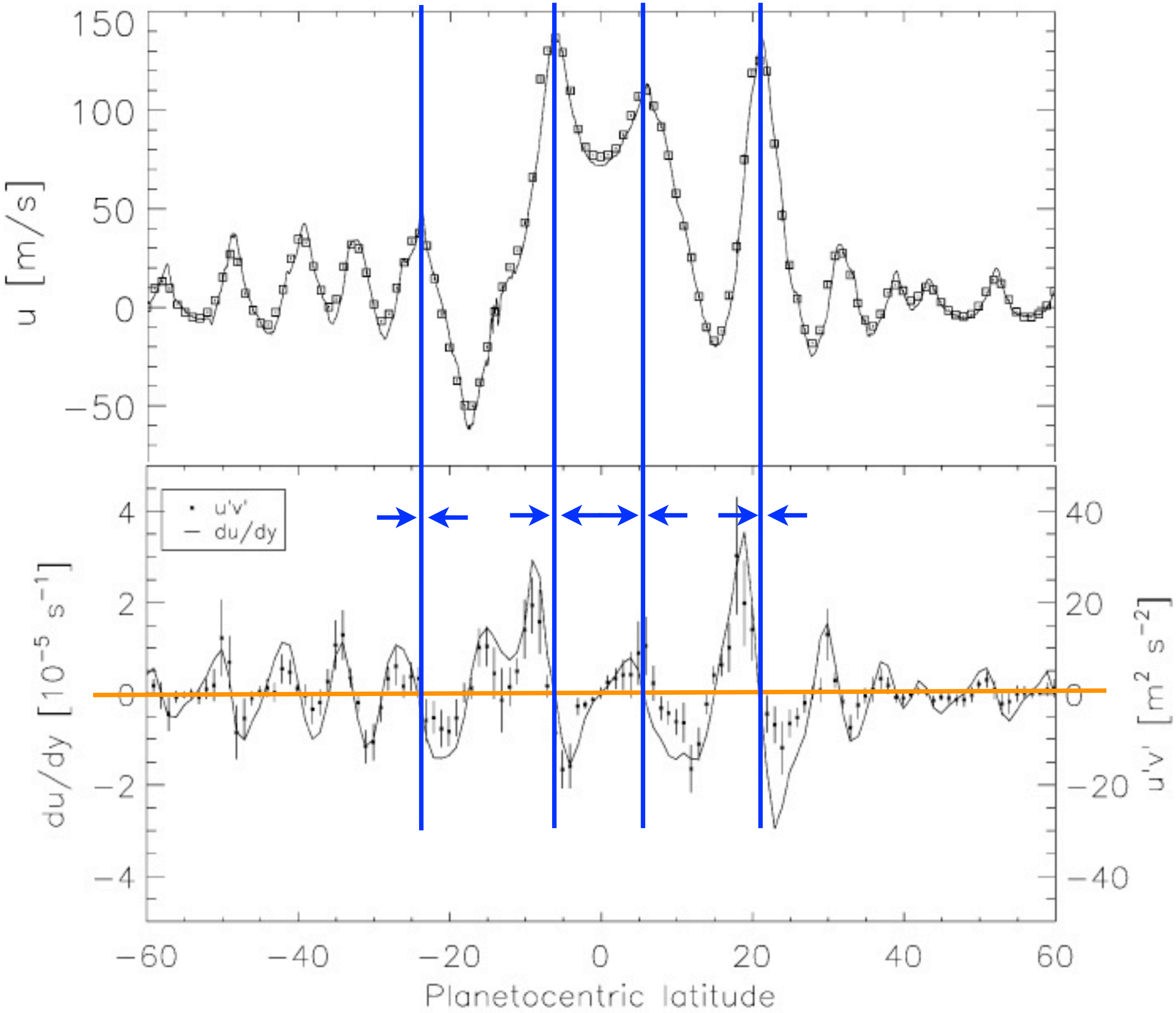
- Emit more energy than they receive from the sun
- Internal heat flux can generate convection
- Differential solar radiative heating from above

	Absorbed insolation	Internal heat flux
Jupiter	8.1 Wm^{-2}	5.7 Wm^{-2}
Saturn	2.7 Wm^{-2}	2.0 Wm^{-2}
Uranus	0.7 Wm^{-2}	0.04 Wm^{-2}
Neptune	0.3 Wm^{-2}	0.4 Wm^{-2}

(Guillot 2005)



Eddy angular momentum flux on Jupiter



(Salyk et al. 2006)

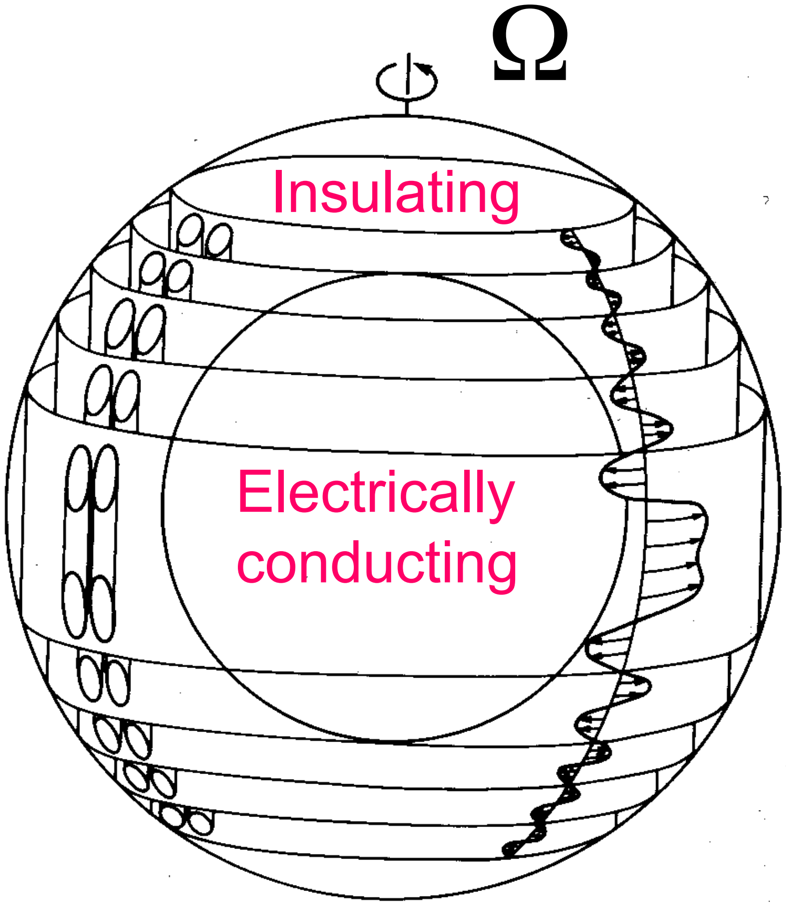
Energetic constraint from AM fluxes

- Eddy AM fluxes imply energy transfer from eddies to mean flow of order 10^{-5} W m^{-3} in upper tropospheres of Jupiter (Salyk et al. 2006) and Saturn (Del Genio et al. 2007)
- Eddy AM fluxes per unit volume cannot extend over more than O(10 km) depth for total transfer not to exceed 10^{-1} W m^{-2}

Eddy angular momentum fluxes (per unit volume) cannot extend unabatedly over great depth and must have baroclinic structure

(Liu and Schneider 2010)

Existing deep-flow models



(Busse, 1983)

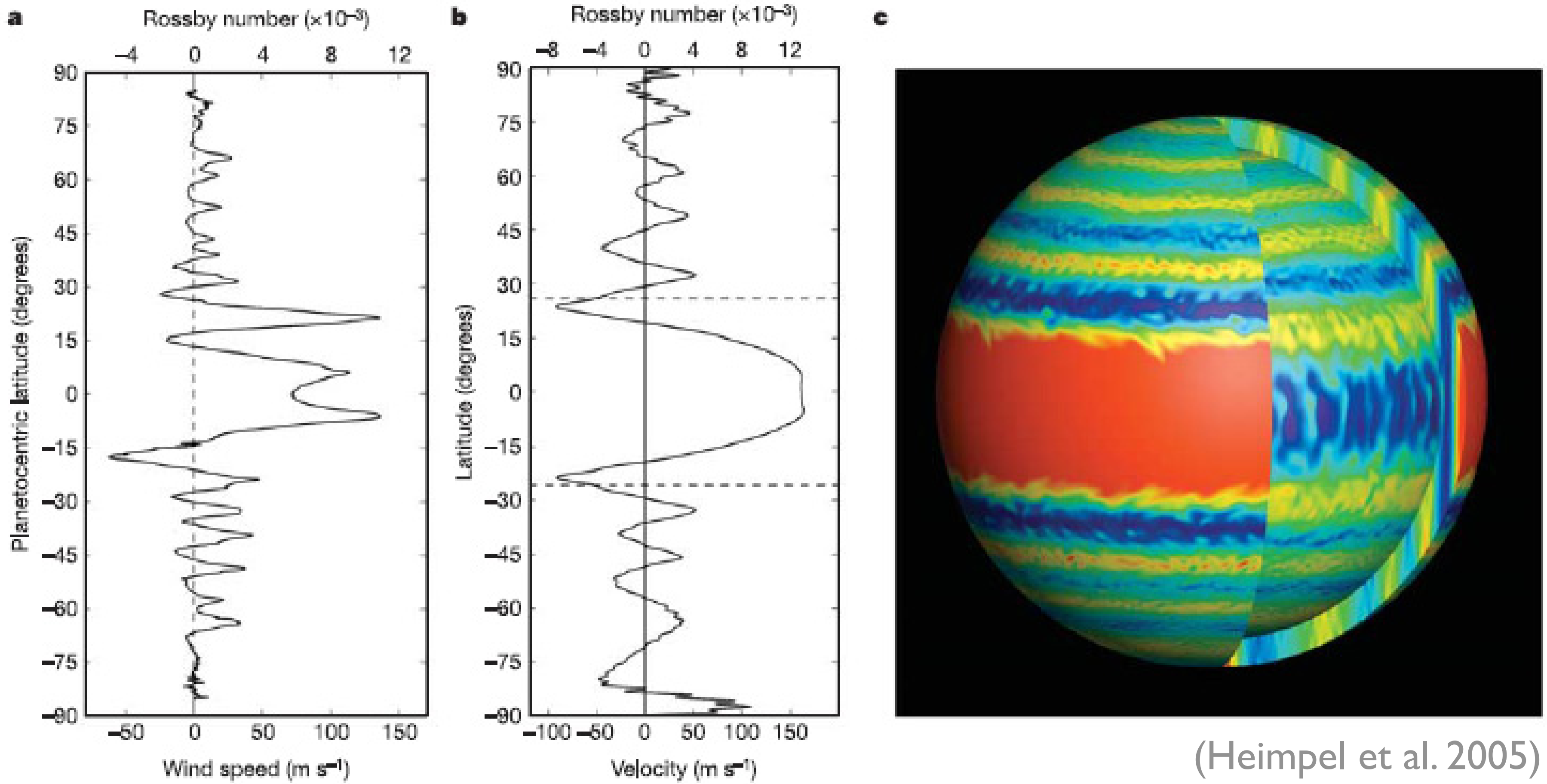
- Rotating Rayleigh-Benard convection (Busse 1976)
- Zonal winds extend along cylinders through insulating layer: O(10^7 km) depth
- Eddy AM fluxes per unit volume roughly constant along cylinders (Kaspi et al. 2009)

With observed upper-tropospheric AM fluxes, eddy-mean flow energy transfer at least O(10^6) too large

Zonal wind in deep-flow model

Jupiter

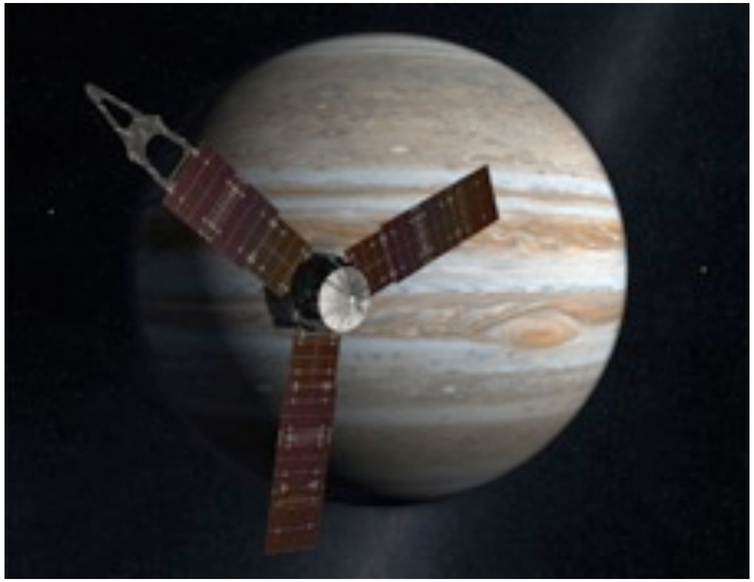
Simulation



(Heimpel et al. 2005)

Internal heat flux at least O(10^6) larger than observed; unclear what accounts for differences between super- and subrotating planets

NASA’s Juno spacecraft is en route to Jupiter



Goal is to measure composition and temperature structure below clouds through gravity and microwave measurements

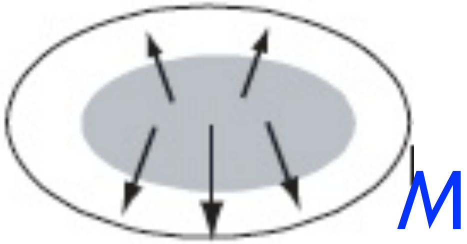
Need to go back to basics to disentangle dynamical from compositional effects...

Hide's theorem and superrotation

If there is any (radial) viscous dissipation of angular momentum,

$$\frac{DM}{Dt} = \frac{\partial}{\partial r}\nu\frac{\partial M}{\partial r},$$

with $M = (a\Omega\cos\phi + u)a\cos\phi,$ interior extrema of angular momentum are impossible in steady, axisymmetric flow.



Therefore, $u \leq \Omega a \sin^2\phi / \cos\phi.$

(Hide 1969; Schneider 1977)

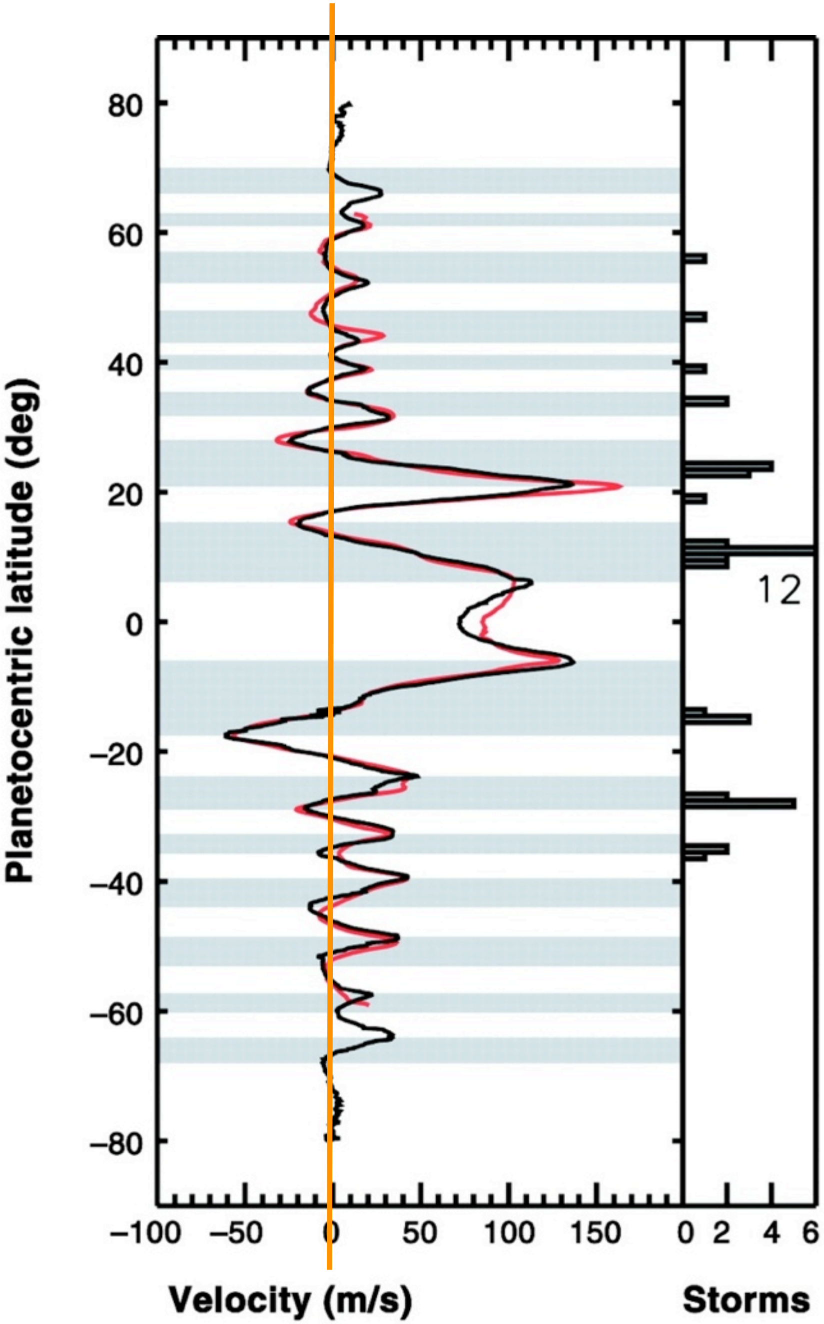
Direction of eddy angular momentum flux

- Eddy AM flux into equatorial region (as observed on Jupiter and Saturn) is necessary to generate and maintain equatorial superrotation

- Generally in rapidly rotating atmospheres, eddy AM fluxes are directed from *wave dissipation regions* into *wave generation regions* (Held 1975, 2000; Rhines 1994)

Wave source in equatorial region can lead to superrotation

Scales of waves on Jupiter



(Porco et al. 2003)

- Gravity wave speed:

$$c \approx 450\,\mathrm{m\,s^{-1}}$$

(Ingersoll & Kanamori 1995)

- Midlatitude Rossby radius:

$$c/f \sim 2000\,\mathrm{km}$$

- Equatorial Rossby radius:

$$\sqrt{c/\beta} \sim 10{,}000\,\mathrm{km} \sim 8^\circ$$

Generation of equatorial waves by convection

Thermodynamic balance in equatorial region (Charney 1963):

$$\cancel{\partial_t b} + \mathbf{v} \cdot \cancel{\nabla_h} b + N^2 w = Q$$

Sufficiently strong convective heating leads to divergence:

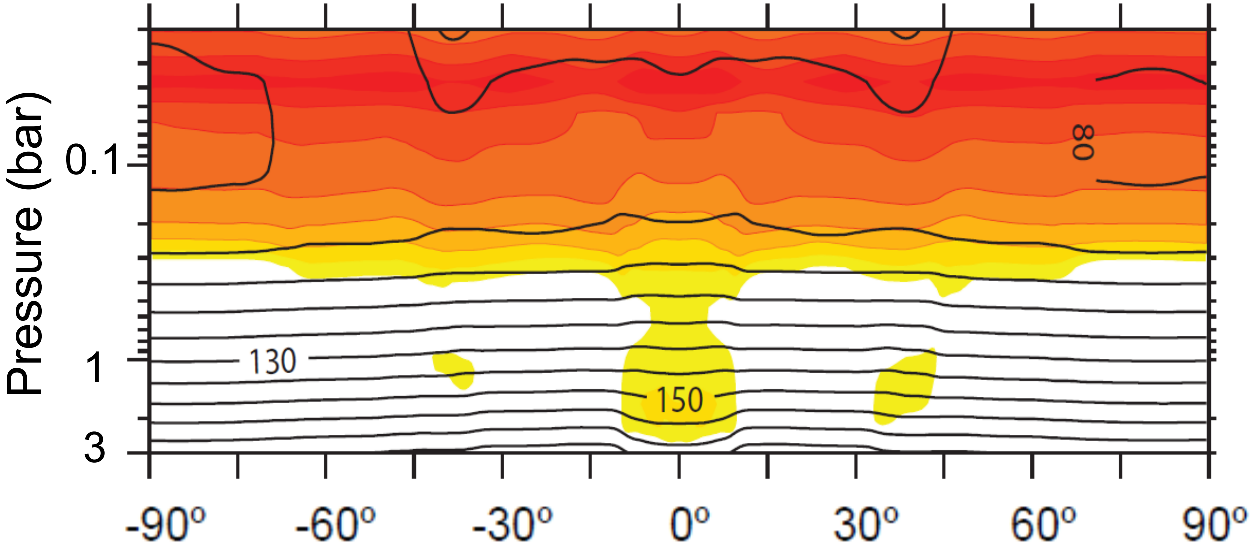
$$\nabla_h \cdot \mathbf{v}_\chi = -\partial_z w = -\partial_z (Q/N^2)$$

Divergence is source of rotational flow (Sardeshmukh & Hoskins 1988):

$$(\partial_t + \mathbf{v}_\Psi \cdot \nabla_h)\zeta_a = -\nabla_h \cdot (\zeta_a \mathbf{v}_\chi)$$

Convective heating at weak stratification generates Rossby waves that propagate out of equatorial waveguide

Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



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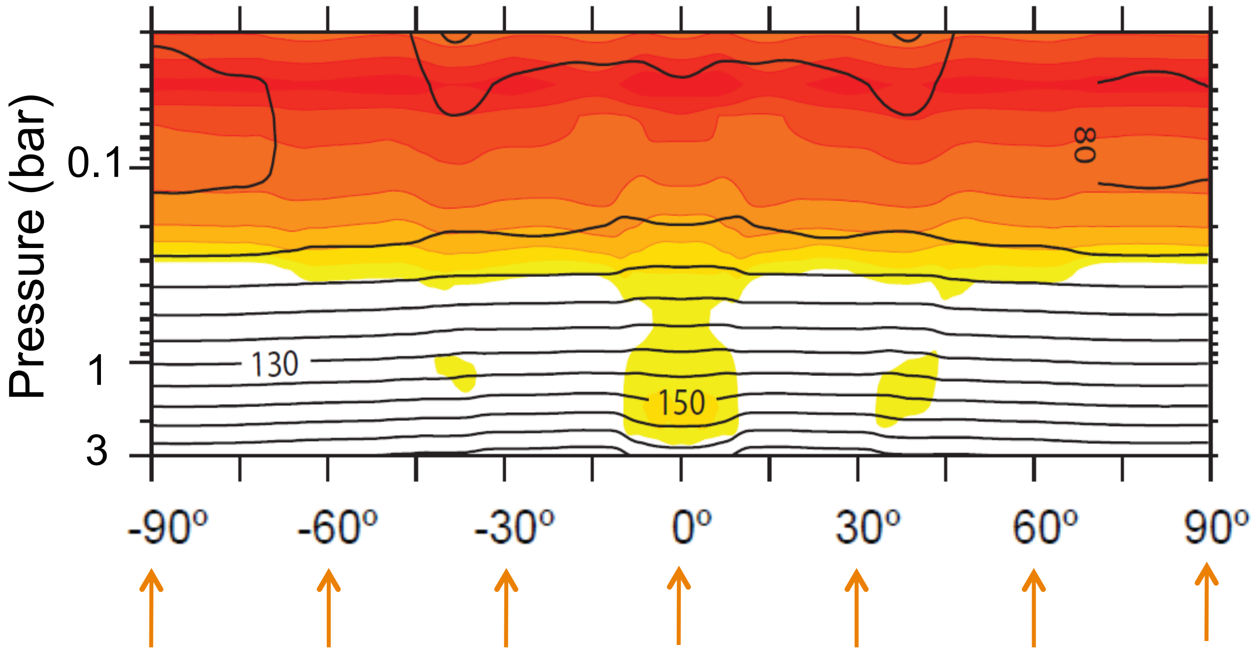

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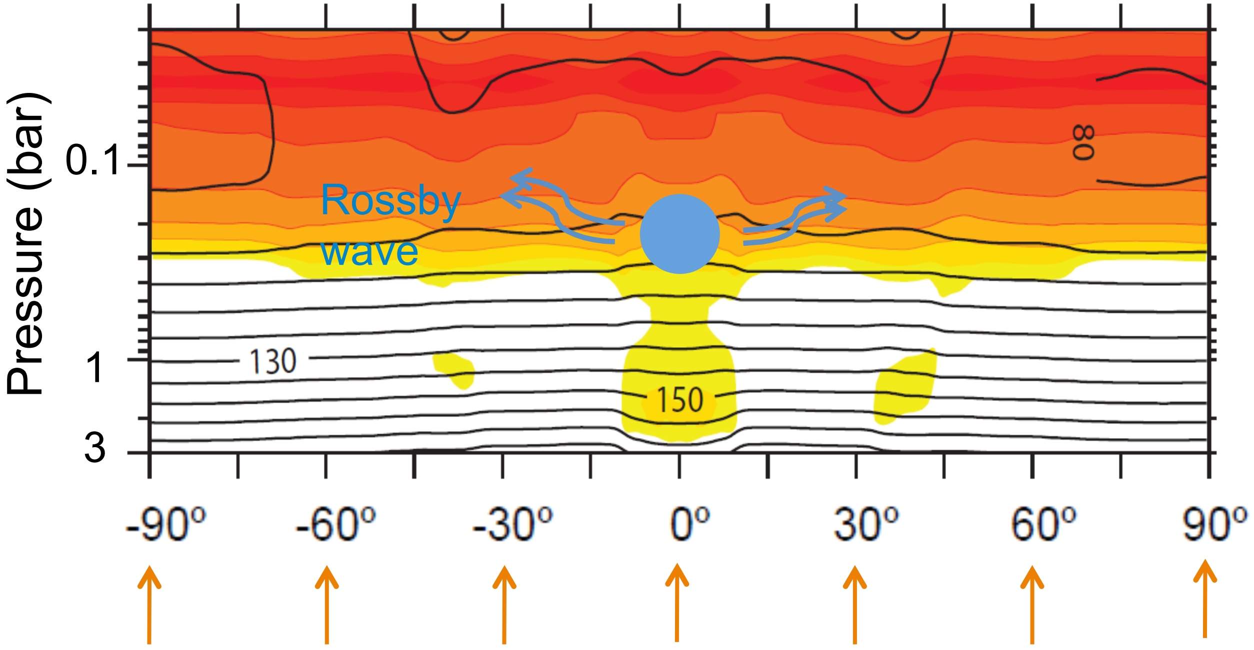
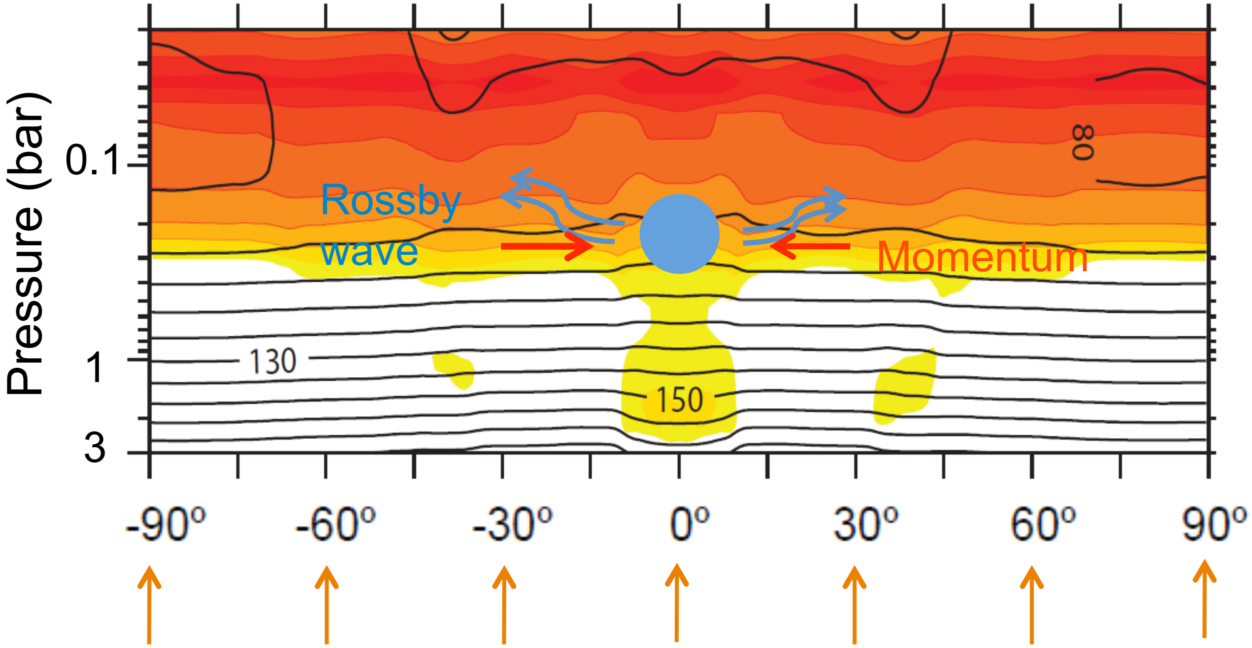


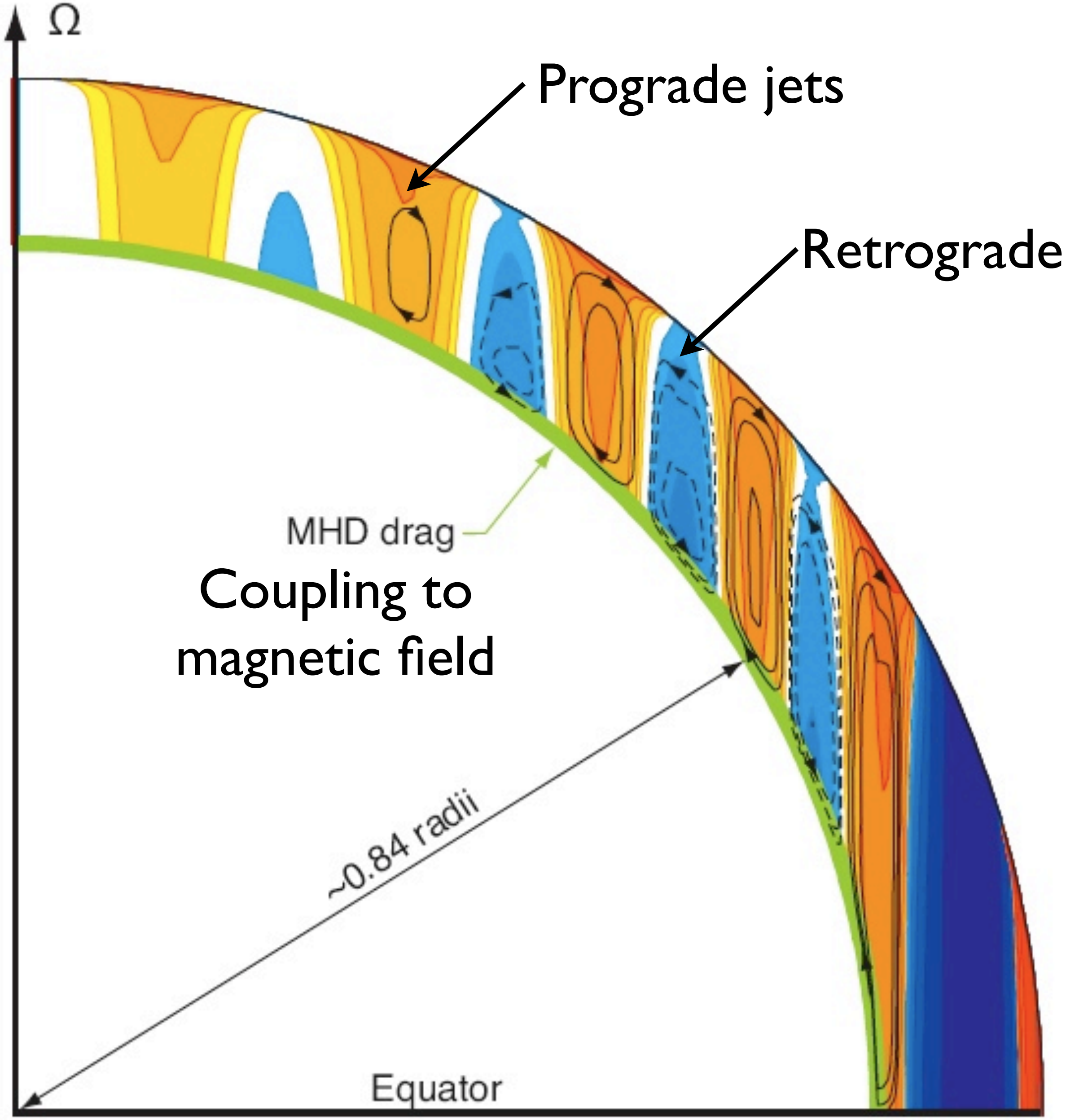
Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



Test ideas with giant planet GCM

- Ideal-gas atmosphere in thin shell with rotation rate, gravitational acceleration, gas constant, etc. of planet
- Scattering gray radiative transfer
- Up to T213 horizontal resolution, 30 vertical levels
- Imposed *uniform* heat flux at lower boundary
- Rayleigh drag at artificial lower boundary at 3 bar

Mean meridional circulations



Prograde jets

Retrograde jets

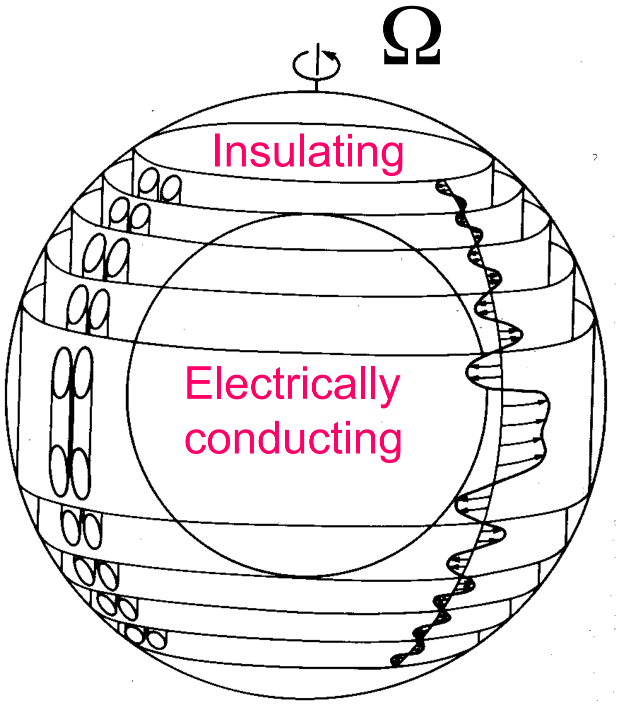
Coupling to magnetic field

(Schneider & Liu 2009)

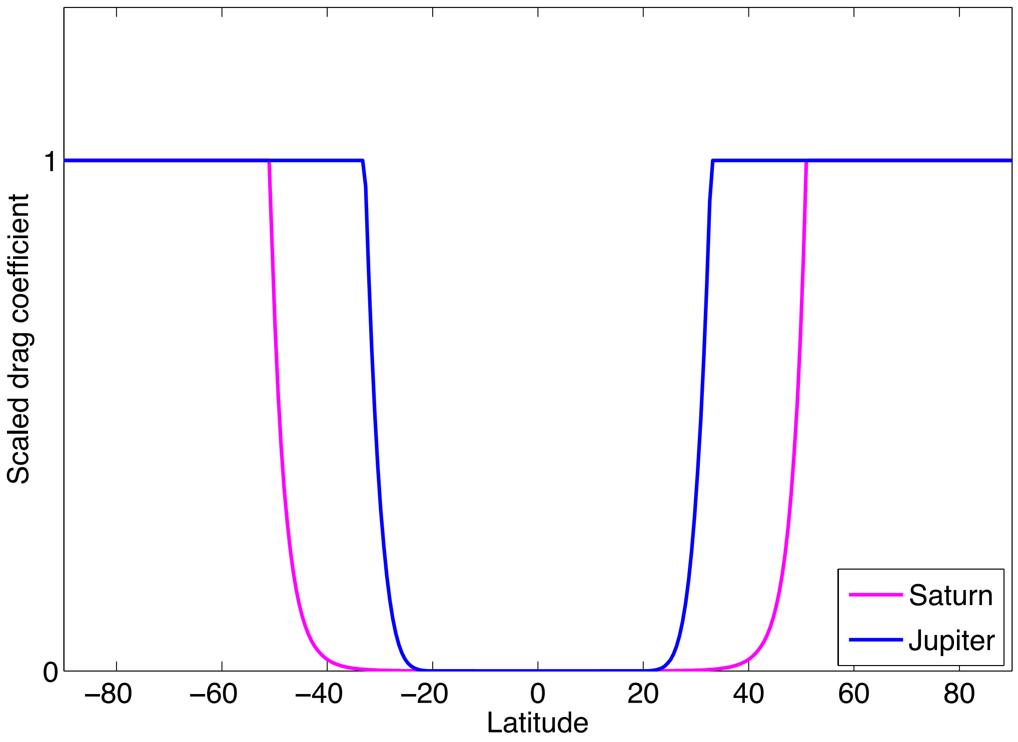
Modeling of deep MHD drag in thin shell

Model momentum dissipation as Rayleigh drag

$$\partial_t \mathbf{v} \cdots = -r\mathbf{v}$$

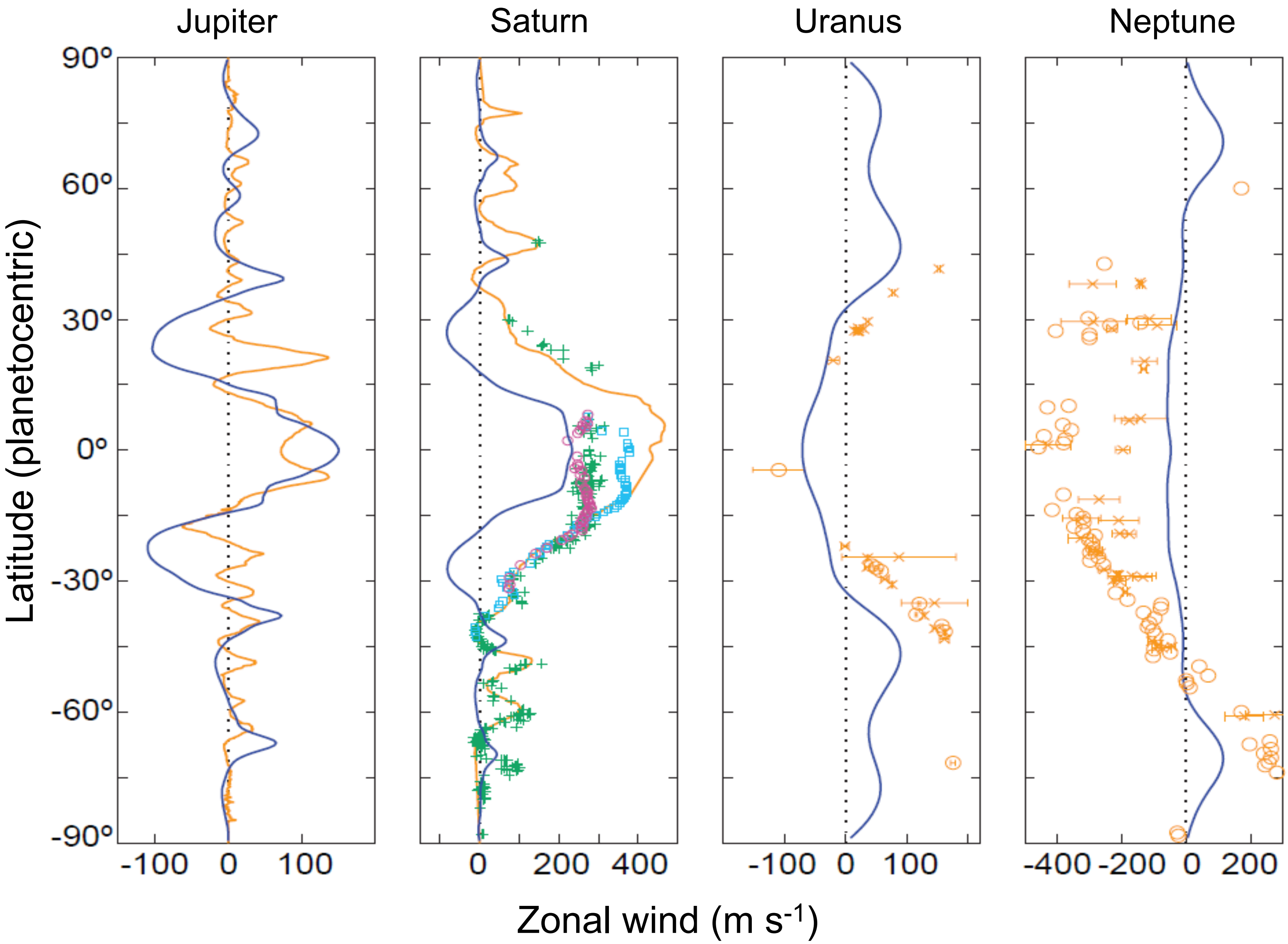


(Busse, 1983)



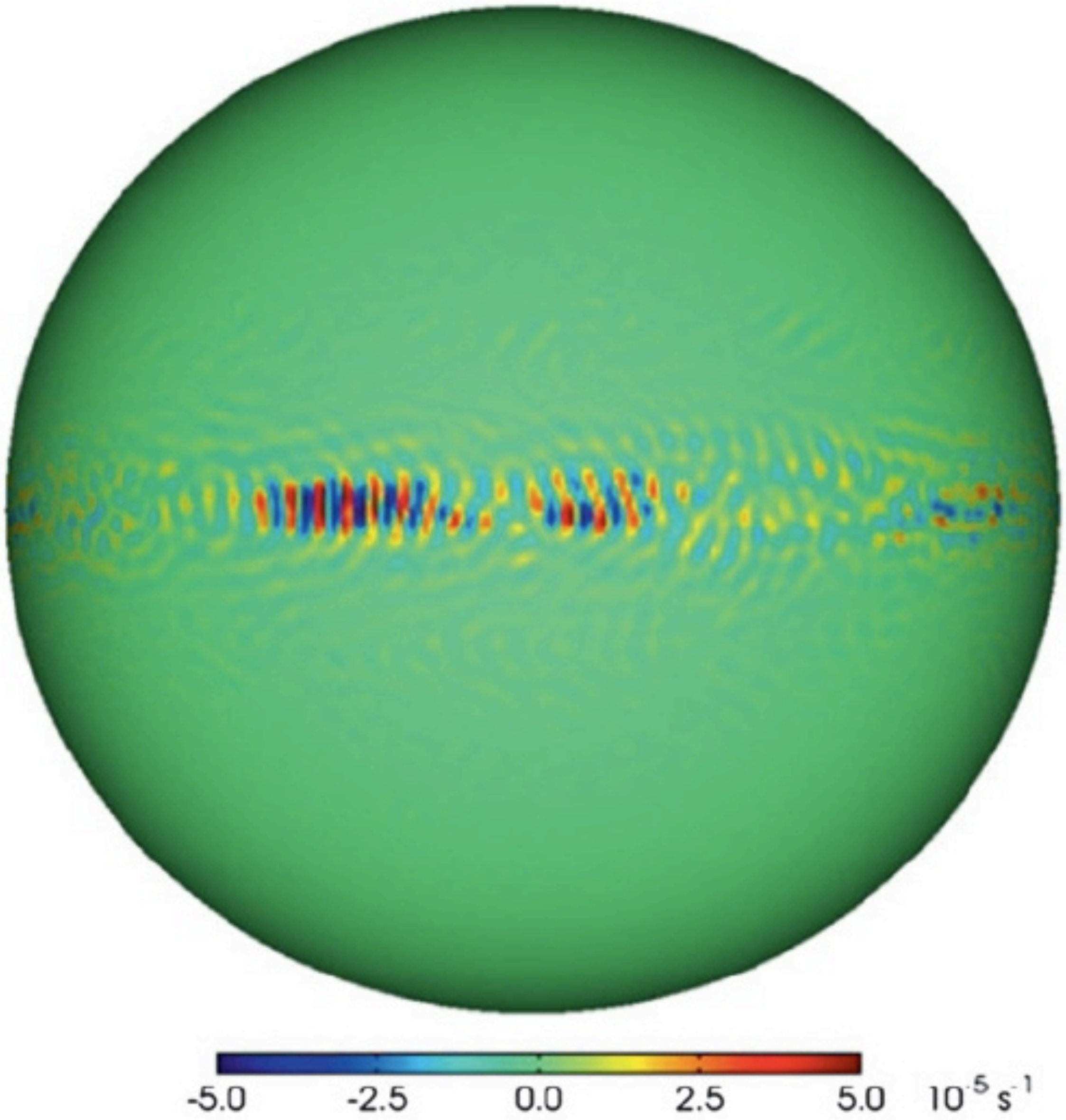
(Liu et al. 2007)

Simulated zonal wind in upper troposphere



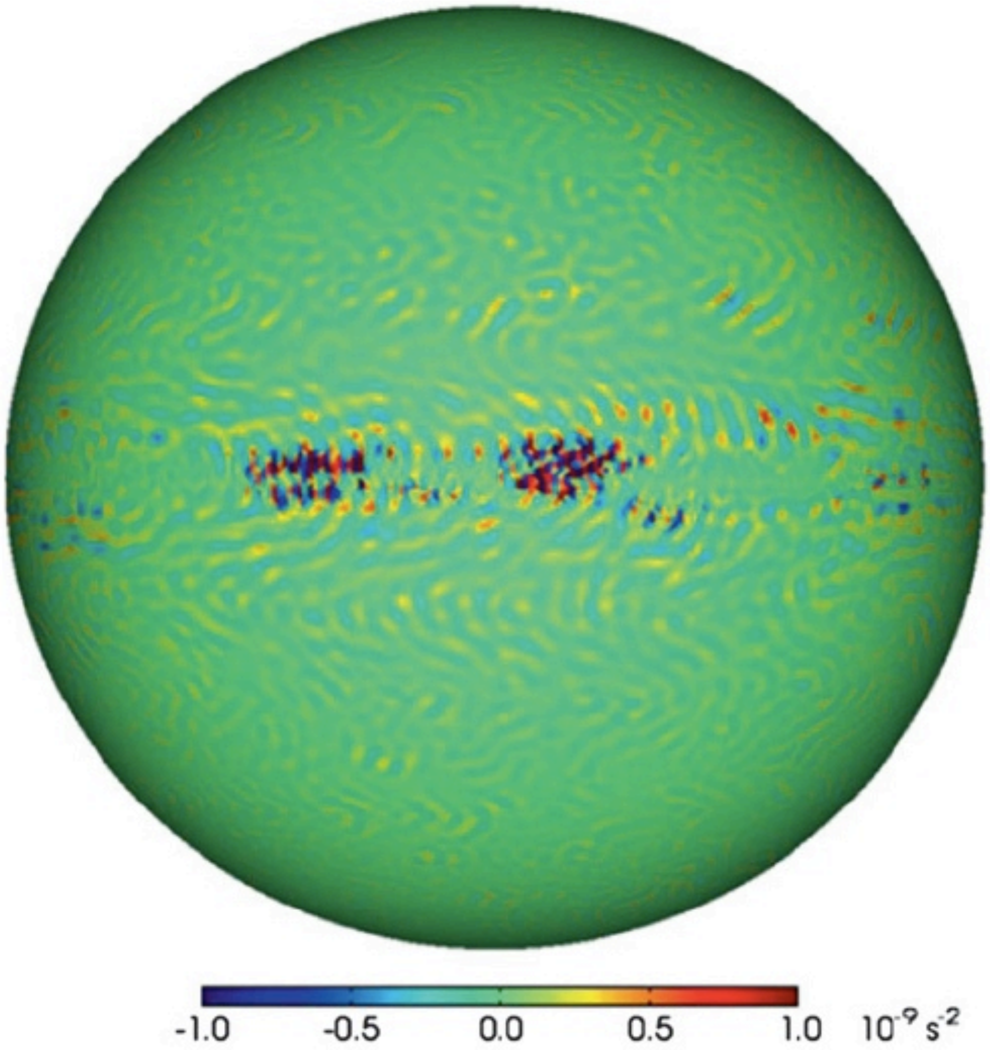
(Liu & Schneider 2010)

Divergence (Jupiter upper troposphere)



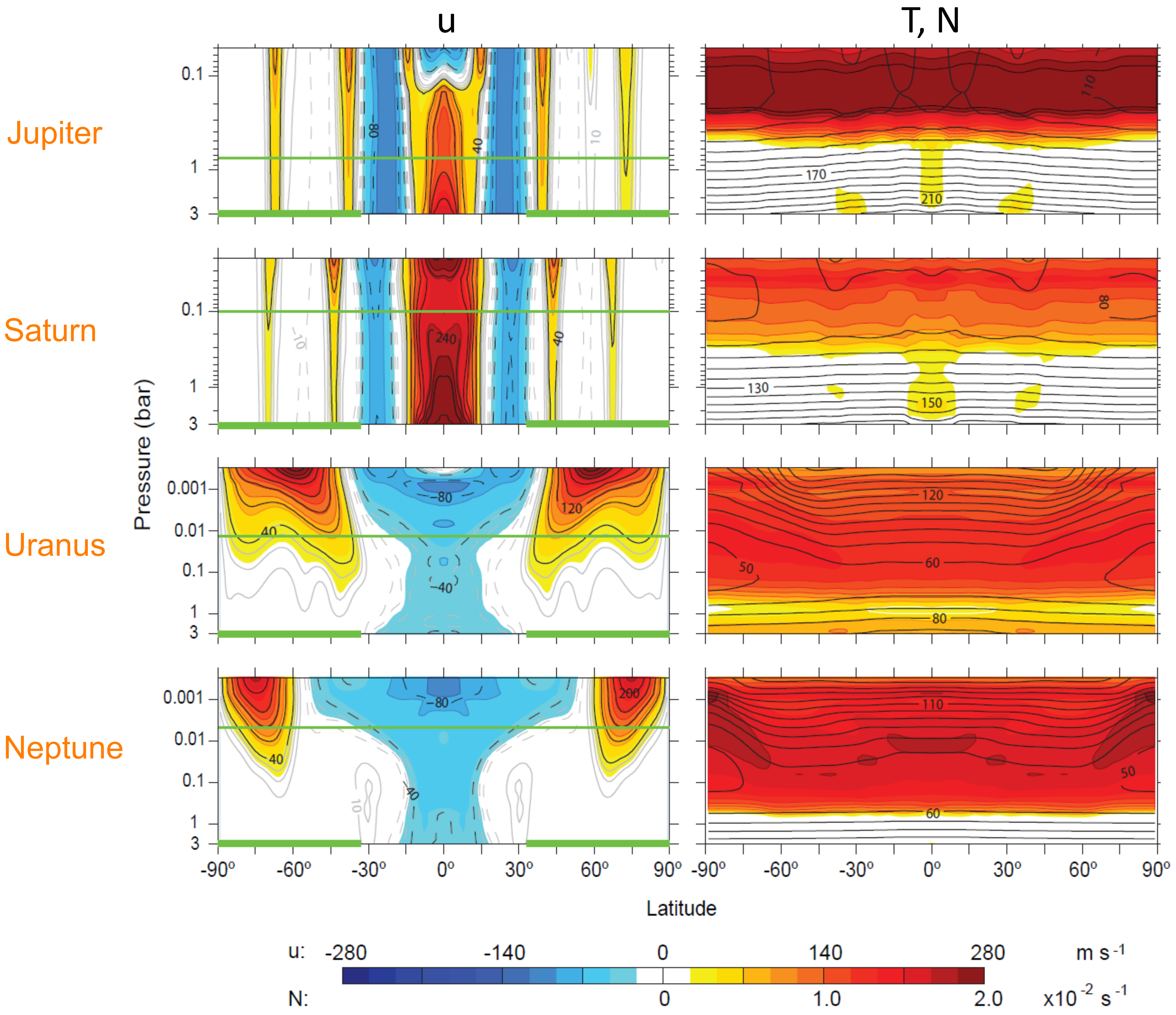
(Schneider & Liu 2009)

Rossby wave source (Jupiter troposphere)



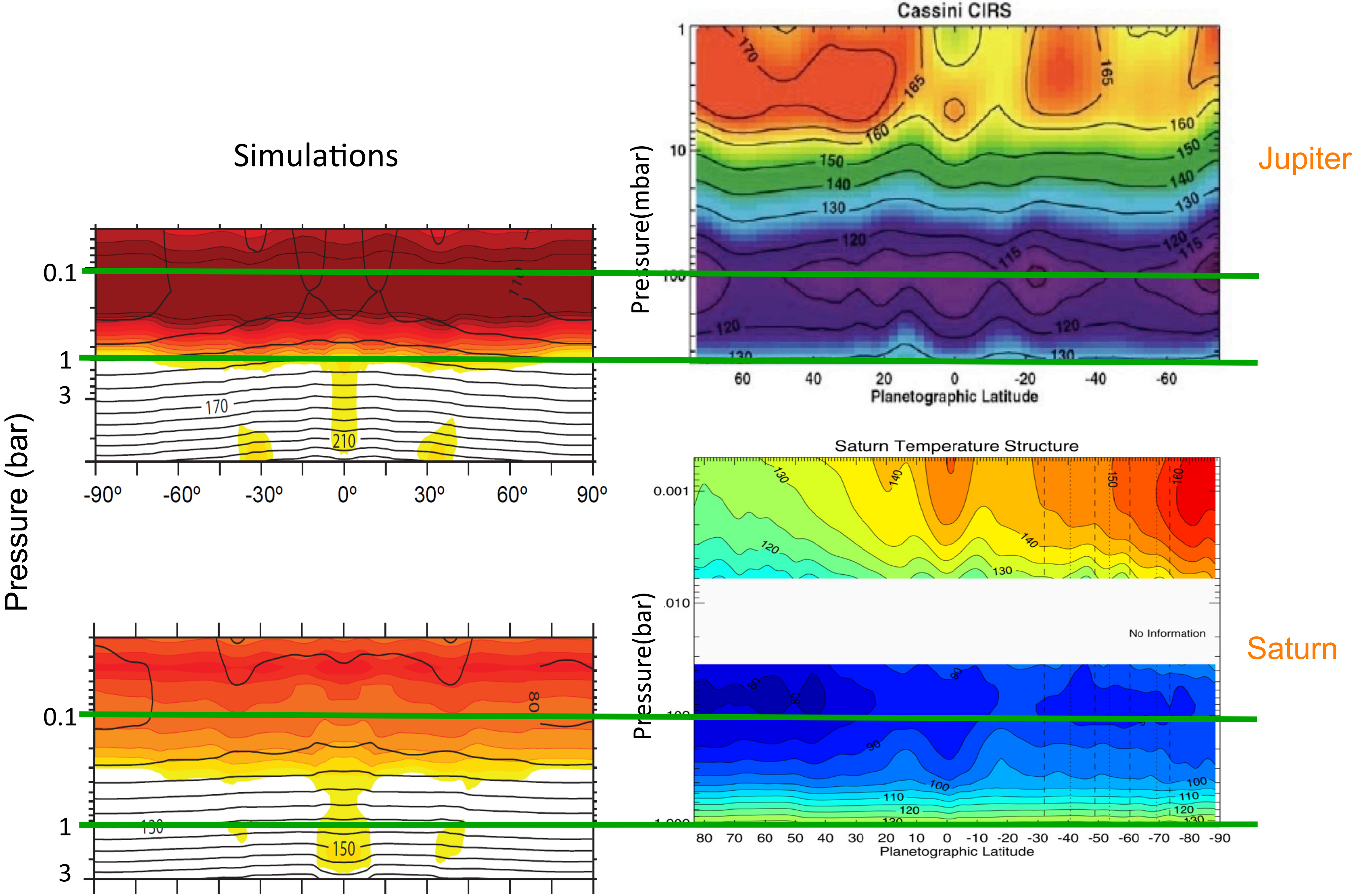
$$R = -\nabla_h \cdot (\zeta_a \mathbf{v}_\chi - \overline{\zeta_a \mathbf{v}_\chi})$$

(Schneider & Liu 2009)



(Liu & Schneider 2010)

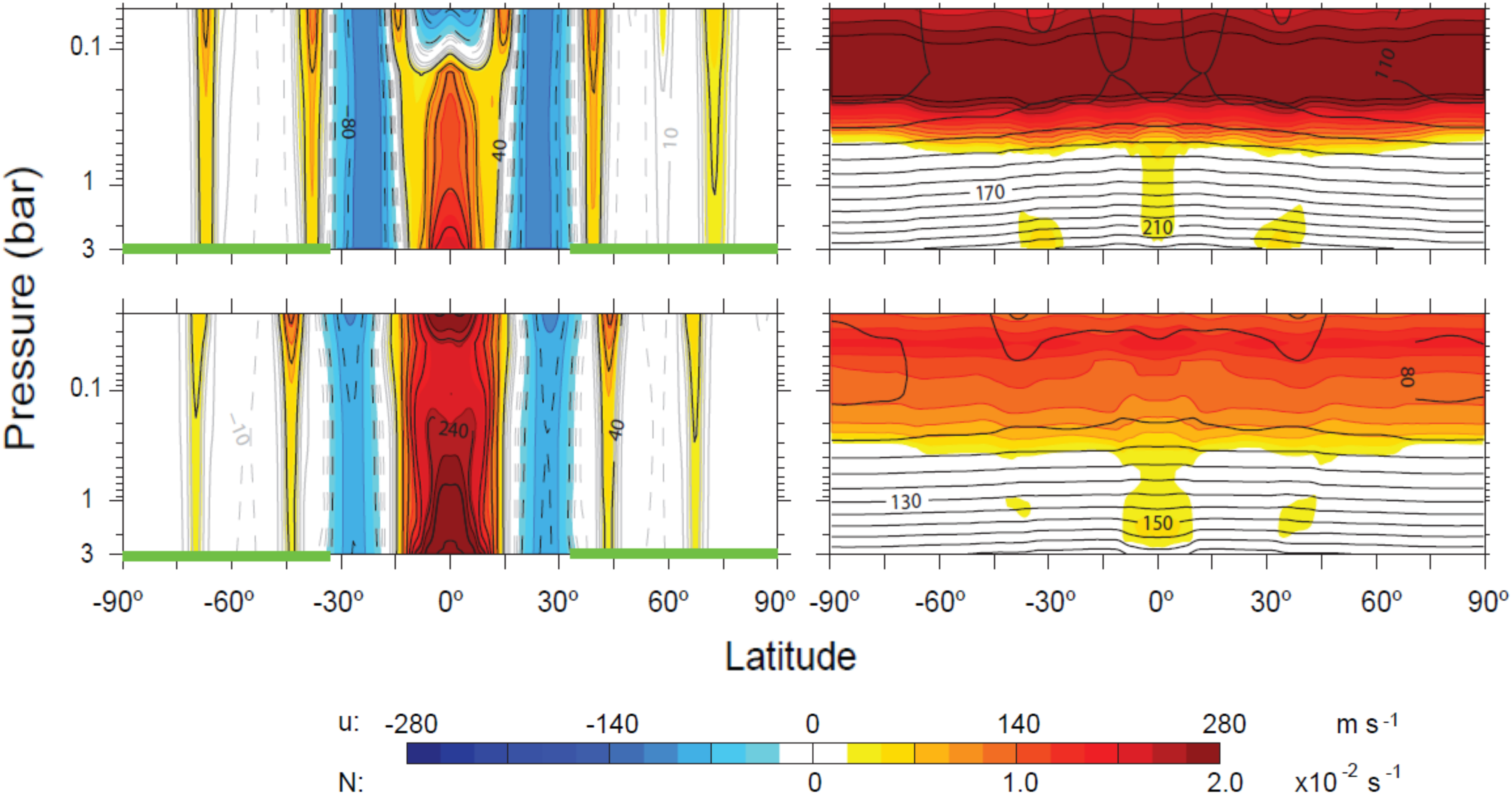
Temperature: Comparison with observations



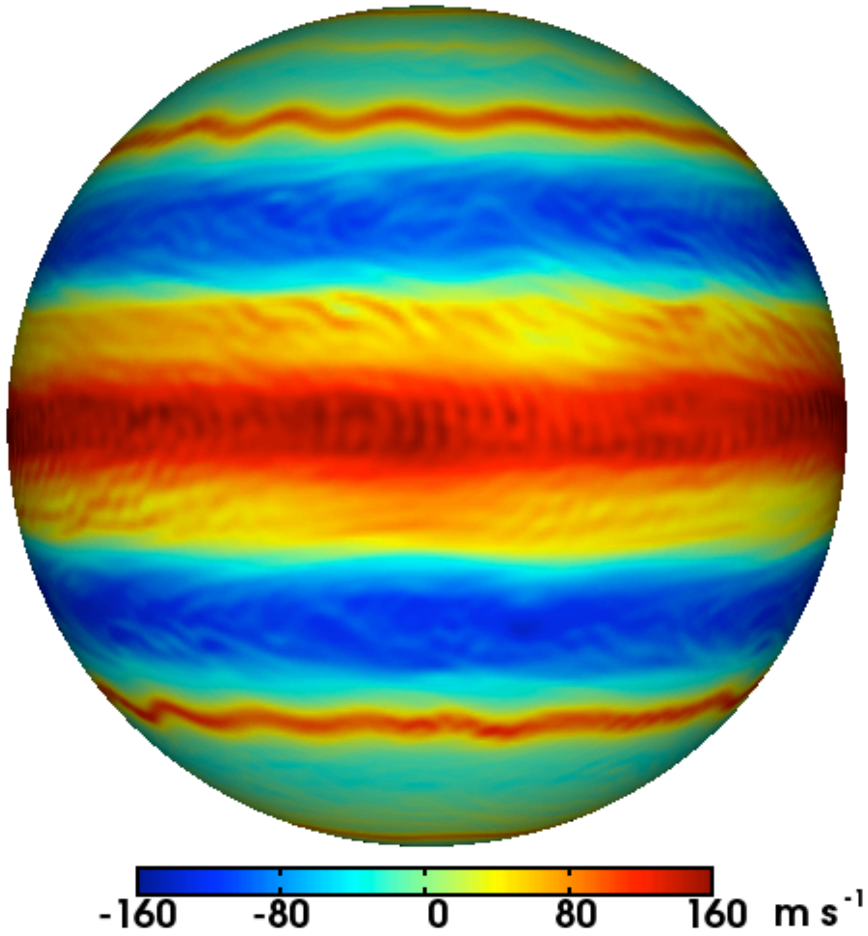
(Simon-Miller et al. 2006; Fletcher et al. 2007)

Why are Jupiter and Saturn superrotating?

--- strong internal heat flux (5.7 W m^{-2} on Jupiter and 2.01 W m^{-2} on Saturn) generates convection.



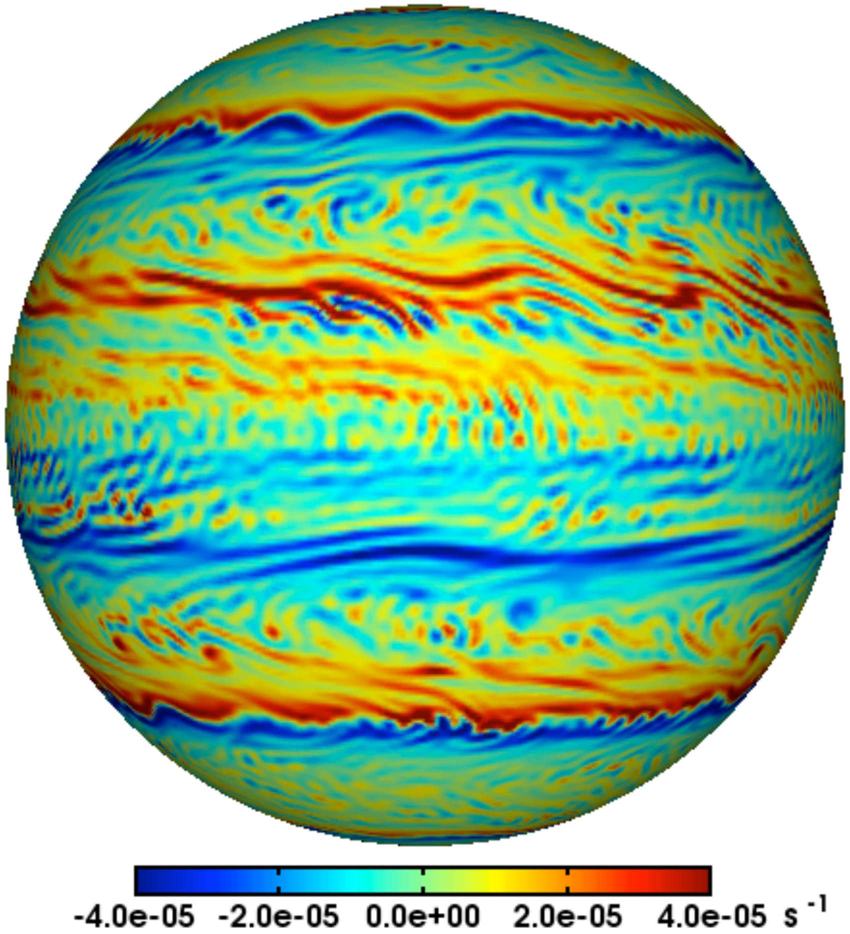
(Liu & Schneider 2010)



Zonal velocity in Jupiter simulation (100 Earth days)

retrograde

prograde



Vorticity in Jupiter simulation (100 Earth days)

(Schneider & Liu 2009)

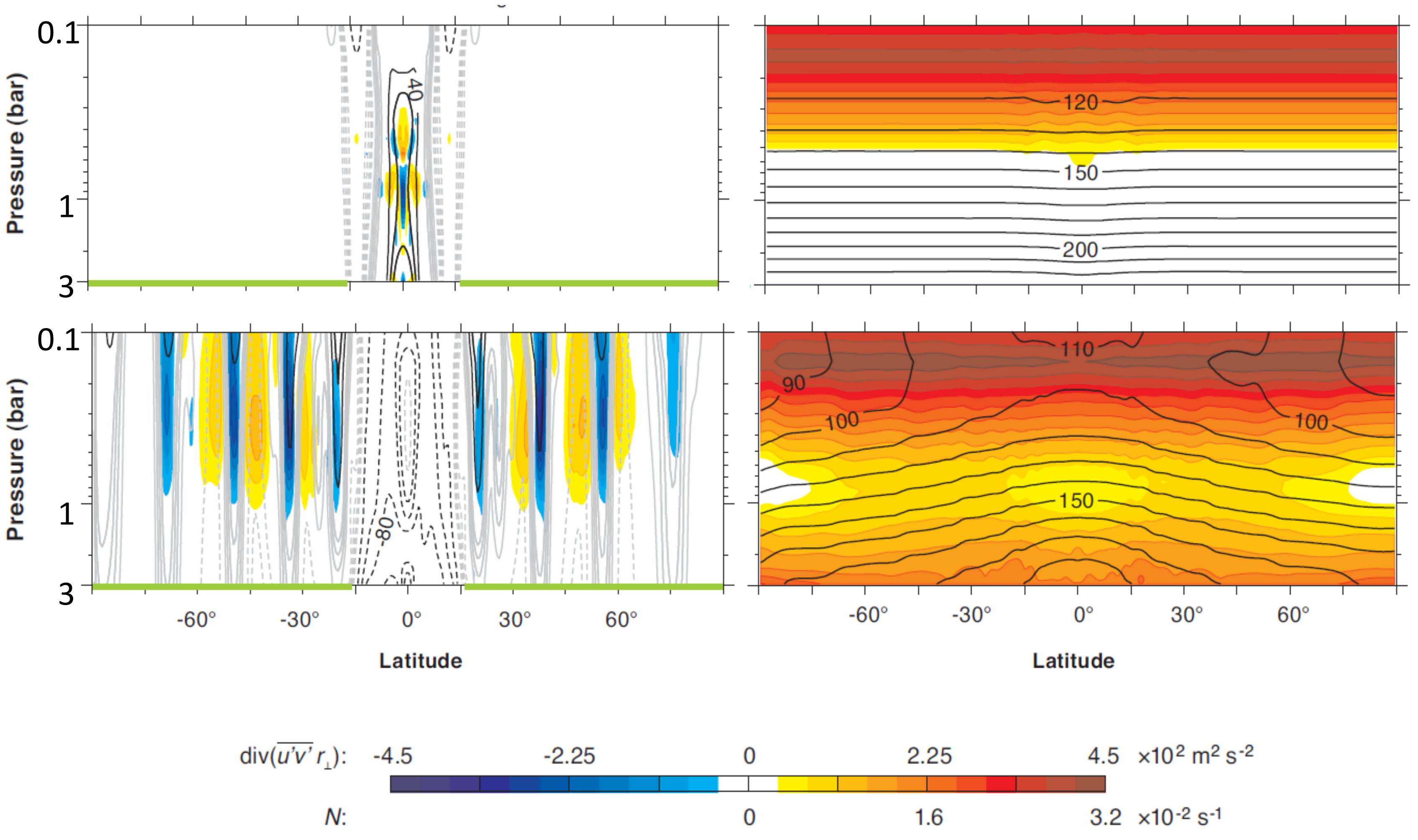
Jupiter control simulations

u, Eddy momentum divergence

T, N

Uniform solar radiation

No internal heatflux



(Schneider & Liu 2009)

Why is Saturn's equatorial jet stronger and wider than Jupiter's?

- Width of the equatorial jet is set by the equatorial Rossby radius:

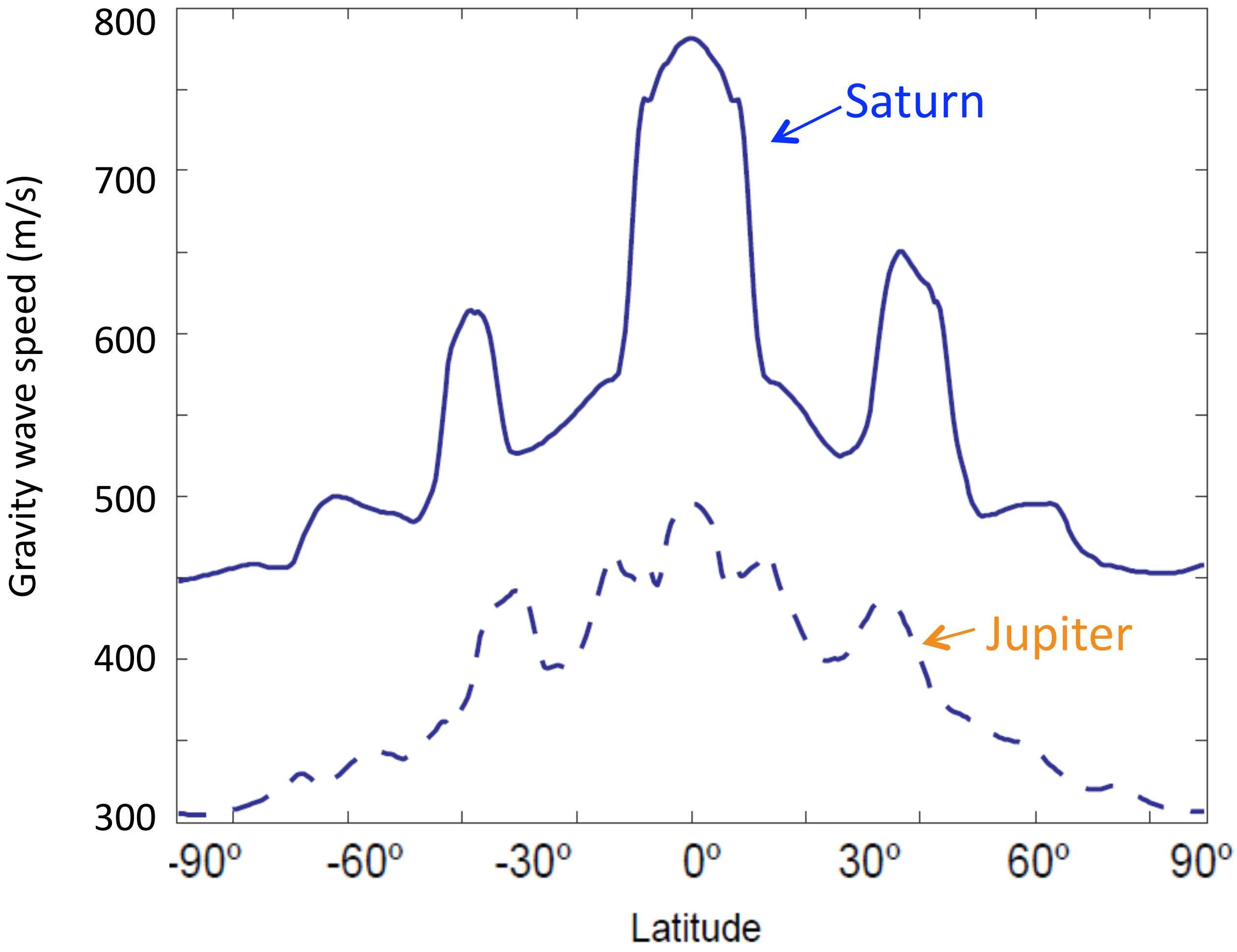
$$L = \sqrt{c/\beta}$$

$$c = \int_{p_t}^{p_s} N_p \, dp$$

$$N_p^2 = -(\bar{\rho}\bar{\theta})^{-1} \overline{\partial_p \theta}$$

- By vorticity mixing argument, strength of the equatorial jet increases with width:

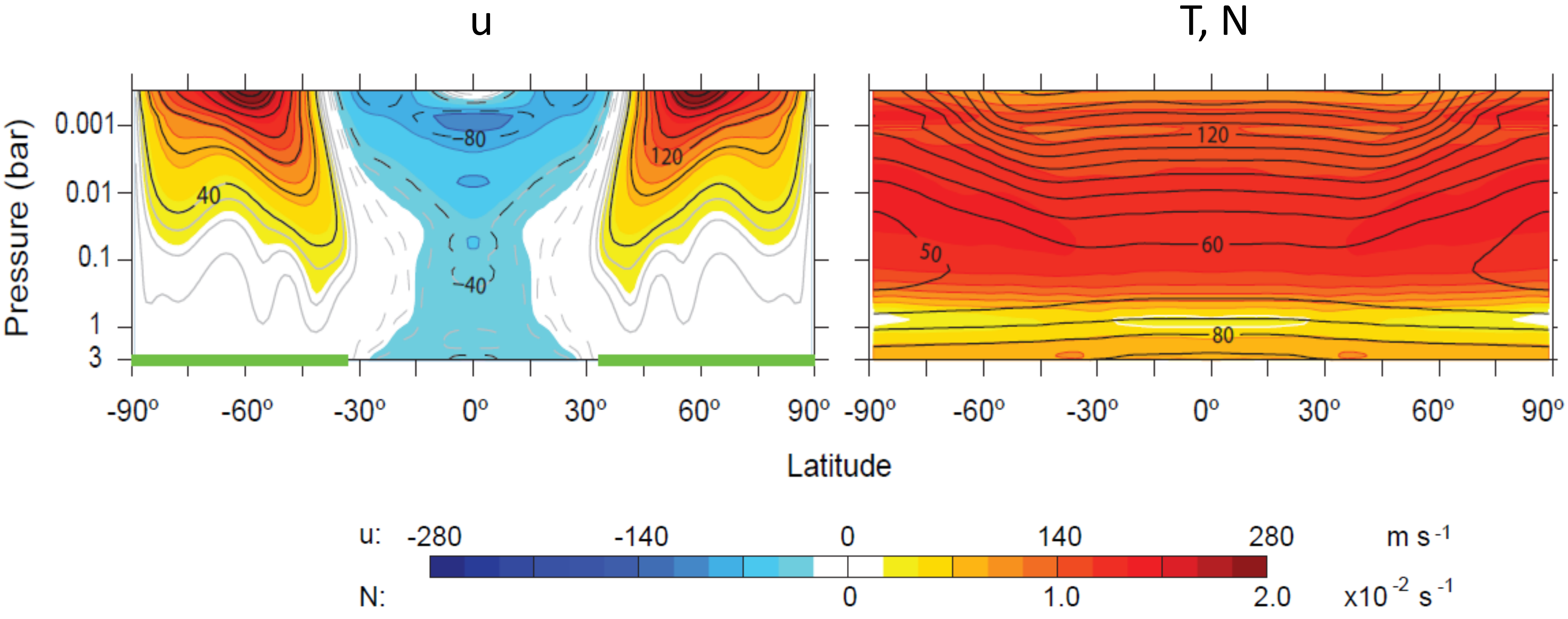
$$U \sim L^2\beta/2 \sim c/2$$



(Schneider & Liu 2009)

Why is Uranus subrotating?

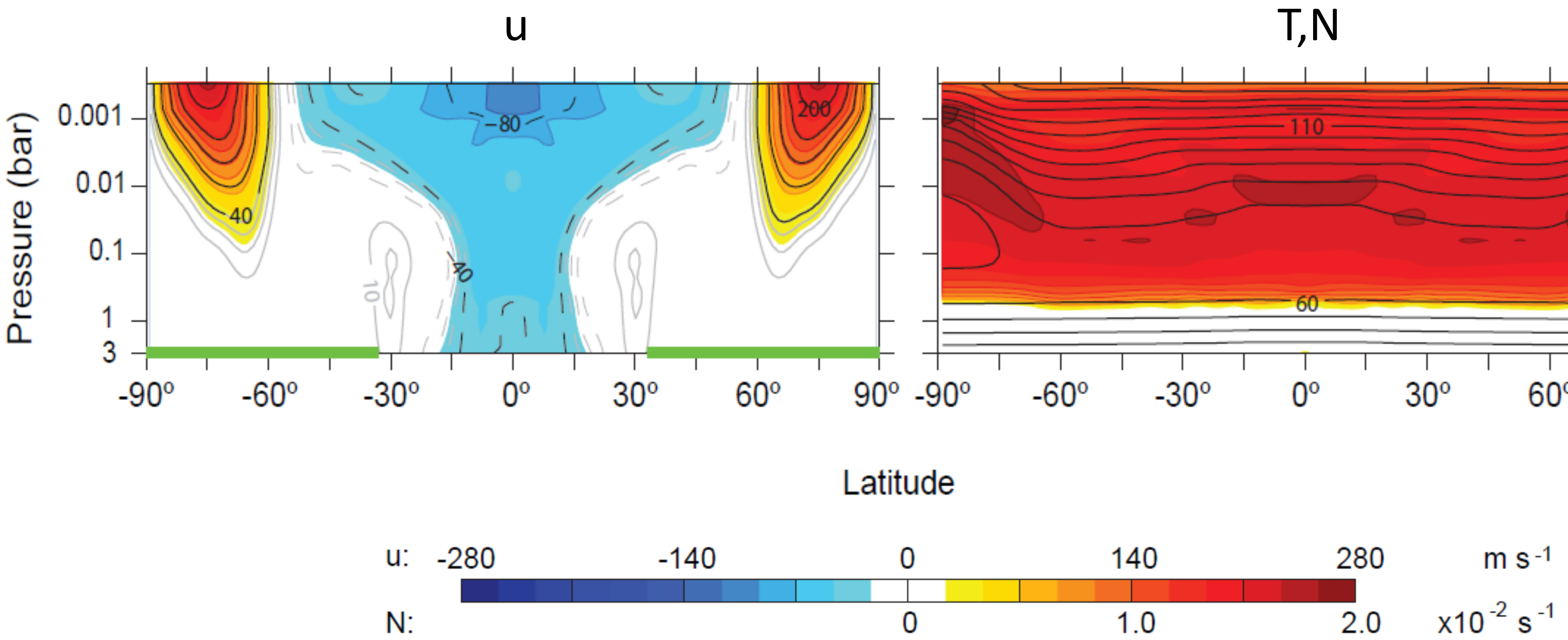
--- Almost no internal heat flux (0.042 W m^{-2}),
the atmosphere is stably stratified.



(Liu & Schneider 2010)

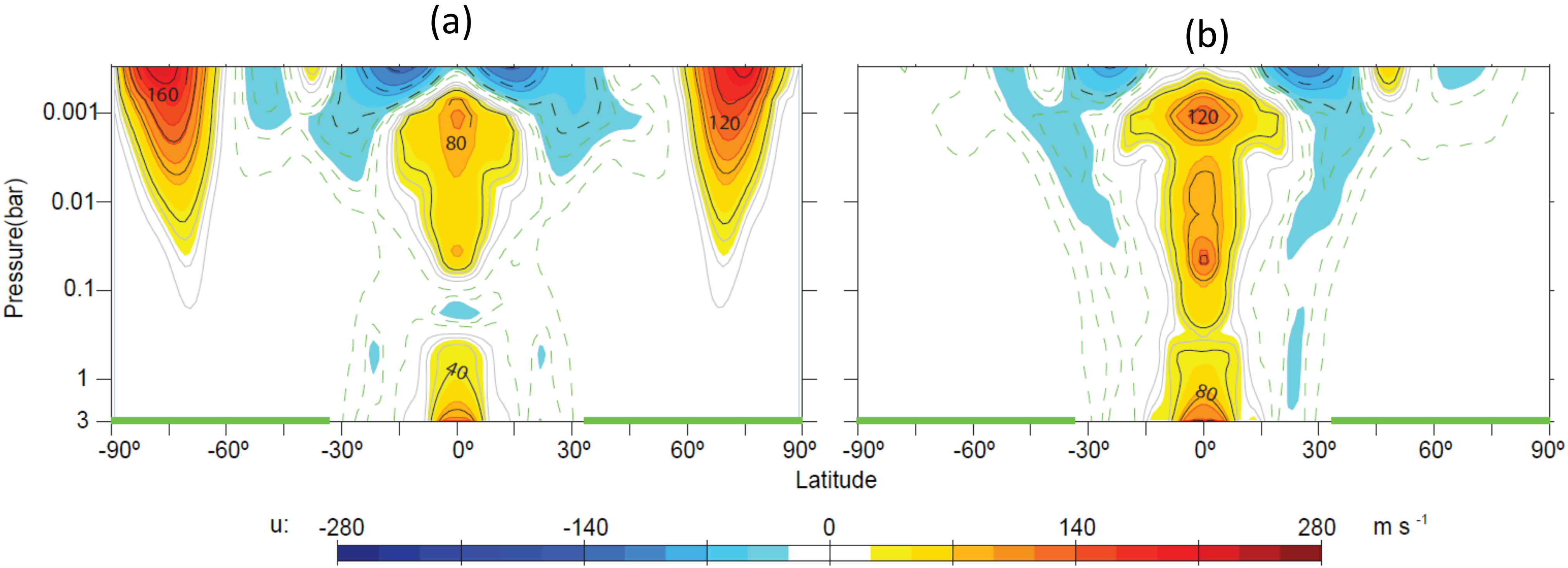
How about Neptune?

--- Has significant internal heat flux (0.43 W m^{-2}), the atmosphere is neutrally stratified below tropopause.



(Liu & Schneider 2010)

Neptune control simulation

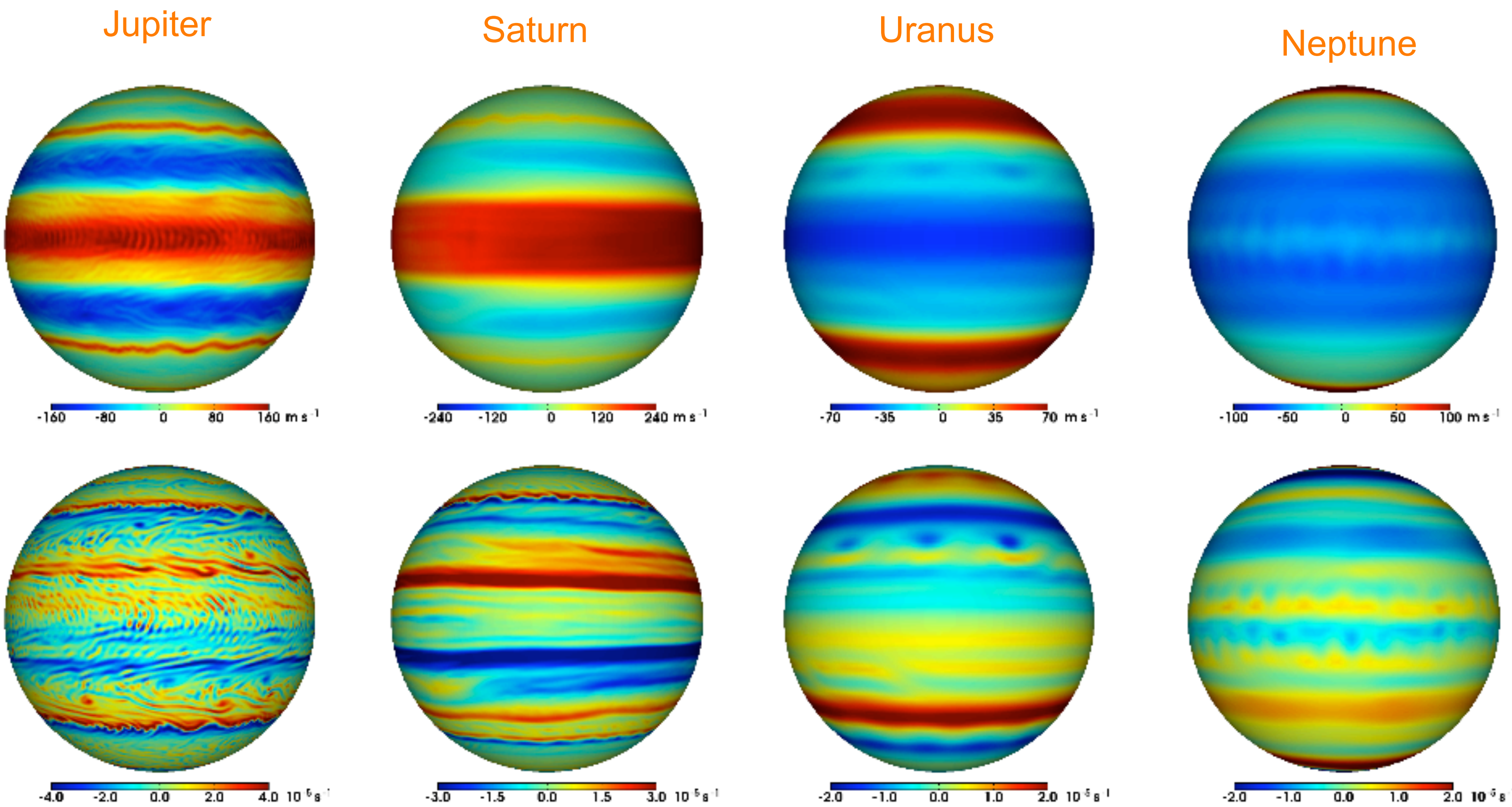


(a) Neptune's insolation and Saturn's internal heat flux 2.01 W m^{-2}

(b) Uniform insolation and Neptune's internal heat flux 0.43 W m^{-2}

(Liu & Schneider 2010)

Instantaneous zonal wind and relative vorticity



Jupiter

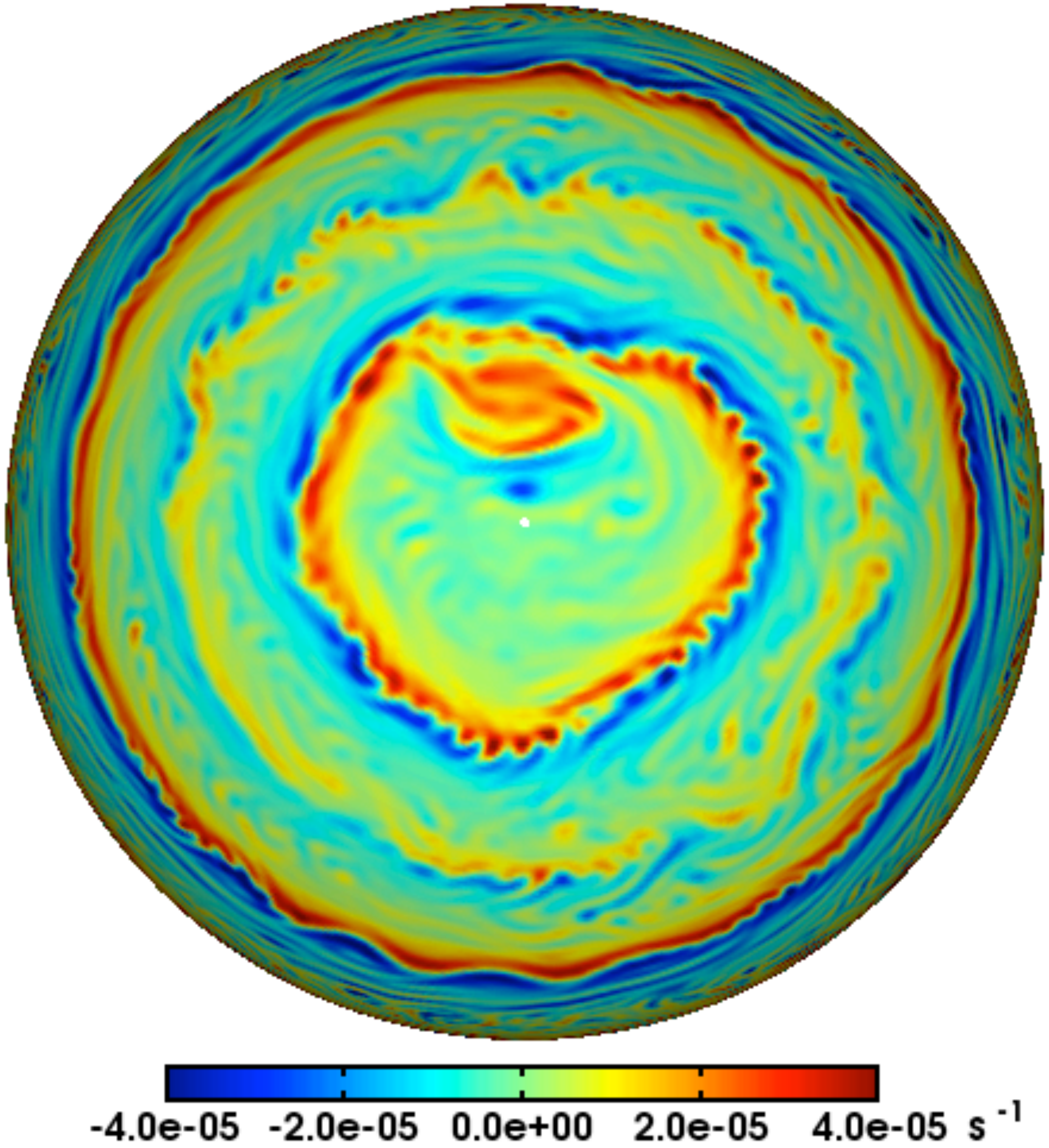
Saturn

Uranus

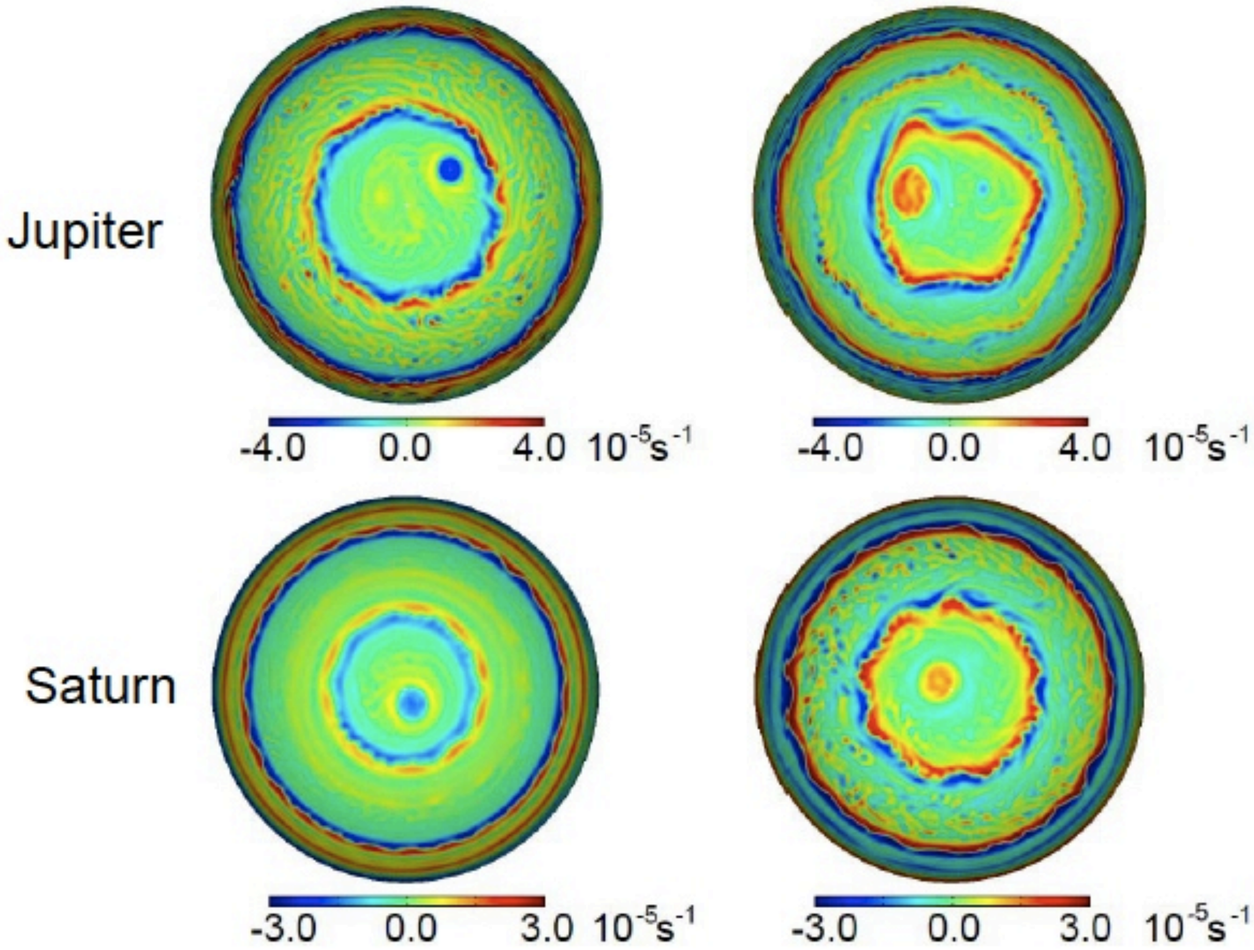
Neptune

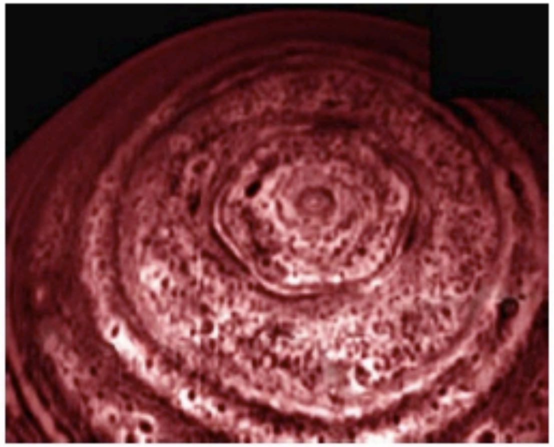
(Liu & Schneider 2010)

Vorticity in Jupiter simulation (north pole)



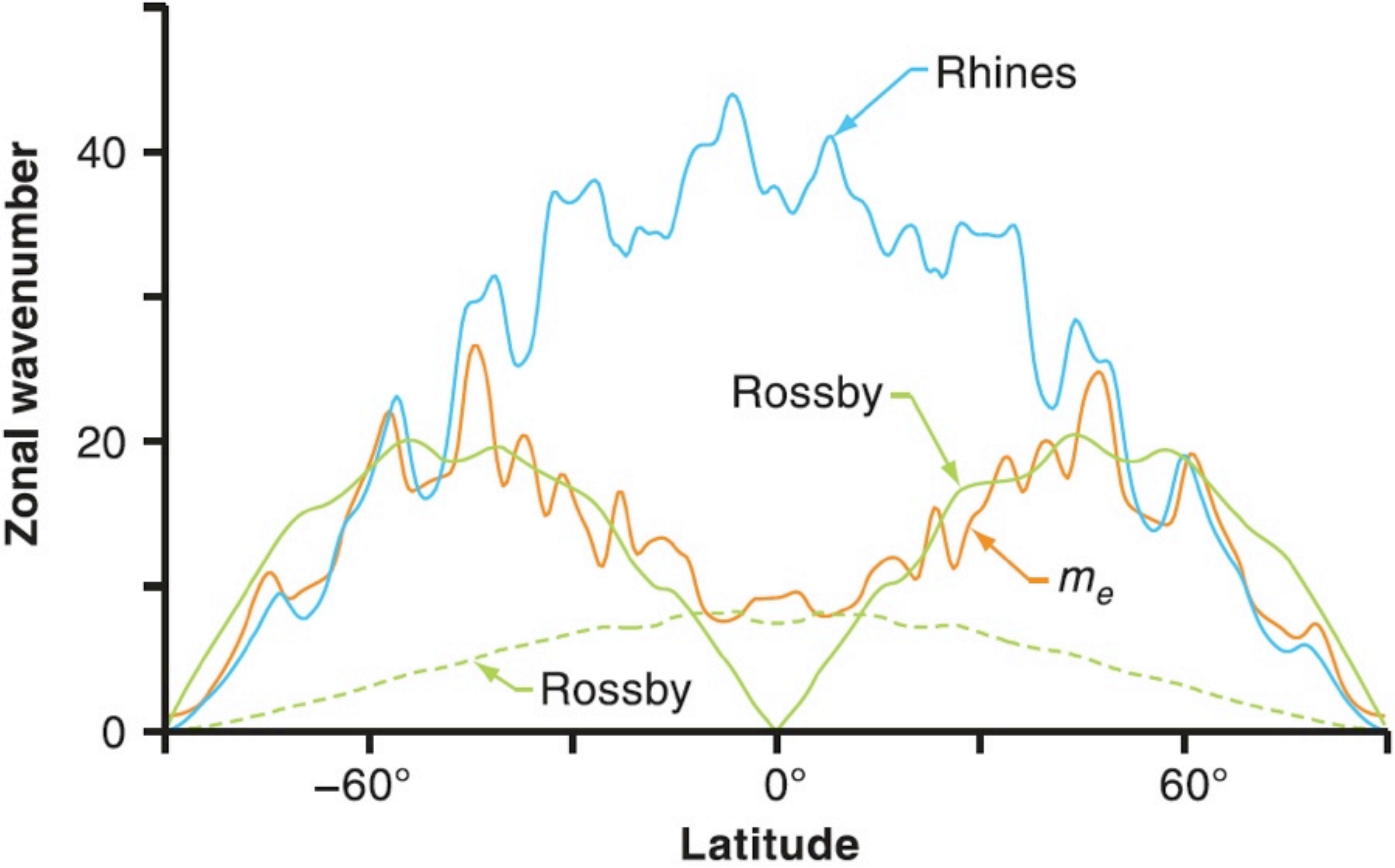
Polar jets and waves





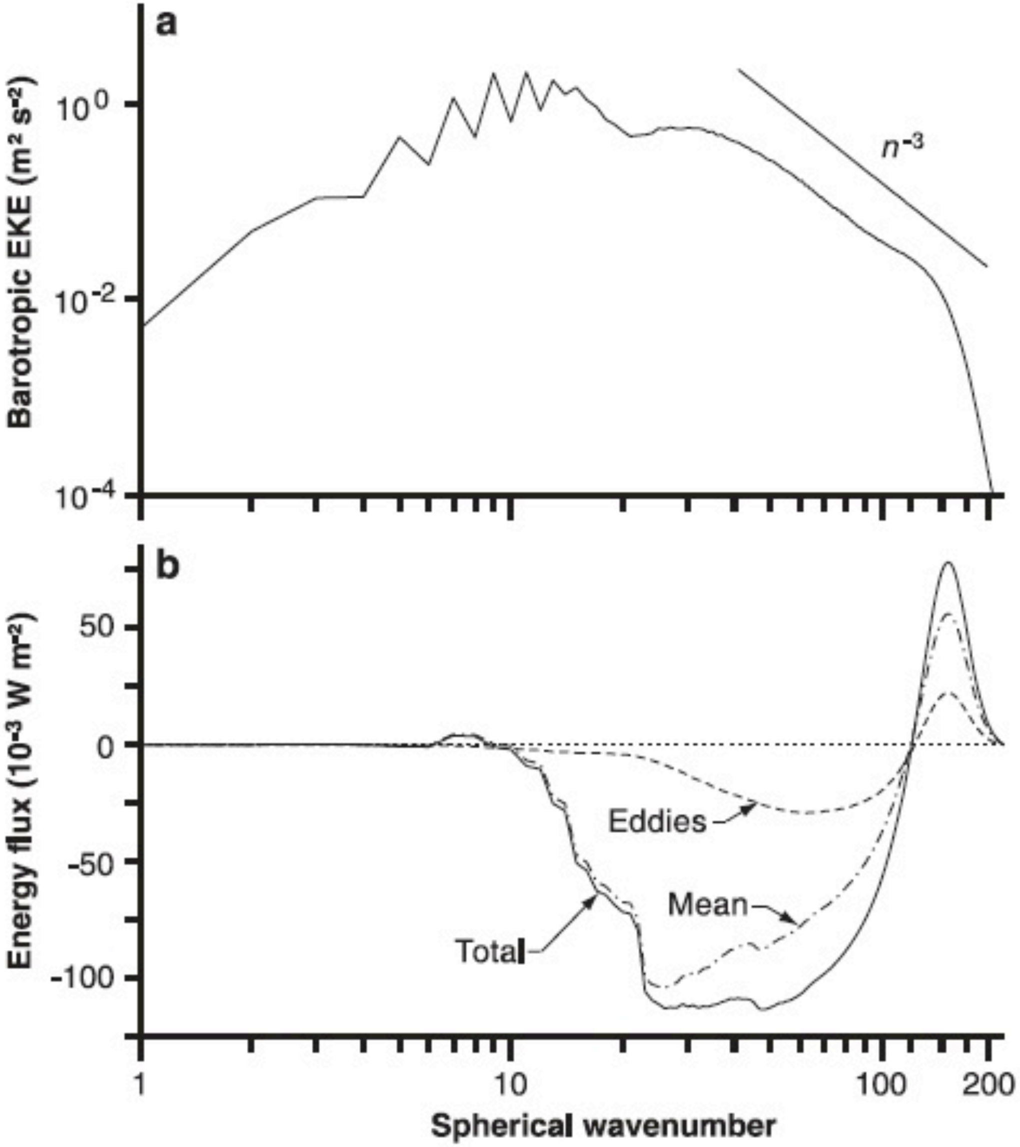
(NASA/JPL, VIMS Team, University of Arizona, http://apod.nasa.gov/apod/ap070403.html)

Eddy length scales (Jupiter simulation)



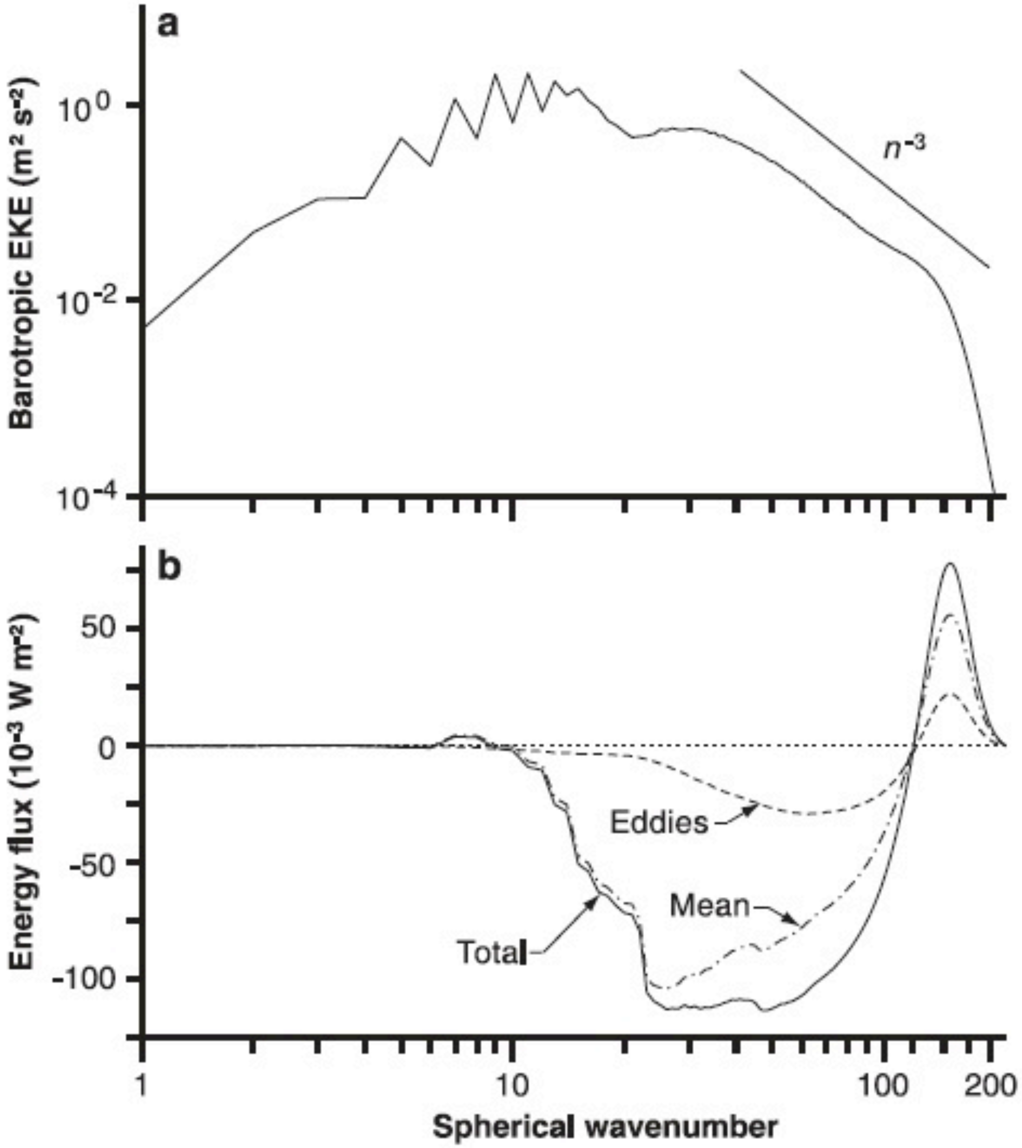
(Schneider & Liu 2009)

EKE spectrum and flux (Jupiter simulation)



(Schneider & Liu 2009)

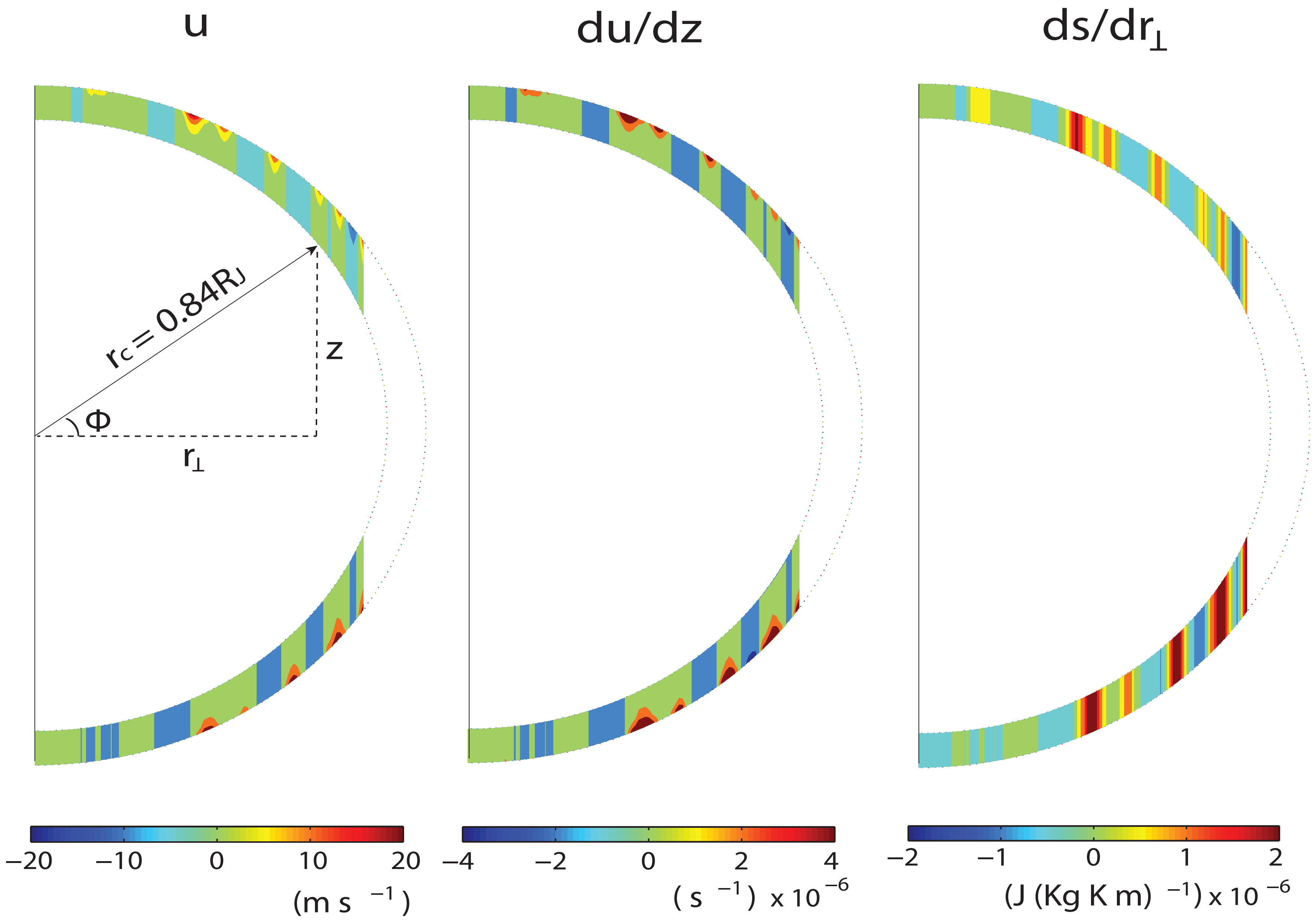
EKE spectrum and flux (Jupiter simulation)



These are testable predictions

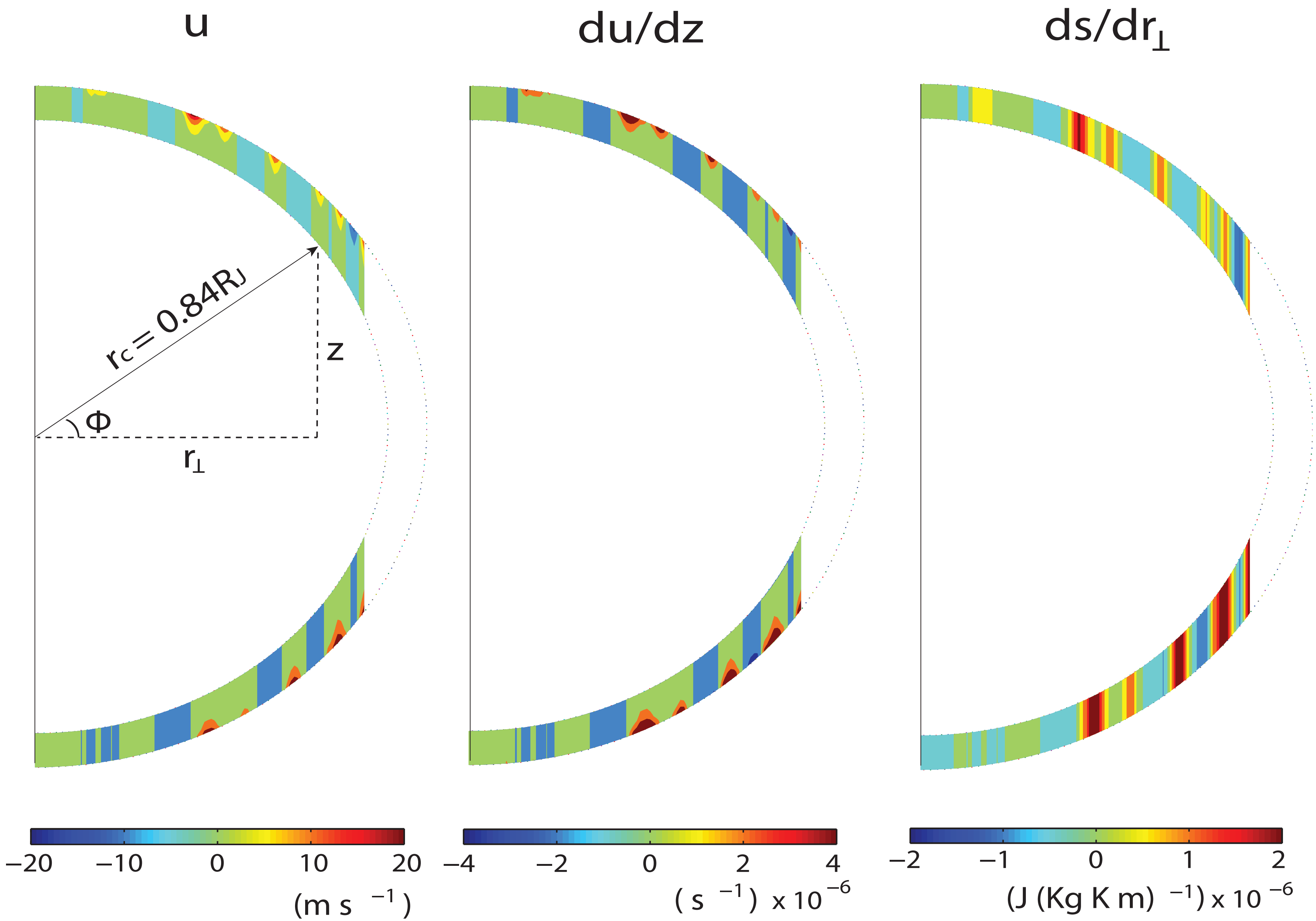
(Schneider & Liu 2009)

Predictions for Juno



(Liu et al. 2011)

Predictions for Juno

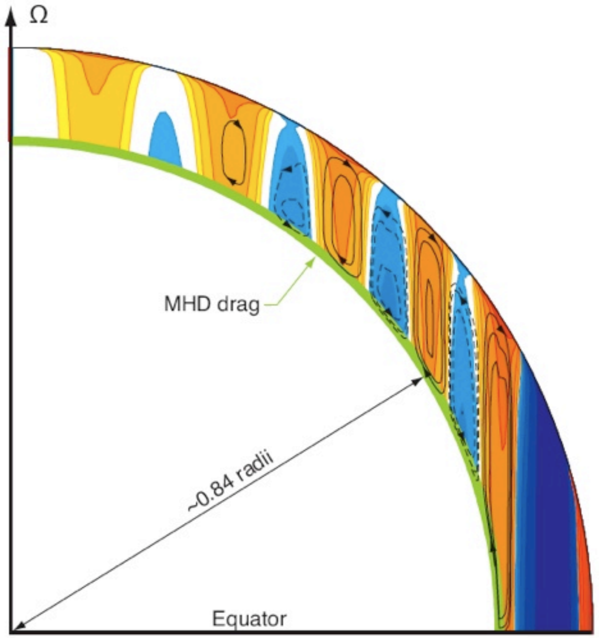


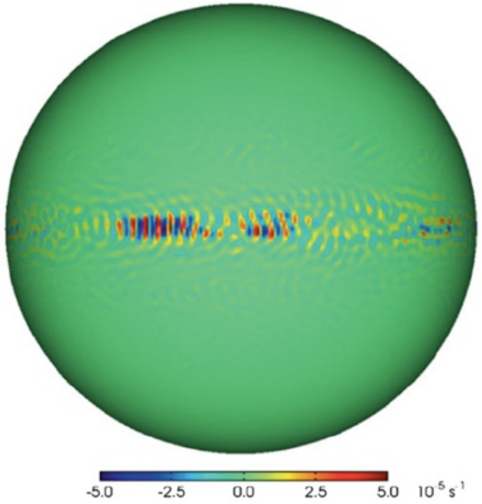
Distinctly measurable gravity signal

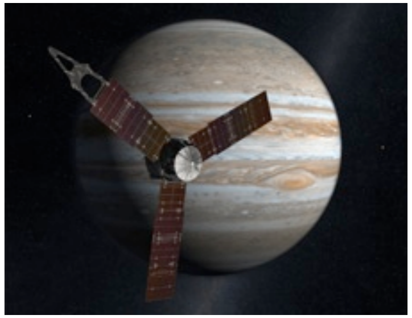
(Liu et al. 2011)

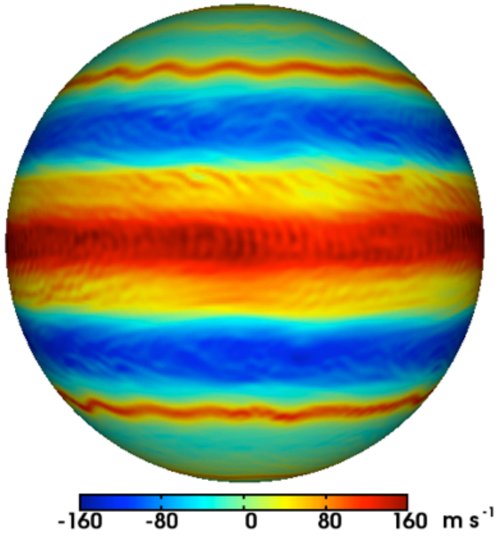
Conclusions

- Off-equatorial jets are baroclinically generated; equatorial superrotation generated by convection
- Internal heat flux destabilizes deep layer and increases baroclinicity
- Convection generates equatorial divergence and Rossby waves, leading to superrotation
- Momentum dissipation by coupling to magnetic field
- No strong turbulence (inverse cascade) necessary
- Theory leads to concrete predictions of gravity and temperature signature (Juno measurement)








Zonal velocity in Jupiter simulation (100 Earth days)