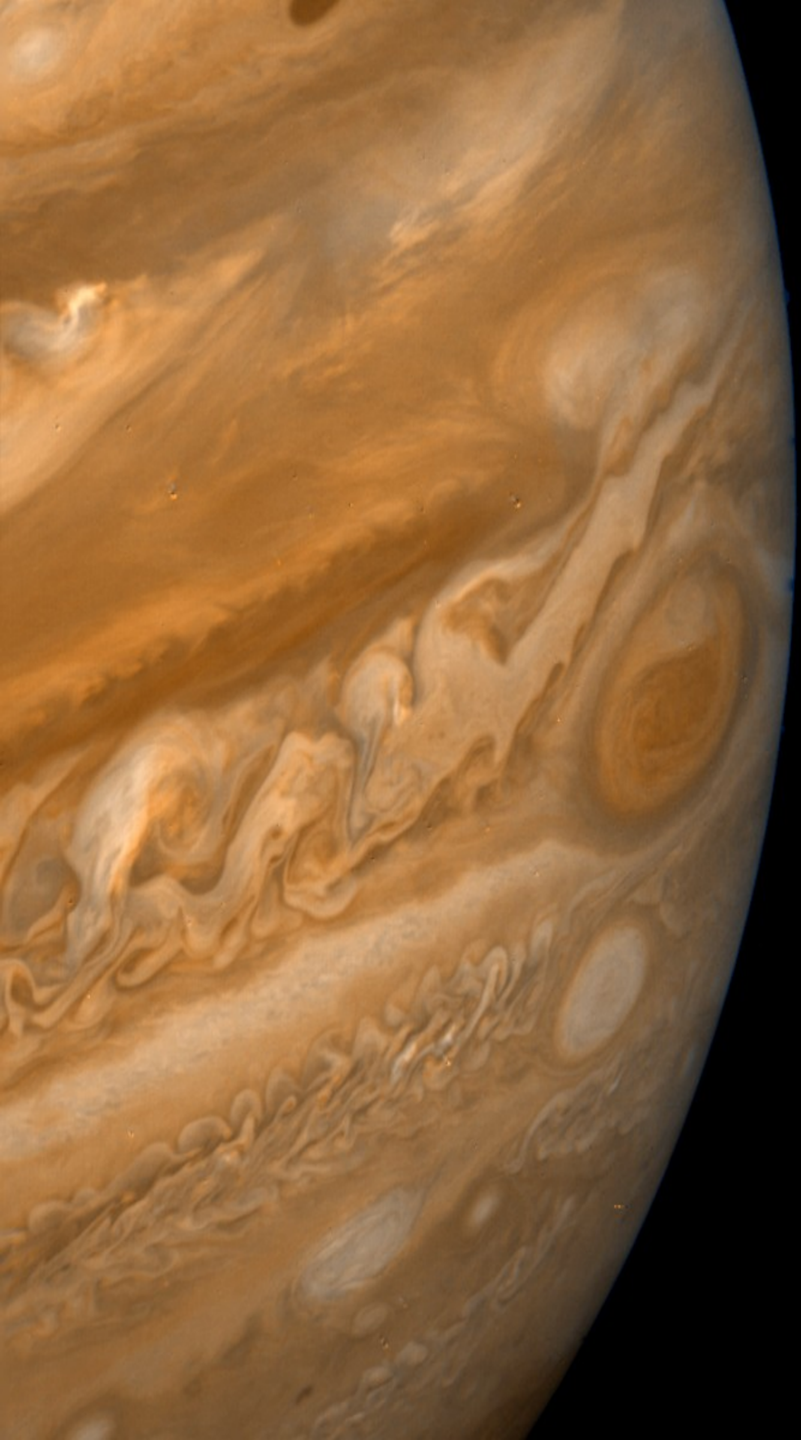


Atmospheric dynamics on gas giants driven by internal convection

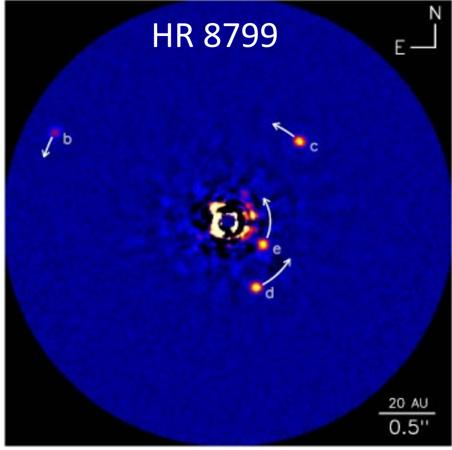
+ the Juno gravity experiment

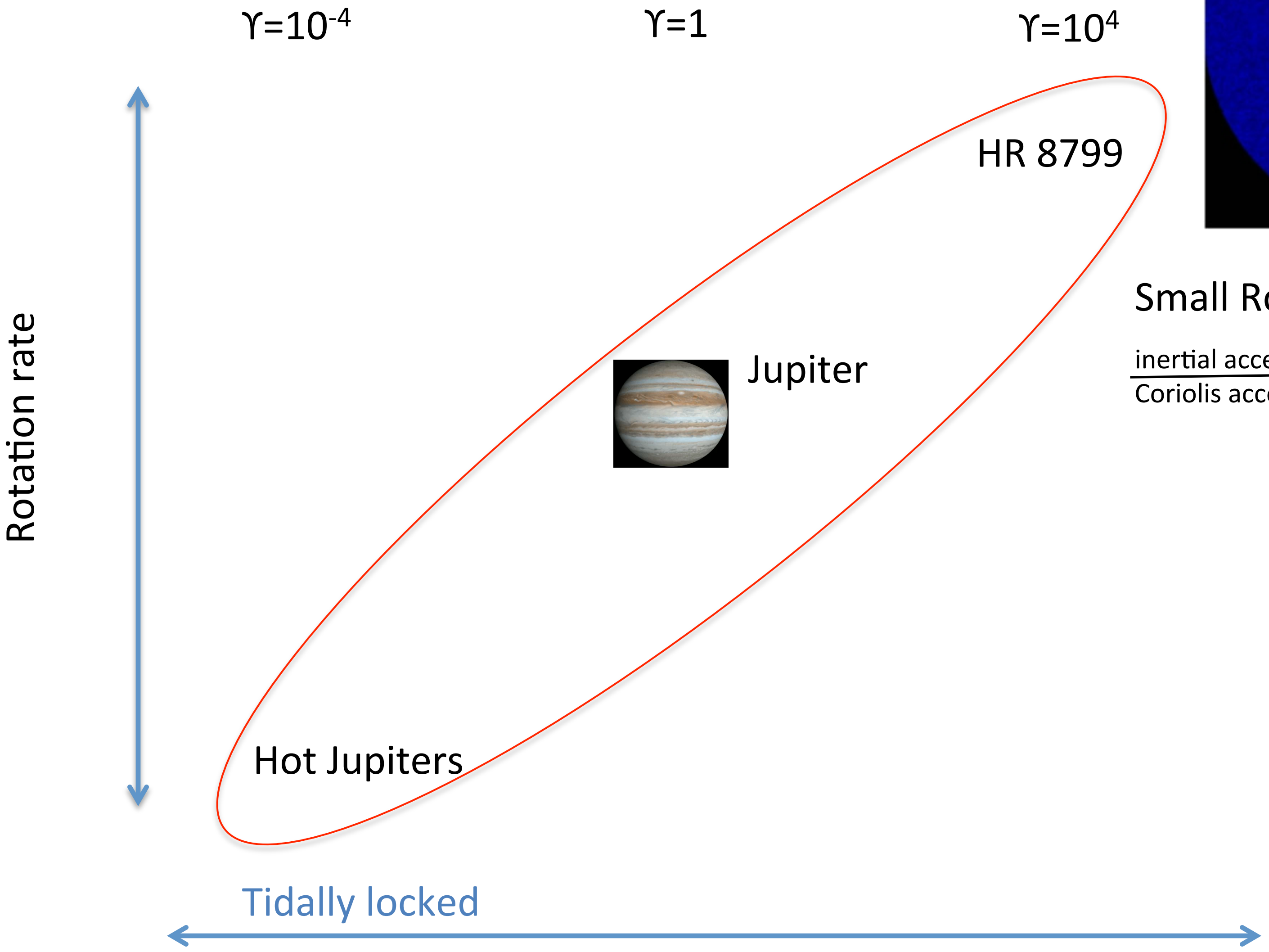
Yohai Kaspi, Weizmann Institute

Glenn Flierl, MIT
Bill Hubbard, U. of Arizona
Adam Showman, U. of Arizona

Exoclimes, Aspen 2012

$$\Upsilon = \frac{\text{Internal haet flux}}{\text{Solar heat flux}}$$





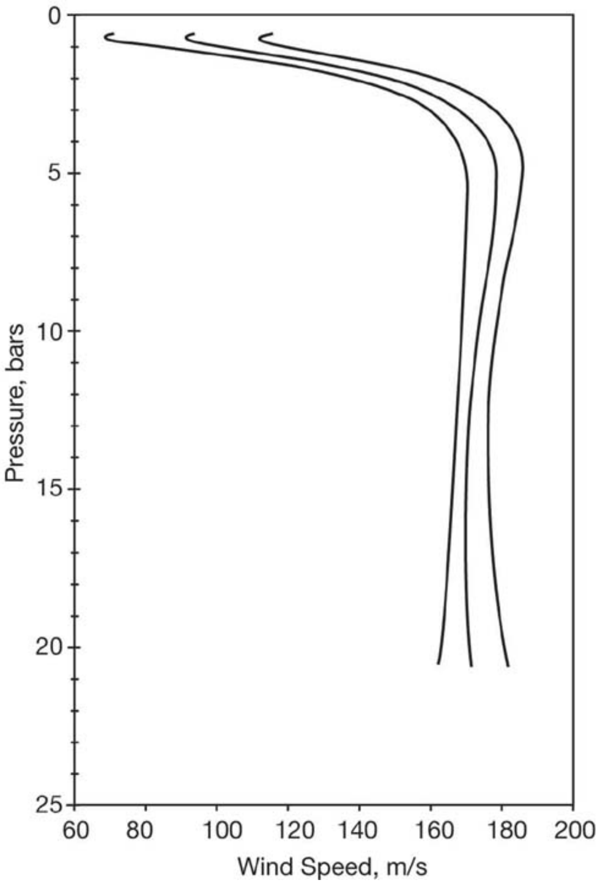
Small Rossby number:

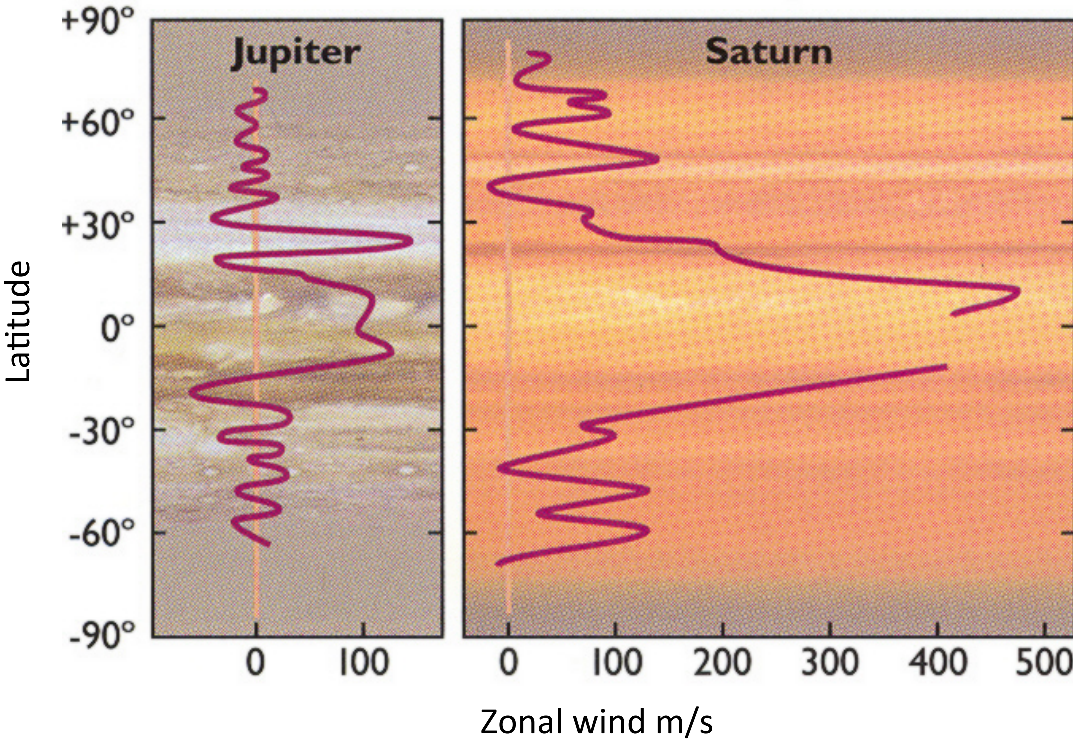
$$\frac{\text{inertial acceleration}}{\text{Coriolis acceleration}} \ll 1$$

Distance from parent star

Atmospheric dynamics on solar system giant planes

Galileo entry probe (1995) detected zonal winds that increase in depth and then remain constant.





Strong winds at cloud level. Both Jupiter and Saturn have a superrotating equatorial jet with multiple zonal jets at higher latitudes.

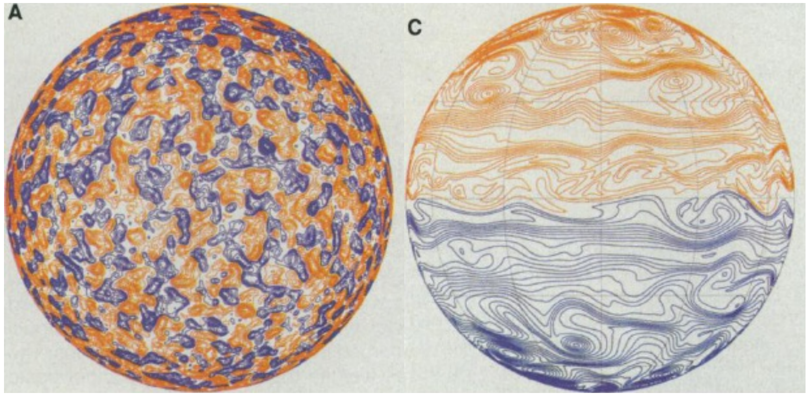
Understanding the zonal winds: Shallow vs. Deep approaches

Shallow Models

Generation of Jets from Geostrophic turbulence.

Rhines (1975), Williams (1978), Cho & Polvani (1996), Williams (2003), Kaspi & Flierl, (2007), Scott & Polvani (2008), Lian & Showman (2010), Liu & Schneider (2010)

Cho & Polvani, 1996

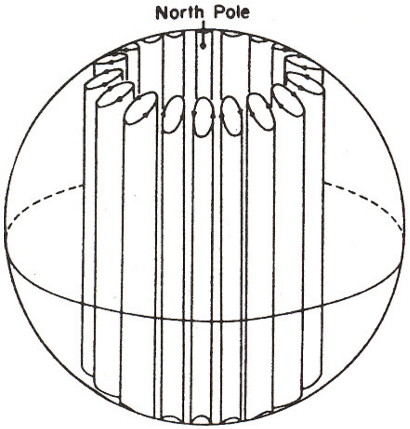


Deep Models

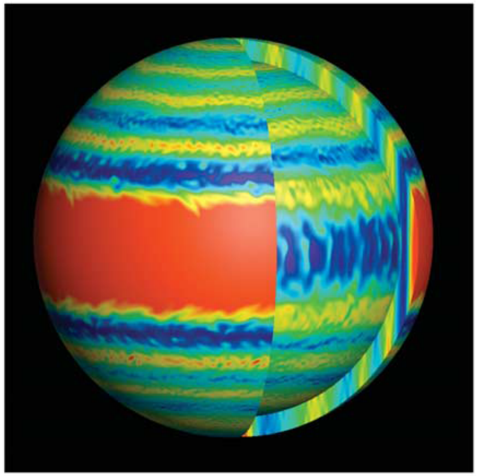
- Heuristic models of columnar convection based on lab convection on experiments. Busse (1970, 1976), Ingersoll & Pollard (1982).

- Numerical Boussinesq convection models Sun et. al. (1993) , Zhang & Schubert (1997), Christensen (2002), Busse (2002), Heimpel et al. (2005), Aurnou et al. (2007).

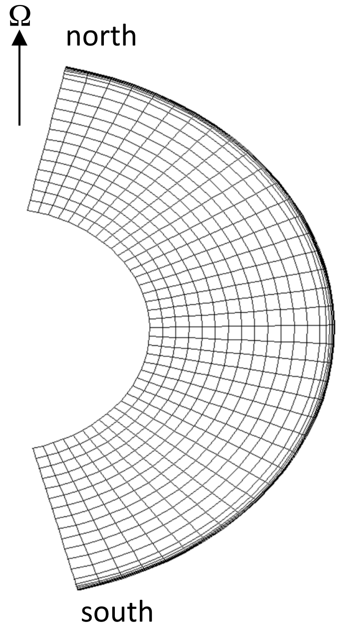
Busse, 1976



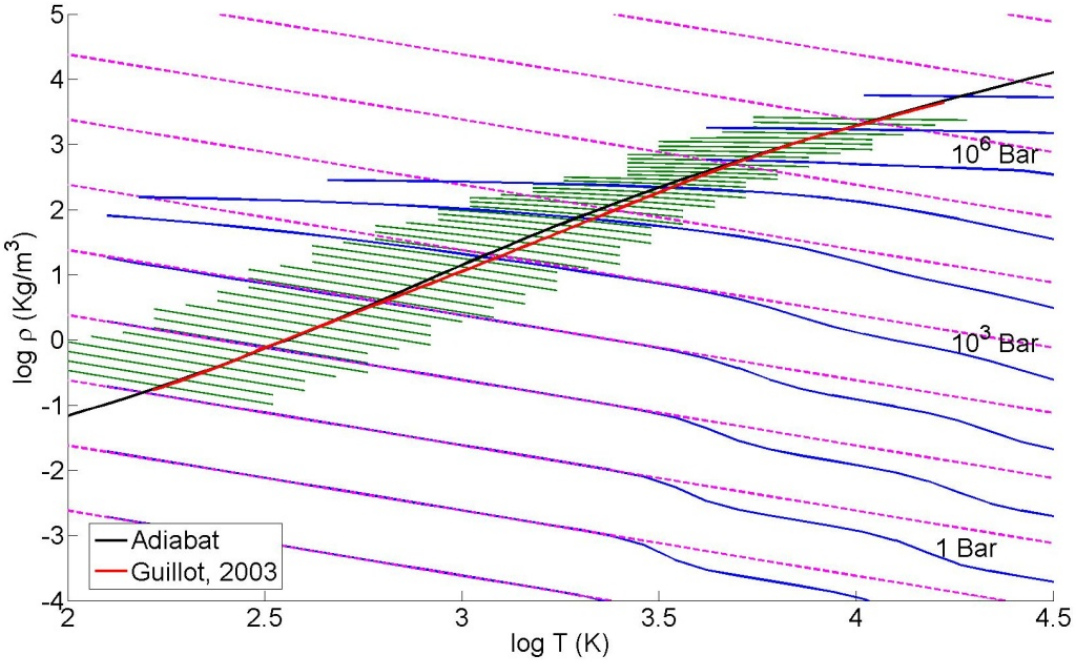
Heimpel et al., 2005



A Deep Anelastic GCM

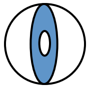


- MITgcm dynamical core
- Deep dynamics – full sphere instead of spherical shell
- Non-Hydrostatic
- Gravity field varying with depth
- Solve for momentum, energy and mass $\nabla \cdot (\bar{\rho} u) = 0$
- Forced by internal heating
- SCVH equation of state (Saumon, 1995)



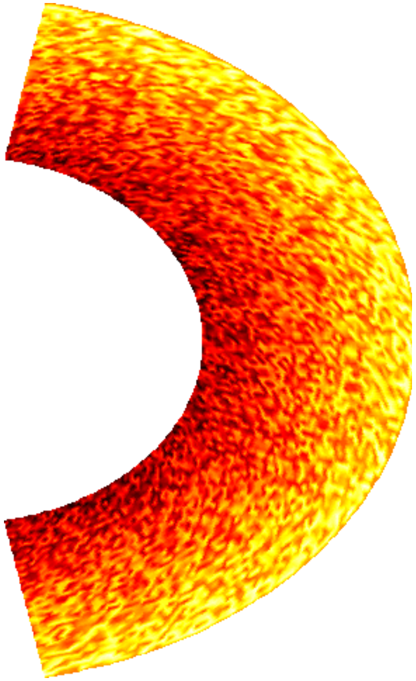
Kaspi et al., 2009

The Effect of Rotation



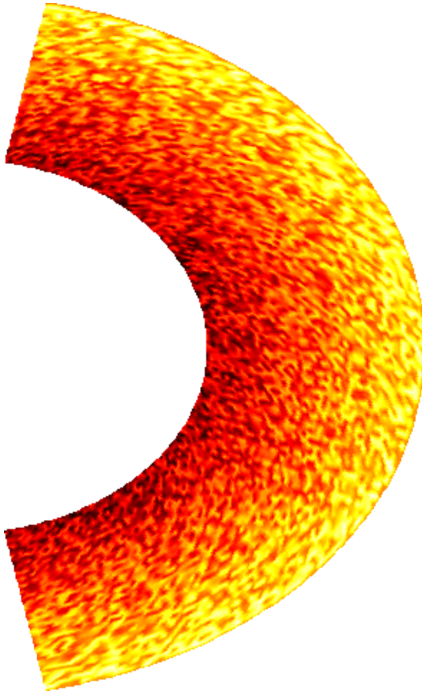
Fast Rotation

10 hr
rotation
period



Slow Rotation

100 hr
rotation
period



yellow = high entropy ⟷ black = low entropy

Alignment with the axis of rotation

Angular momentum: $M = \Omega r^2 \cos^2\theta + ur\cos\theta \approx \Omega r^2 \cos^2\theta$

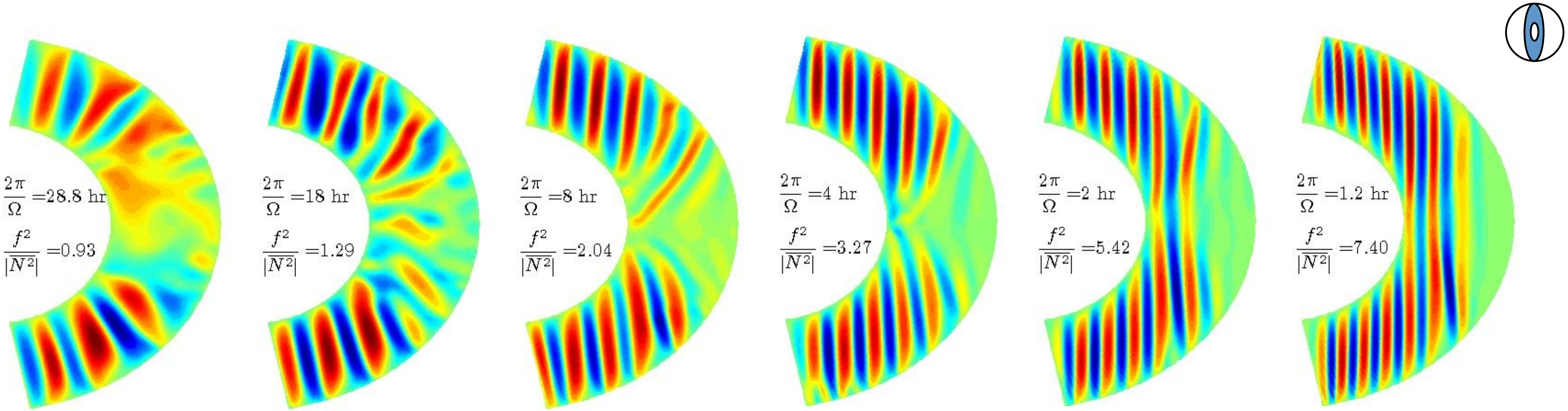
Small Rossby number $\frac{u}{\Omega L} << 1$

Thus to leading order angular momentum surface are aligned with the axis of rotation.

Angular momentum arguments lead to: $\vec{u} \cdot \nabla M \approx 0$

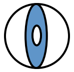
For fast rotation there is no flow across angular momentum surfaces except near the boundaries.

streamfunction: $\nabla \times \Psi = \overline{\rho}\vec{u}$

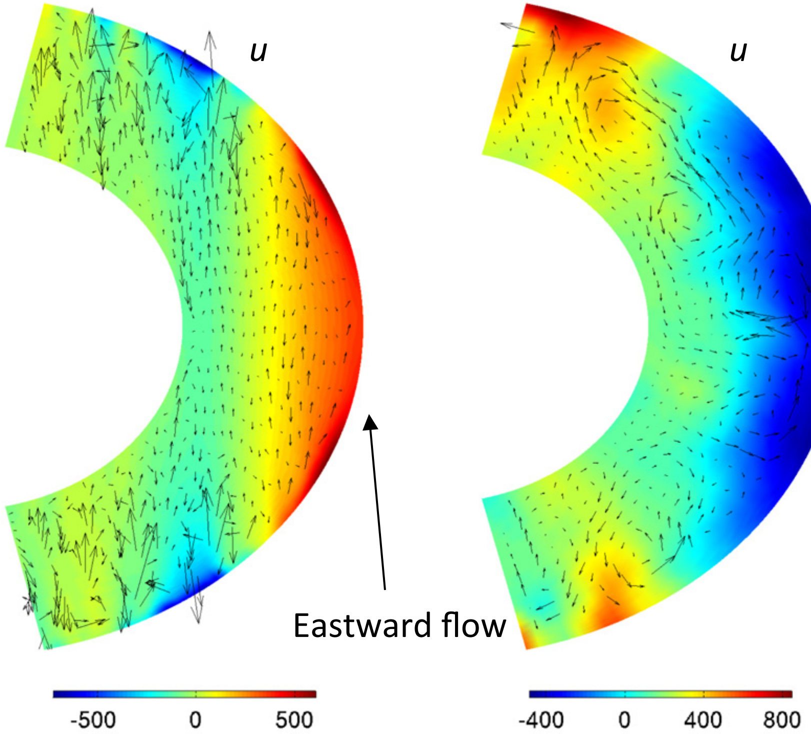


slow rotation ↔ fast rotation

Equatorial superrotation



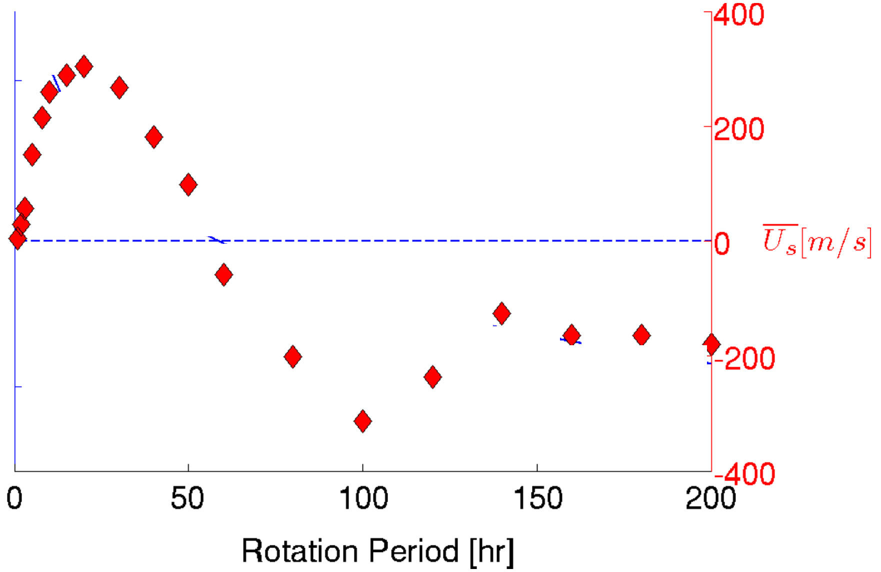
10 hr
rotation
period



Eastward flow

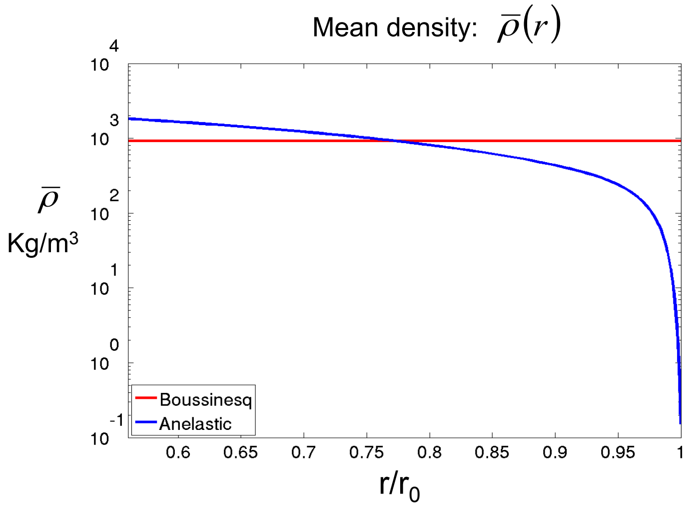
100 hr
rotation
period

Westward flow

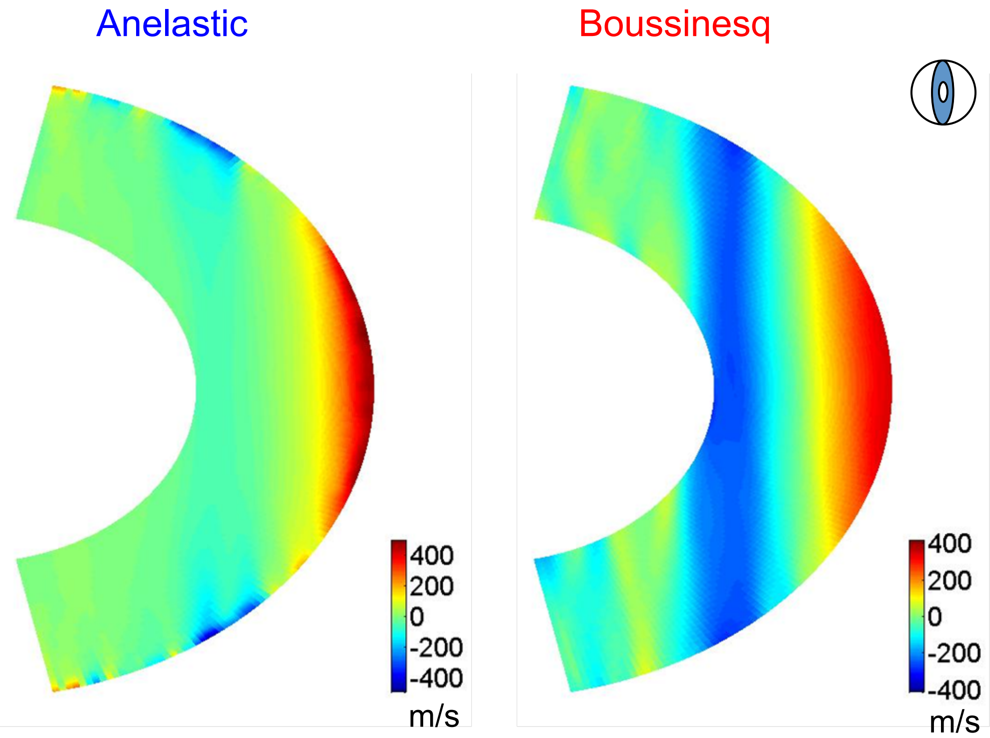


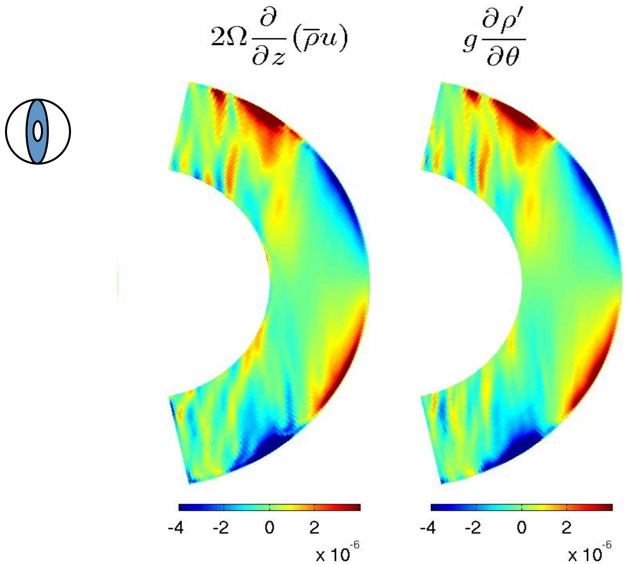
← Equatorial surface
zonal velocity

The effect of compressibility



Zonally averaged zonal velocity





Vorticity equation:

$$\boxed{2\Omega\cdot\nabla\left(\bar{\rho}\vec{u}\right)=\nabla\rho'\times\vec{g}_0}$$

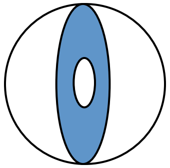
$$2\Omega\frac{\partial}{\partial z}\left(\cancel{\bar{\rho}}u\right)=g\frac{1}{r}\frac{\partial\rho'}{\partial\theta}=\alpha_s\cancel{\bar{\rho}}g\frac{1}{r}\frac{\partial s'}{\partial\theta}+\cancel{\beta\bar{\rho}g\frac{1}{r}\frac{\partial p'}{\partial\theta}}$$

$$\alpha_s=\frac{1}{\rho}\left(\frac{\partial\rho}{\partial s}\right)_p \qquad \beta=\frac{1}{\rho}\left(\frac{\partial\rho}{\partial p}\right)_s$$

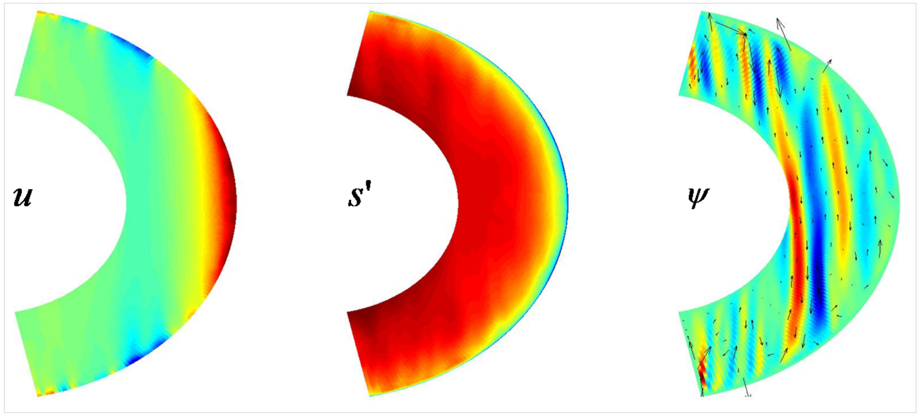
expansivity compressibility

Kaspi et al. 2009

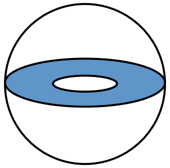
Meridional section



- Zonal velocity
- Entropy
- 2D streamfunction

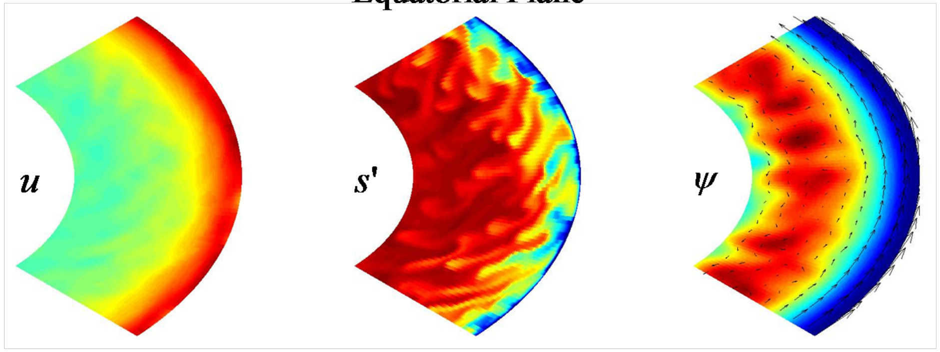


Equatorial section

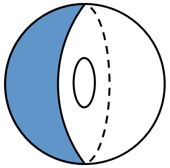


- Zonal velocity
- Entropy
- 2D streamfunction

Equatorial Plane

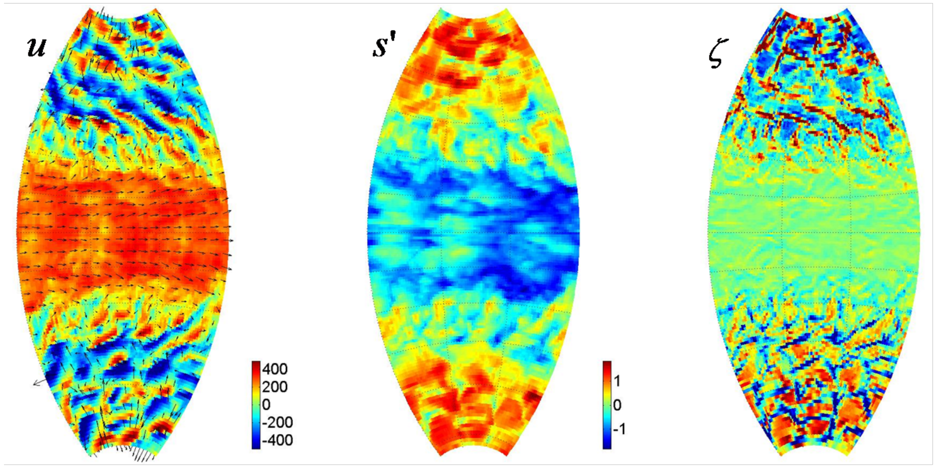


1 Bar Surface:

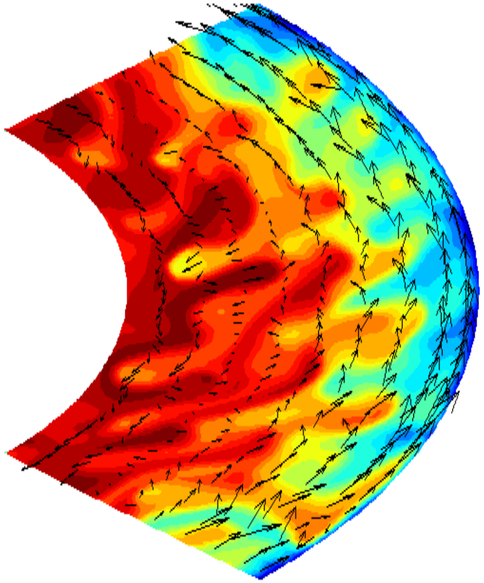


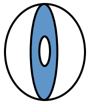
- Zonal velocity
- Entropy
- Vertical vorticity

Surface

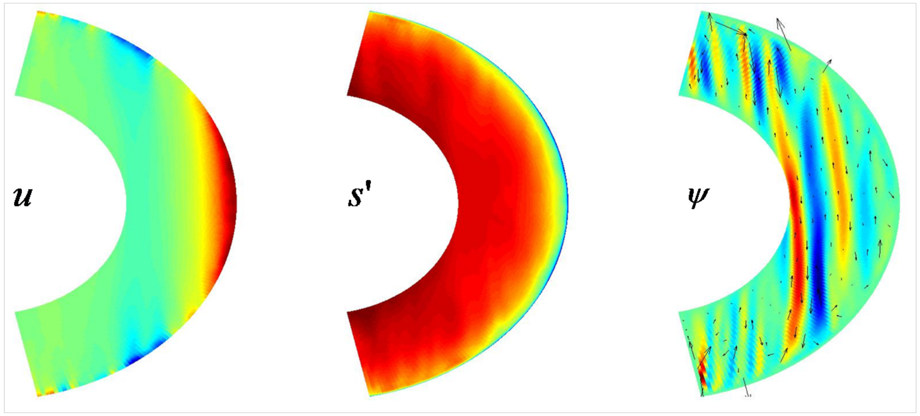


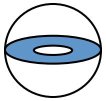
Entropy anomaly on the equatorial plane





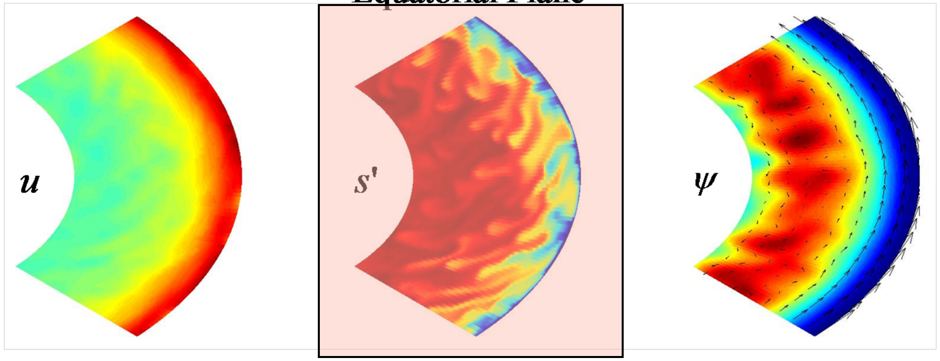
- Zonal velocity
- Entropy
- 2D streamfunction

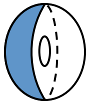




- Zonal velocity
- Entropy
- 2D streamfunction

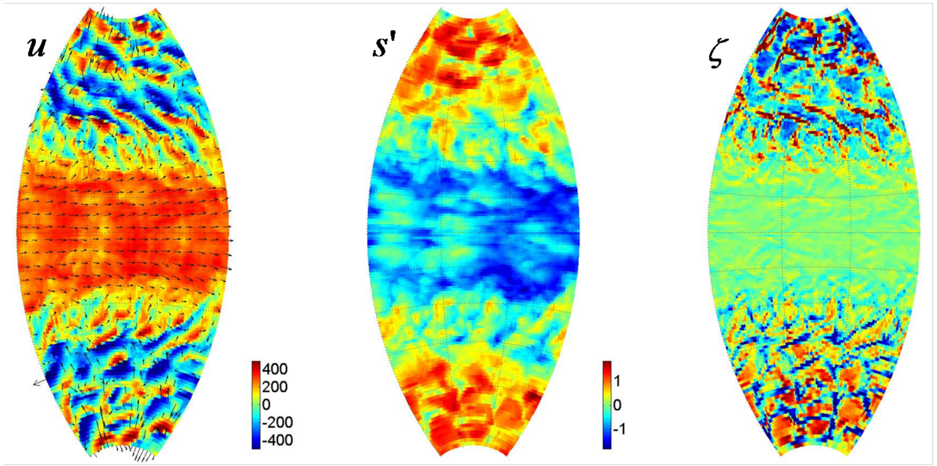
Equatorial Plane



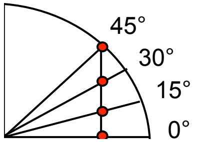


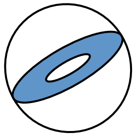
- Zonal velocity
- Entropy
- Vertical vorticity

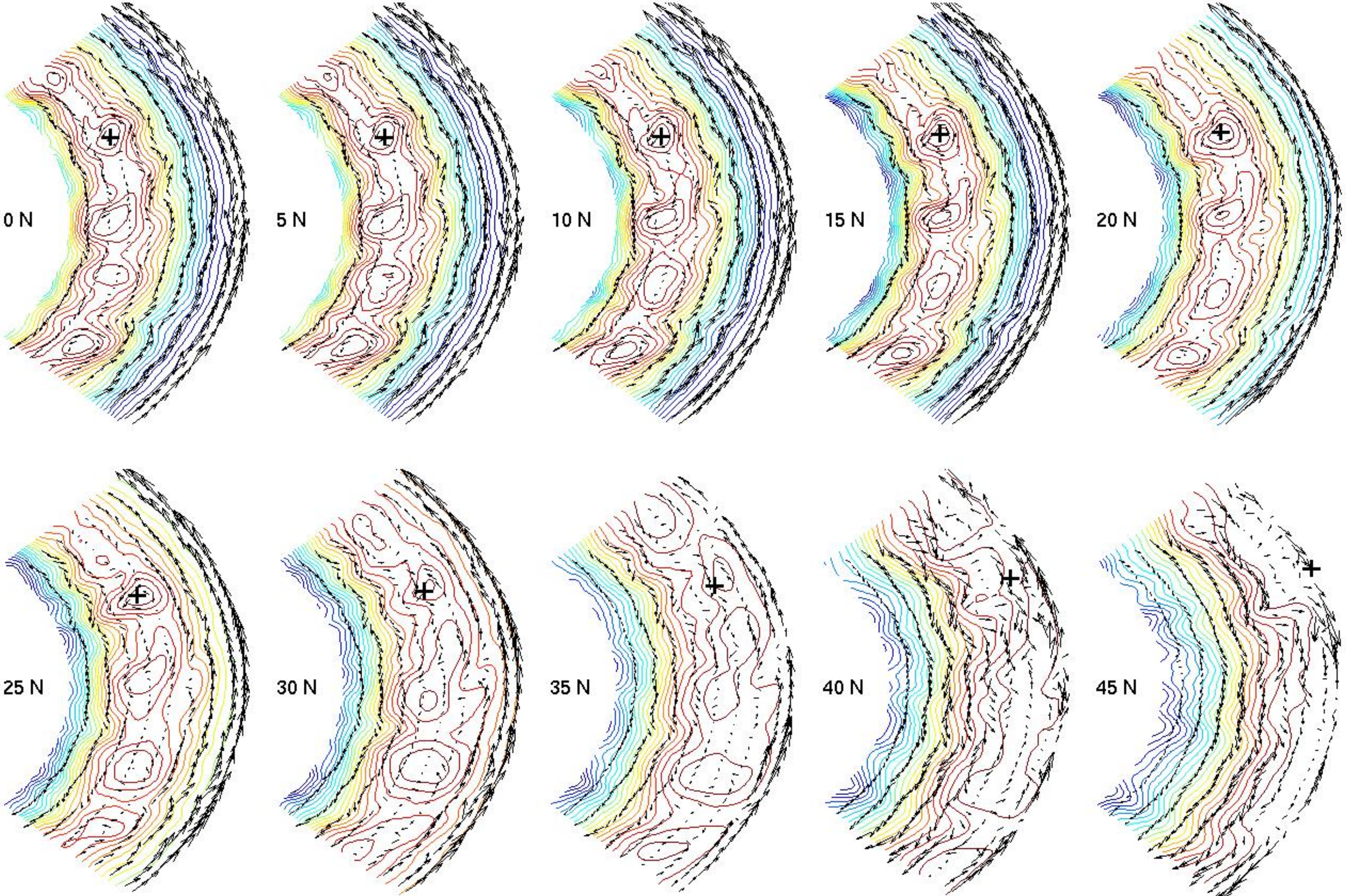
Surface



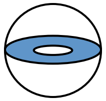
streamfunction on surfaces of constant latitudinal angle

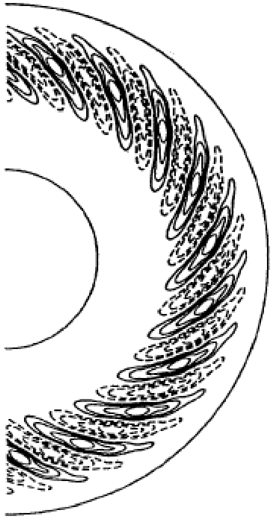






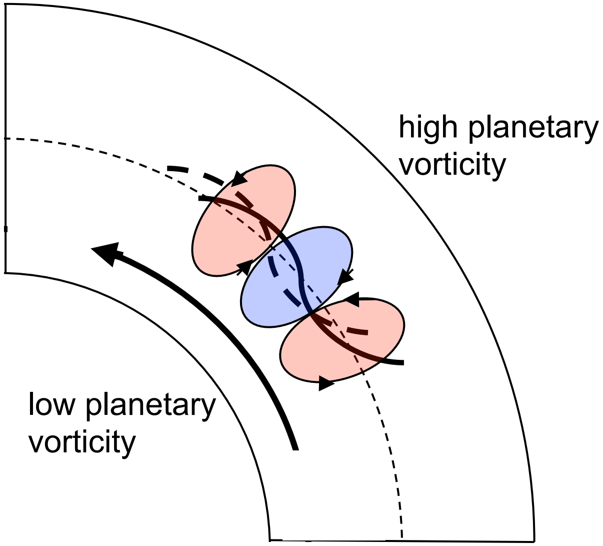
Mechanism for equatorial superrotation





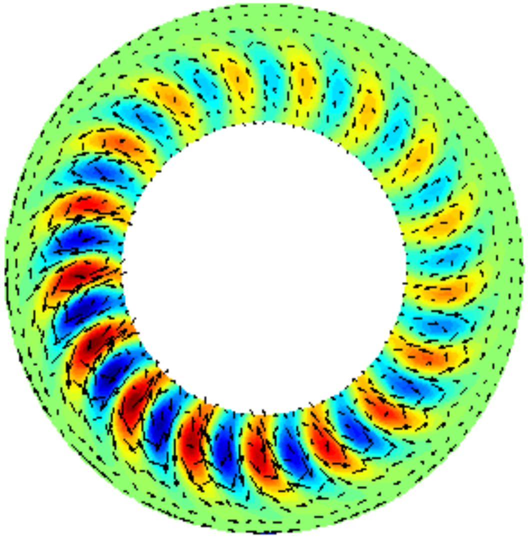
Analytic solutions to linear convection in a rotating sphere. (Zhang and Schubert, 1997)

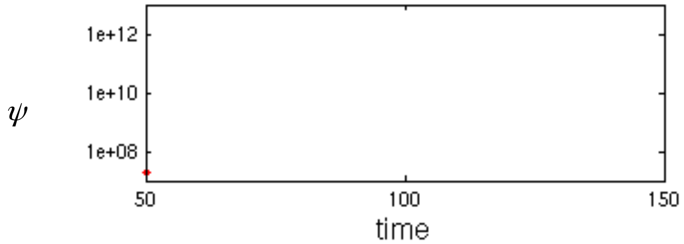
Potential vorticity $q = \dfrac{2\Omega\cos\theta + \zeta}{H}$



Rossby wave like mechanism on the equatorial plane (Busse, 1994).

Weakly supercritical GCM simulation





$$u'w' > 0$$

Mean zonal velocity

$$u = \bar{u} + u'$$

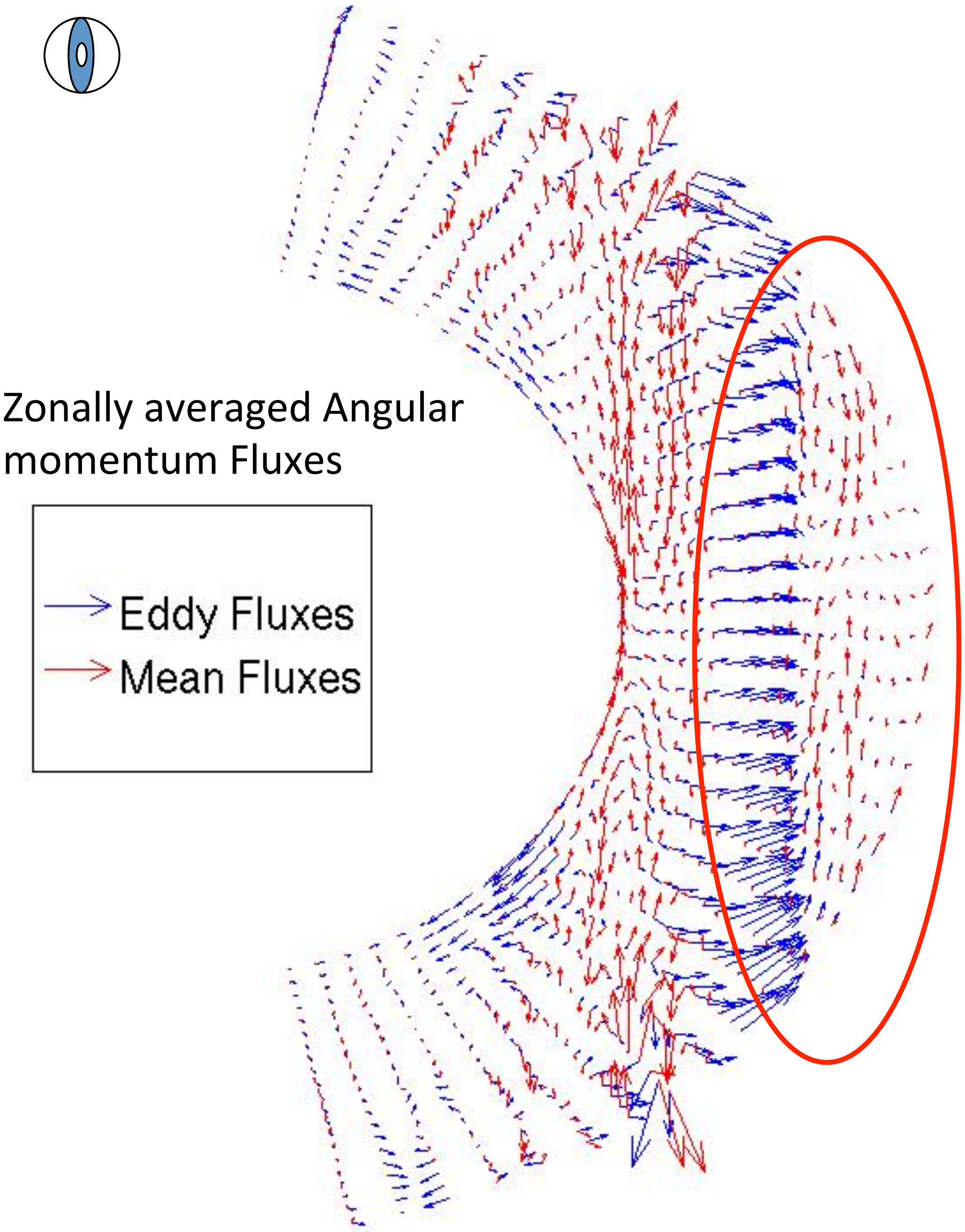
eddy zonal velocity

Angular momentum: $$M = \Omega r^2 \cos^2\theta + ur\cos\theta$$

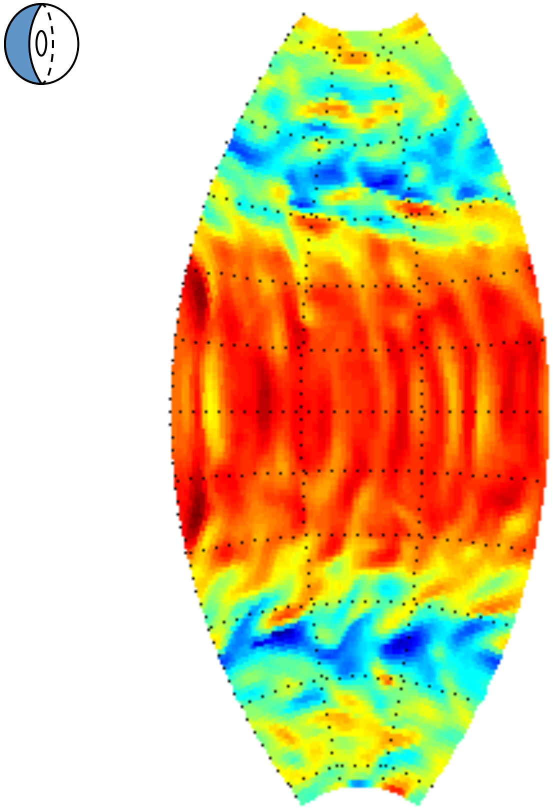
Angular momentum conservation: $$\frac{\partial \bar{M}}{\partial t} + \frac{1}{\bar{\rho}}\nabla\cdot\left(\bar{\rho}\bar{u}\bar{M}\right) + \frac{1}{\bar{\rho}}\nabla\cdot\left(\overline{\bar{\rho}\vec{u}'M'}\right) = \nu\nabla^2\bar{M}$$

Equatorial superrotation

Zonally averaged Angular momentum Fluxes



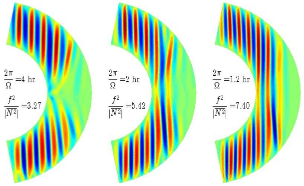
Surface zonal velocity



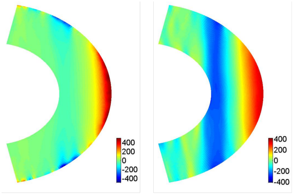
time: 35.0 days

Summary

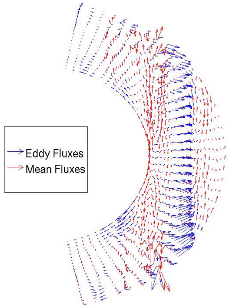
- In a rapidly rotating system convection aligns with the direction of the axis of rotation.



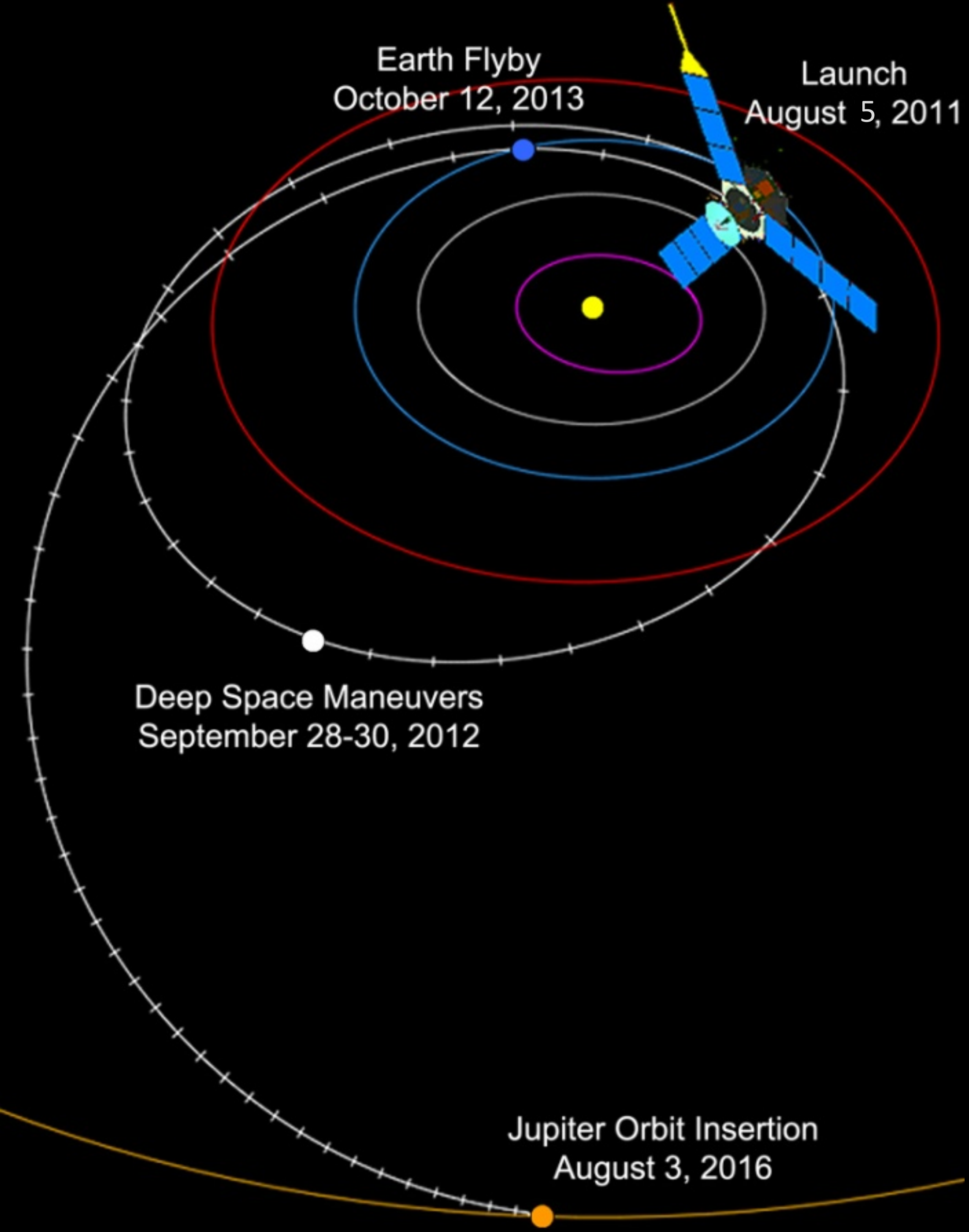
- The effect of compressibility is shear in the direction of the axis of rotation.

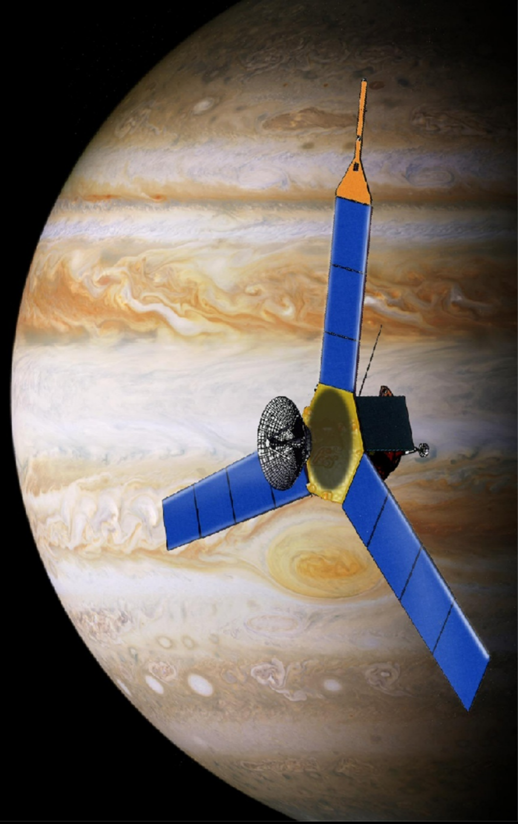


- Equatorial superrotation due to an angular momentum flux divergence driven by interior turbulence.



Juno





- Launch: August 2011
- Arrive at Jupiter: August 2016
- 33 polar orbits
- Average orbit time: 11 days
- Perijove distance: 4000 km
- Apojove distance: 39 Jupiter radii
- Orbital longitudinal separation: 192°

Analysis of Jupiter's Gravity Spectrum

$$J_n = \frac{1}{a^n M}\int r^n P_n(\theta)\,\rho(r,\theta,\varphi)\,d^3r$$

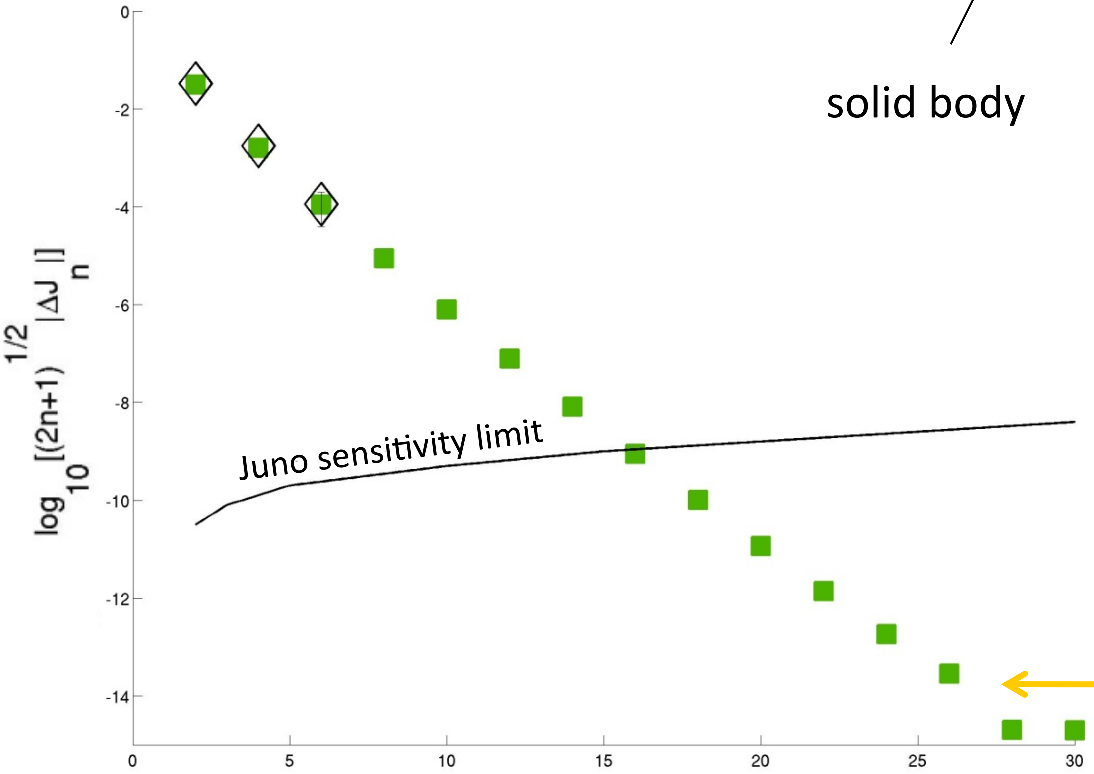
$$\uparrow$$

$$\rho = \overline{\rho} + \rho'$$

a = planet radius
M = total mass
P_n = Legendre polynomial

solid body

dynamics



solid body

Hubbard 1999

Analysis of Jupiter's Gravity Spectrum

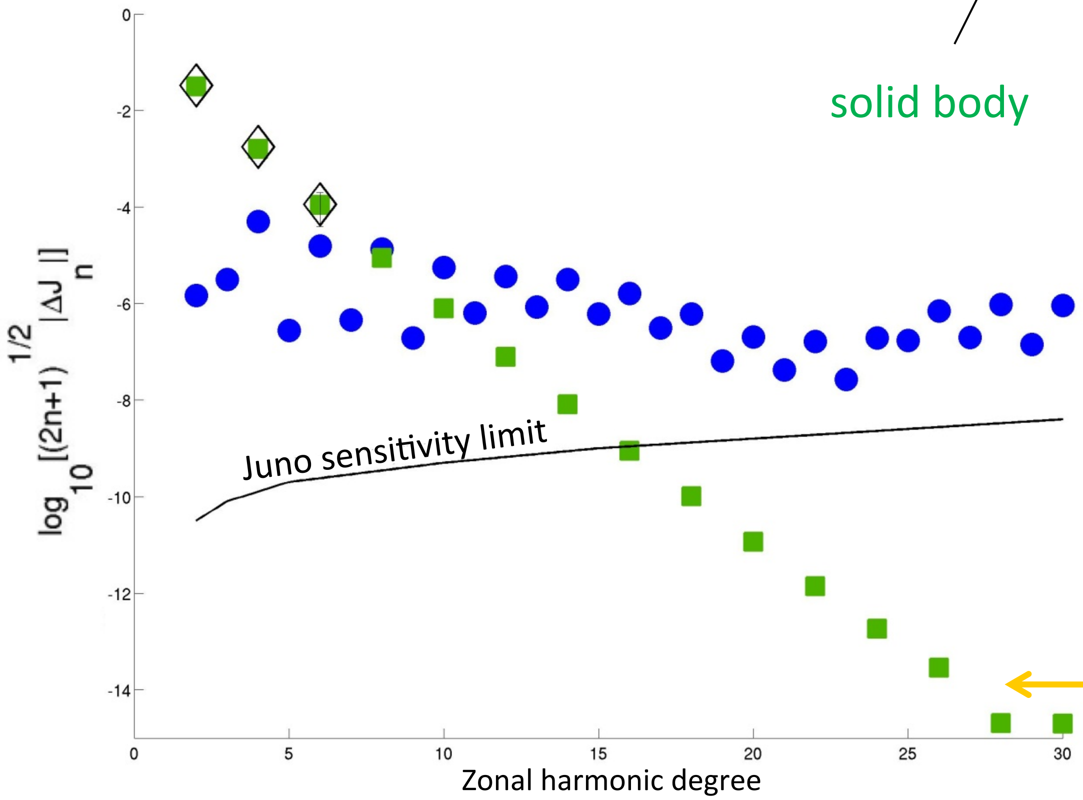
$$J_n = \frac{1}{a^n M}\int r^n P_n(\theta)\underset{\uparrow}{\rho}(r,\theta,\varphi)d^3r$$

a = planet radius
M = total mass
P_n = Legendre polynomial

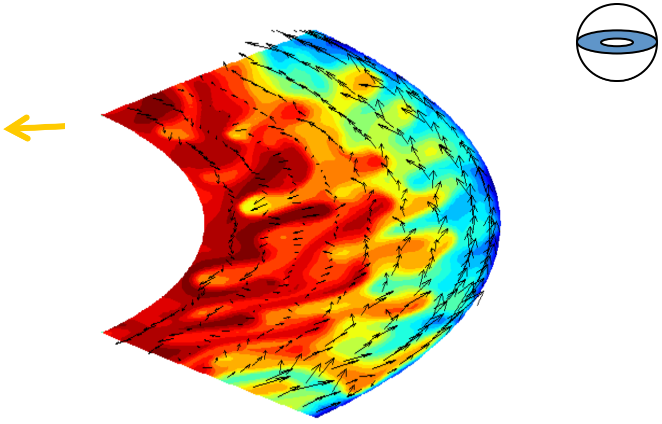
$$\rho = \overline{\rho} + \rho'$$

solid body

dynamics



Entropy anomaly on the equatorial plane



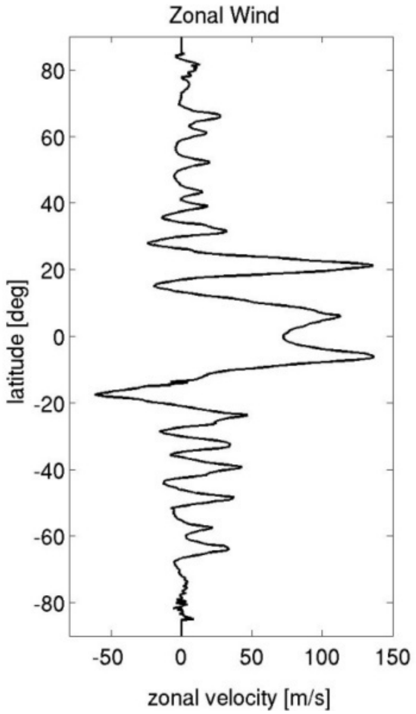
Solid Body

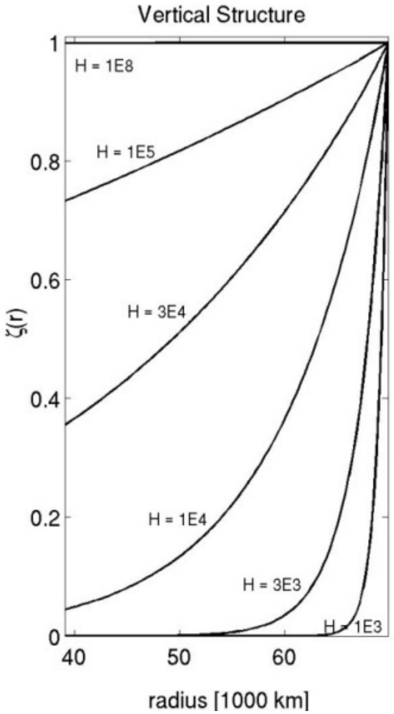
Kaspi et al. 2010

A second approach:

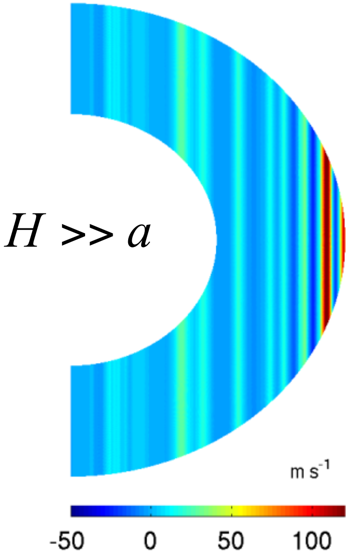
Thermal-wind balance model:
Uses the observed winds on Jupiter and assumes an idealized interior vertical structure with a decay length *H.*

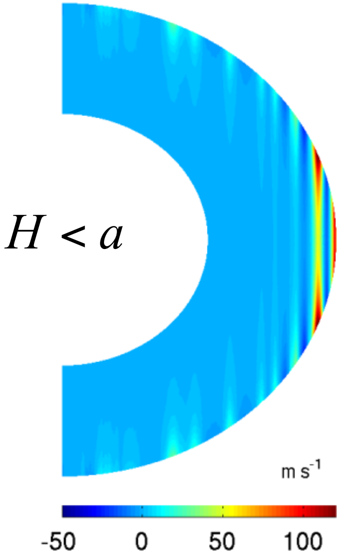
$$u = u_{cyl} e^{-\left(\frac{a-r}{H}\right)}$$





$u(r,\theta)$


$H >> a$

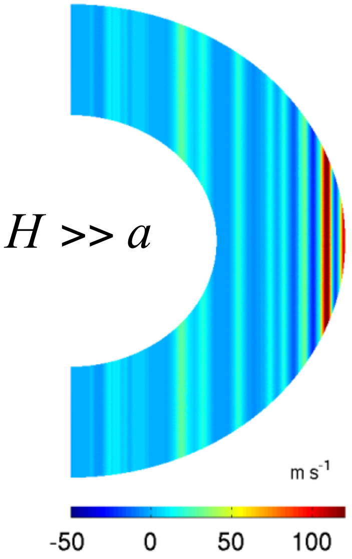

$H < a$

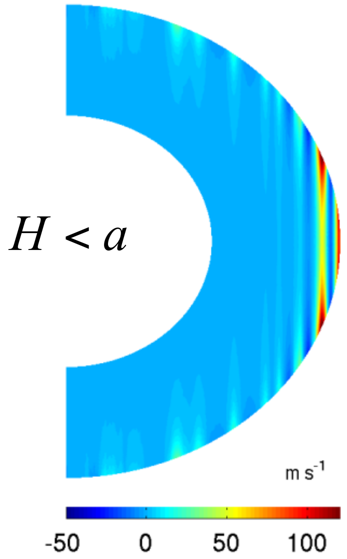
A second approach:

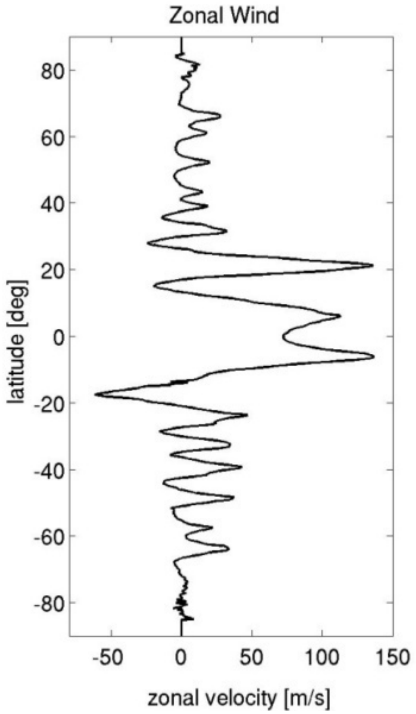
Thermal wind balance model:
Uses the observed winds on Jupiter and assumes an idealized interior vertical structure with a decay length *H.*

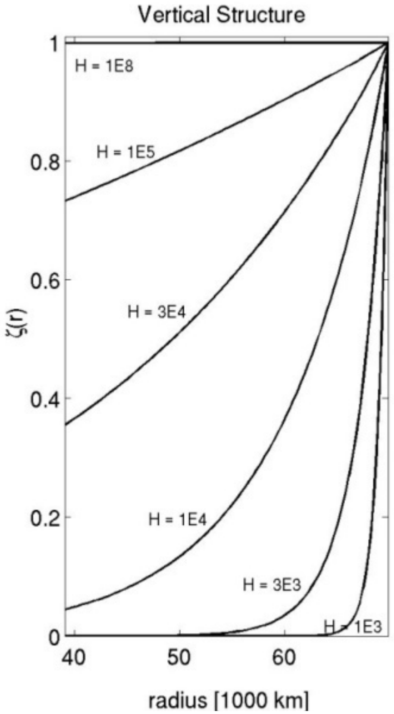
$$\boxed{2\Omega\cdot\nabla\left(\bar{\rho}\vec{u}\right)=\nabla\rho'\times\vec{g}_0}$$

$u(r,\theta)$

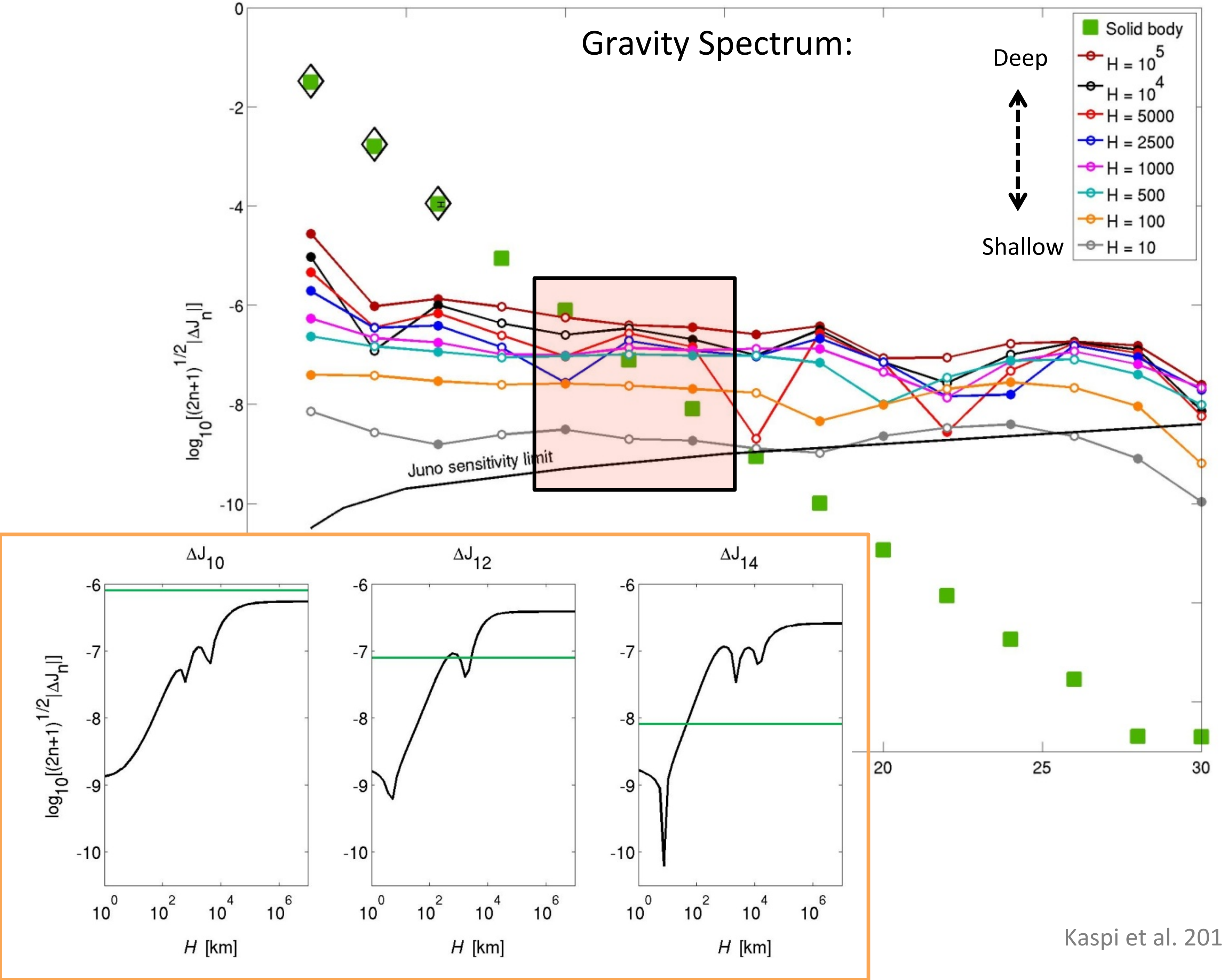






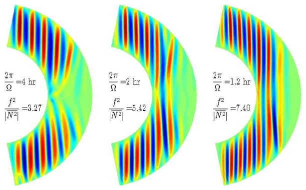


Gravity Spectrum:

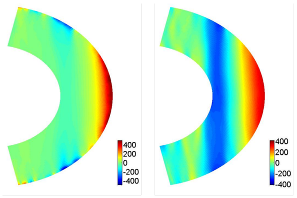


Kaspi et al. 2010

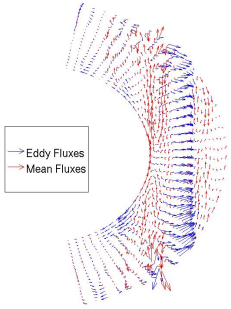
Summary



- In a rapidly rotating system convection aligns with the direction of the axis of rotation.



- The effect of compressibility is shear in the direction of the axis of rotation.
- Equatorial superrotation due to an angular momentum flux divergence driven by interior turbulence.



Juno

- On Jupiter zonal harmonics beyond degree 10 are affected stronger by the winds than the solid body component.
- If the winds are even a few hundred kms deep, we expect them to be measurable by Juno.