Atmospheric Circulation of Giant Planets Inside and Outside the Solar System

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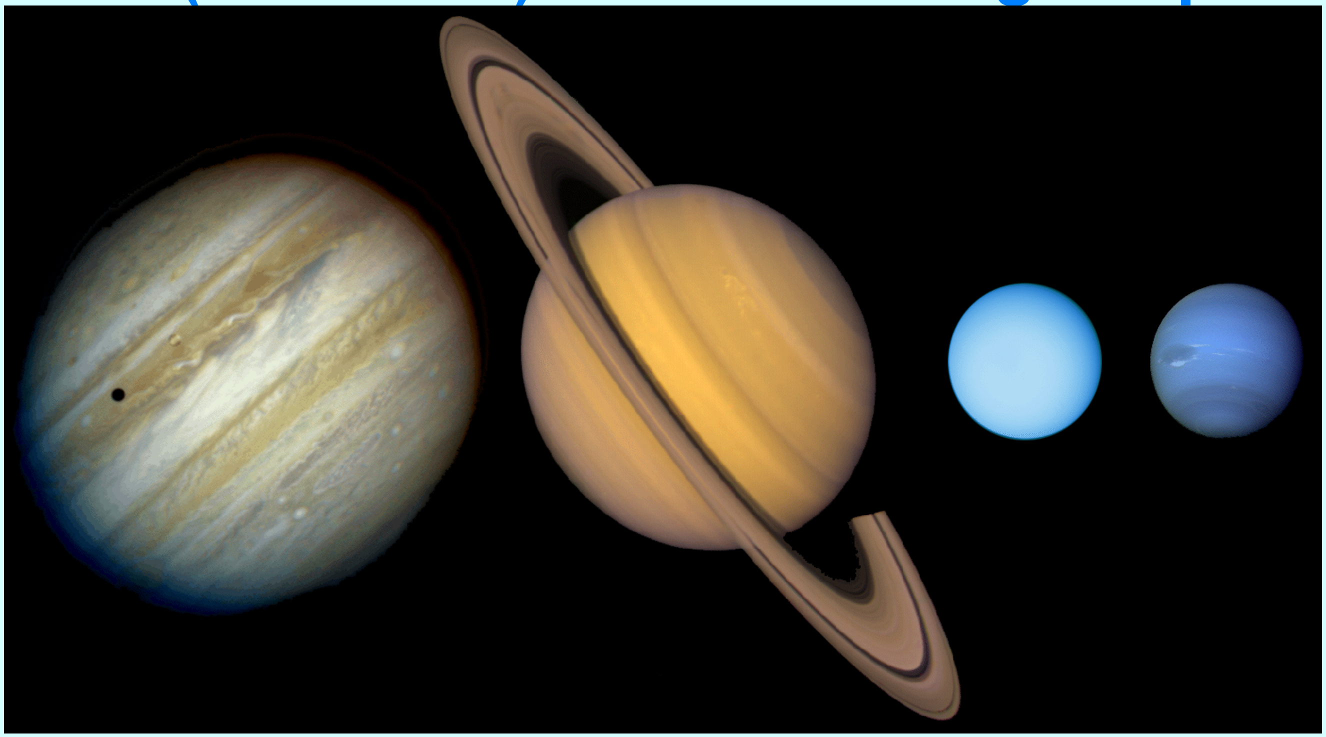
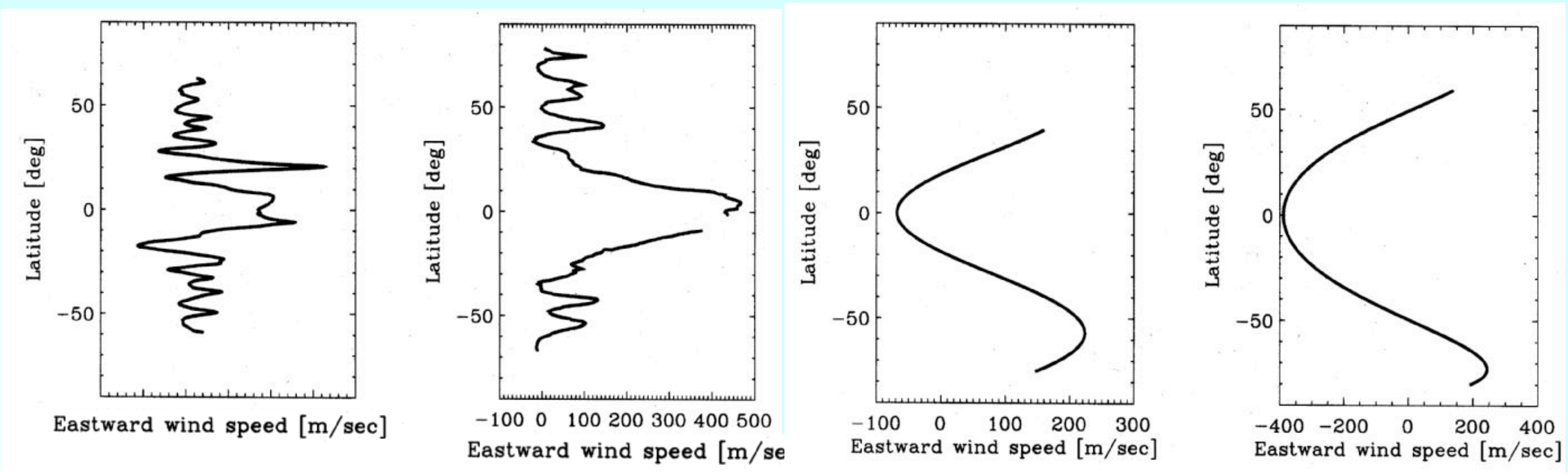
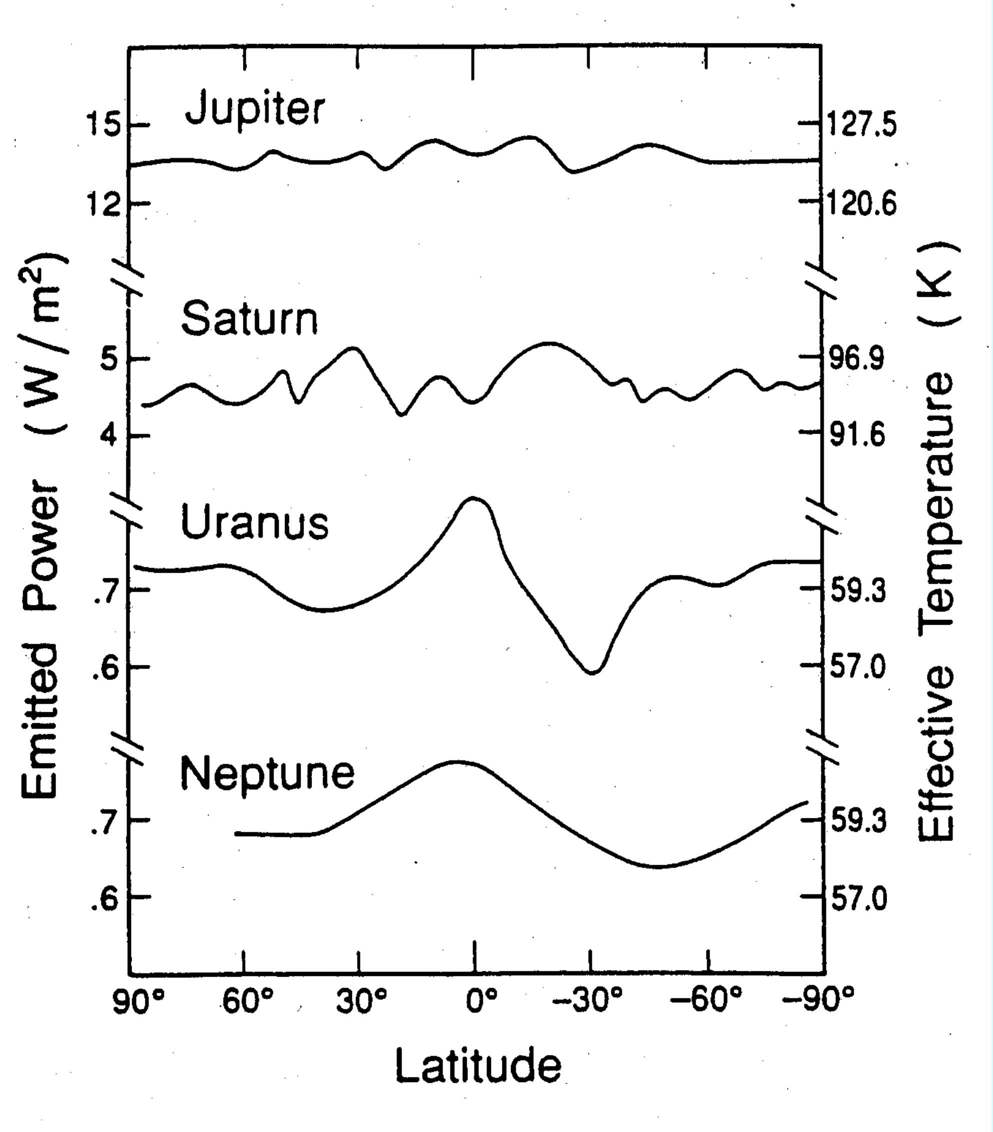
Zonal (east-west) winds on the giant planets



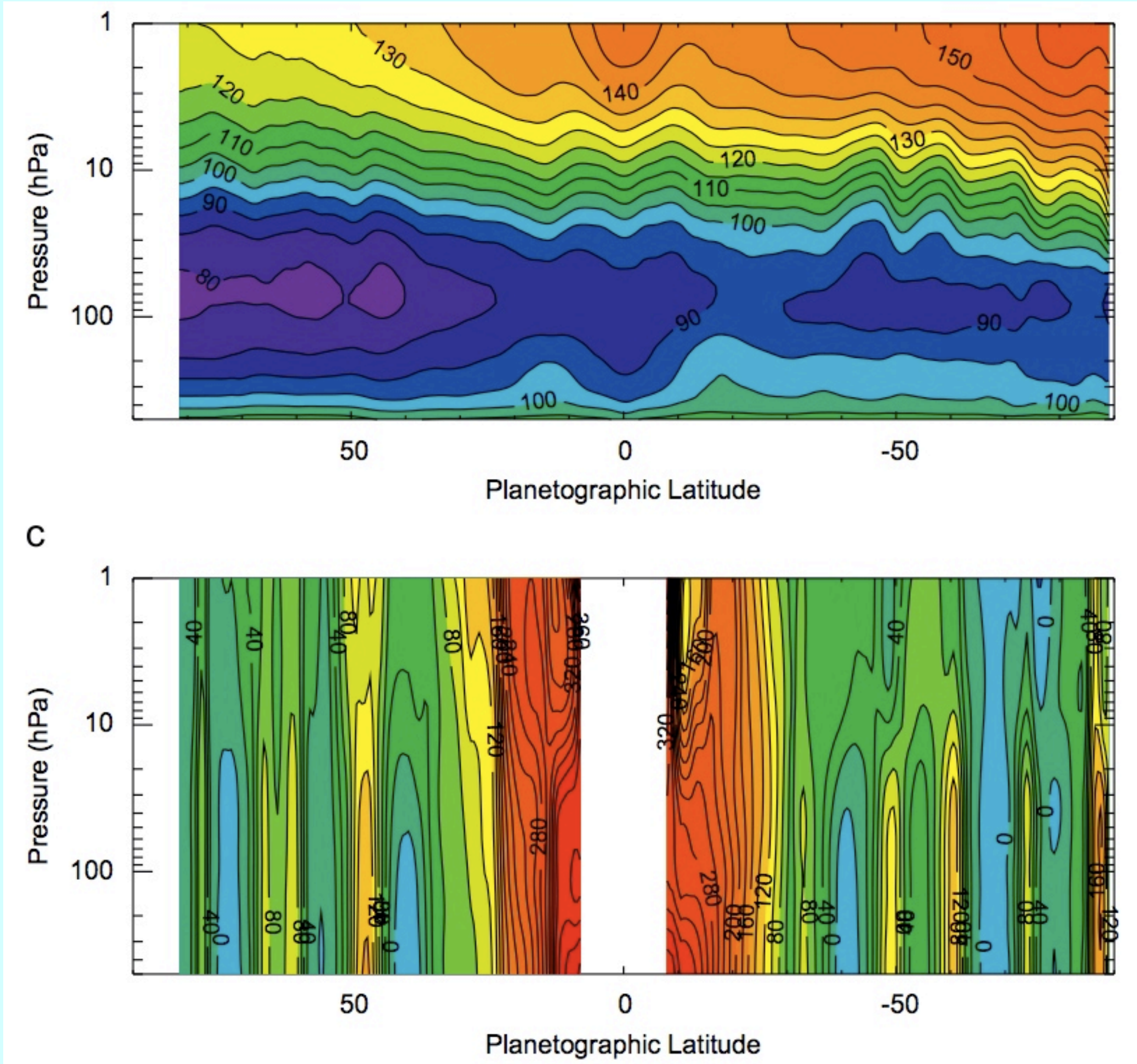


Temperatures are relatively homogeneous:



Ingersoll (1990)

Jet structure in stratospheres known from thermal wind



Saturn

Read et al. (2009)

Puzzles

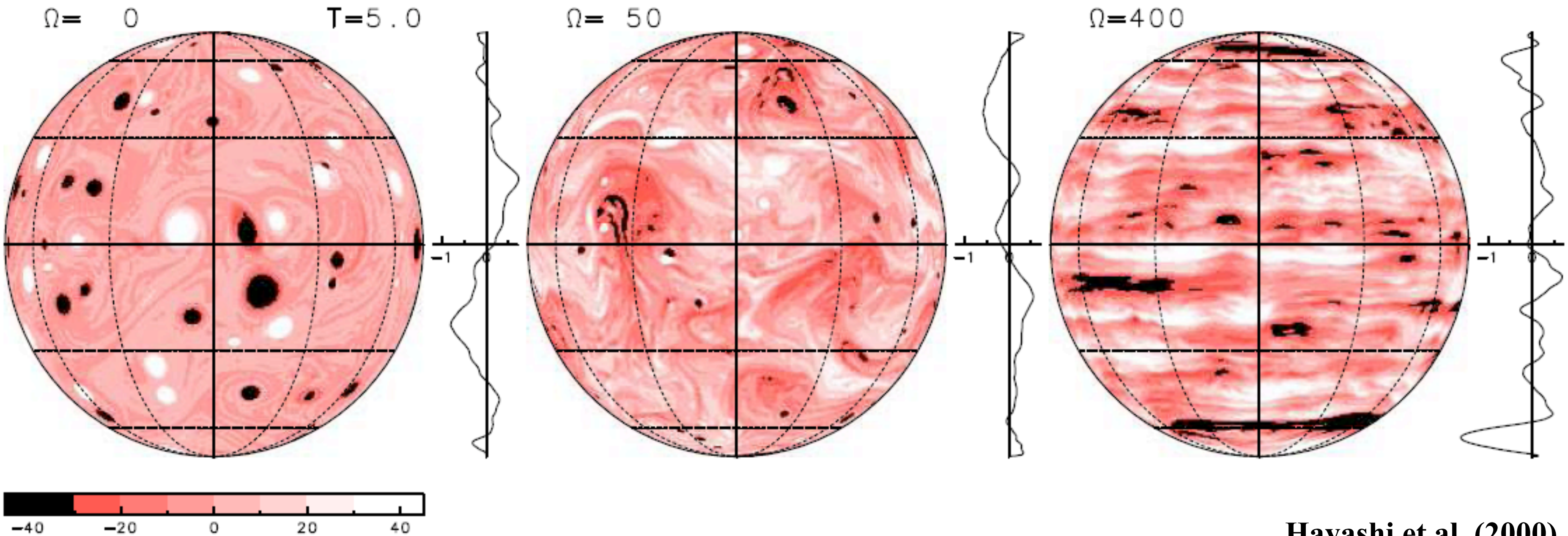
- **What causes the banded structure, with ~20 jets on Jupiter and Saturn yet only ~3 on Uranus and Neptune? What is the jet-pumping mechanism? How deep do the jets extend?**

- **Why do Jupiter and Saturn have superrotating equatorial jets whereas Uranus and Neptune do not?**

- **What causes the vortices? What controls their behavior? How do they interact with the jets?**

- **What is the temperature structure and mean circulation of the stratosphere and upper troposphere?**

Rotation causes east-west (zonal) banding in planetary atmospheres



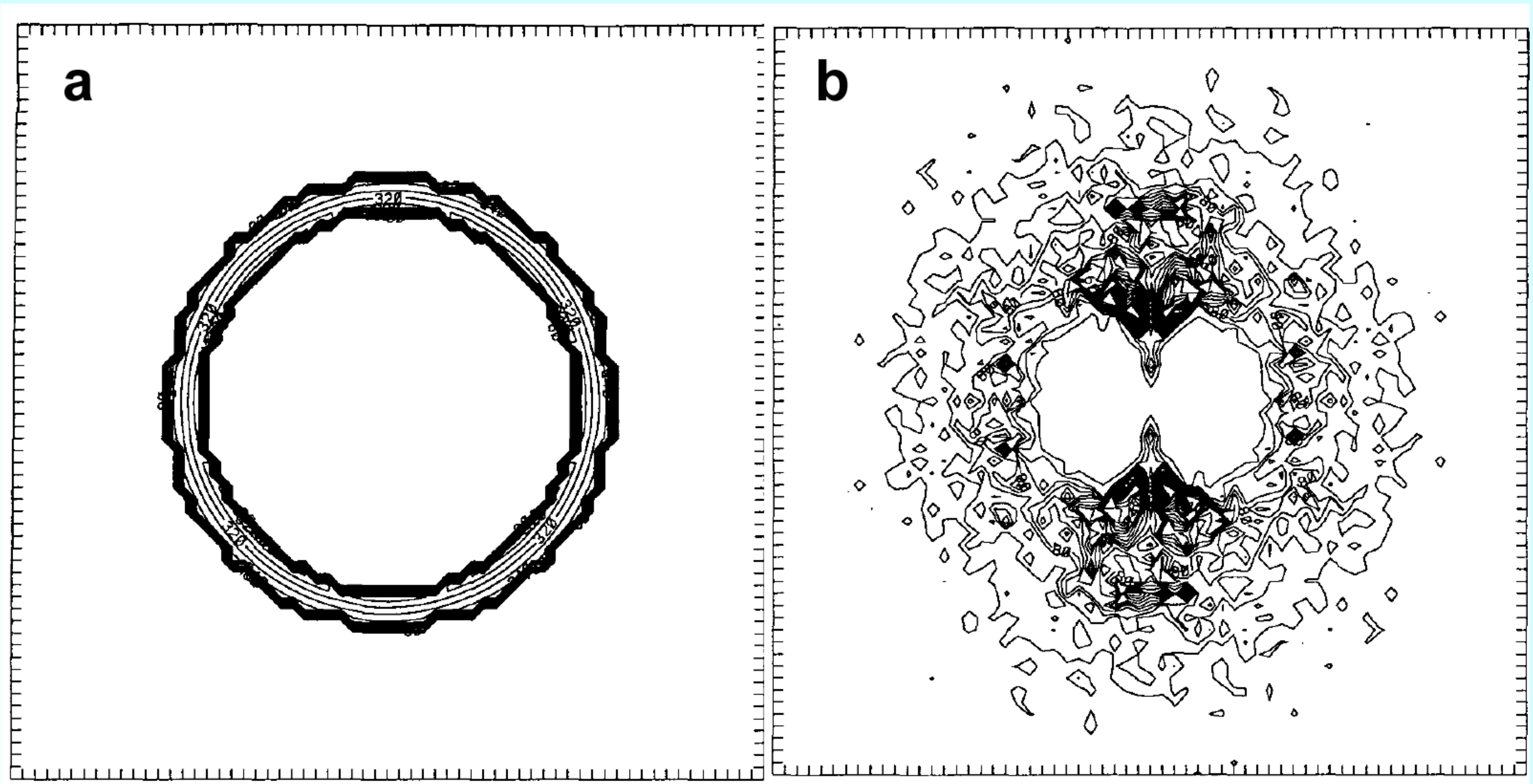
Hayashi et al. (2000)

Even Venus (rotation period 243 Earth days) is banded, suggesting that transition to a banded flow can happen at *very low* rotation rates

Most planetary atmospheres should exhibit a banded flow pattern!

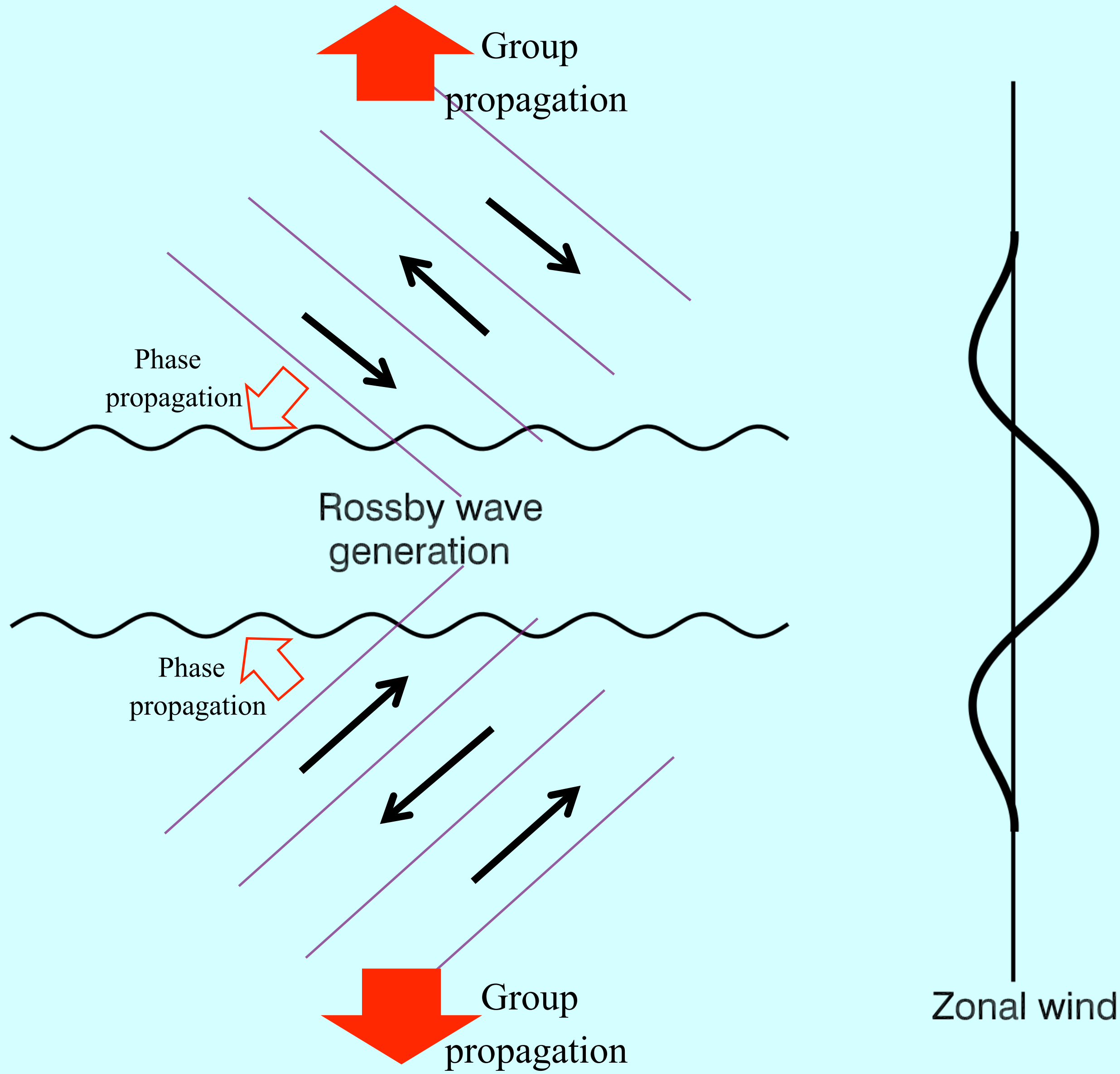
The importance of Rossby waves: anisotropy promotes banding

$$\frac{d(\zeta + f)}{dt} = 0 \quad \Rightarrow \quad \frac{\partial \zeta}{\partial t} + \underbrace{\vec{v} \cdot \nabla \zeta}_{U^2/L^2} + \underbrace{v\beta}_{U\beta} = 0$$



Vallis and Maltrud (1993)

The importance of Rossby waves: jet formation

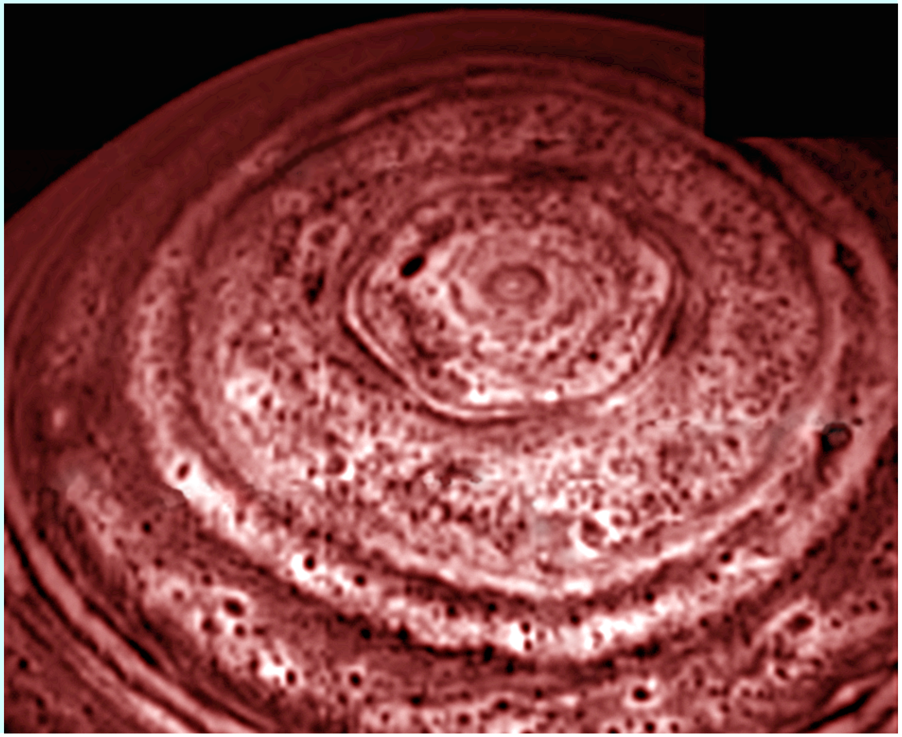


What controls the size and shape of flow structures?

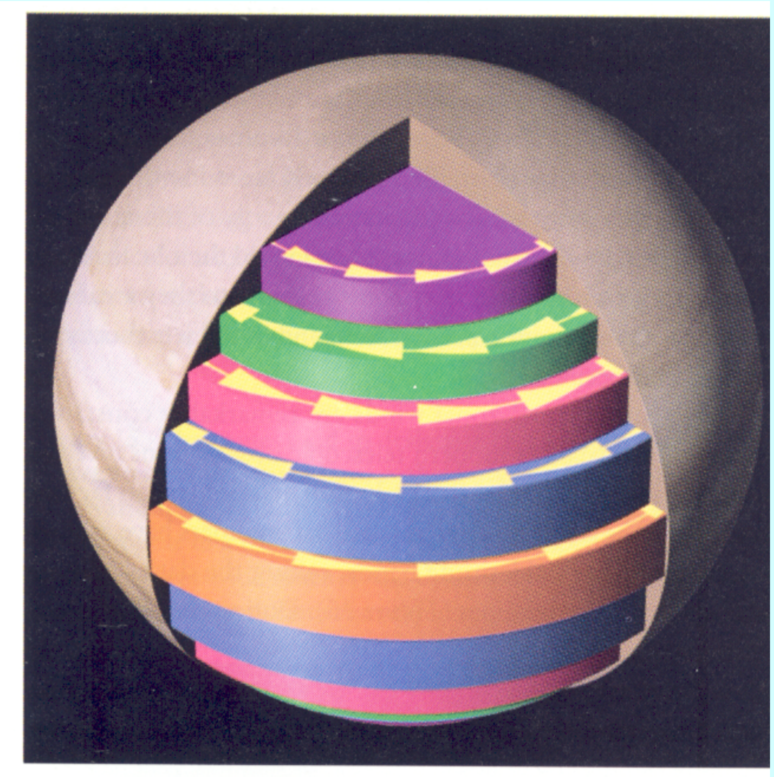
- **Rhines length**, $(U/\beta)^{1/2}$, is the scale at which planetary rotation causes east-west elongation (jets).
- **Deformation radius**, c/Ω, is a natural scale of vortex formation and flow instability

On Jupiter/Saturn, these lengths are << planetary radius

On most hot Jupiters, they are close to planetary radius. Jets and vortices should therefore be global in scale.

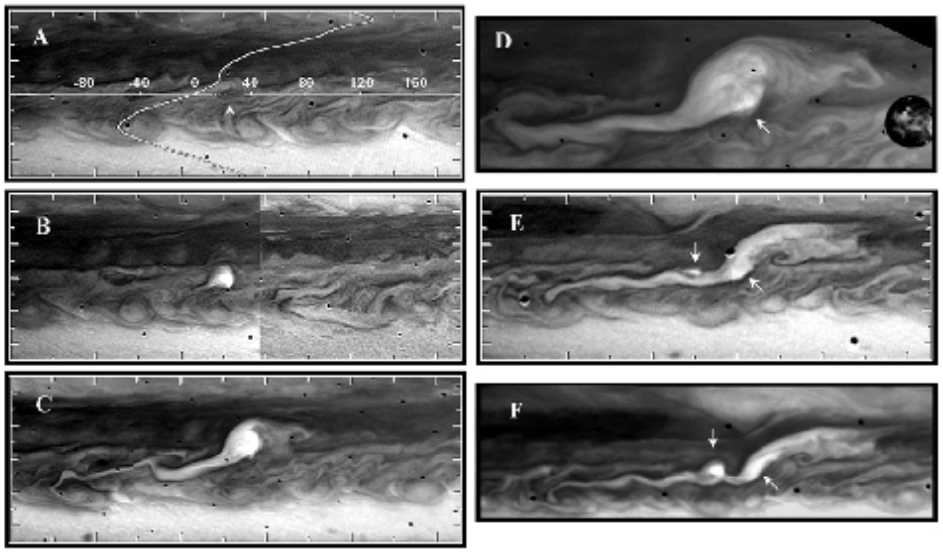


Basic Jet Scenarios



- **Models for jet structure:**
  - ***<u>Shallow:</u>*** **Jets confined to outermost scale heights below the clouds**
  - ***<u>Deep:</u>*** **Jets extend through molecular envelope (Taylor-Proudman theorem)**

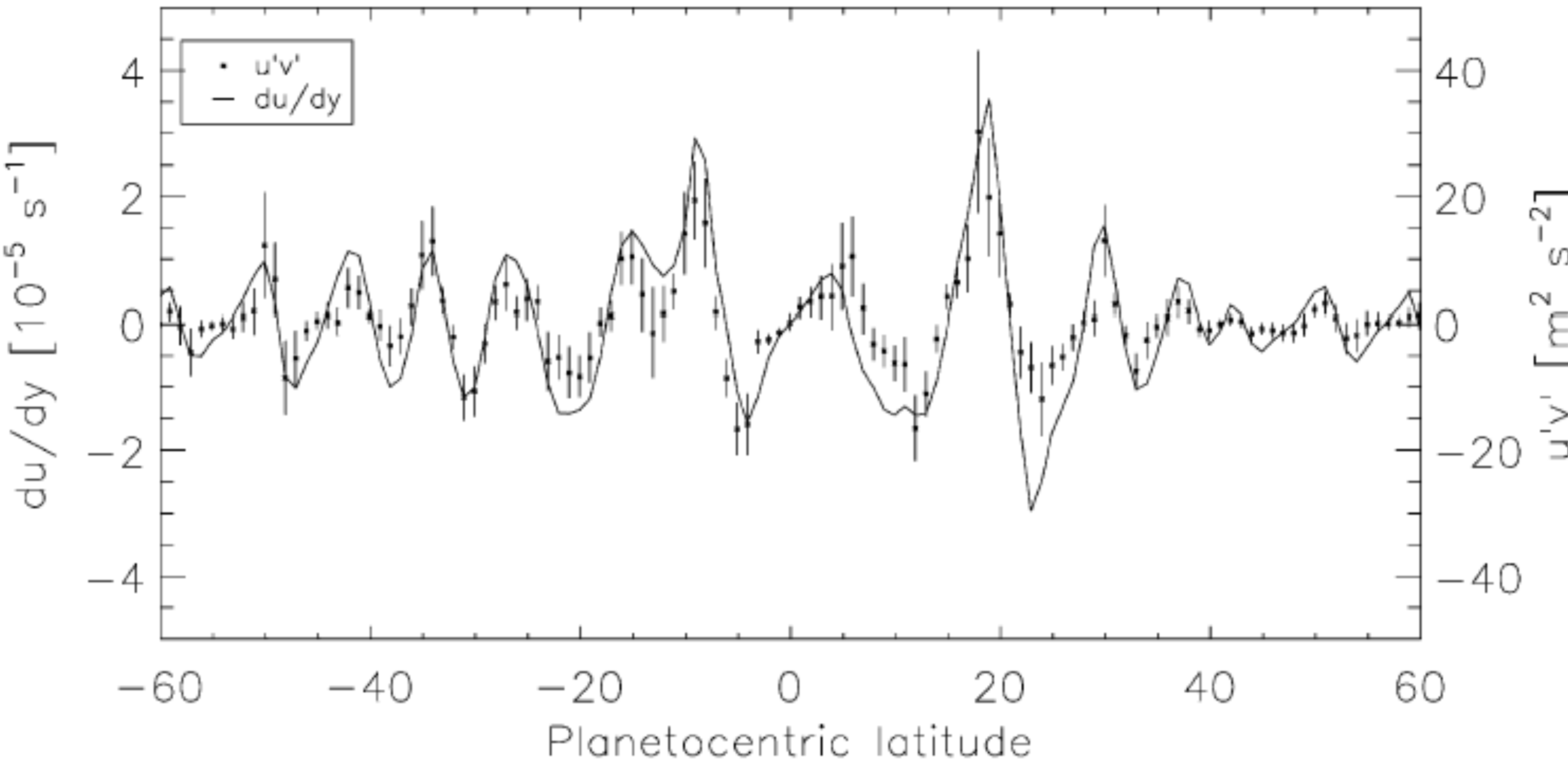
- **Models for jet pumping:**
  - ***<u>Shallow:</u>*** **Turbulence at cloud level (thunderstorms or baroclinic instabilities)**
  - ***<u>Deep:</u>*** **Convective plumes penetrating the molecular envelope**



One must distinguish jet *structure* and *forcing* – they are distinct issues!

Evidence for jet pumping at the cloud level

Small eddies transport momentum upgradient into the jets, thereby accelerating them. This transfers energy directly from the small eddies to the large jets:

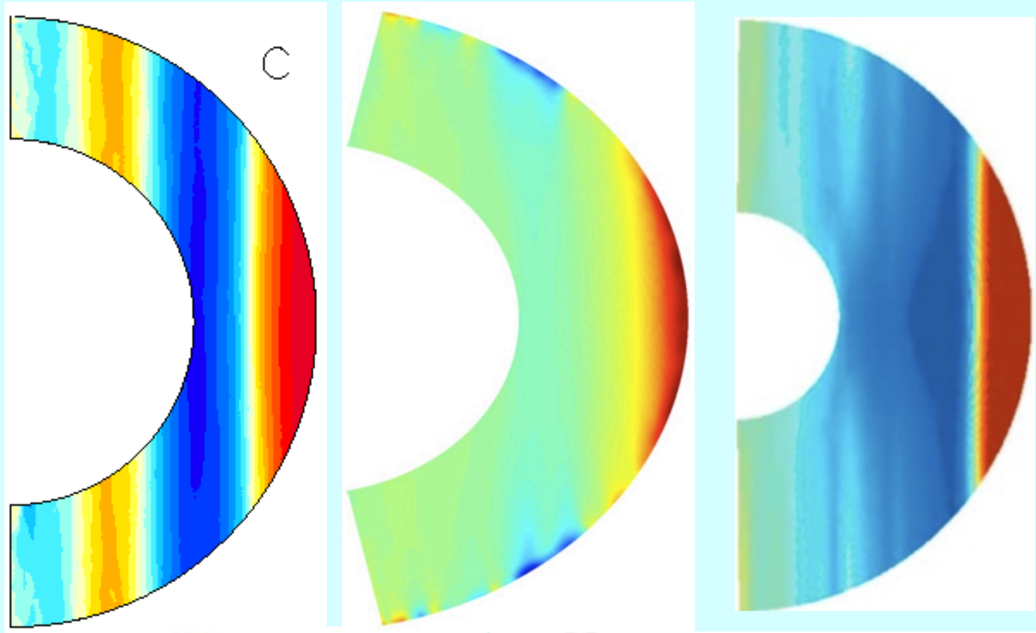


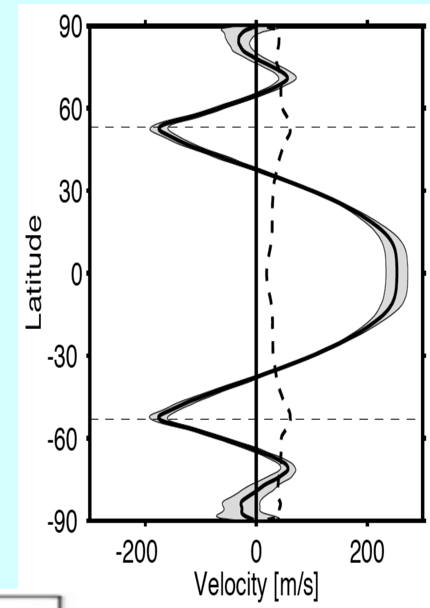
Salyk et al. (2006); Del Genio et al. (2007)

Deep convection models

Thick shell

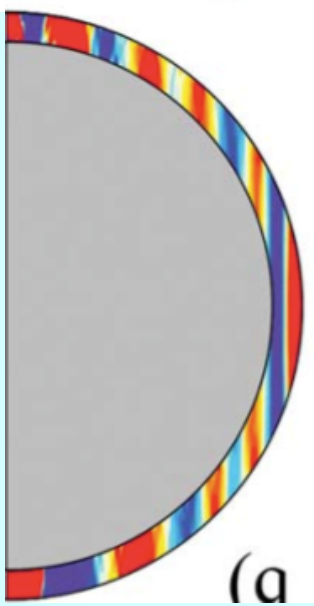
(Christensen 2002;
Aurnou & Olson '01;
Kaspi et al. 2009,
Heimpel &
Gomez-Perez '11)

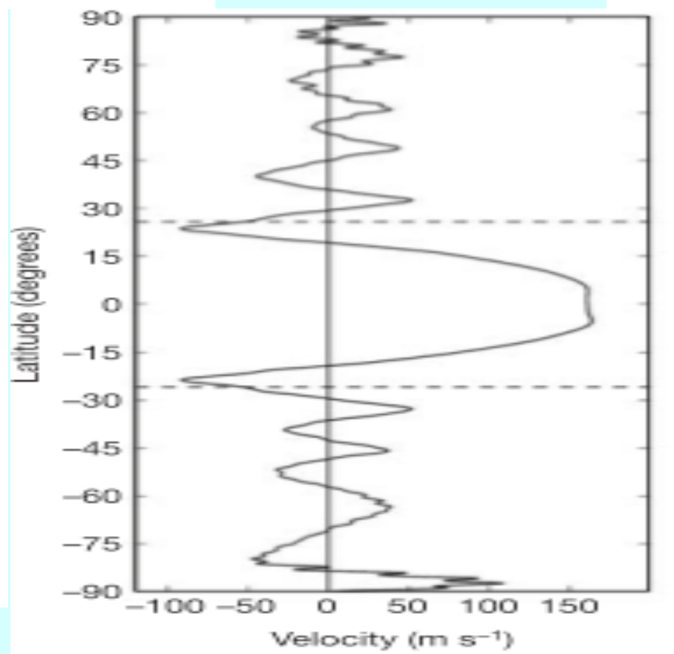




Thin shell

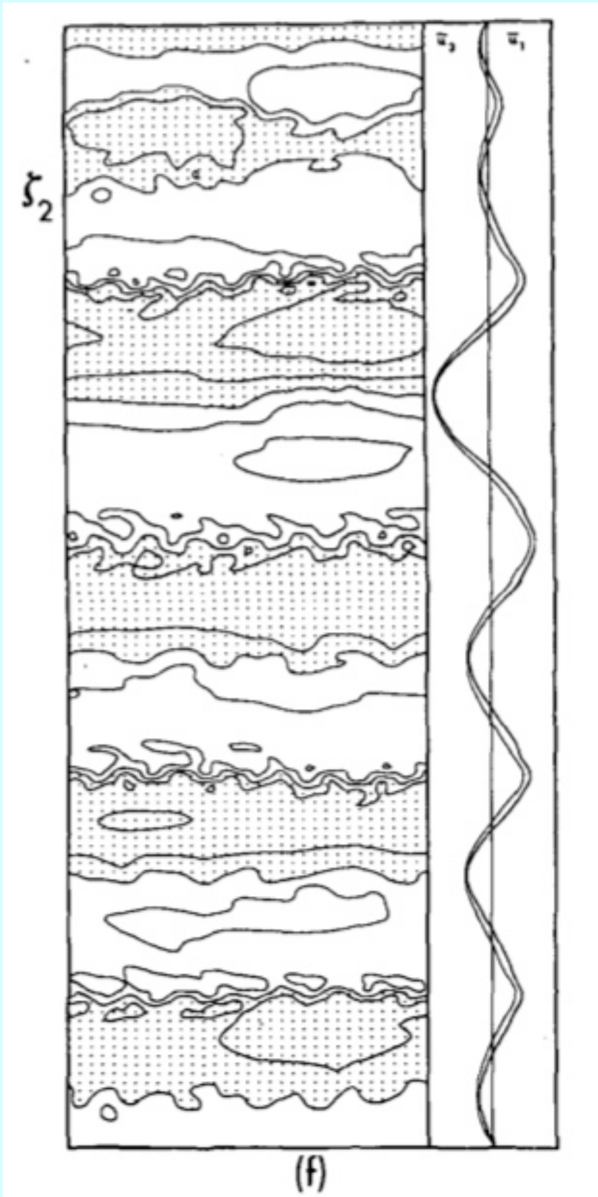
(Heimpel et al. 2005;
Heimpel & Aurnou 2007;
Aurnou et al. 2008)

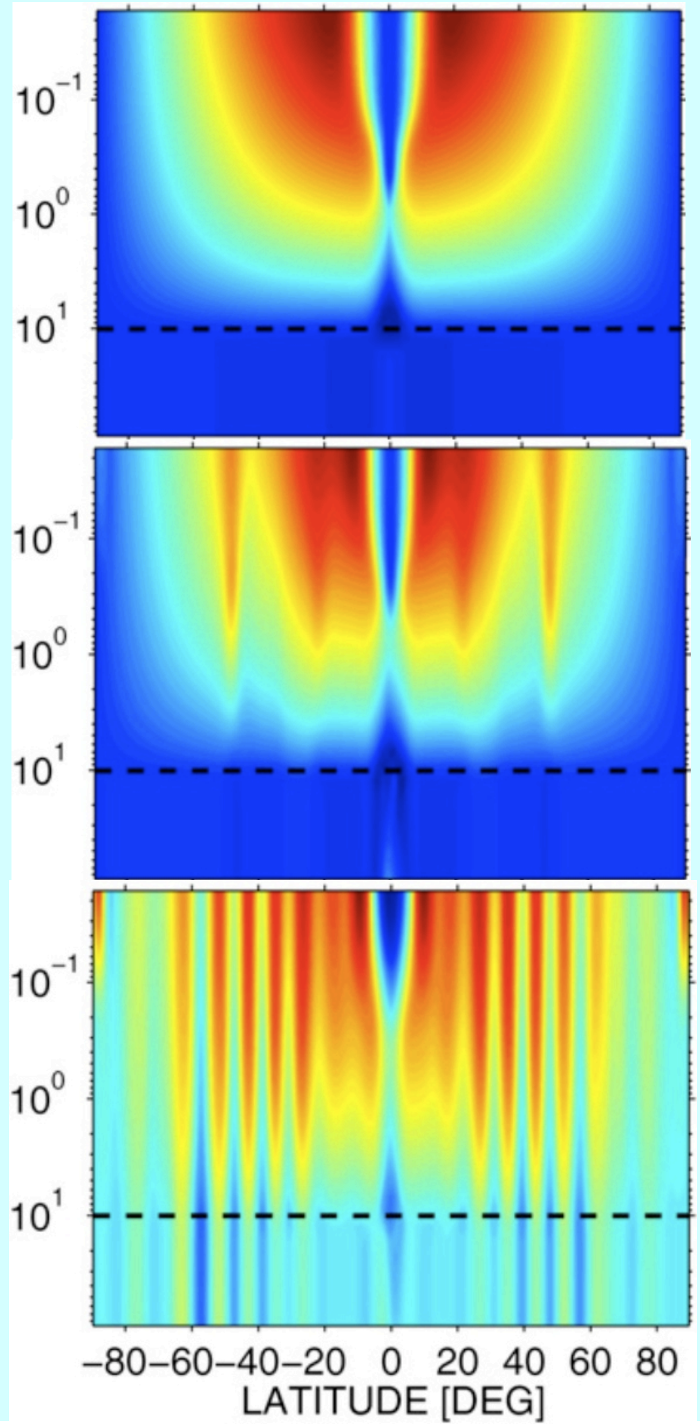




Atmosphere models

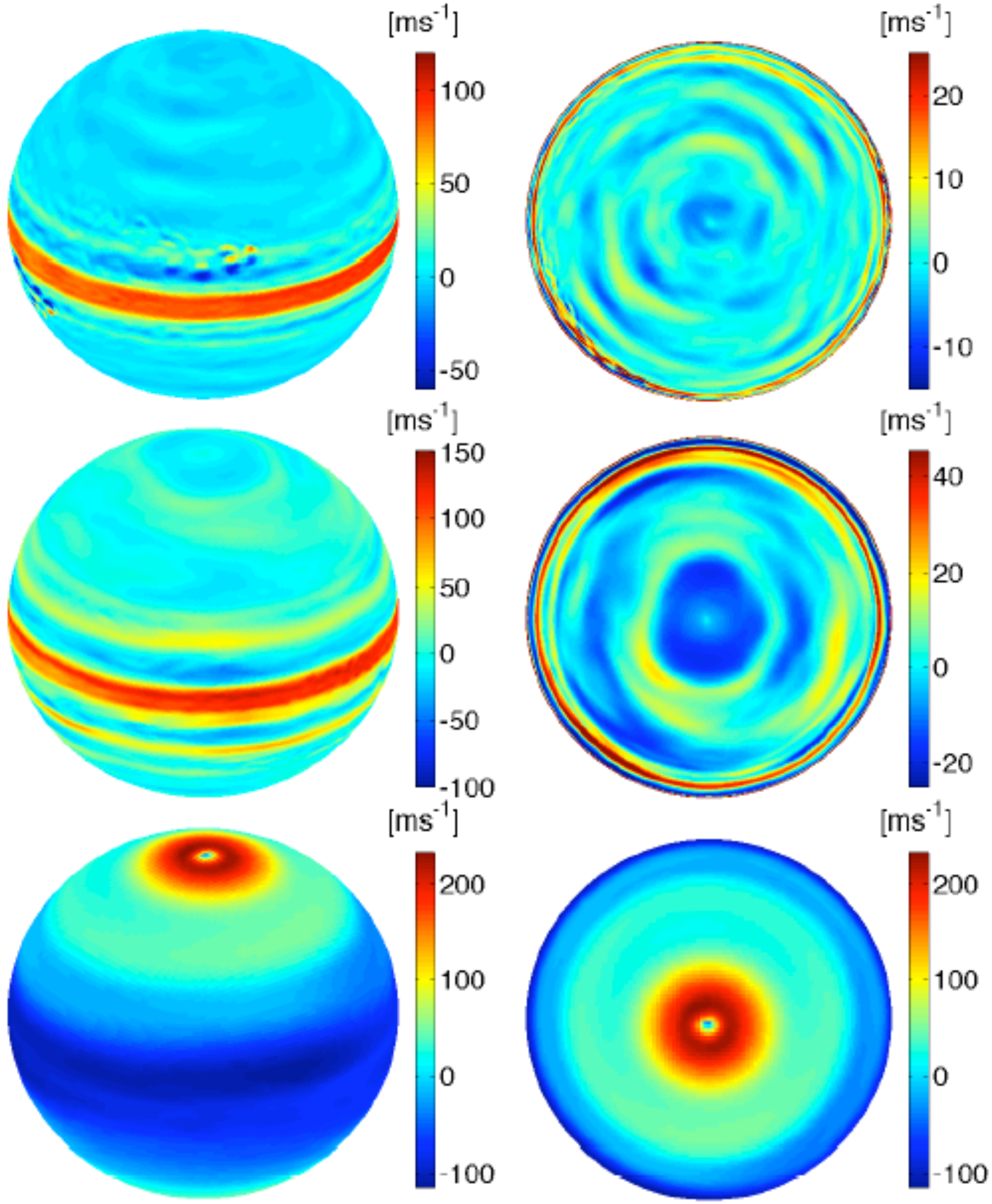
Williams (1979)





Lian & Showman (2008)

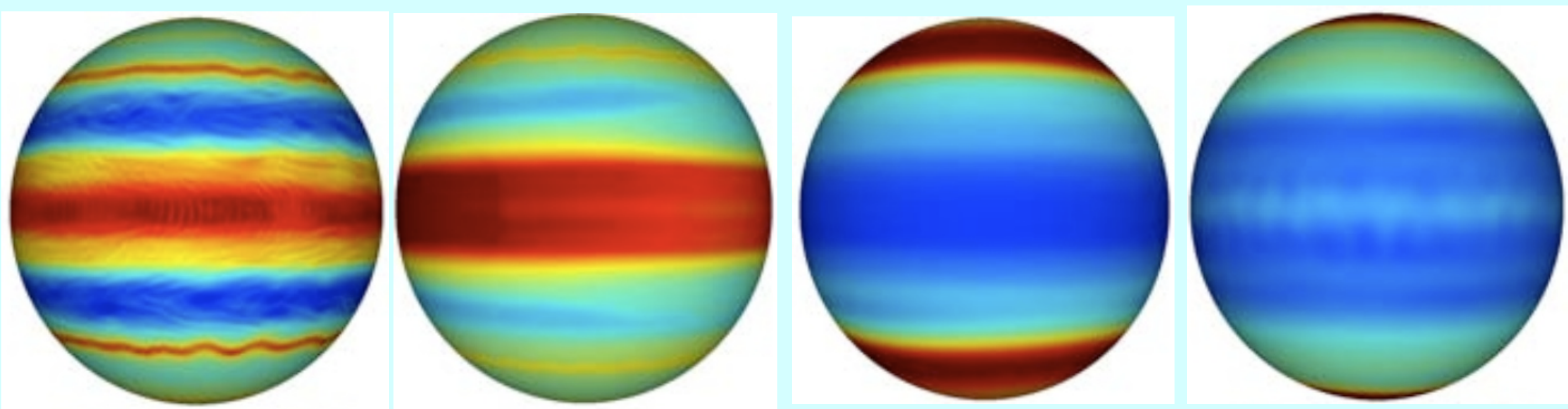
Lian & Showman (2010)



Jupiter

Saturn

Uranus/Neptune



Liu & Schneider (2010)

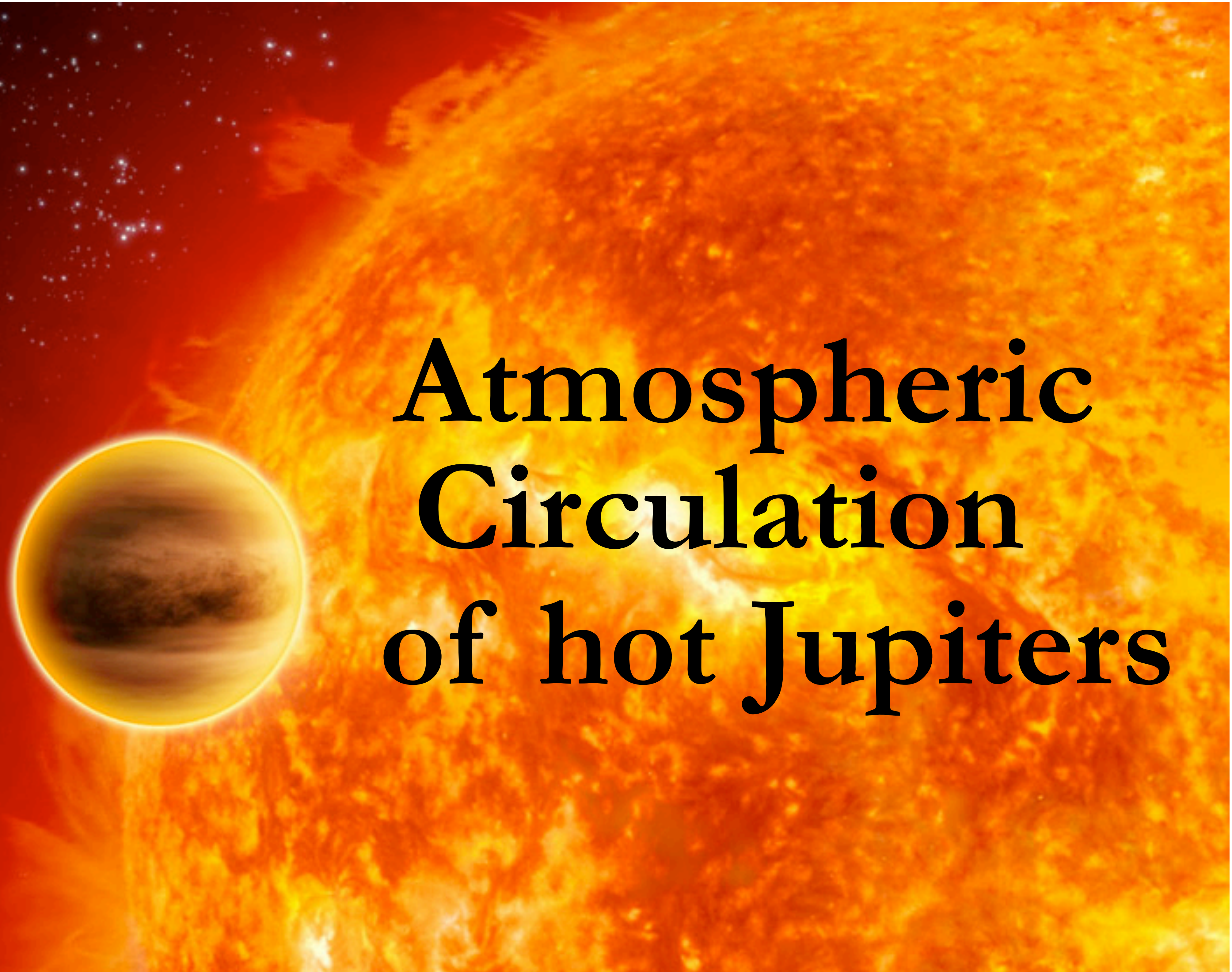
Conclusions

- **Jets dominate the circulation of the giant planets. They result from turbulent-mean-flow interactions modified by β, driven by a mix of thunderstorms, baroclinic instabilities, and deep convection. Despite progress, we still do not understand what sets the mean jet speeds.**

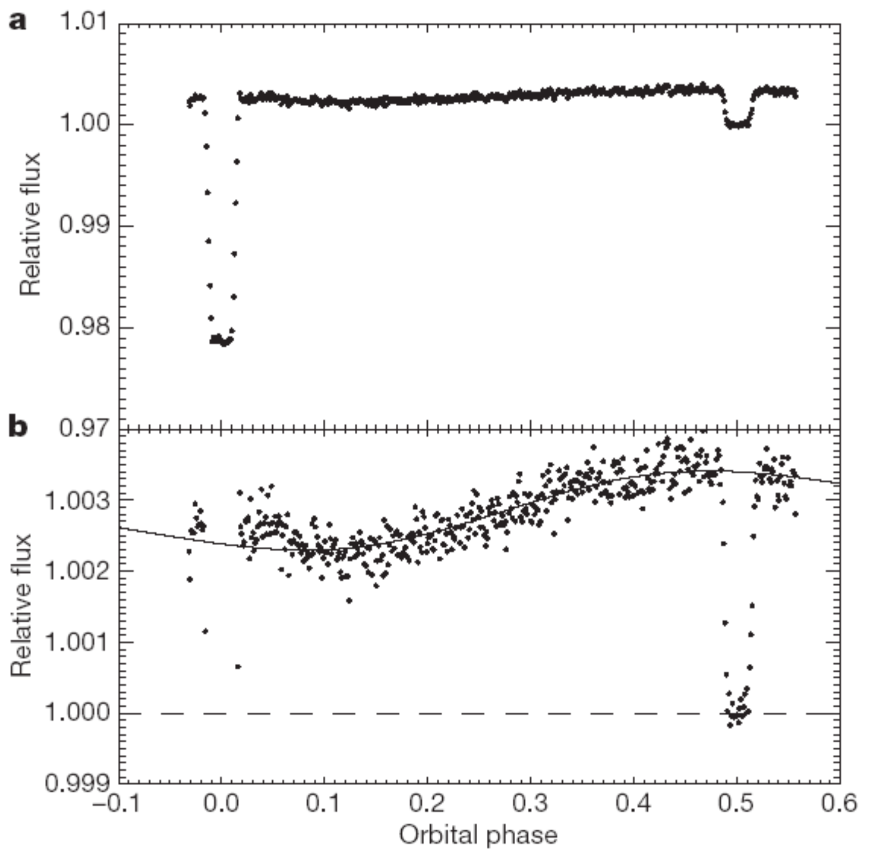
- **Deep convection models robustly produce equatorial superrotation, but they tend to produce mid-latitude jets that are too wide. Models that incorporate both radial density variations and MHD do not yet exist.**

- **Atmosphere models can robustly produce numerous Jupiter-like midlatitude jets via baroclinic instability and/or moist convection. In the absence of equatorial convection, the equatorial superrotating jet is not reproduced.**

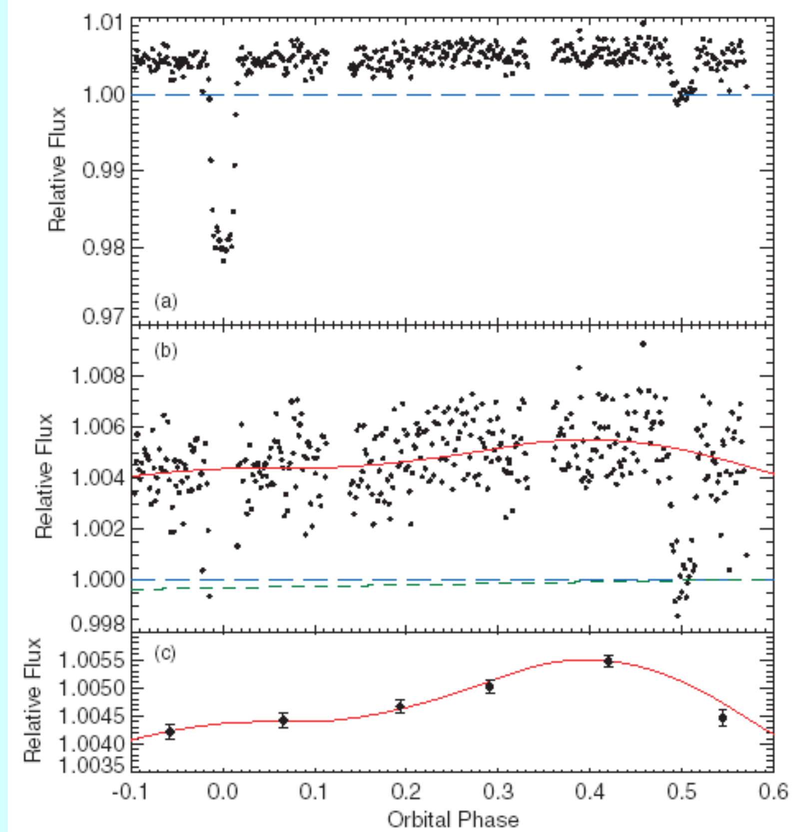
- **Introducing moist or dry convection into these models allows them to explain both superrotating equatorial jets and numerous midlatitude jets as on Jupiter and Saturn. Such models also now successfully reproduce the equatorial *subrotation* on Uranus and Neptune.**


Atmospheric
Circulation
of hot Jupiters

Spitzer light curves for HD 189733b

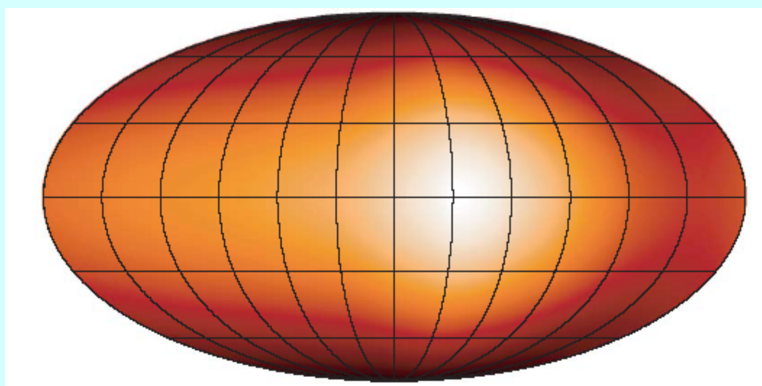


8 μm

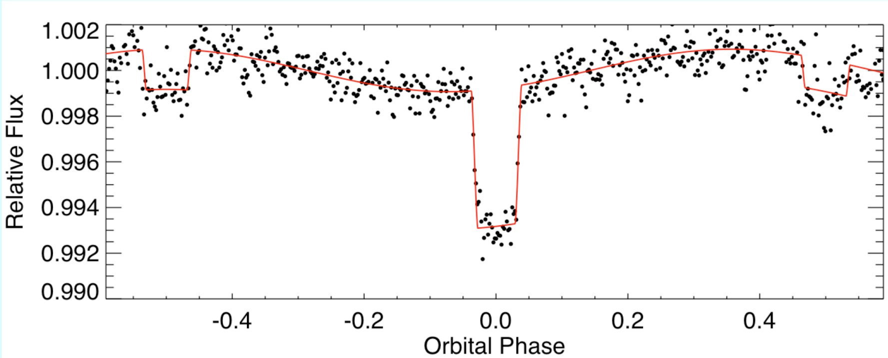


24 μm

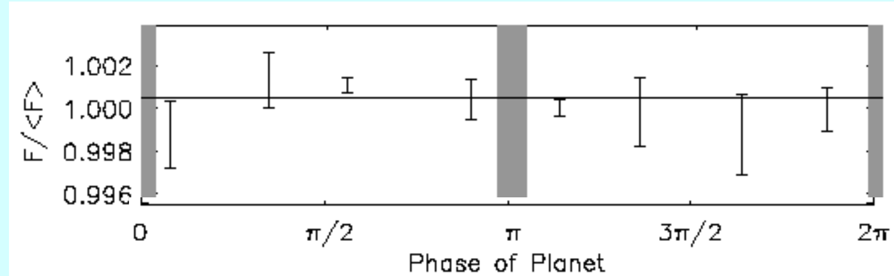
Knutson et al. (2007, 2009)



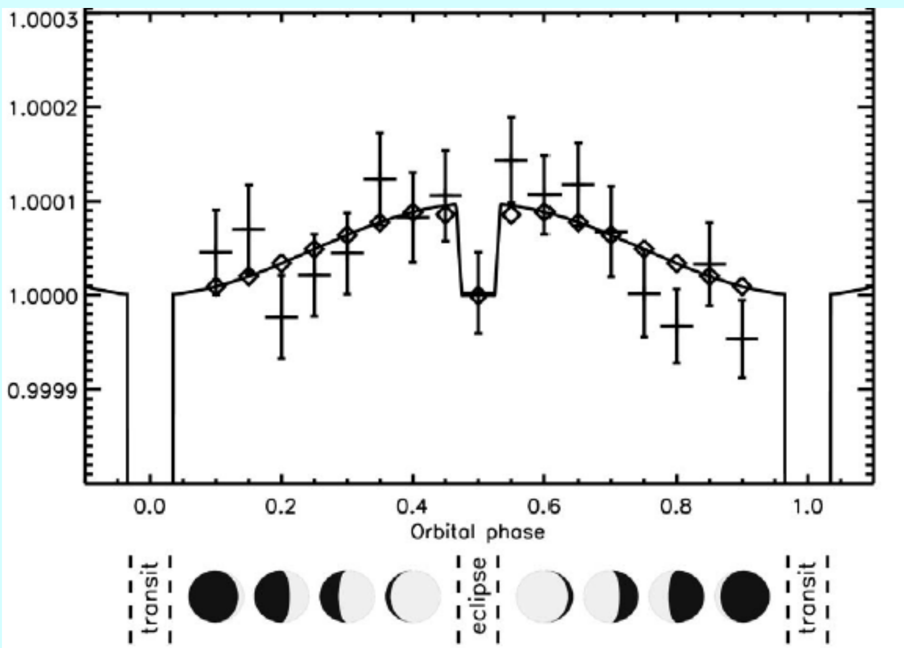
Lightcurves for hot Jupiters



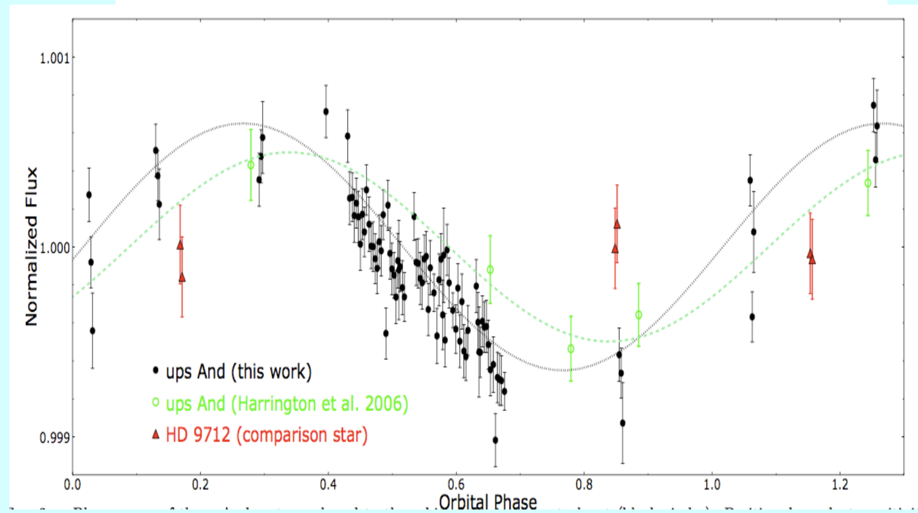
HAT-P-7b (Knutson et al., unpublished; Borucki et al. 2009)



HD209458b (Cowan et al. 2007)



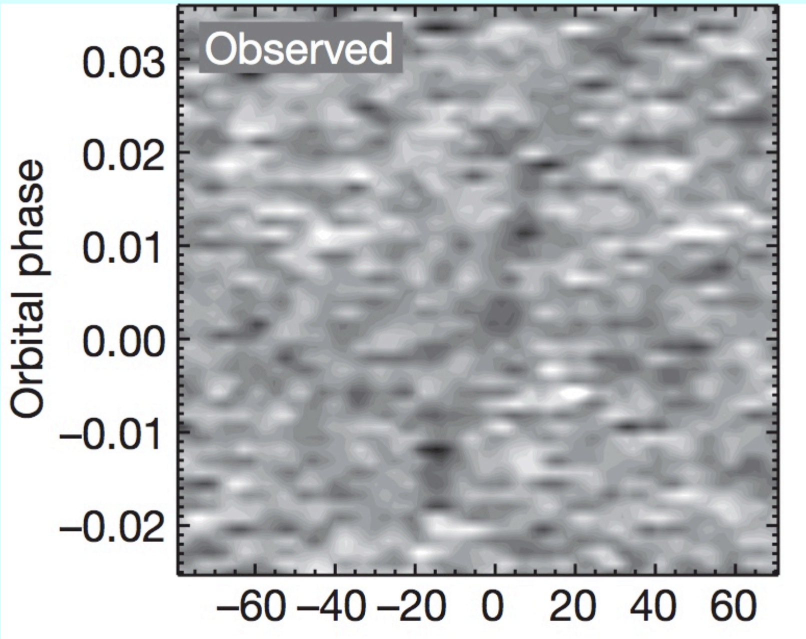
CoRoT-1b (Snellen et al. 2009)

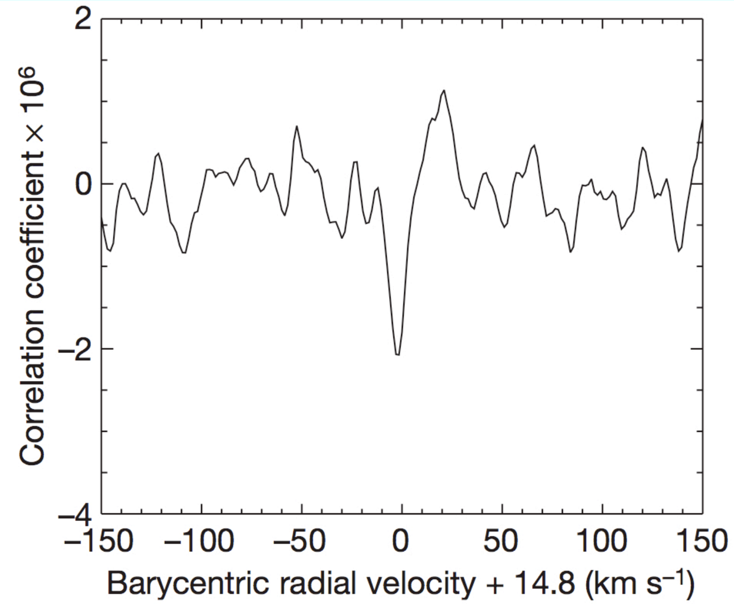


Ups And b (Crossfield et al. 2010)

Doppler detection of winds on HD 209458b!

- Snellen et al. (2010, Nature) obtained high-resolution 2 μm spectra of HD 209458b during transit with the CRIRES spectrograph on the VLT





- Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b

- Interpreted as winds flowing from day to night at high altitude (~0.01-0.1 mbar)

Motivating questions

- **What are the fundamental dynamics of this novel, highly irradiated circulation regime? Can we explain lightcurves of specific hot Jupiters? What is the mechanism for displacing the hottest regions on HD 189733b?**
- **What are the expected wind regimes, and how do they depend on parameters (irradiation, drag, rotation rate, etc)? Can we explain the Doppler measurements of HD 209458b?**
- **What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? Can we explain the increasing trend of day-night flux contrast with incident stellar flux?**
- **Looking forwarrd, how does the circulation interact with the interior? Does it affect the evolution? What is the circulation of more weakly irradiated objects (directly imaged planets and brown dwarfs)?**

Dynamical regime of hot Jupiters

- **Circulation driven by global-scale heating contrast: ~10^5 W/m^2 of stellar heating on dayside and IR cooling on nightside**

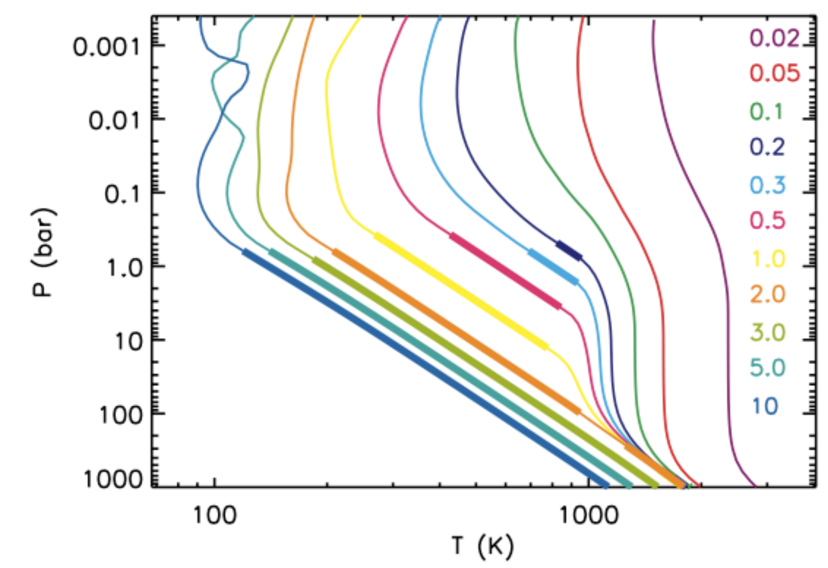
- **Rotation expected to be synchronous with the 1-10 day orbital periods; Coriolis forces important but not dominant**

- **Weather occurs in a statically stable radiative zone extending to ~100-1000 bar**

- **For km/sec winds,**

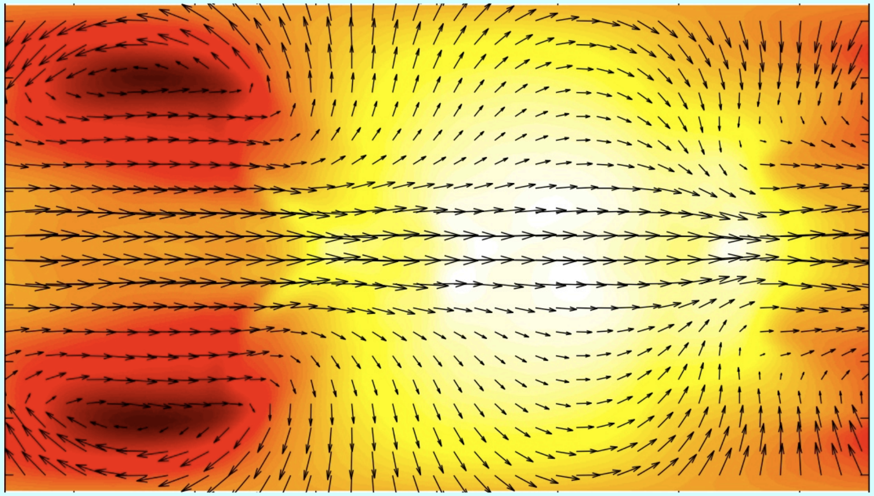
  $\tau_{rad} \ll \tau_{advect}$ **for** $p < 1$ **bar; large temperature contrasts**

  $\tau_{rad} \gg \tau_{advect}$ **for** $p > 1$ **bar; temperatures homogenized**

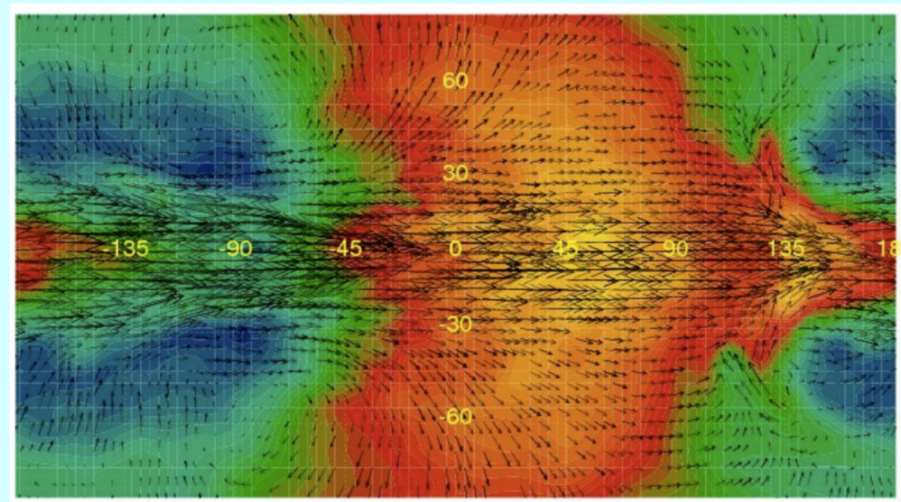


Fortney et al. (2007)

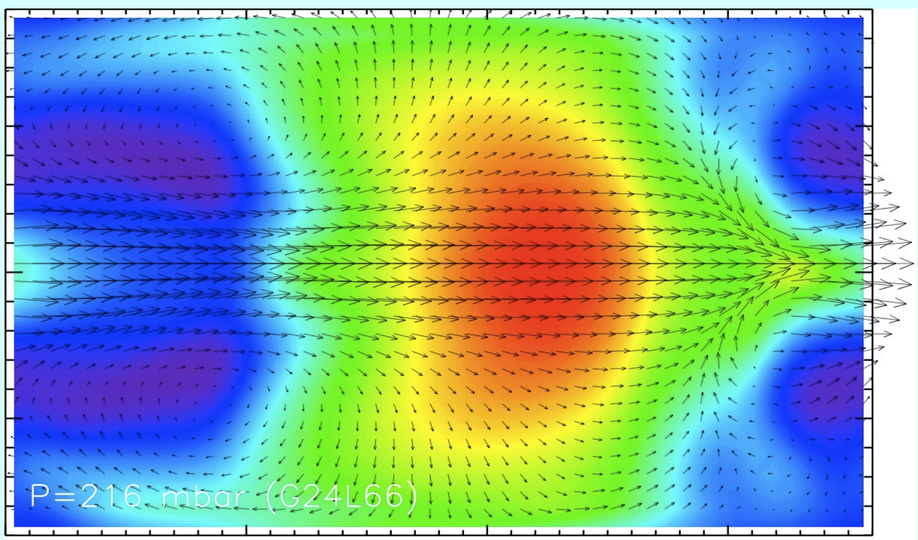
Hot Jupiter circulation models typically predict several broad, fast jets including equatorial superrotation



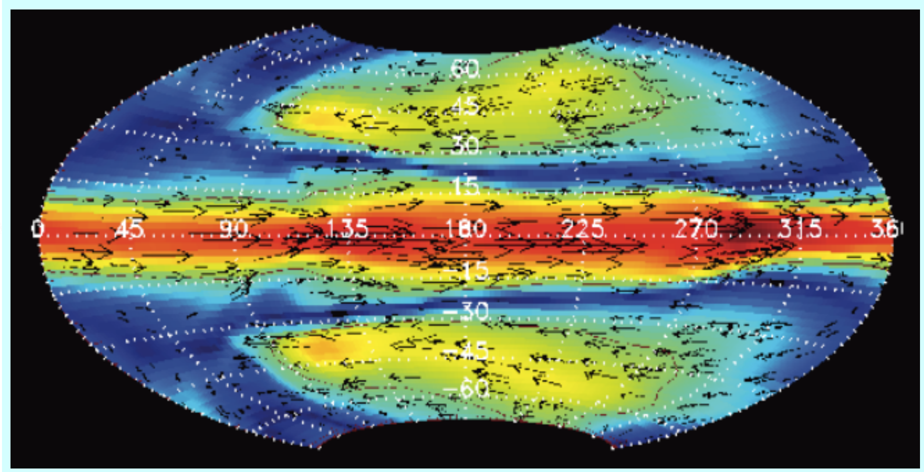
Showman et al. (2009)



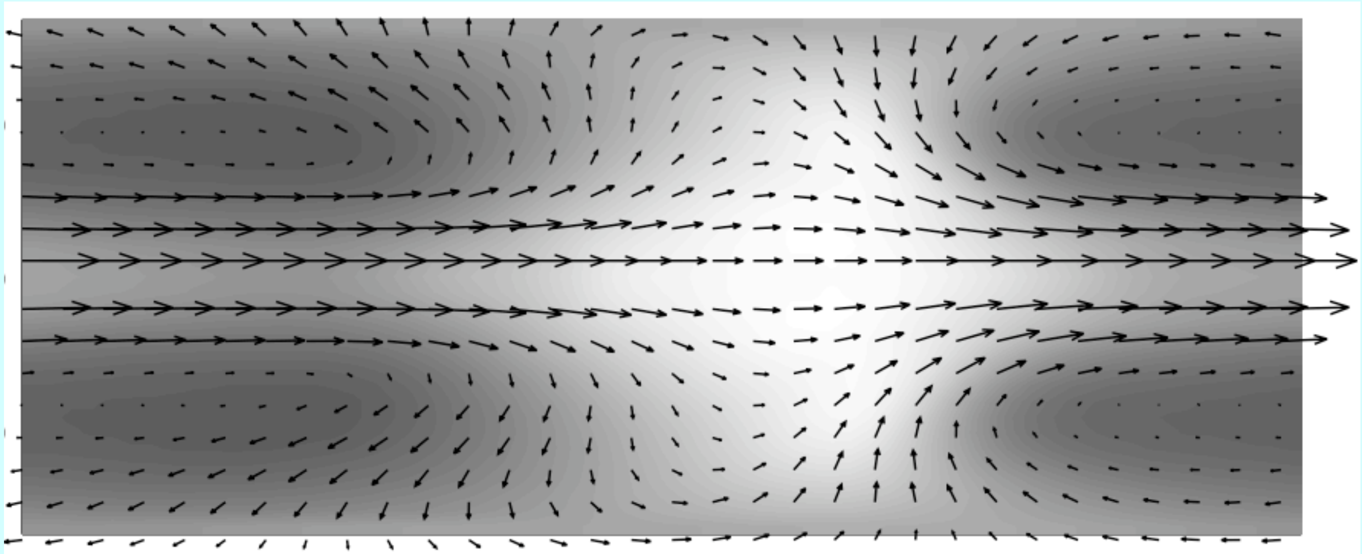
Rauscher & Menou (2010)



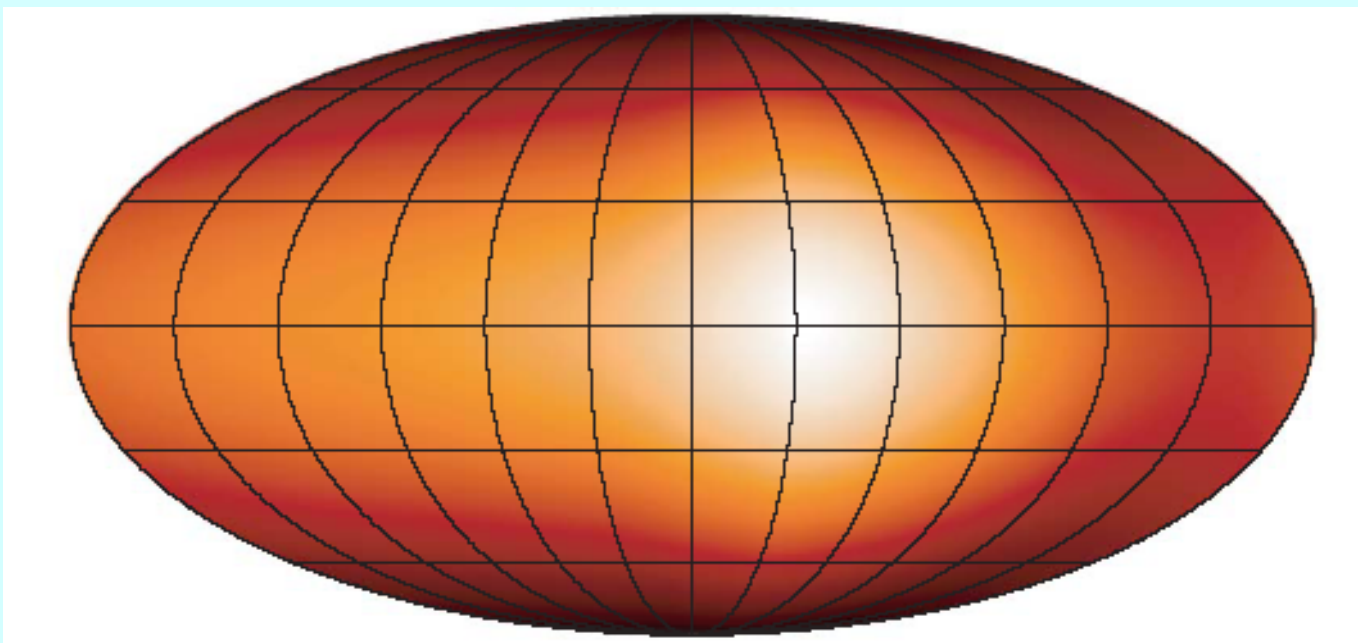
Heng et al. (2010)



Dobbs-Dixon & Lin (2008)

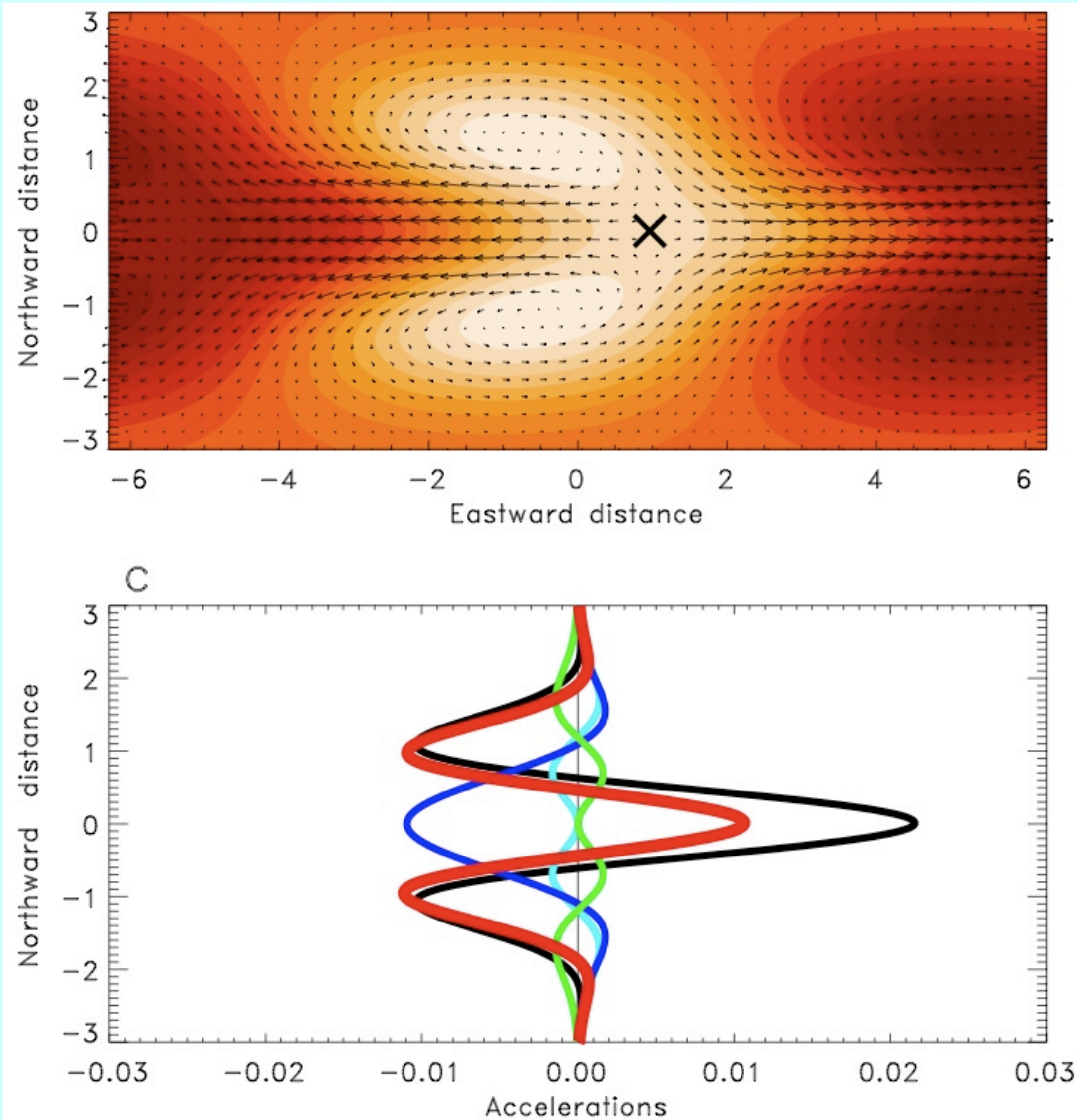


Showman & Guillot (2002)



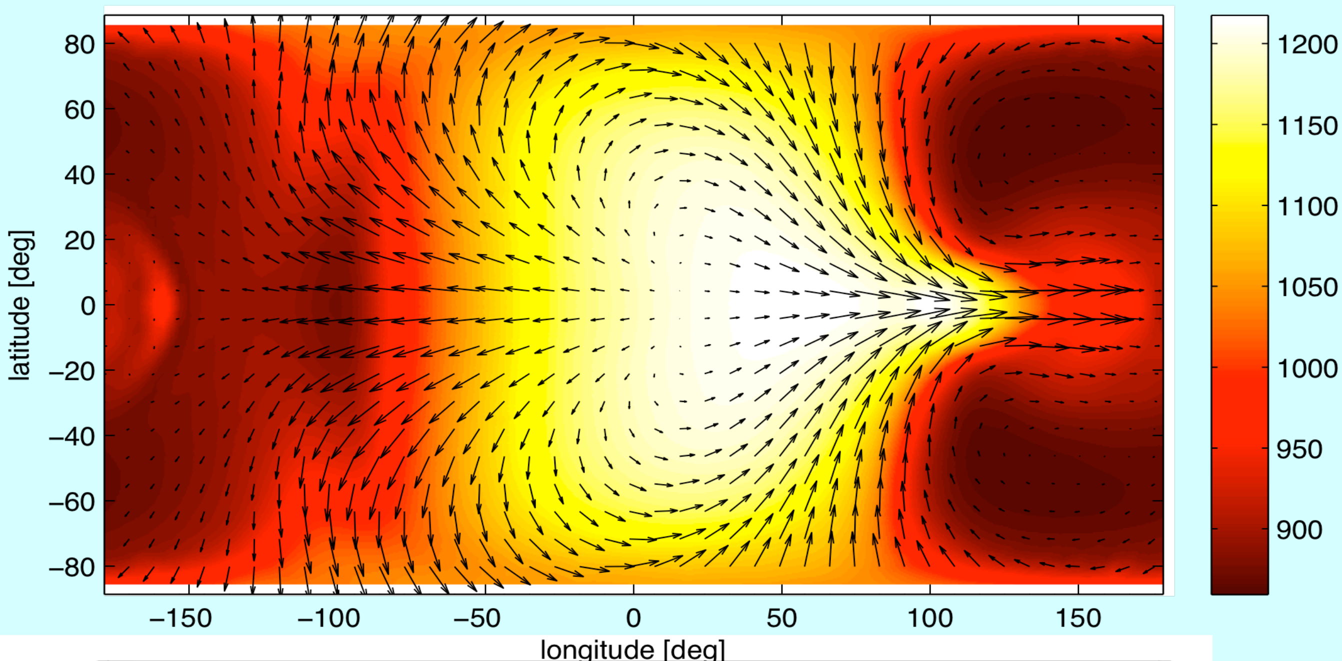
Knutson et al. (2007)

Showman & Polvani (2011) showed that these jets result from momentum transport by standing, planetary-scale waves driven by the day-night thermal forcing

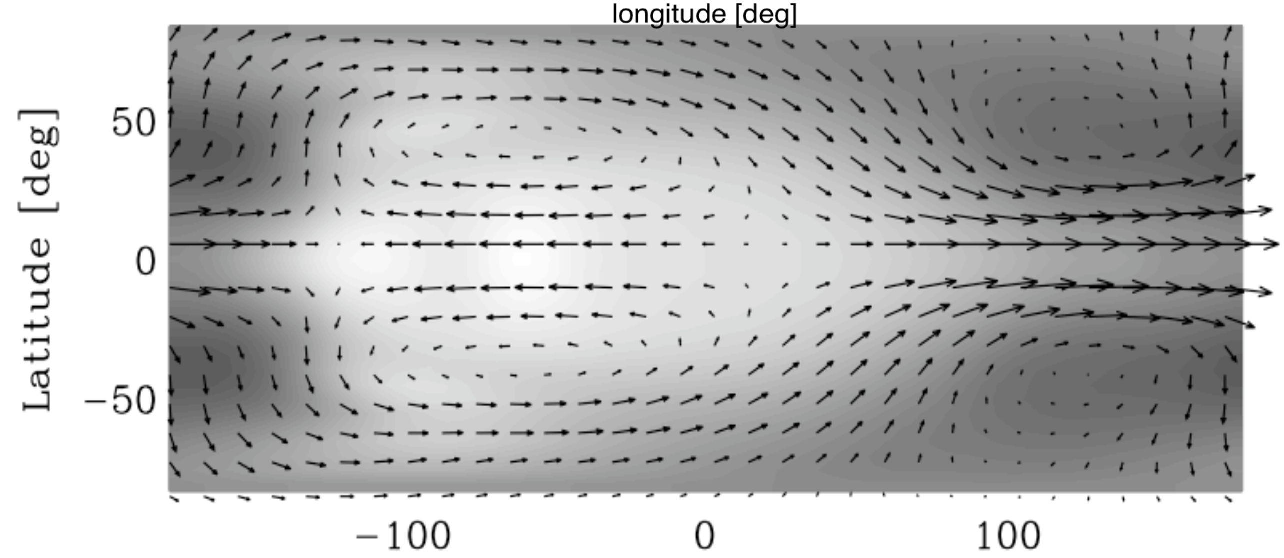


Showman & Polvani (2 011, *ApJ* 738, 71)

"Gill" pattern is clearly evident in spin-up phase of 3D hot Jupiter simulations



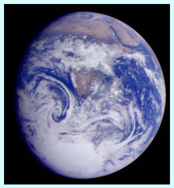
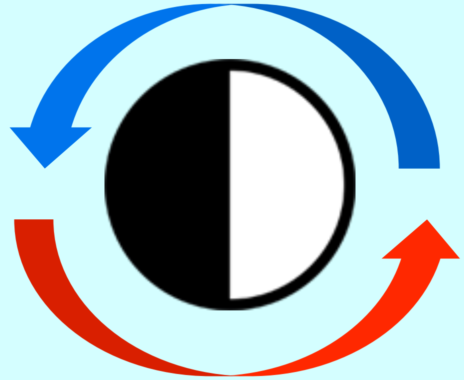
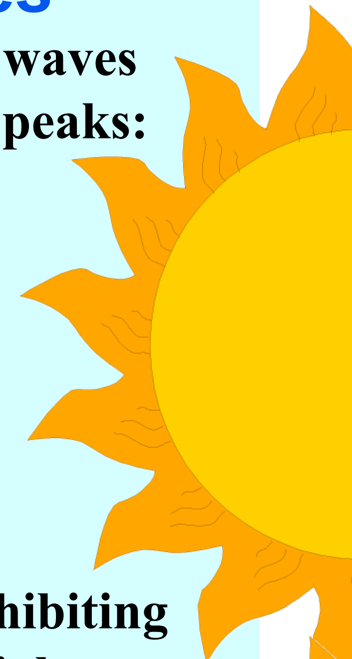
Showman & Polvani (2011)



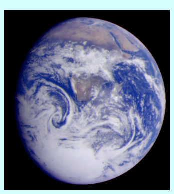
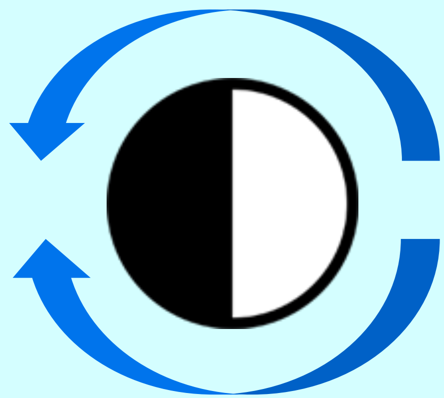
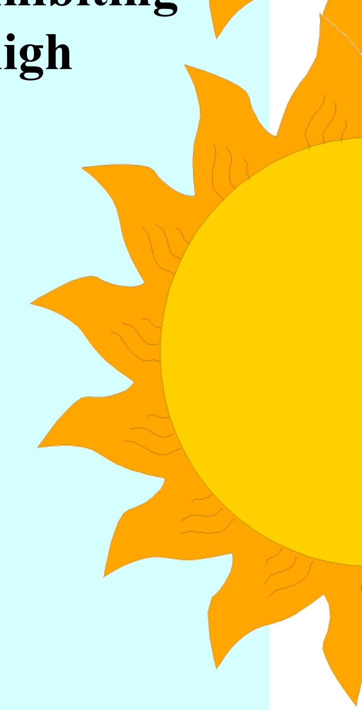
Showman & Guillot (2002)

This dynamical theory predicts two regimes

- **At weak-to-moderate stellar fluxes and friction, standing planetary waves induce zonal jets. This causes bimodal blue and redshifted velocity peaks:**

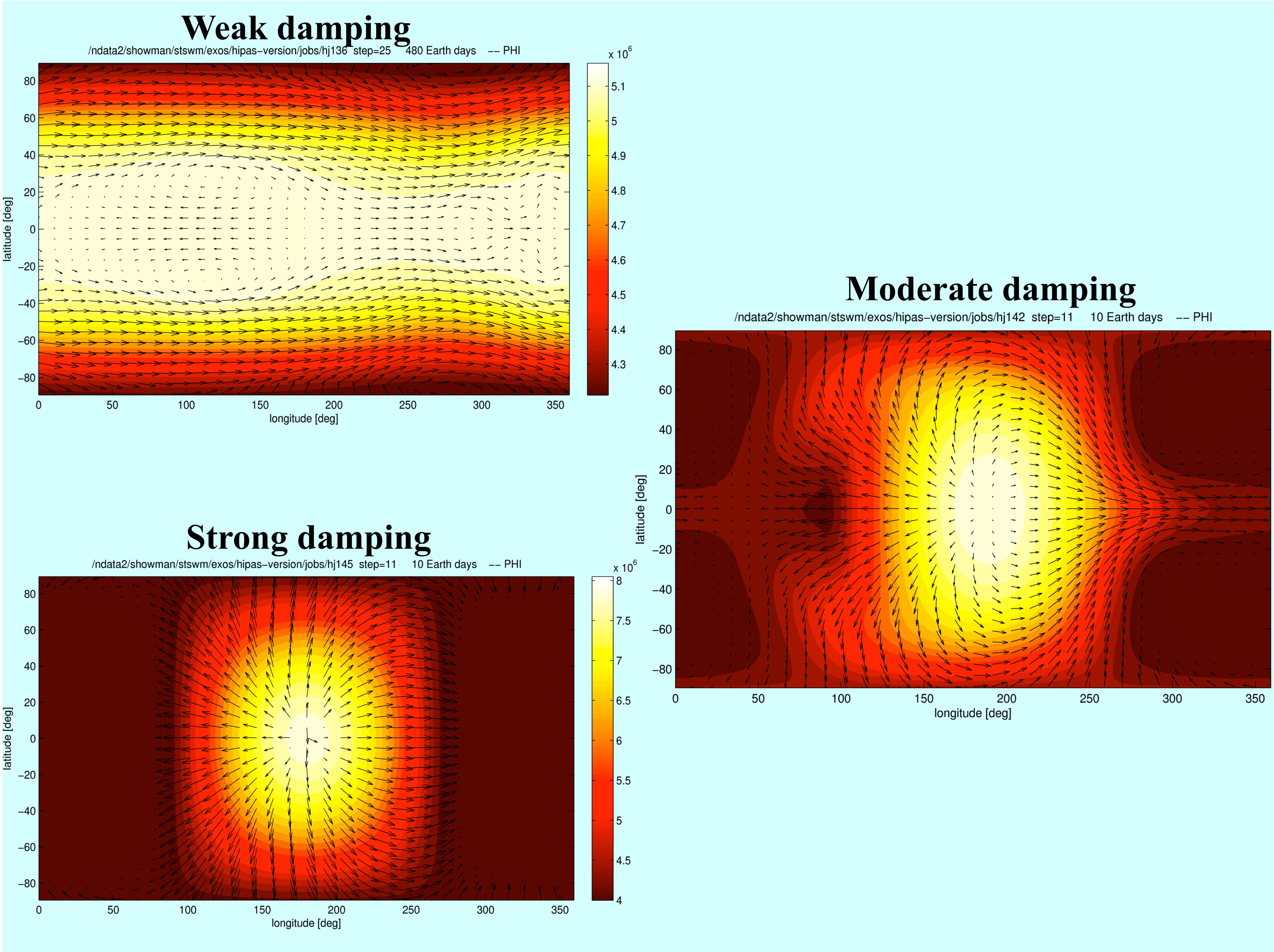
- **Extreme stellar fluxes and/or friction damp the planetary waves, inhibiting zonal jet formation and leading to predominant day-night flow at high altitude. This causes a predominant blueshifted velocity peak:**

Transition between regimes should occur when damping timescales are comparable to wave propagation time across a hemisphere:

Kelvin wave propagation speed $\sim NH$

Propagation time across hemisphere $\sim \dfrac{a}{NH} \sim 10^5 \text{ sec}$


Weak damping
/ndata2/showman/stswm/exos/hipas−version/jobs/hj136 step=25 480 Earth days −− PHI
latitude [deg]
longitude [deg]
x 10^6
Strong damping
/ndata2/showman/stswm/exos/hipas−version/jobs/hj145 step=11 10 Earth days −− PHI
latitude [deg]
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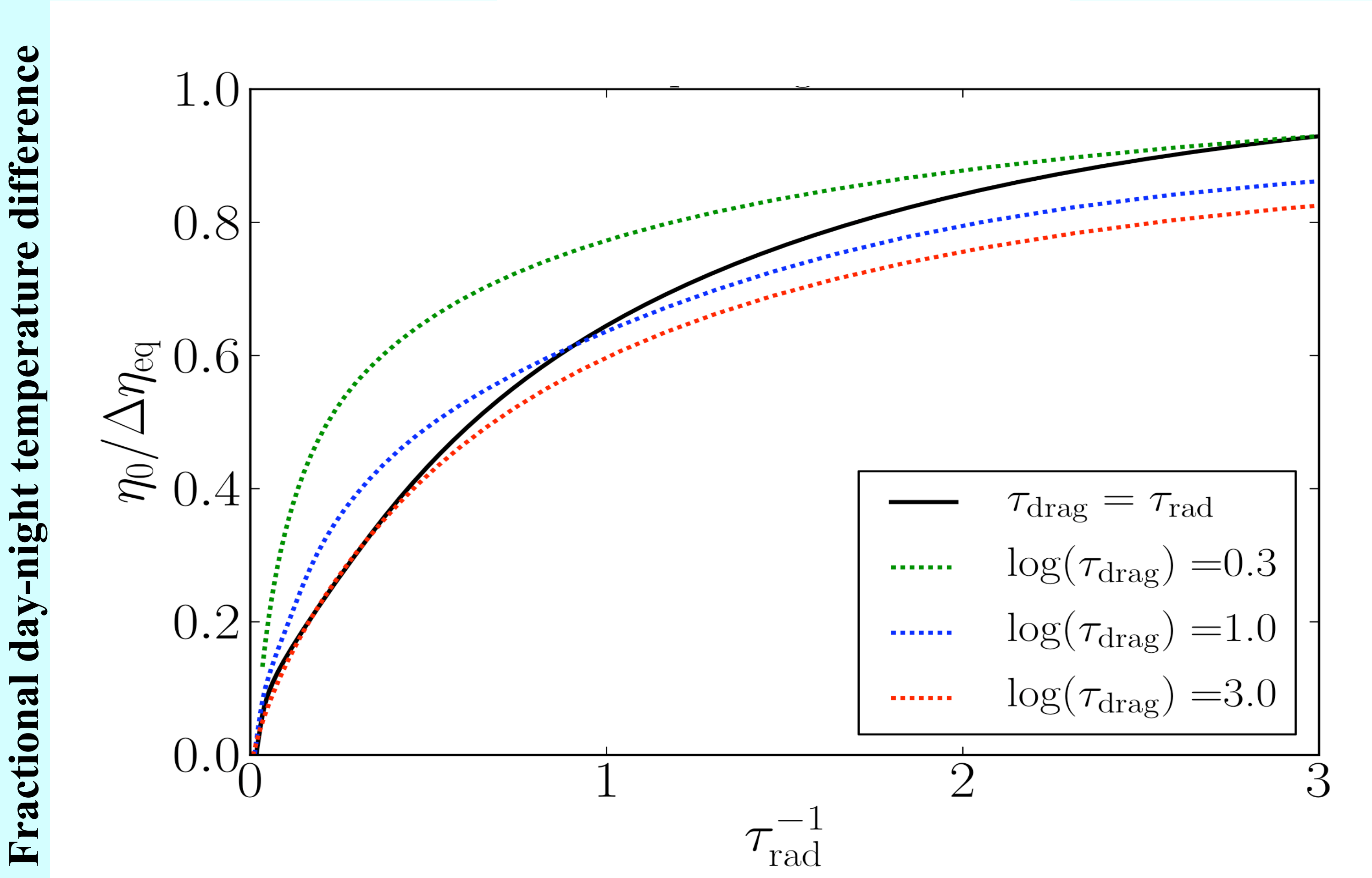
x 10^6
Moderate damping
/ndata2/showman/stswm/exos/hipas−version/jobs/hj142 step=11 10 Earth days −− PHI
latitude [deg]
longitude [deg]
x 10^6

Models predict increasing day-night temperature contrasts with increasing insolation

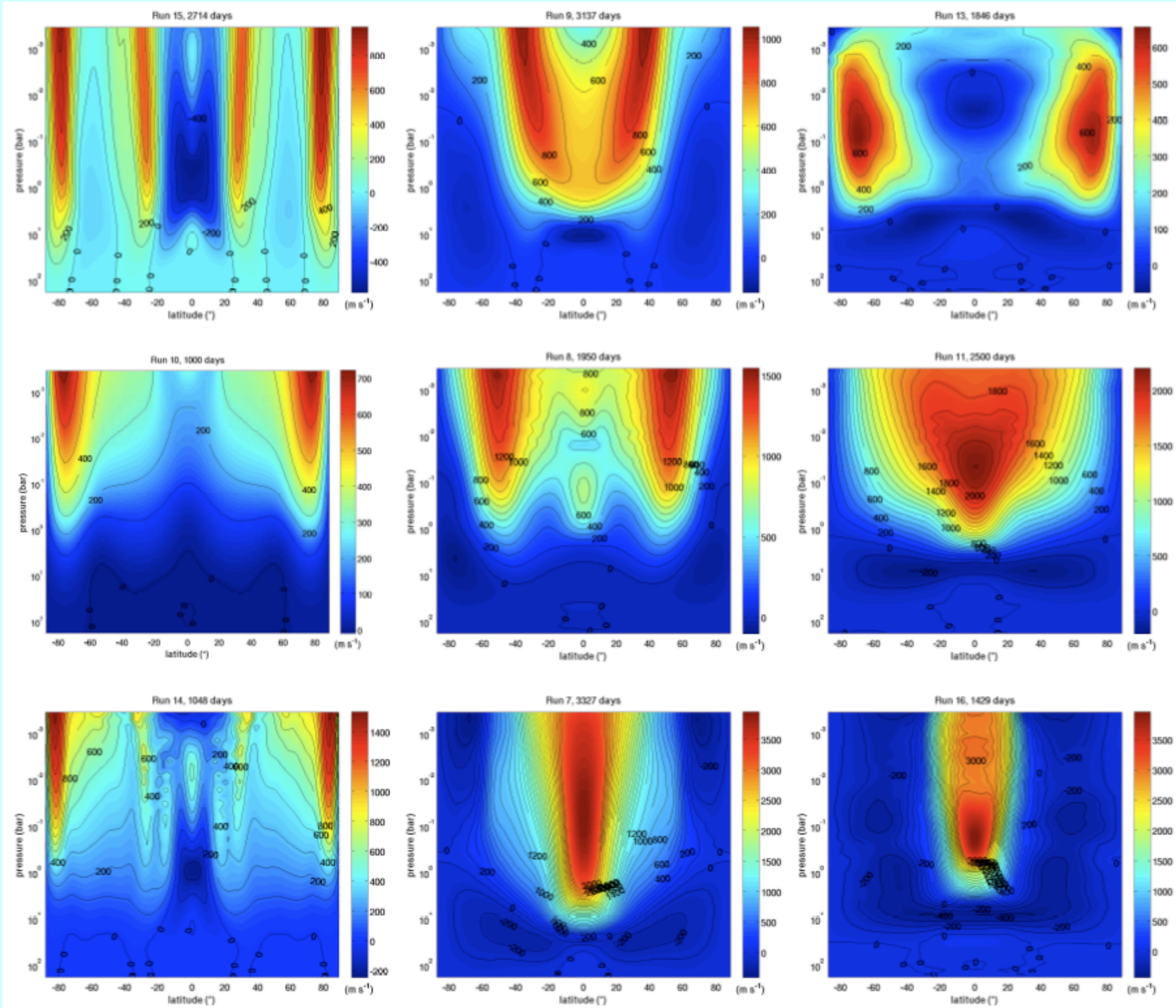


Perez-Becker & Showman (in prep)

This helps explain the emerging observational trend of larger day-night flux contrasts at larger stellar flux (cf Harrington's talk)

See also talk by Heng

Dependence of wind on rotation rate and orbital distance

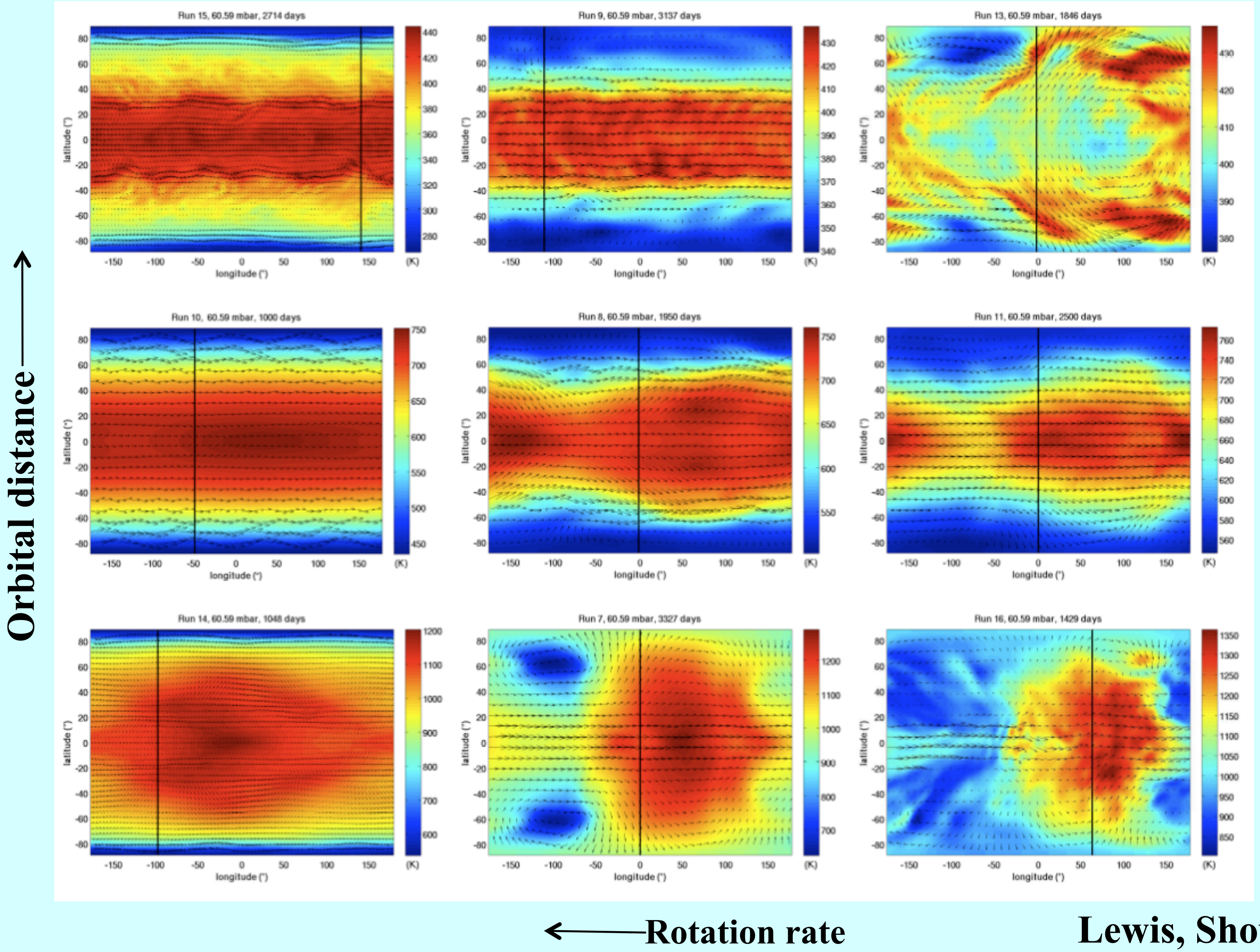


Orbital distance ⟶

⟵ Rotation rate

Showman, Lewis

Dependence of temperature on rotation rate and orbital distance

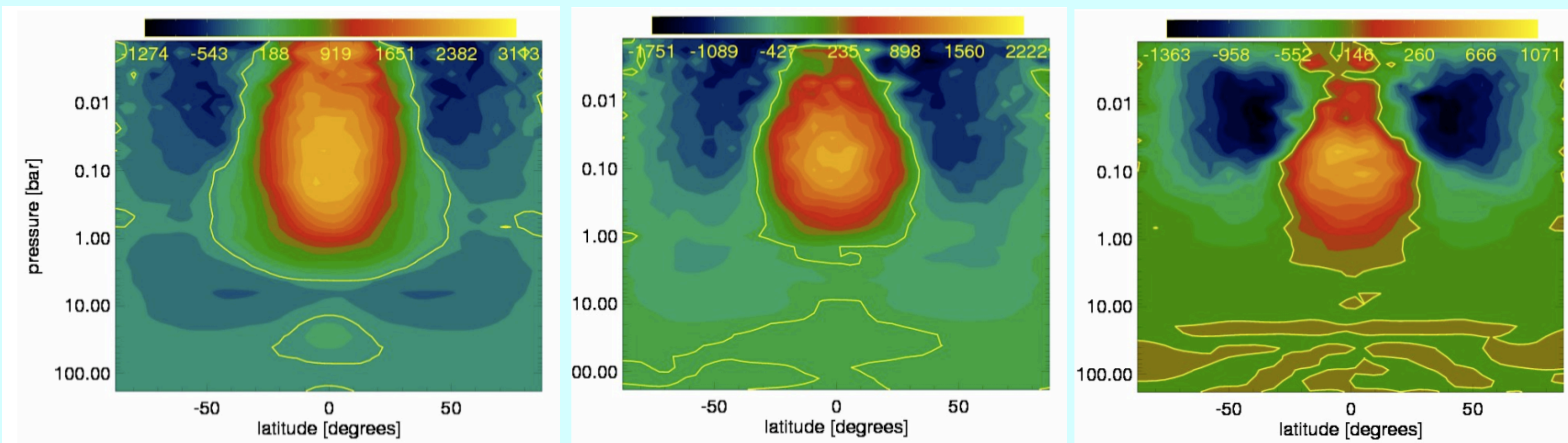


Lewis, Showman

Friction

- **Sources of frictional damping are poorly understood. Possibilities:**
  - **Sub-grid-scale turbulence**
  - **Sub-grid-scale wave generation/breaking/absorption**
  - **Drag and dissipation associated with MHD effects (Perna et al. 2010, Batygin & Stevenson 2010, Menou 2011)**

Weak drag **Medium drag** **Strong drag**



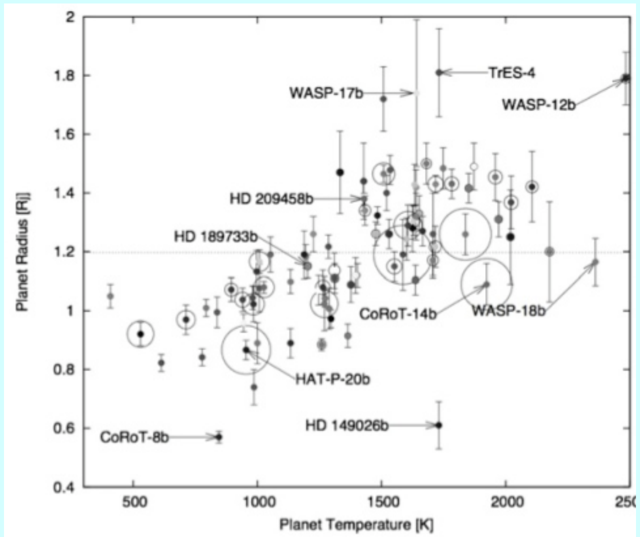
Perna et al. (2010)

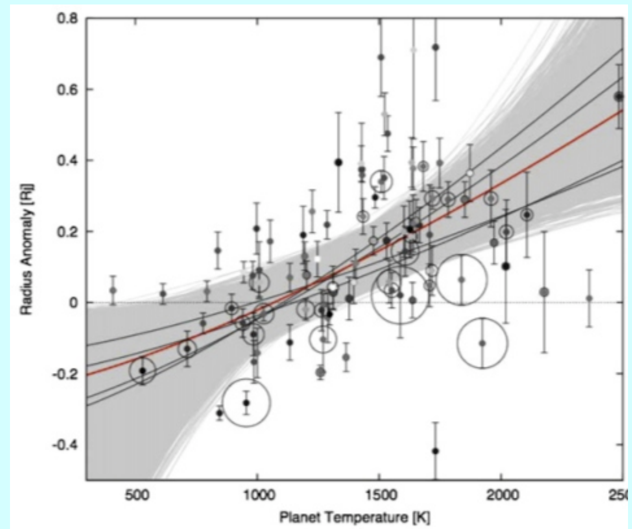
- **Note that equilibration of jet speeds a given level—say the photosphere-- need not require drag *at those levels* (e.g., drag could occur at bottom, with eddy-jet pumping at the photosphere balanced by Coriolis acceleration/ advection).**

See talk by Rauscher

Does the circulation affect the interior evolution?

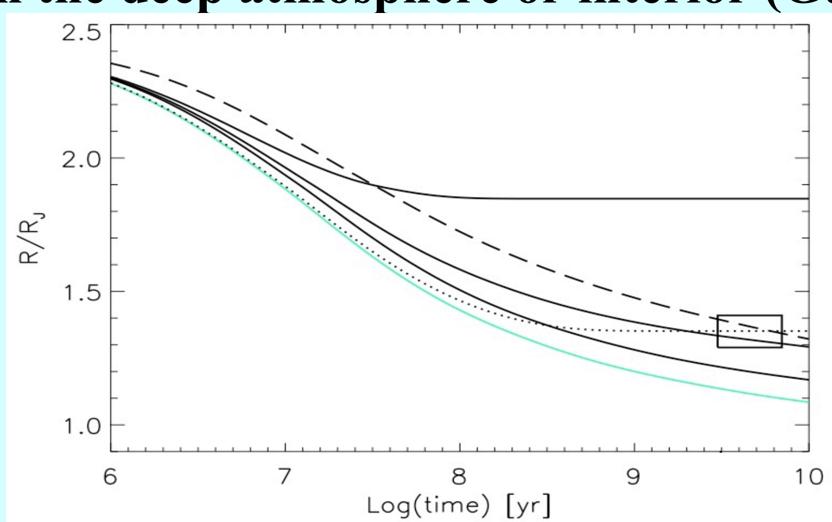
- **The radius anomaly problem: many hot Jupiters are too big!**





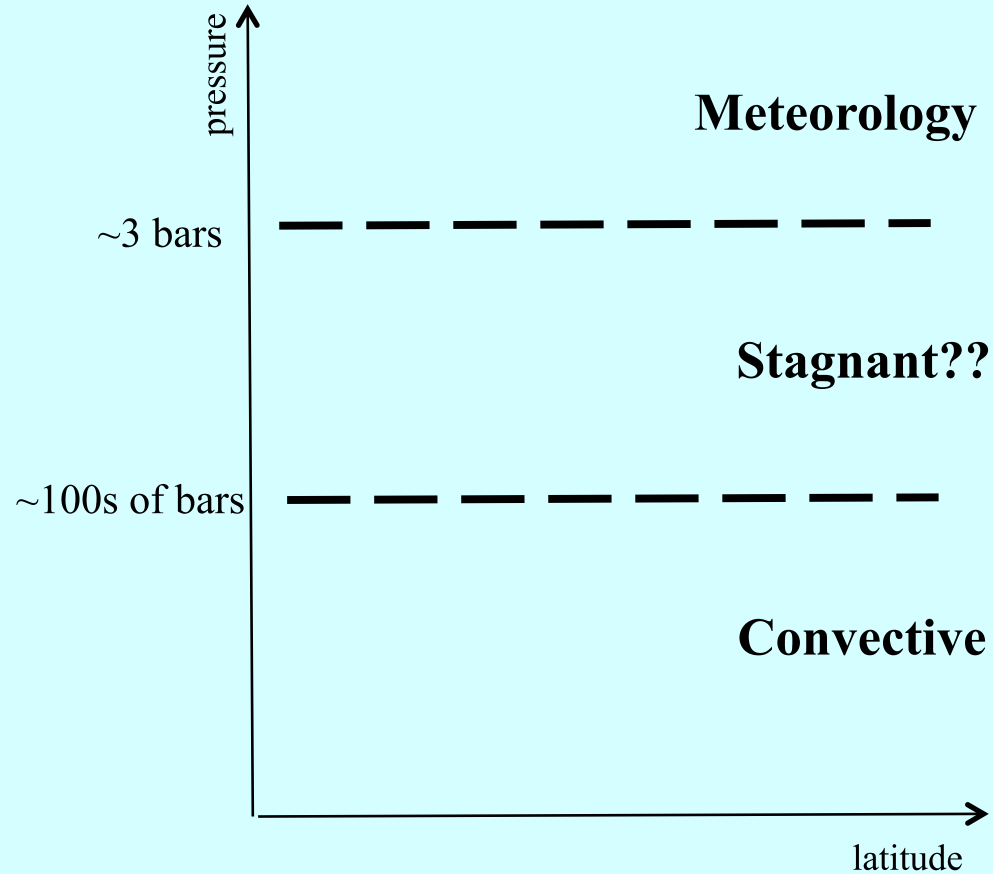
Laughlin et al. (2011)

- **Among the many proposed solutions is that the atmospheric circulation dissipates energy in the deep atmosphere or interior (Guillot and Showman 2002):**



Mechanisms of downward energy transport

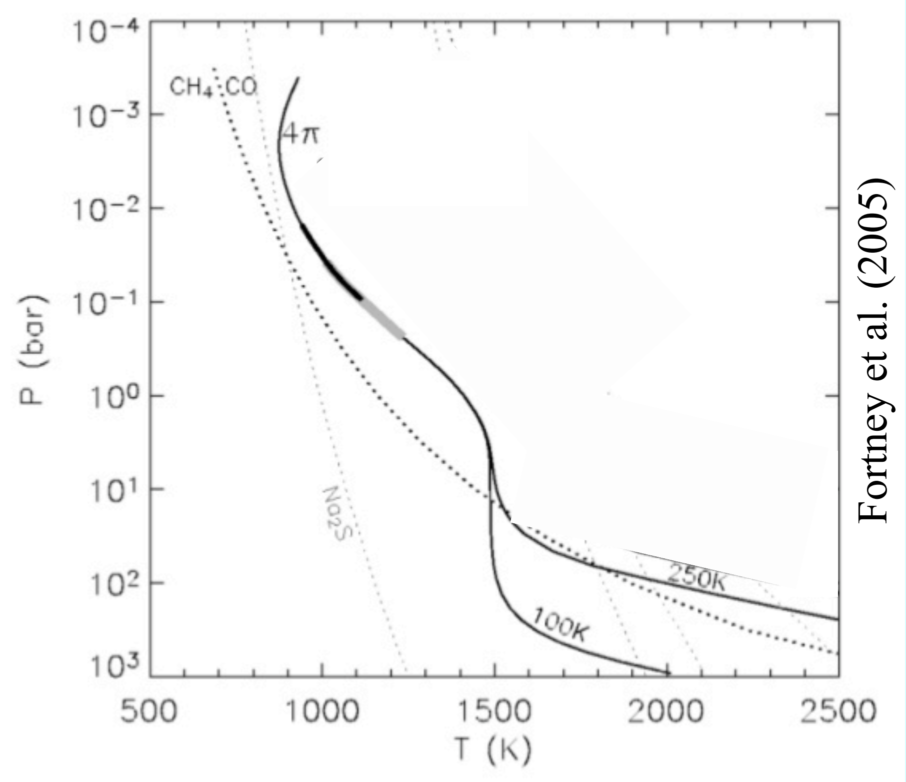
- **Turbulent mixing (Youdin & Mitchell 2010)**
- **Meridional circulations**
- **Atmospheric waves**



Possibility of feedback

Downward energy transport mechanisms work best when stratification is small and planet's heat flux is large

This may allow a feedback wherein bloated planets have much greater weather heating than normal planets.



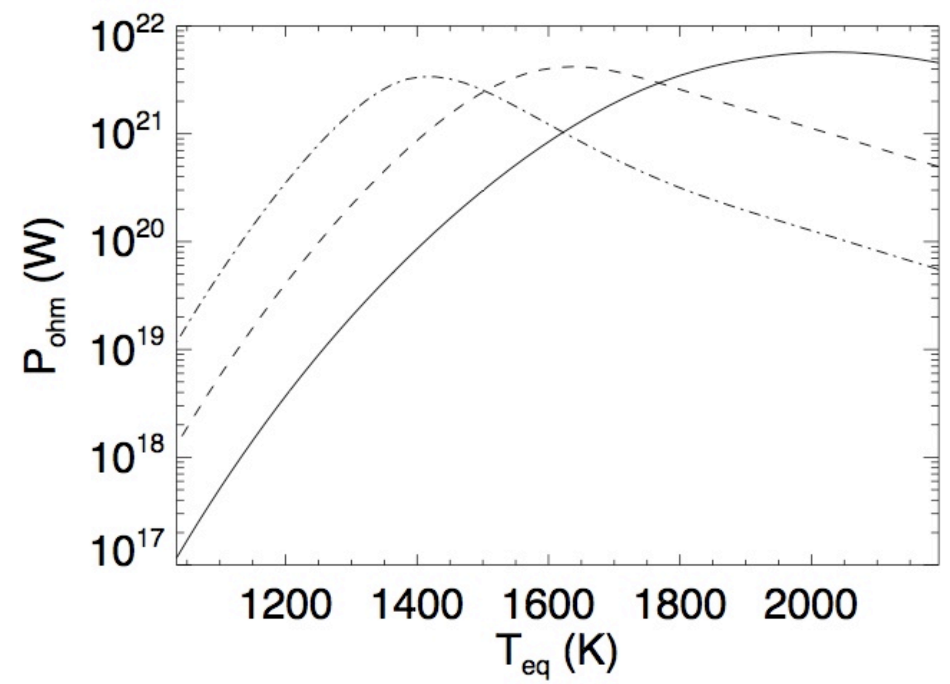
Fortney et al. (2005)

The assumption that all planets will have the same weather heating (e.g., ~1%) is likely incorrect!

Inflation through Ohmic dissipation

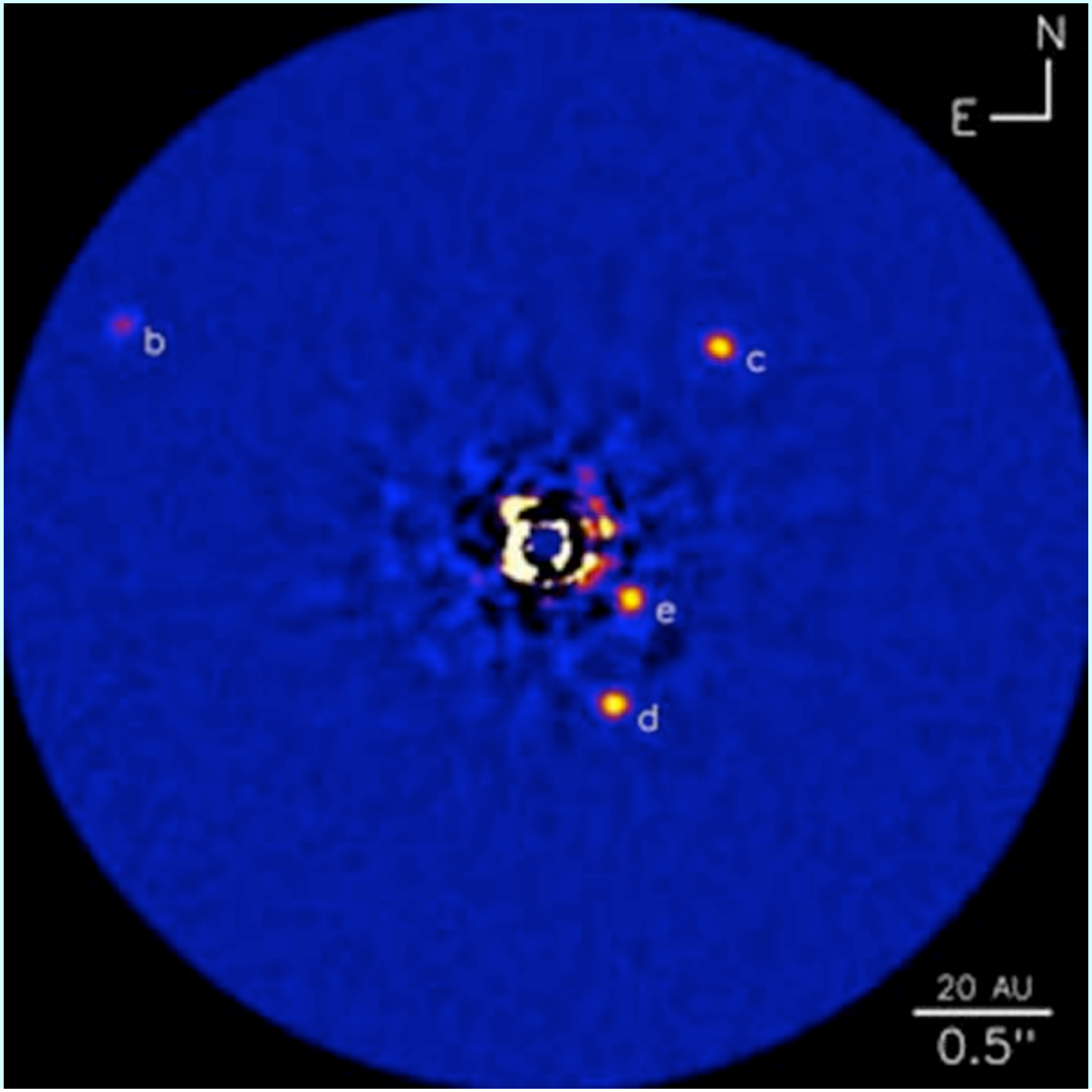
- Batygin & Stevenson (2010) and Perna et al. (2010) suggested that electric currents resulting from wind motions could cause Ohmic dissipation, explaining the radius problem

- Menou (2011) presented scalings suggesting the effect will exhibit a peak

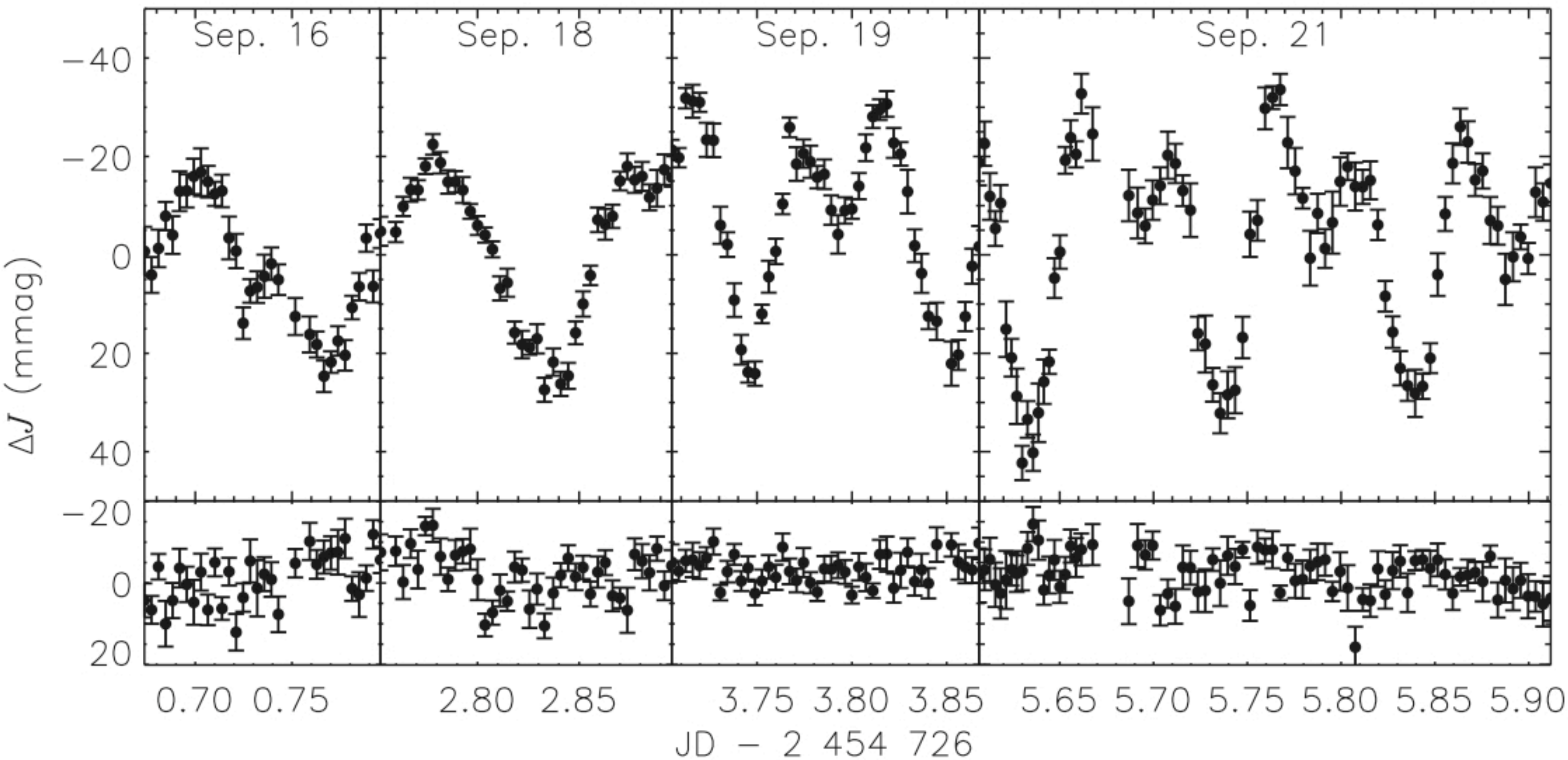


- Some authors have suggested that strong winds at ~10 bars are necessary. This may be difficult because time to pump jets there is ~10^8-10^9 sec. A magnetic drag timescale shorter than this would lead to weak winds there.

A new frontier: directly imaged planets and brown dwarfs



T2.5 brown dwarf SIMP 0136 shows weather variability



Artigau et al. (2009)

Conclusions

Hot Jupiters occupy a dynamically unique regime of atmospheric circulation that does not exist in our Solar System. The intense day-night radiative forcing produces wind speeds >1 km/sec and temperature contrasts of ~200-1000 K. The winds can distort the temperature pattern in a complex manner, with important implications for lightcurves and spectra.

The radiative forcing generates equatorial superrotation that can displace the hottest regions to the east of the substellar point, explaining the observed offset on HD 189733b. The superrotation results from up-gradient momentum transport due to standing Rossby and Kelvin waves triggered by the longitudinal (day-night) heating variations.

The theory predicts regime transitions: Modest irradiation/friction allows the waves to generate zonal jets, but strong irradiation/friction damps the waves, leading to day-to-night flow with weak zonal jets. This leads to distinct Doppler signatures and can explain the Doppler measurement of HD 209458b.

The same regime transition explains the observed transition from small to large day-night temperature contrast at increasing stellar irradiation.

Many questions remain: Does the atmospheric circulation help explain the inflated radii of hot Jupiters? What is the atmospheric circulation of directly imaged planets and brown dwarfs? Stay tuned!