Atmospheric Dynamics of Giant Planets Inside and Outside the Solar System

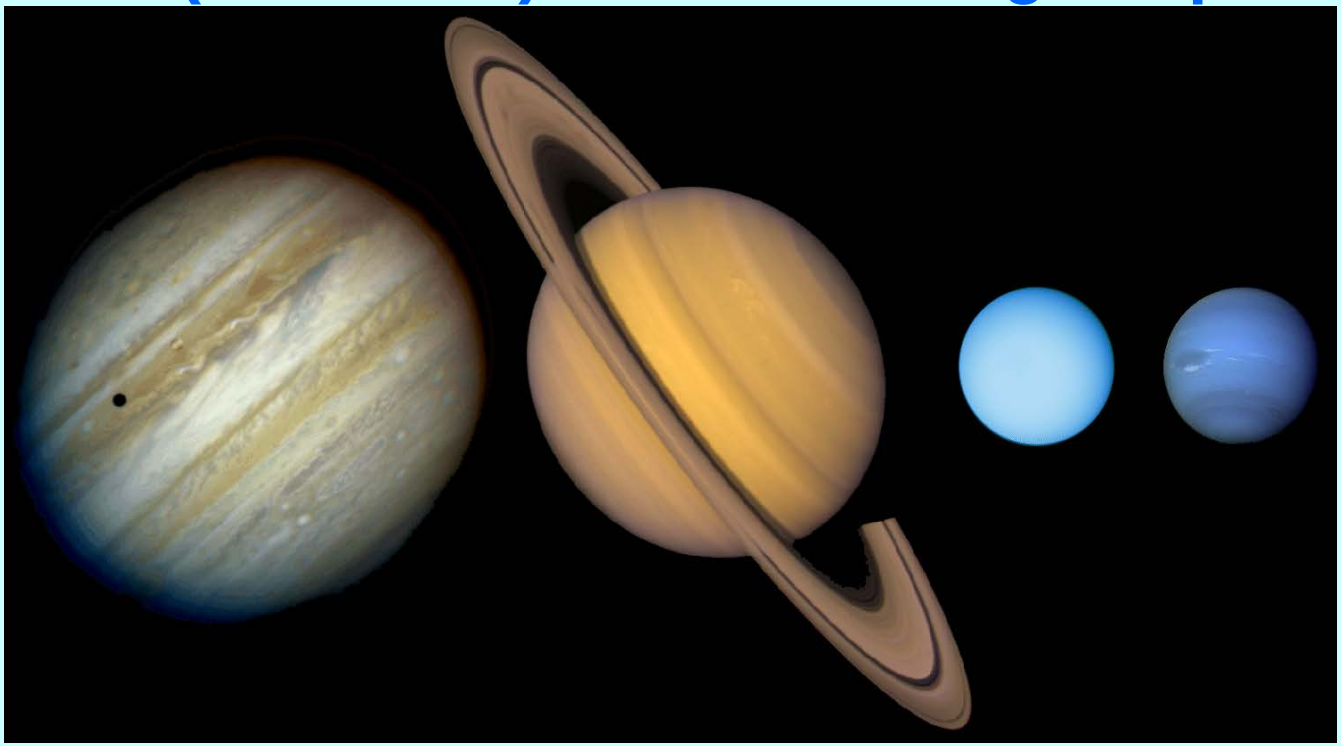
Adam P. Showman
University of Arizona

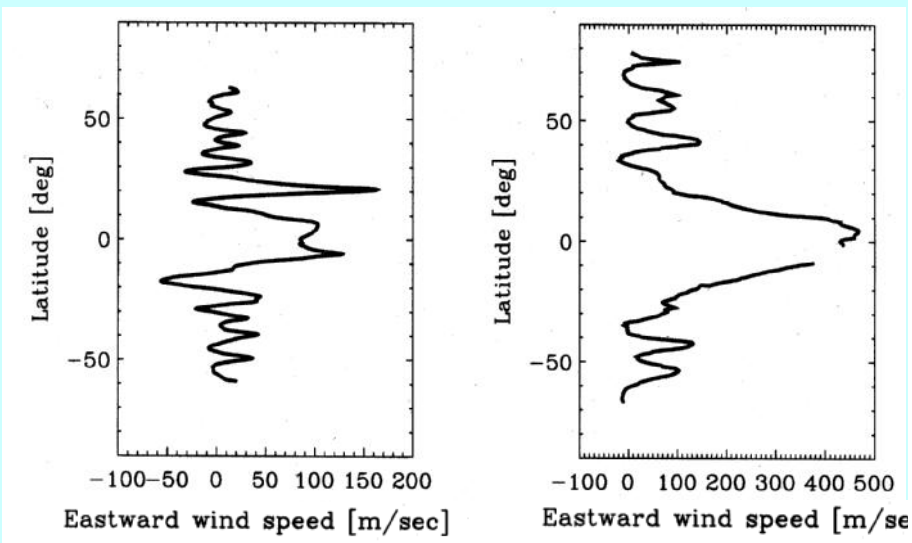
Collaborators: Yuan Lian, Yohai Kaspi, Lorenzo Polvani, Jonathan Fortney, Nikole Lewis, Daniel Perez-Becker, Mark Marley, Heather Knutson,

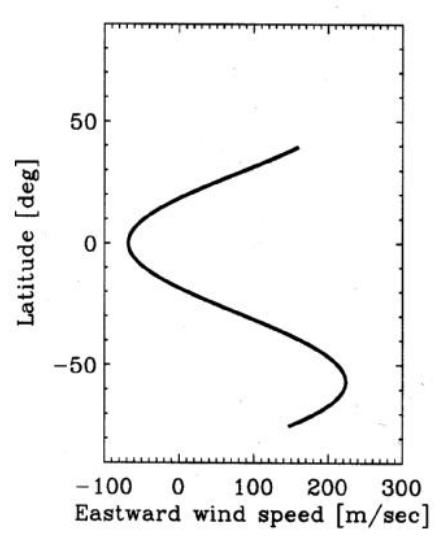
Outline

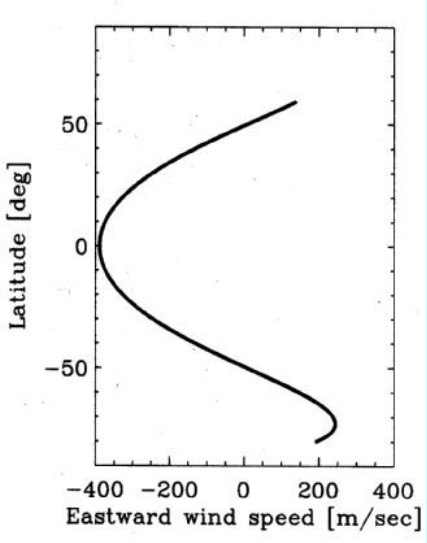
- **Giant planets in the Solar System**
  - **Observational background**
  - **New results inferring the depth of jet streams on Uranus and Neptune**
  - **How are the jets formed?**
    - **brief background**
    - **results of global 3D models with a hydrological cycle**
- **Exoplanets: the hot Jupiters**
  - **Motivations and observational methods/results**
  - **Explanation for equatorial superrotation in hot Jupiter regime**
  - **Regime transitions: day-night temperature differences and wind regimes, and tests with data**
  - **From hot to cool Jupiters and the continuum to Jupiter itself**
- **Brown dwarfs**
  - **Observational aspects and expected dynamical regimes**
  - **Convective interior structure**
  - **Atmospheric circulation via absorption of waves propagating from below**

Zonal (east-west) winds on the giant planets

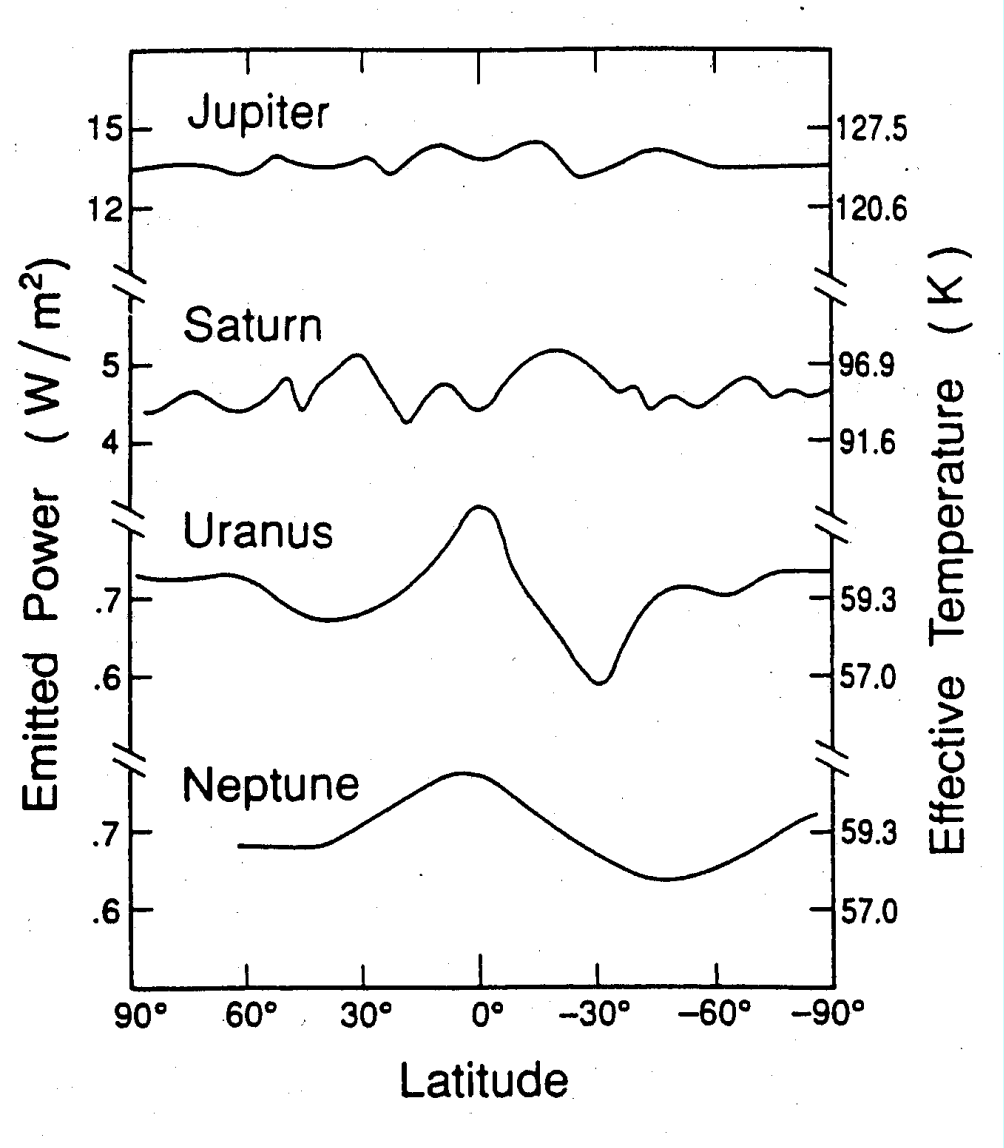






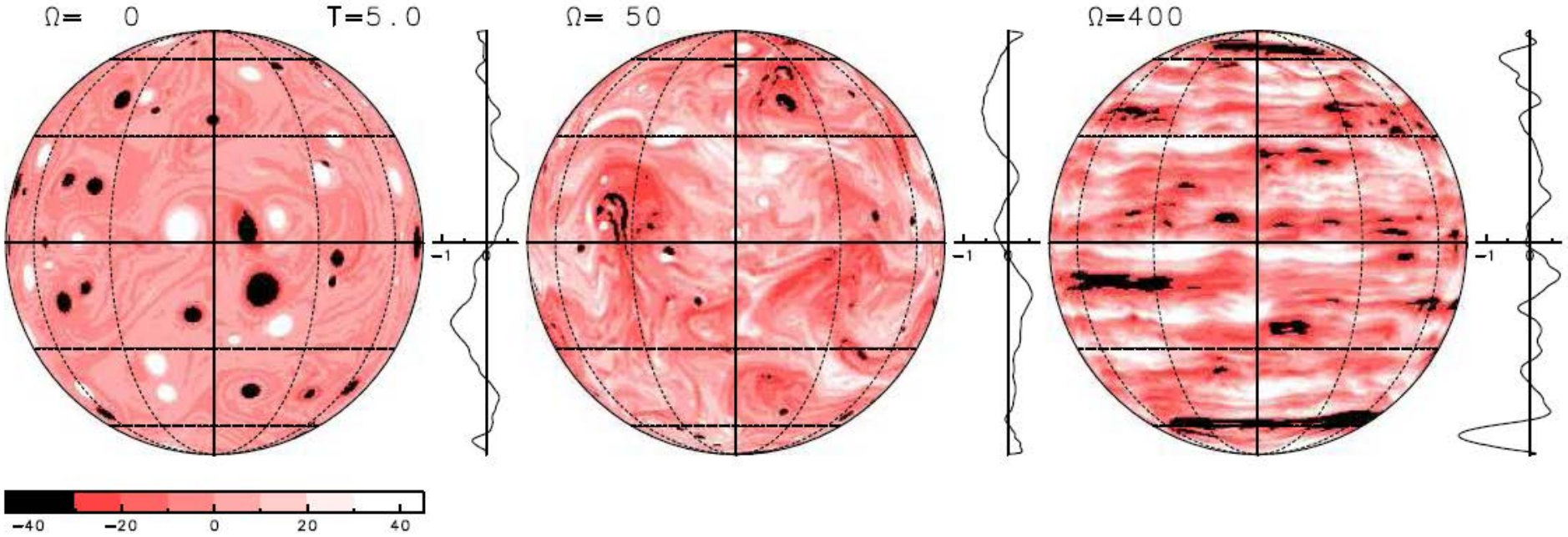


Temperatures are relatively homogeneous:



Ingersoll (1990)

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



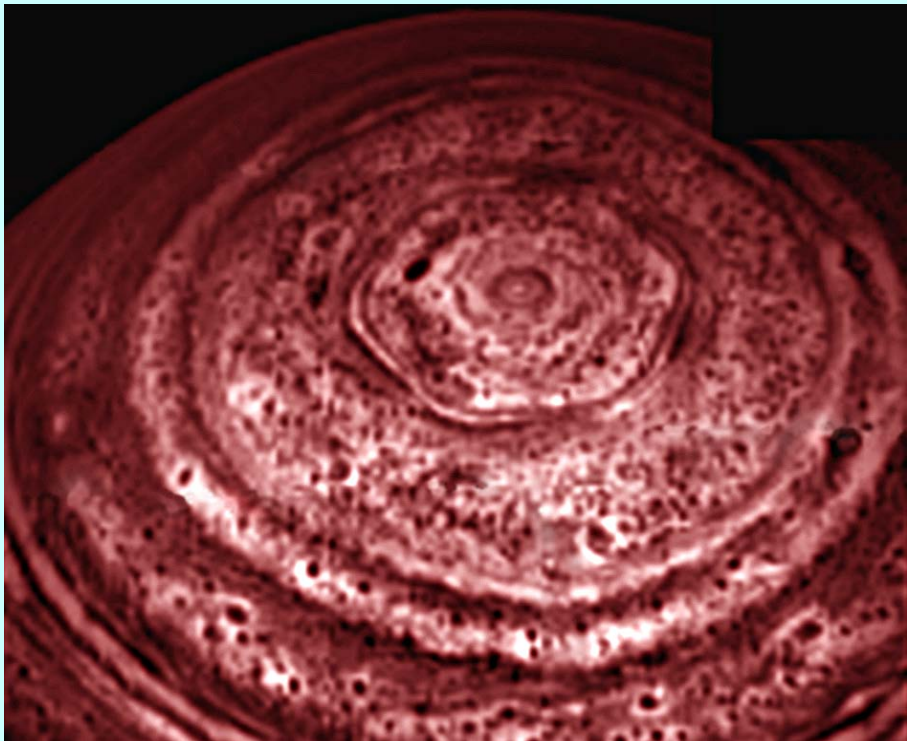
Hayashi et al. (2000)

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 and brown dwarfs, these lengths are << planetary radius

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

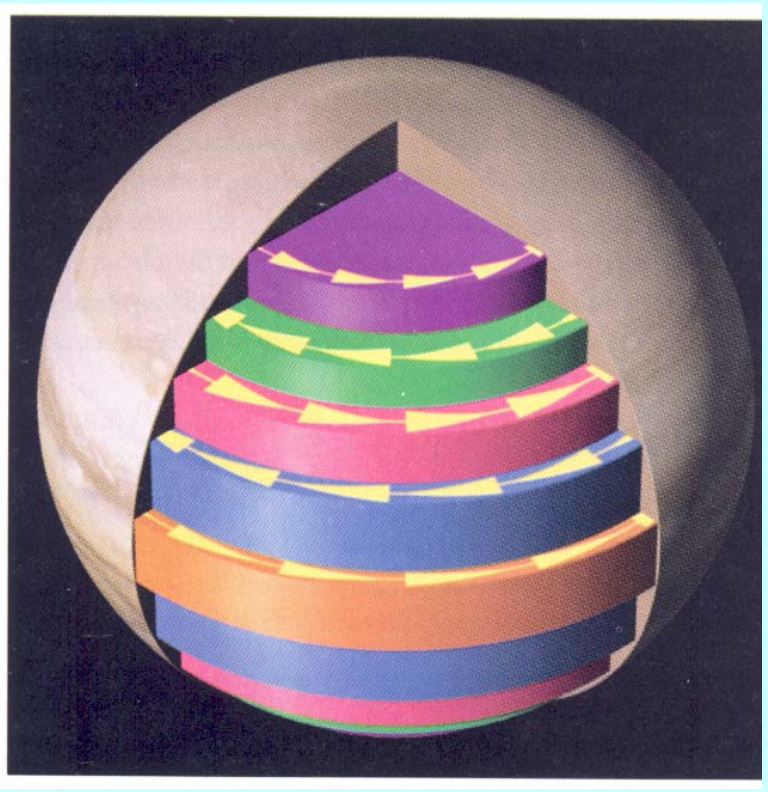


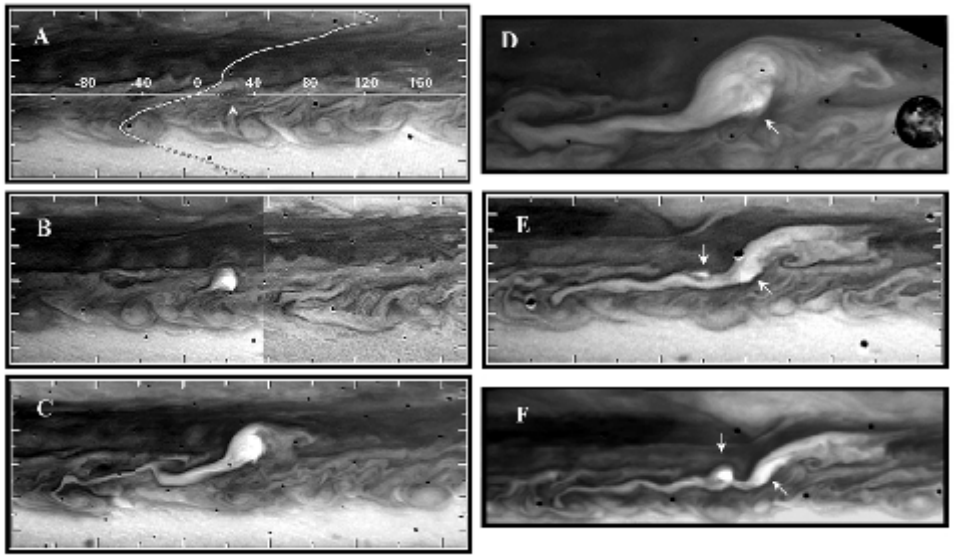
Basic Jet Scenarios

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

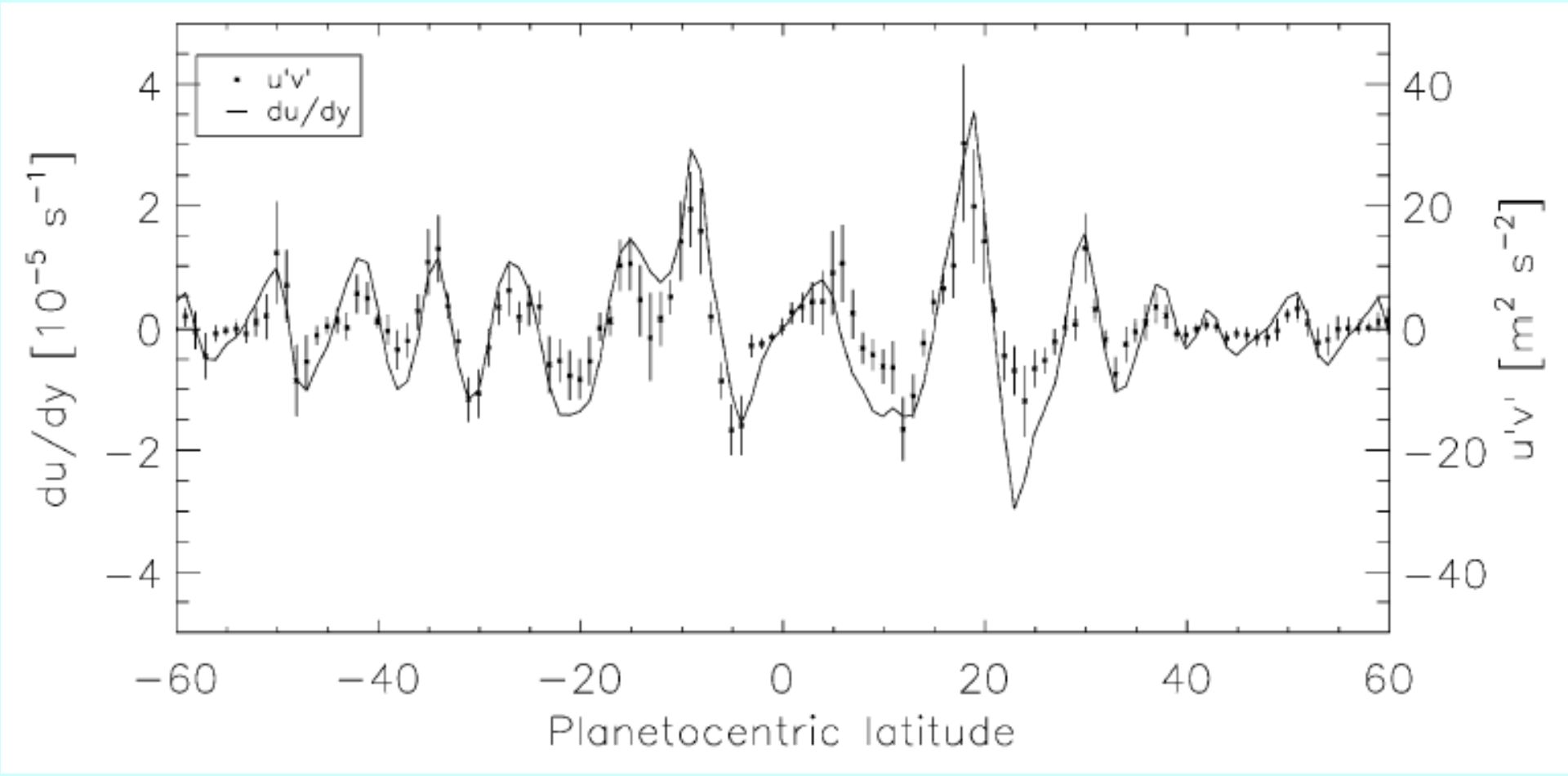
- **Models for jet pumping:**
  - ***Shallow:*** **Turbulence at cloud level (thunderstorms or baroclinic instabilities)**
  - ***Deep:*** **Convective plumes penetrating the molecular envelope**

These issues are among the most important unsolved problems in planetary atmospheres!





Evidence for eddy-momentum convergences at cloud level



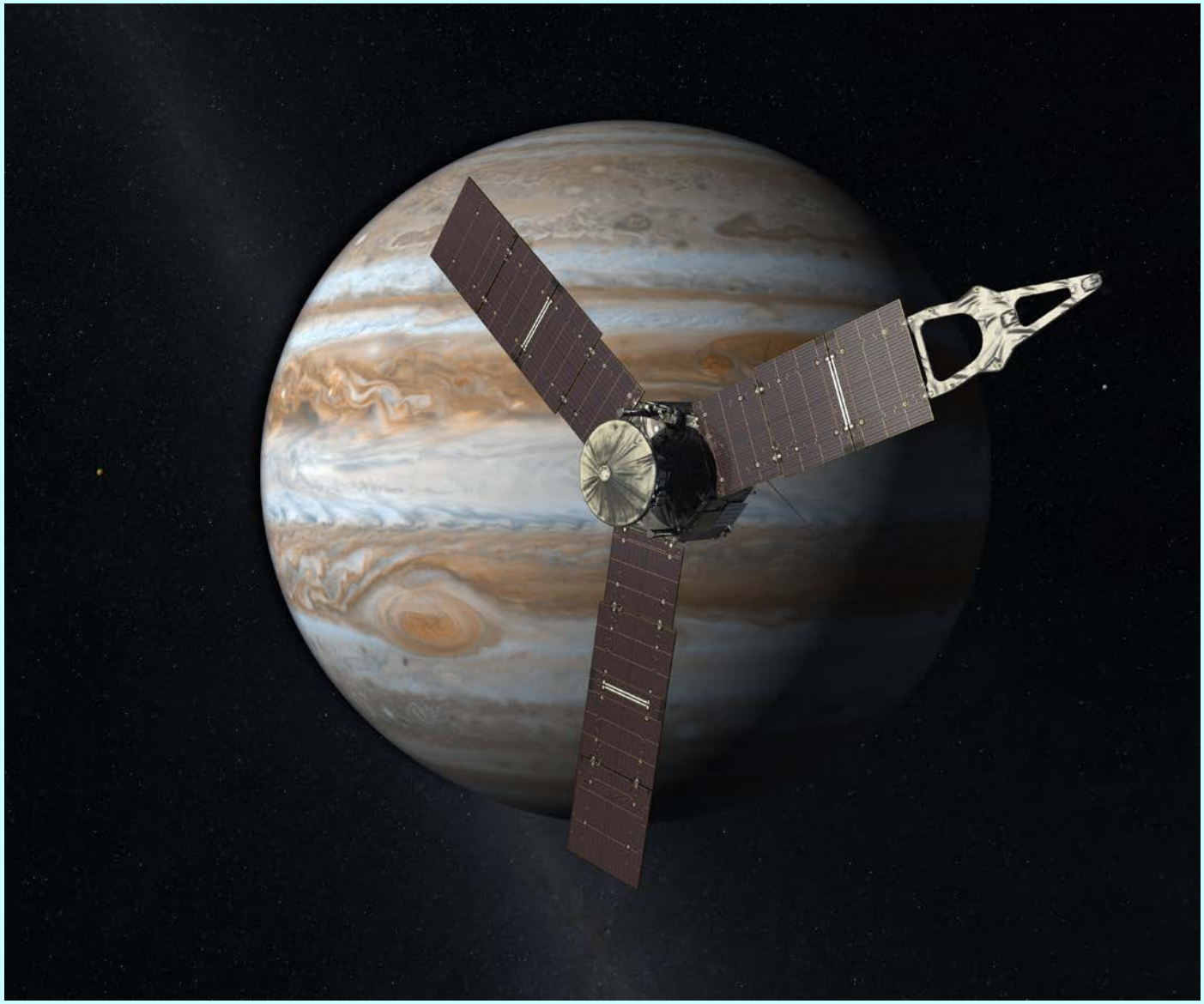
These measurements demonstrate that the jets *are* being driven at cloud level.

Salyk et al. (2006); Del Genio et al. (2007, 2012)

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?**

Gravitational sounding of giant planet interiors: answering the question of how deep the jets extend



National Aeronautics and Space Administration

Juno Payload System Overview

Phillip Morton, Payload System Manager **Mark Boyles, Deputy Payload System Manager** **Randy Dodge, Payload System Engineer**

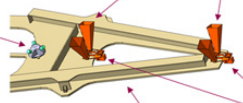
Jet Propulsion Laboratory, California Institute of Technology

Scalar Helium Magnetometer (SHM)

SHM will measure the magnitude of the magnetic field in Jupiter's environment with great accuracy.

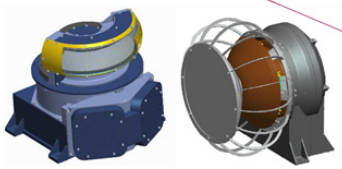
Advanced Stellar Compass (ASC)

ASC accurately measures the orientation of the magnetometers.



Jovian Auroral Distributions Experiment (JADE)

JADE will measure the distribution of electrons and the velocity distribution and composition of ions.

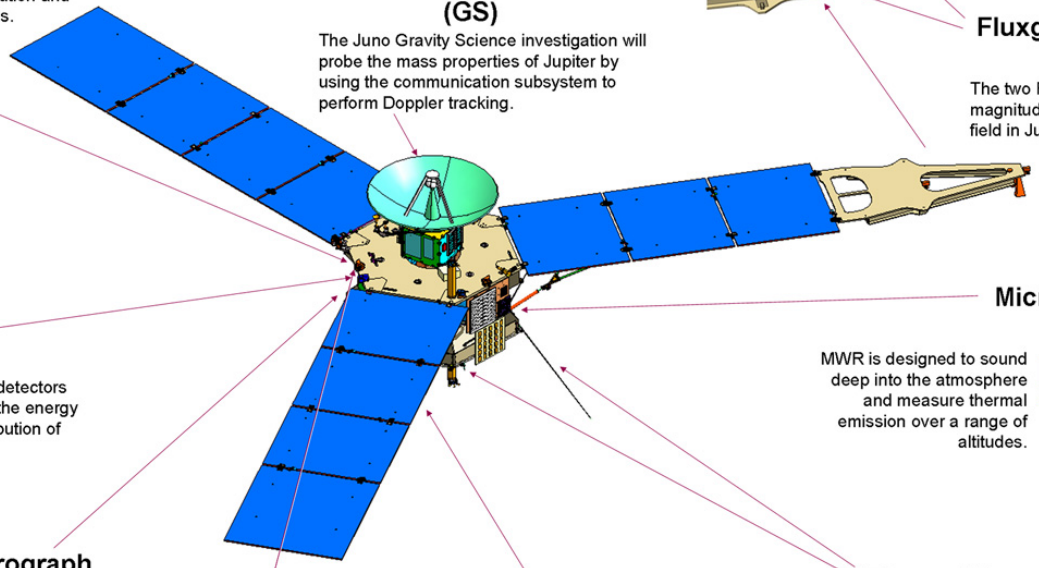


Gravity Science (GS)

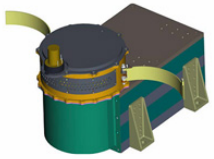
The Juno Gravity Science investigation will probe the mass properties of Jupiter by using the communication subsystem to perform Doppler tracking.

Fluxgate Magnetometer (FGM)

The two FGM sensors will measure the magnitude and direction of the magnetic field in Jupiter's environment.



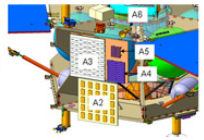
Jupiter Energetic-particle Detector Instrument (JEDI)



JEDI is a suite of detectors that will measure the energy and angular distribution of charged particles.

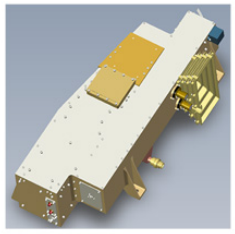
Microwave Radiometer (MWR)

MWR is designed to sound deep into the atmosphere and measure thermal emission over a range of altitudes.

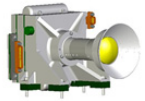


Ultraviolet Spectrograph (UVS)

UVS is an imaging spectrograph that is sensitive to ultraviolet emissions.



JunoCam

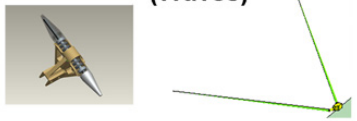


JunoCam will provide visible-color images of the Jovian cloud tops.

Jovian Infrared Auroral Mapper (JIRAM)

JIRAM will acquire infrared images and spectra of Jupiter. JIRAM is located on the bottom deck.

Plasma Waves Instrument (Waves)



Waves will measure plasma waves and radio waves in Jupiter's magnetosphere.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

This document has been reviewed for export control and it does NOT contain controlled technical data.

Juno preparation and launch August 5, 2011

Gravitational signature of internal dynamics

Gravitational potential represented as

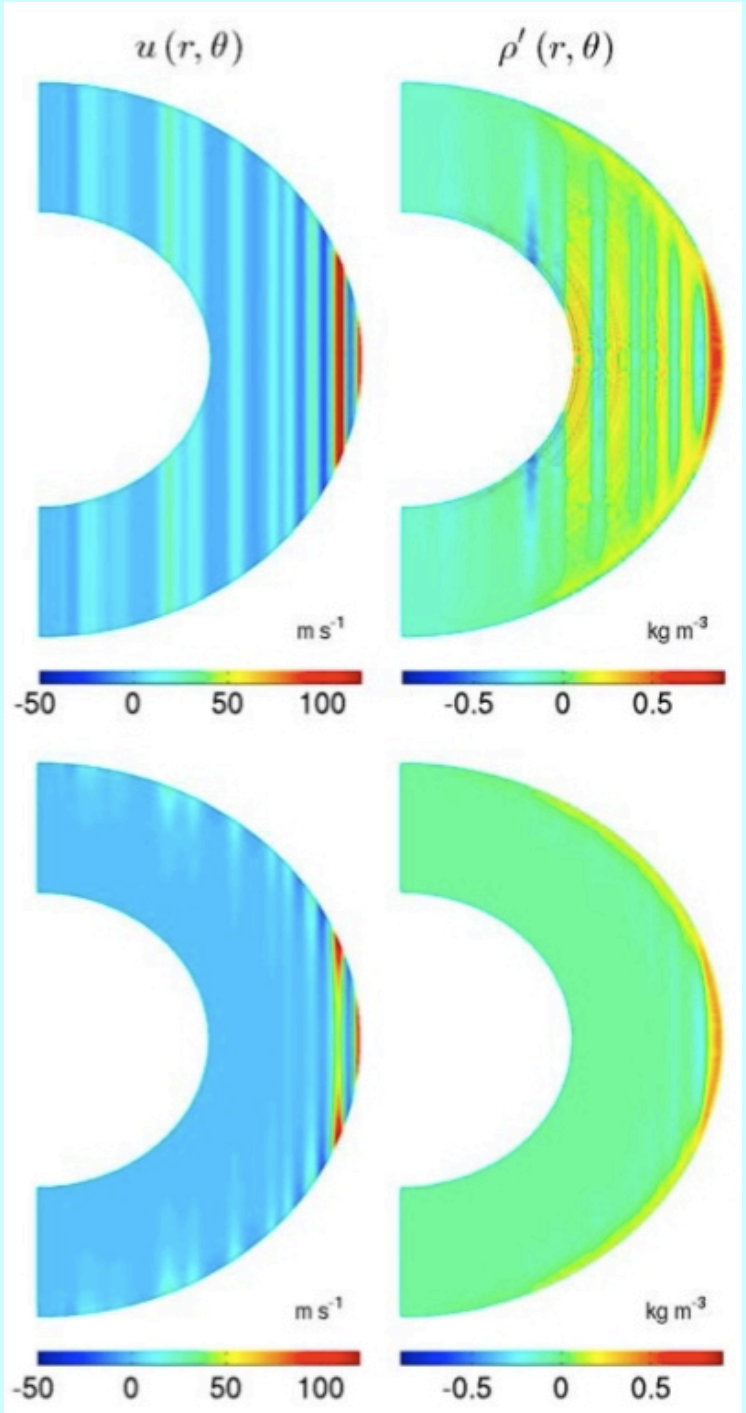
$$V(\vec{r}) = \frac{GM}{r}\left[1 - \sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^n J_n P_n(\mu)\right]$$

where J_n are the gravitational harmonics, defined as

$$J_n = -\frac{1}{Ma^n}\int_0^a \int_0^{2\pi} \int_{-1}^{1} r'^{2+n} P_n(\mu')\rho(r',\mu',\phi')\,d\mu'\,d\phi'\,dr'$$

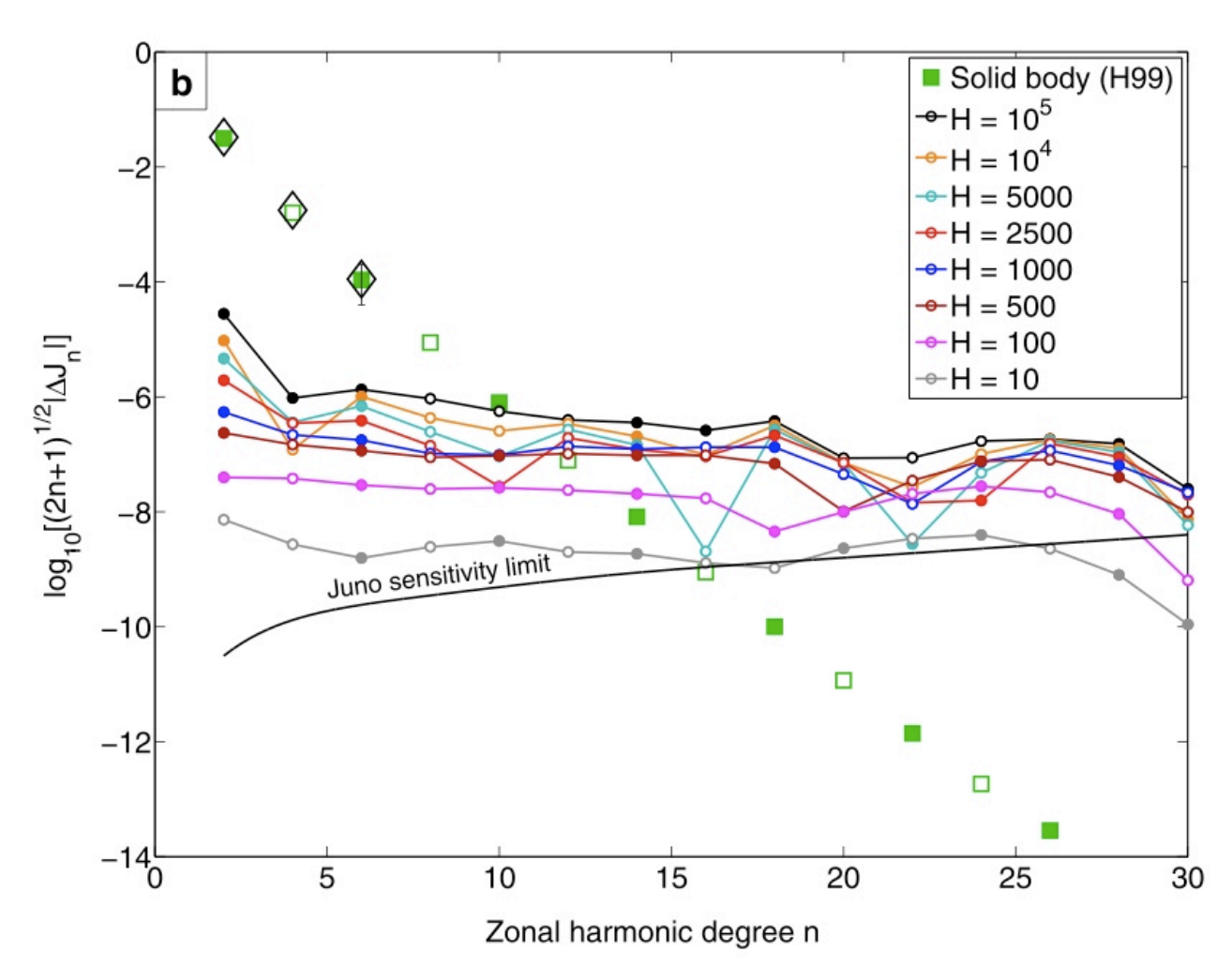
where ρ is density, P_n are Legendre polynomials, a is planetary radius, r is radial distance, ϕ is longitude, and μ is cosine of angle from rotation axis to a given point.

(See Hubbard 1984 for a review.)



Kaspi, Hubbard, Showman, & Flierl (2010)

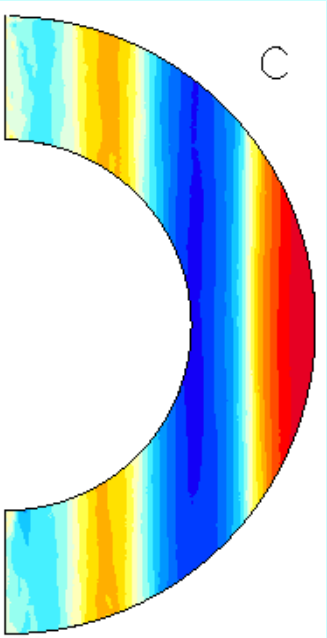
Predicted Jupiter gravity spectrum for various depths of zonal flow

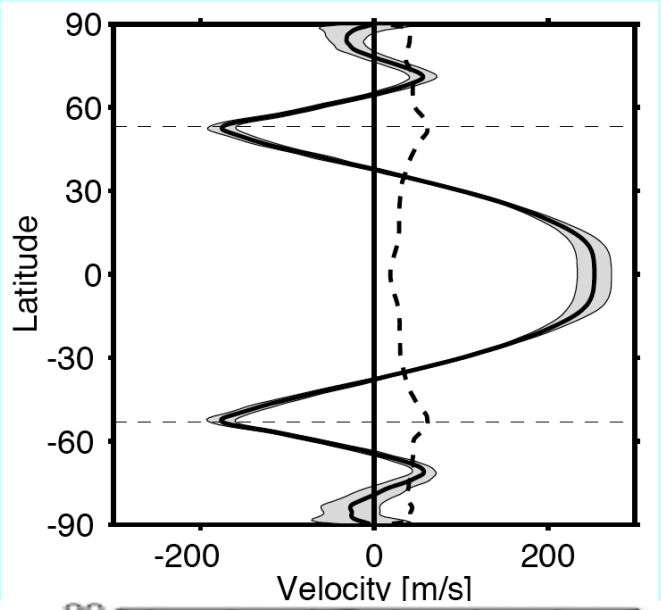


Kaspi, Hubbard, Showman, & Flierl (2010)

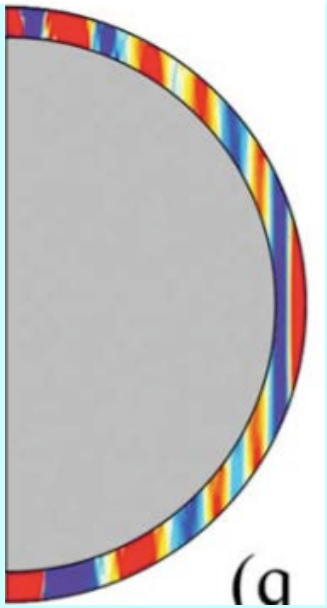
Key point: gravitational signature of jets will be detectable by Juno if jets extend at least ~500 km into the interior. Juno will measure to J_{12} or J_{14}. Jets dominate over solid-body rotation beyond J_{10} if they extend deeply enough.

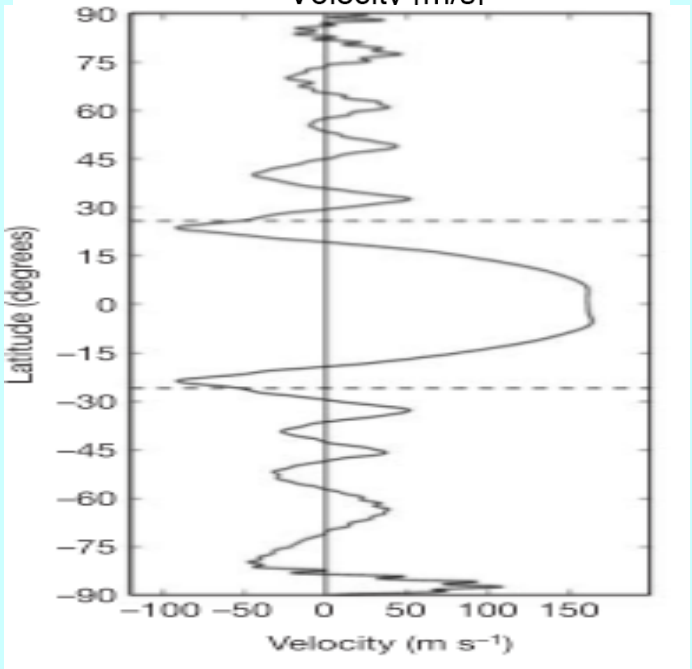
Deep convection models





Thick shell
(Christensen 2001, 2002; Aurnou & Olson 2001; Kaspi et al. 2009, Jones & Kuzanyan 2009, Showman et al. 2011, etc)

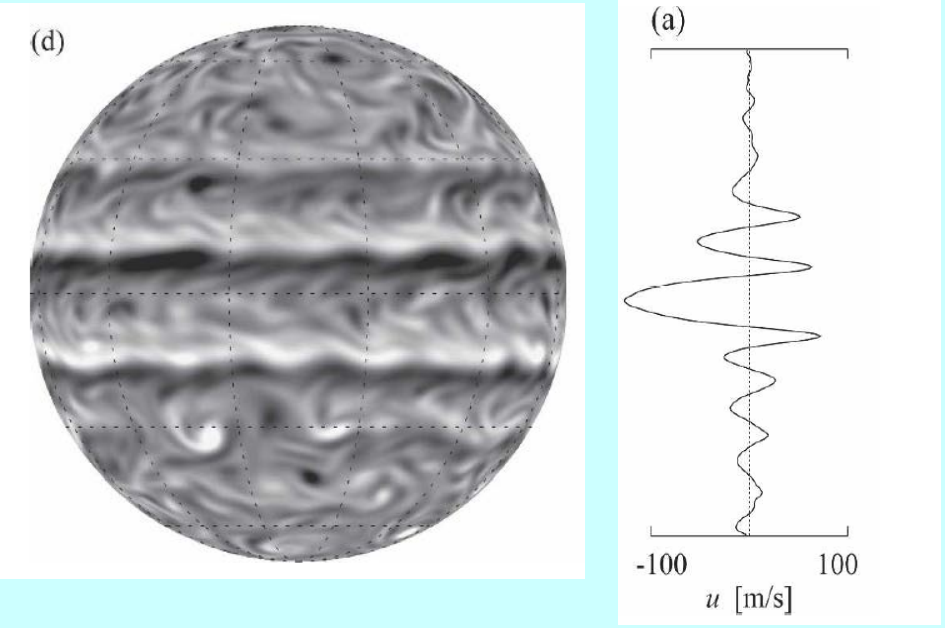




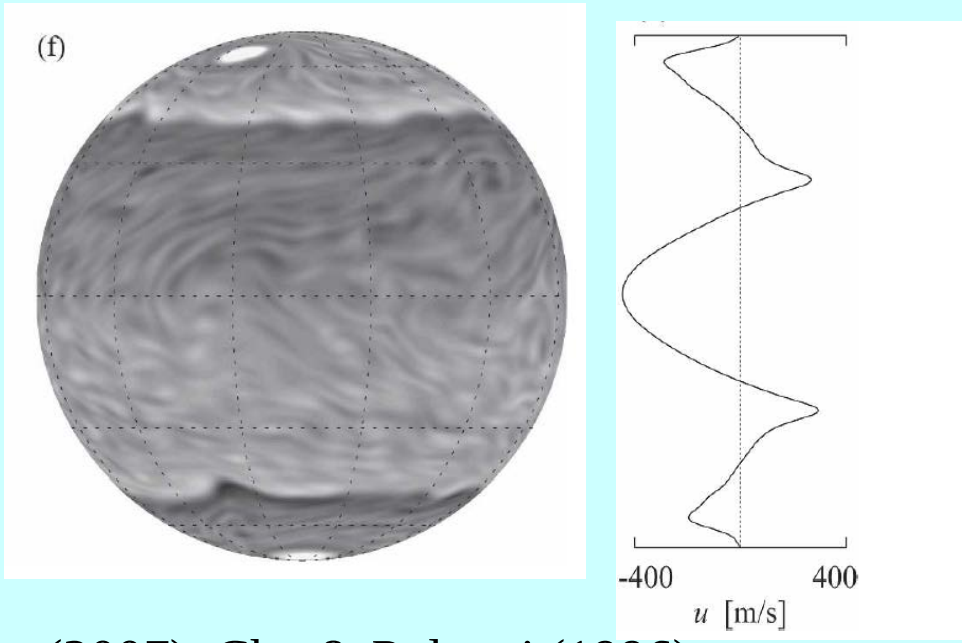
Thin shell
(Heimpel et al. 2005; Heimpel & Aurnou 2007; Aurnou et al. 2008)

One-layer shallow-water models

Jupiter



Uranus/Neptune



Scott & Polvani (2007); Showman (2007); Cho & Polvani (1996)

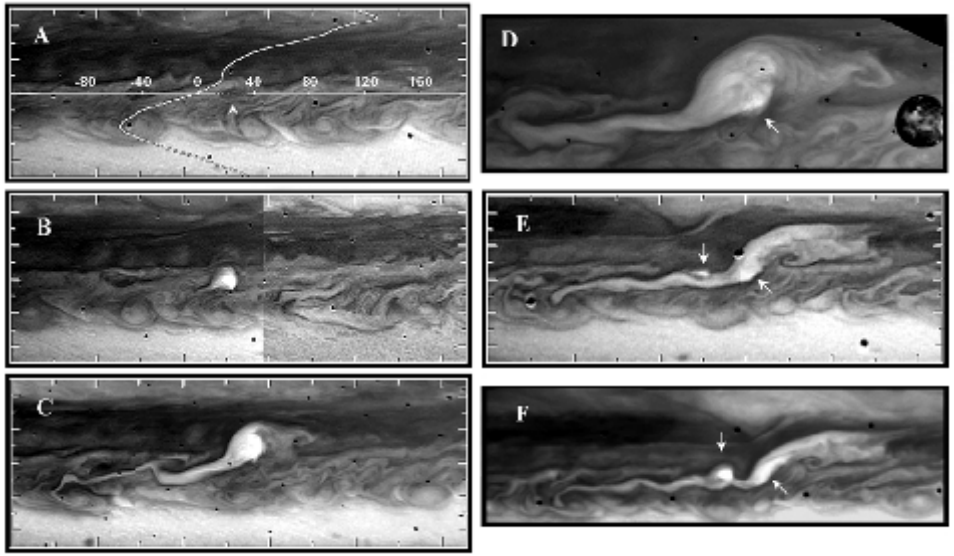
These deep and one-layer shallow models have not self-consistently predicted the equatorial jet directions

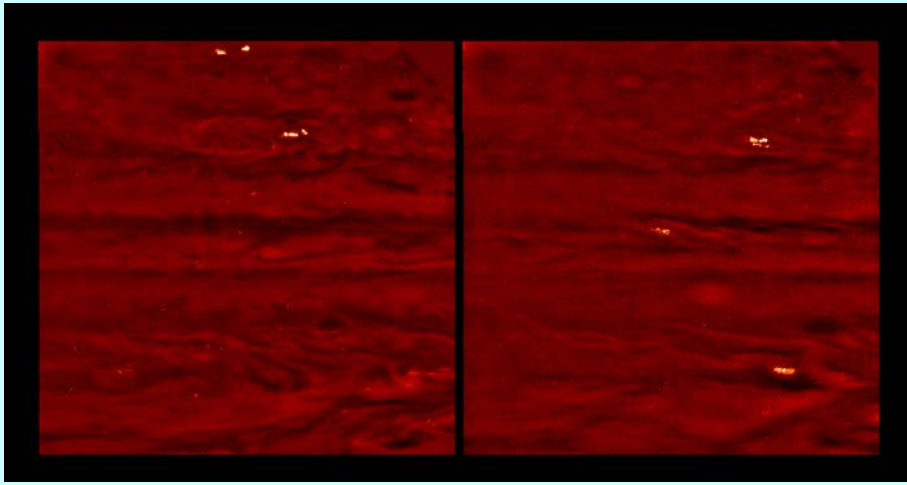
Importance of Latent Heating

- **Moist convection has been observed on Jupiter and Saturn: bright clouds that exhibit lightning and expand to ~1000 km over a few days**

- **Water abundances are uncertain, but best guesses range from ~3 times solar (Jupiter) to ~30-40 times solar or more (Uranus/Neptune)**

- **Cloud-tracking observations show that eddies at cloud level pump momentum up-gradient into the jets**





Motivating questions

1. Can a model with latent heating in the cloud layer produce multiple jet streams with the properties observed on Jupiter, Saturn, Uranus, and Neptune?

2. Why do Jupiter and Saturn have superrotating equatorial jets whereas Uranus and Neptune do not? Can the jet profiles on all four planets be explained by a single unifying mechanism?

3. Can we explain other observations, such as the small latitudinal temperature variations, the existence of storms, etc?

The Model

- **We solved the full nonlinear 3D primitive equations on a sphere using the MITgcm including advection of water vapor**

- **If water vapor is supersaturated, we relax its mixing ratio back to saturation and apply latent heating to the energy equation.**

- **Radiation treated with Newtonian cooling.**

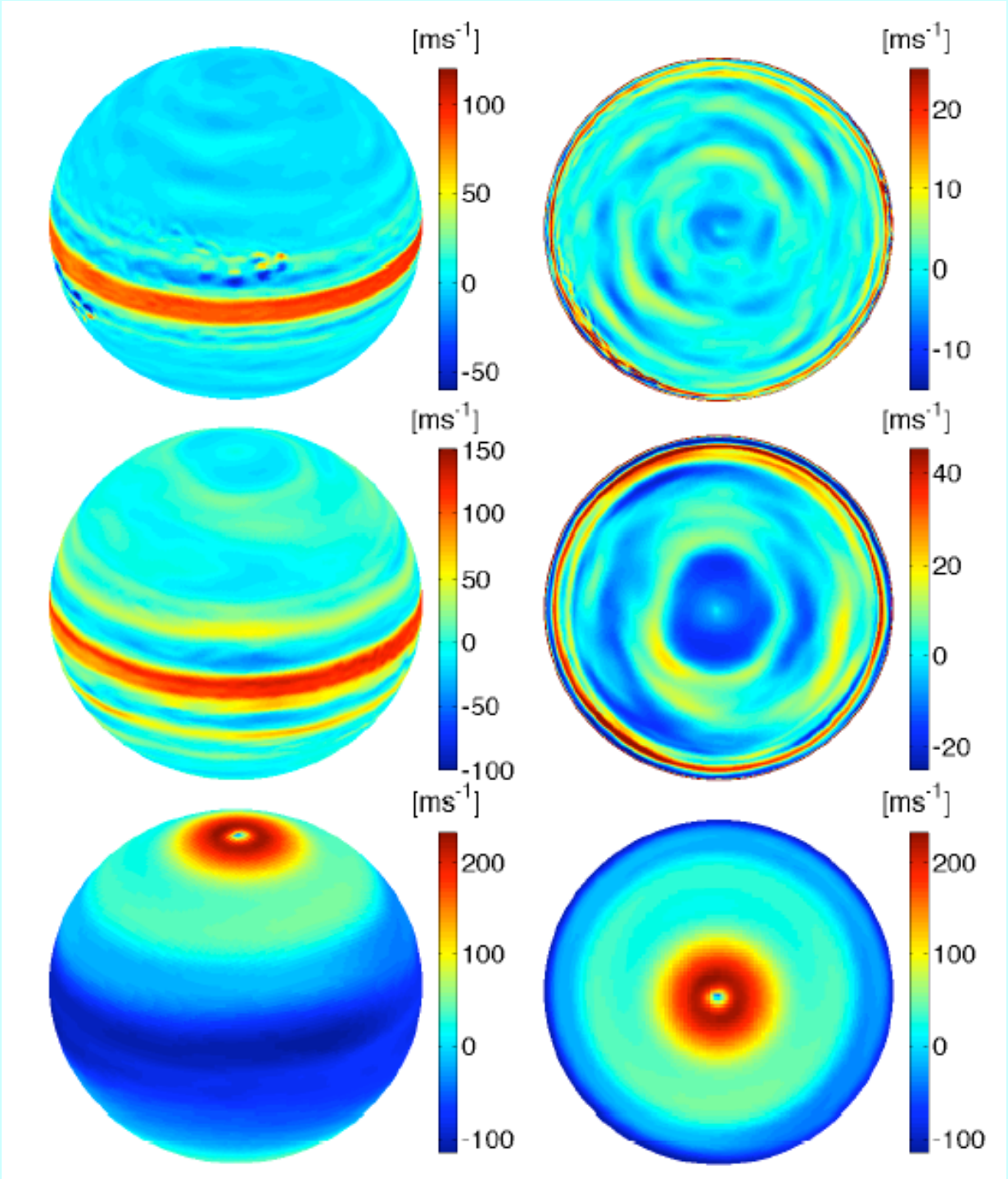
- **No microphysics.**

$$\frac{dq}{dt} = -\left(\frac{q - q_{\text{sat}}}{\tau_{\text{cond}}}\right)\delta + Q_{\text{deep}}$$

$$\frac{d\theta}{dt} = \frac{\theta_{\text{eq}} - \theta}{\tau_{\text{rad}}} + \frac{L\theta}{c_p T}\left(\frac{q - q_{sat}}{\tau_{cond}}\right)\delta$$

- **Where δ=1 when $q \geq q_{\text{sat}}$ and δ=0 otherwise.**

Lian & Showman (2010)

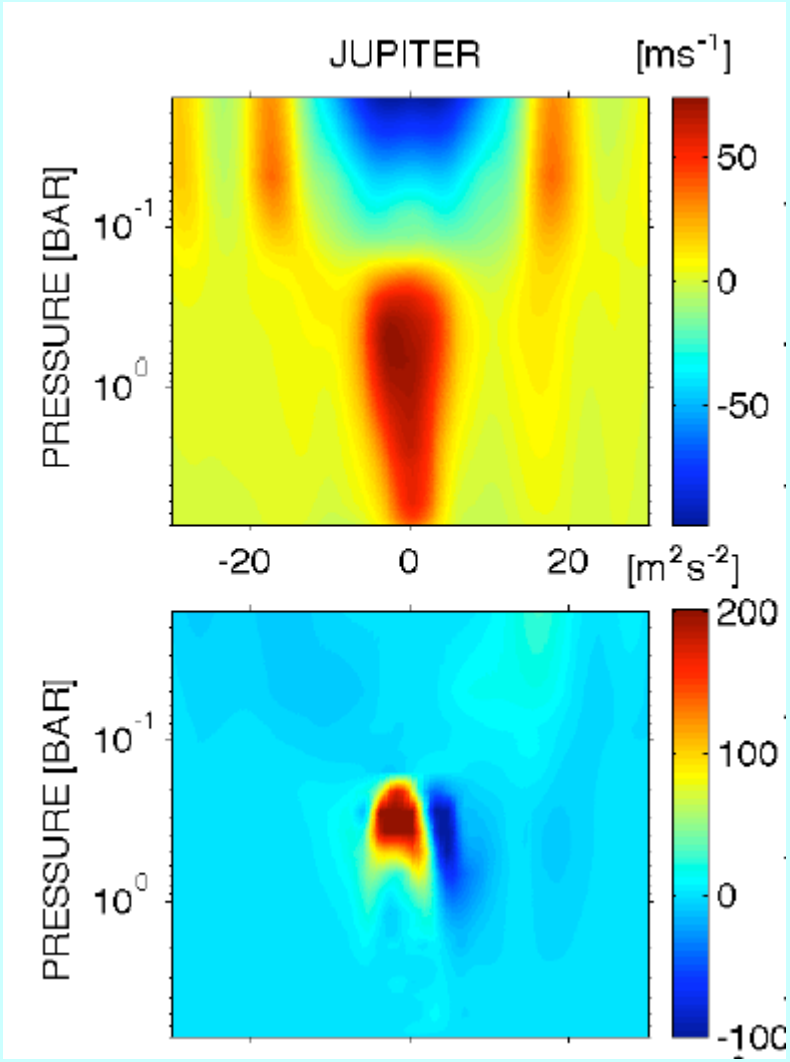


Jupiter

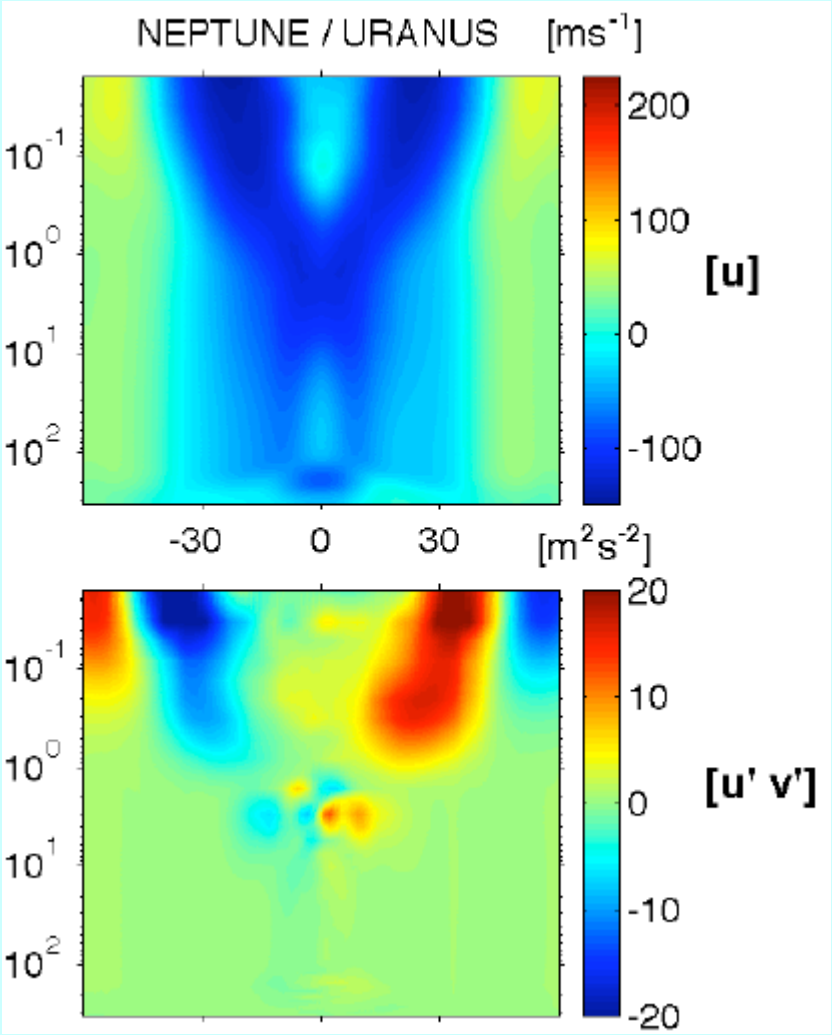
Saturn

Uranus/Neptune

Eddy pumping of equatorial jet



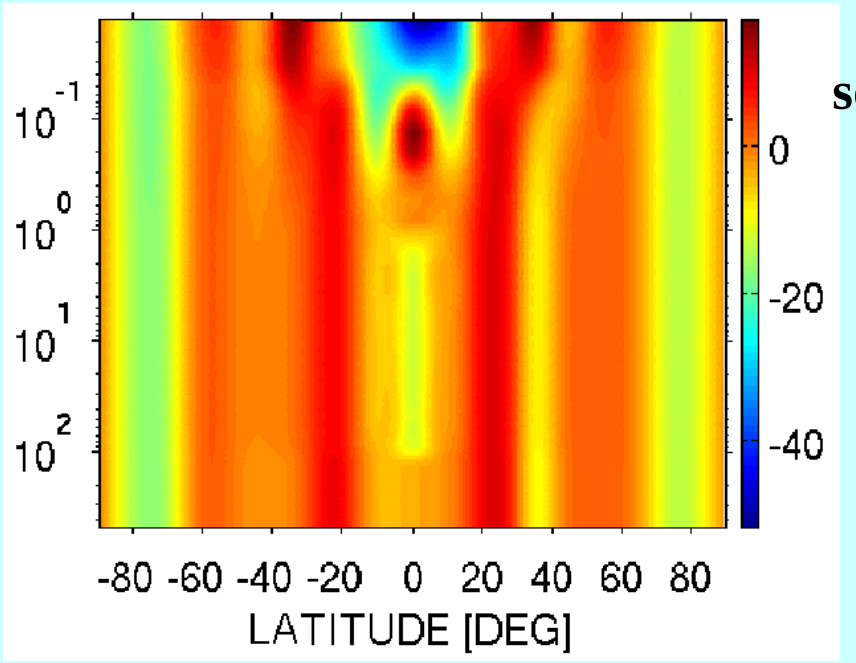
Latitude [deg]



Latitude [deg]

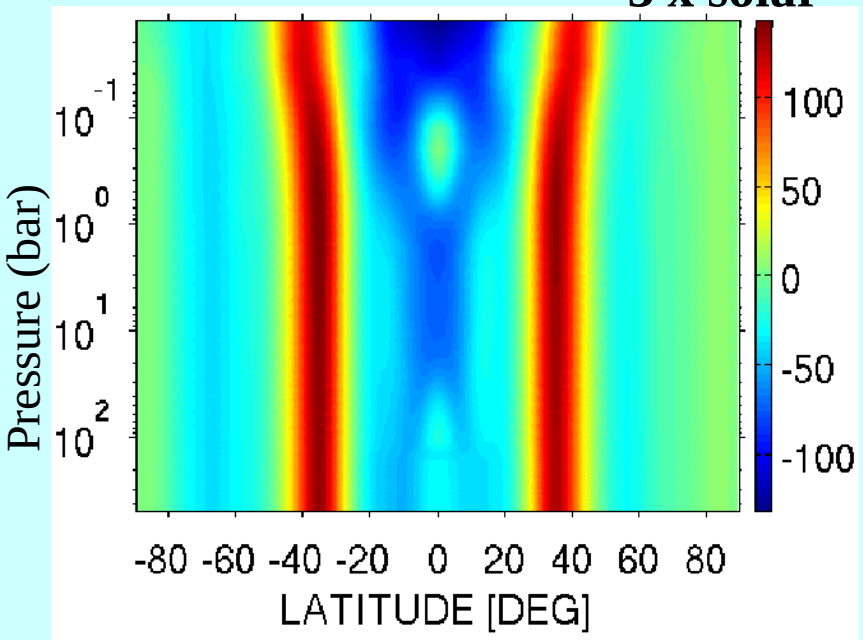
Lian & Showman (2010)

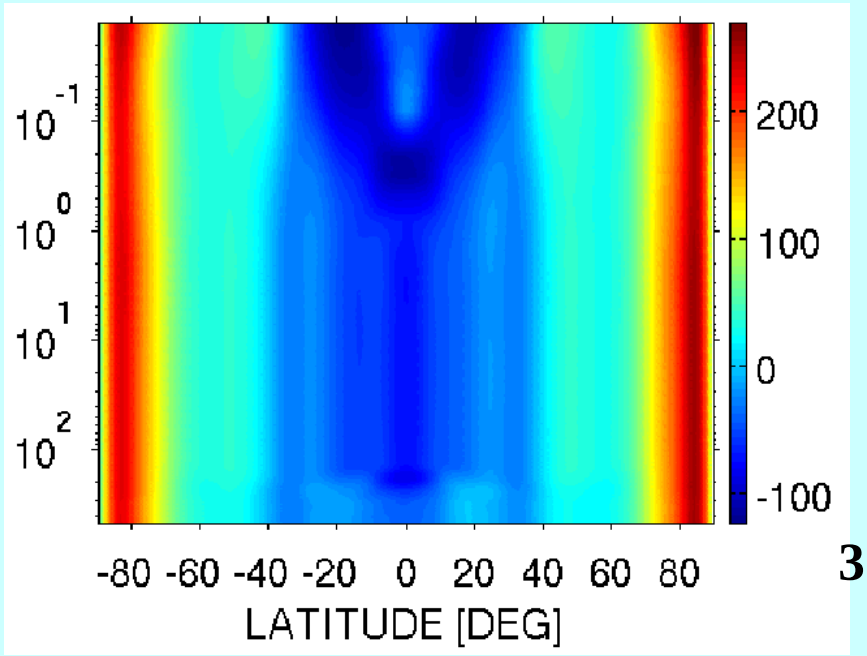
Uranus/Neptune zonal winds



solar water

3 x solar

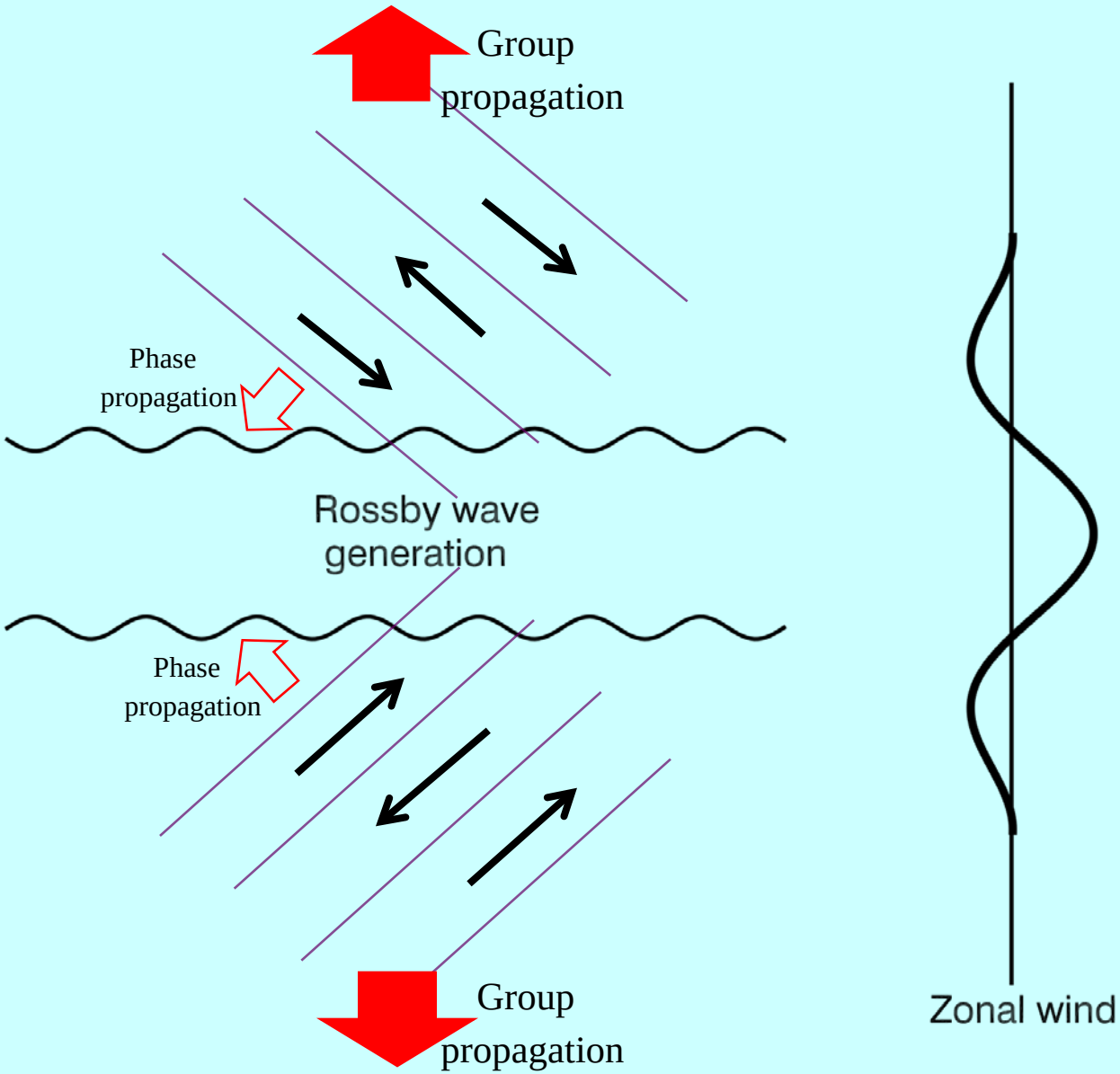




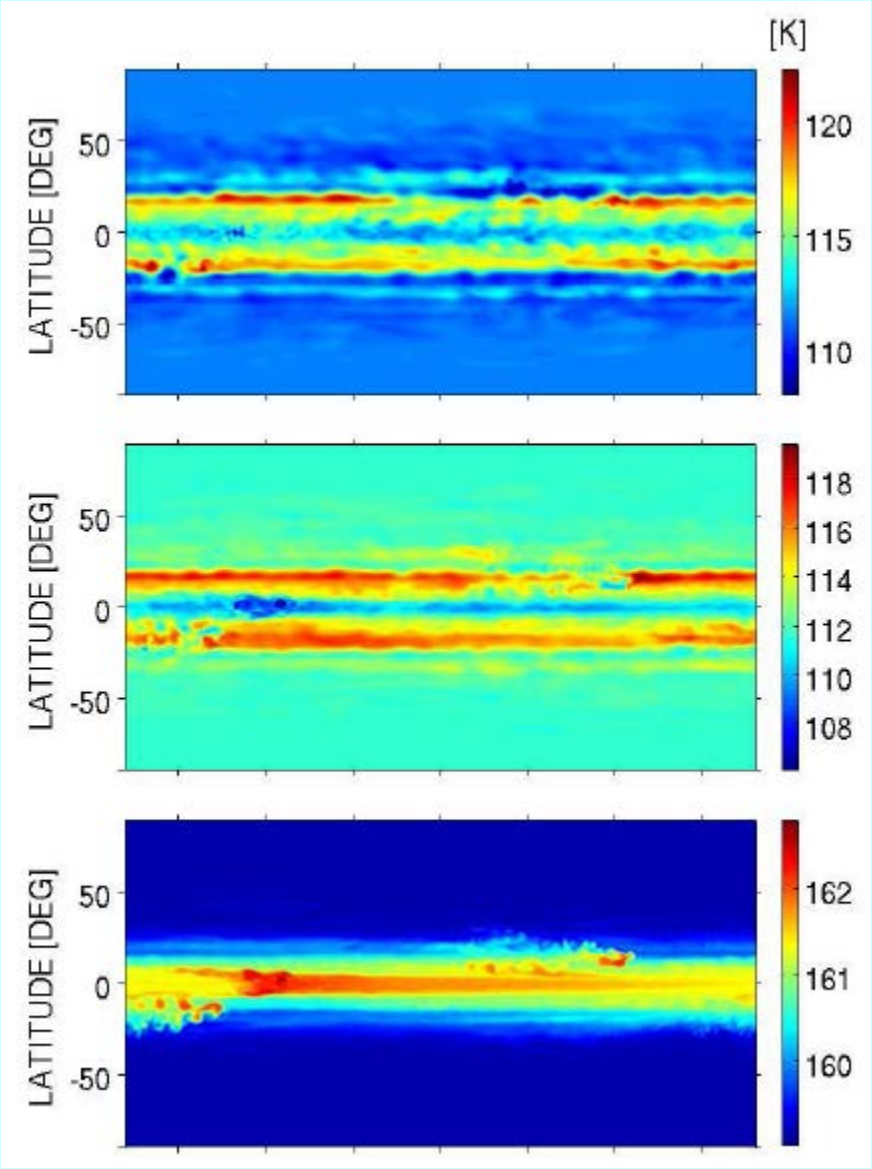
30 x solar

Lian & Showman (2010)

The importance of Rossby waves: jet formation



Jupiter temperature structure

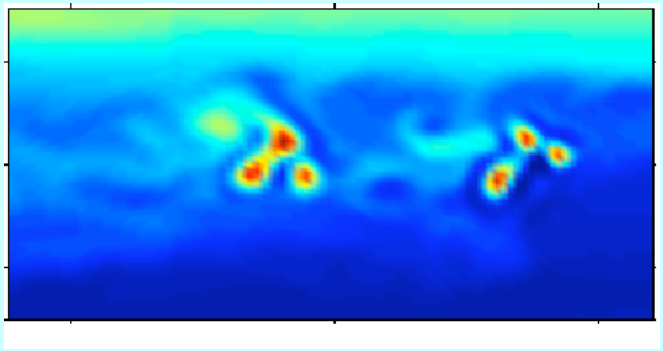


0.1 bar

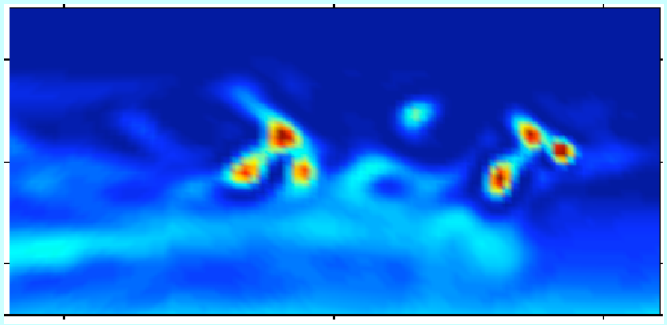
0.2 bar

0.9 bar

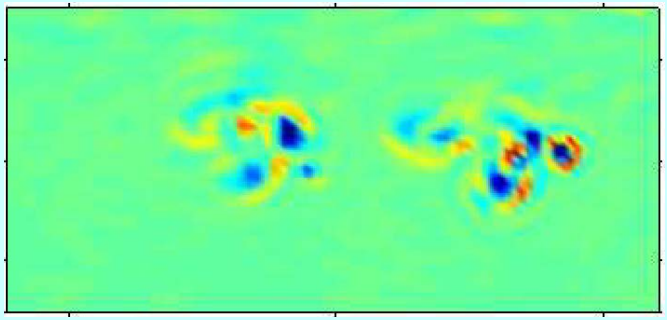
Lian & Showman (2010)



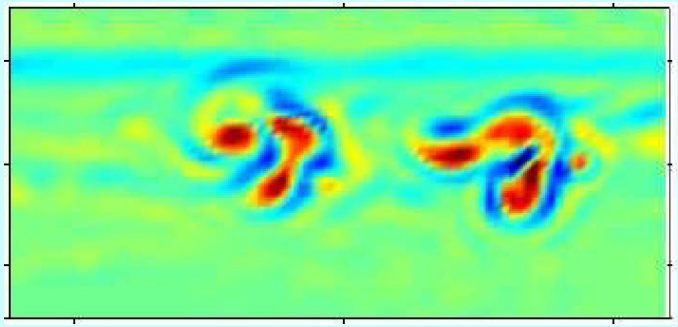
Temperature (5 bars)



Humidity (5 bars)

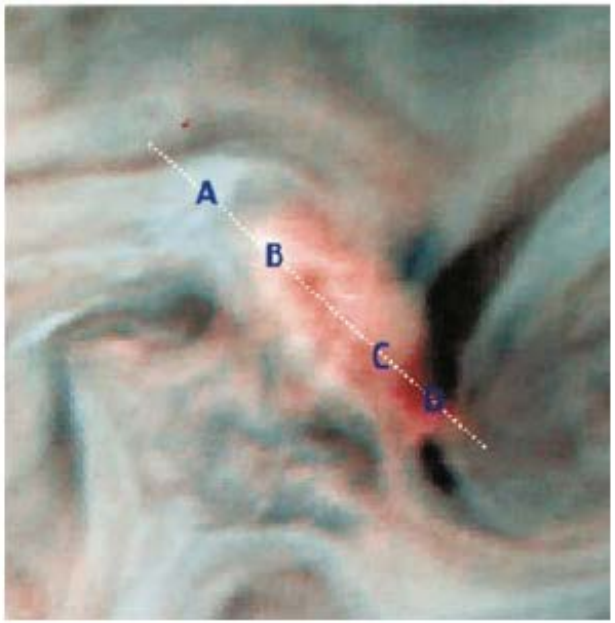


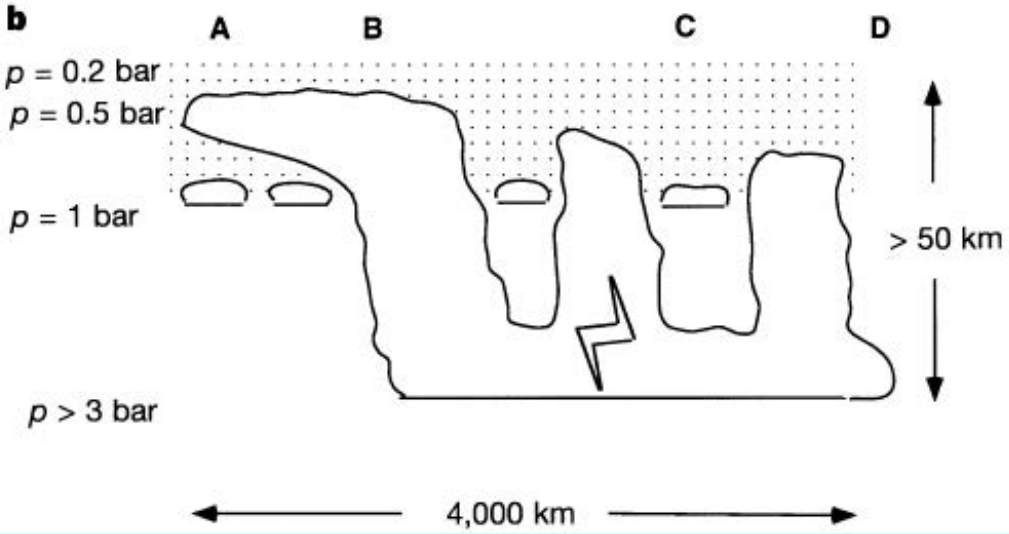
Vertical velocity (1 bar)



Vorticity (1 bars)

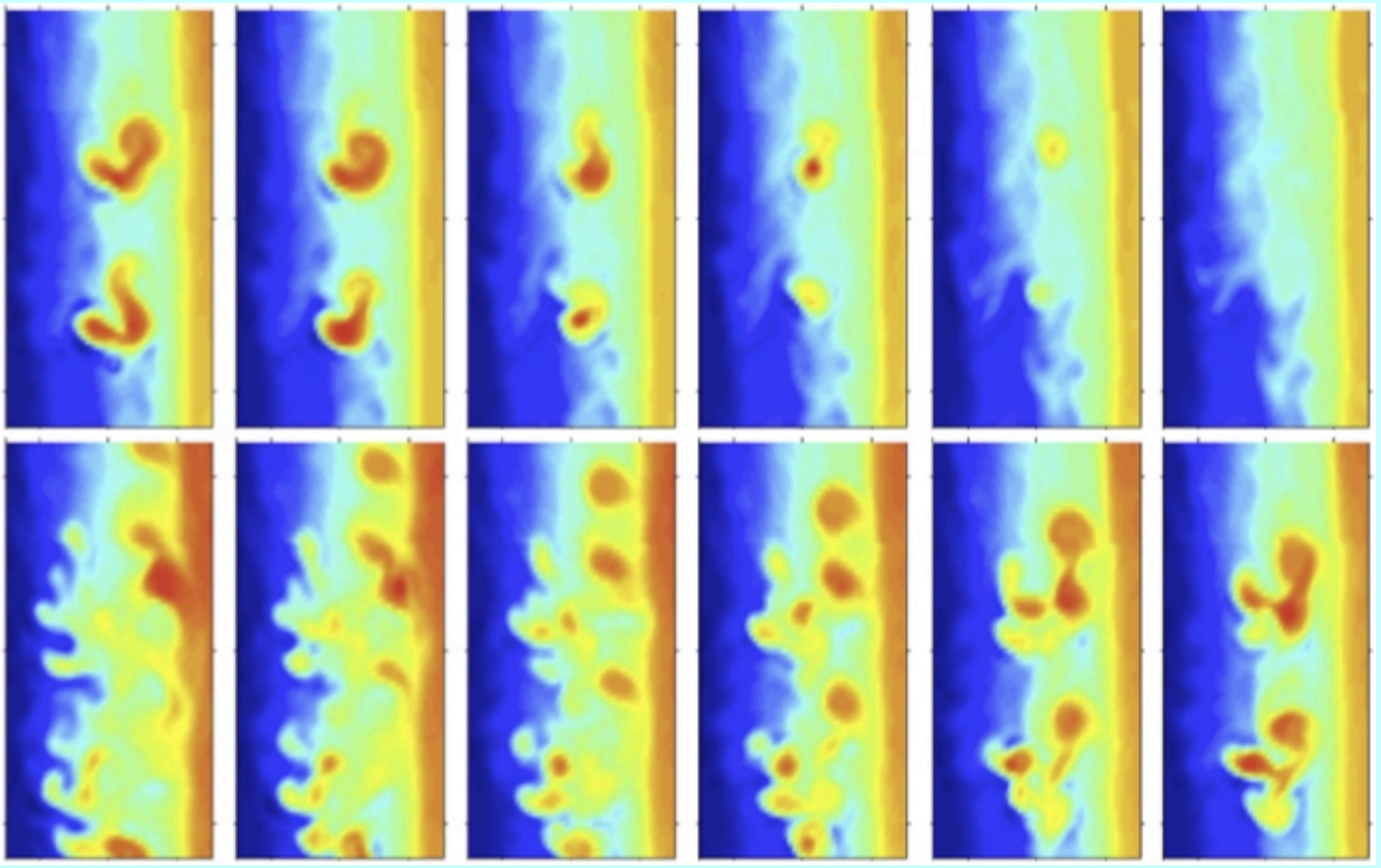
Lian & Showman (2010)





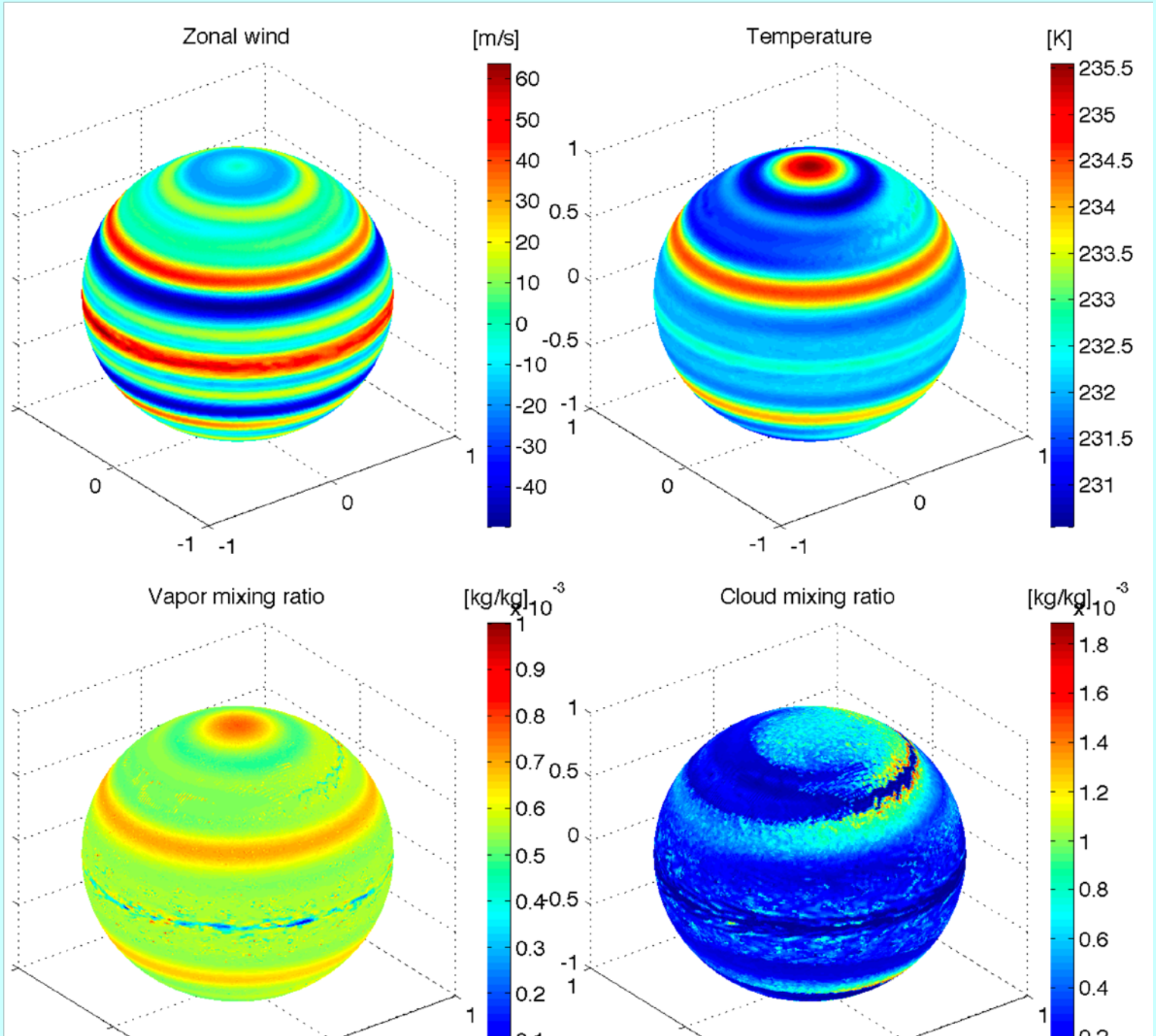
Gierasch et al. (2000)

Lian & Showman (2010)



Lian & Showman (2010)

Jupiter models including hydrological cycle and water clouds



Lian & Showman (AGU 2012)

Conclusions

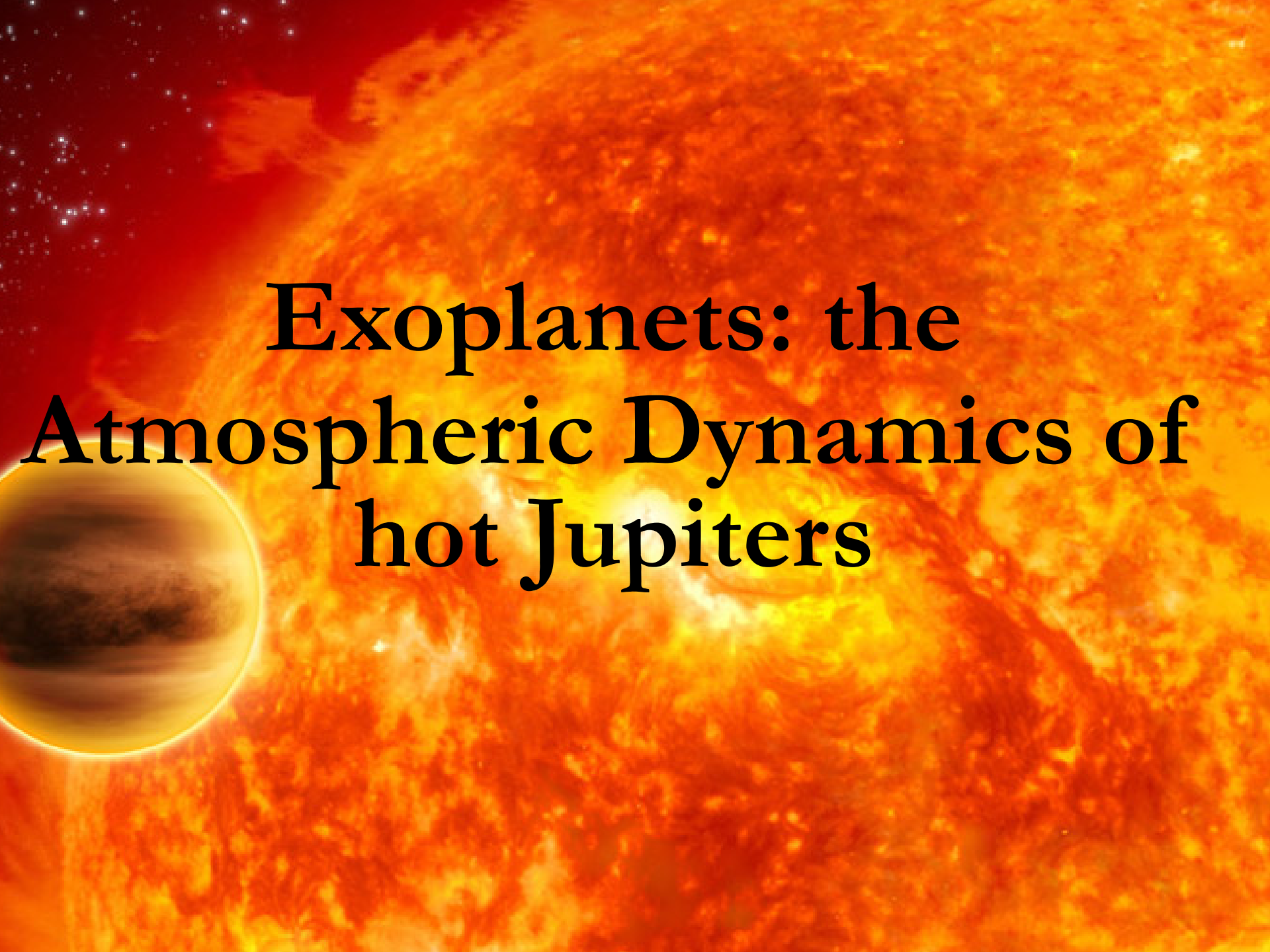
- **Juno should be able to detect the gravitational signature of Jupiter's jets if they extend 500 km or deeper into the interior. The internal dynamics should dominate over rotation in gravitational moments beyond J_{10}.**

- **On Uranus and Neptune, the observed J_4 implies that the fast zonal jets seen at the cloud layer must be confined to these planets' atmospheres. This would seem to emphasize atmospheric processes for the mechanisms maintaining the jets.**

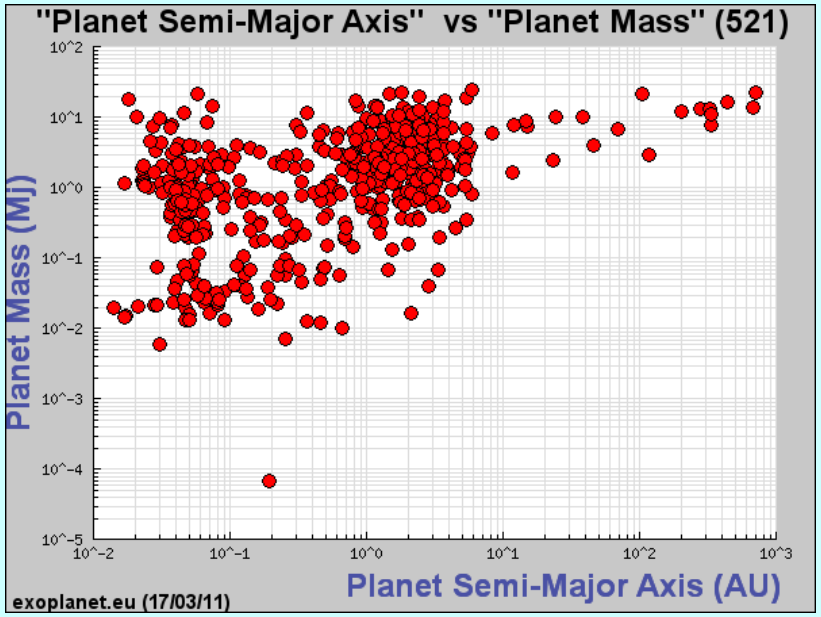
- **3D models with a hydrological cycle and latent heating show the development of numerous banded jet streams similar to those on the giant planets. Jupiter and Saturn-like cases naturally develop ~20-odd jets, while Uranus/Neptune-like cases develop ~3 jets.**

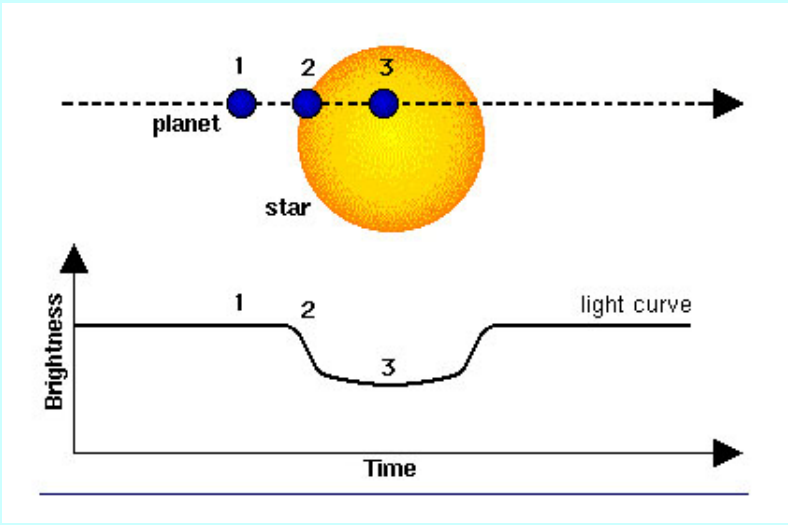
- **Consistent with observations, the Jupiter-like and Saturn-like cases spontaneously develop equatorial *superrotation* while the Uranus/Neptune-like cases develop equatorial *subrotation*.**

- **These models show the spontaneous development of storm-like features, qualitatively consistent with observed storms on Jupiter and Saturn**

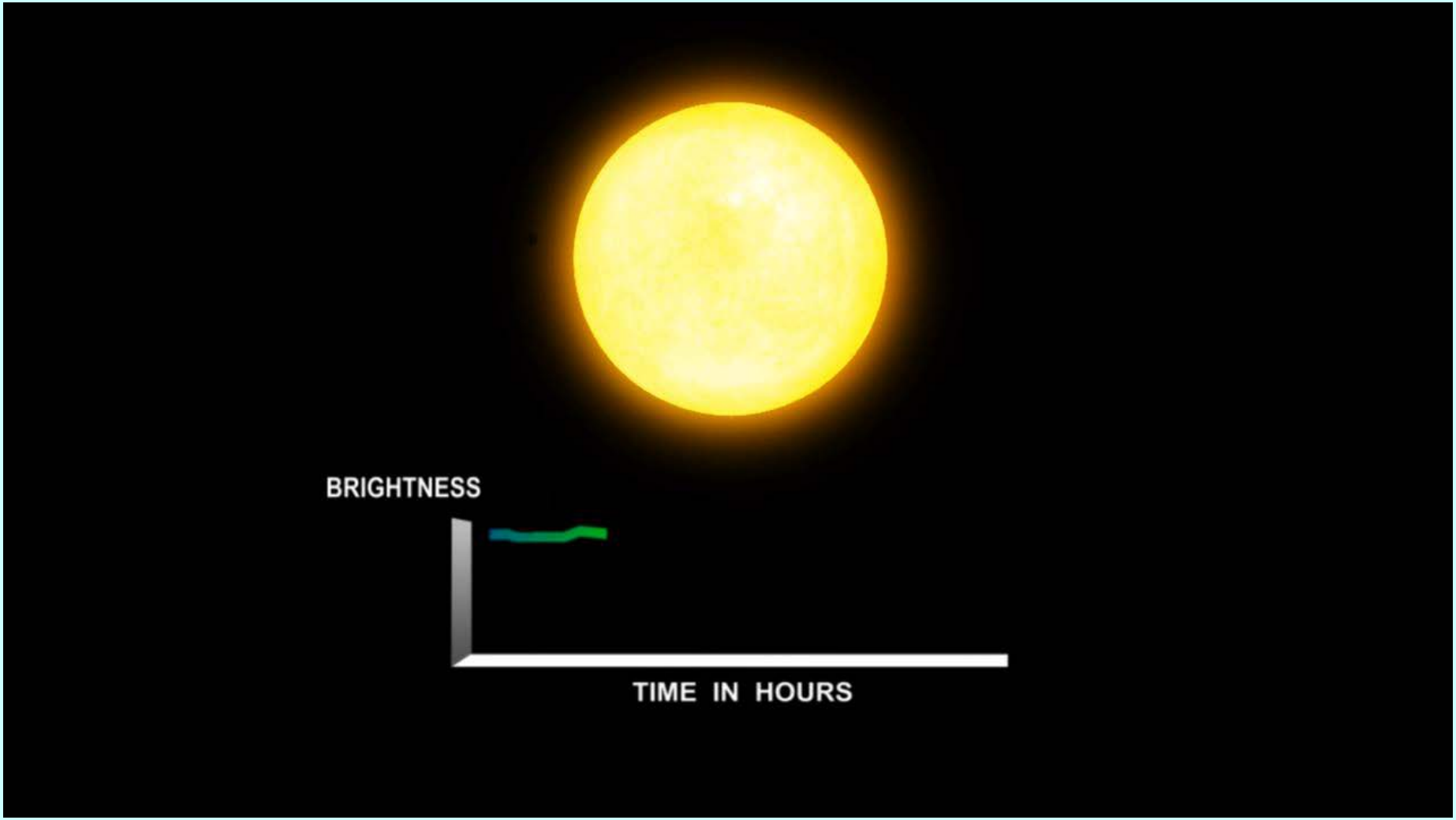

Exoplanets: the
Atmospheric Dynamics of
hot Jupiters

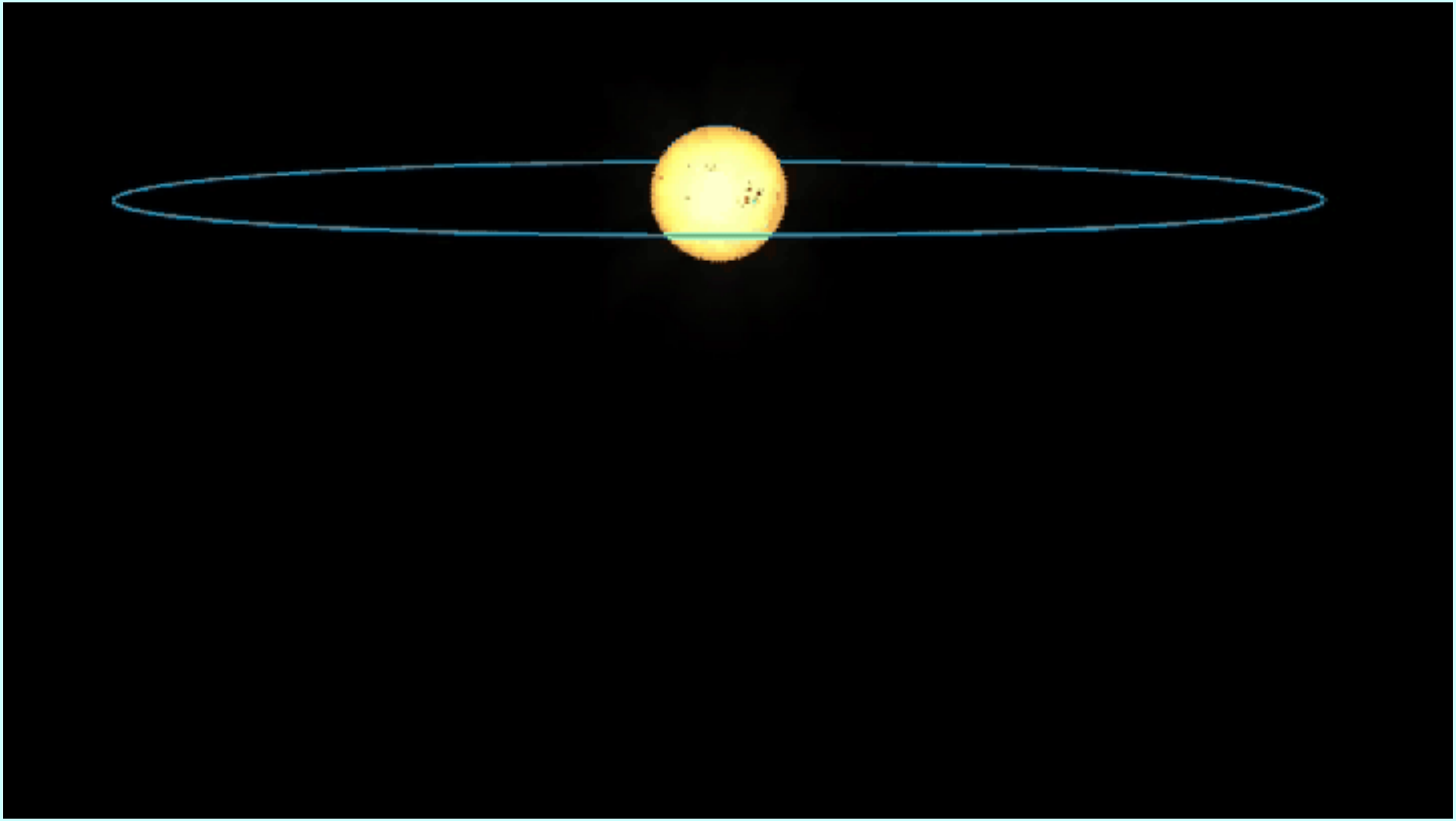
Exoplanets: an exploding new field

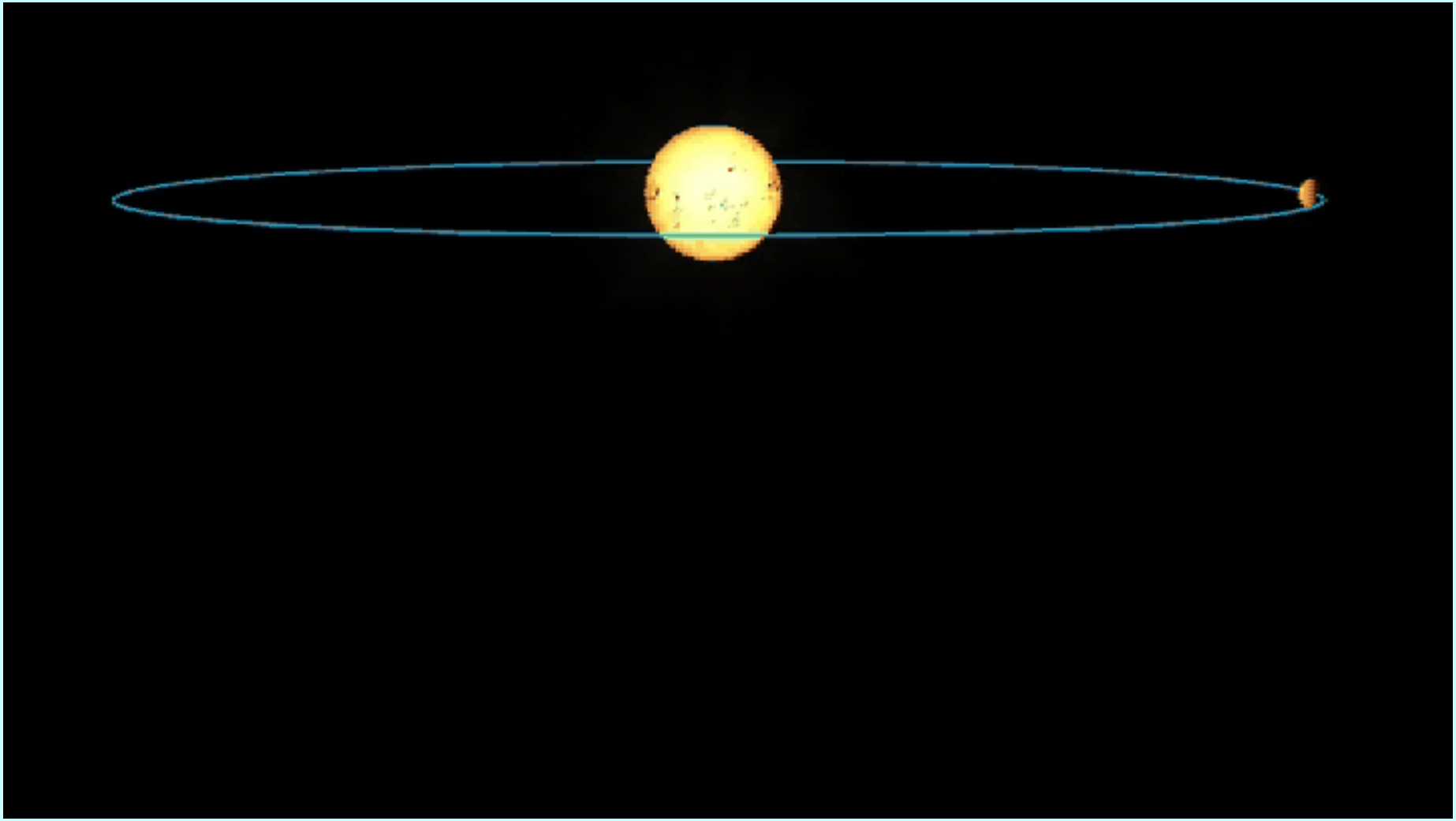




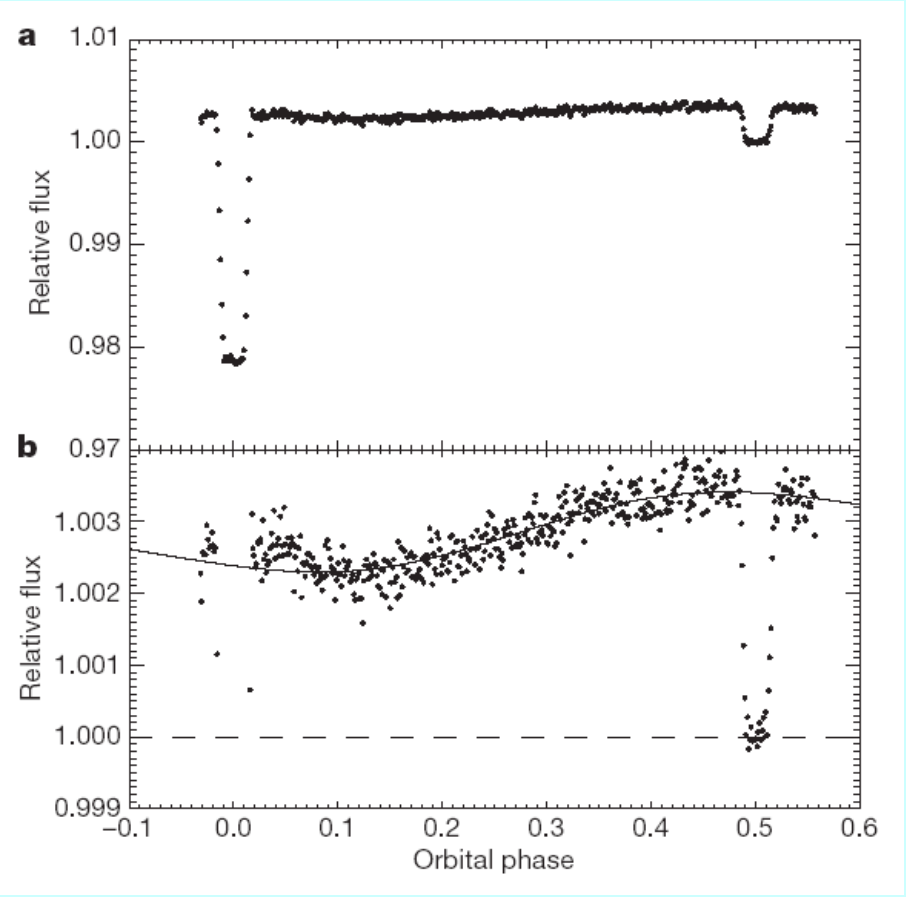
- **Almost 900 known extrasolar planets, most discovered with the "Doppler" method (plus ~2300 candidates from the NASA Kepler mission).**
- **~300 planets detected with "transit" method (allows characterization)**
- **Together, these data give mass, radius, mean density, and orbital properties**
- **Many are Jupiter-mass planets very close to their stars: the "hot Jupiters"**


BRIGHTNESS
TIME IN HOURS

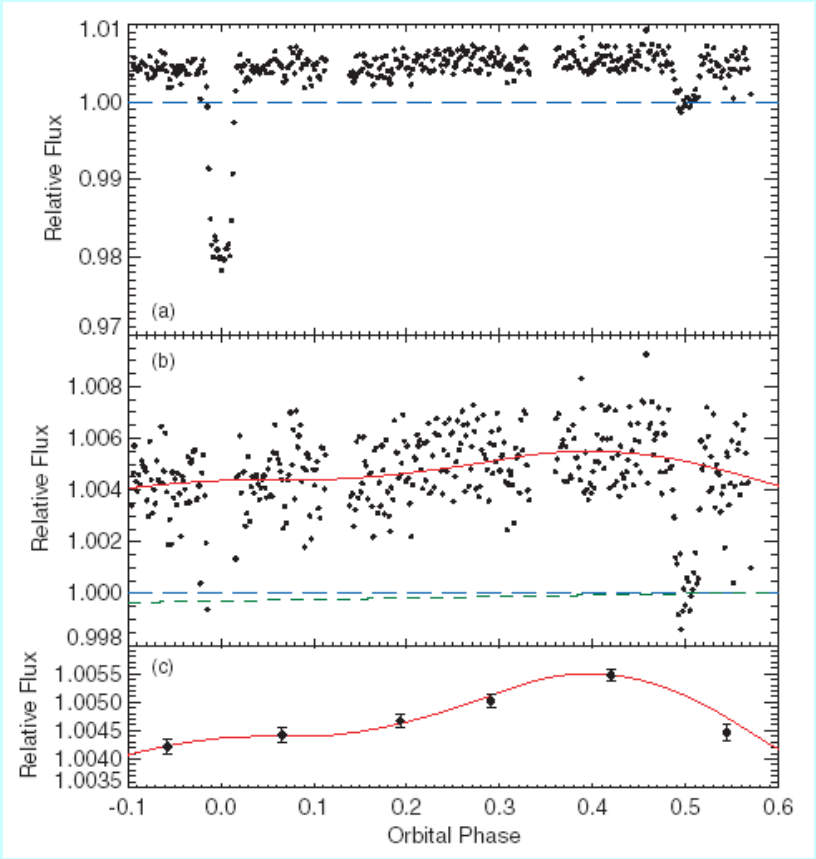




Spitzer light curves for HD 189733b

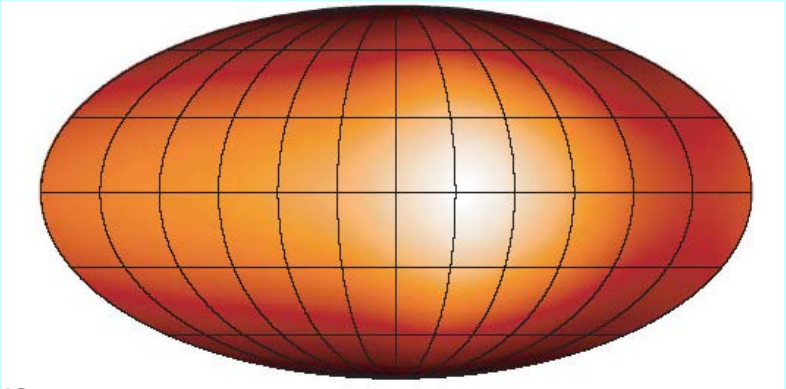


8 μm

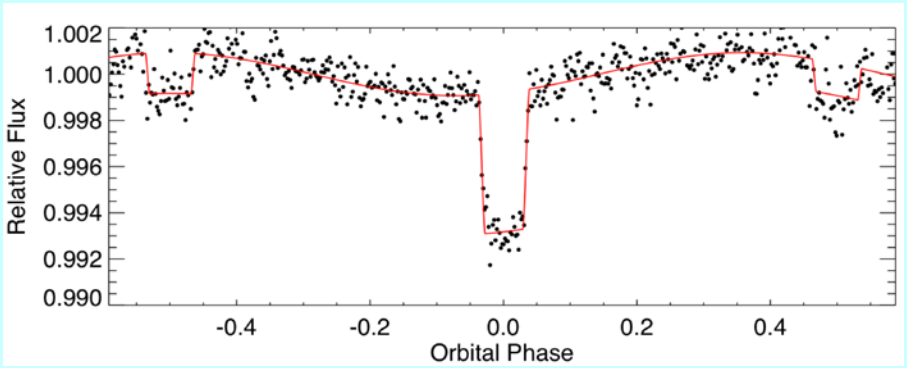


24 μm

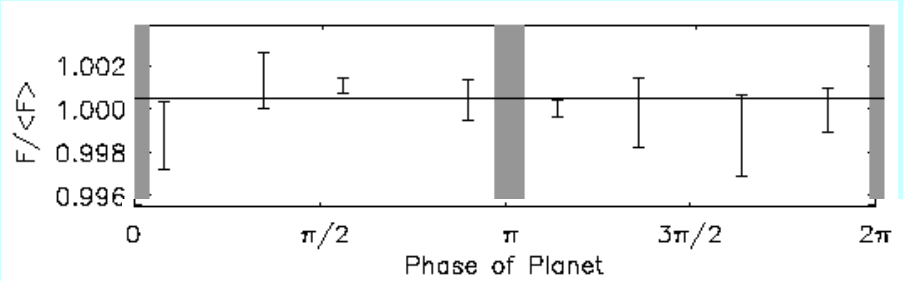
Knutson et al. (2007, 2009)



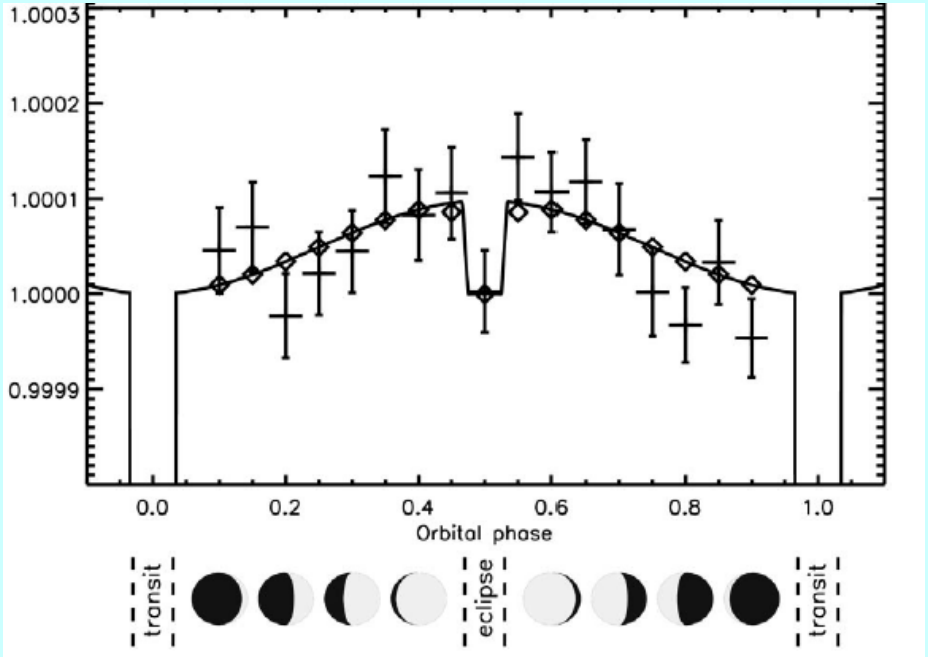
Lightcurves for hot Jupiters



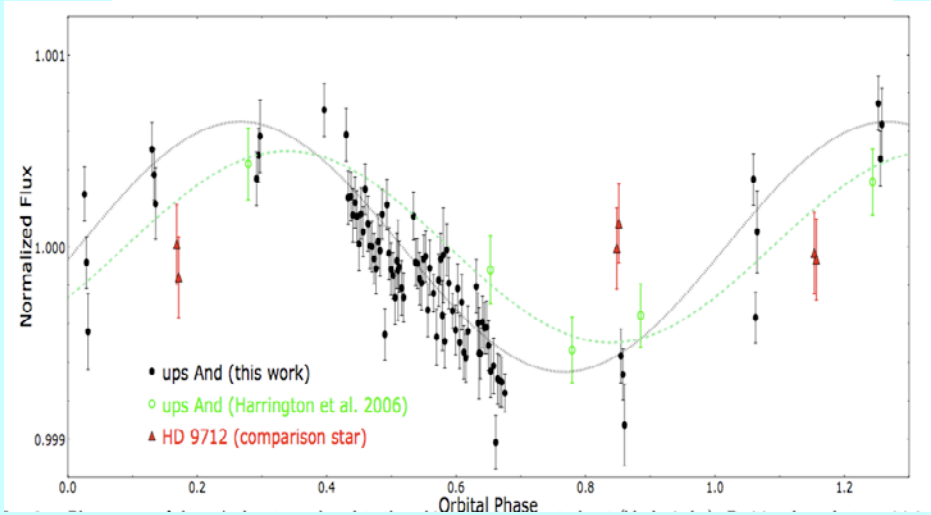
HAT-P-7b (Knutson et al., unpublished; Borucki et al. 2009)



HD209458b (Cowan et al. 2007)

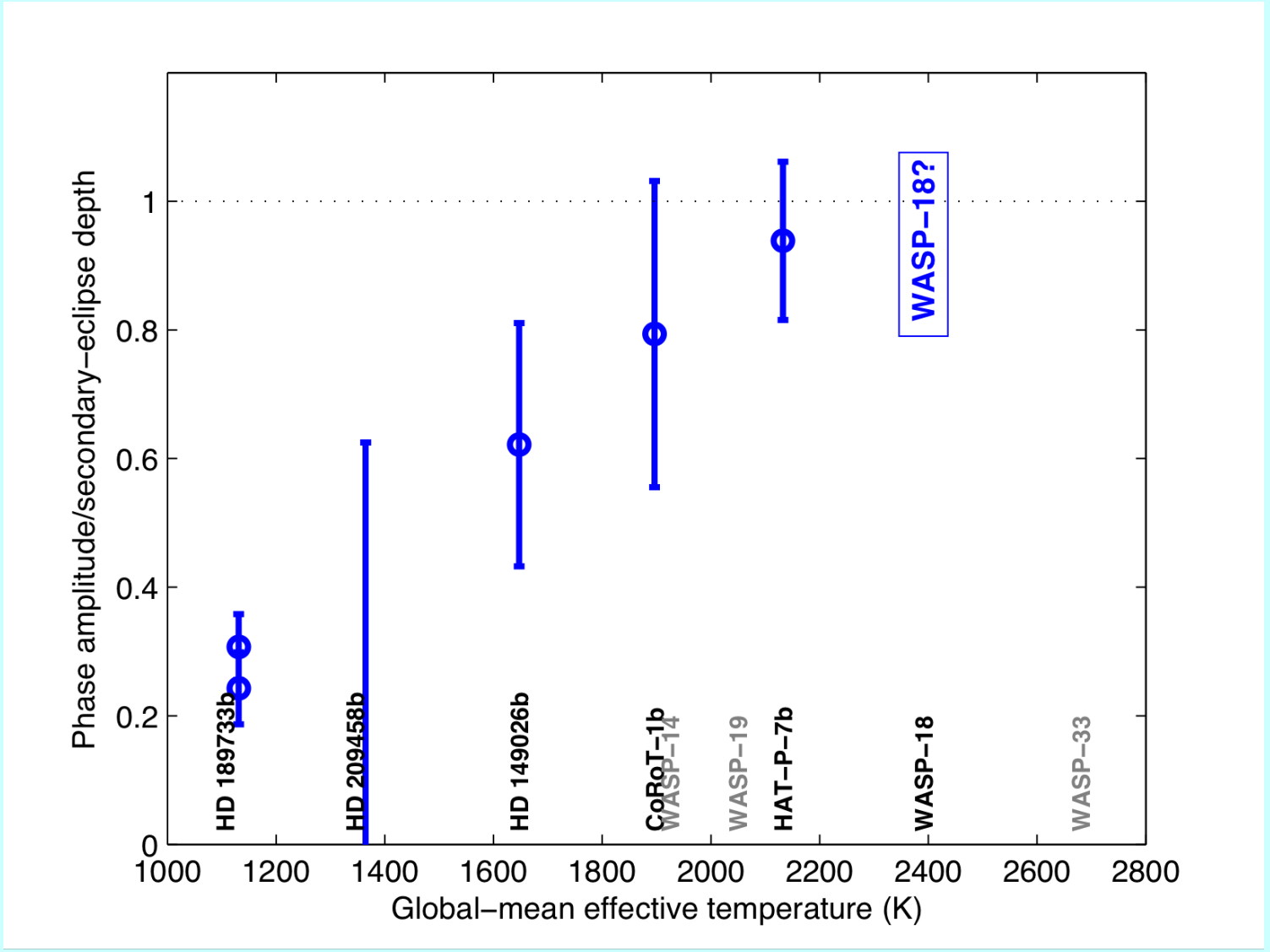


CoRoT-1b (Snellen et al. 2009)



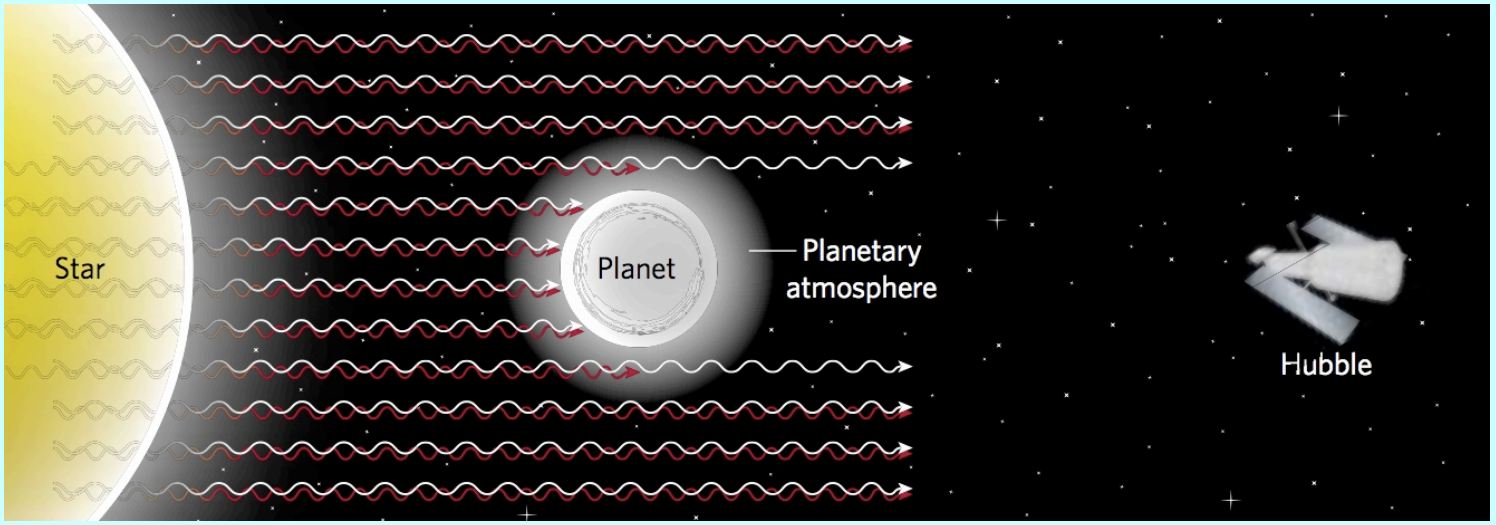
Ups And b (Crossfield et al. 2010)

Results from lightcurves: dependence of day-night flux contrast on effective temperature

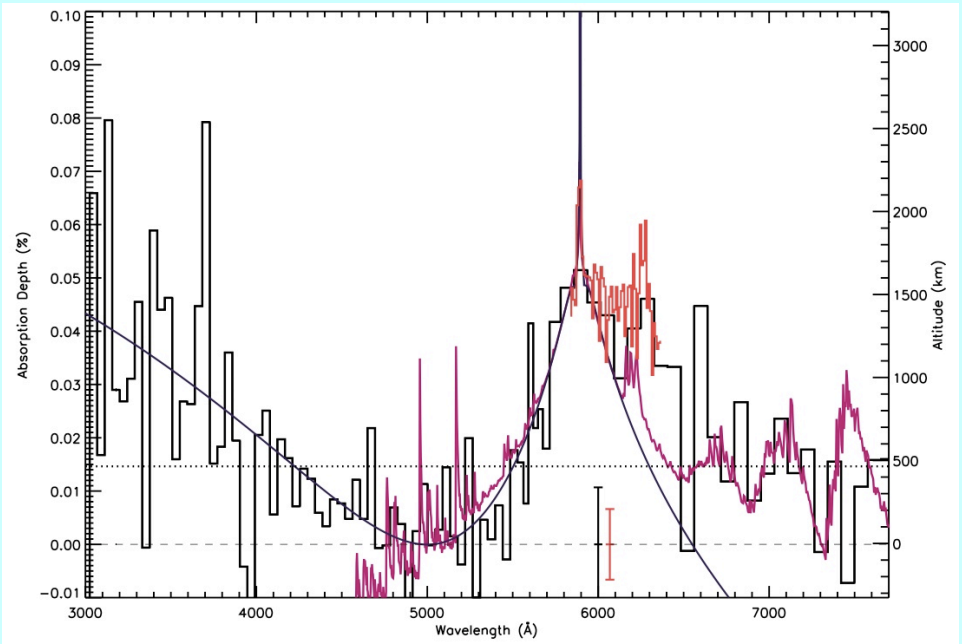


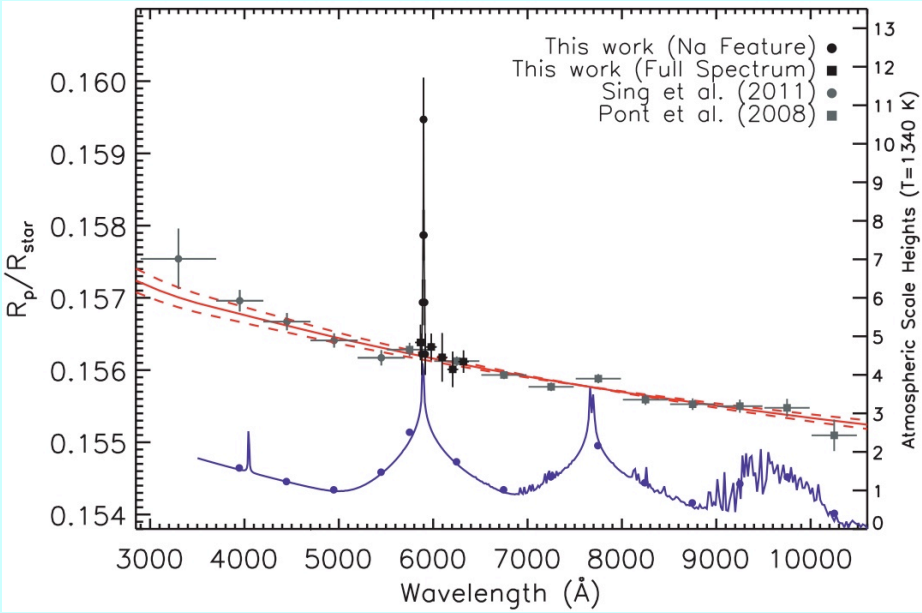
A trend seems to be emerging: more strongly irradiated planets have larger fractional day-night temperature differences at the photosphere

Exoplanet characterization: Transit spectroscopy



Showman (2008)

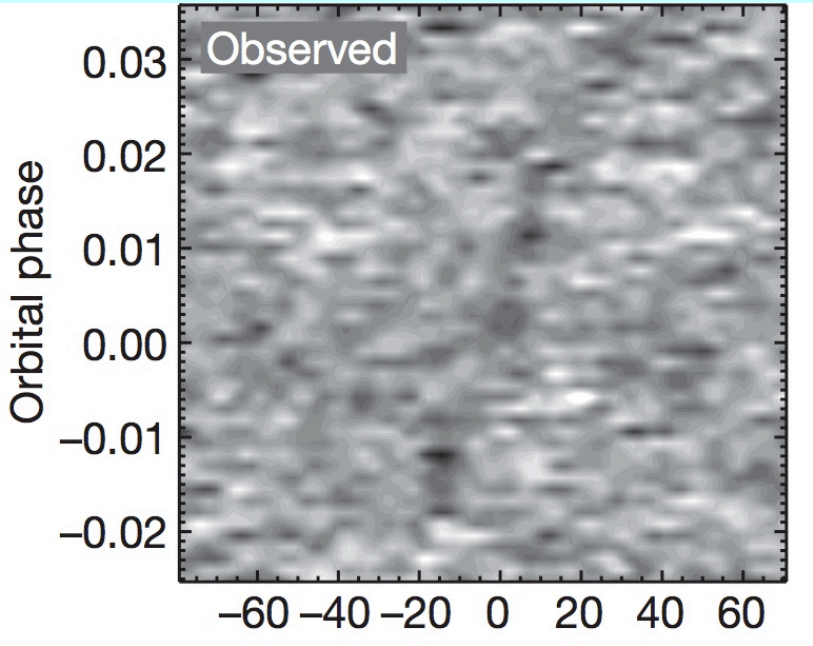


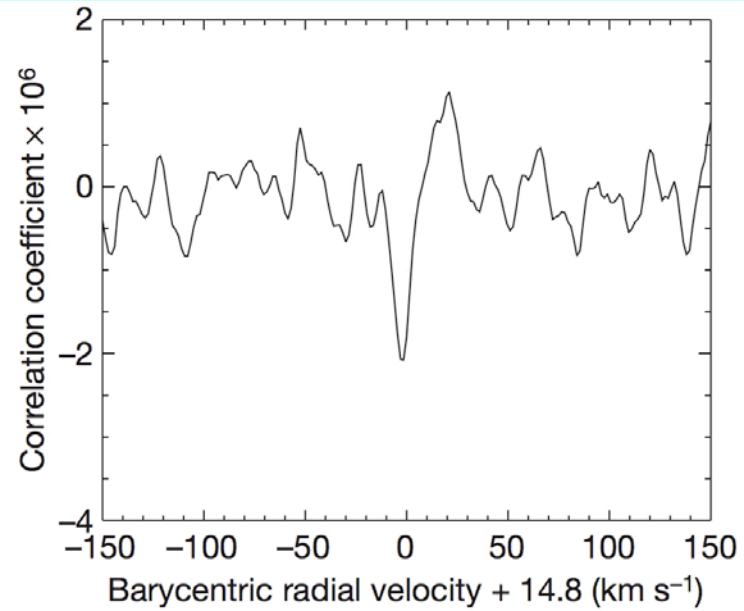


Sing et al. (2008, 2009), Vidal-Madjar et al. (2011), Huitson et al. (2012),Gibson et al. (2012), Barman (2007), Tinetti et al. (2007), Swain et al. (2008),…..

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?**

- **What is the temperature distribution of exoplanets? What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? What is the mechanism for displacing the hottest regions on HD 189733b?**

- **What are the fundamental wind regimes? Are there regime transitions, and if so, what causes them? What is the connection to dynamical regimes of solar-system planets?**

- **How does the circulation interact with the interior? Does it affect the evolution and radius?**

- **What processes control mixing in hot-Jupiter atmospheres? To what extent can chemistry *affect* and/or *probe* the dynamics?**

- **What is the atmospheric state and climate of terrestrial exoplanets? How does circulation help control habitability on these worlds?**

Spectroscopy, lightcurves, eclipse mapping, Doppler measurements, etc--both from the ground and space—can address these questions

Dynamical regime of hot Jupiters

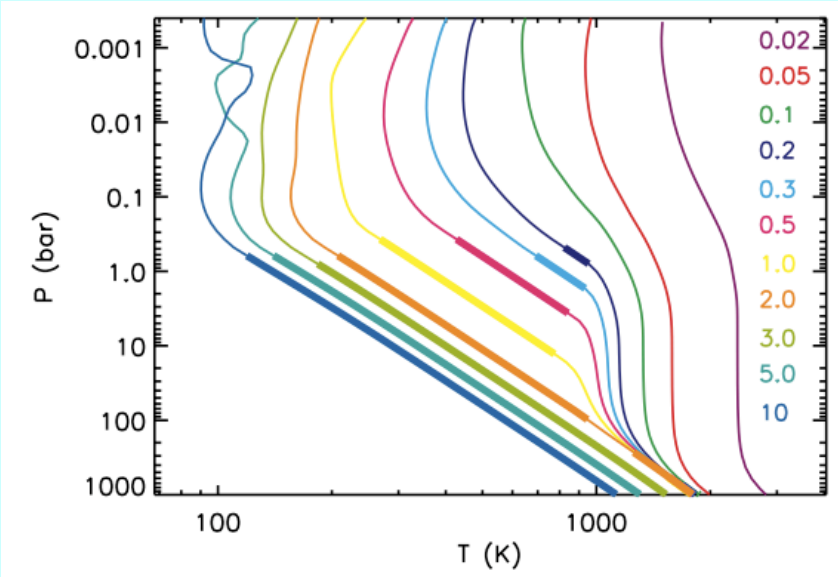
- **Circulation driven by global-scale heating contrast: ~10^5 W/m^2 of stellar heating on dayside and IR cooling on nightside**

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

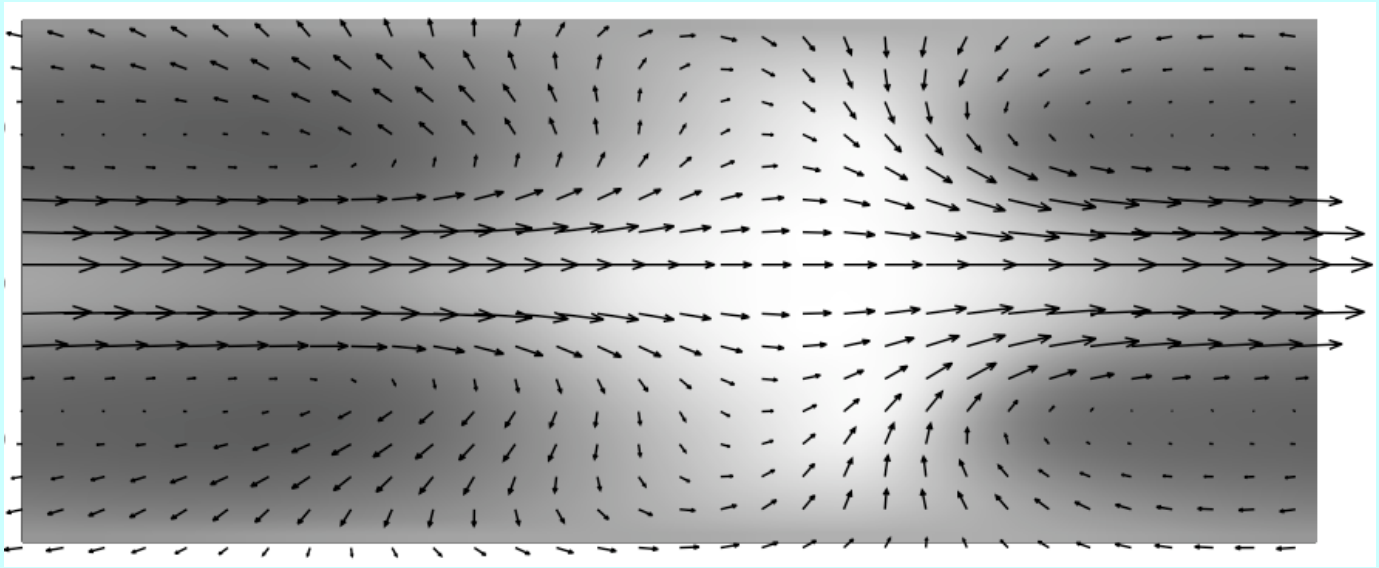
- **Weather occurs in a statically stable radiative zone extending to ~100-1000 bar**

- **Rossby deformation radius typically comparable to a planetary radius**

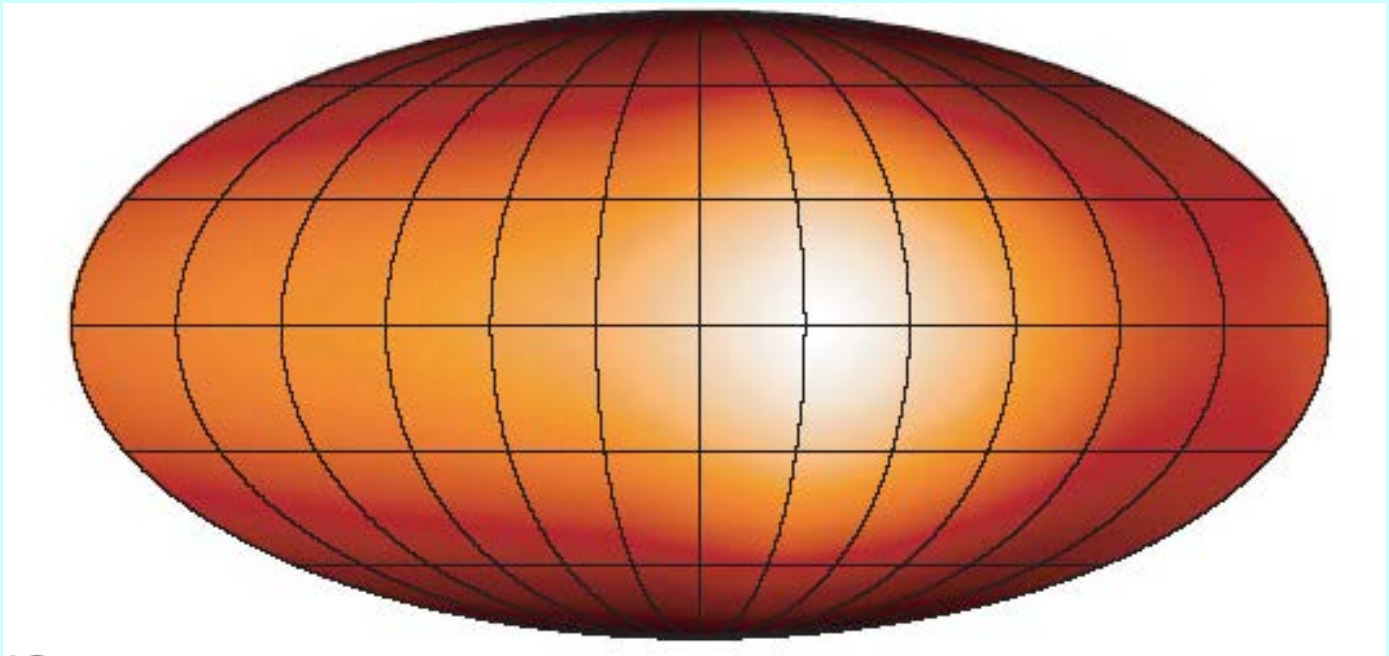
- **Simple scaling suggests fast wind speeds, e.g., u~2 km/sec, implying Rossby numbers Ro ~ 1.**



Fortney et al. (2007)

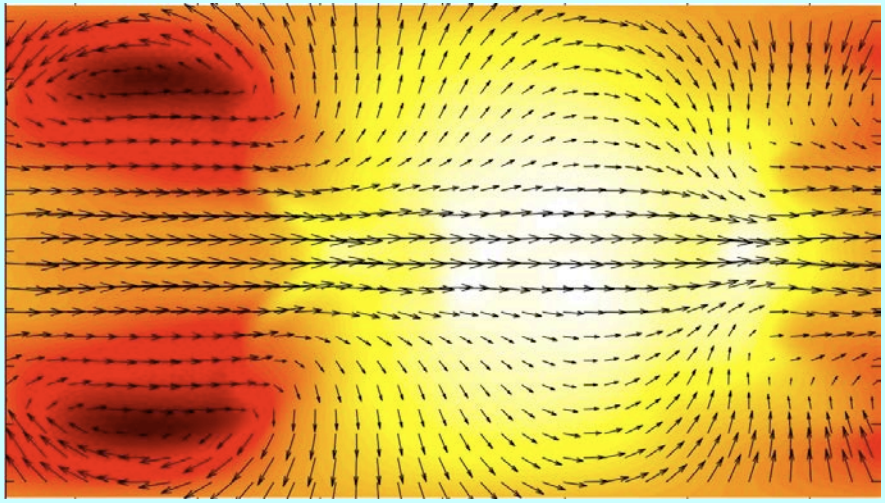


Showman & Guillot (2002)

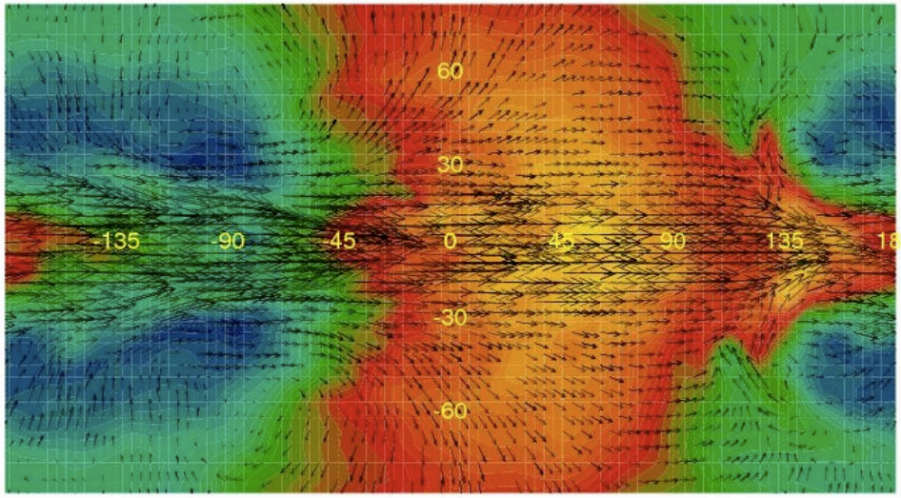


Knutson et al. (2007)

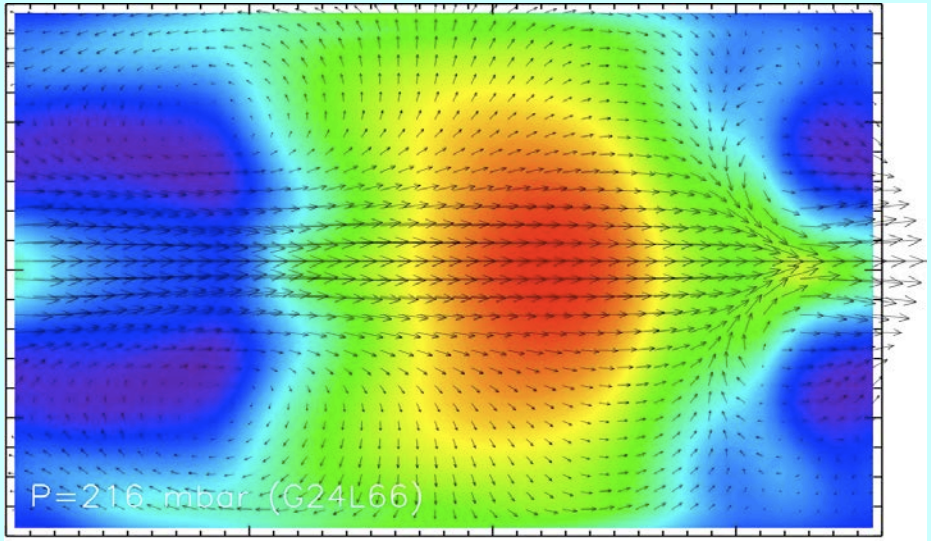
Hot Jupiter circulation models typically predict several broad, fast jets, often including equatorial superrotation



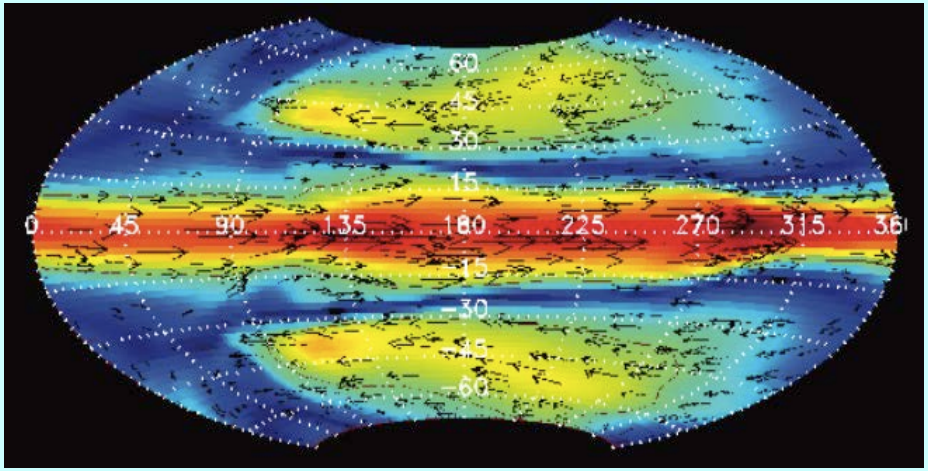
Showman et al. (2009)



Rauscher & Menou (2010)

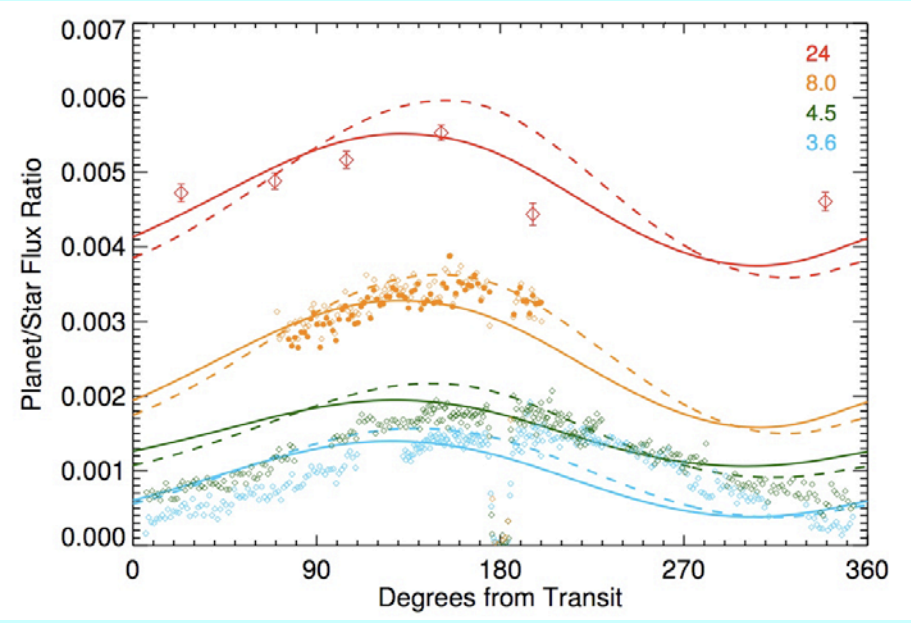


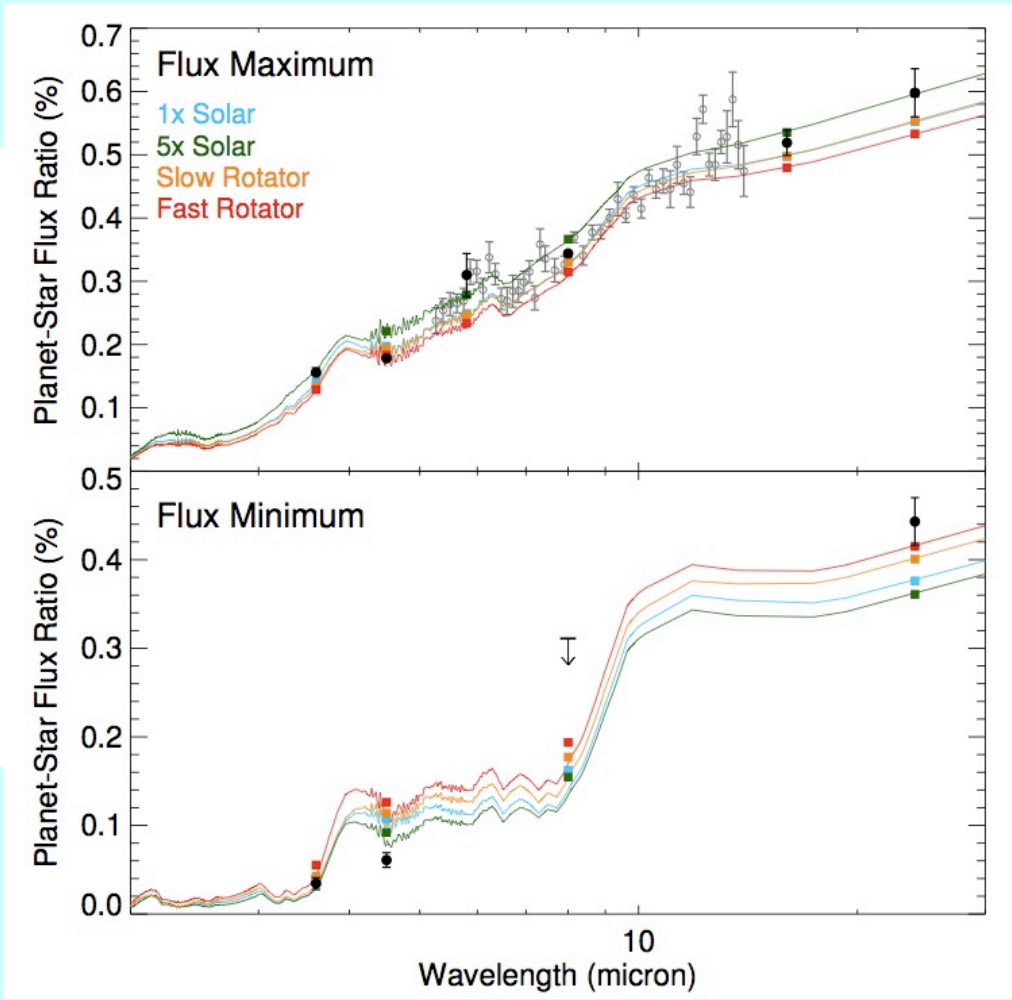
Heng et al. (2010)



Dobbs-Dixon & Lin (2008)

Data-model comparisons





Knutson et al. (2012), Showman et al. (2009)

Let's focus on three topics for hot Jupiters

- **What is the mechanism for the equatorial superrotation?**

- **How should the day-night temperature difference and wind regime vary from hot to very hot Jupiters? Can we explain the emerging observational trend from lightcurves? What are implications for Doppler detections of atmospheric winds?**

- **How should dynamics vary for exoplanets more distant from their stars? What is the continuum between hot Jupiters and Jupiter itself?**

Simple models to isolate superrotation mechanism

- **To capture the mechanism in the simplest possible context, adopt the shallow-water equations for a single fluid layer:**

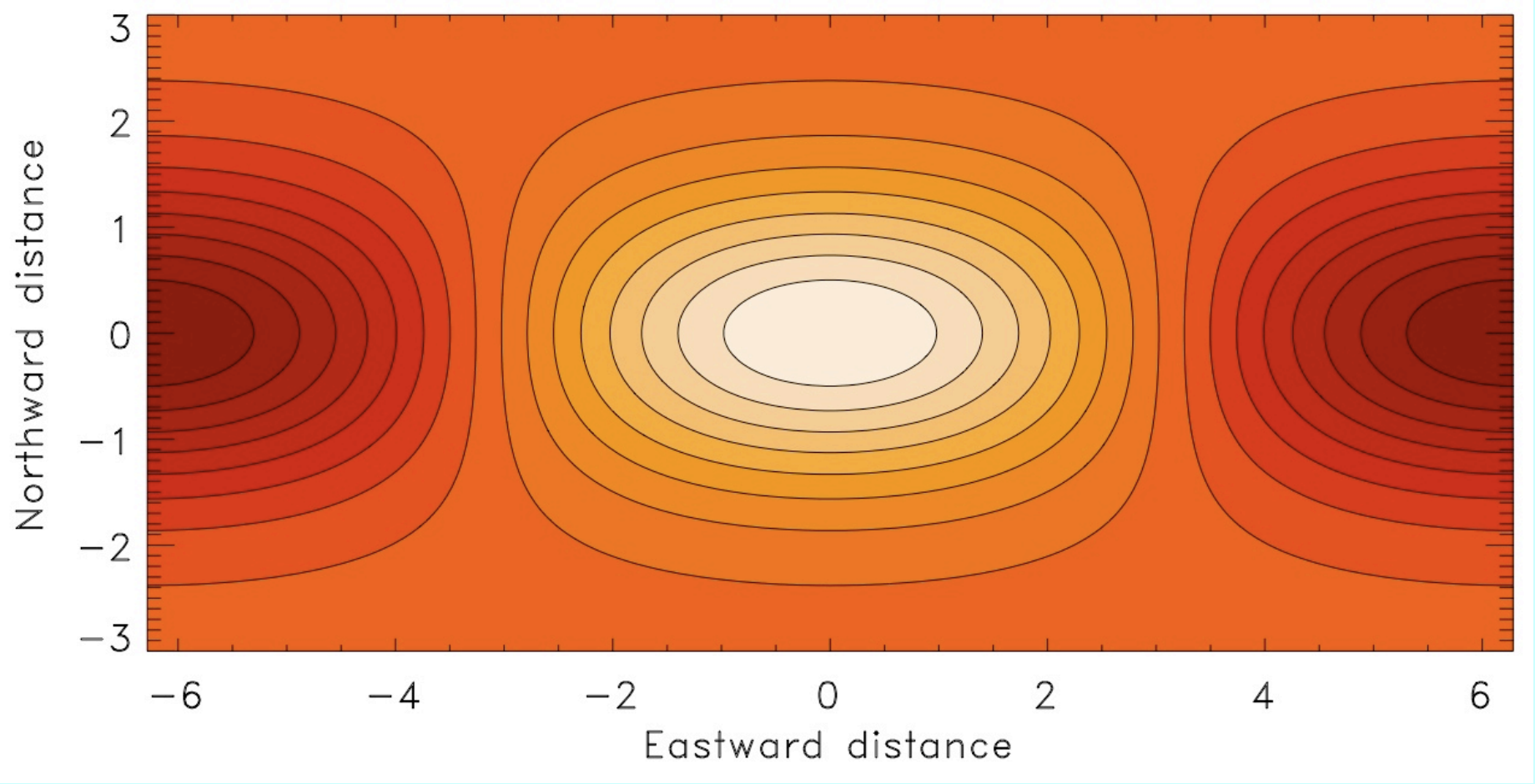
$$\frac{d\vec{v}}{dt} + g\nabla h + f\hat{k}\times\vec{v} = -\frac{\vec{v}}{\tau_{drag}} - \vec{v}\frac{Q_h}{h}\delta$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(h\vec{v}) = \frac{[h_{eq}(x,y) - h]}{\tau_{rad}} \equiv Q_h$$

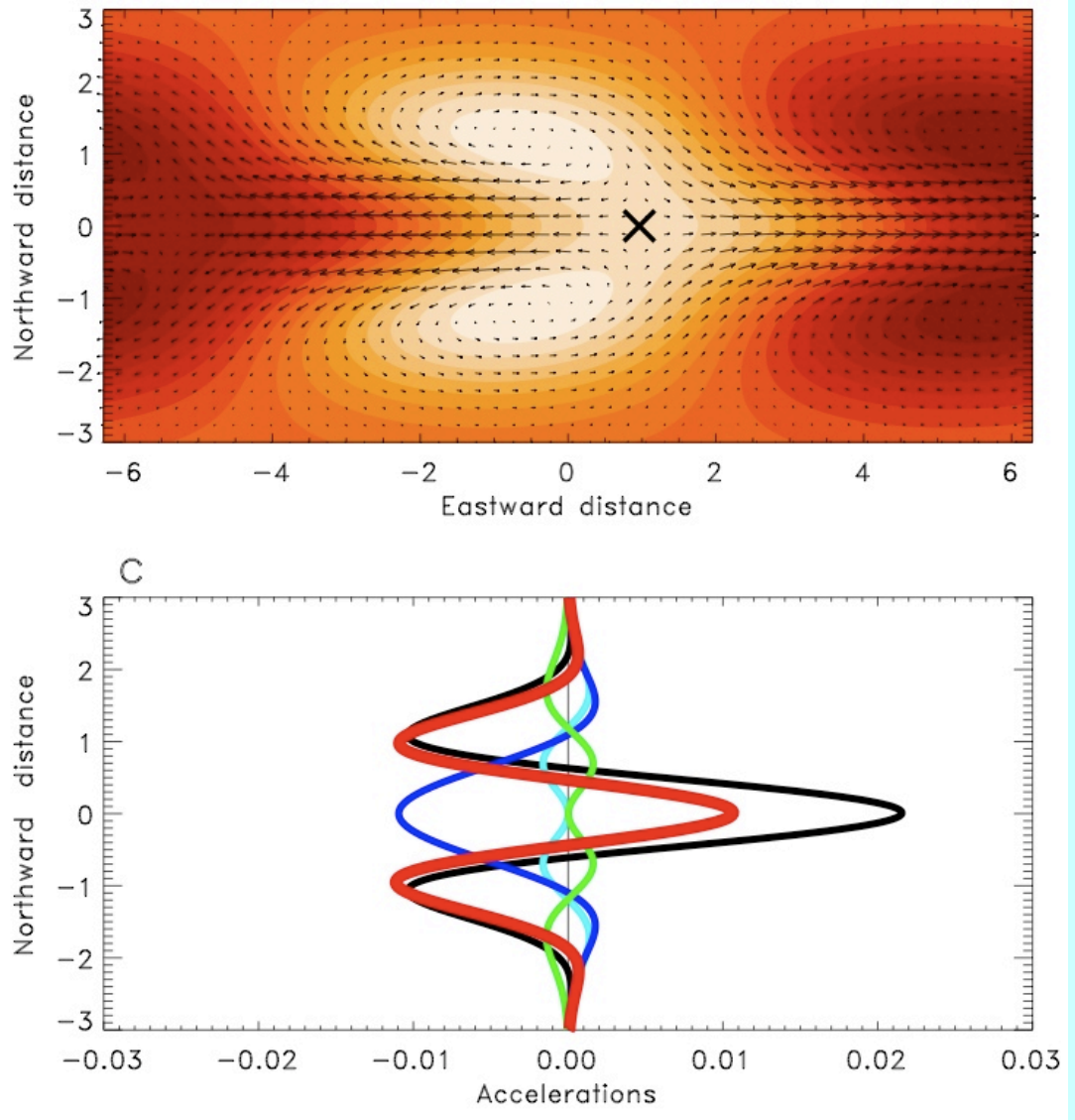
where $[h_{eq}-h]/\tau_{rad}$ represents thermal forcing/damping, $-v/\tau_{drag}$ represents drag, and where δ=1 when Q_h>0 and δ=0 otherwise

- **First consider linear, steady analytic solutions and then consider full nonlinear solutions on a sphere.**

Forcing



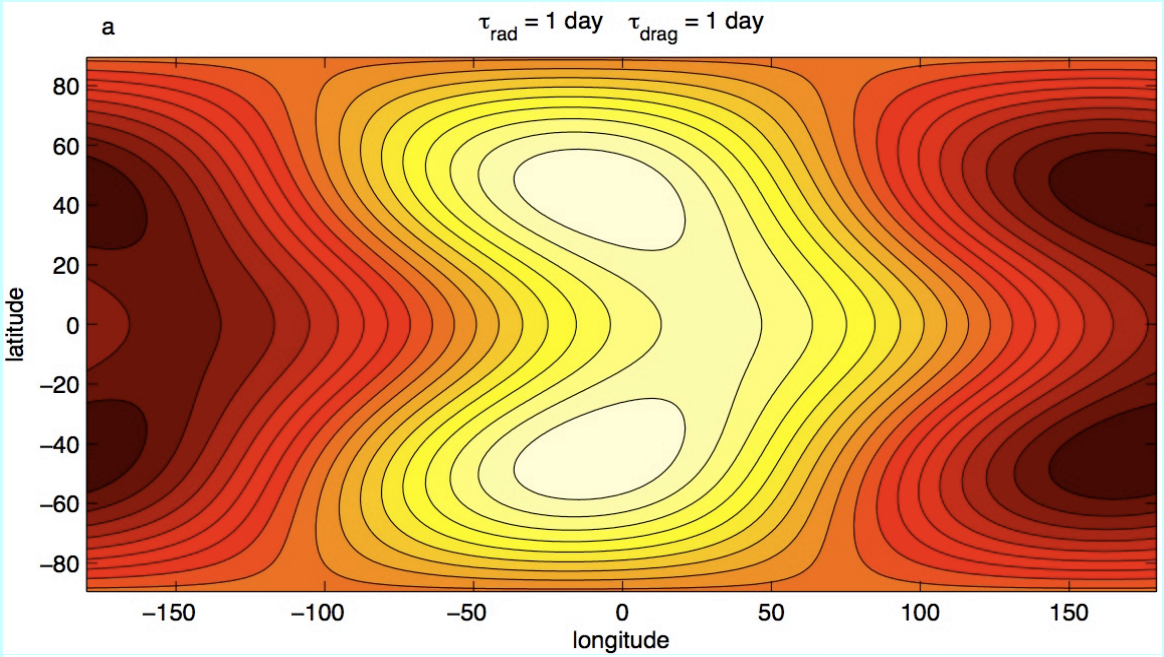
Analytical solution of standing, steady wave response to day-night thermal forcing

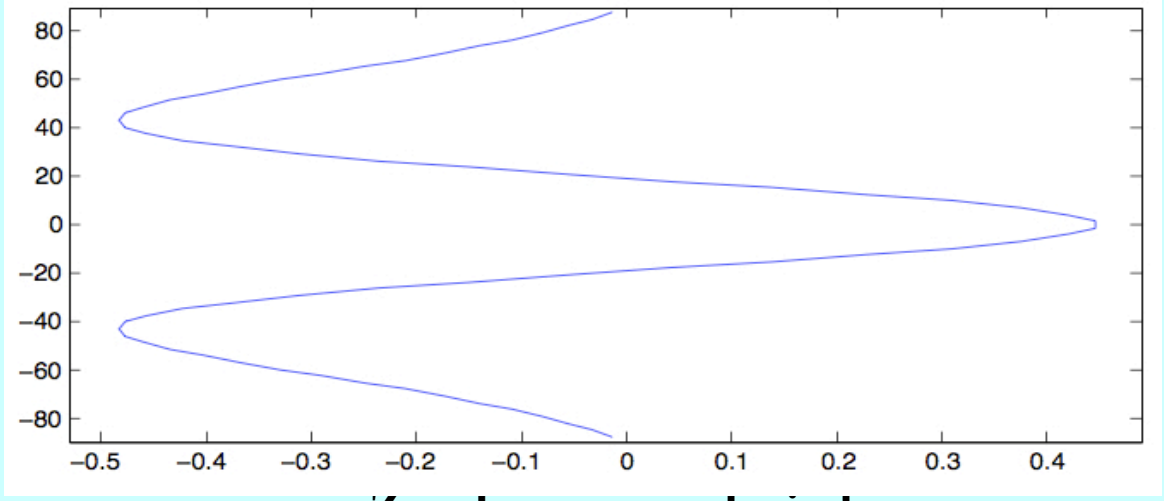


Showman & Polvani (2011), *ApJ* 738, 71

- **The response corresponds to standing, equatorially trapped Kelvin and Rossby waves**
- **The Kelvin waves propagate to east, Rossby waves to west, leading to a chevron pattern with velocities tilted NW-SE (SW-NE) in northern (southern) hemisphere**
- **This causes an equatorward flux of eddy momentum and drives superrotation**

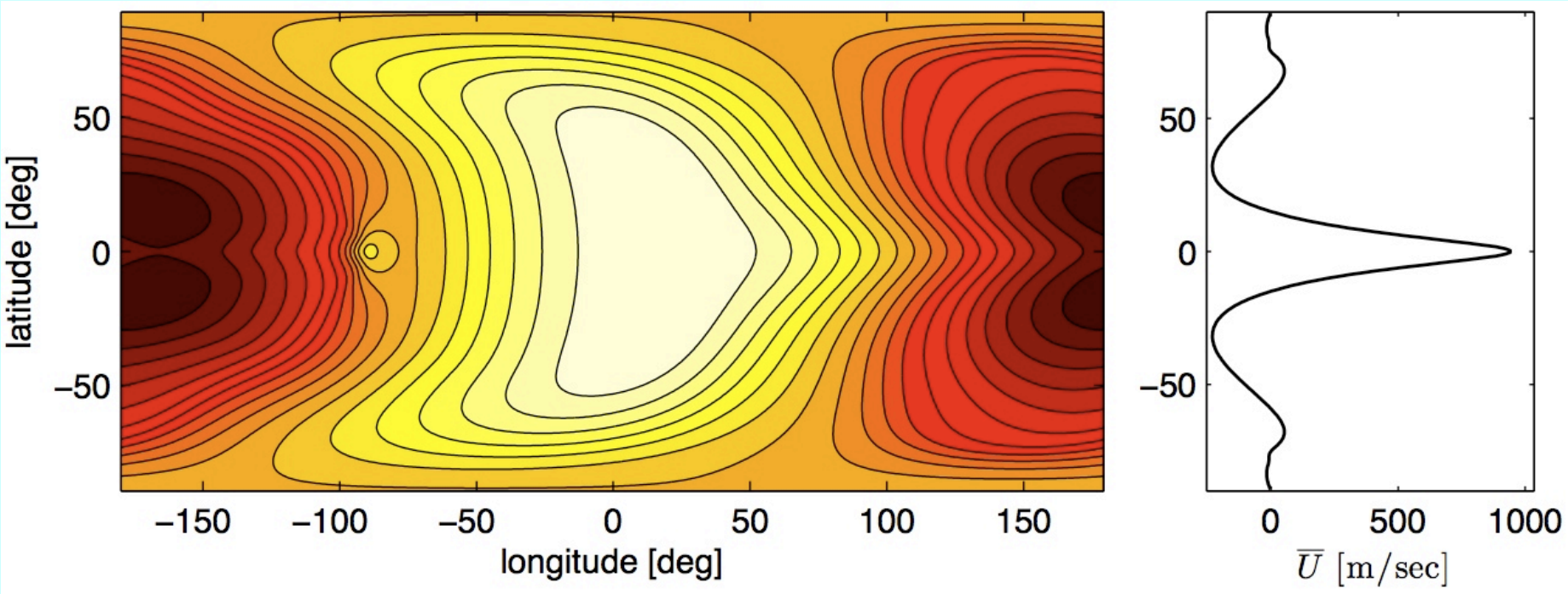
Linear response of shallow-water model to steady day-night forcing in full spherical geometry: the results qualitatively match our analytic β plane solutions





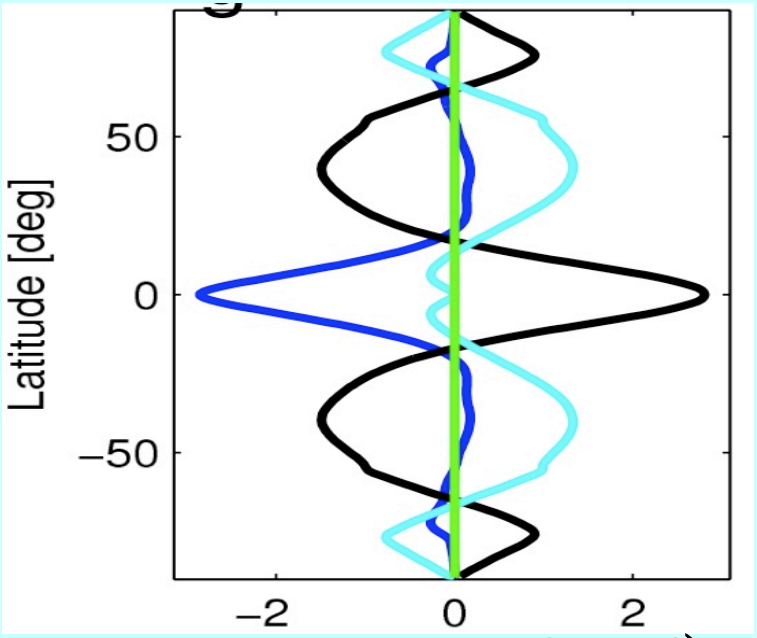
Zonal-mean zonal wind

Showman & Polvani (2011)



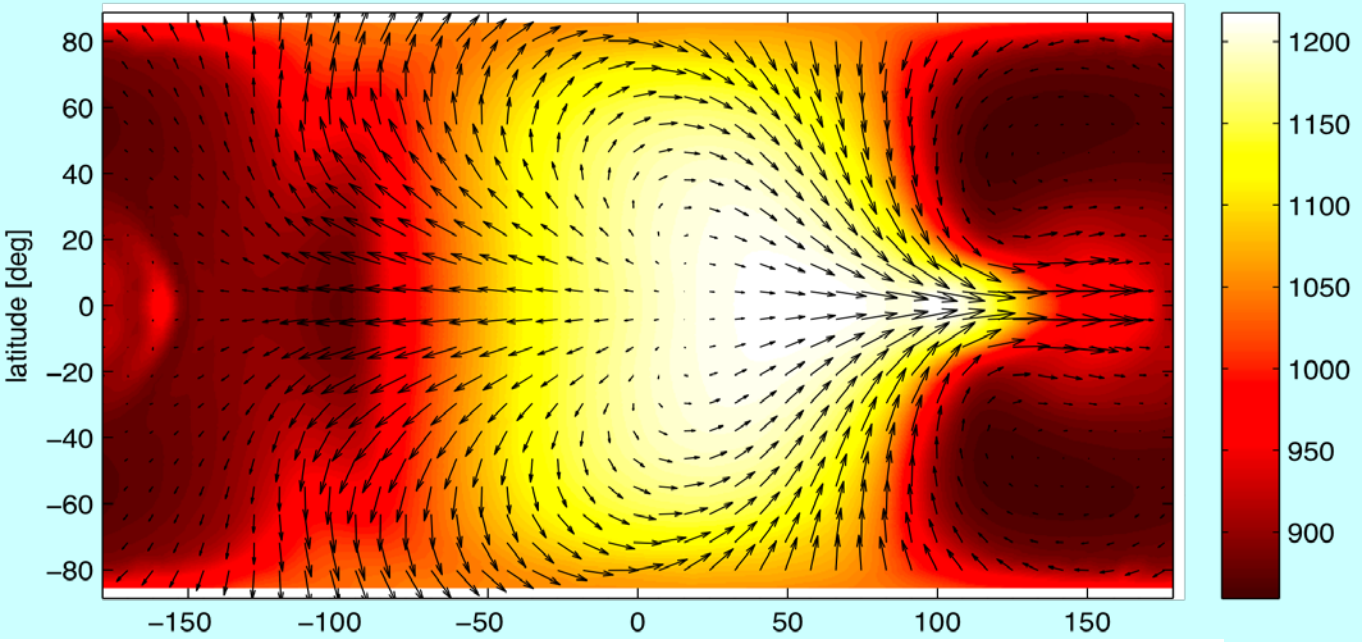
At high amplitude, non-linearities affect the solution, but the results are qualitatively similer.

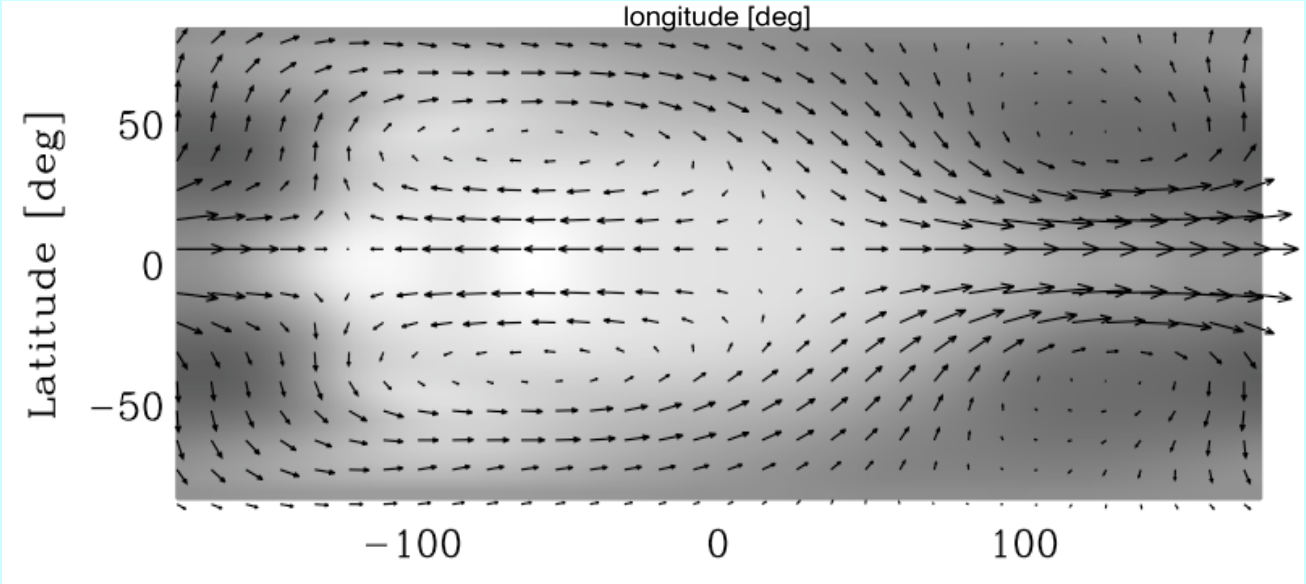
Standing Kelvin and Rossby waves drive a fast equatorial superrotation.



Showman & Polvani (2011)

This Rossby/Kelvin wave pattern is clearly evident in spin-up phase of 3D hot Jupiter simulations





Showman & Guillot (2002)

Our dynamical theory predicts two regimes

1. **At weak-to-moderate stellar fluxes and friction, planetary (Rossby and gravity) waves induce zonal jets and adjust the thermal structure, leading to small day-night temperature differences.**

2. **Extreme stellar fluxes and/or friction damp the planetary waves, inhibiting zonal jet formation and leading to a large day-night temperature difference.**

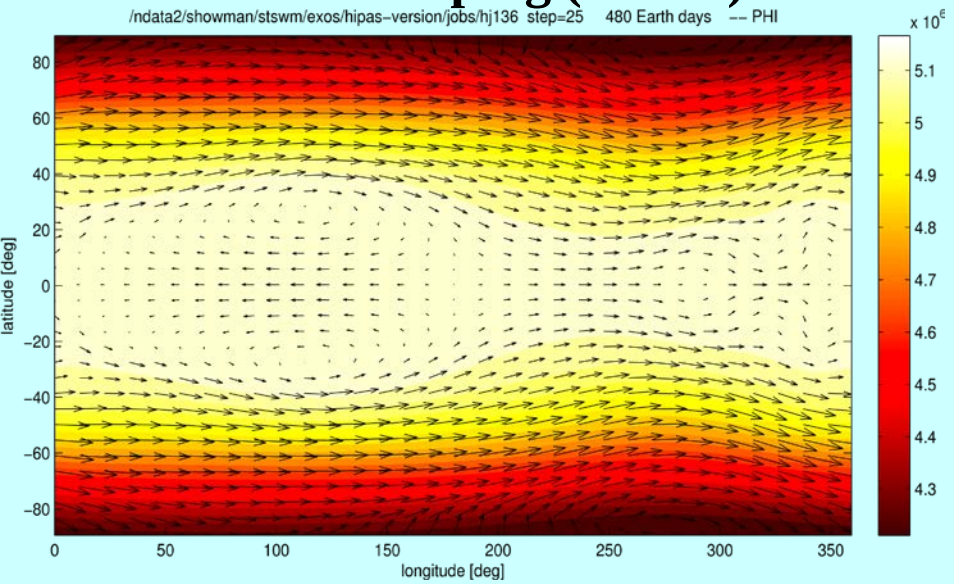
Transition between regimes should occur when damping timescales are comparable to wave propagation time across a hemisphere:

Kelvin wave propagation speed $\sim NH$

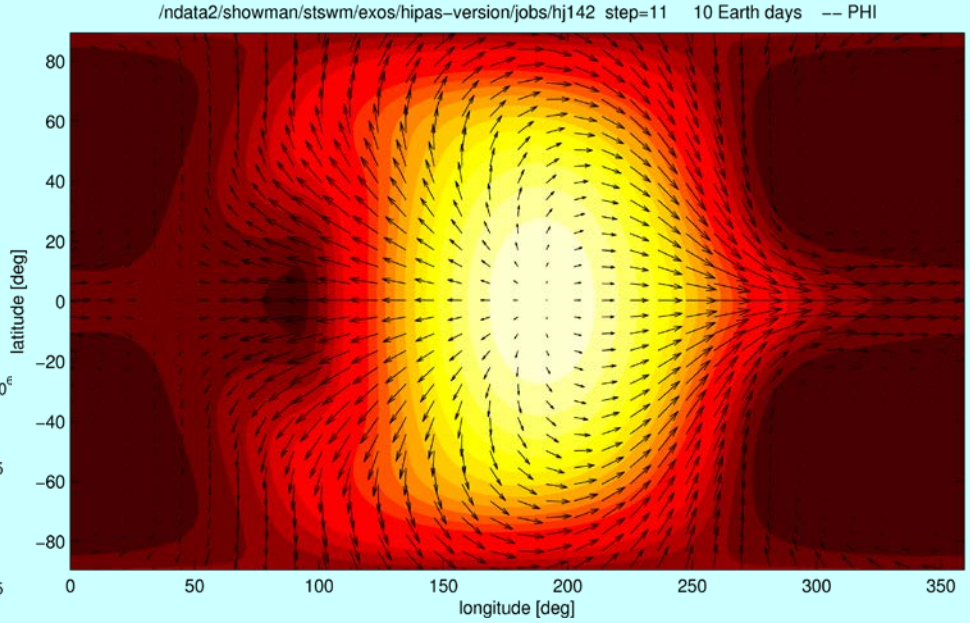
Propagation time across hemisphere $\sim \dfrac{a}{NH} \sim 10^5$ sec

From Warm to Very Hot Jupiters

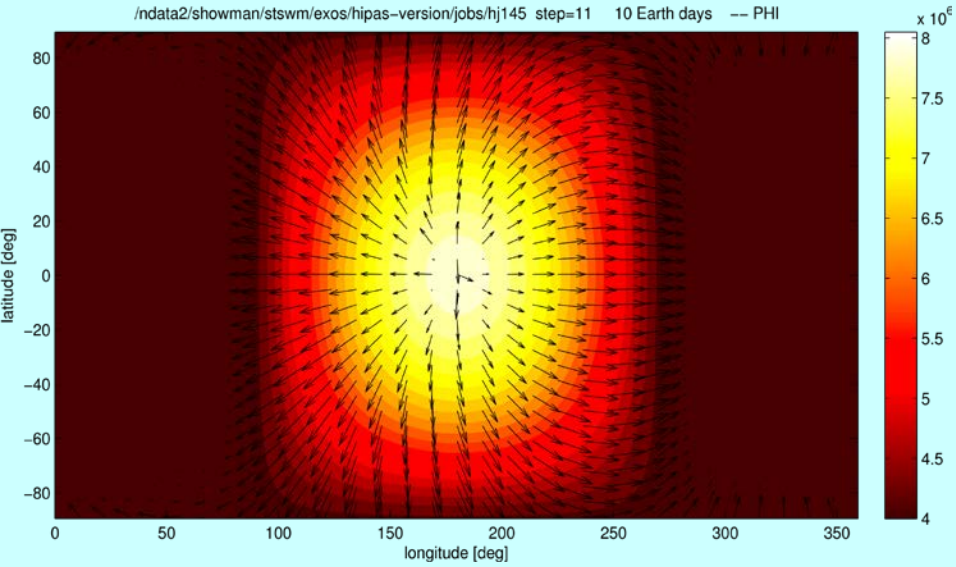
Weak damping (Warm)



Medium damping (Hot)



Strong damping (Very Hot)



Showman et al. (2013)

Conclusions: hot Jupiters

- **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 day-night forcing generates planetary-scale waves that pump momentum to the equator, leading to equatorial superrotation that explains the observed hot-spot offset on HD 189733b.**

- **On *very* hot Jupiters, the strong radiation/friction damps these waves, preventing their ability to adjust the thermal structure and leading to large day-night temperature differences. On *warm* Jupiters, radiative damping is weaker, and the waves efficiently mute the longitudinal thermal differences. Our models thus explain the emerging observational trend of increasing fractional day-night temperature difference with incident stellar flux.**

- **The same dynamics predicts a transition in wind regime: from zonally banded flows at weak irradiation to a day-night flow at strong irradiation. This explains the blue-shifted Doppler measurement of HD 209458b and leads to a prediction for future measurements.**