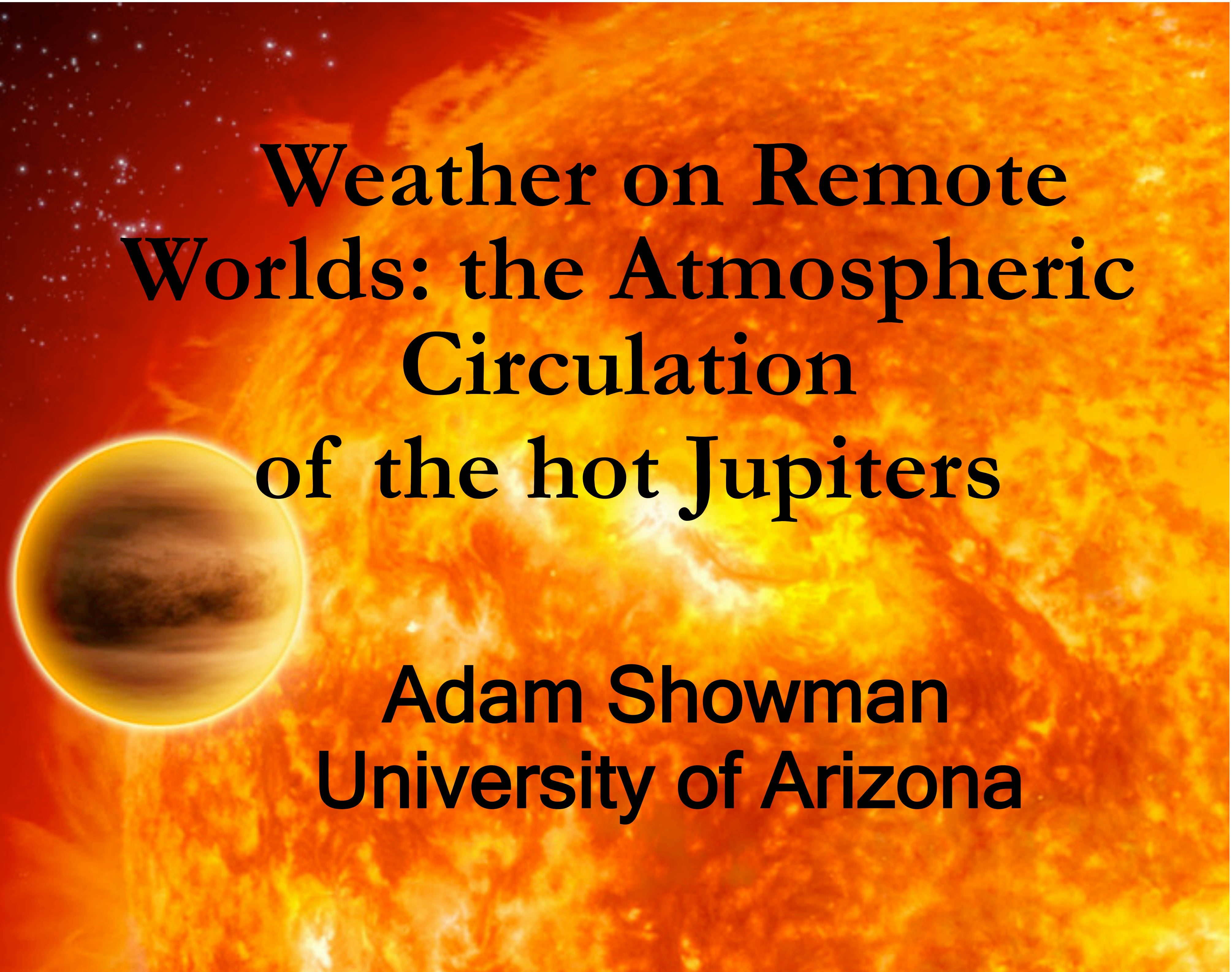


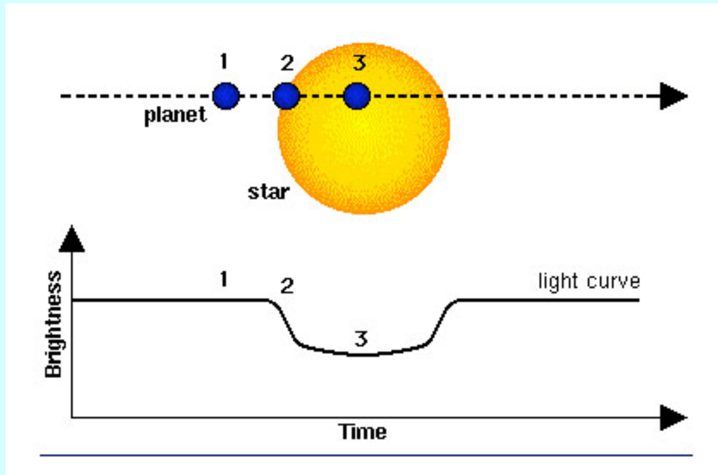
Weather on Remote Worlds: the Atmospheric Circulation of the hot Jupiters

Adam Showman
University of Arizona

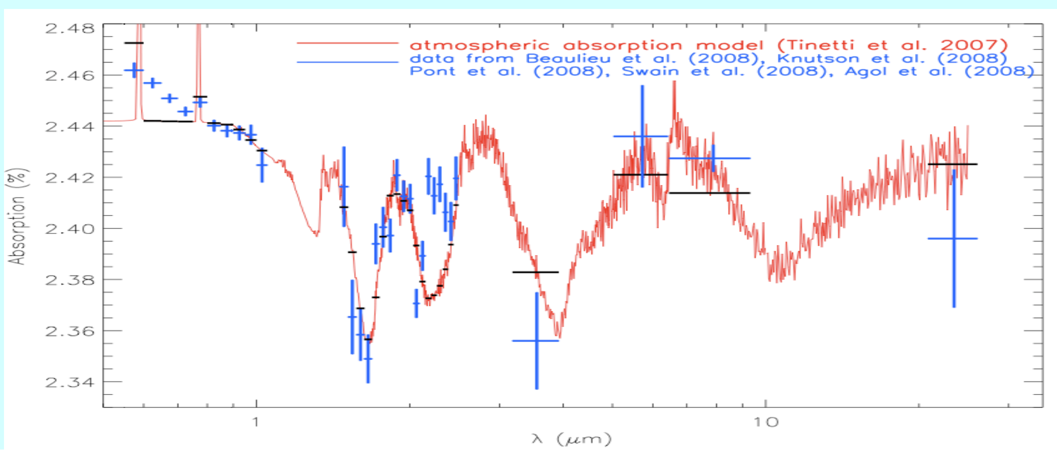
Exoplanets: an exploding new field

- **Almost 540 known extrasolar planets, most discovered with the "Doppler" method.**

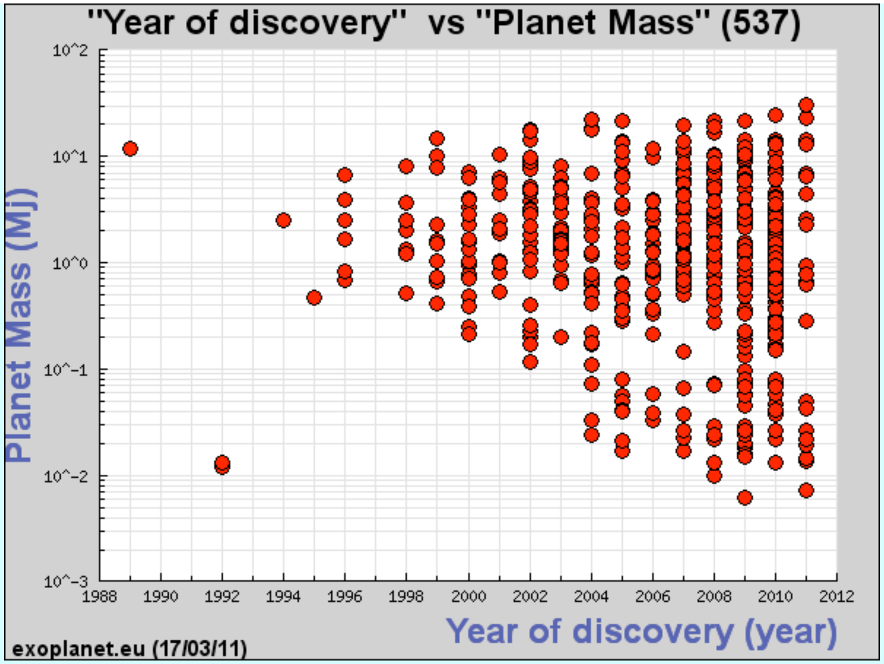
- **Over 120 planets have been detected with "transit" method:**

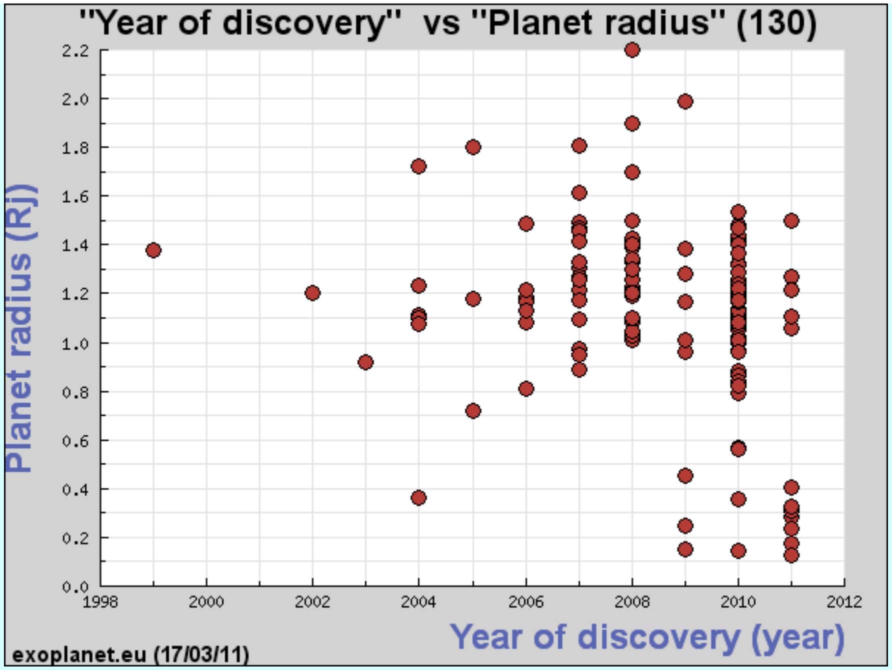


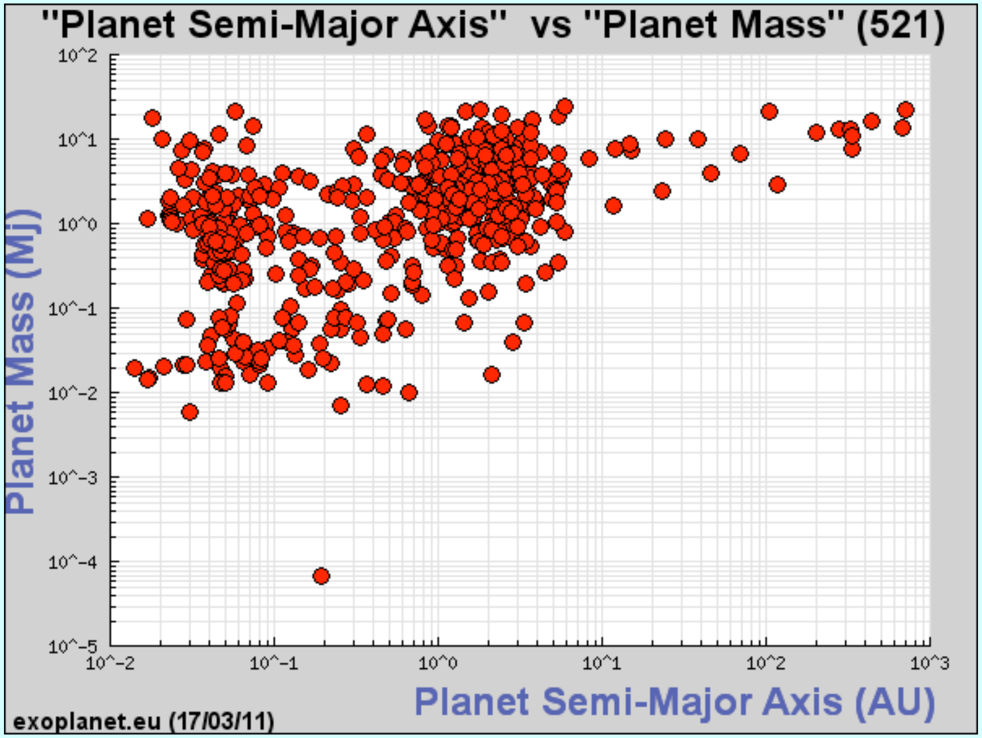
- **Together, these give the planetary mass, radius, and orbital properties. In favorable cases, atmospheric composition can even be determined:**



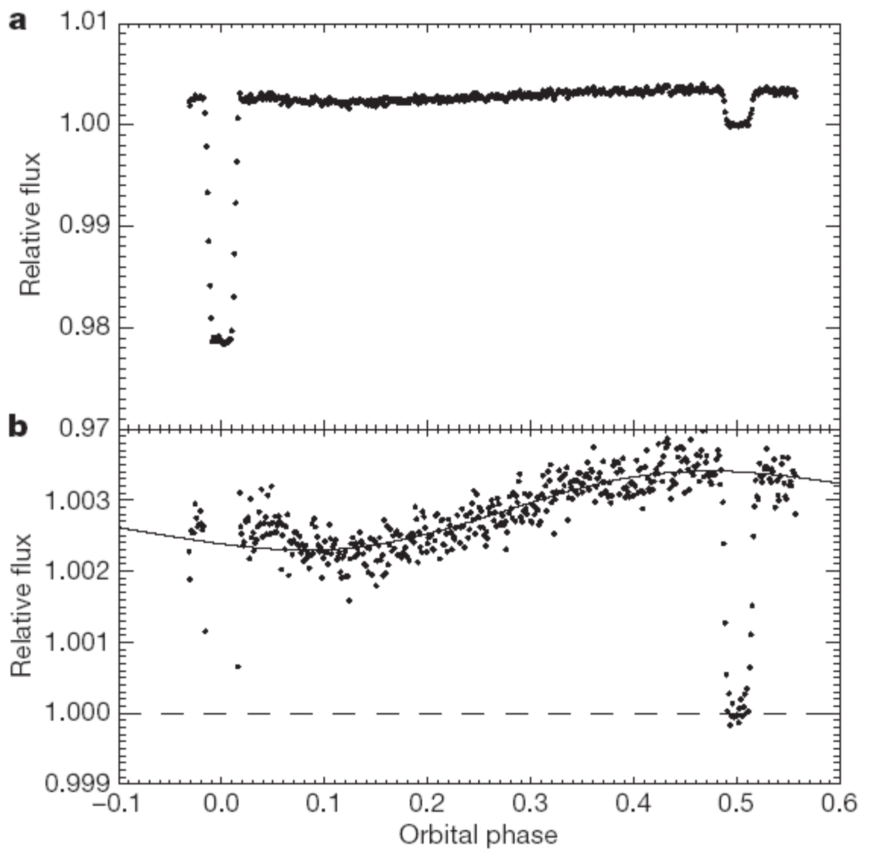
Agol et al.


"Year of discovery" vs "Planet Mass" (537)
Planet Mass (Mj)
Year of discovery (year)
exoplanet.eu (17/03/11)

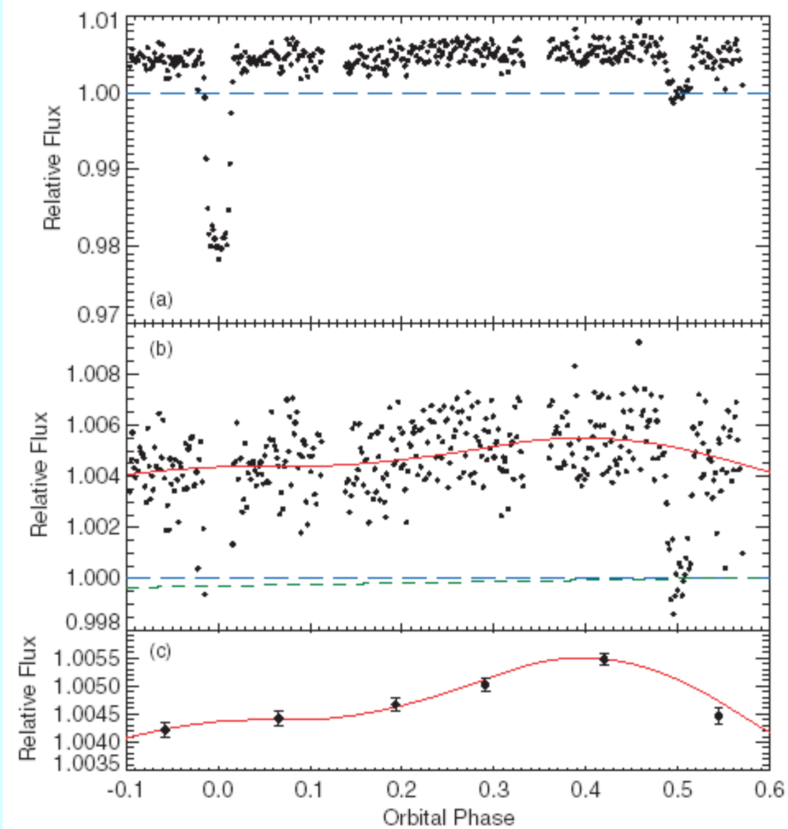

"Year of discovery" vs "Planet radius" (130)
Planet radius (Rj)
Year of discovery (year)
exoplanet.eu (17/03/11)


"Planet Semi-Major Axis" vs "Planet Mass" (521)
Planet Mass (Mj)
Planet Semi-Major Axis (AU)
exoplanet.eu (17/03/11)

Spitzer light curves for HD 189733b

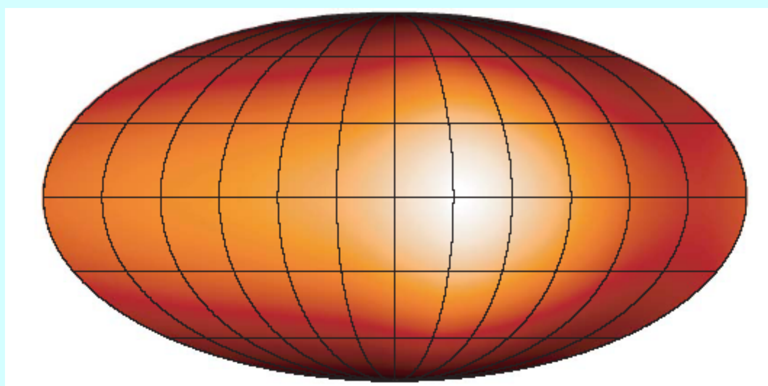


8 μm

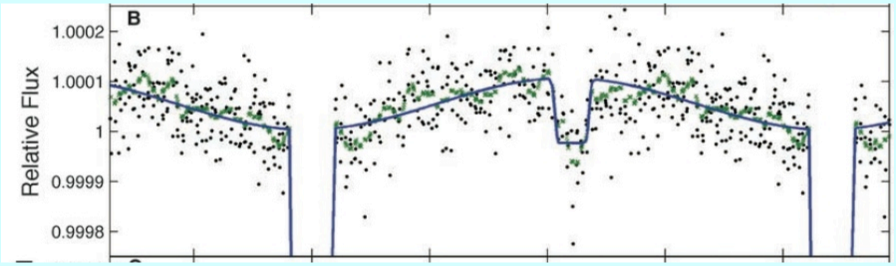


24 μm

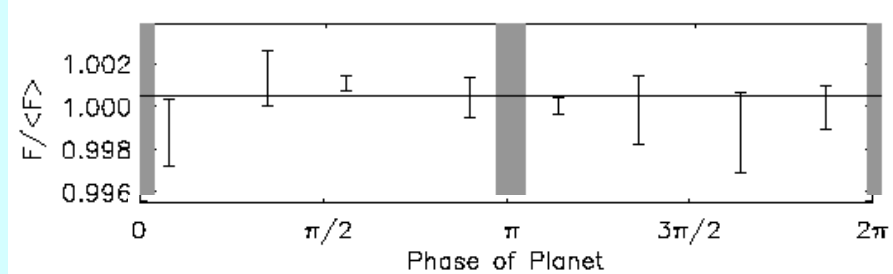
Knutson et al. (2007, 2009)



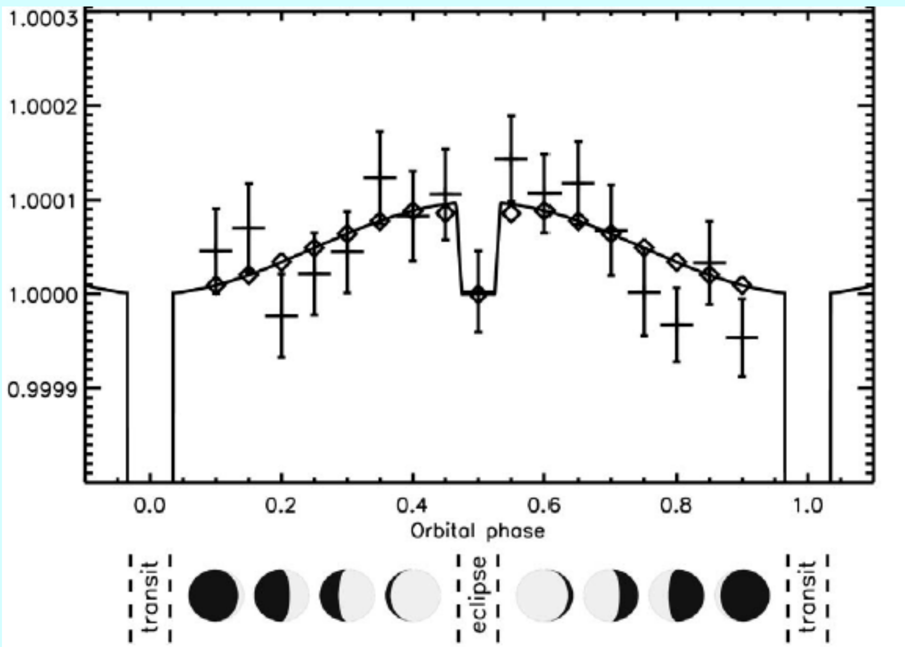
Lightcurves for hot Jupiters



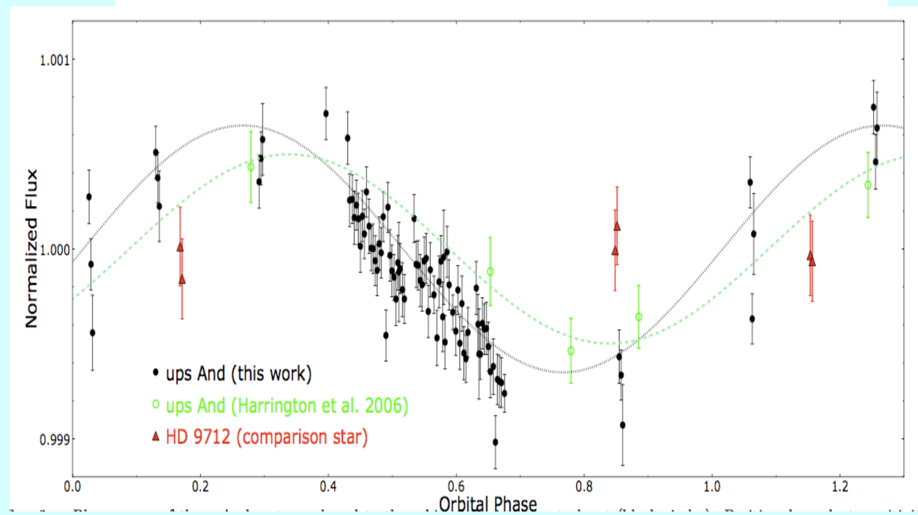
HAT-P-7b (Borucki et al. 2009)



HD209458b (Cowan et al. 2007)



CoRoT-1b (Snellen et al. 2009)



Ups And b (Crossfield et al. 2010)

Why study the circulation?

Many exoplanets will occupy dynamically unusual regimes unavailable in our Solar System. Studying them broadens our understanding of meteorology, climate, and planetary habitability.

The circulation shapes the <u>IR spectra</u>, <u>lightcurves</u>, <u>cloudiness</u> (visible albedo), <u>evolution</u>, <u>climate</u>, and <u>chemistry</u>. To explain these, we must understand the circulation. Existing spectra/lightcurves already challenge our understanding, with much more ahead.

Exoplanets raise many fundamental questions concerning the mechanisms that control the mean climate, geometry and speed of the winds, the day-night (or equator-to-pole) temperature differences, long-term evolution, and habitability of planets generally.

The wonder of it all: We're unveiling weather on planets dozens or hundreds of light years away!

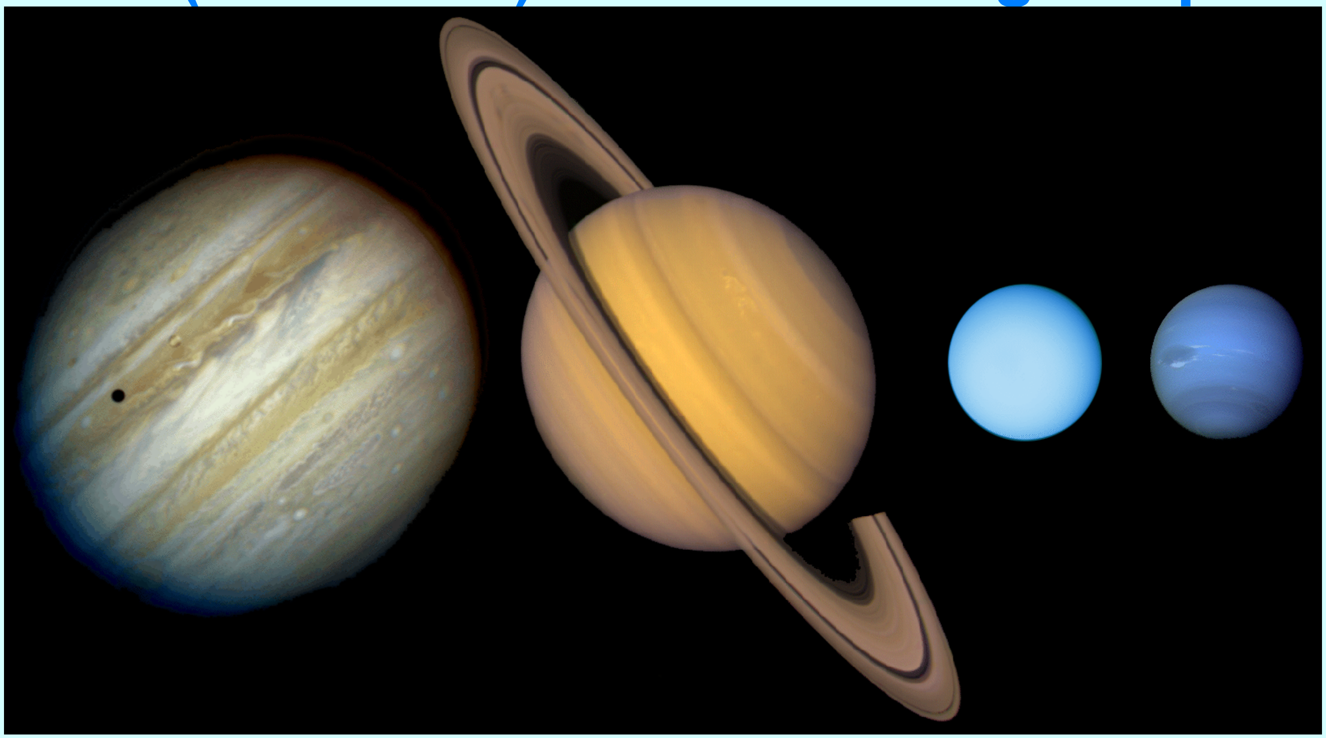
Motivation

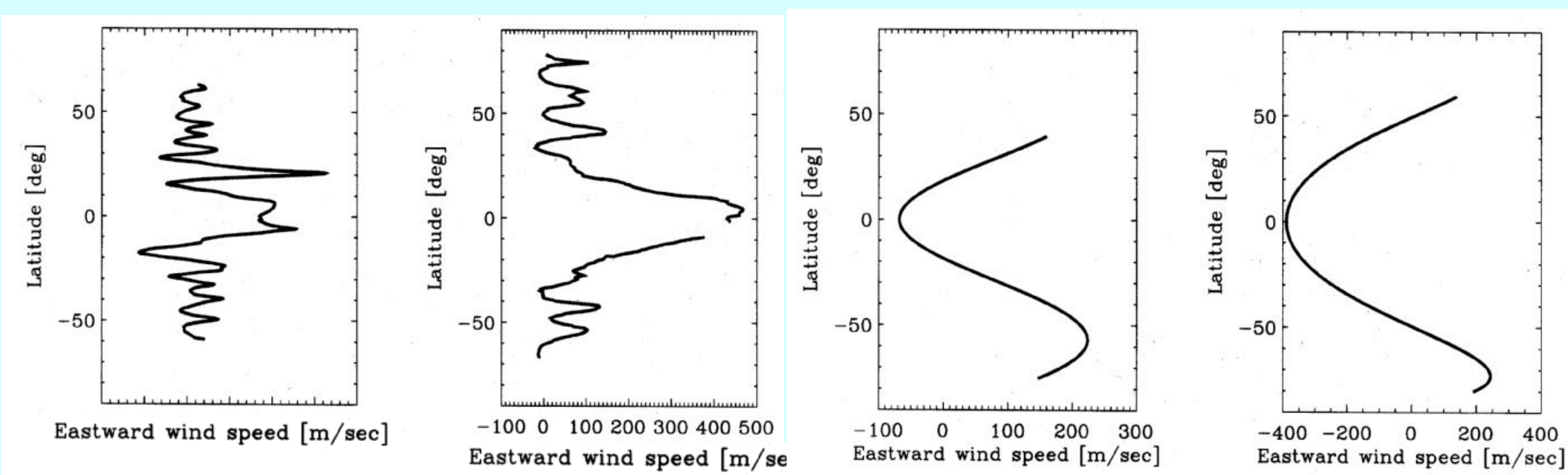
- **Light curves show evidence for atmospheric circulation, and the circulation will affect other observations (secondary eclipse photometry/spectra, etc) too. Can we explain these observations?**

- **What are the fundamental dynamics of this novel circulation regime? How is it similar/different to that on Solar-System planets?**

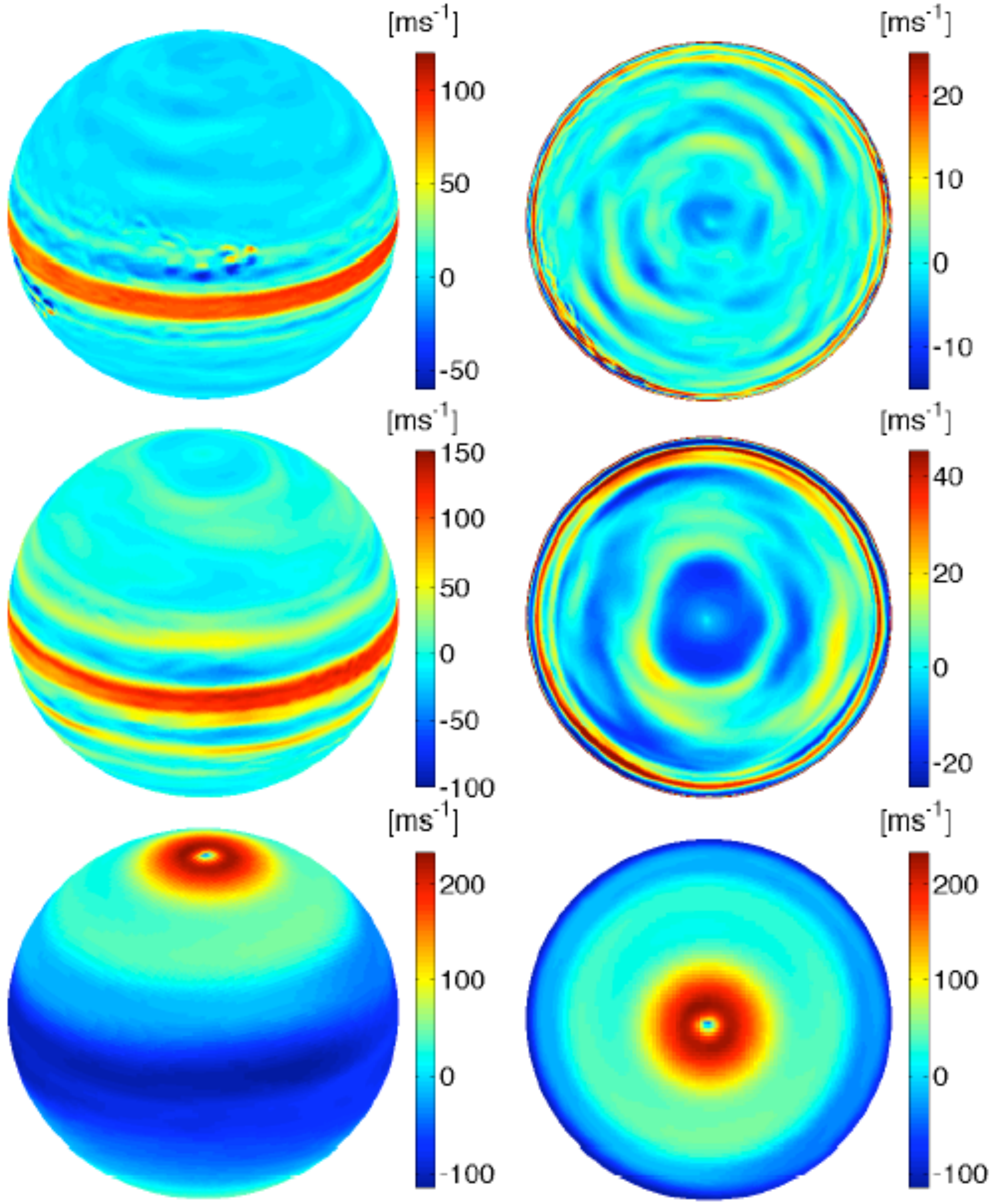
- **How do dynamics depend on planetary rotation rate, stellar irradiation, atmospheric metallicity, etc? Are there multiple dynamical regimes, and if so, what governs them? What are implications for observations?**

Zonal (east-west) winds on the giant planets





Lian & Showman (2010)



Jupiter

Saturn

Uranus/Neptune

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**

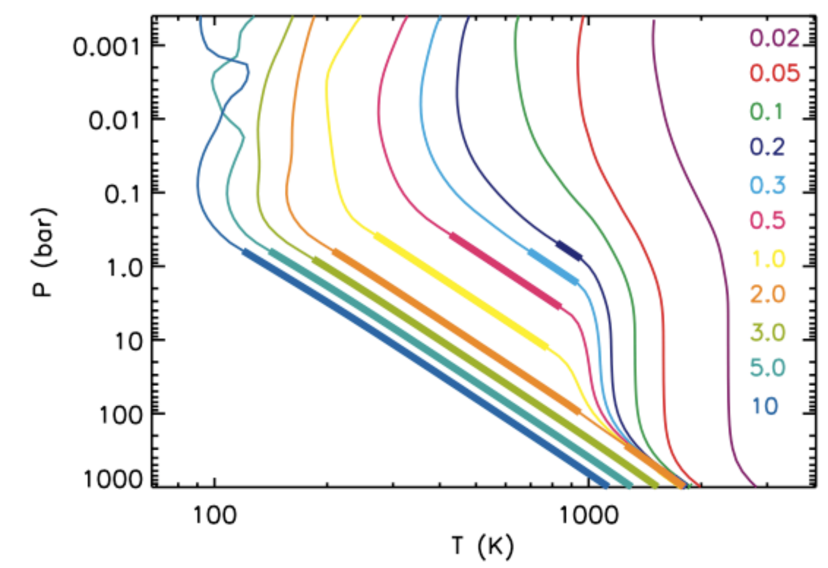
- **Rotation expected to be synchronous with the 1-10 day orbital periods; Coriolis forces important but not dominant**

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

- **Timescale arguments:**

  $\tau_{rad} << \tau_{dyn}$ for $p < 1$ bar; large temperature contrasts

  $\tau_{rad} >> \tau_{dyn}$ for $p > 1$ bar; temperatures homogenized



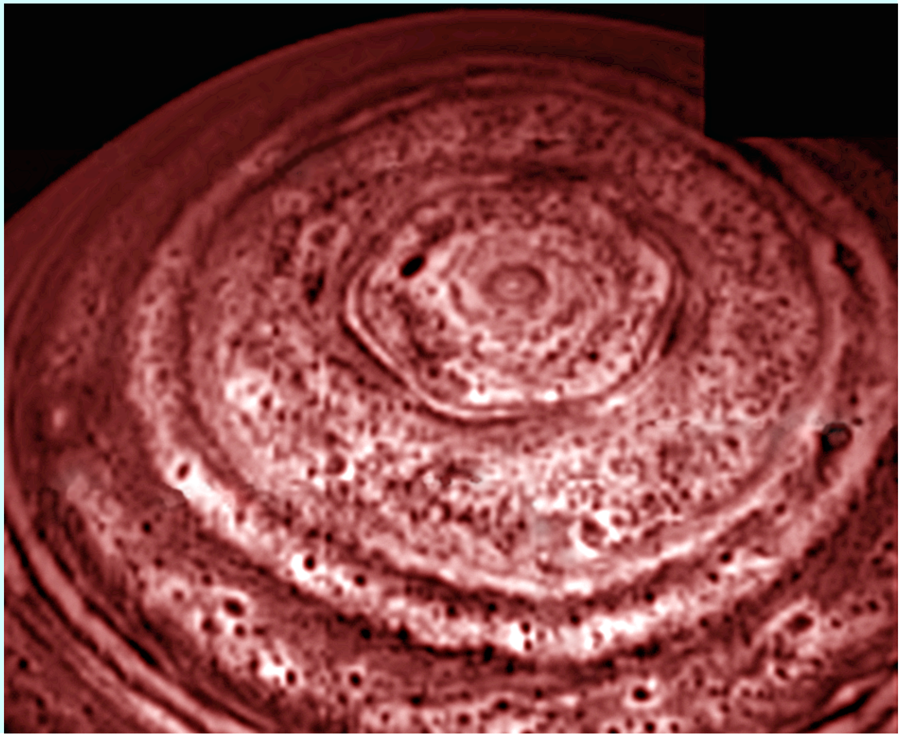
Fortney et al. (2007)

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

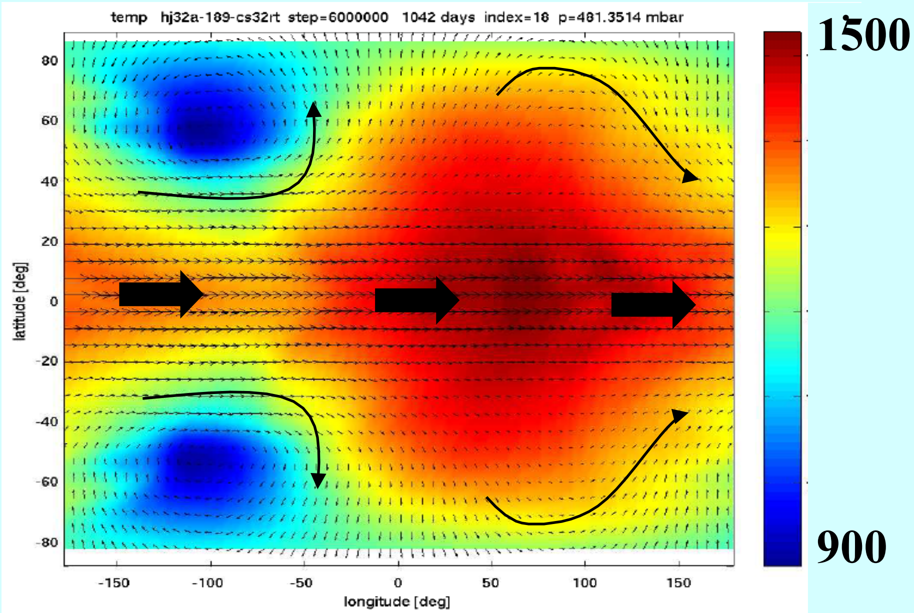
On most hot Jupiters, they are close to planetary radius. Jets and vortices should therefore be global in scale.

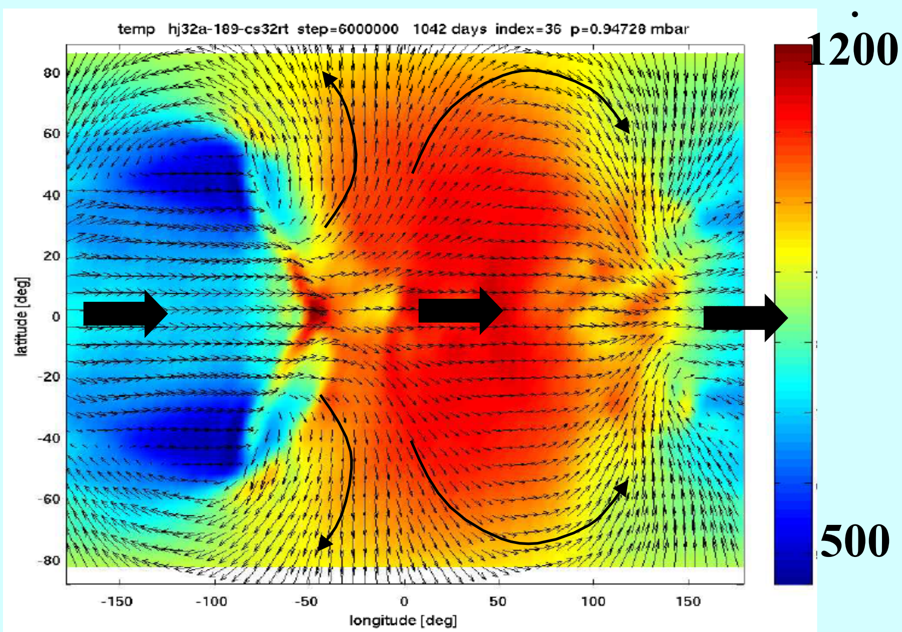


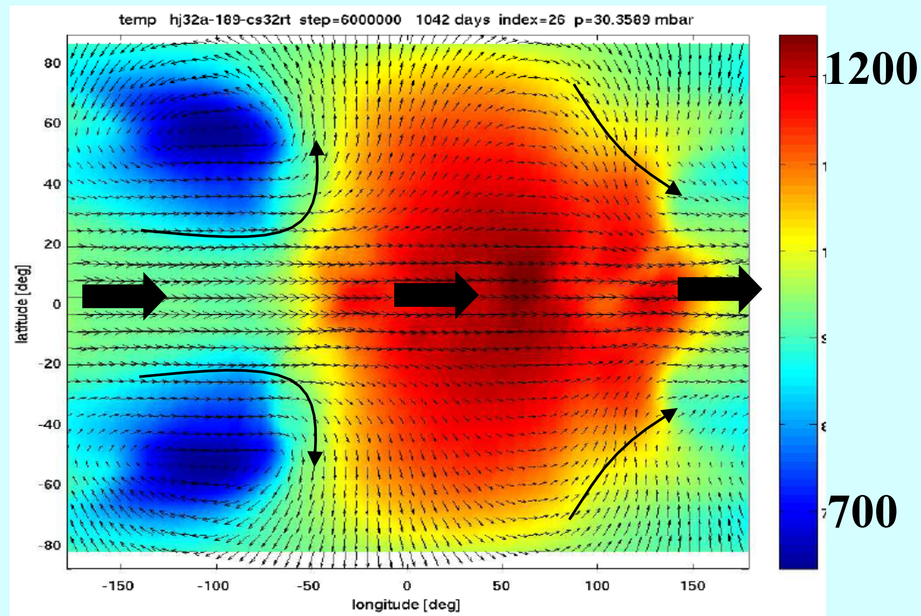
The Model

- **We solved the full nonlinear primitive equations in the stably stratified radiative zone on the whole sphere using the MITgcm**
- **Radiative transfer: plane-parallel multi-stream using correlated-k. Use 1, 5, or 10 x solar metallicity; equilibrium chemistry; no clouds**
- **Thermodynamic heating rate calculated as vertical divergence of net vertical radiative flux**
- **Domain: 0.2 mbar – 200 bars; impermeable bottom boundary; free-slip horizontal momentum boundary conditions at top & bottom**
- **Assume a synchronously rotating planet with parameters for HD209458b or HD189733b. Initial temperature profile taken from 1D evolution calculations; zero initial wind.**

HD 189733b, solar

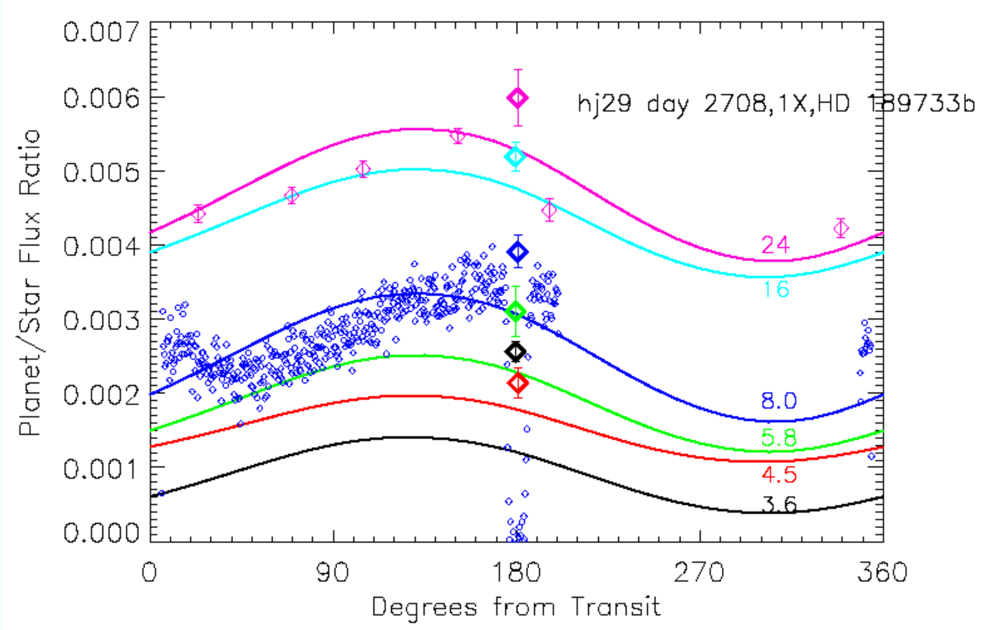


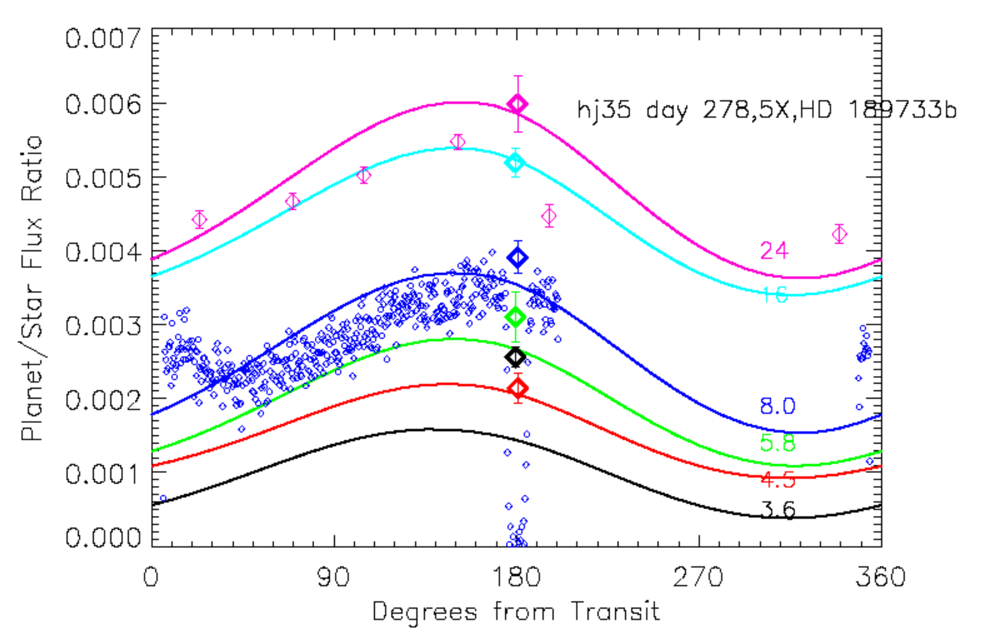




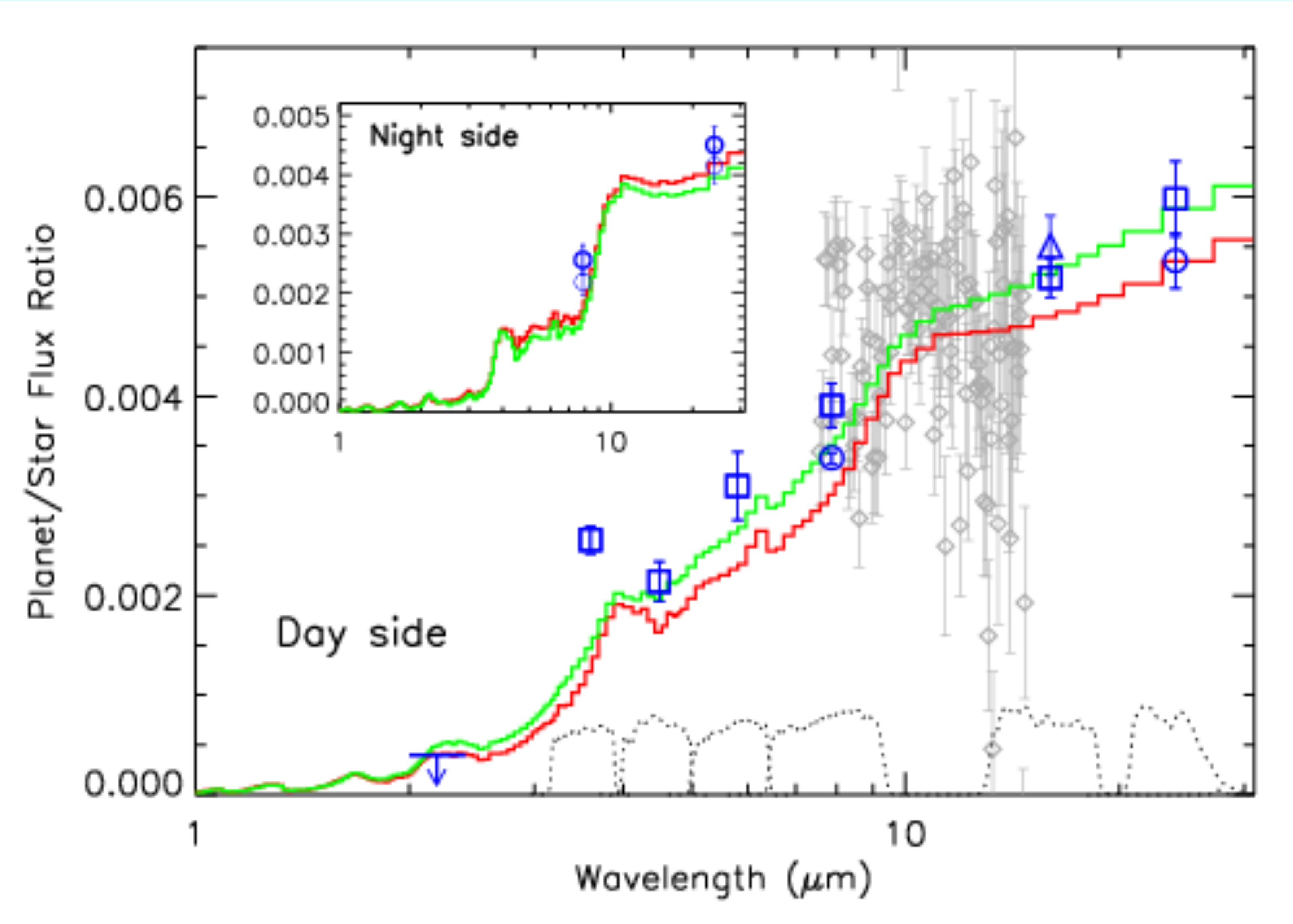
Showman et al. (2009)

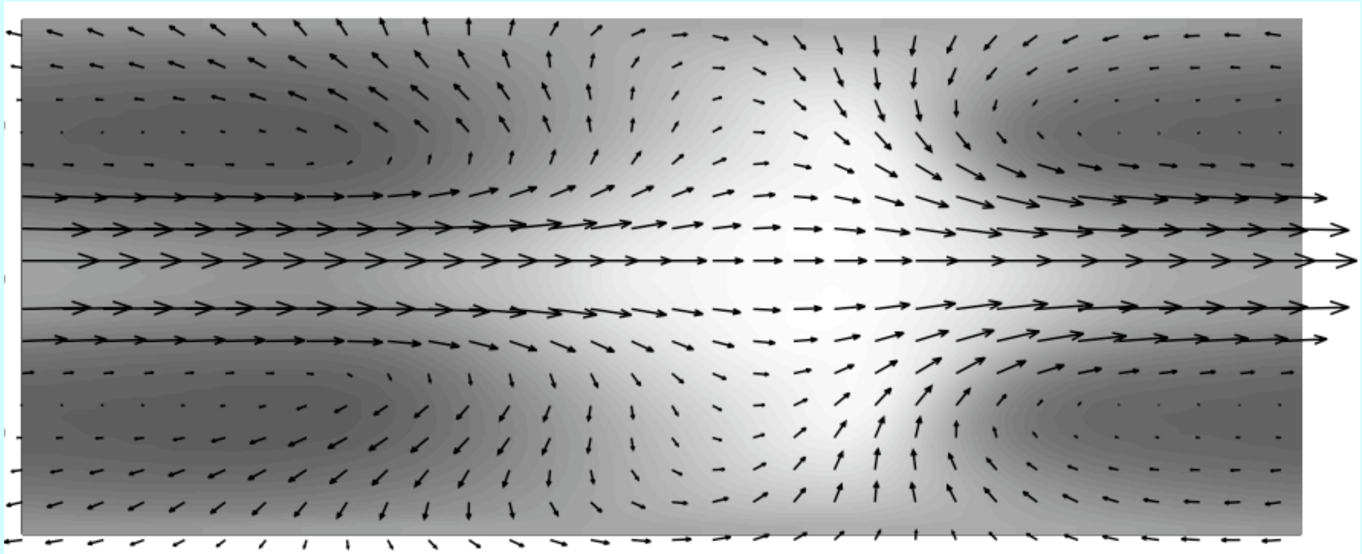
Lightcurves: HD 189733b, solar (top) and 5 x solar (bottom)



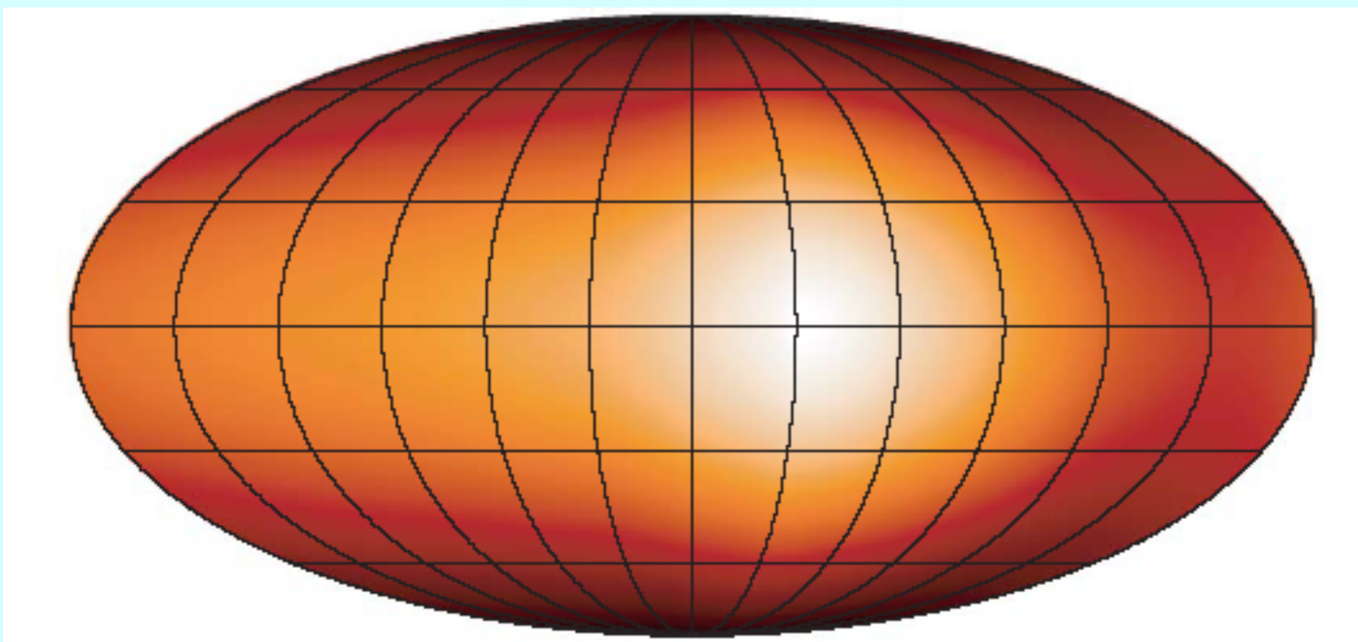


Secondary eclipse spectra: HD 189733b



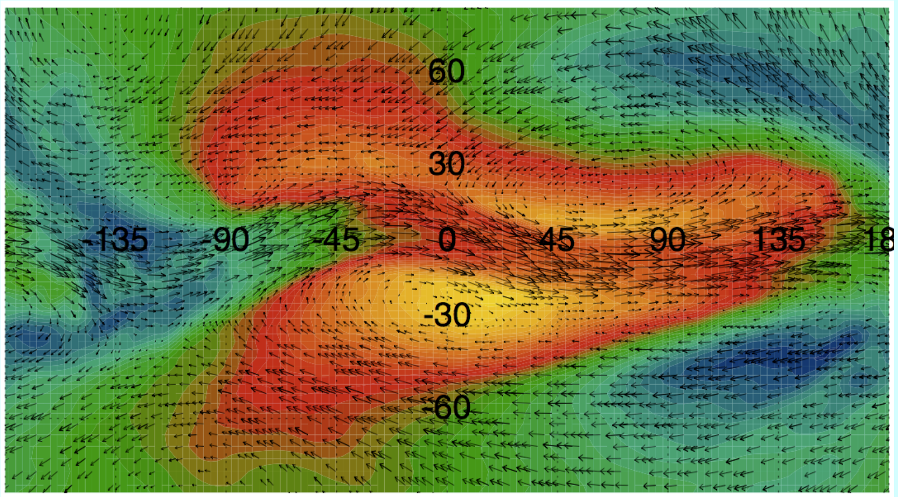


Showman & Guillot (2002)

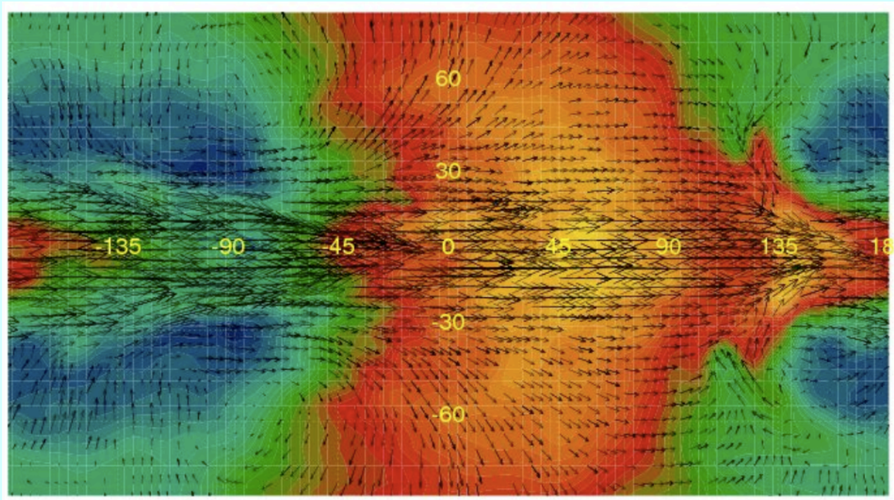


Knutson et al. (2007)

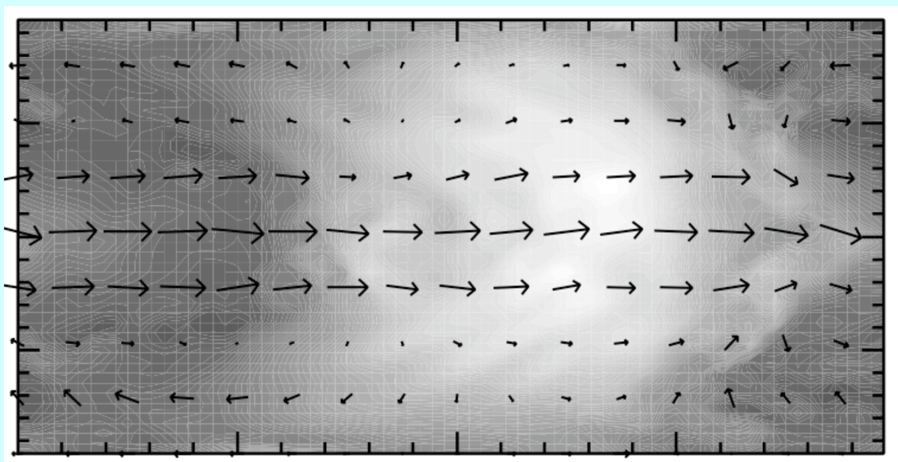
Equatorial superrotation is a common outcome of hot Jupiter circulation models



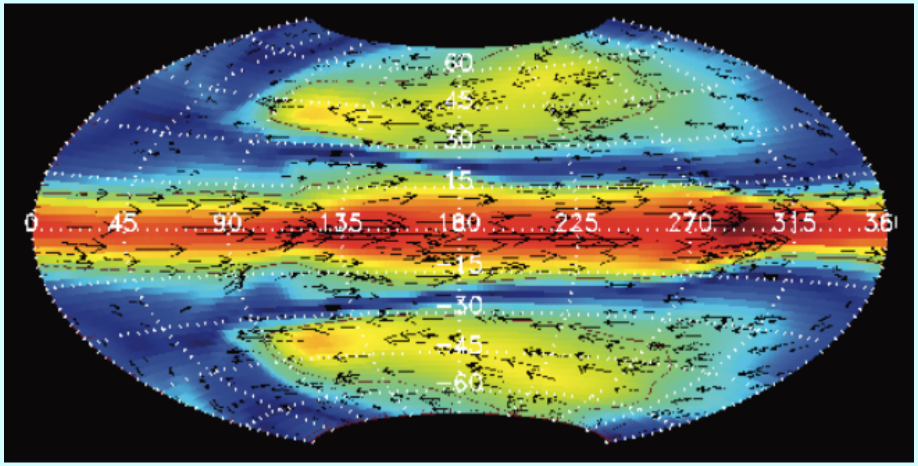
Menou & Rauscher (2009)



Rauscher & Menou (2010)



Cooper & Showman (2005, 2006)



Dobbs-Dixon & Lin (2008, 2010)

Terrestrial Superrotation: A Bifurcation of the General Circulation

MAX J. SUAREZ AND DEAN G. DUFFY

Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland

(Manuscript received 12 February 1991, in final form 9 December 1991)

Equatorial Superrotation and Maintenance of the General Circulation in Two-Level Models

R. SARAVANAN

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

(Manuscript received 26 March 1992, in final form 23 June 1992)

Equatorial Superrotation and the Factors Controlling the Zonal-Mean Zonal Winds in the Tropical Upper Troposphere

IAN KRAUCUNAS AND DENNIS L. HARTMANN

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

Tropical Wave Driving of the Annual Cycle in Tropical Tropopause Temperatures. Part II: Model Results

W. A. NORTON

NCAS Centre for Global Atmospheric Modelling, Department of Meteorology, University of Reading, Reading, United Kingdom

(Manuscript received 16 March 2005, in final form 19 August 2005)

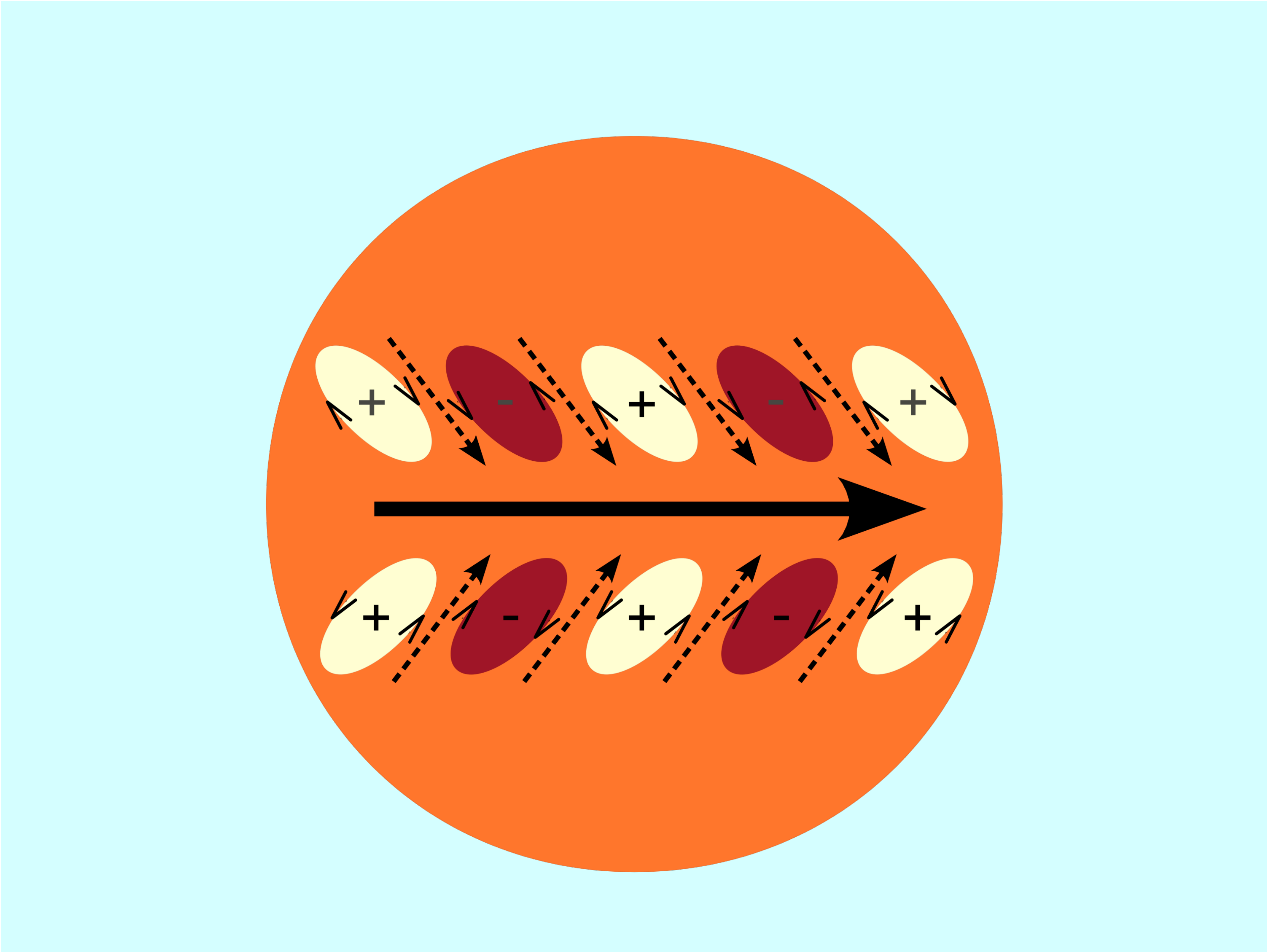
What causes the equatorial superrotation?

Hide's theorem: **Superrotating equatorial jets (corresponding to local maxima of angular momentum) cannot result from axisymmetric circulations (e.g., angular-momentum conserving Hadley cells).**

Such jets must instead result from up-gradient momentum transport by waves and/or turbulence

Rossby waves are a possible candidate (Held 1999): they cause eastward acceleration where they are generated and westward acceleration where they dissipate/break

For a hot Jupiter, the asymmetric forcing (dayside heating, nightside cooling) is a natural generator of planetary-scale Rossby waves … thus causing the equatorial superrotation!



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:**

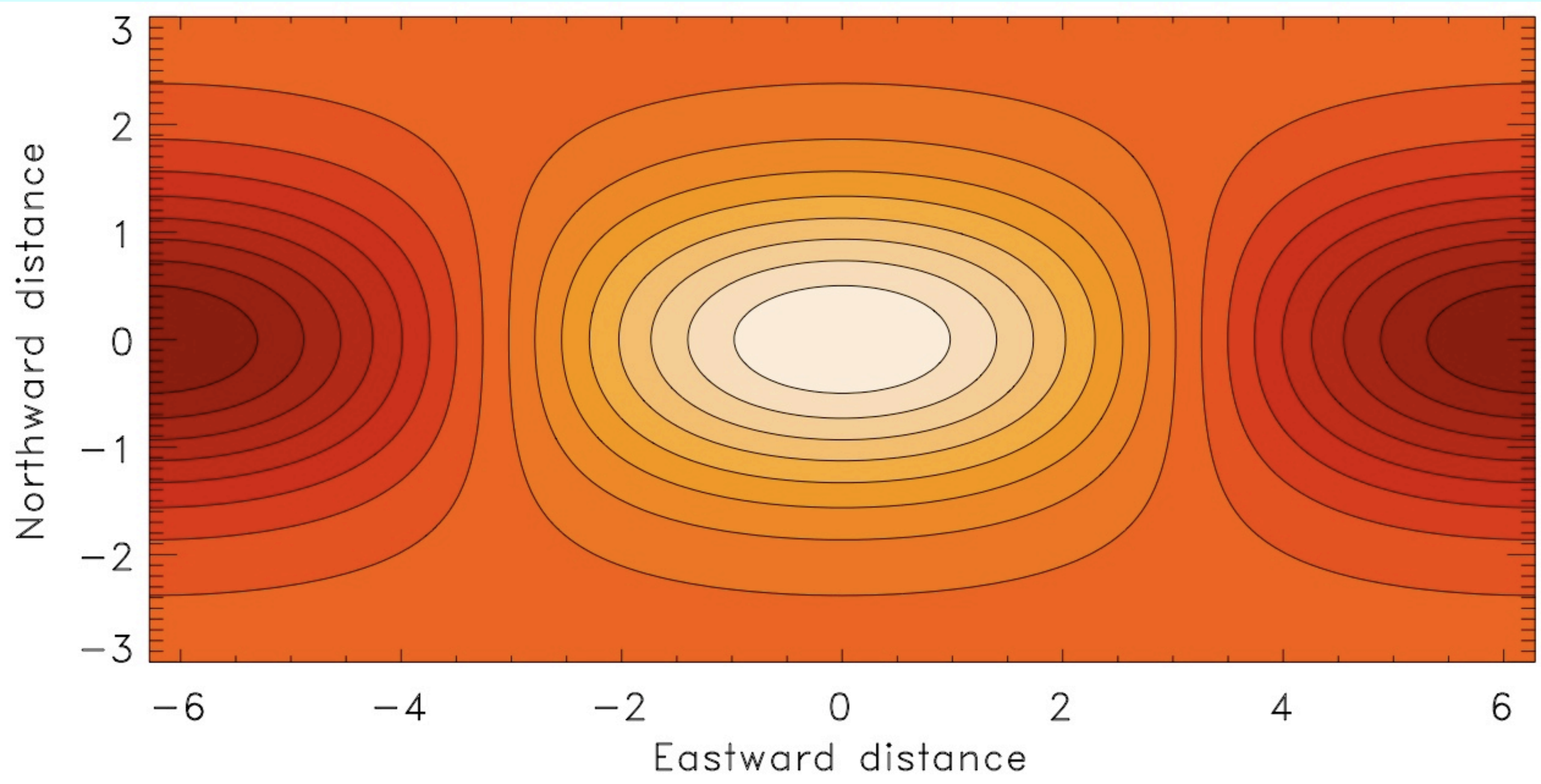
$$\frac{d\vec{v}}{dt} + g\nabla h + fk \times \vec{v} = -\alpha\vec{v} - \vec{v}\,\frac{Q_h}{h}\delta$$

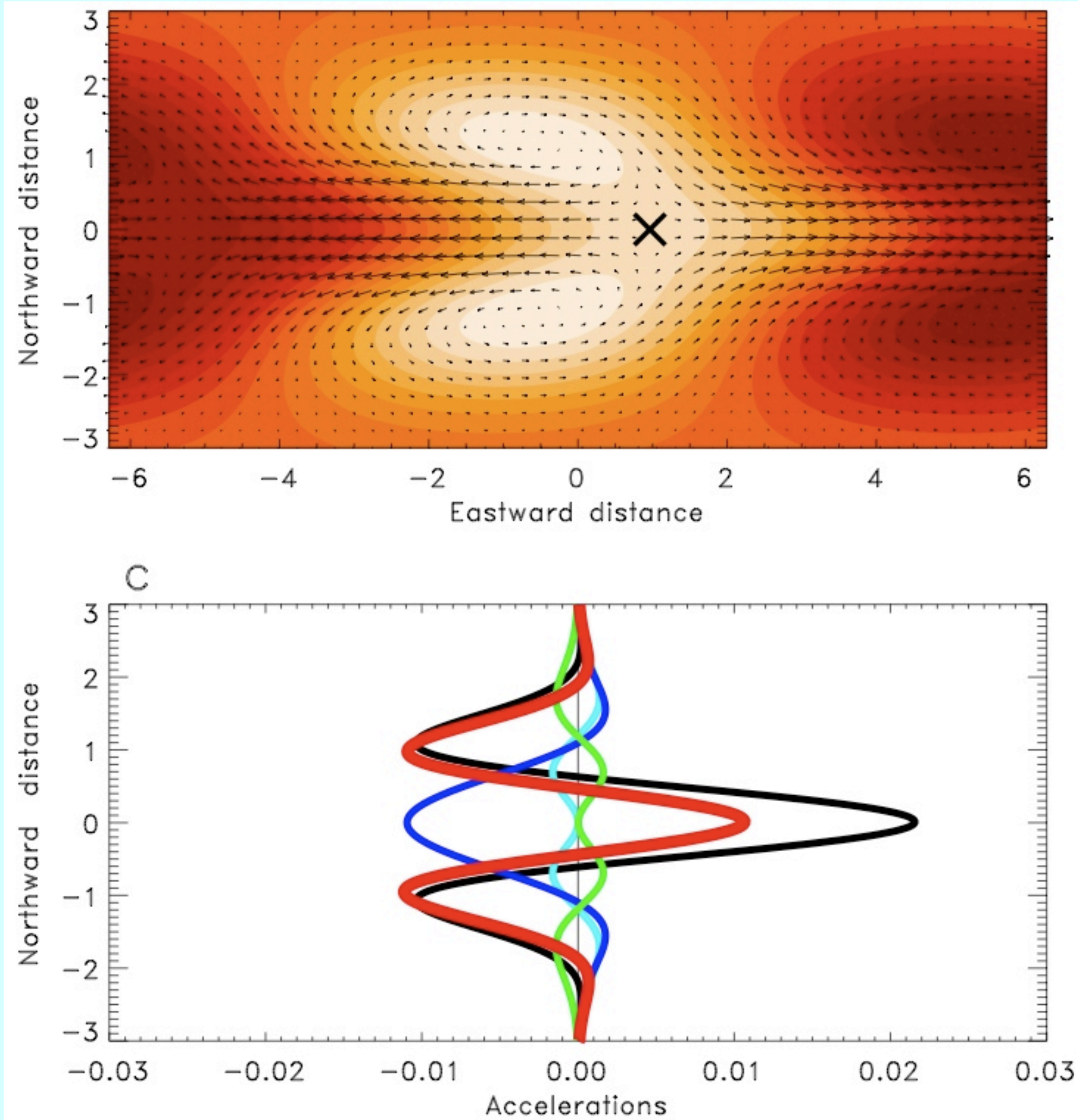
$$\frac{\partial h}{\partial t} + \nabla \cdot (h\vec{v}) = \gamma[h_{eq}(x,y) - h] \equiv Q_h$$

where $\gamma[h_{eq}-h]$ represents thermal forcing/damping, αv represents drag, and where $\delta=1$ when $Q_h>0$ and $\delta=0$ otherwise

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

Forcing

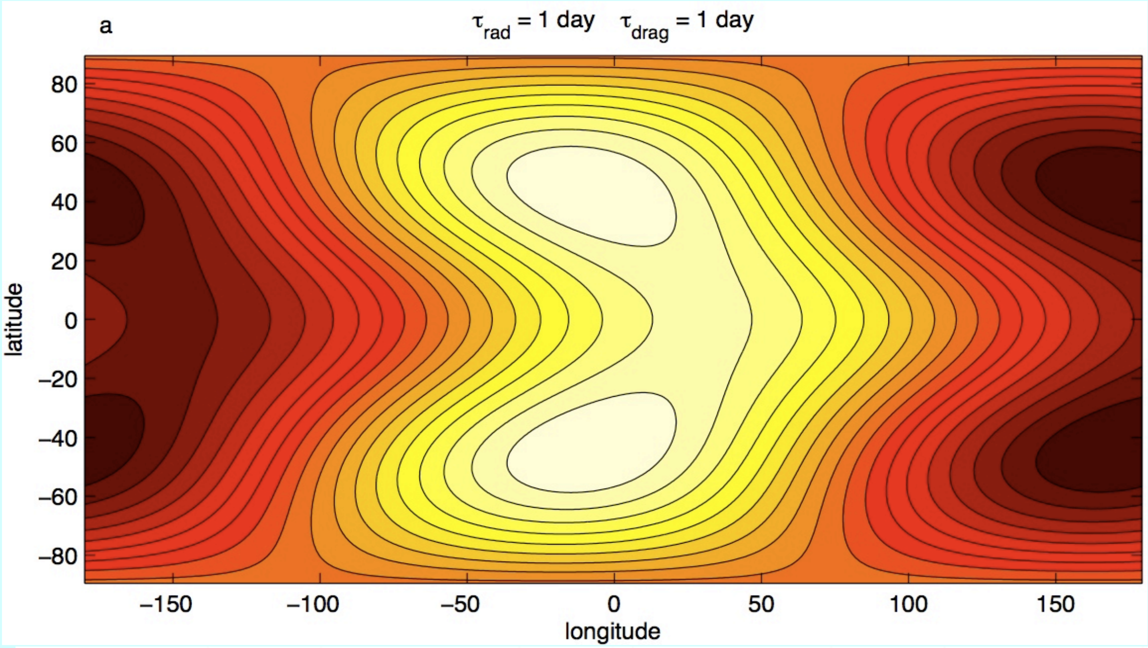


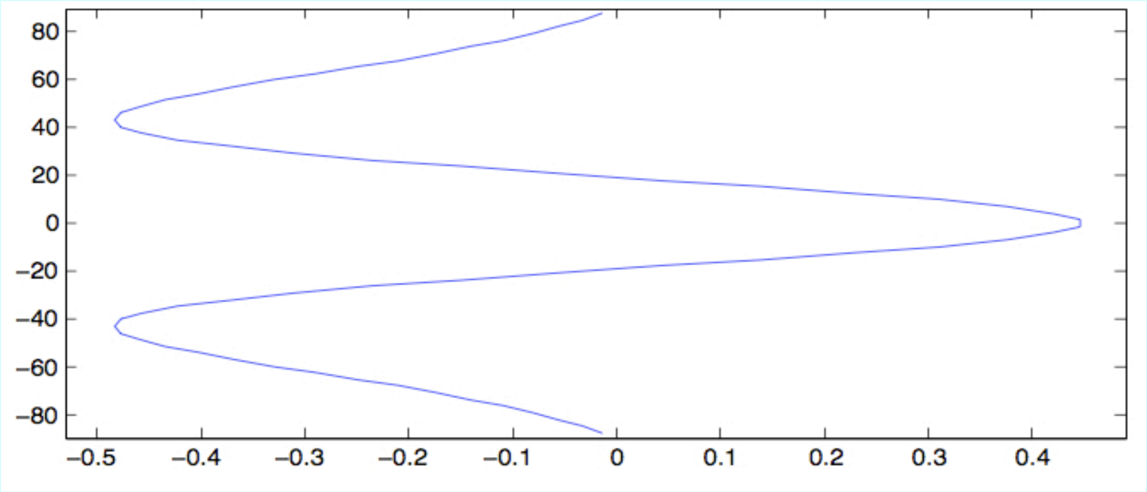


$$\frac{\partial \overline{u}}{\partial t} = -\frac{1}{\overline{h}}\frac{\partial}{\partial y}[\overline{(hv)'u'}] + \frac{1}{\overline{h}}\overline{u'Q_h'} + \ldots$$

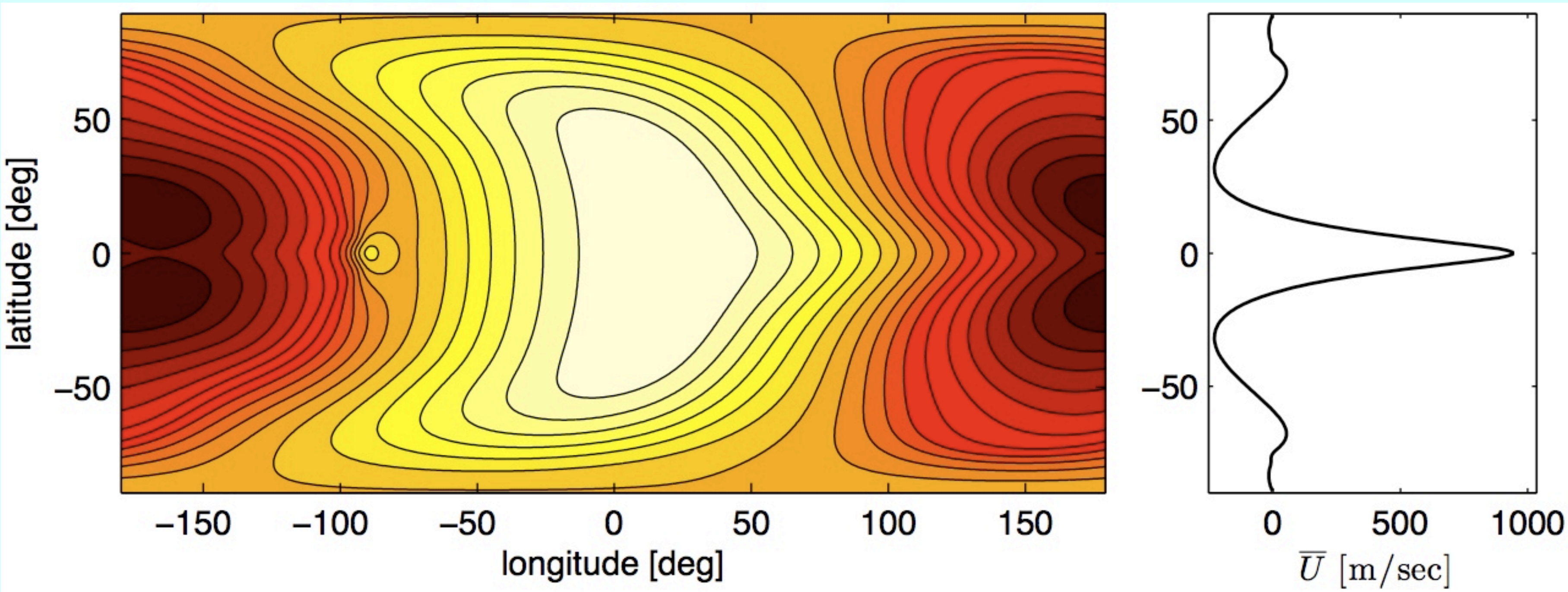
Showman & Polvani (submitted)

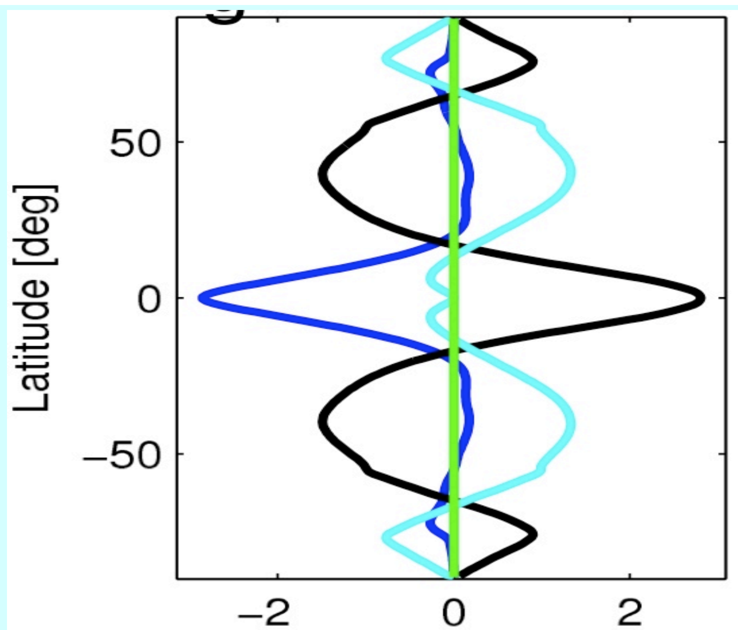
Full nonlinear spherical shallow-water solution for steady day-night forcing





Zonal-mean zonal wind

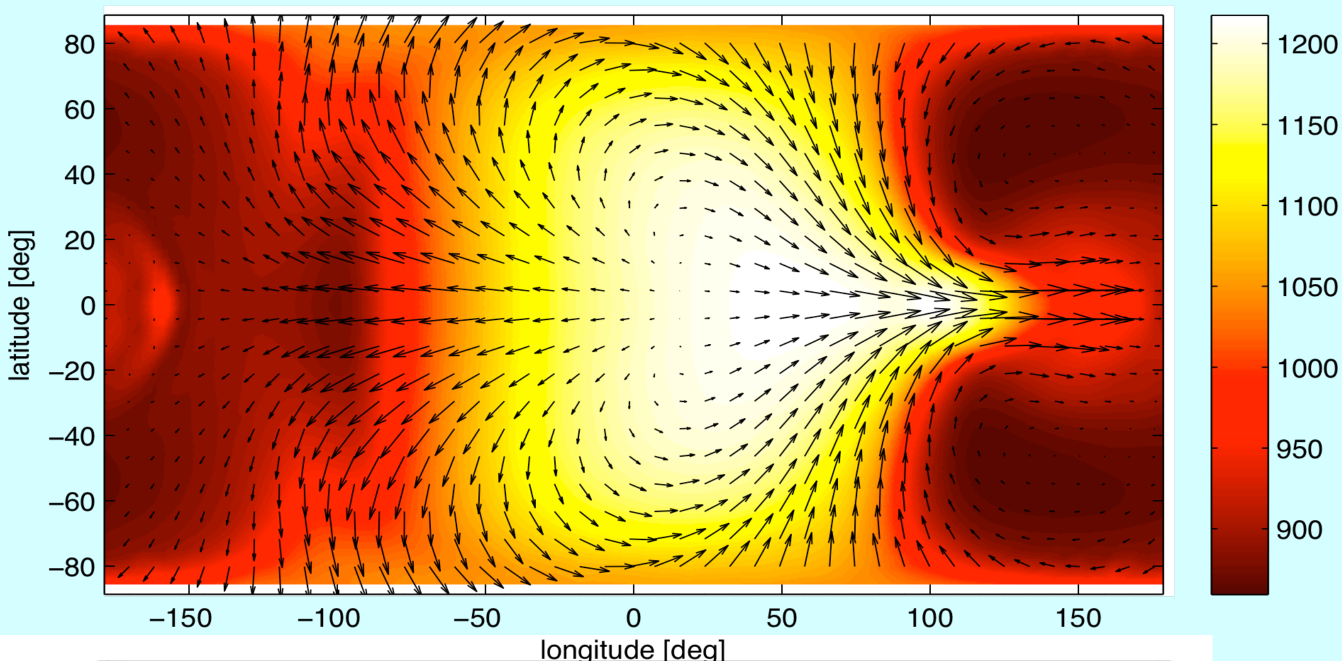


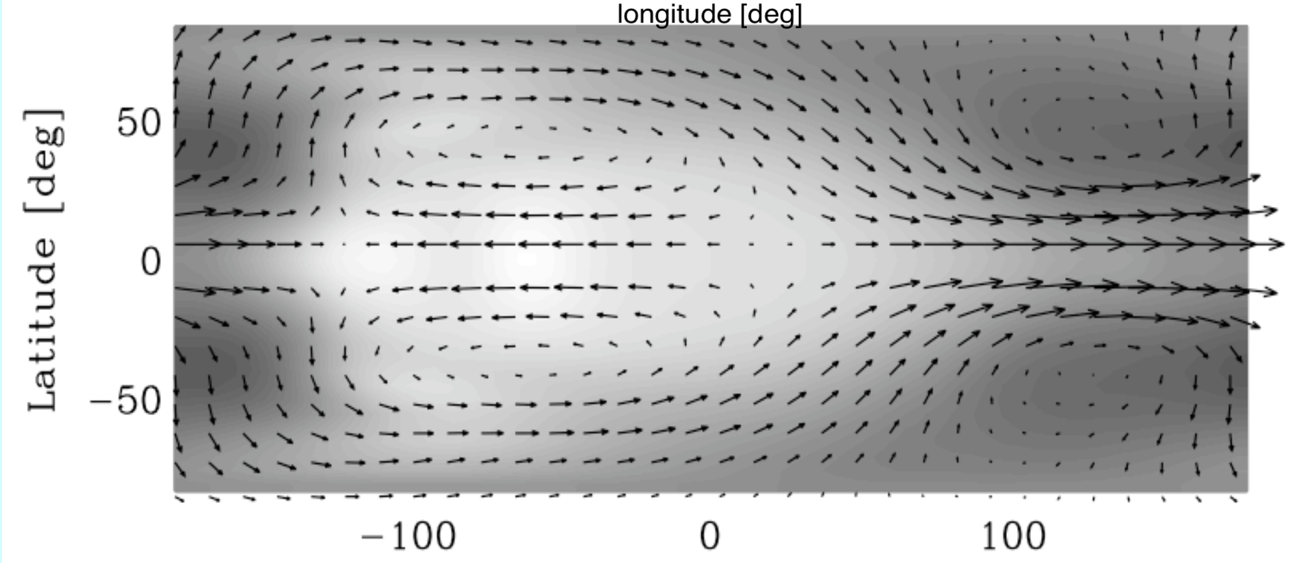


Acceleration (10^{-3} m/sec^2)

Showman & Polvani (submitted)

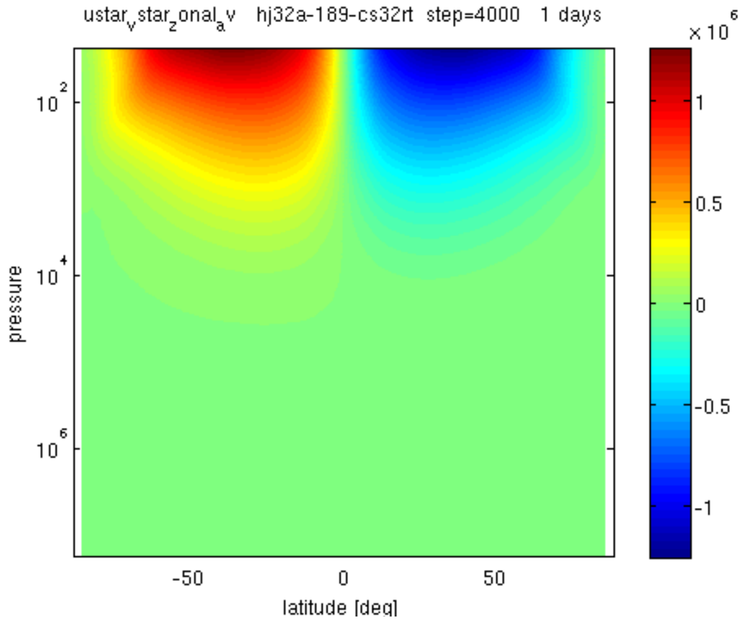
"Gill" pattern is clearly evident in spin-up phase of 3D hot Jupiter simulations

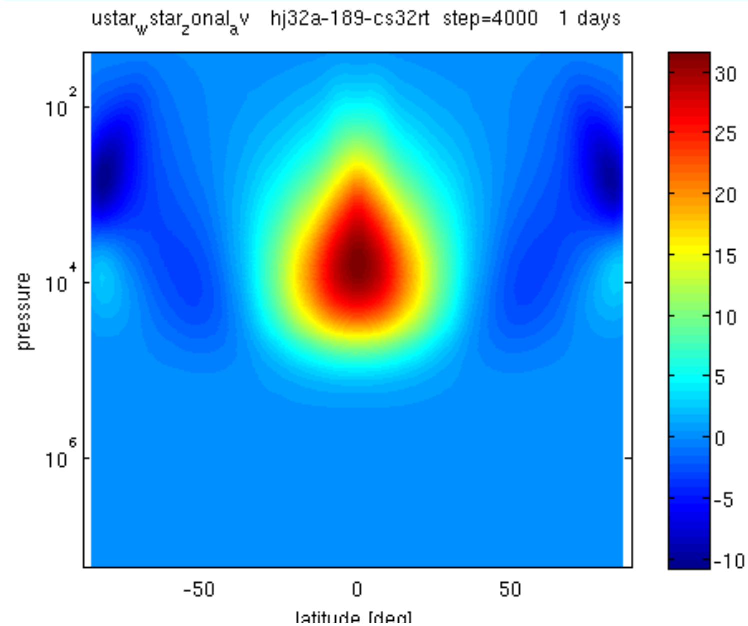




Showman & Guillot (2002)

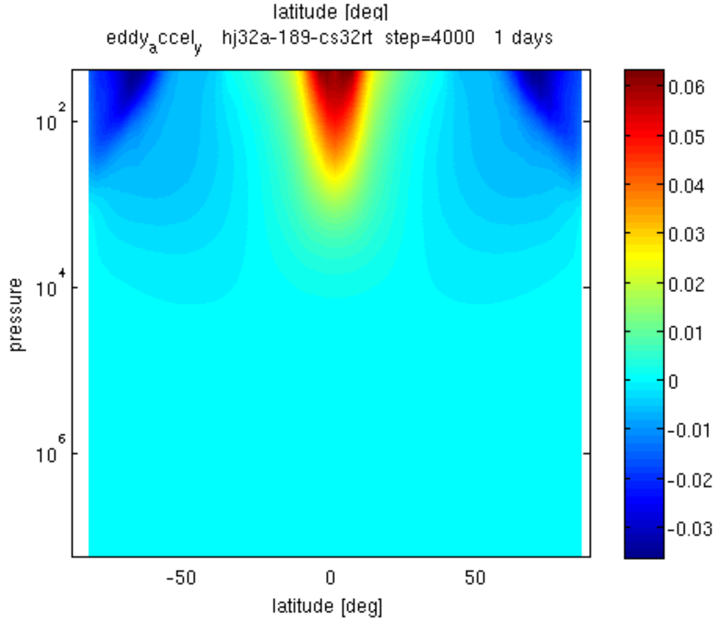
$\overline{u'v'}$

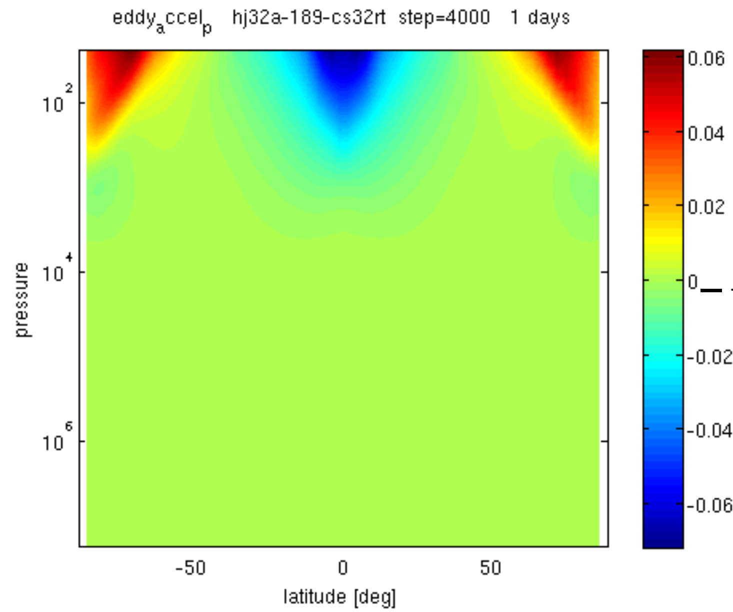




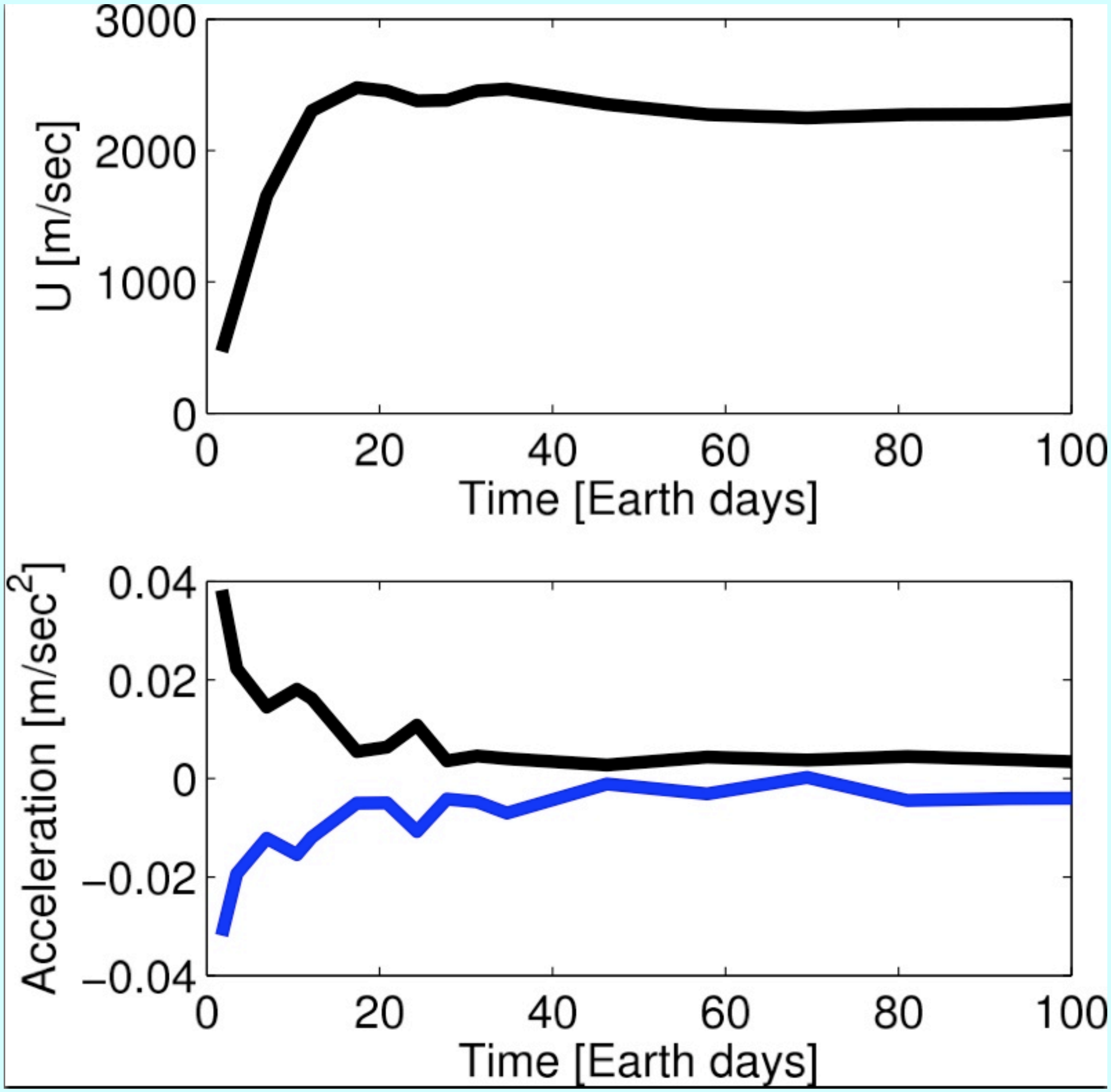
$\overline{u'\omega'}$

$-\frac{\partial}{\partial y}(\overline{u'v'})$

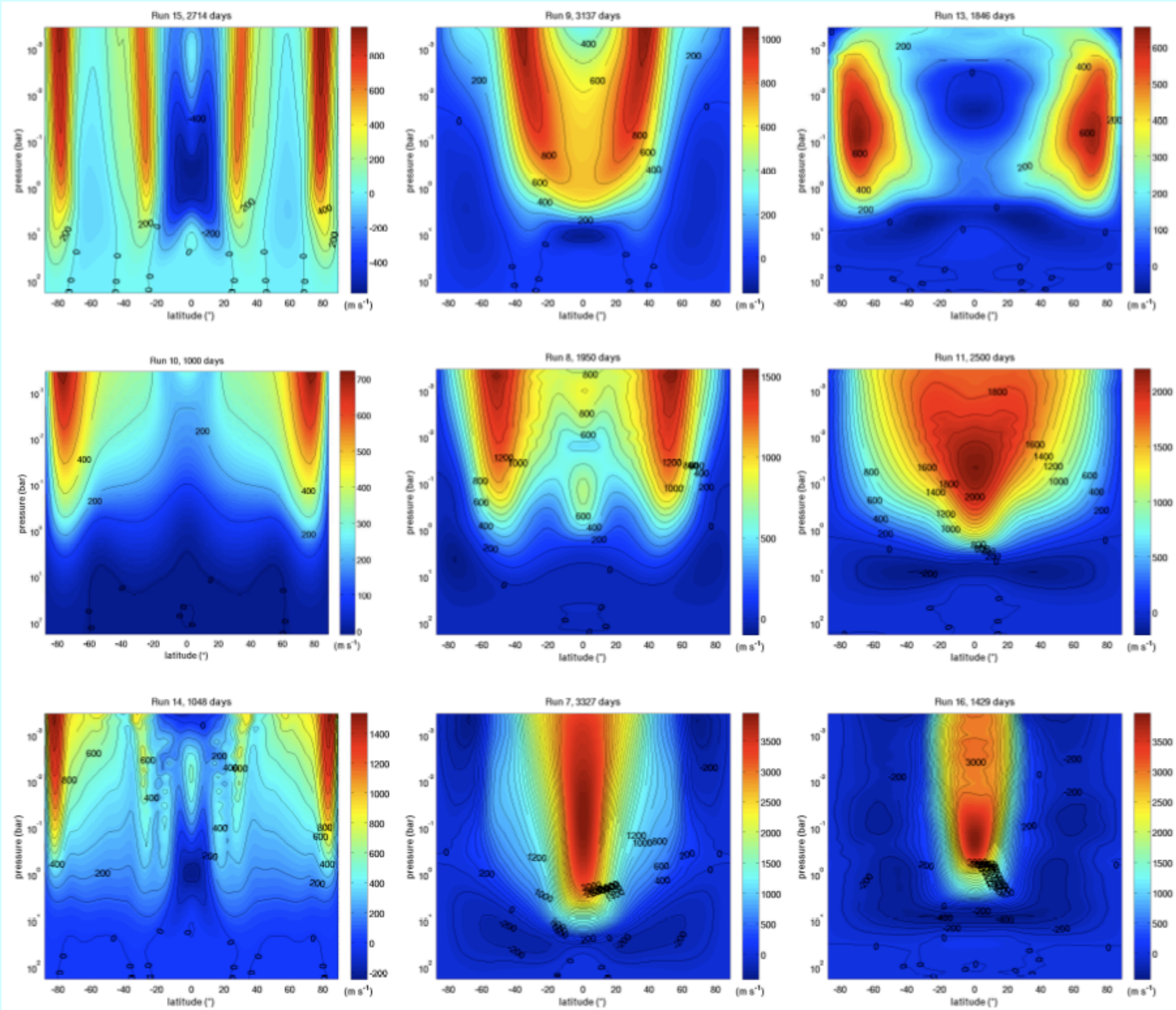




$-\frac{\partial}{\partial p}(\overline{u'\omega'})$


3000
2000
1000
0
U [m/sec]
0
20
40
60
80
100
Time [Earth days]
0.04
0.02
0
−0.02
−0.04
Acceleration [m/sec^2]
0
20
40
60
80
100
Time [Earth days]

Dependence of wind on rotation rate and orbital distance

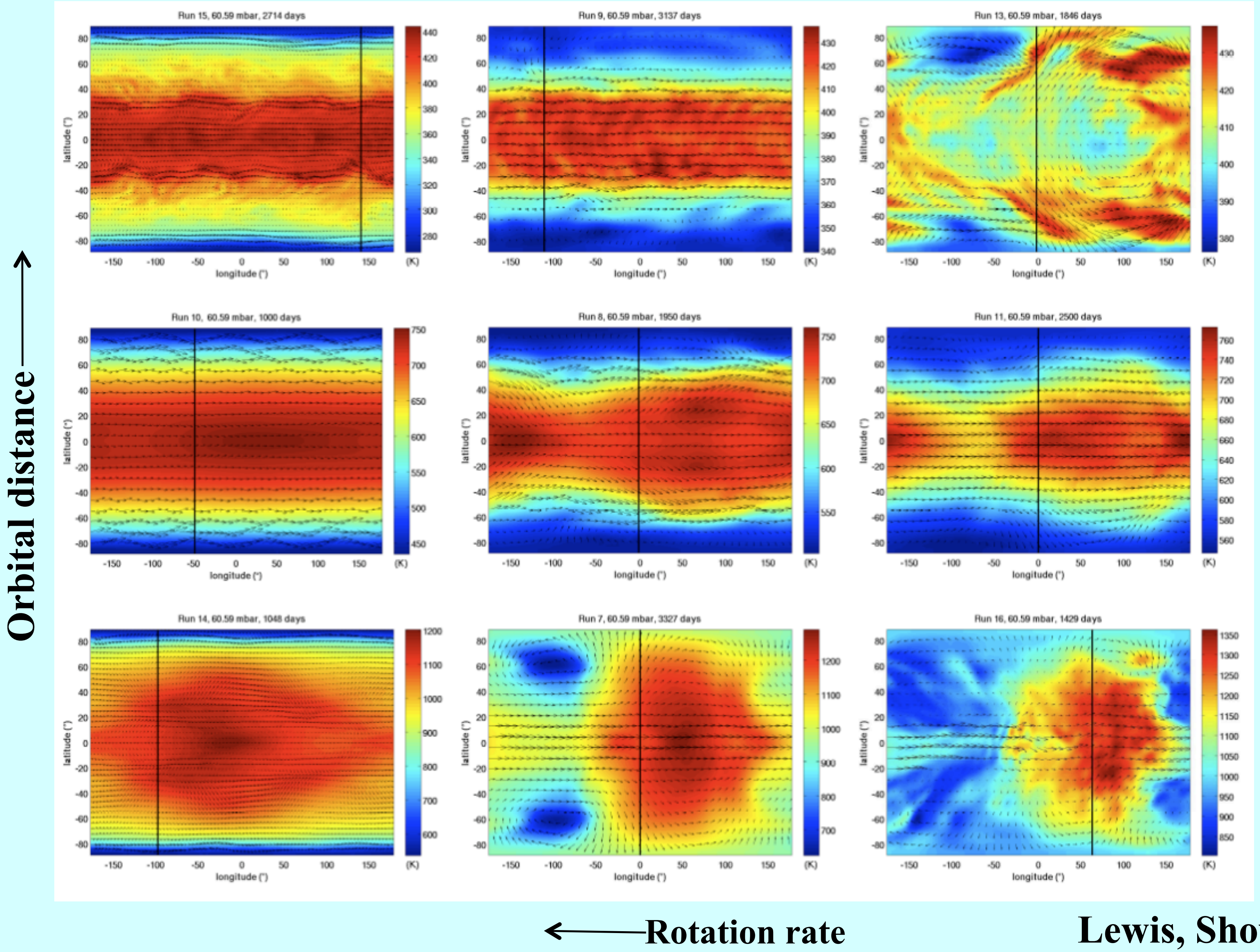


Orbital distance →

← Rotation rate

Lewis, Showman

Dependence of temperature on rotation rate and orbital distance



Lewis, Showman

Conclusions

The intense radiation produces winds > 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.

For synchronously rotating planets, our models produce equatorial superrotation that displaces the hottest regions to the east of the substellar point. The superrotation results from up-gradient wave transport because of standing Rossby and Kelvin waves triggered by the longitudinal (day-night) heating variations.

The mechanism of equatorial superrotation is cleanly demonstrated in a sequence of simple models; the phase tilts that pump momentum equatorward result from the eastward propagation of Kelvin waves and westward propagation of Rossby waves.

A regime shift occurs from a circulation regime dominated by equatorial superrotation under synchronous rotation and short radiative time constants to a circulation dominated by midlatitude eastward jets when the rotation rate is fast and/or radiative time constants are long.