Atmospheric Dynamics of Jupiters (hot and not)

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Why study the circulation?

Hot Jupiters occupy a dynamically distinct regime unavailable in our Solar System. Studying them broadens our understanding of meteorology.

The circulation shapes the <u>IR spectra</u>, <u>lightcurves</u>, <u>cloudiness</u> (visible albedo), <u>evolution</u>, and <u>chemistry</u>. To explain these, we must understand the circulation.

Existing spectra/lightcurves already challenge our understanding. Future Spitzer, Kepler, groundbased, and JWST data will revolutionize our opportunity to probe these worlds.

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

Zonal (east-west) winds on Solar System giants

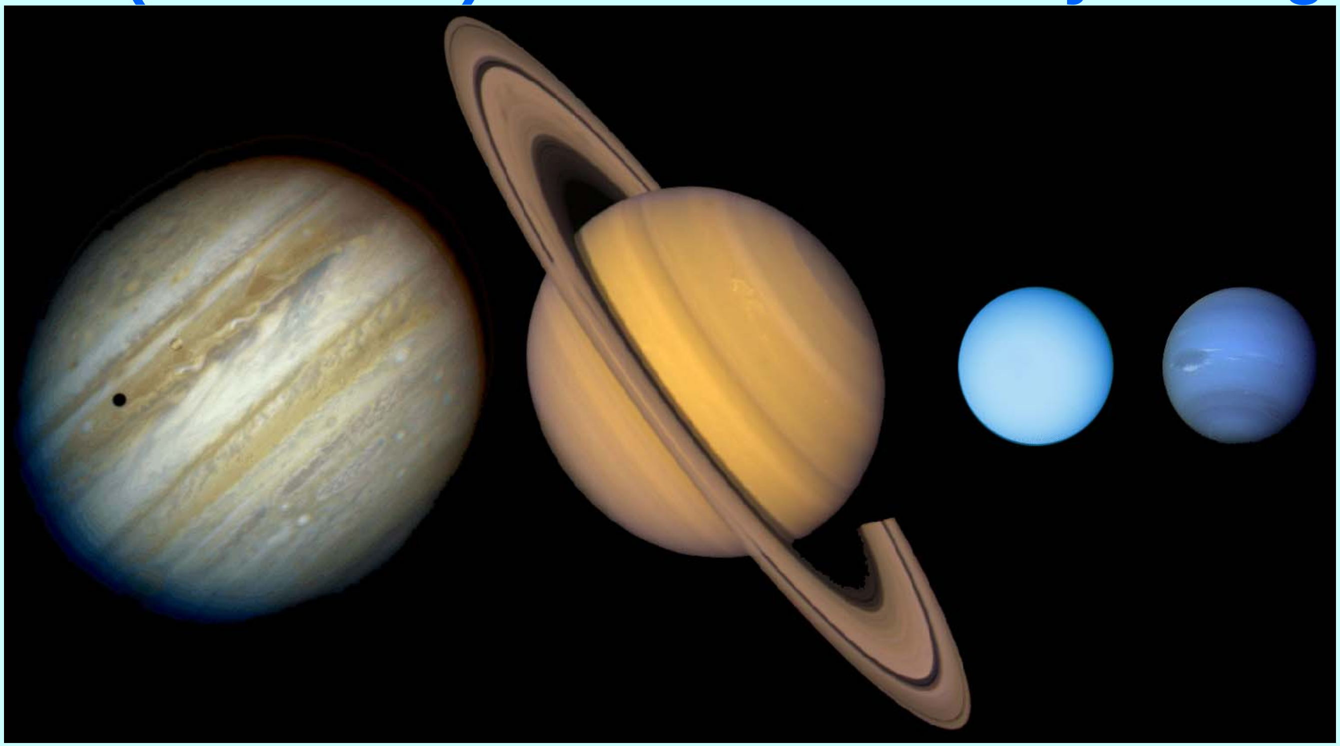
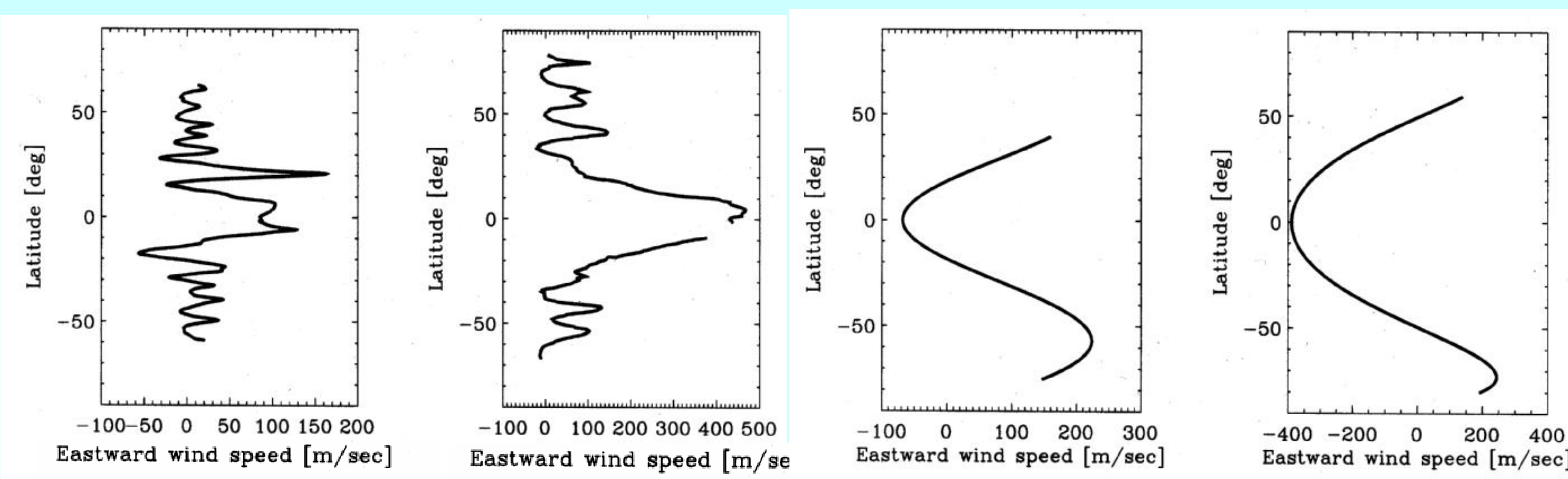


Image: Calvin Trillin



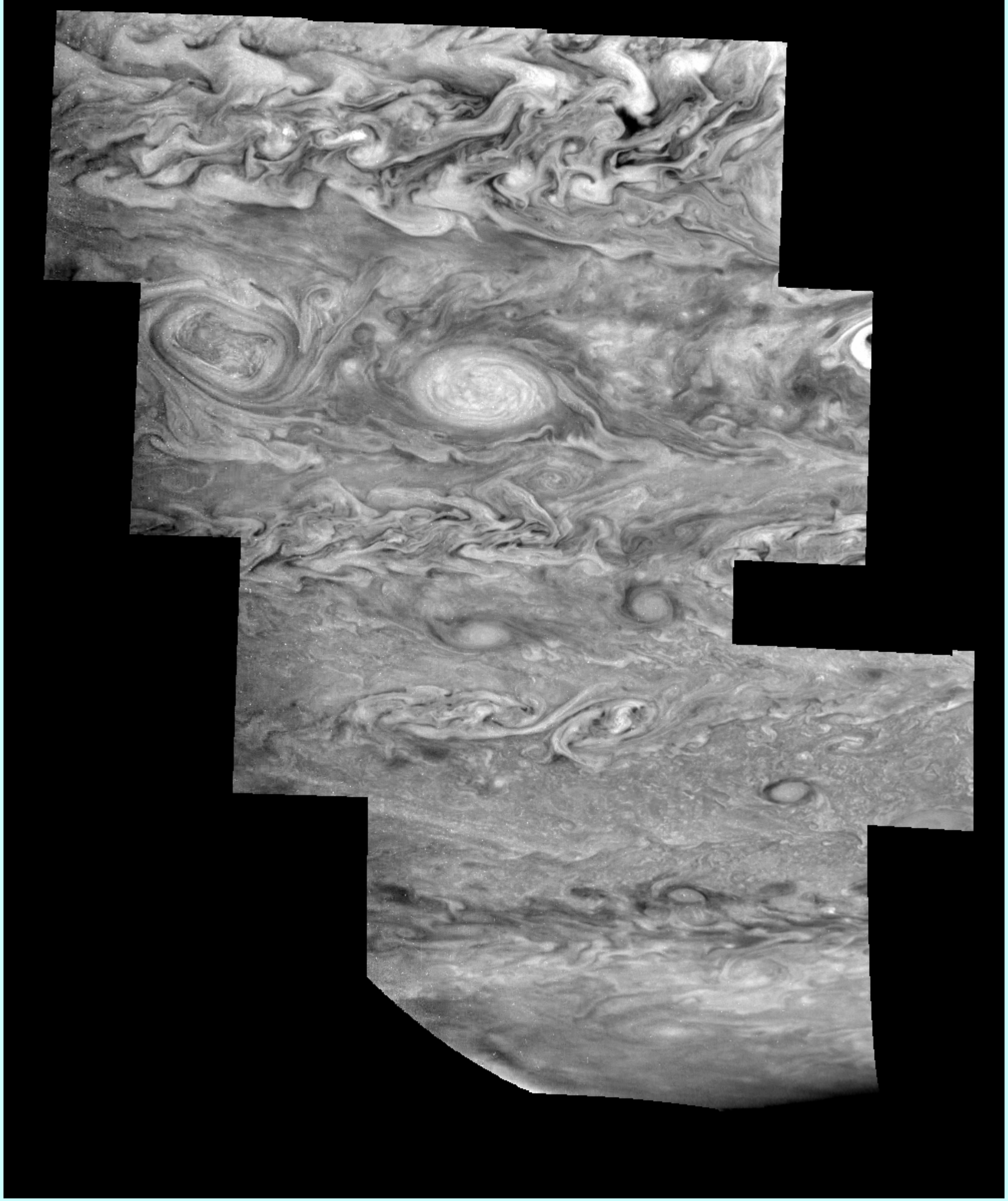
Key length scales

- **<u>Rhines length</u>**, $(U/\beta)^{1/2}$, is the scale at which planetary rotation causes east-west elongation (jets).

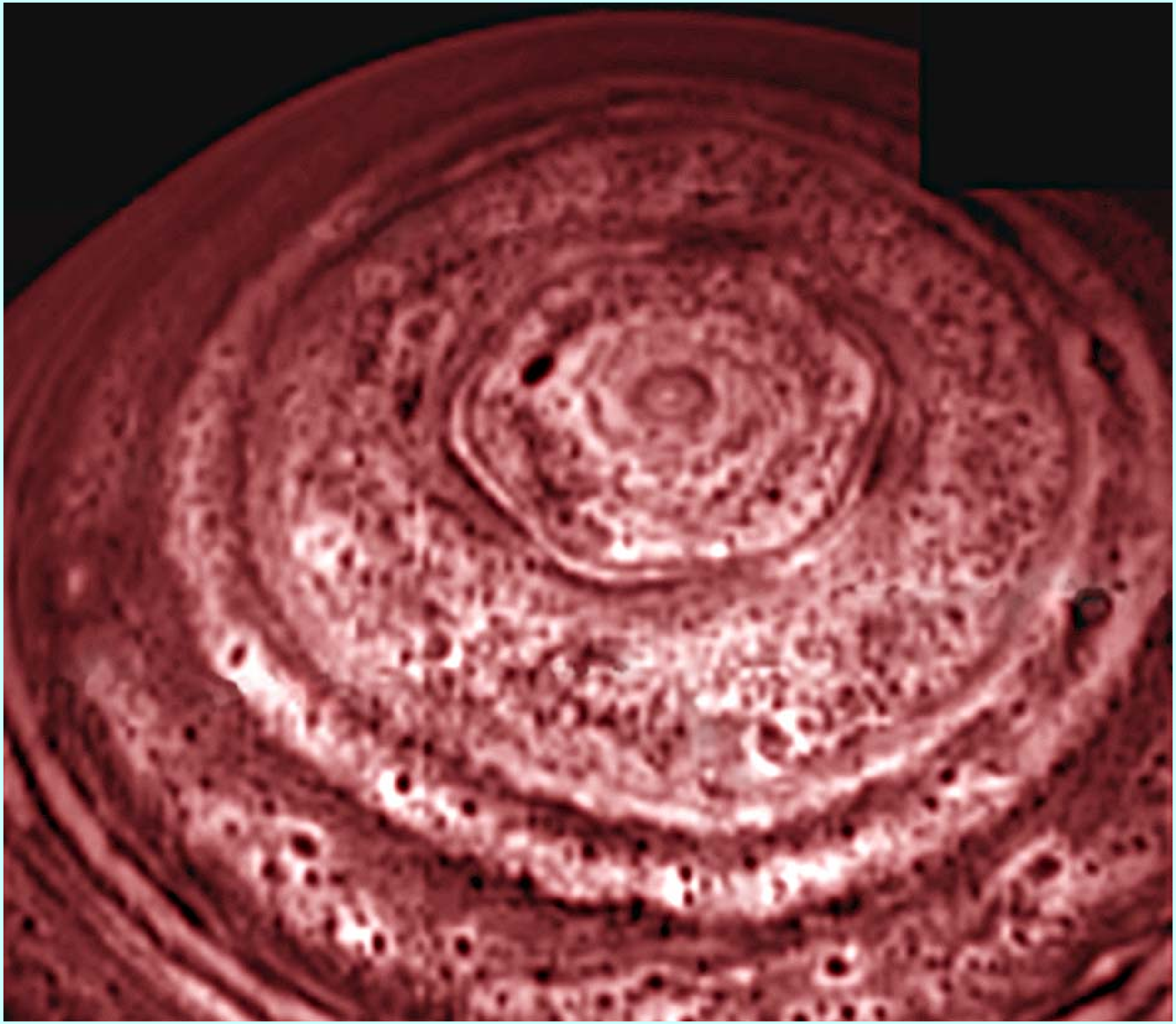
- **<u>Deformation radius</u>**, $N H/\Omega$, is the scale at which pressure perturbations are resisted by the Coriolis force. Vortices often have sizes near the deformation radius.

On Jupiter, these lengths are ~2000-10,000 km (<< planetary radius), which explains why Jupiter has narrow jets and tiny vortices.

Slow rotation on hot Jupiters means that, on hot Jupiters, Rhines length and deformation radius are close to planetary radius. Jets and vortices should therefore be global in scale (Showman and Guillot 2002, Menou et al. 2003).



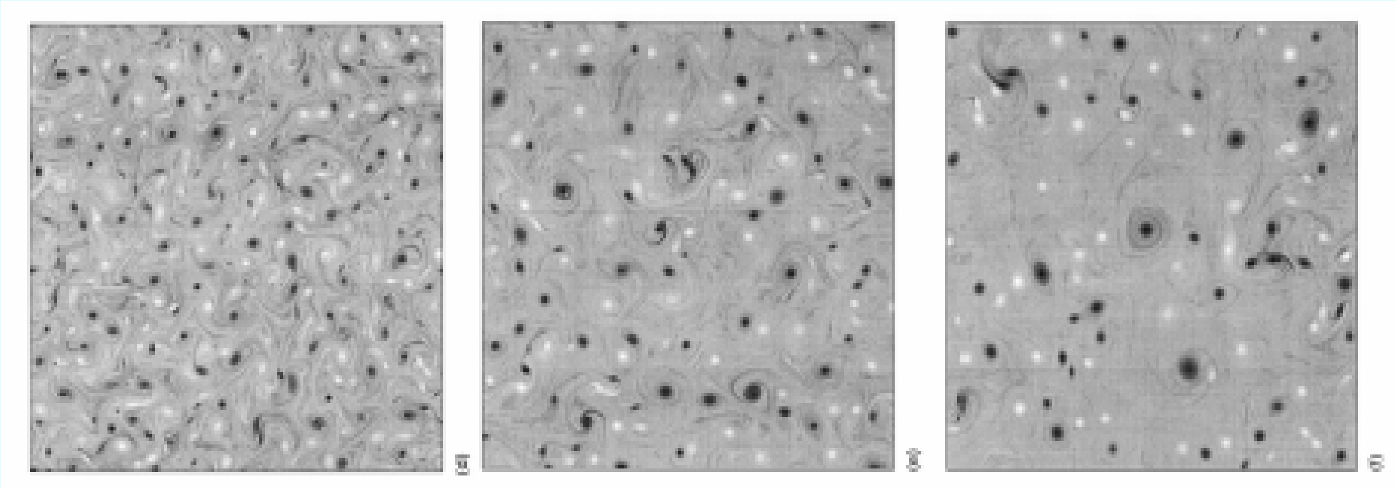
Jupiter



Saturn

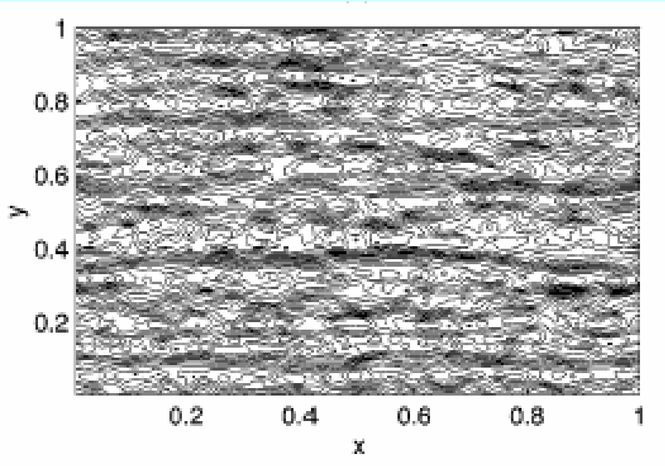
Banded structure results from modification of an inverse cascade by planetary rotation:

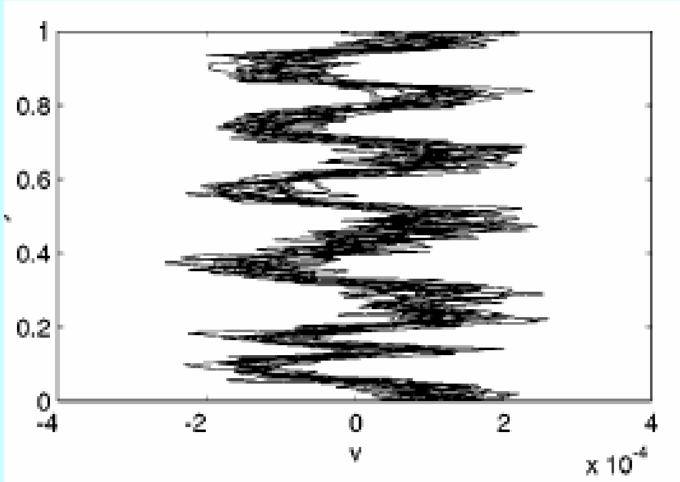
- **Small-scale 2D turbulence undergoes an inverse cascade that transfers the energy to large-scale structures:**



Bracco et al. (2000)

- **Gradient of planetary rotation causes anisotropy, leading to east-west elongation (jets):**

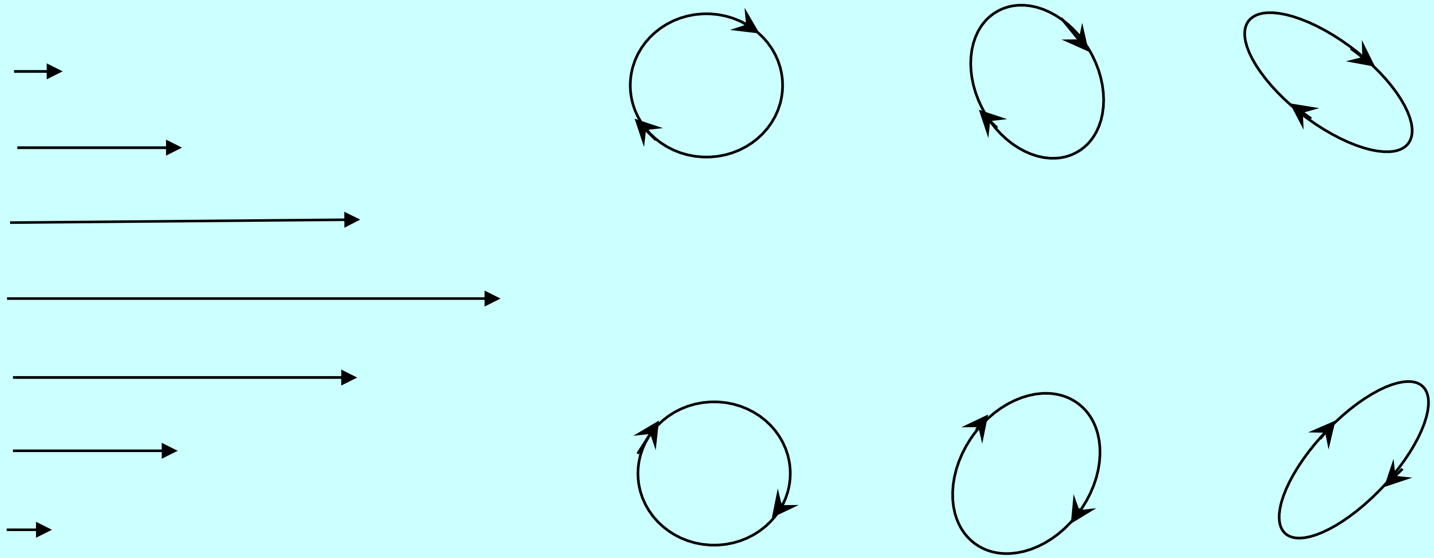




Marcus et al. (2000)

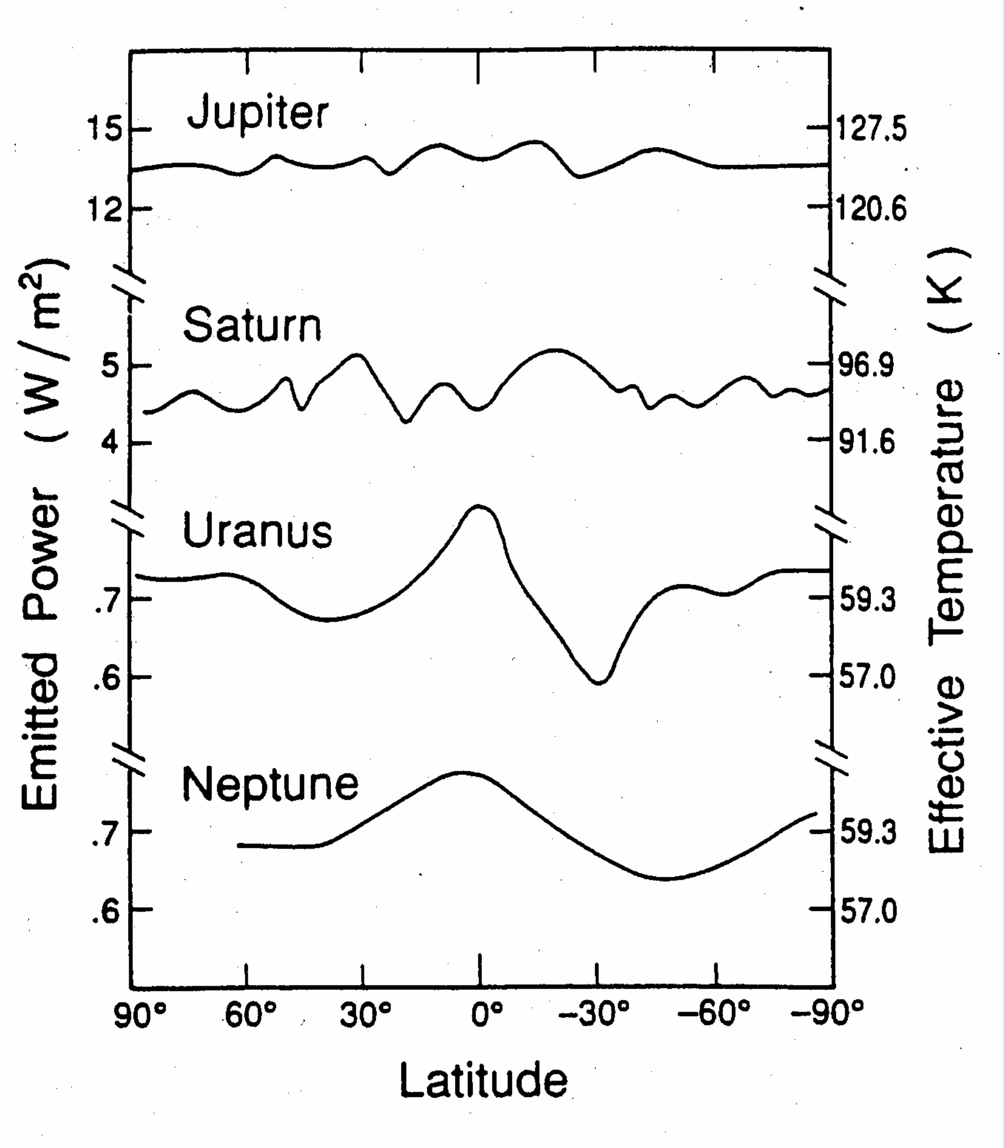
What is the process that drives the jets?

Eddies tilt into the jet shear, leading to an up-gradient transfer of momentum into the jets. This is a positive feedback!



Eddies thus provide the energy that pumps the flow. They are small on solar-system giants (convection), but they may be larger on hot Jupiters (day-night heating gradient)

Temperatures are relatively homogeneous on Solar-System giants:



Temperature contrasts can be understood with timescale arguments

- **If $\tau_{rad} << \tau_{advect}$: large temperature contrasts**
  $\tau_{rad} >> \tau_{advect}$: temperatures homogenized

- **Terrestrial planets fit expectations: longer τ_{rad} leads to smaller ΔT; faster longitudinal advection implies smaller ΔT in longitude than latitude.**

	τ_{rad}	$\tau_{advect, lon}$	ΔT_{lon}	$\tau_{advect, lat}$	ΔT_{lat}
Venus	**years**	**Days**	**< few K**	**Weeks**	**few K**
Earth	**Weeks-months**	**1 day**	**~10 K**	**Weeks**	**20-30 K**
Mars	**Days**	**1 day**	**~50 K**	**Weeks**	**~100 K**

- **Giant planet interiors: Convective mixing times are short (decades?) but radiative times are geological, so interior entropy is homogenized. On solar system giants, this constant-entropy interior "outcrops" at the photosphere, leading to nearly constant photospheric temperatures.**

- **Hot Jupiters: homogenized interior is hidden below a deep radiative zone, so large day-night temperature contrasts are possible depending on τ_{rad} and τ_{advect} near the photosphere.**

Of course, one must understand something about the dynamics to estimate τ_{advect}!

Dynamical regime of hot Jupiters

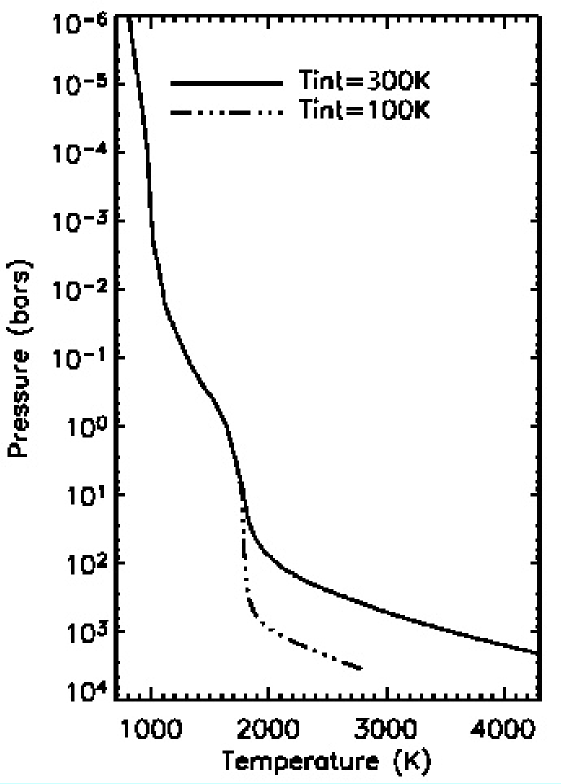
- Circulation driven by global-scale heating contrast: ~10^5 W/m^2 of stellar heating on dayside and IR cooling on nightside

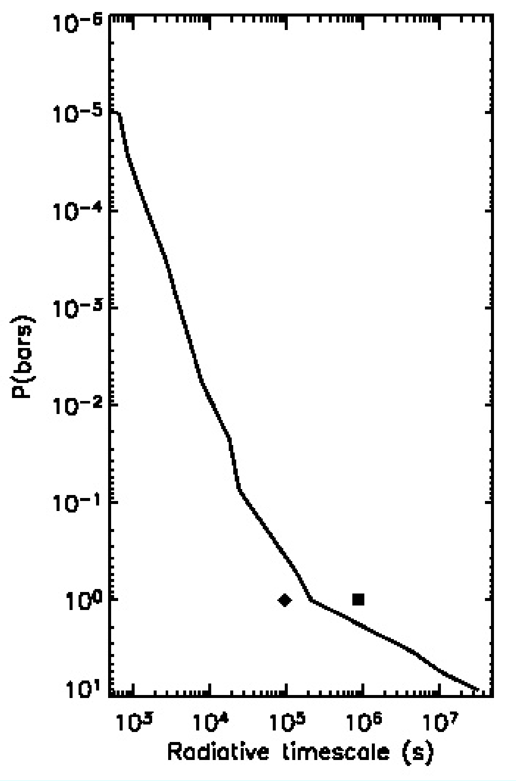
- Rotation expected to be synchronous with the 2-4 day orbital periods; Coriolis forces important but not dominant

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

- For km/sec winds,
  $\tau_{rad} << \tau_{advect}$ for $p < 1$ bar; large temperature contrasts

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





Iro et al. (2005)

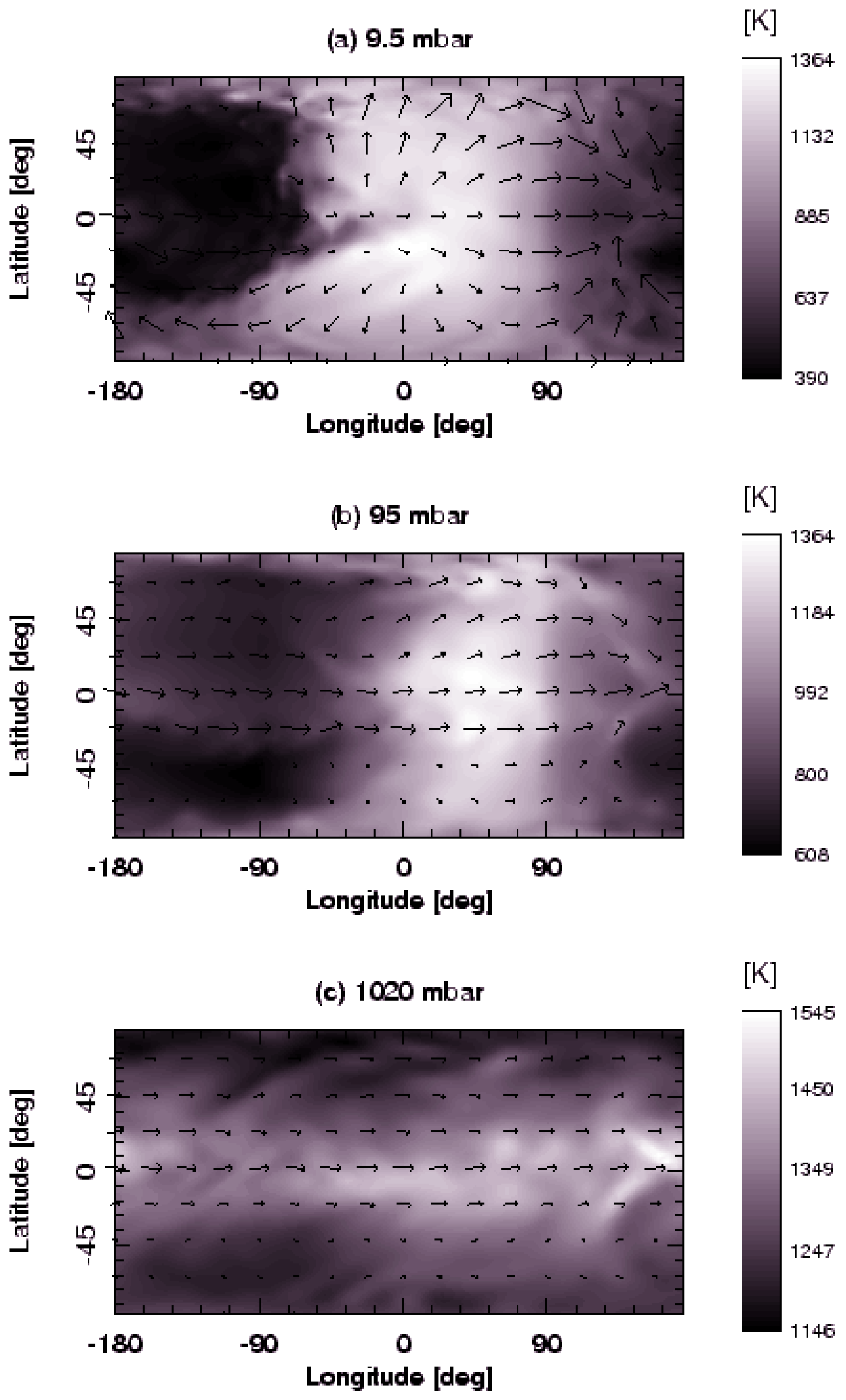
Approaches

- **Two-dimensional shallow-water-type: Cho et al. (2003, 2006); Langton and Laughlin (2007)**

- **Two-dimensional equatorial cross-section: Burkert et al. (2005)**

- **Three-dimensional: Showman and Guillot (2002), Cooper and Showman (2005, 2006); Dobbs-Dixon and Lin (2007); Showman et al. (2007, in prep)**

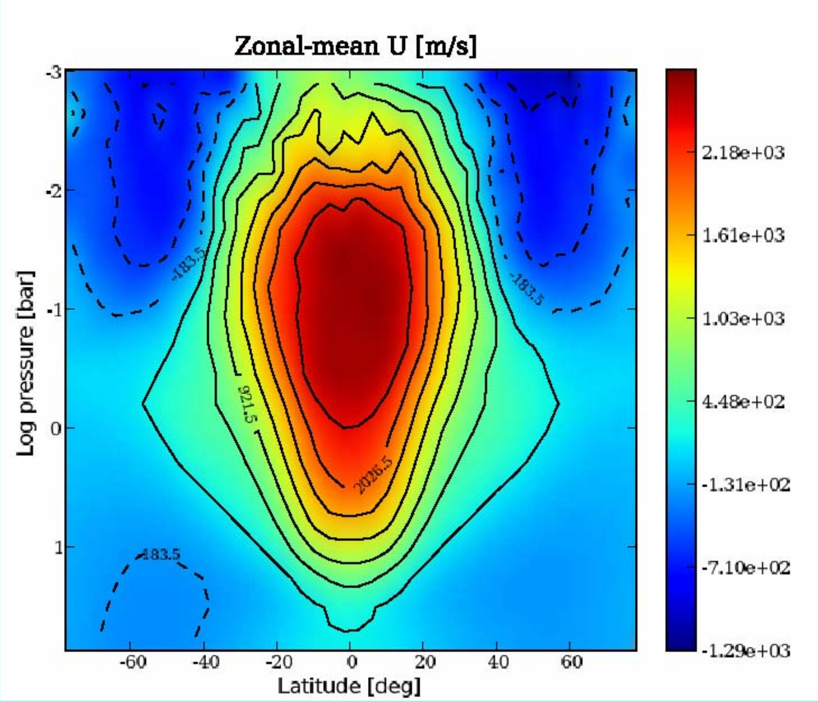
Forcing in all published models is simplified; no models yet include realistic radiative transfer.

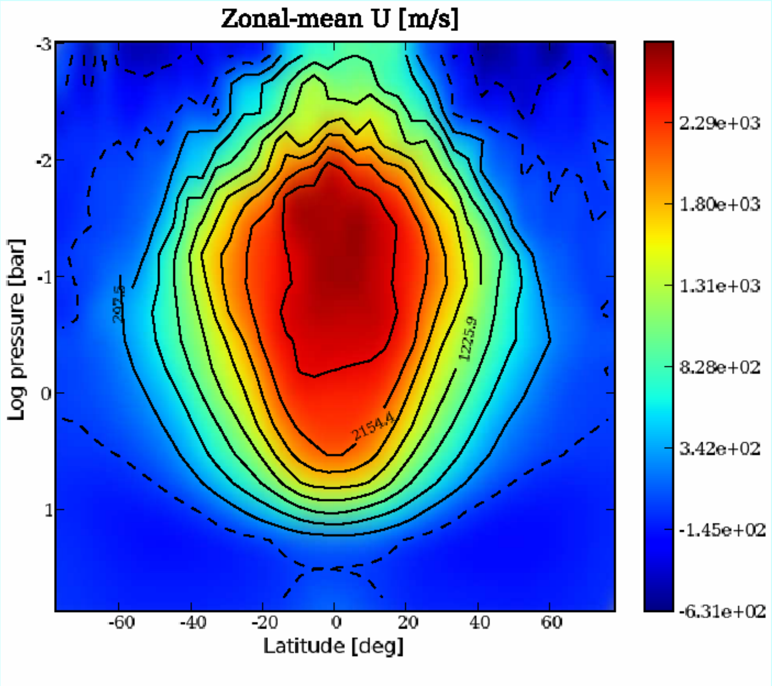


3D HD209458b simulation (Cooper, Showman, Fortney, Marley)

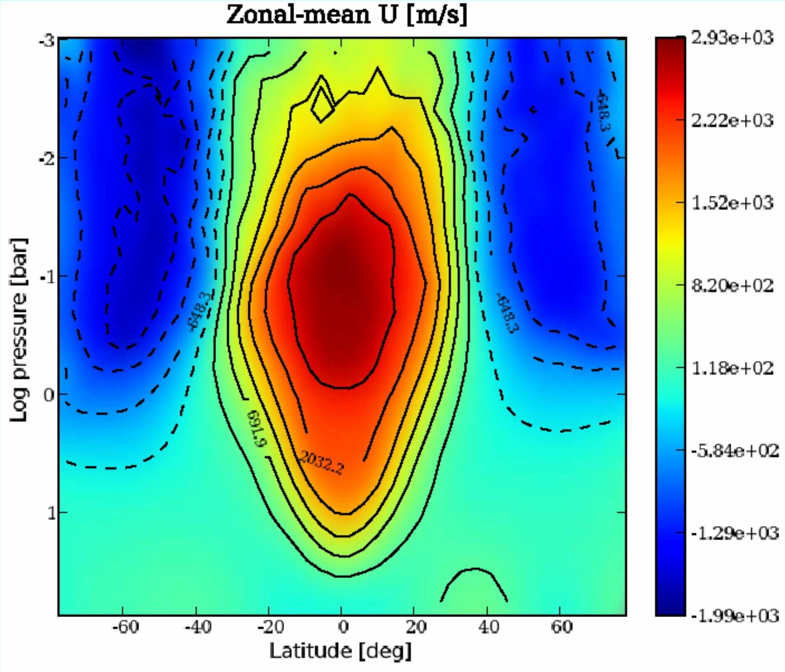
HD209458b

Ω nominal

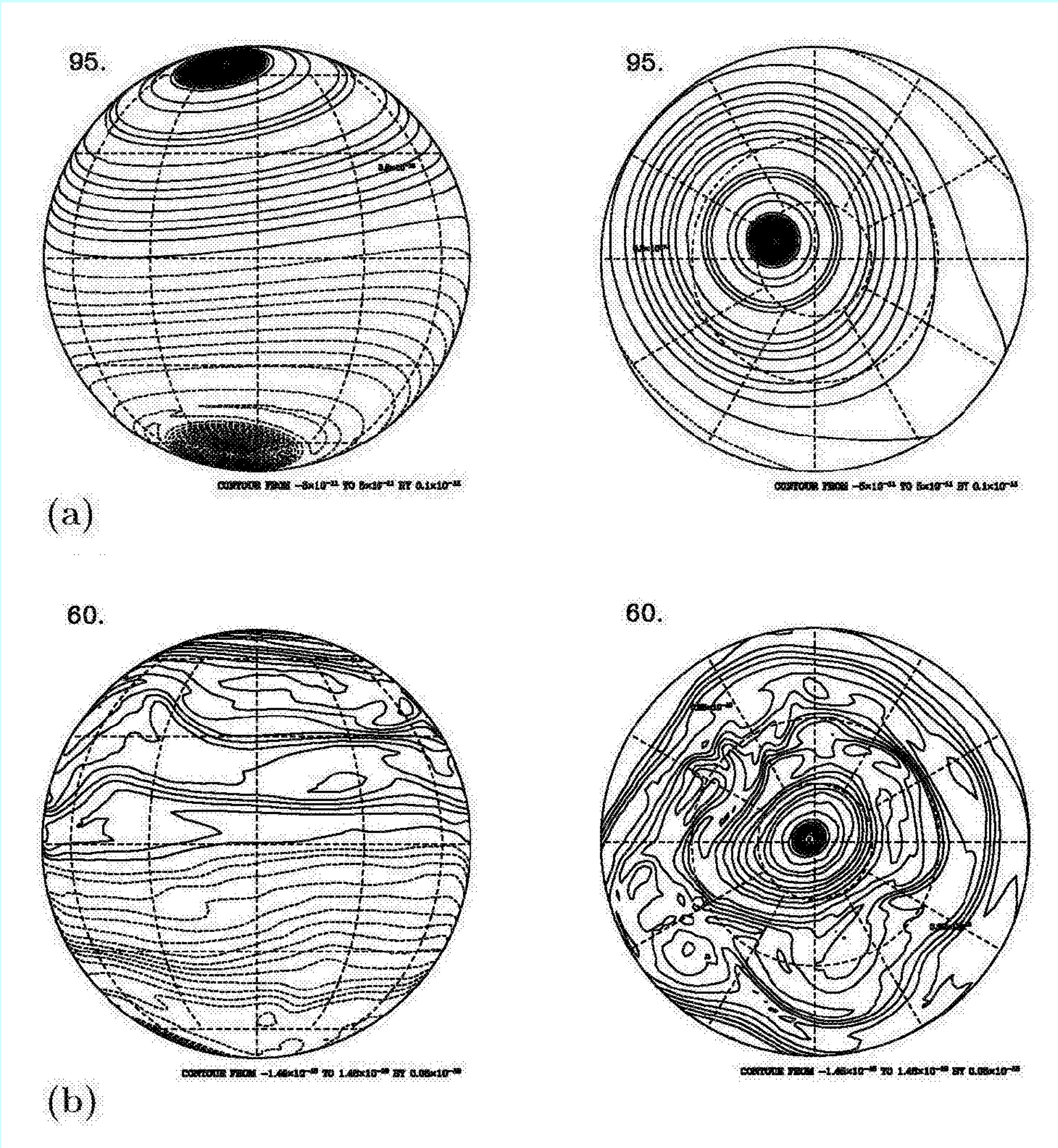


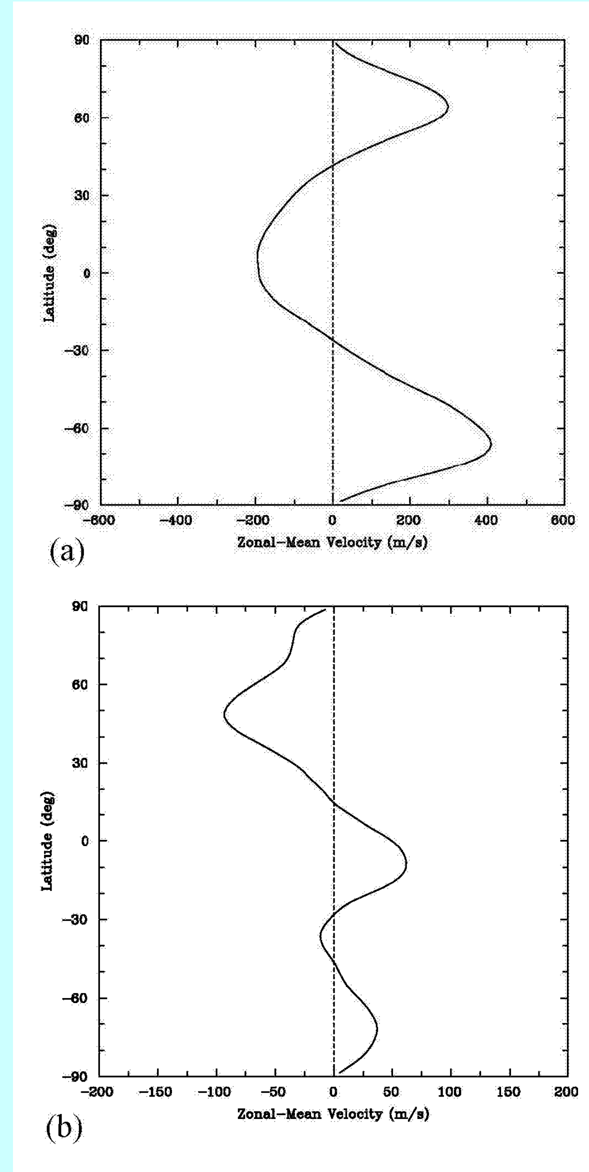


Ω half nominal

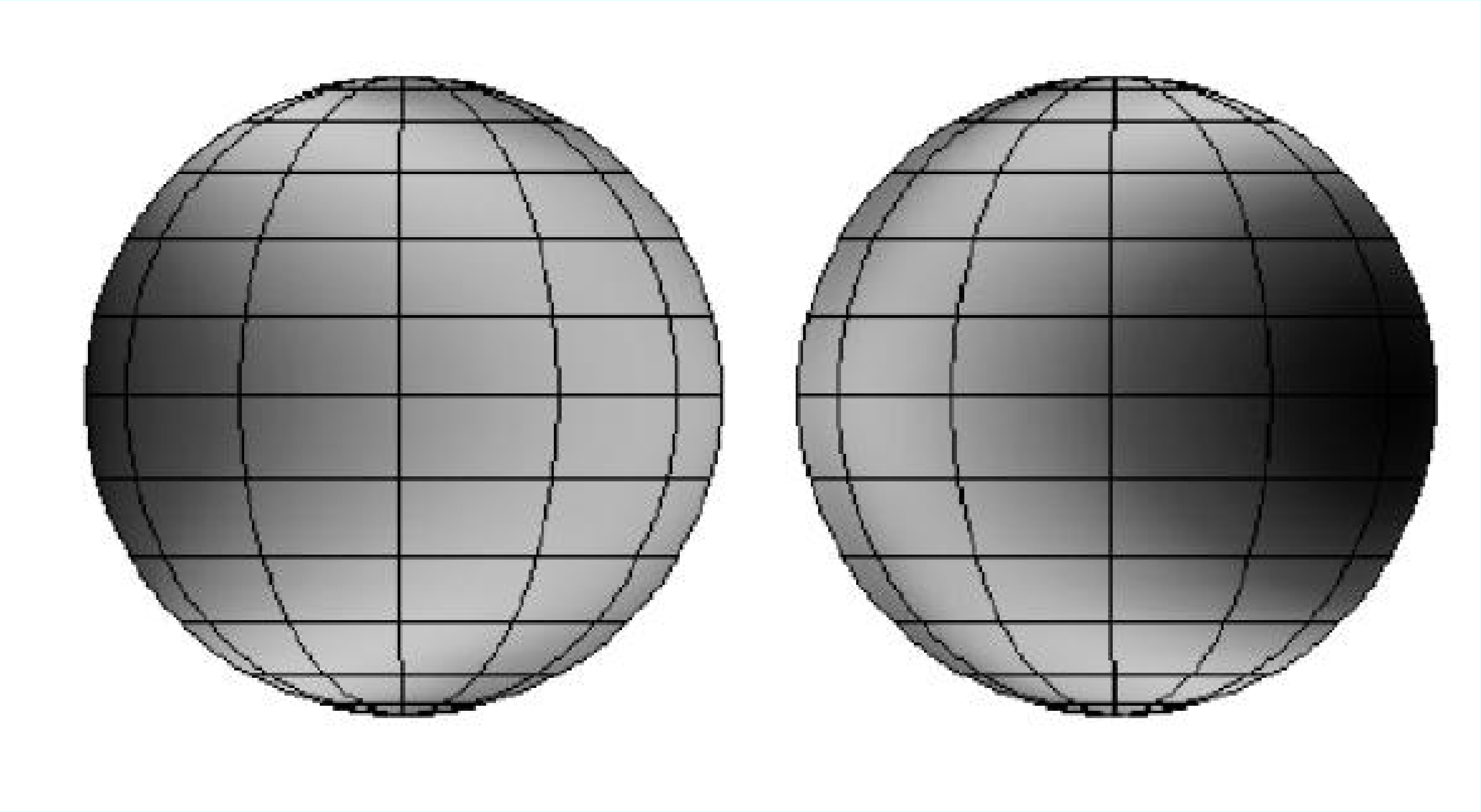


Ω twice nominal

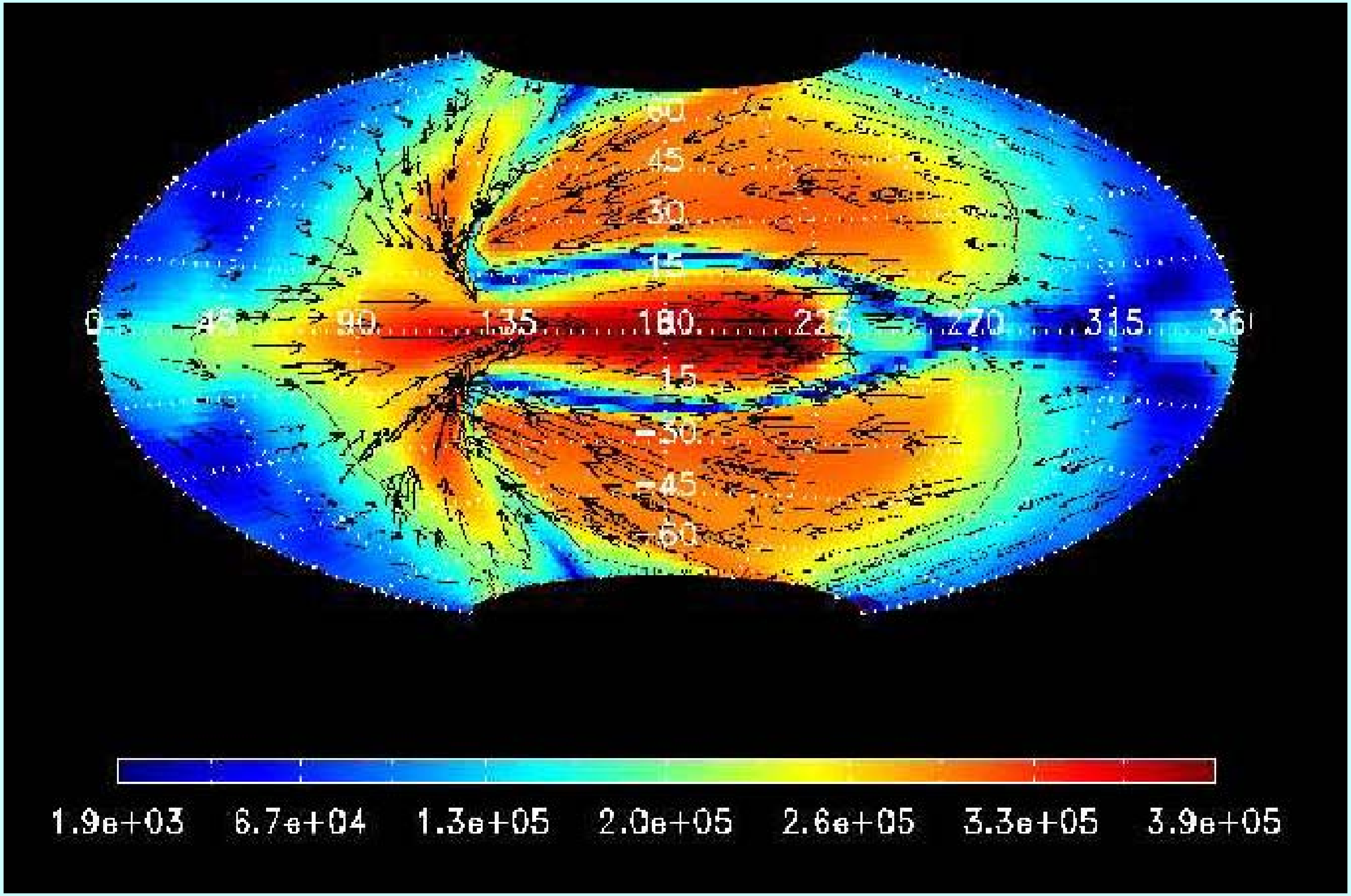




HD209458b -- Cho et al. (2006)

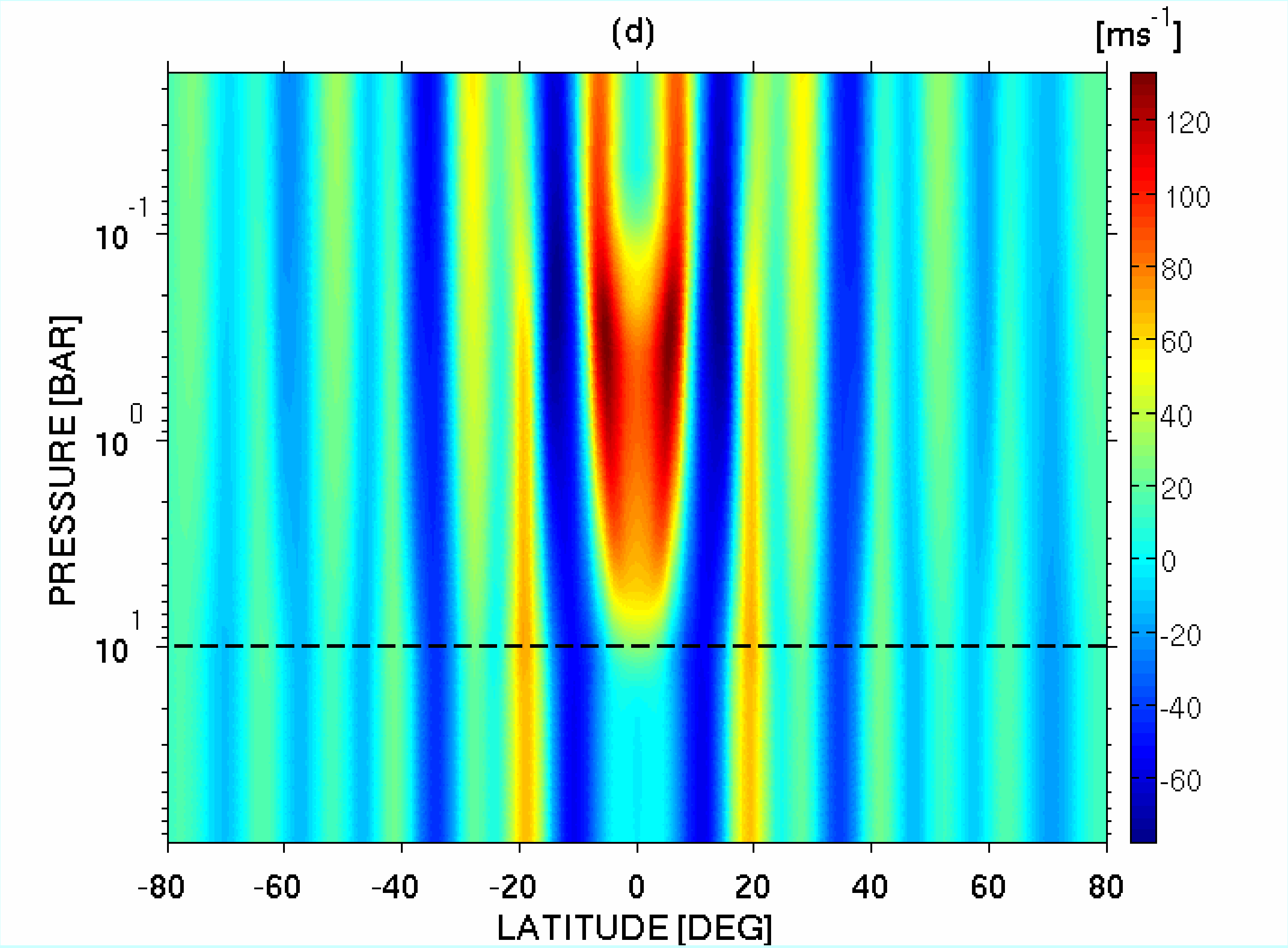


Shallow-water HD209458b (Langton and Laughlin 2007)



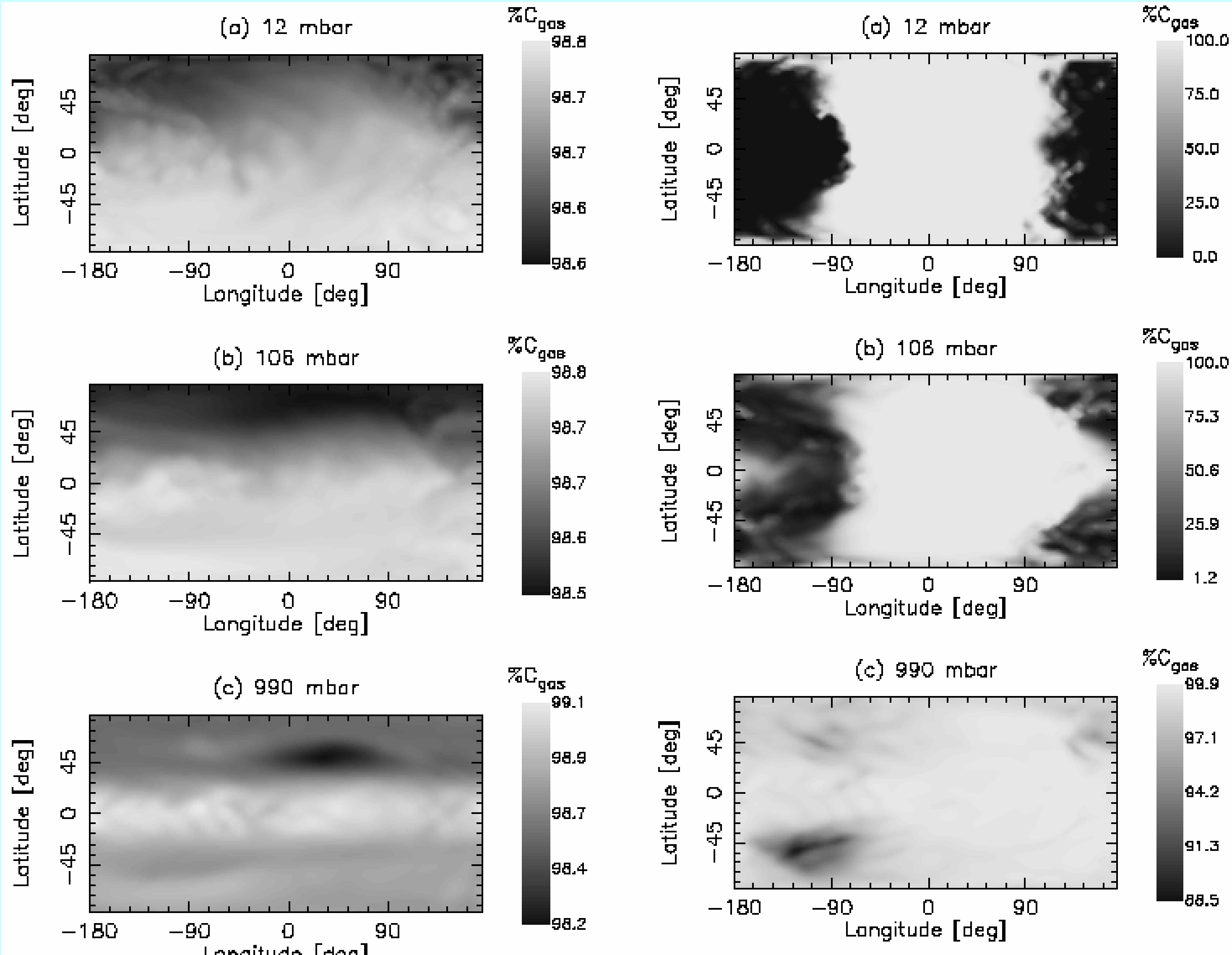
Dobbs-Dixon and Lin (2007)

Jupiter: fast rotation leads to many jets



Lian and Showman (2007)

Chemical disequilibrium: Dynamical models predict homogenization of CO on hot Jupiters

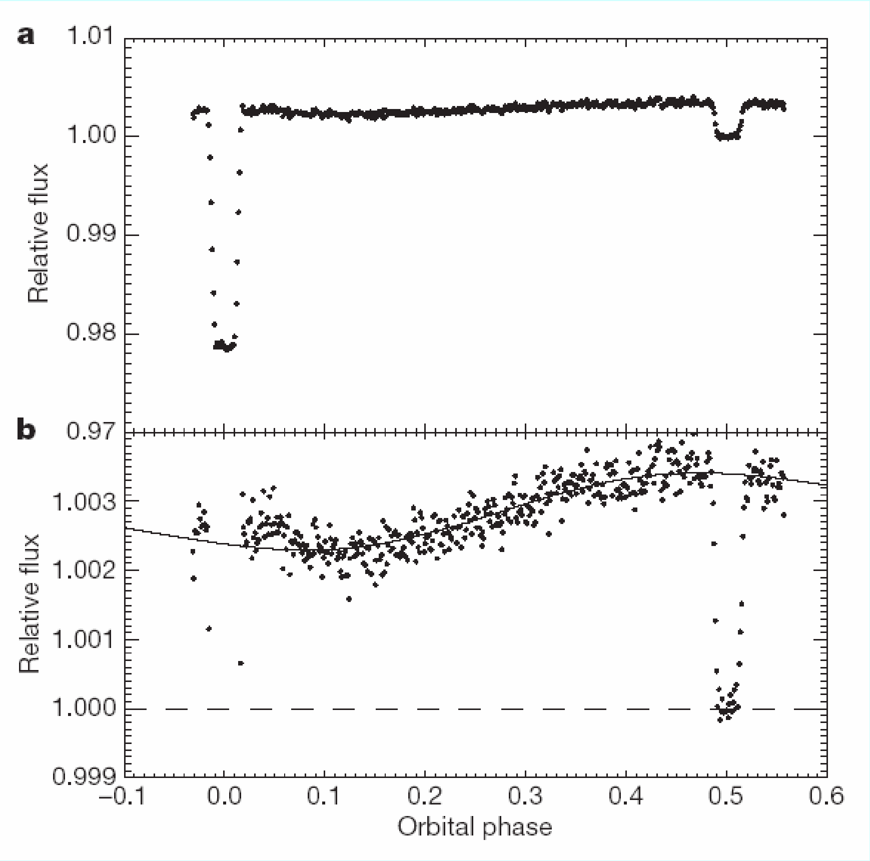


Dynamical prediction

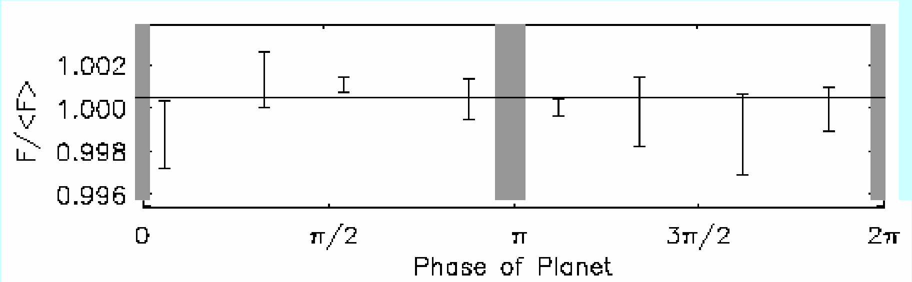
Equilibrium CO

Cooper and Showman (2006)

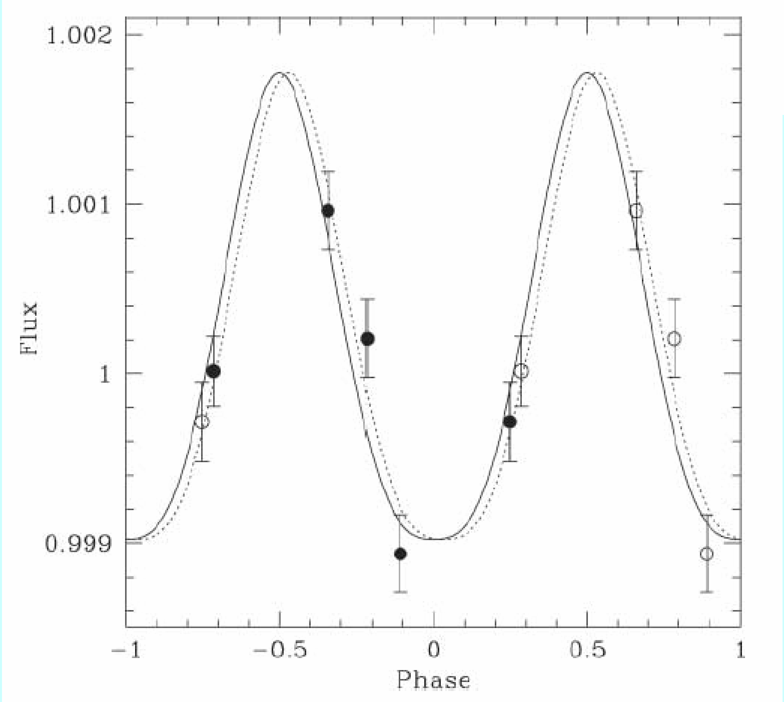
Spitzer 8- and 24-μm lightcurves for hot Jupiters



HD189733b (Knutson et al. 2007)

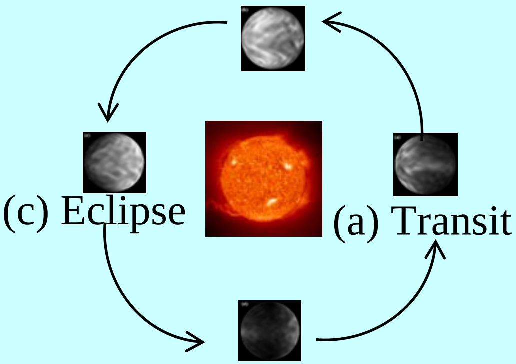


HD209458b (Cowan et al. 2007)

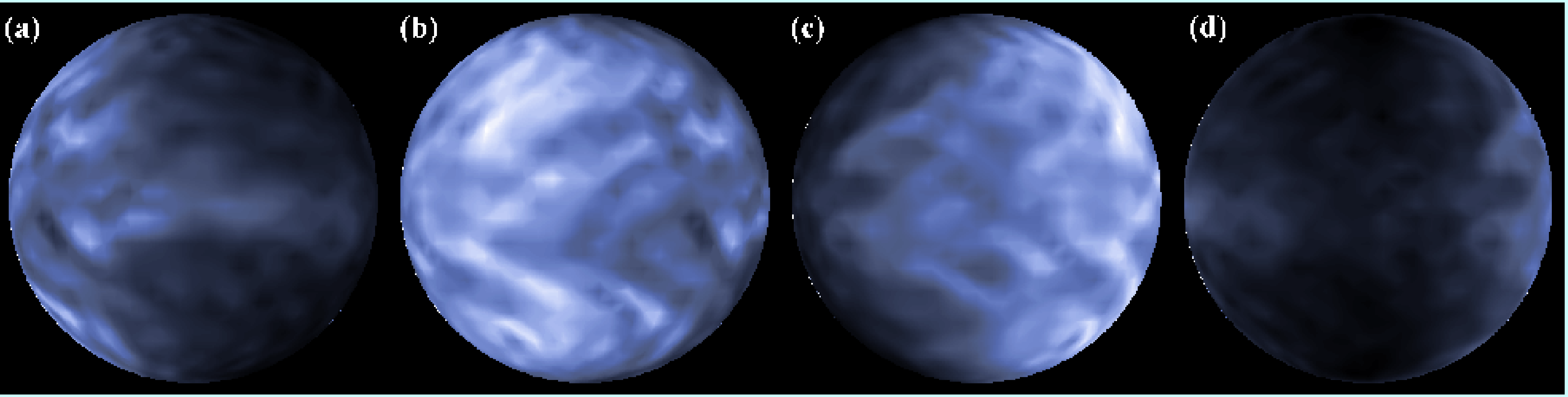


Ups And b (Harrington et al. 2006)

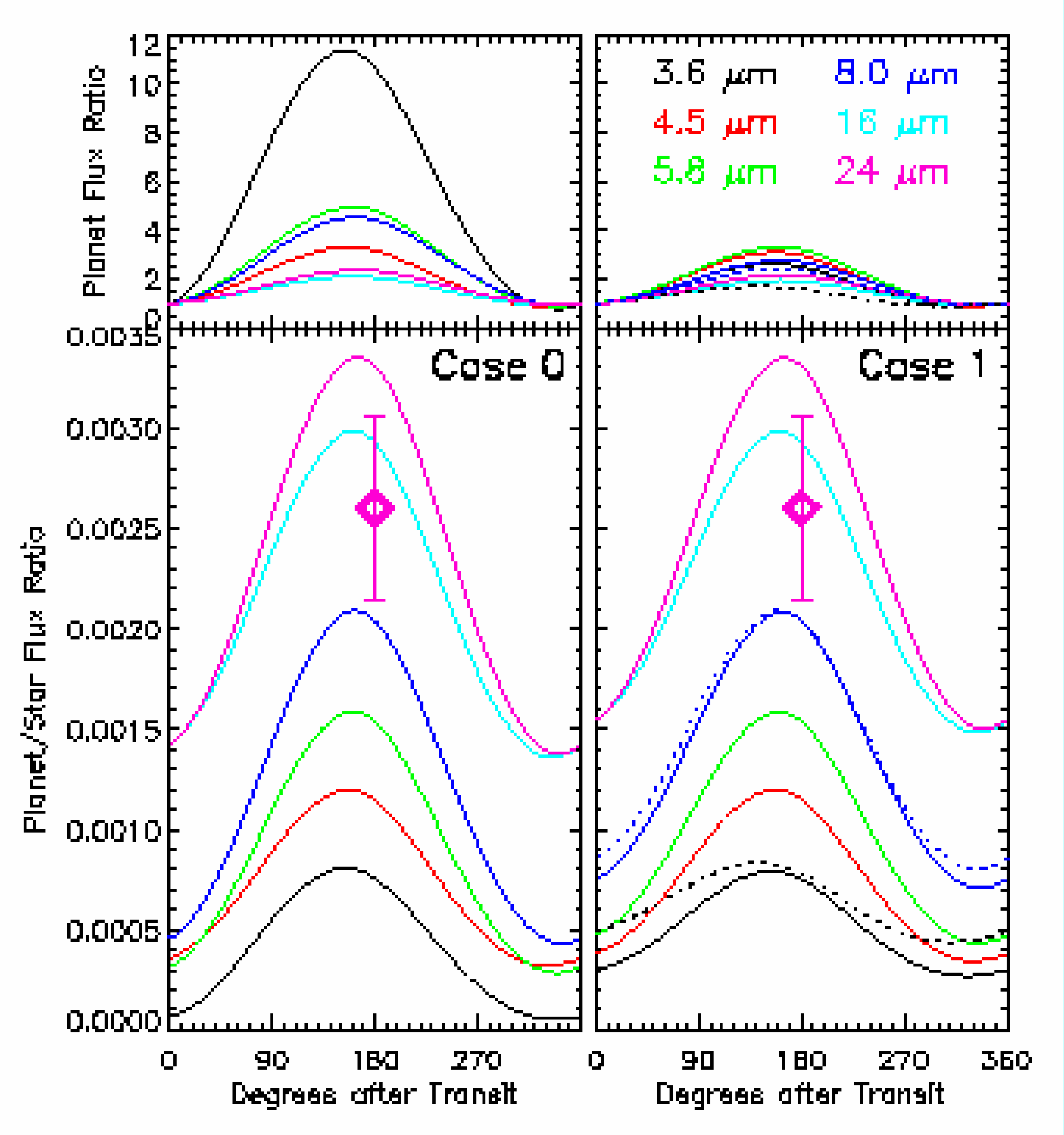
Orbital phases in the infrared



Observer

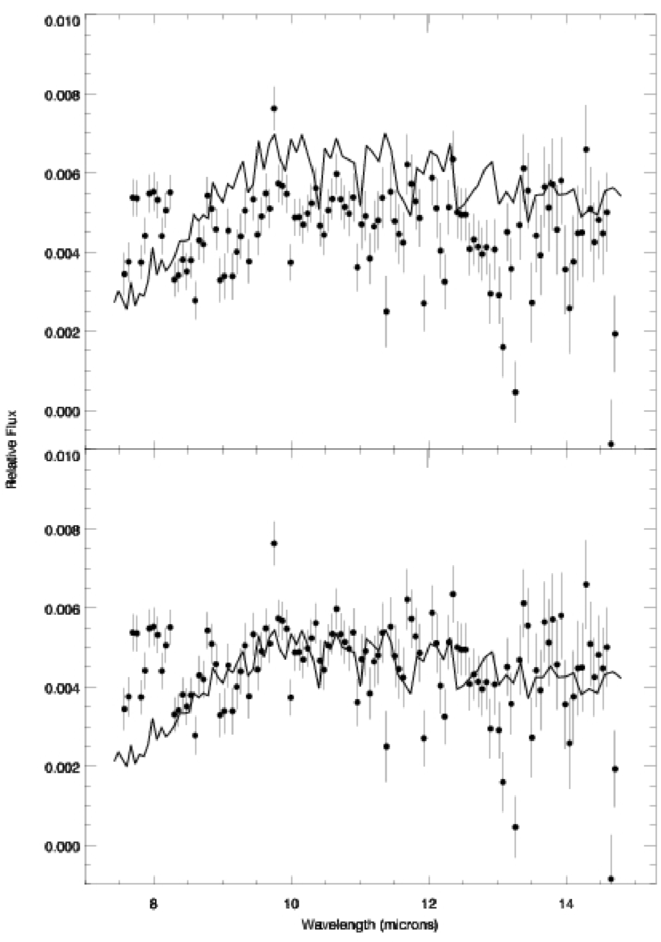


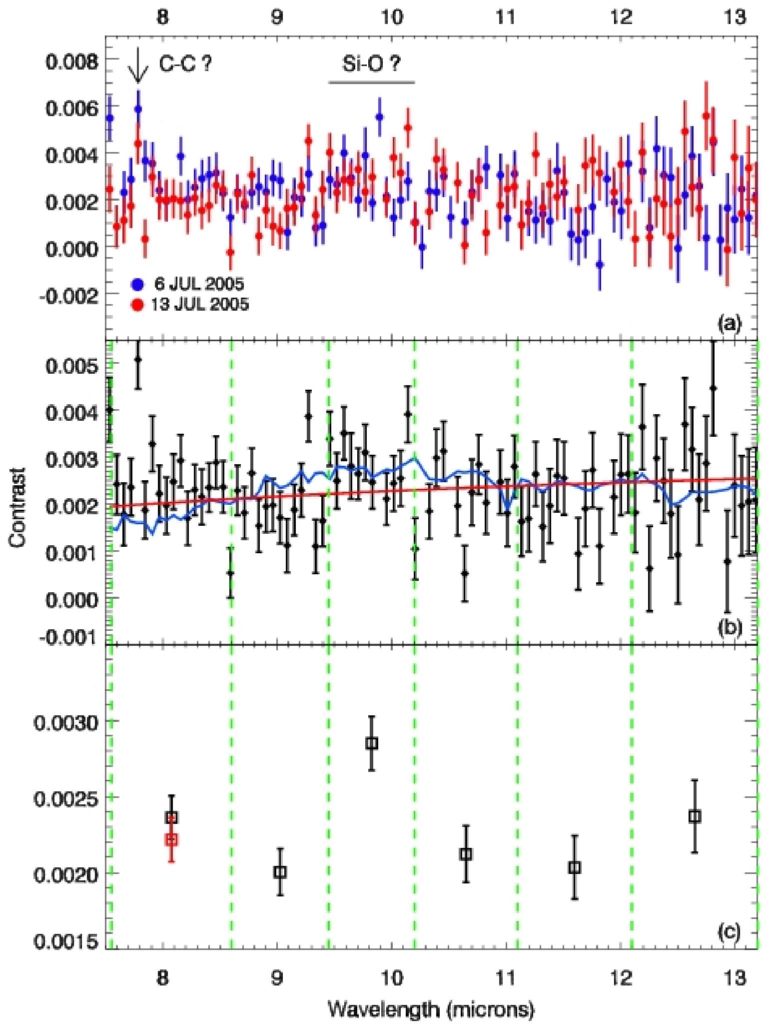
Predicted lightcurves for HD209458b



Fortney et al. (2006);
Cooper and Showman (2005, 2006)

Observed spectra of extrasolar planets!

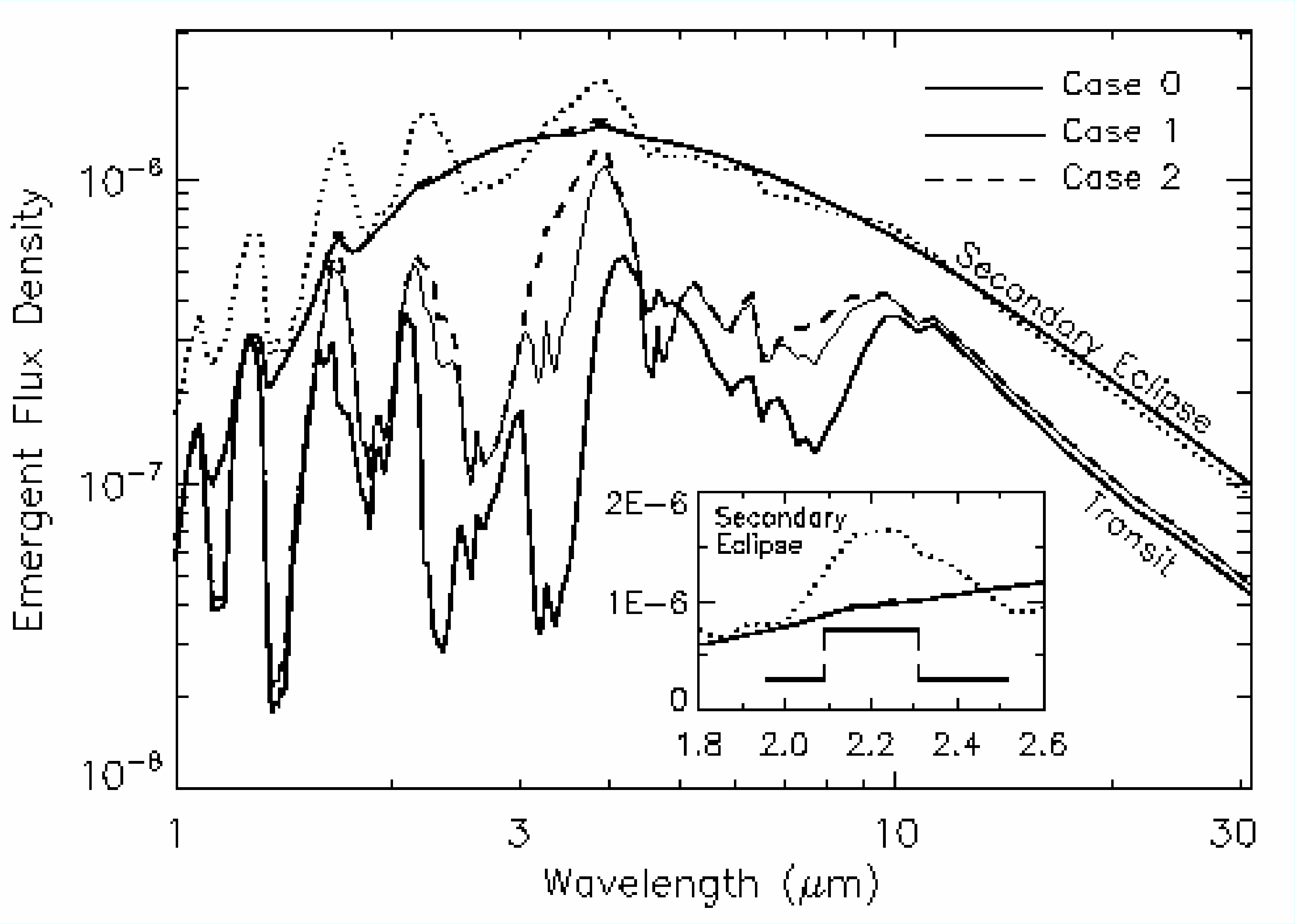




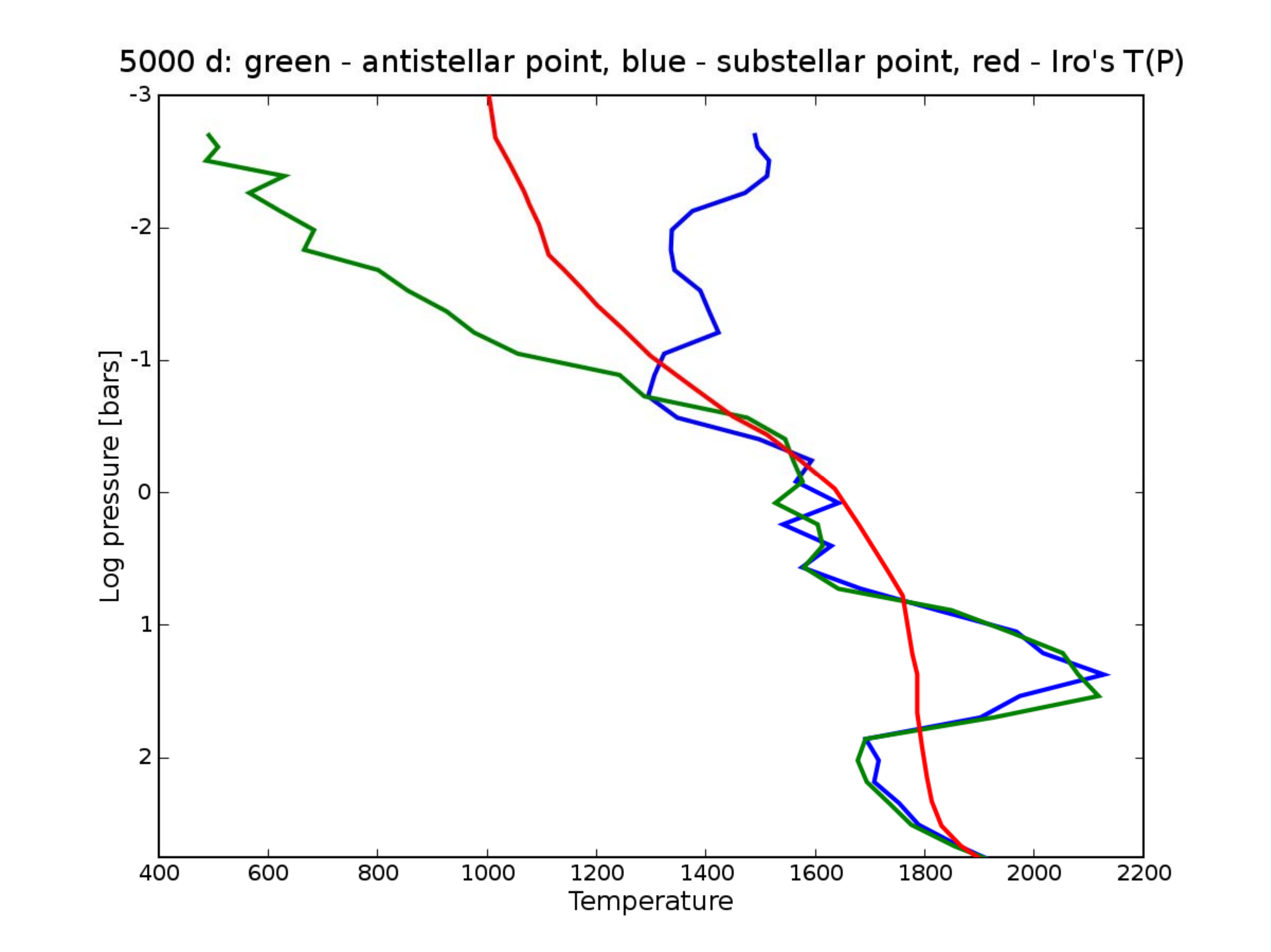
HD189733b
Grillmair et al. (2007)

HD209458b
Richardson et al. (2007)

Predicted infrared spectra for HD209458b

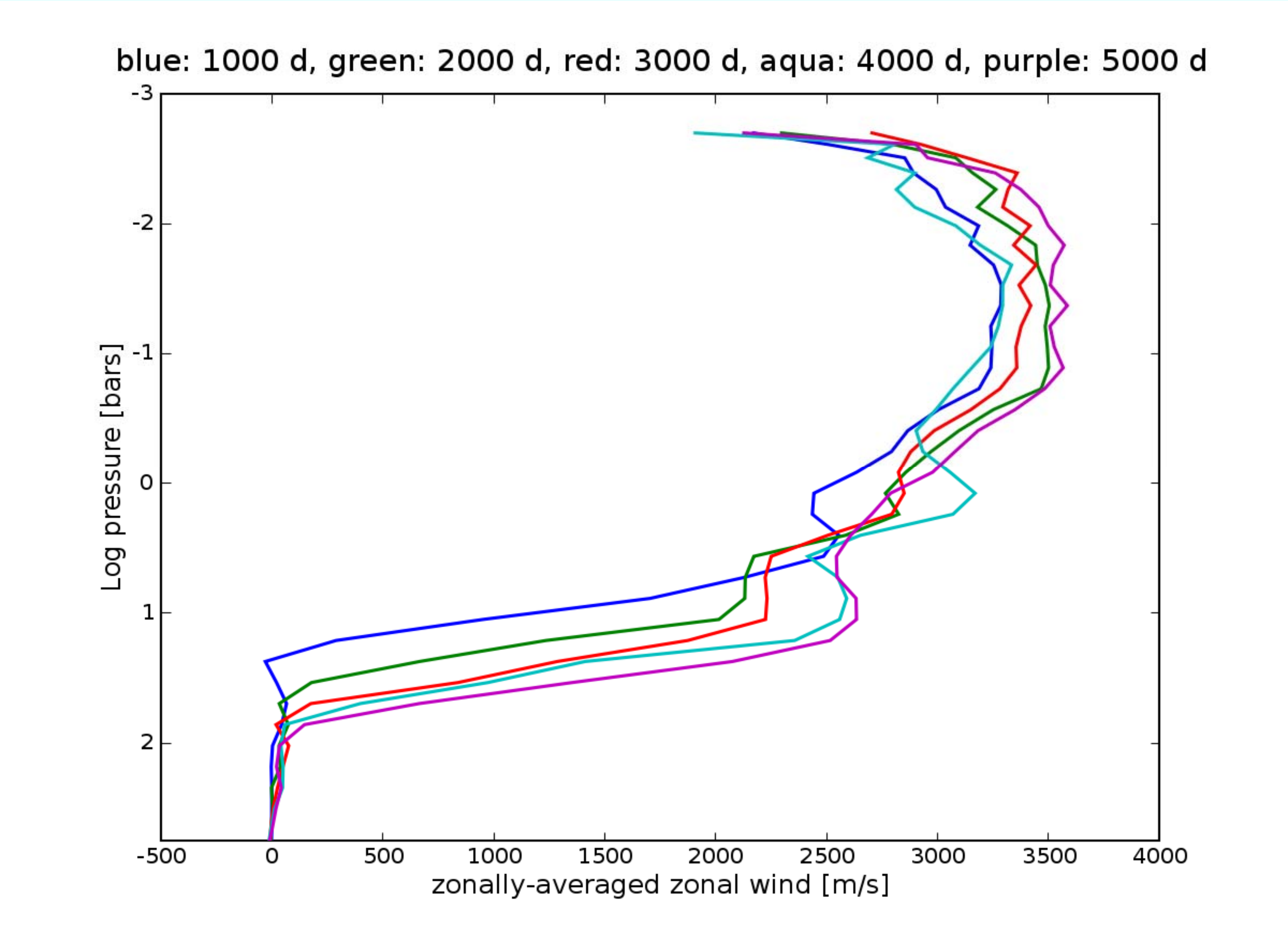


Fortney et al. (2006); Cooper and Showman (2005, 2006)



Dynamics naturally produces a dayside inversion -- even when none exists in radiative equilibrium!

Winds gradually penetrate below heated region



Downward kinetic energy flux ~10^3 W/m^2 ~ 1% of absorbed stellar flux

Conclusions: hot Jupiters

The intense radiation produces winds > 1 km/sec and temperature contrasts up to ~500-1000 K. All studies predict that the atmosphere contains only a small number of wide jets. Faster rotation leads to narrower jets, consistent with Rhines length and deformation radius arguments.

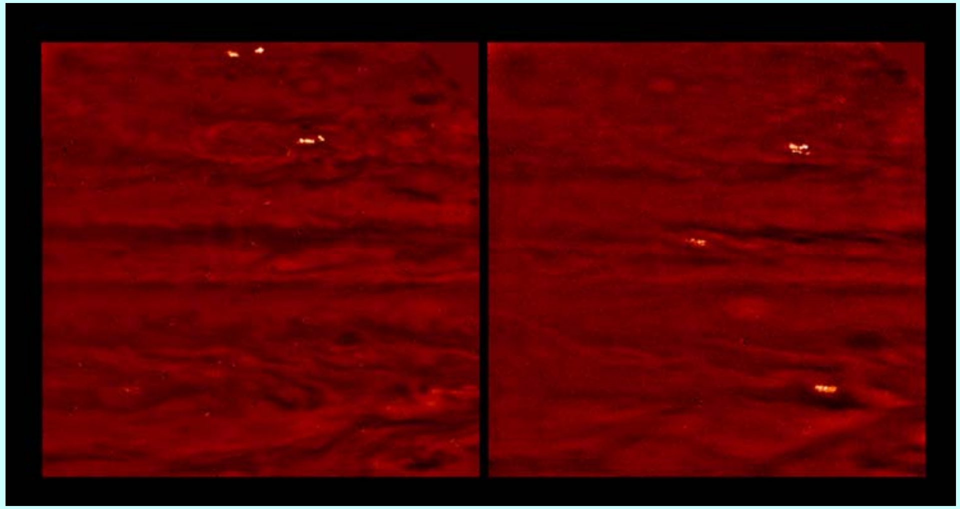
At the probable photosphere (~50 mbar), the winds blow the hottest regions downwind by ~15-20^{o} longitude, but above, the hot regions track the dayside. At 8-μm, our HD209458b simulations predict factor-of-3 flux variations between dayside to nightside, slightly greater than suggested by current lightcurves.

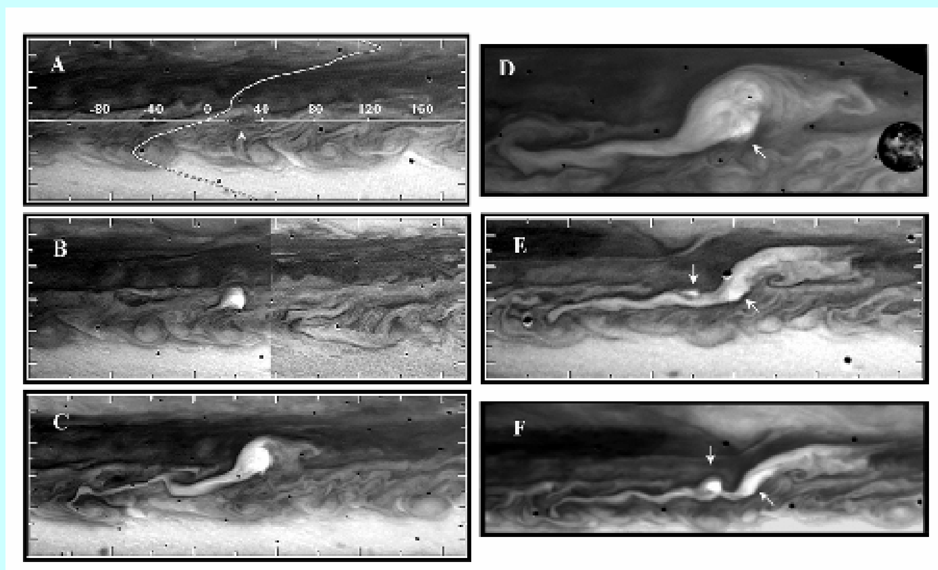
Expect disequilibrium chemistry. CO should be homogenized at and above the photosphere.

Dynamics naturally produces a near-isothermal dayside, which washes out spectral features and produces a blackbody-like spectrum.

Downward energy fluxes reach 10^3 W/m^2 at the ~10-100 bar level, which could influence the evolution.

Flow on Solar-system giants driven by convection and small-scale instabilities:





On hot Jupiters, the key eddies may be much larger (i.e., day-night heating gradient)