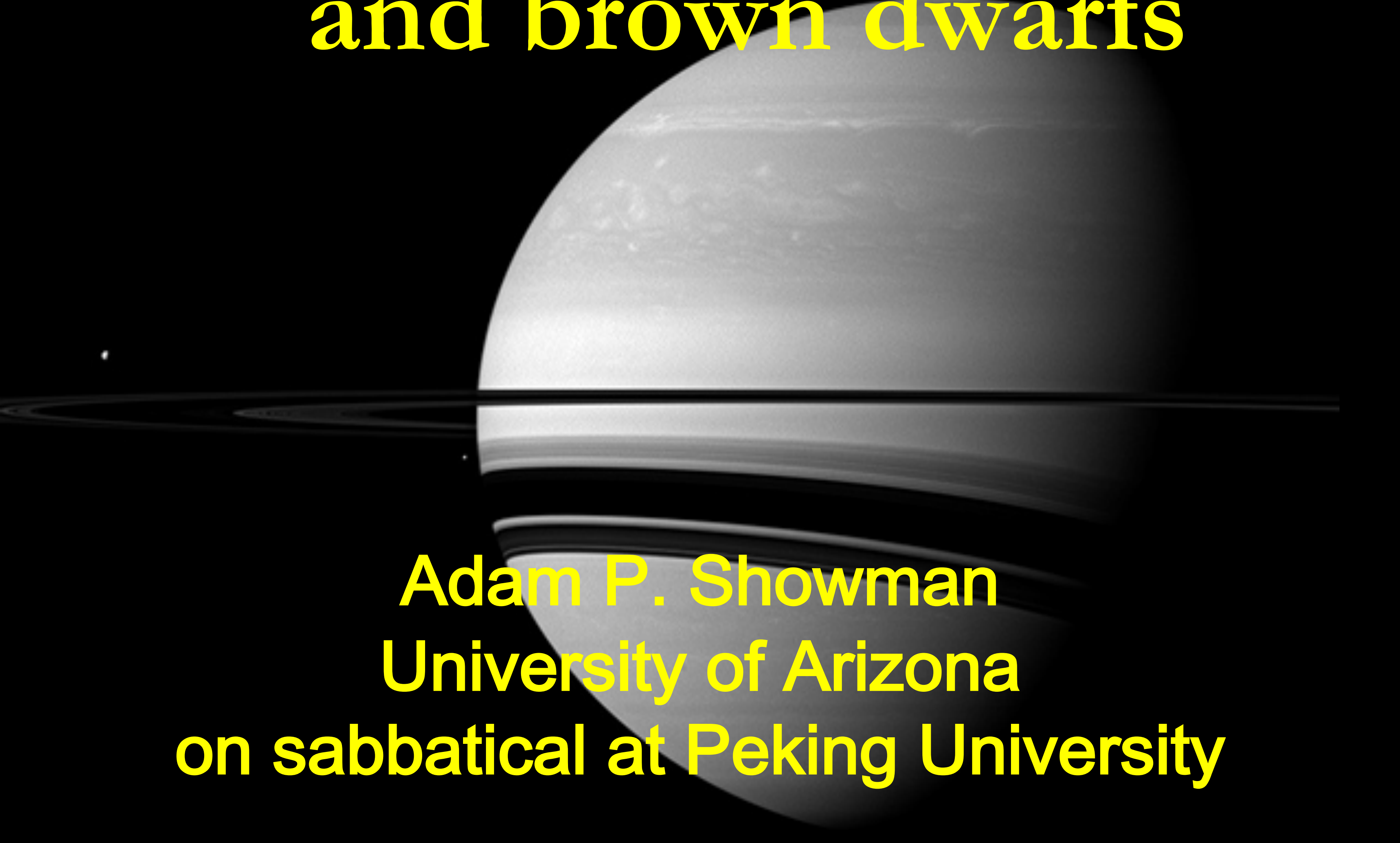
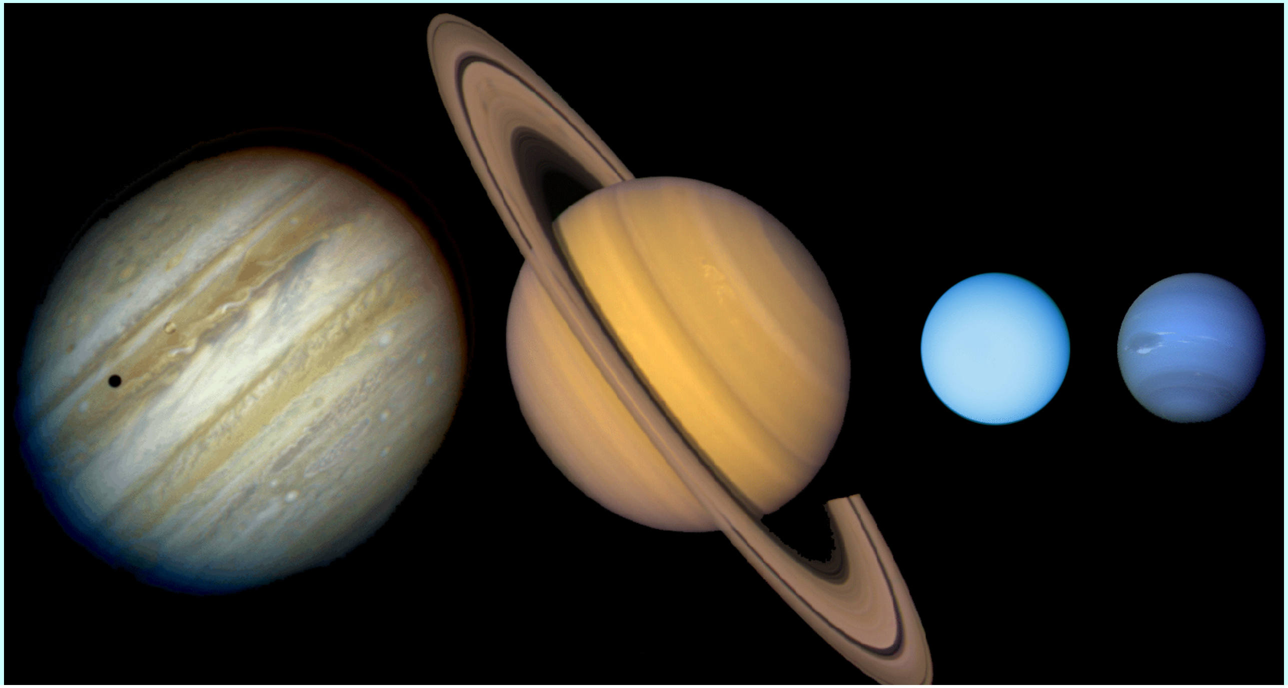
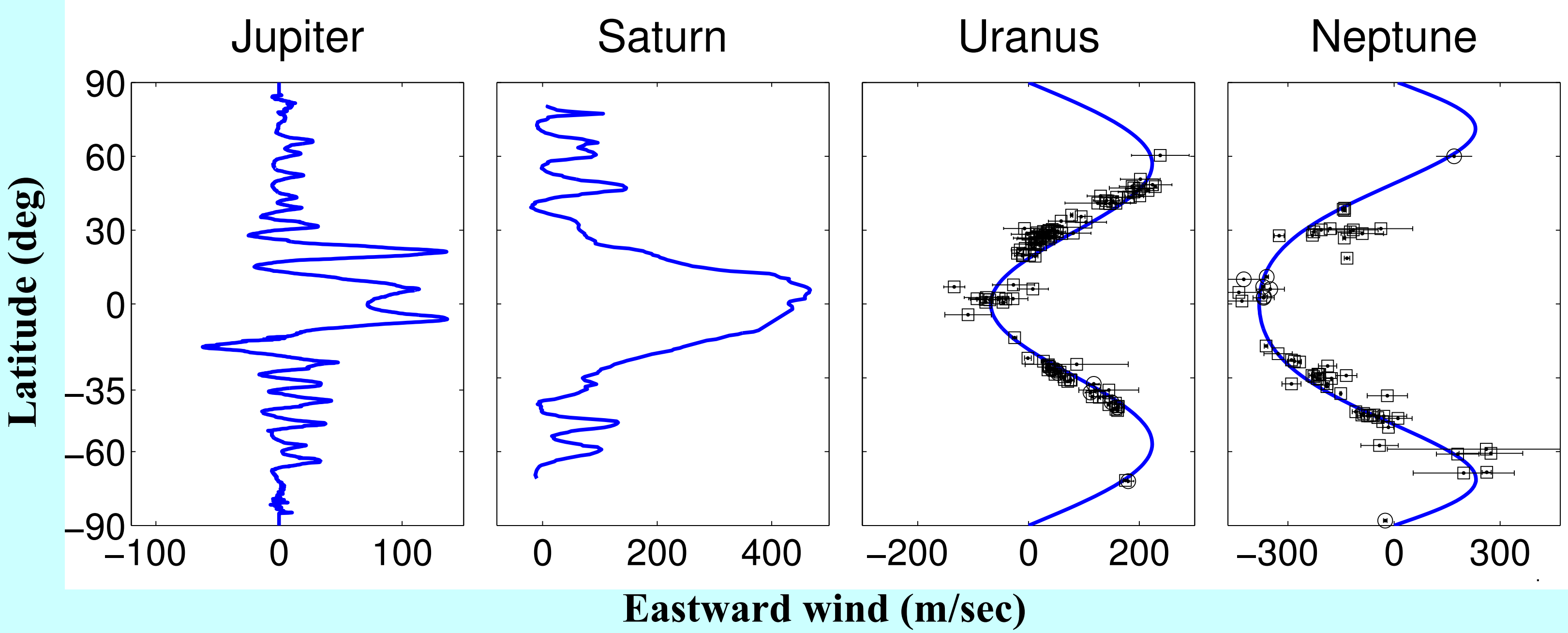


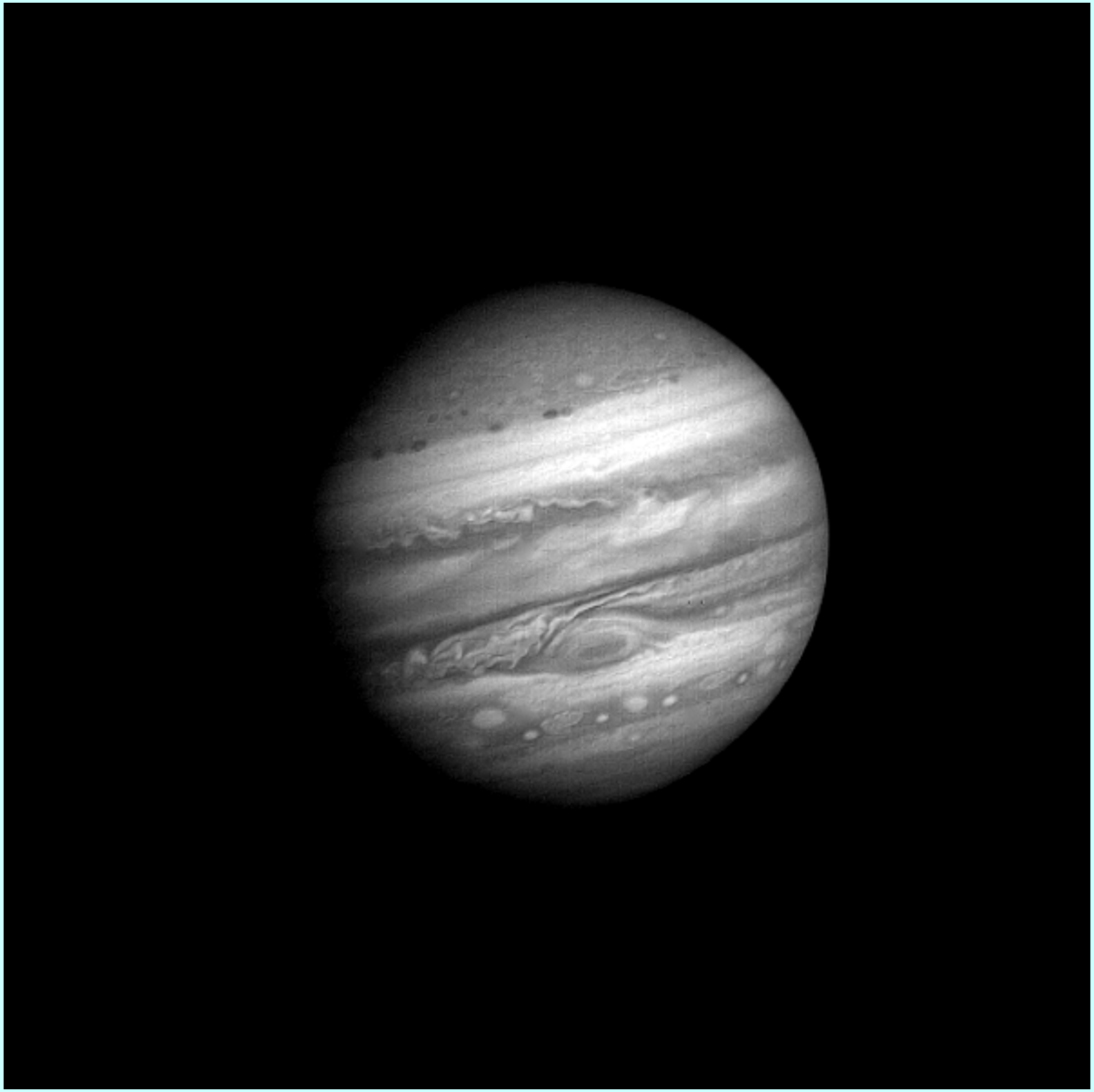
Lecture 4: Giant planets and brown dwarfs

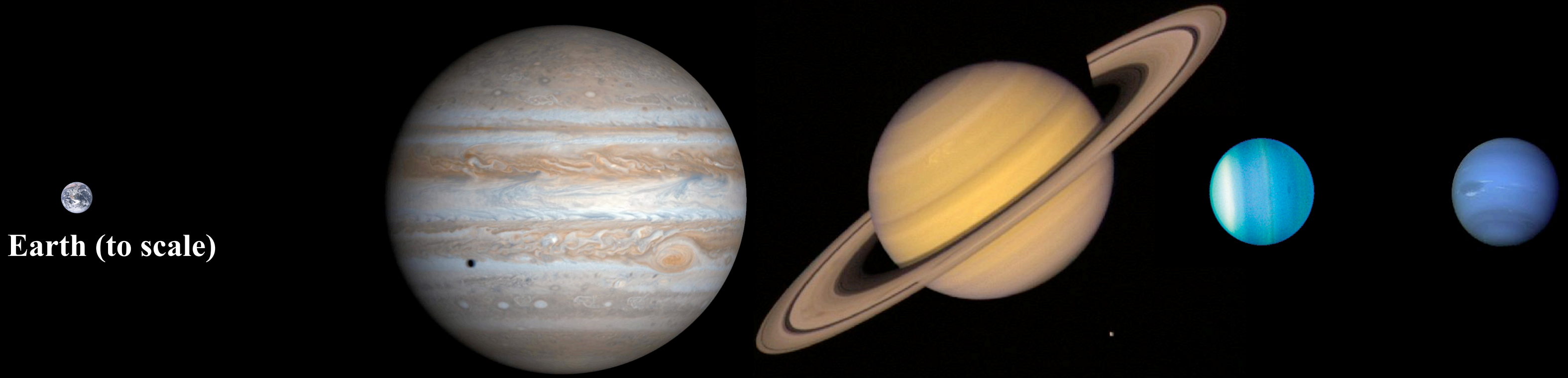
Adam P. Showman
University of Arizona
on sabbatical at Peking University

Zonal winds on the giant planets





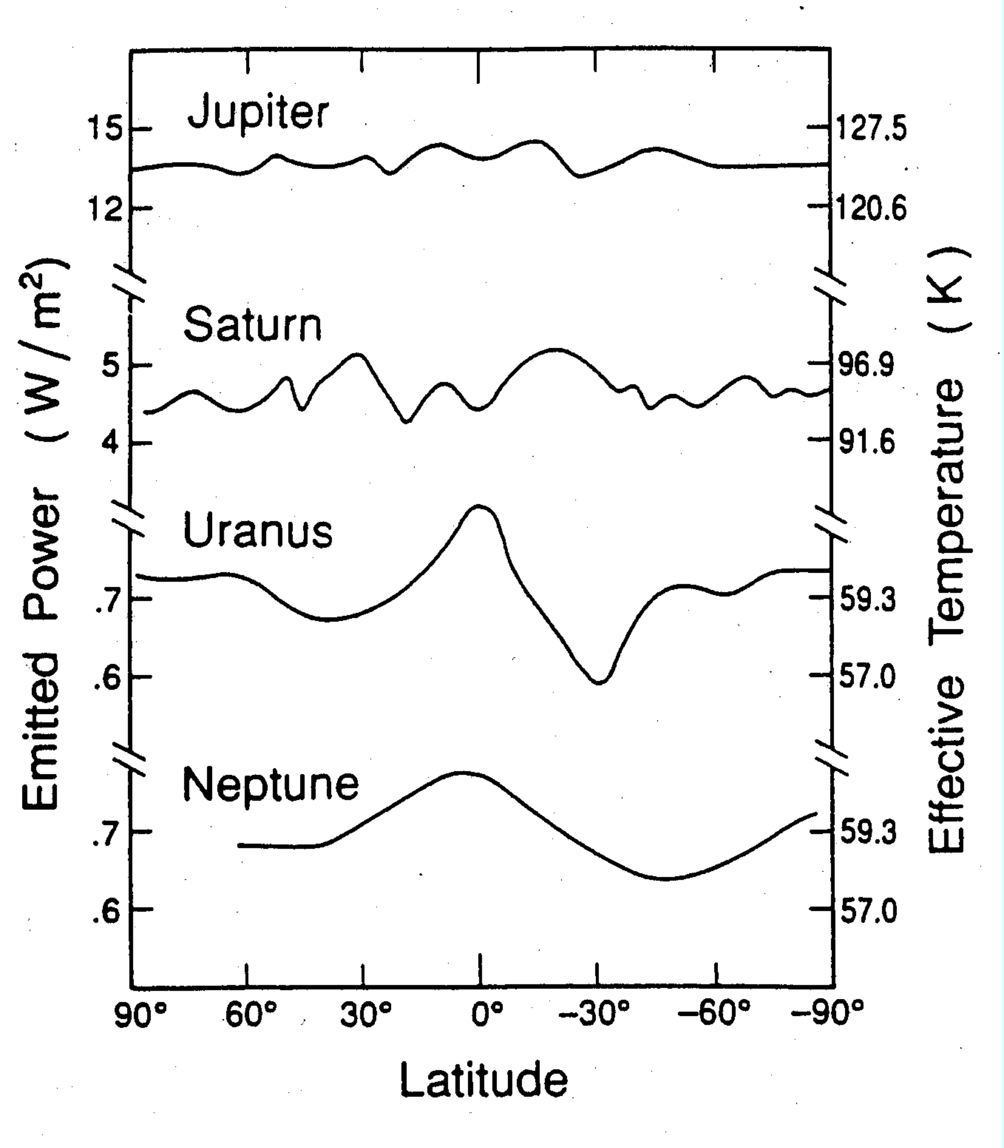




	Jupiter	Saturn	Uranus	Neptune
Rotation (hours)	9.92	10.57	17.24	16.11
Mean radius (km)	69,911	58,232	25,362	24,622
Max. wind velocity (m/s)	140	480	240	380
Obliquity	3°	27°	98°	28°
Rossby number, $u/\Omega L$	0.02	0.04	0.1	0.1

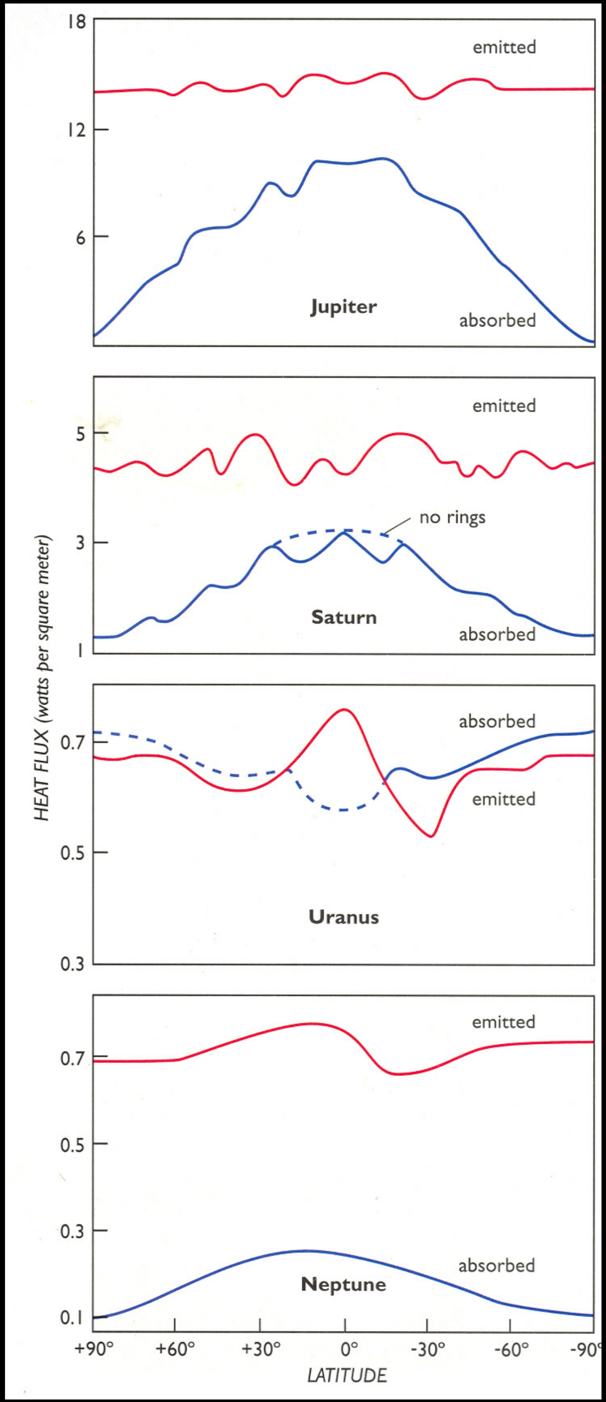
Small Rossby number $u/\Omega L \ll 1$ implies geostrophic balance – a balance between Coriolis accelerations and pressure-gradient forces at large scale

Temperatures are relatively homogeneous:



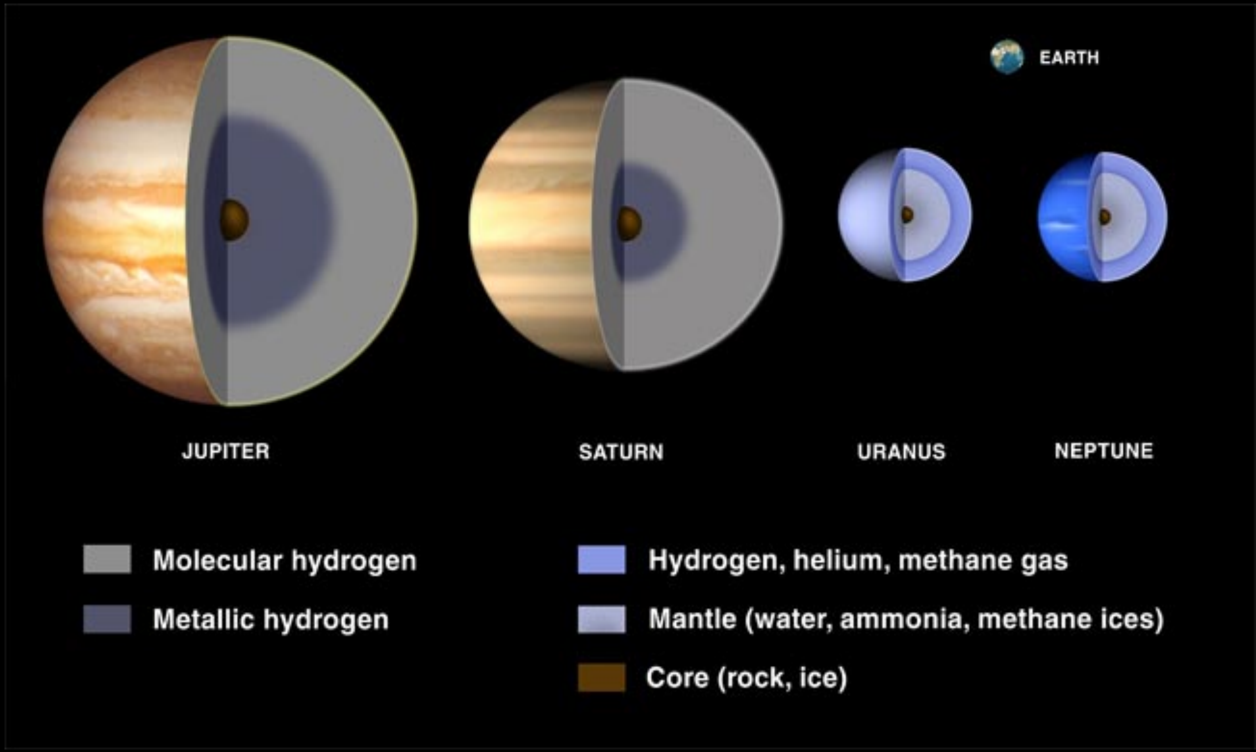
Ingersoll (1990)

Energy budgets

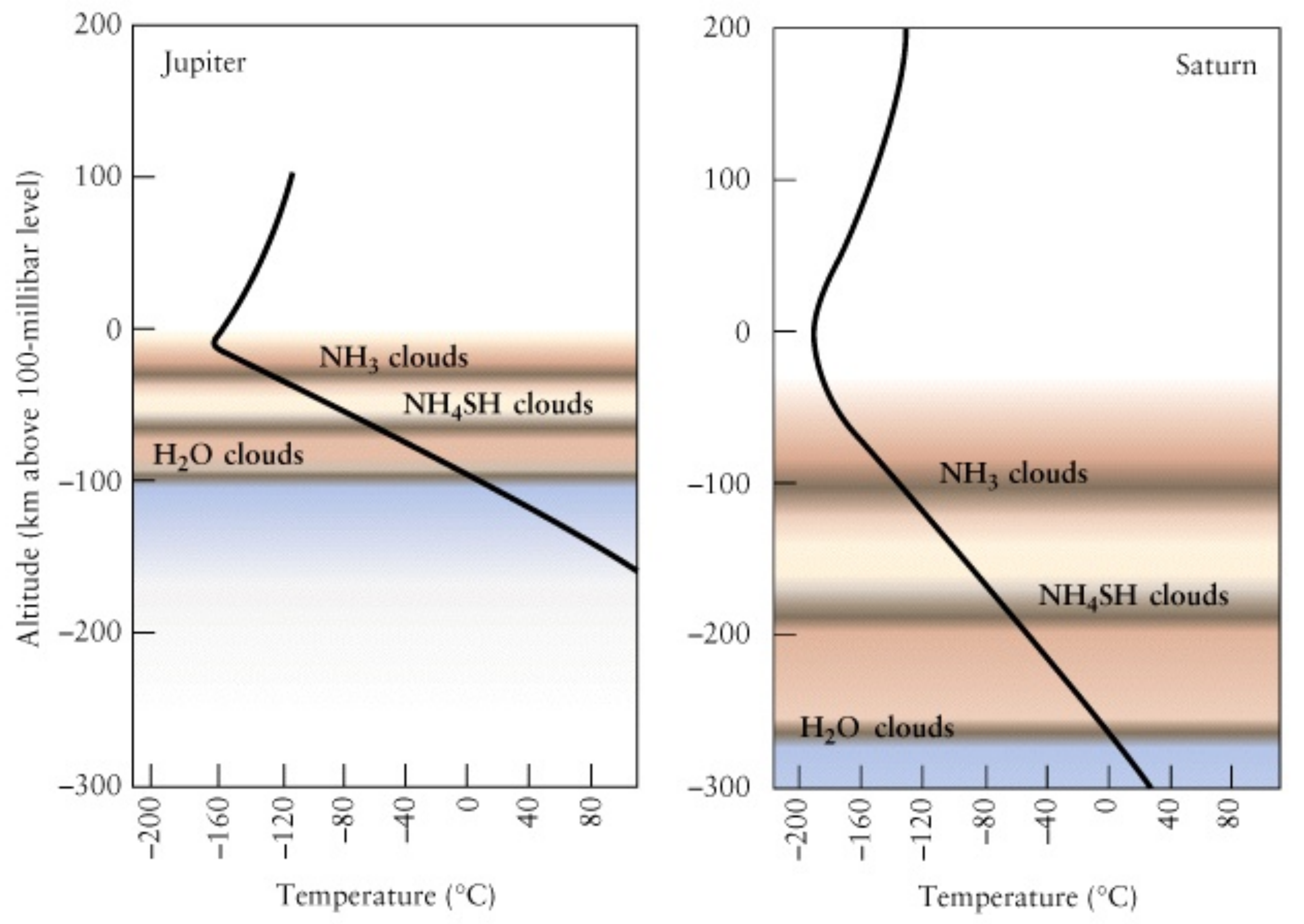


Internal heat fluxes are substantial compared to solar flux on Jupiter, Saturn and Neptune

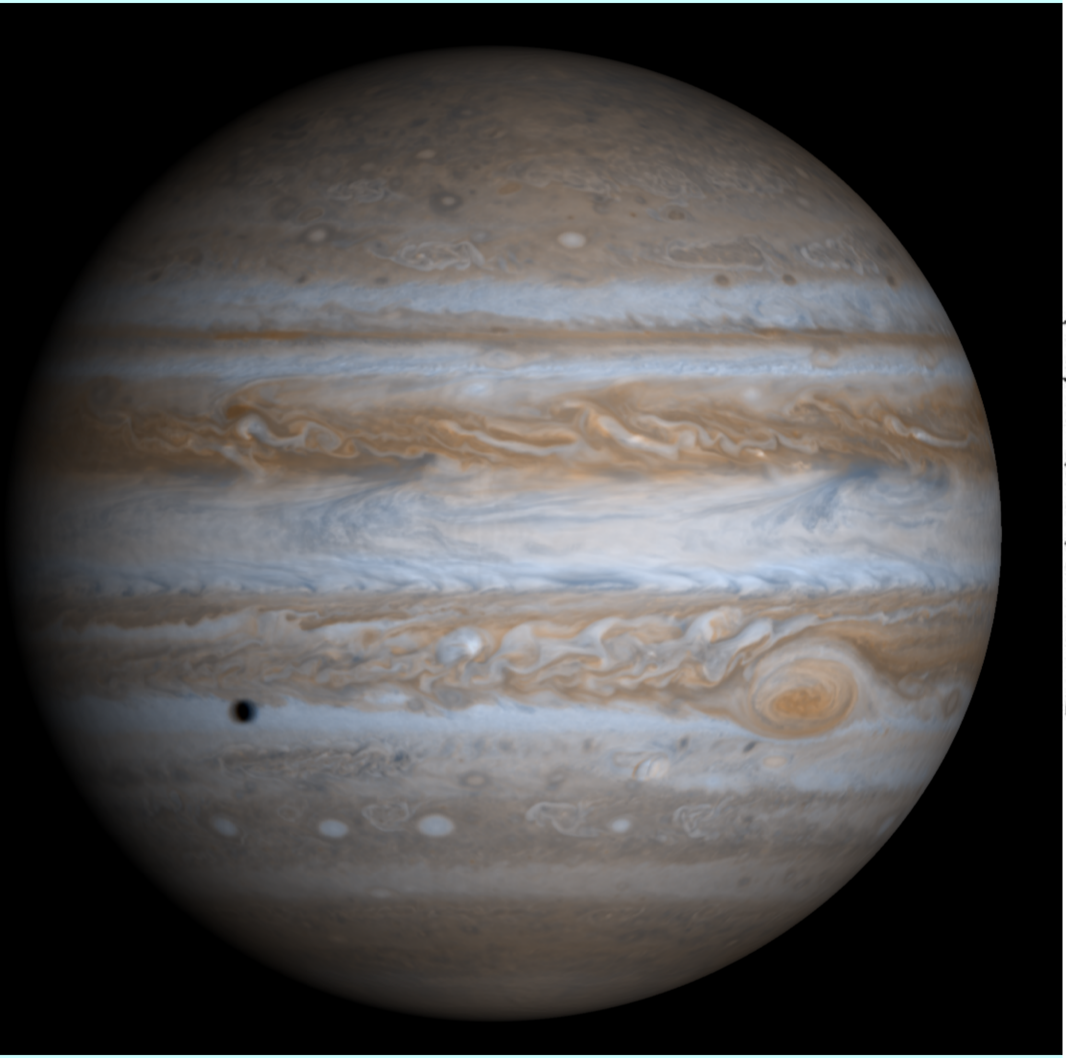
Internal structure:

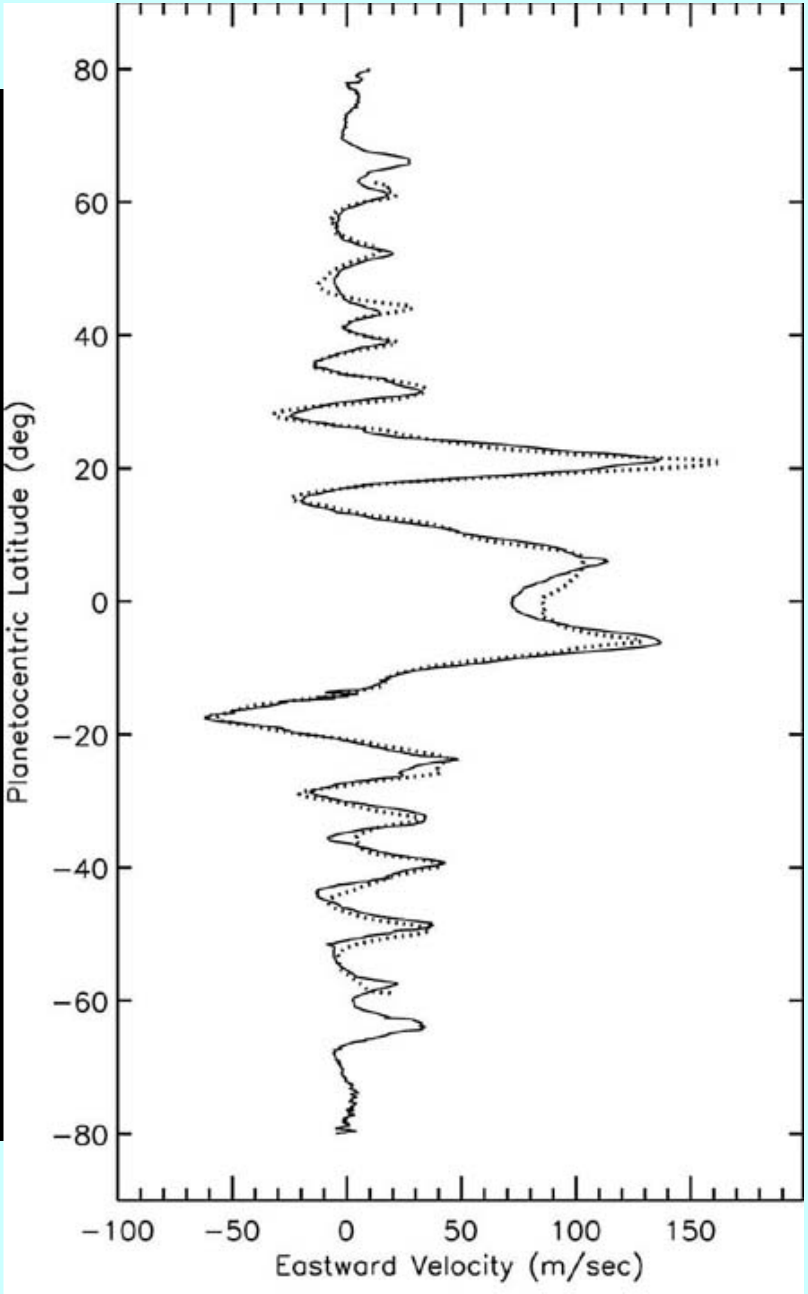


Jupiter and Saturn’s temperatures and clouds



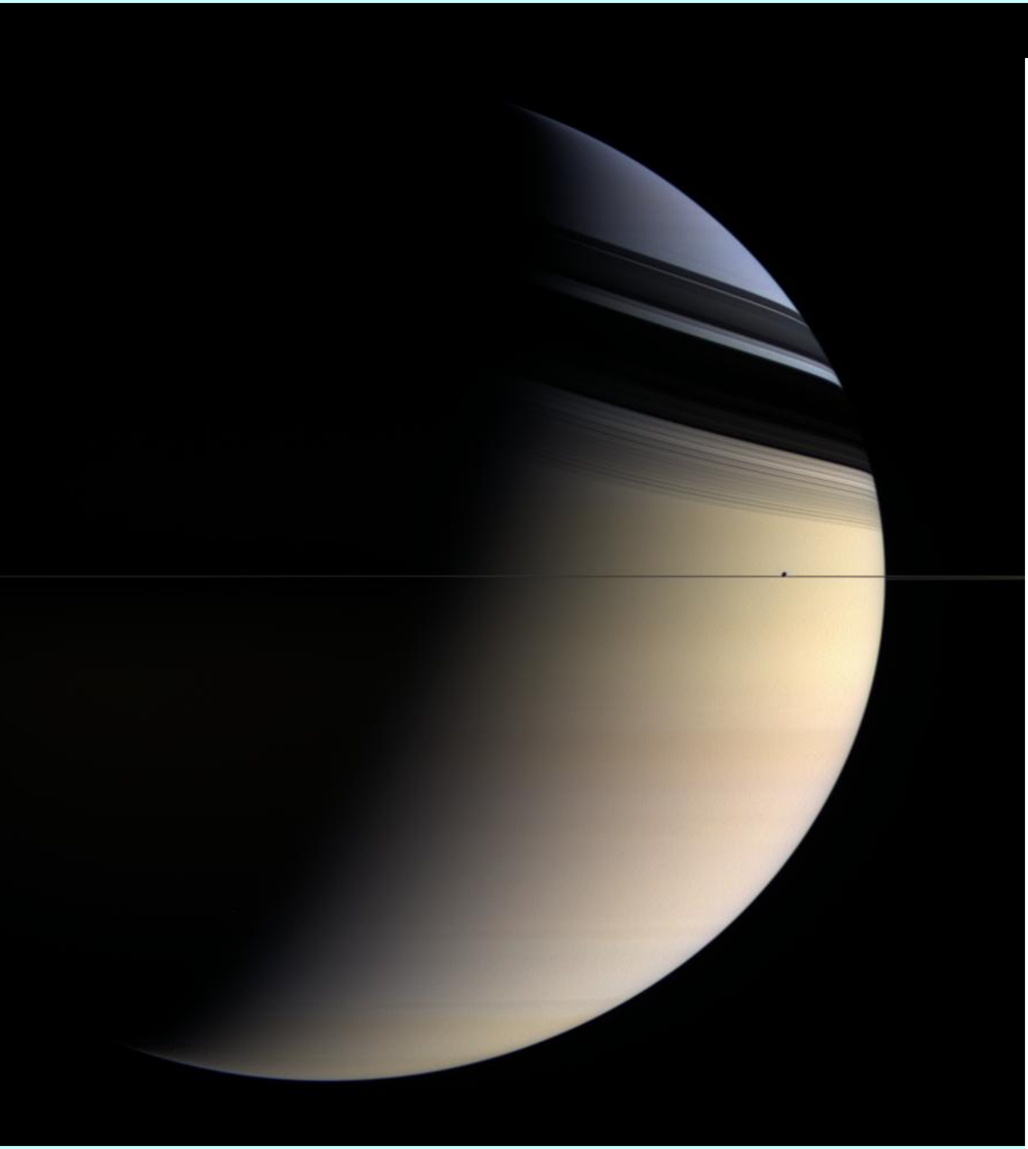
Jupiter's Zonal Winds

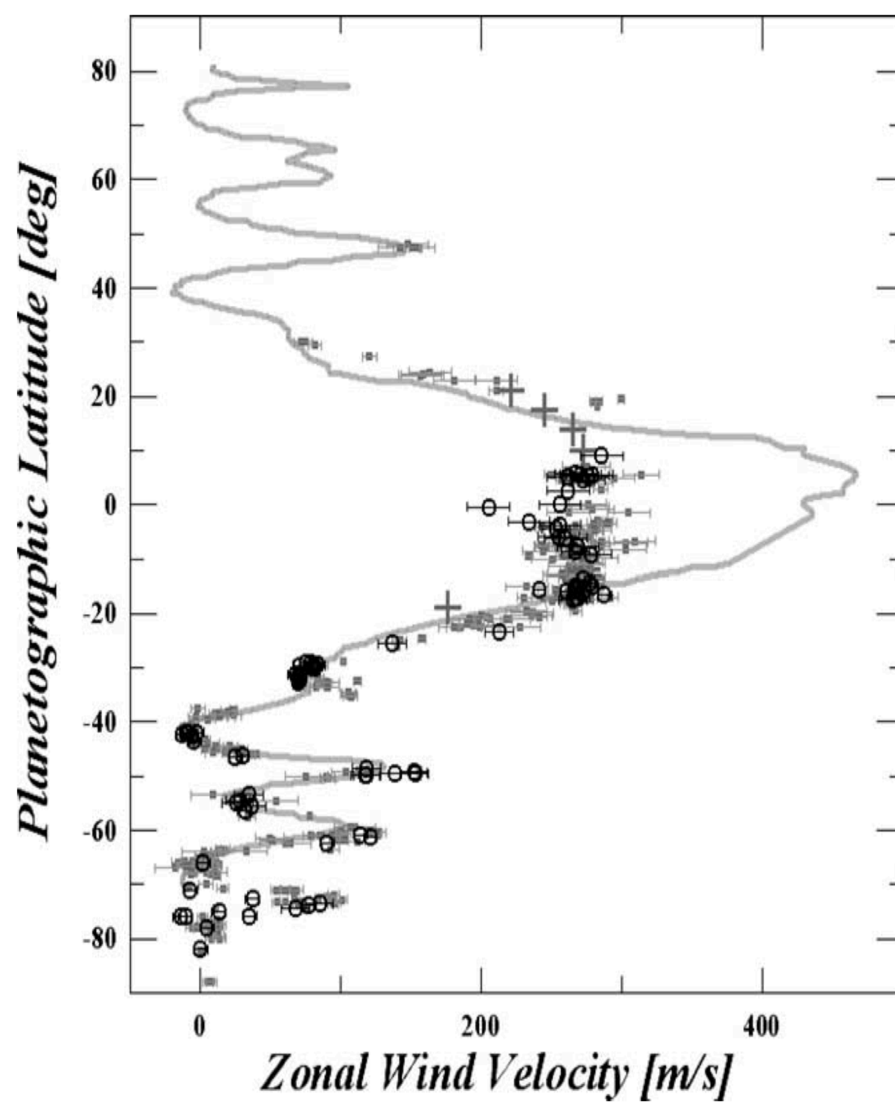




Limaye (1986), Porco et al. (2003)

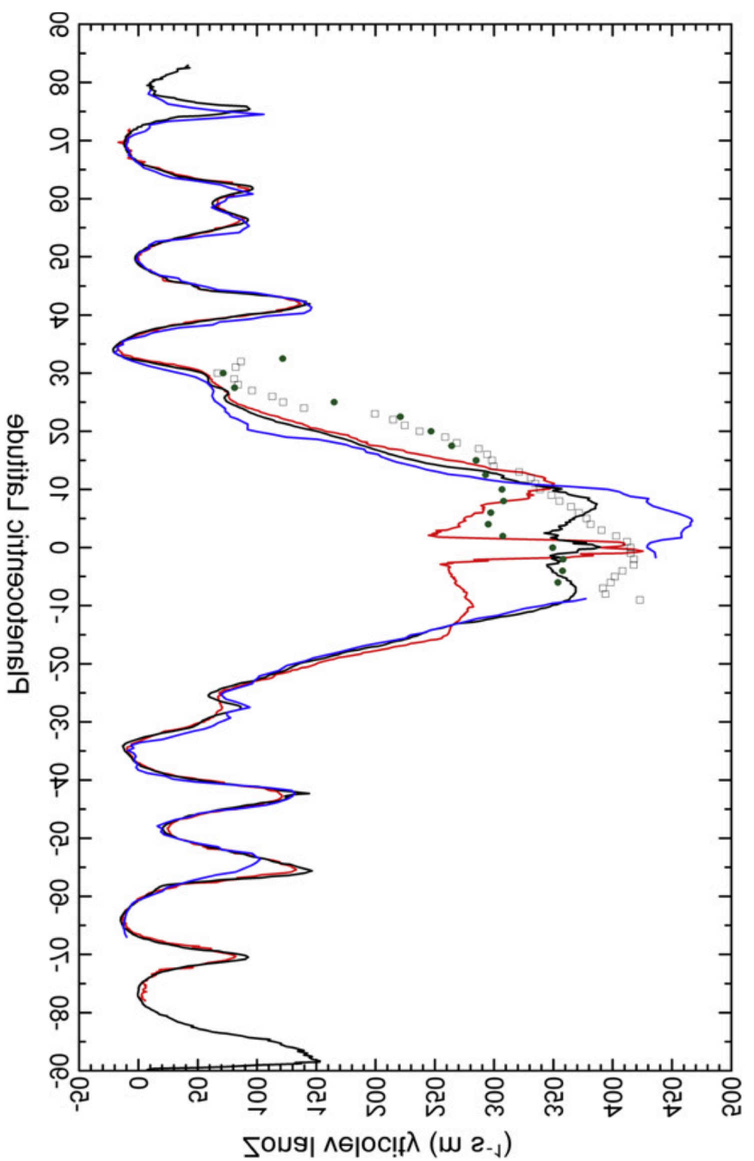
Saturn’s zonal winds at the dawn of Cassini





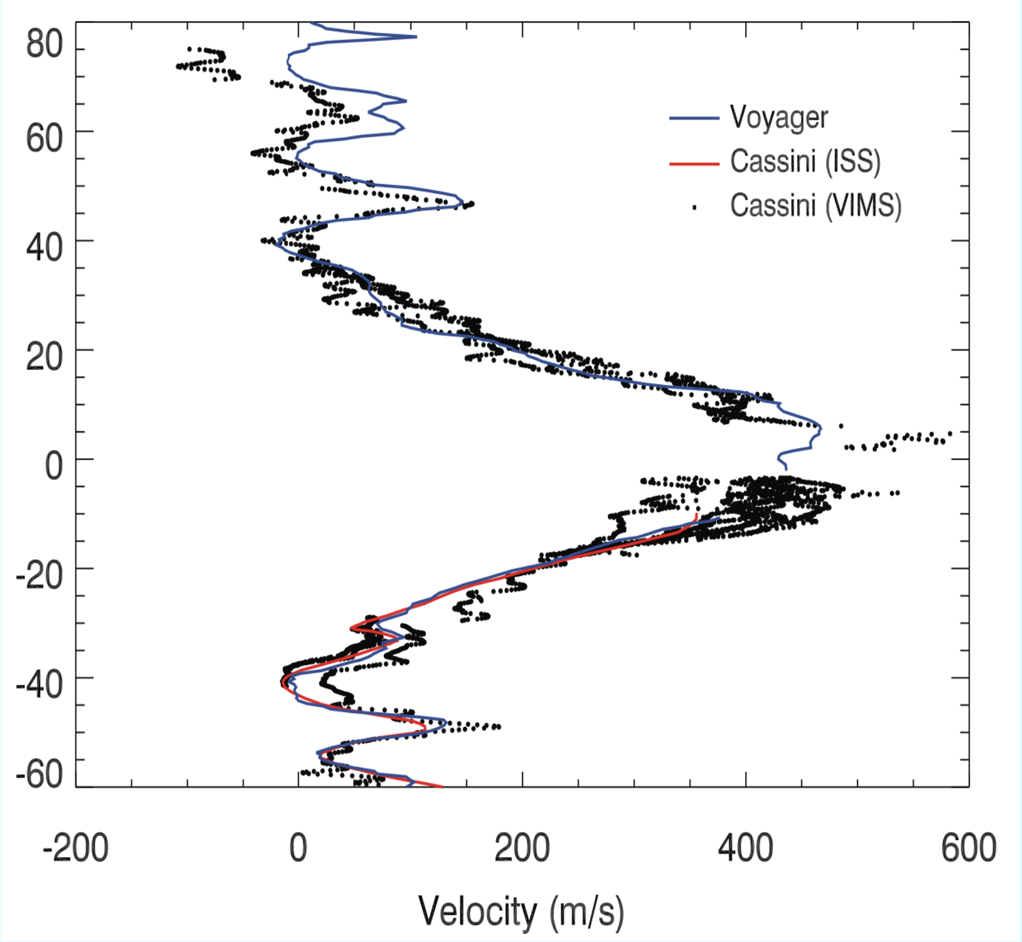
Sanchez-Lavega et al. (2004, 2007); Porco et al. (2005)

Cassini confirmed strong vertical shear at the equator with a slowdown in the upper troposphere (relative to Voyager).



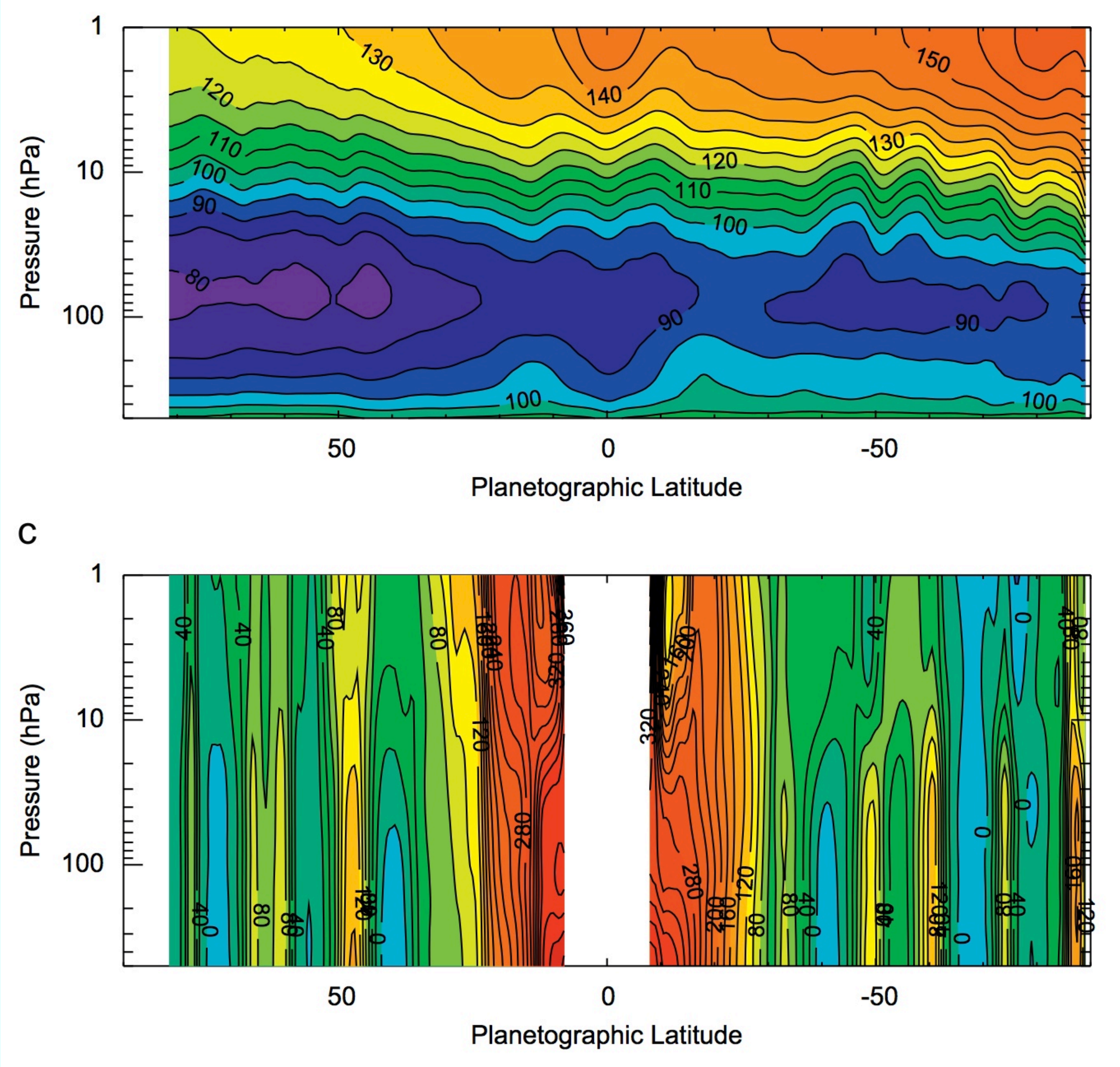
Latitude (deg)

Zonal wind speed (m/sec)



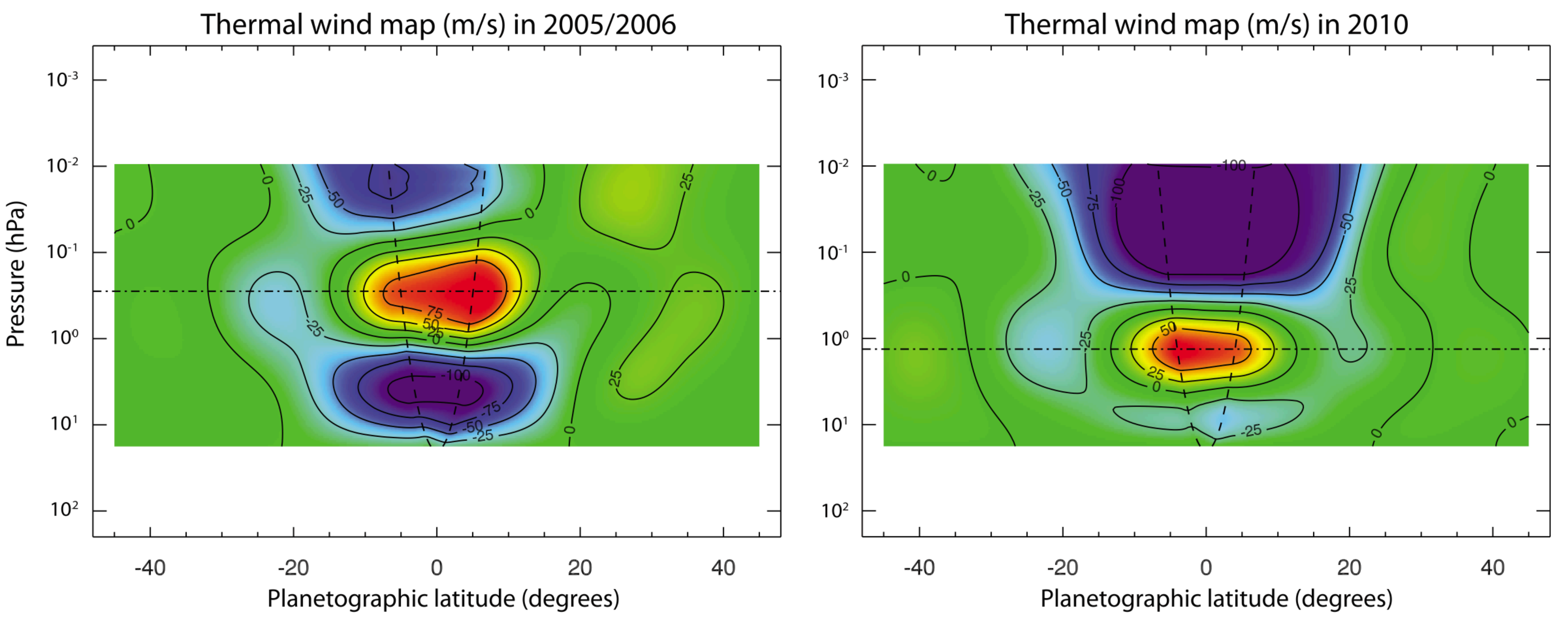
Choi et al. (2009), Garcia-Melendo et al. (2010, 2011)

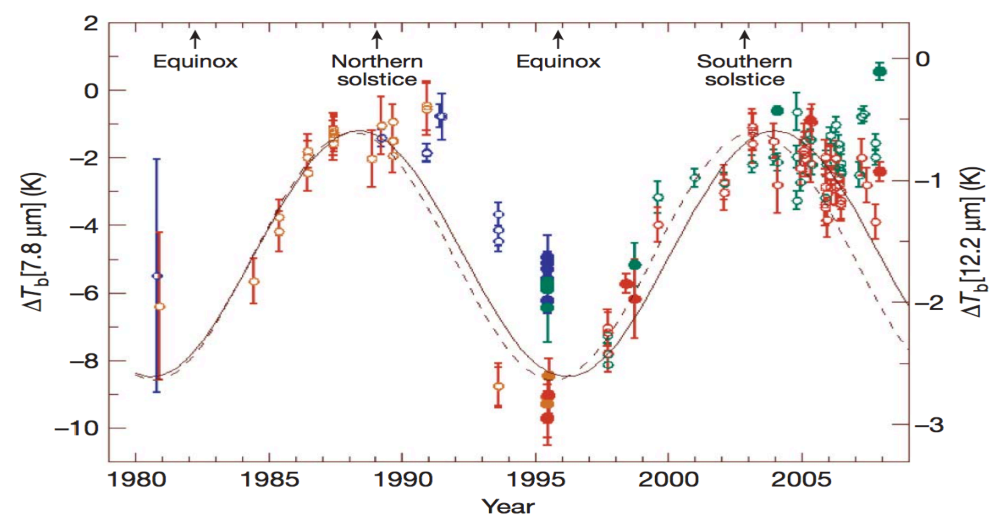
Thermal and jet structure above the clouds



Read et al. (2009);
Flasar et al. (2005);
Li et al. (2008)

Stratospheric equatorial jet oscillations



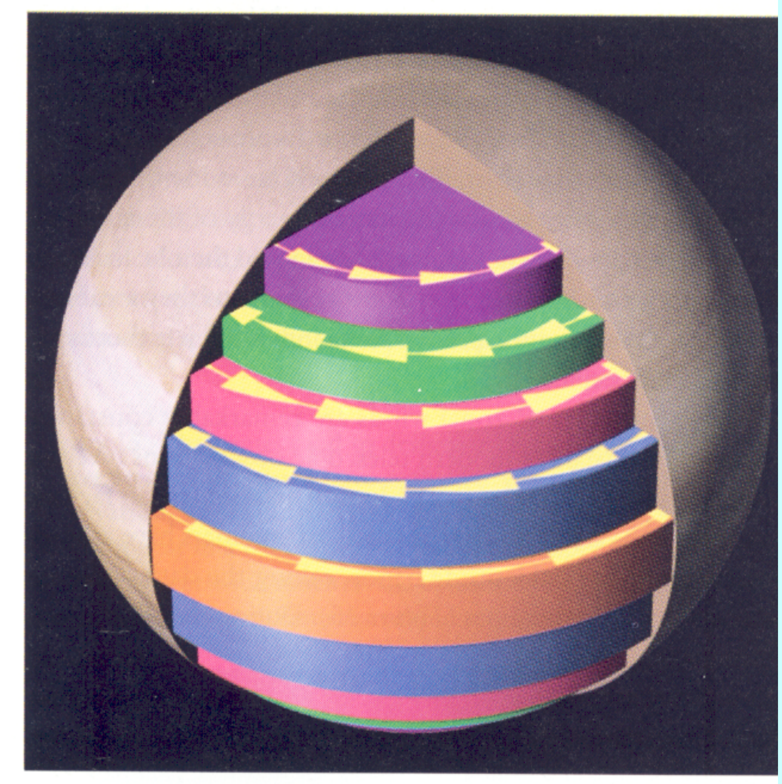


Guerlet et al. (2011),
Orton et al. (2008);
Fouchet et al. (2008);
Schinder et al. (2011);
Li et al. (2011)

Basic Jet Scenarios

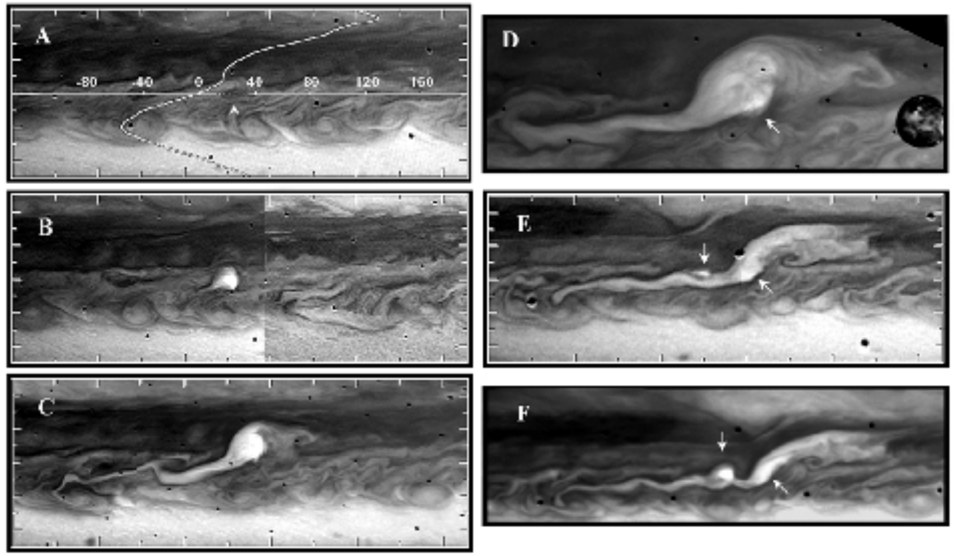
- Models for jet structure:
  - *Shallow:* Jets confined to outermost scale heights below the clouds
  - *Deep:* Jets extend through molecular envelope (Taylor-Proudman theorem)

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



These are among the most important unsolved problems in planetary atmospheres.

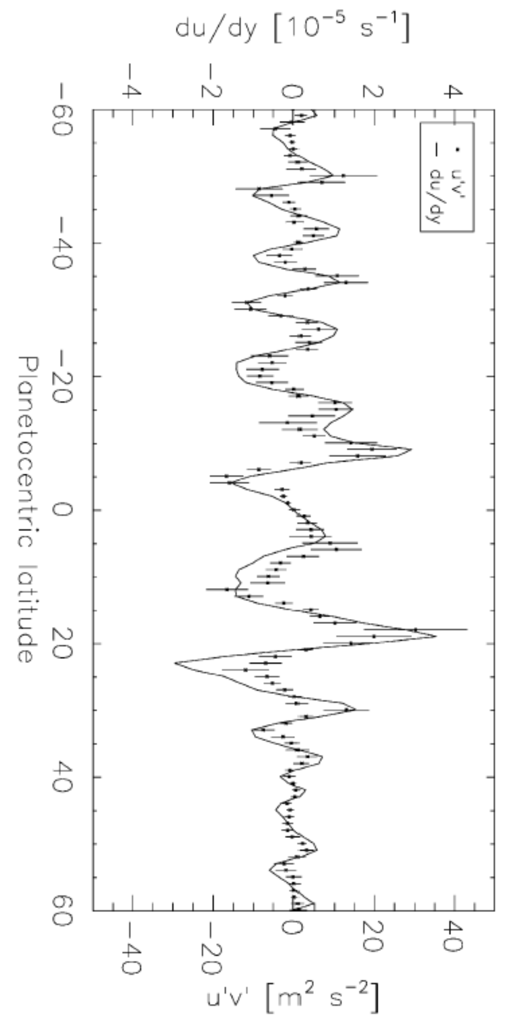
Note that the issues of structure and forcing are distinct!



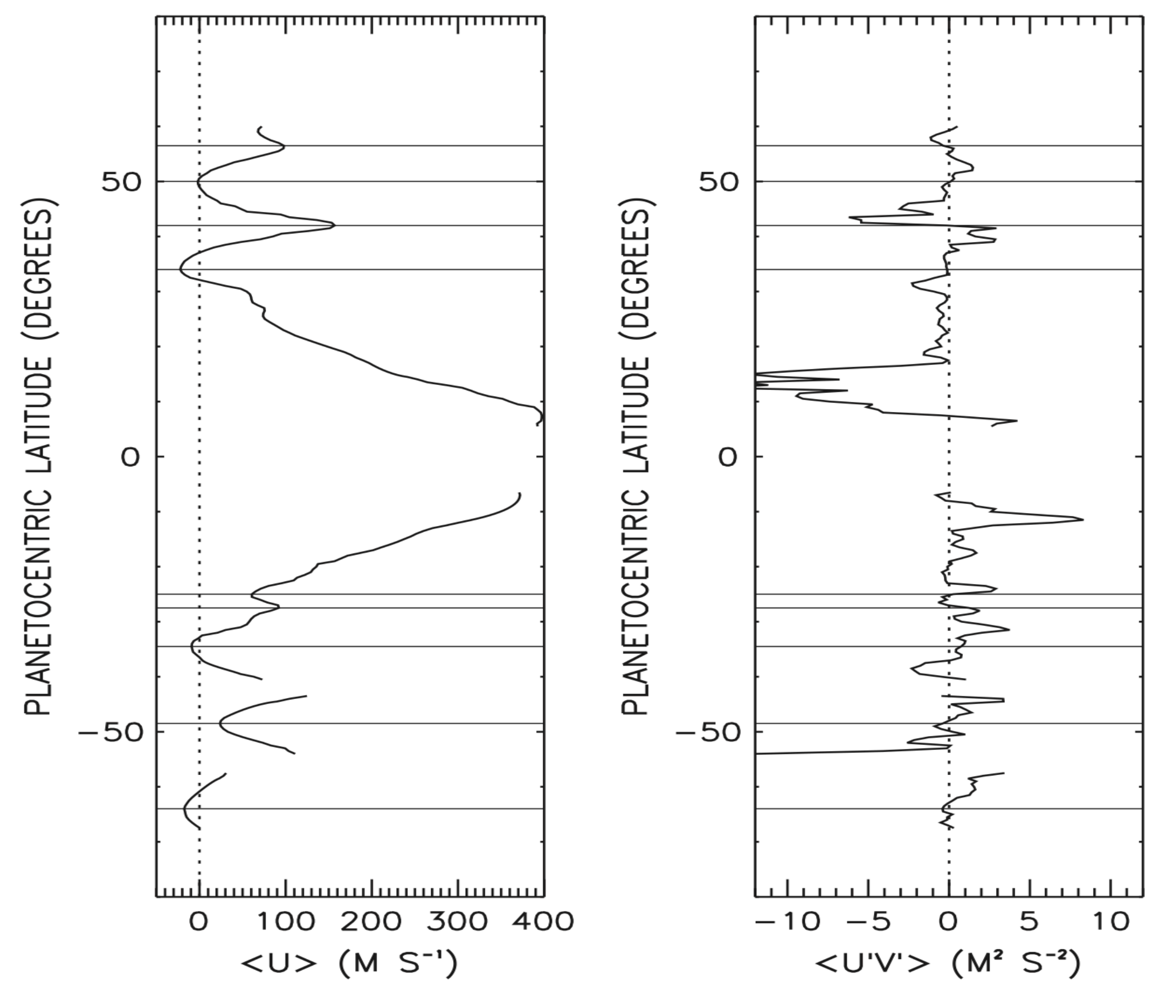
Rotation also causes alignment of convection at large scales

Evidence for eddy-momentum convergences into the jets at cloud level

Jupiter



Saturn



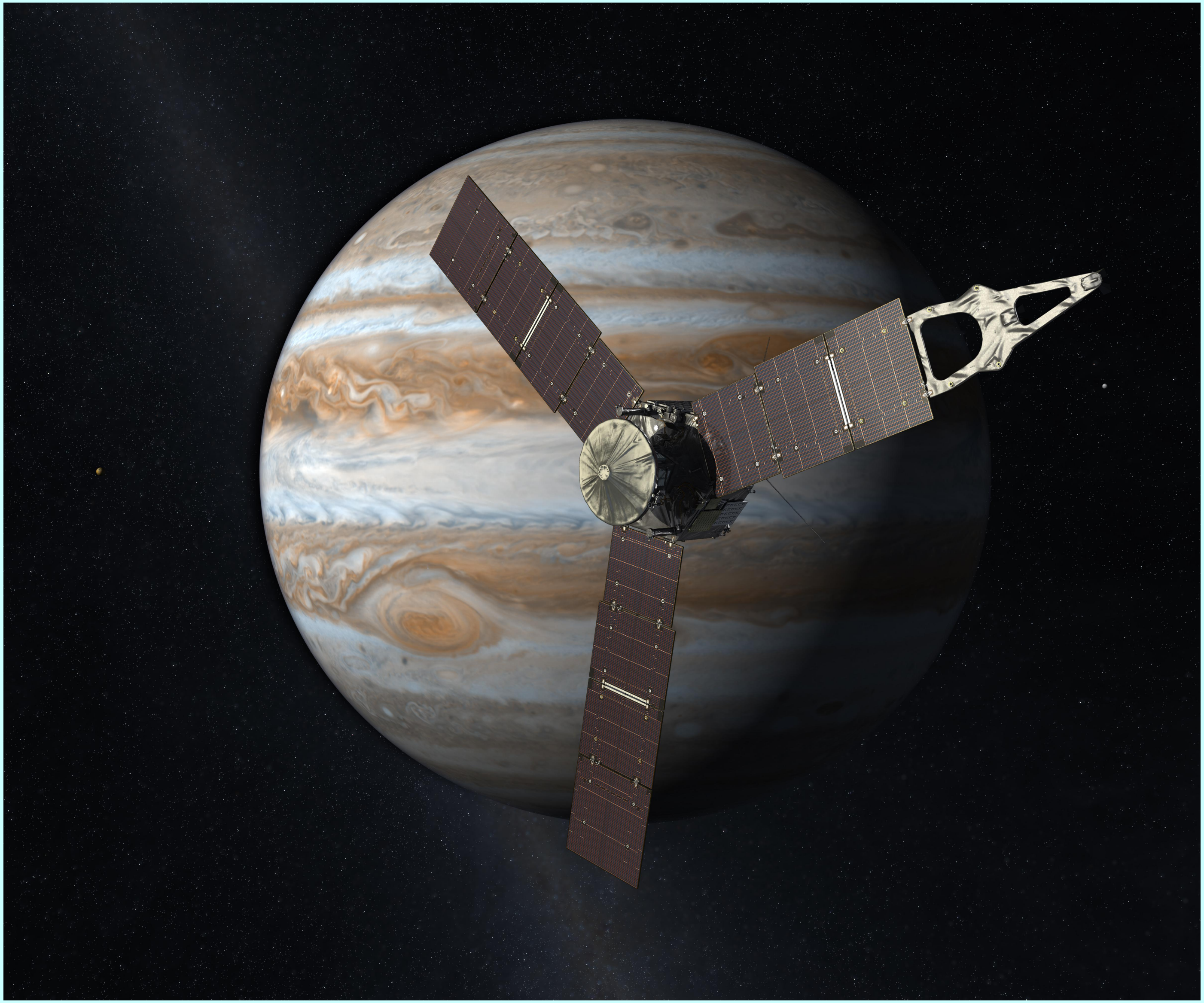
These measurements demonstrate that the jets *are* being driven at cloud level.

Salyk et al. (2006), Del Genio et al. (2007), Del Genio & Barbara (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



Gravitational signature of internal dynamics

On the giant planets, the dynamics may involve a considerable fraction of the mass, and therefore density fluctuations due to dynamics may be detectable in the gravity field.

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

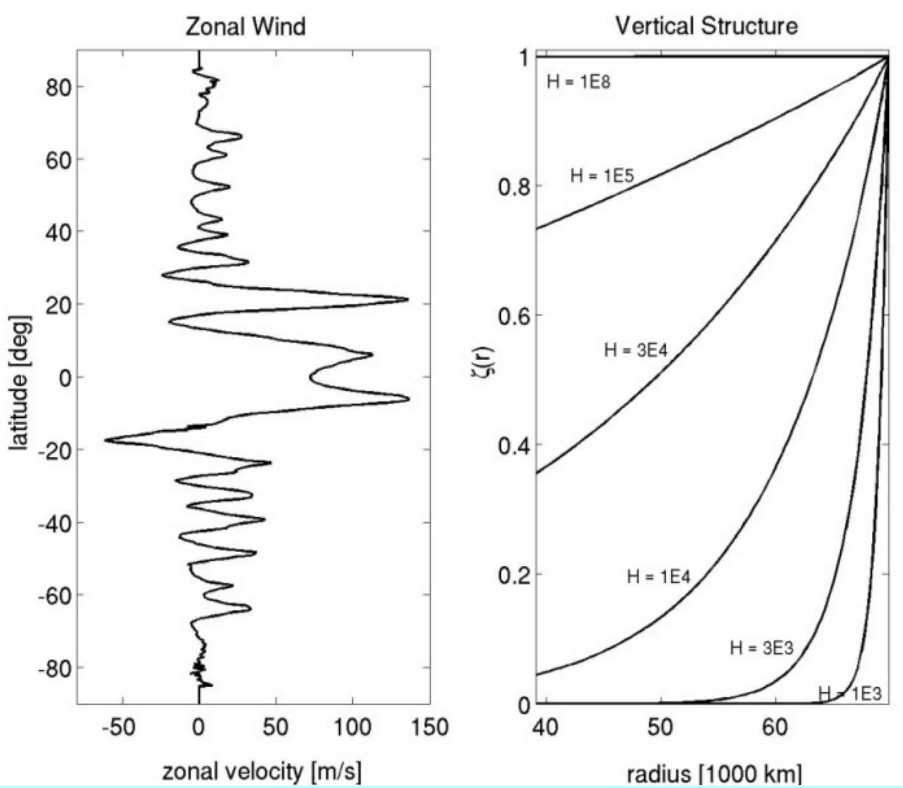
$$J_n = -\frac{1}{Ma^n}\int r^n P_n(\mu)\rho(r,\mu,\phi)d^3r$$

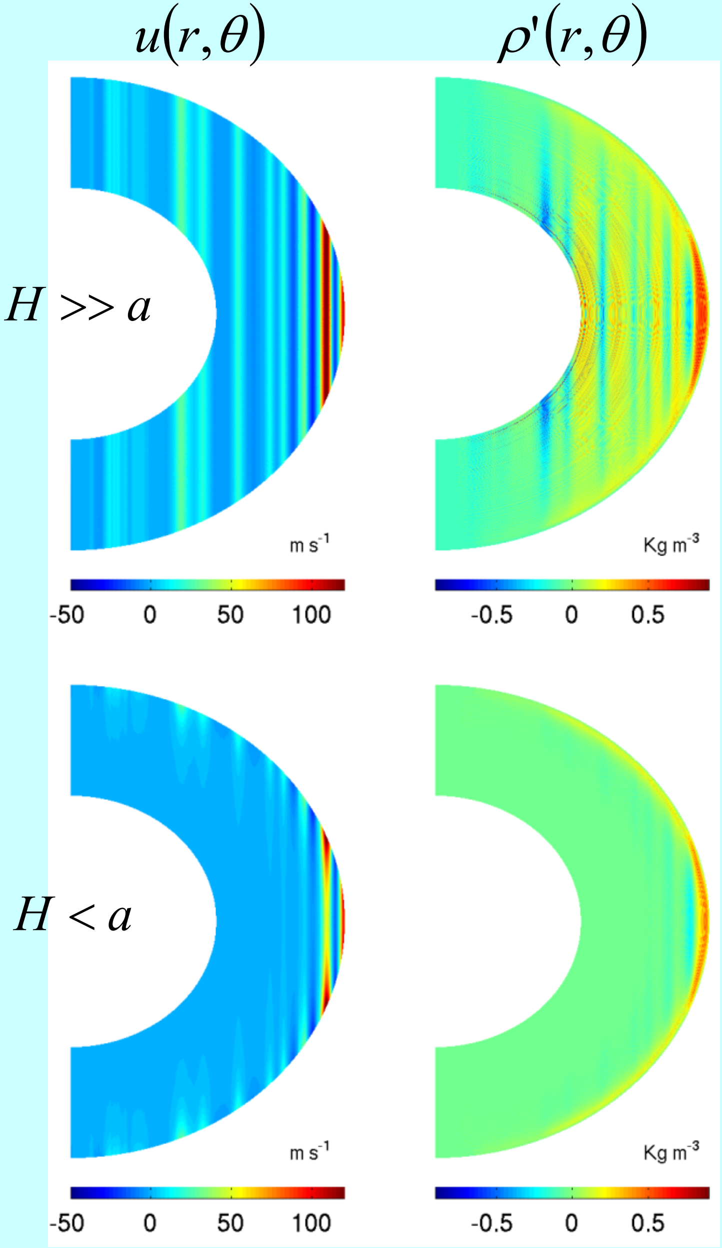
ρ is density, P_n are Legendre polynomials, a is planetary radius, r is radial distance, ϕ is longitude, μ is cosine of angle from rotation axis, and M is total mass.

(See Hubbard 1984 for a review.)

- **Use the observed winds and assume an idealized interior vertical structure with a decay length *H*.**

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

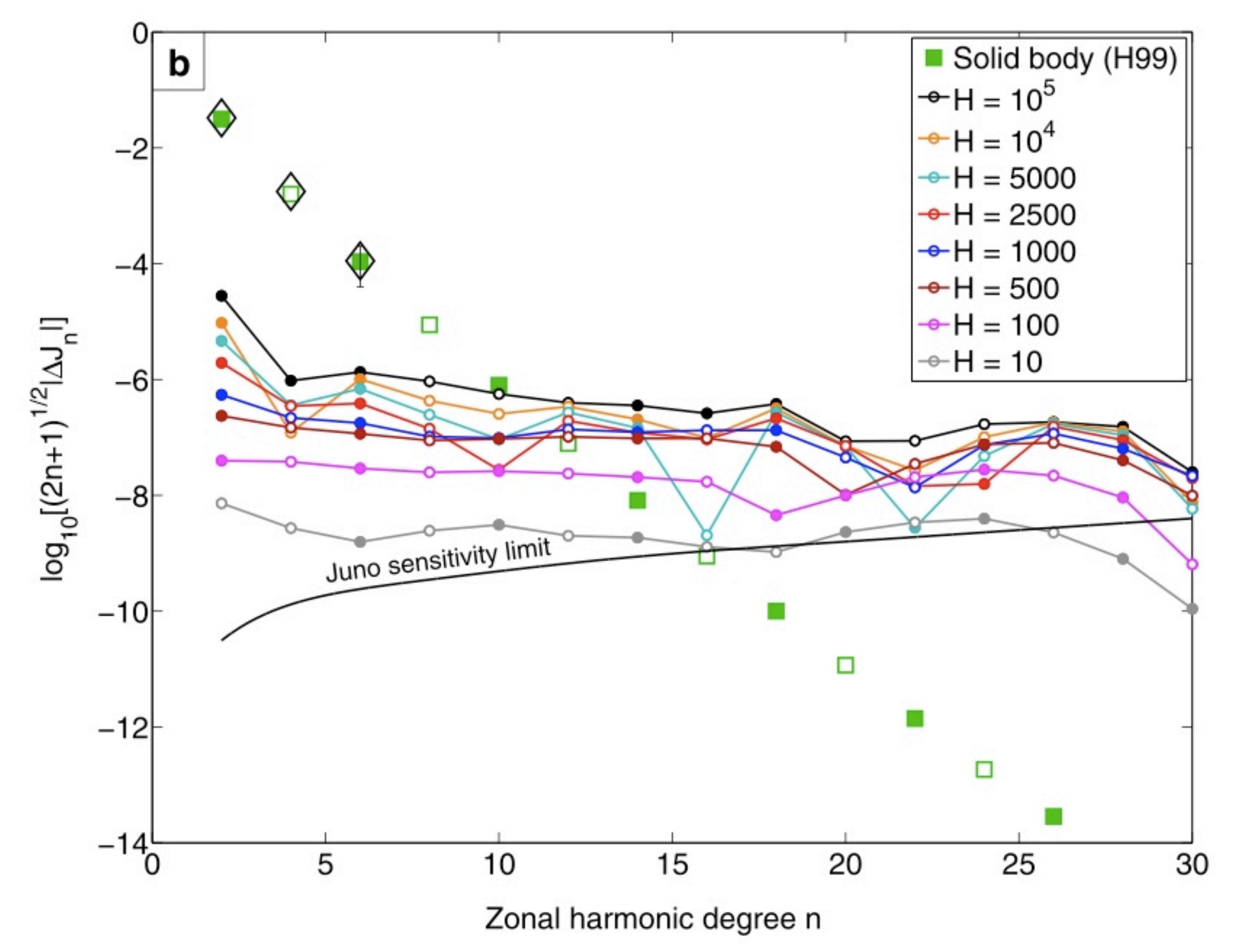




Kaspi, Hubbard, Showman, & Flierl (2010)

- **Calculate corresponding density structure from thermal wind equation.**

Predicted Jupiter gravity spectrum for various depths of zonal flow

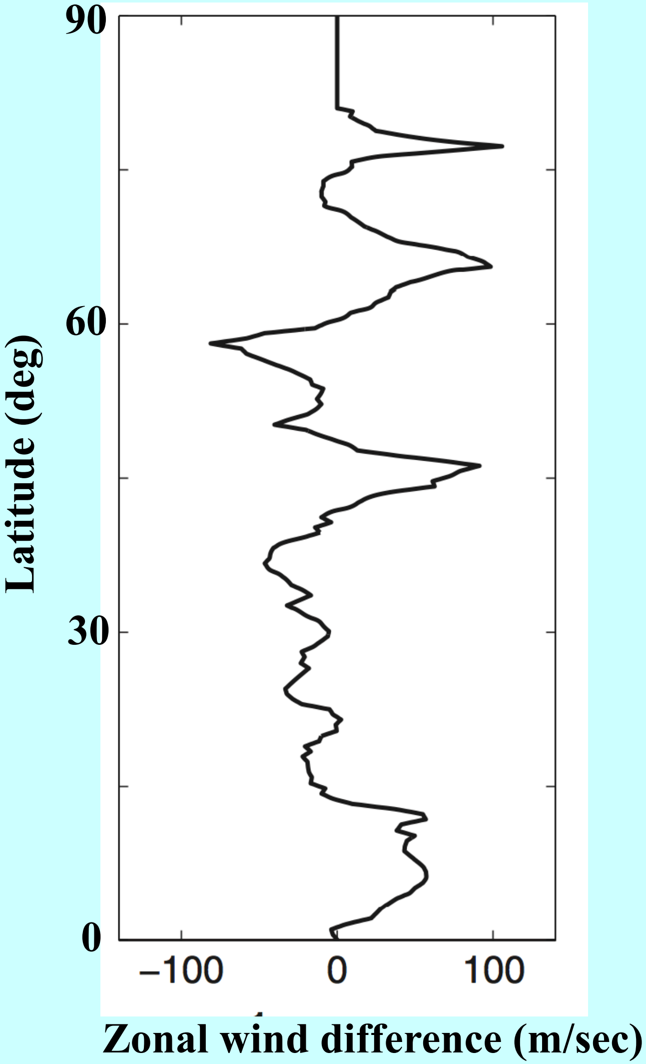


Kaspi, Hubbard, Showman, & Flierl (2010)

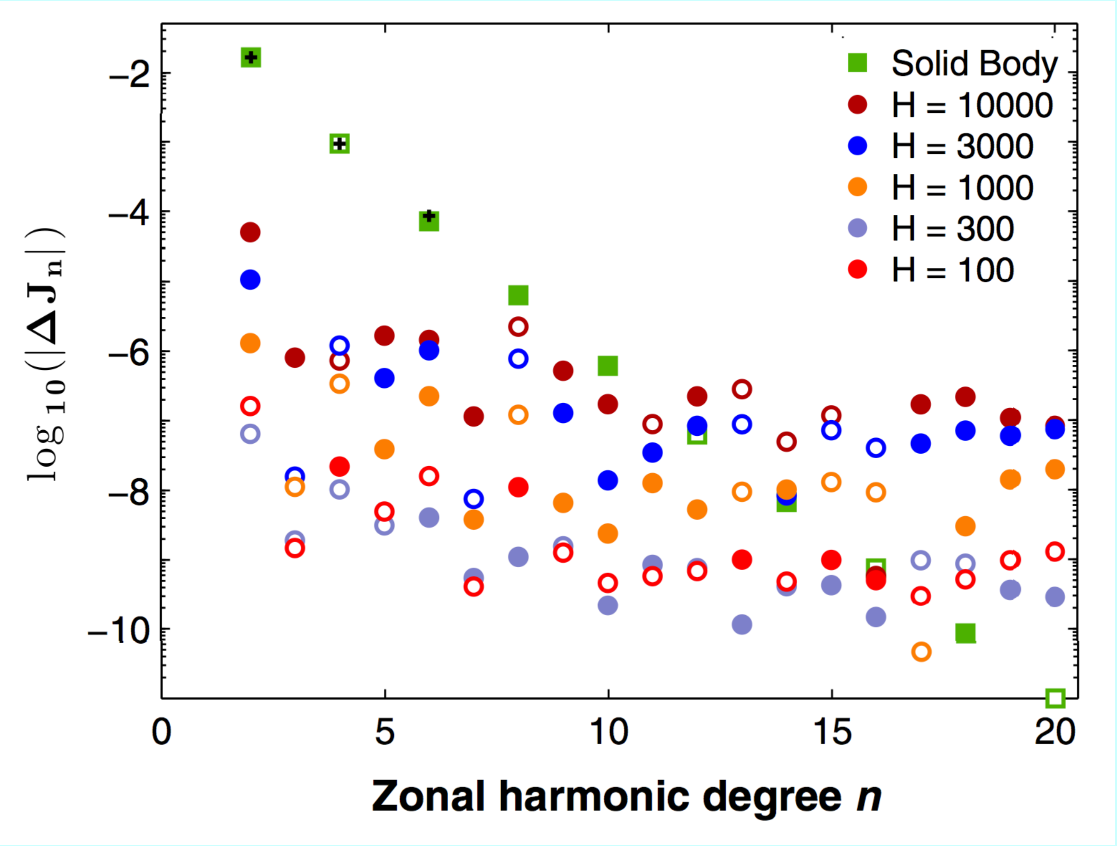
Key point: gravitational signature of jets will be detectable by Juno if jets extend at least ~500 km into the interior. Juno will measure to J_{12} or J_{14}. Jets dominate over solid-body rotation beyond J_{10} if they extend deeply enough.

Odd gravity harmonics are a very sensitive probe of deep dynamics

Hemispheric (N minus S) difference in Saturn zonal winds

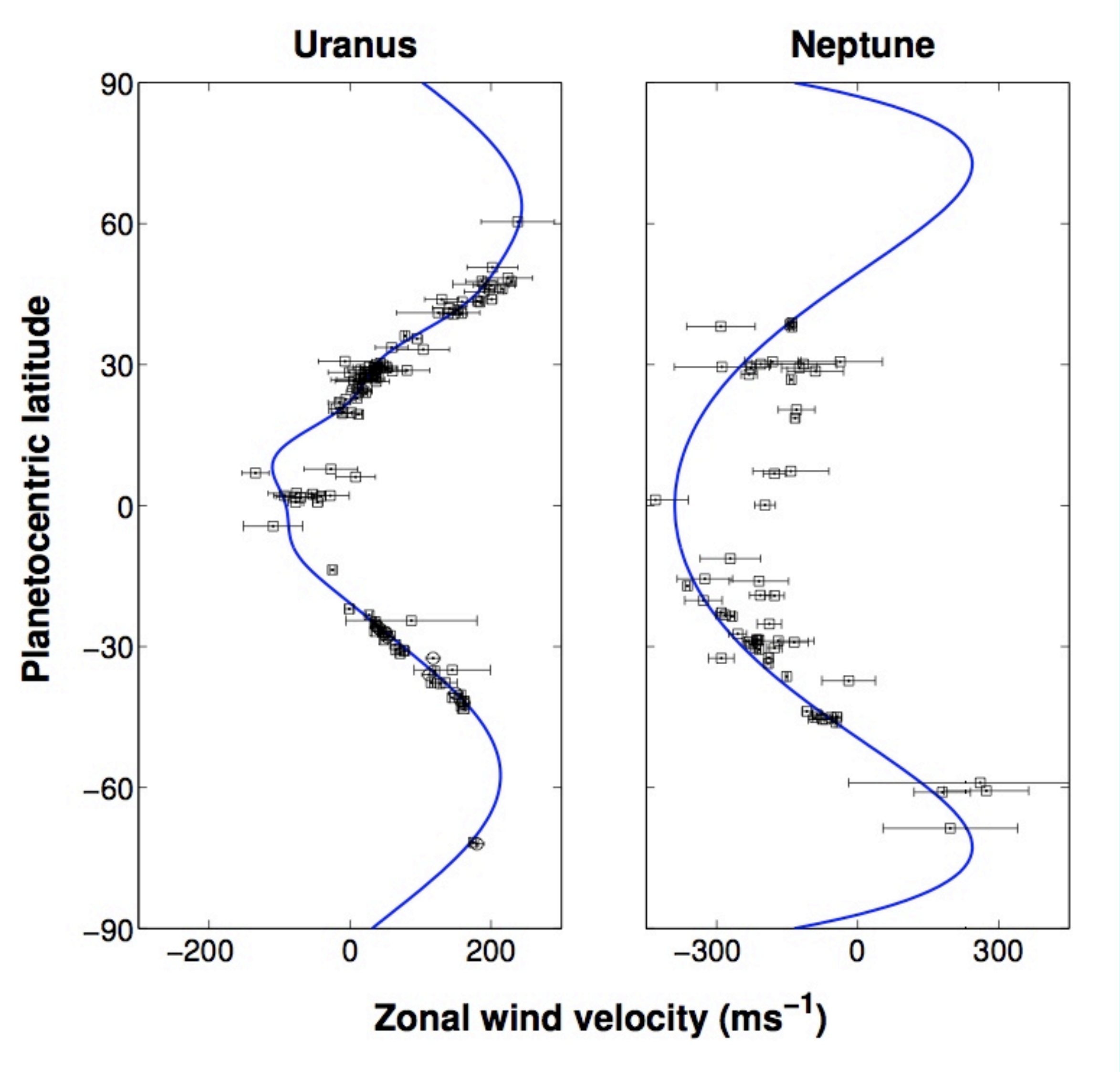


Gravity spectrum under various assumptions for how deep the jets penetrate



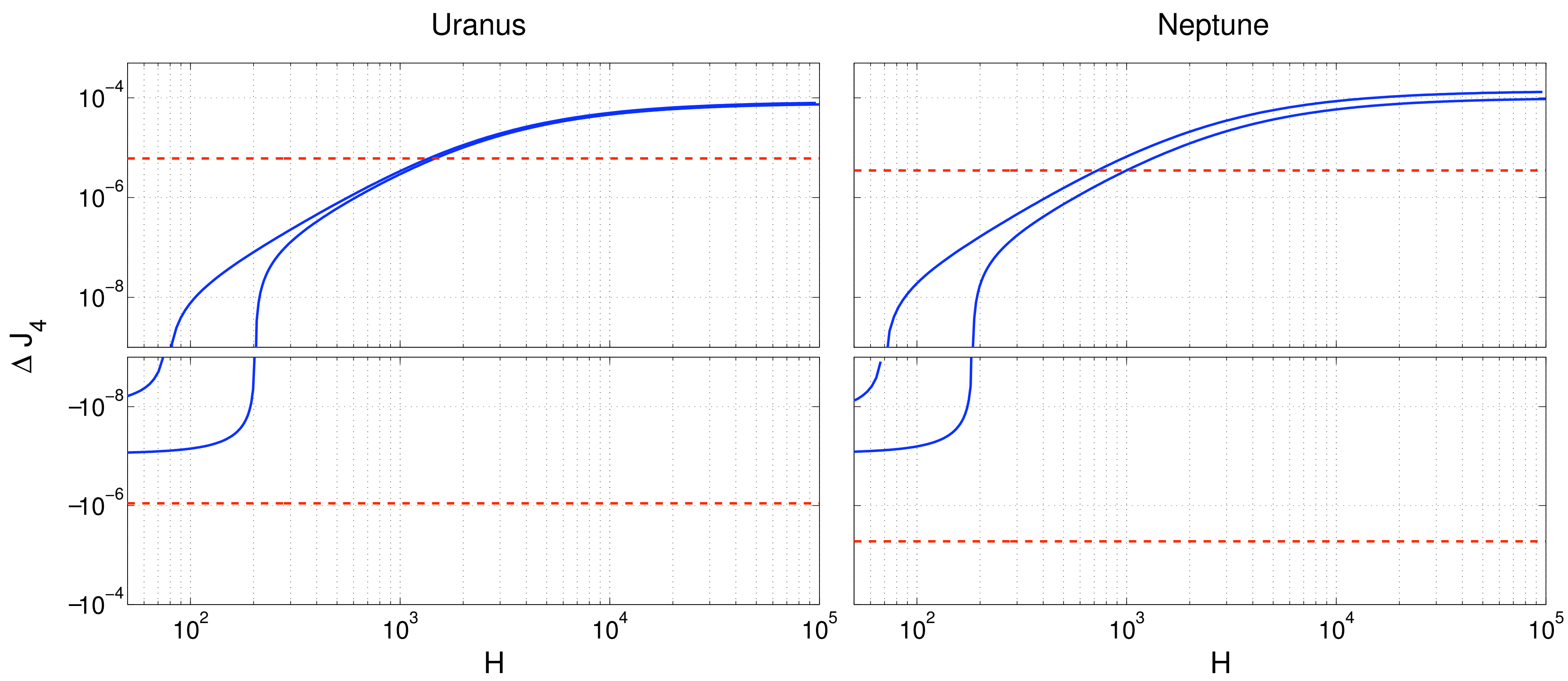
Kaspi (2013)

What about Uranus and Neptune?



Observed jets are broad, and winds are fast. Thus, winds cause a large perturbation to low gravity harmonics like J_4. This suggests that *we can constrain depth of jets on Uranus and Neptune now with current data—namely, J2 and J4*—unlike the case of Jupiter where we need a close flying orbiter like Juno.

Atmospheric confinement of jets on Uranus and Neptune!

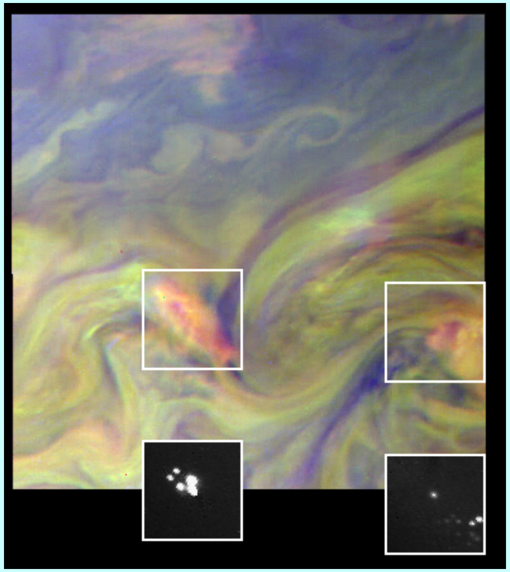


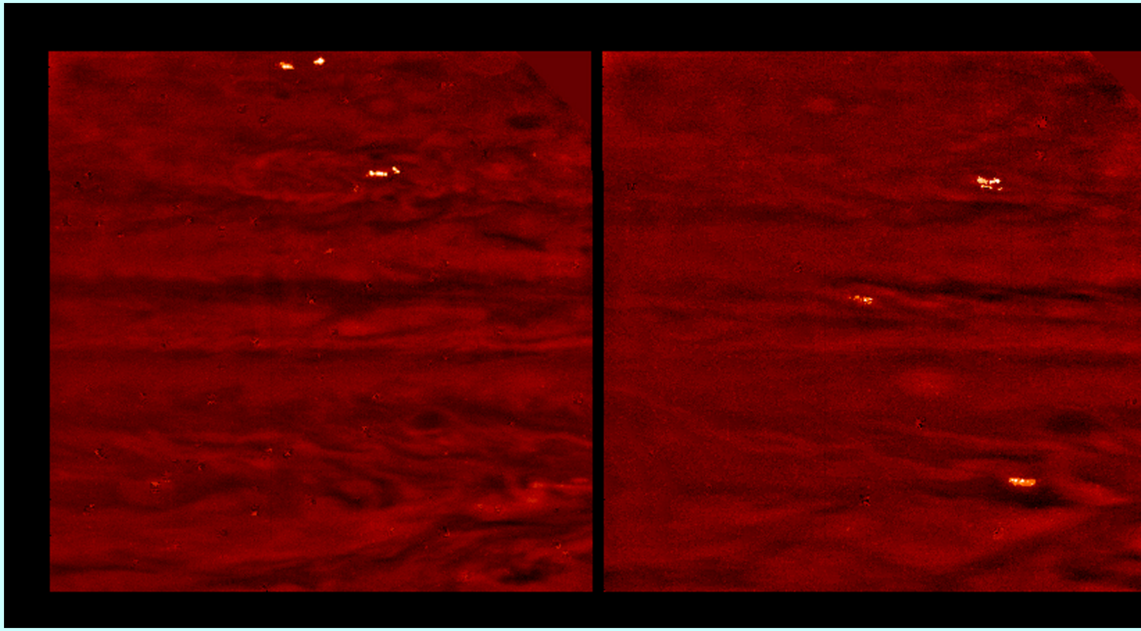
If winds extend too deeply, the meteorological perturbation to J_4 would exceed the maximum possible difference between the observed J_4 and the allowable J_4 from static, wind-free models. This implies that:

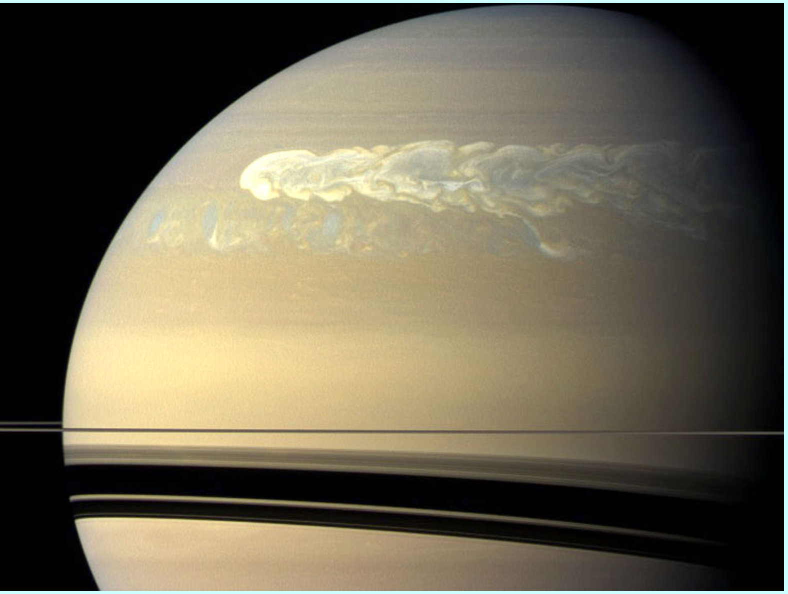
- **On Neptune, winds confined to outermost ~1000 km (~3000 bars, 0.2% of planetary mass)**
- **On Uranus, winds confined to outermost ~1500 km (~4000 bars, 0.35% of planetary mass)**

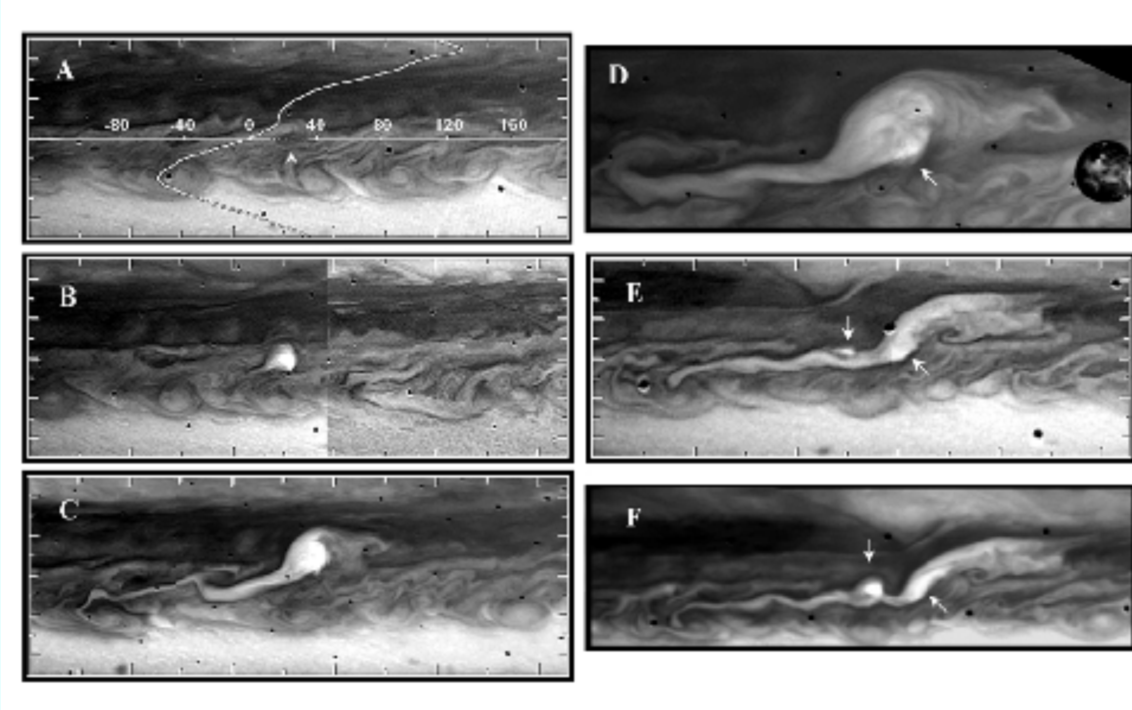
Kaspi, Showman, et al. (2013)

Storms and lightning



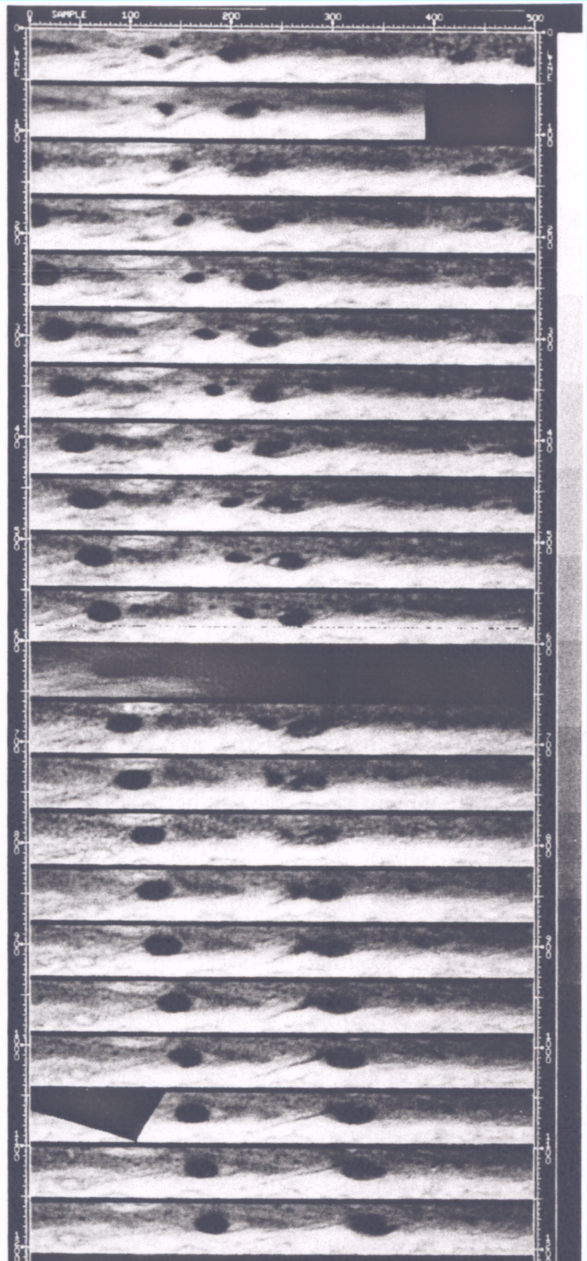


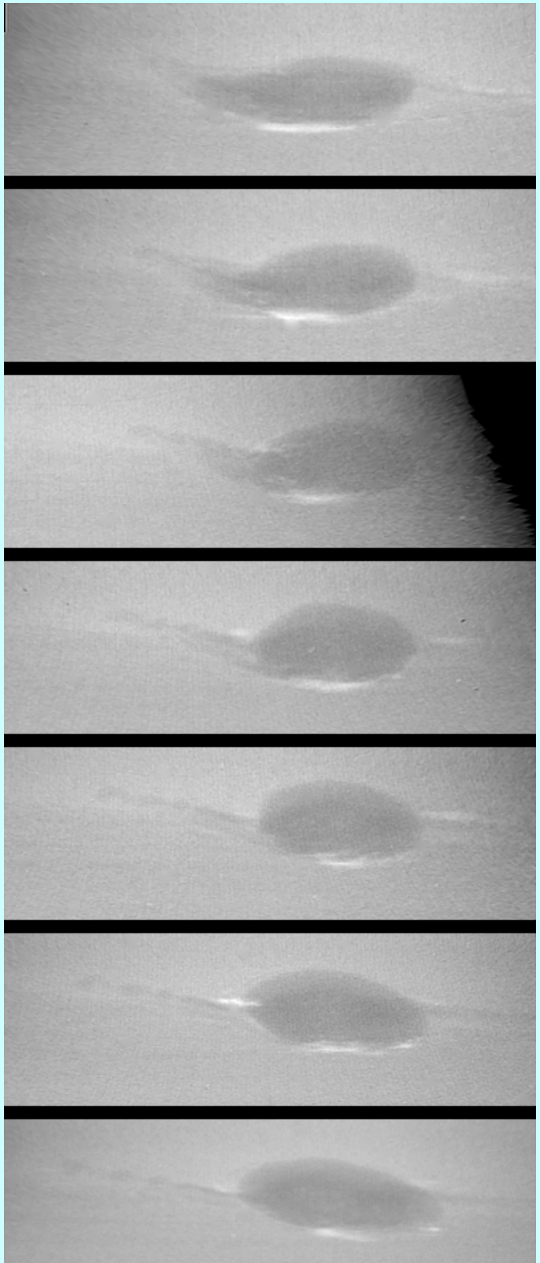




Vortex behavior

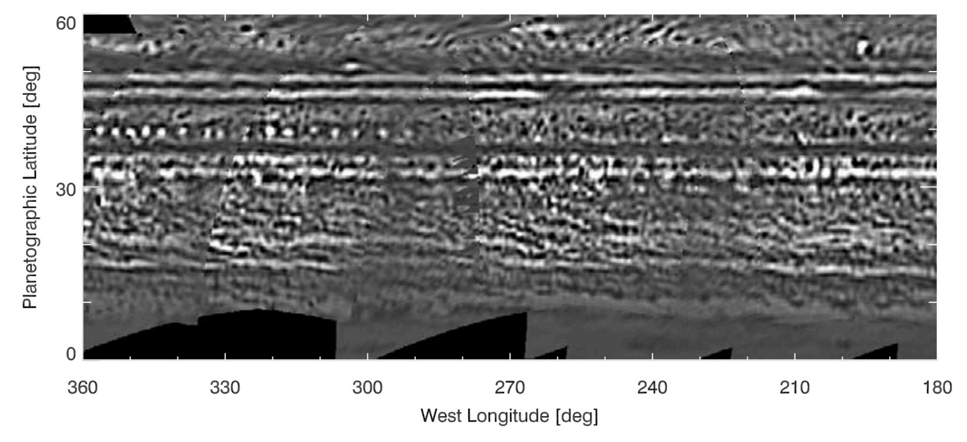
Jupiter

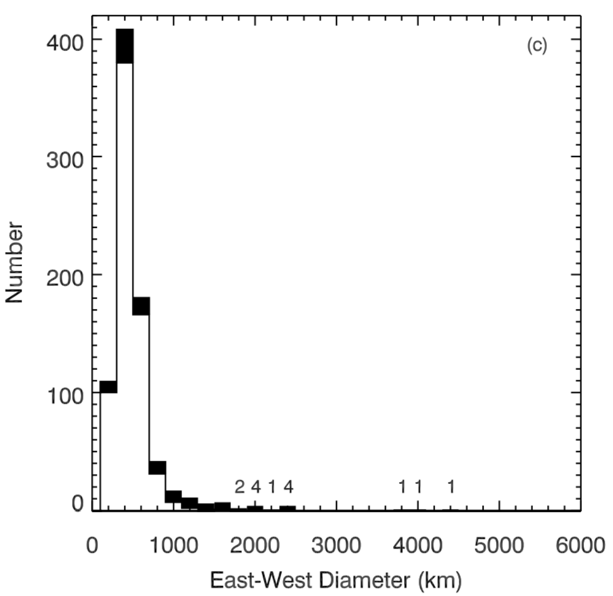


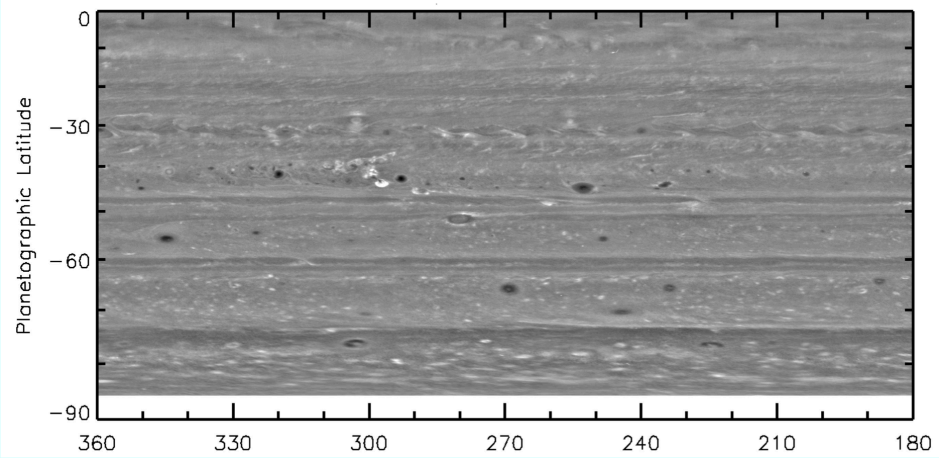


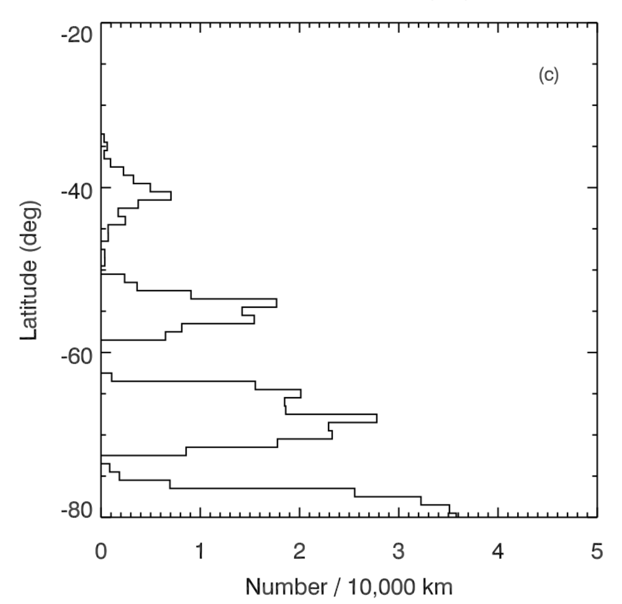
Neptune

Local features on Saturn





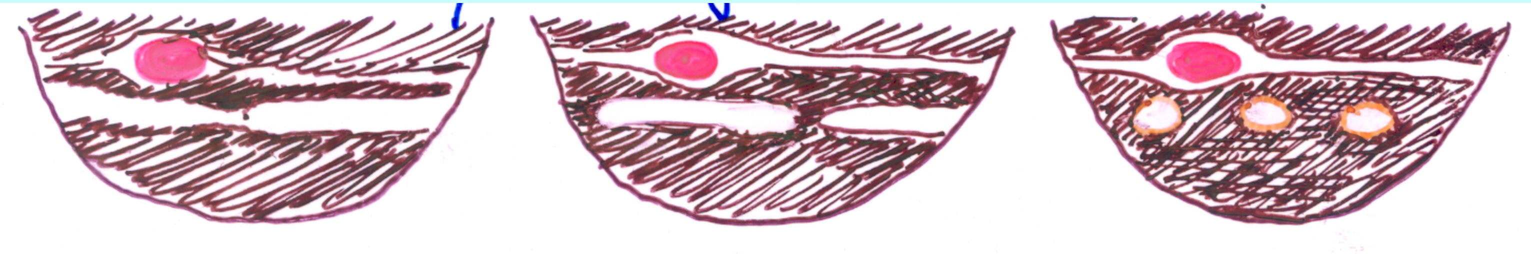




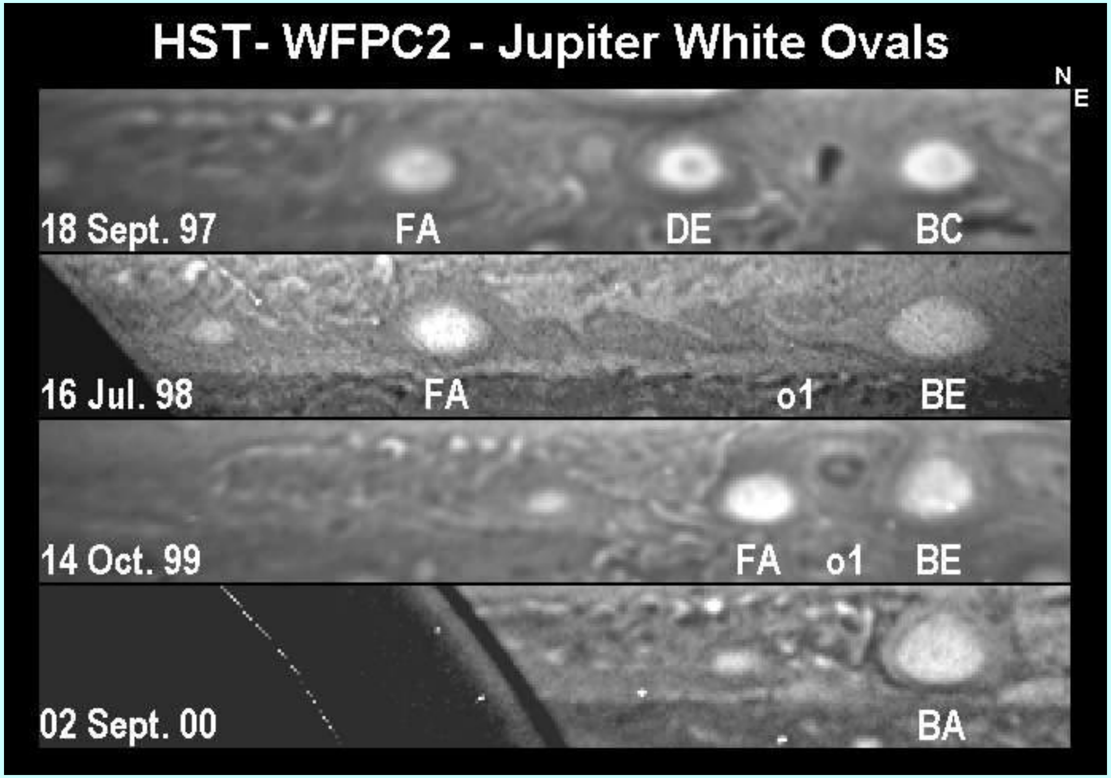
Vasavada et al. (2006), Choi et al. (2009)

Spots cluster at a certain size (~500-1000 km), putting constraints on the deformation radius

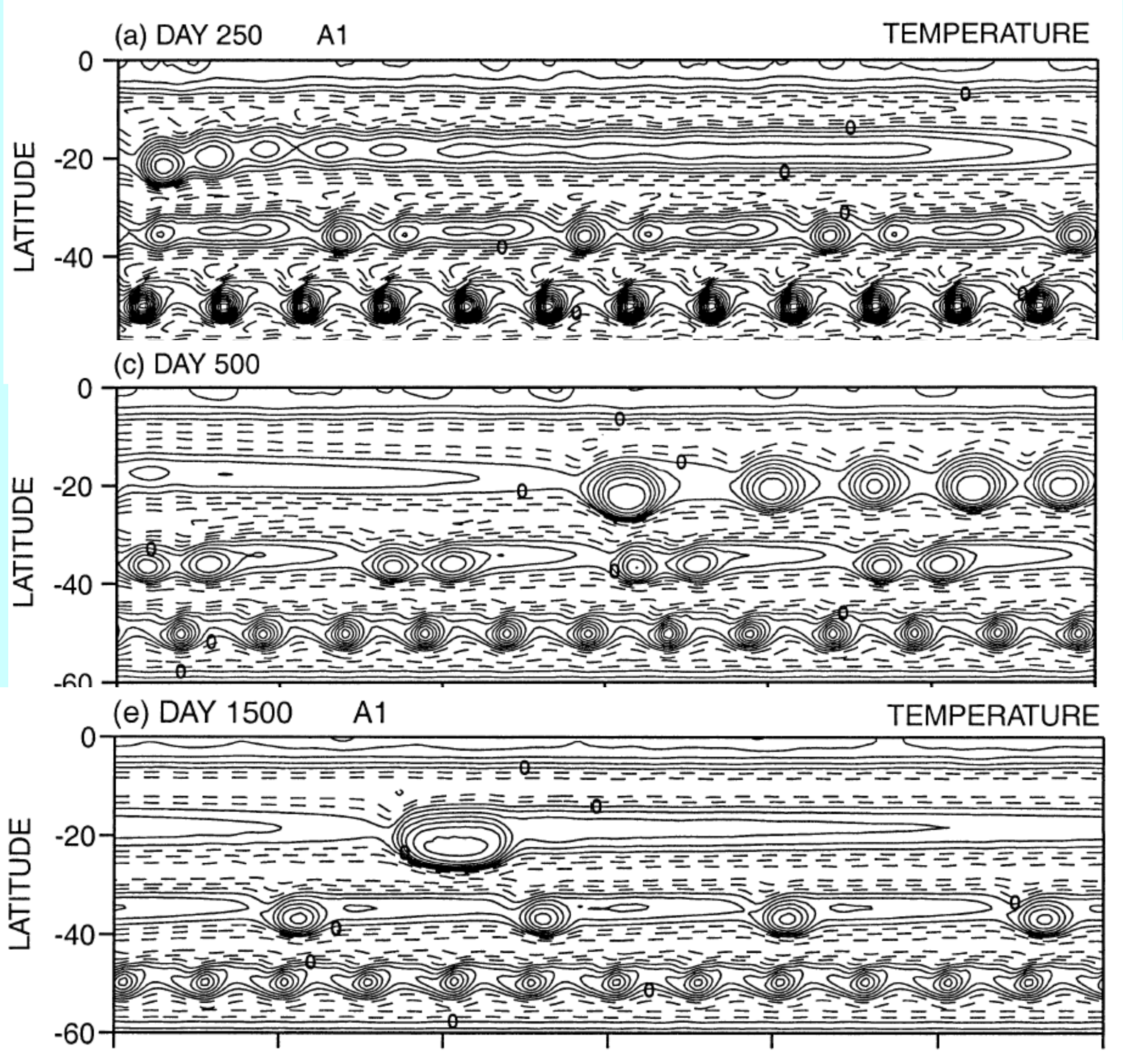
The White Ovals formed in 1938-40 during an instability on a jet:



There were 3, but 2 merged in 1998 and the remaining 2 merged in 2000, leaving only one left:

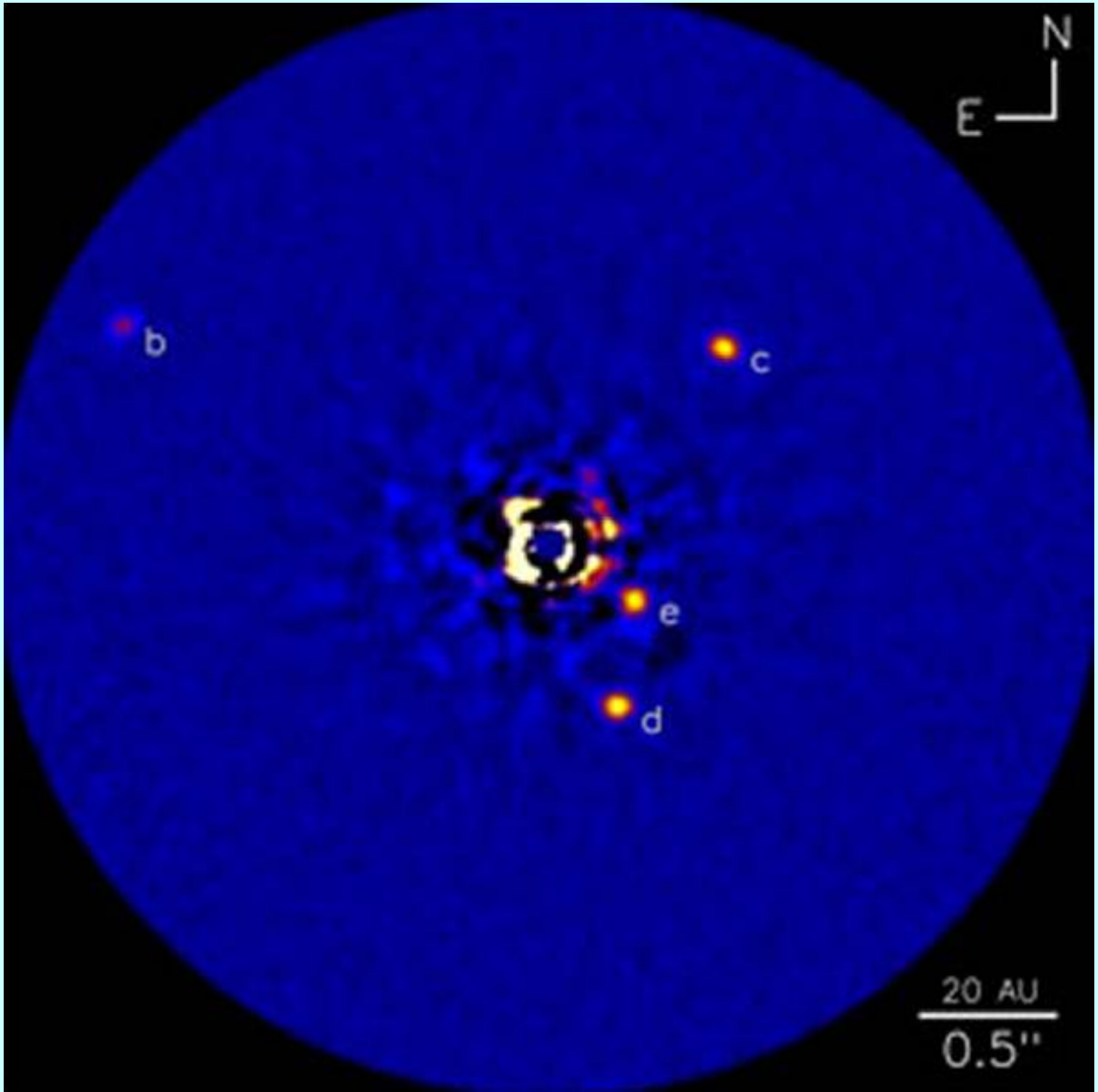


Models support the idea that large Jovian ovals formed by jet instability:



Williams (2002); Dowling & Ingersoll (1989), Read & Hide (1983, 1984), Sommeria et al. (1988)

A new frontier: directly imaged planets and brown dwarfs



Brown dwarf basics

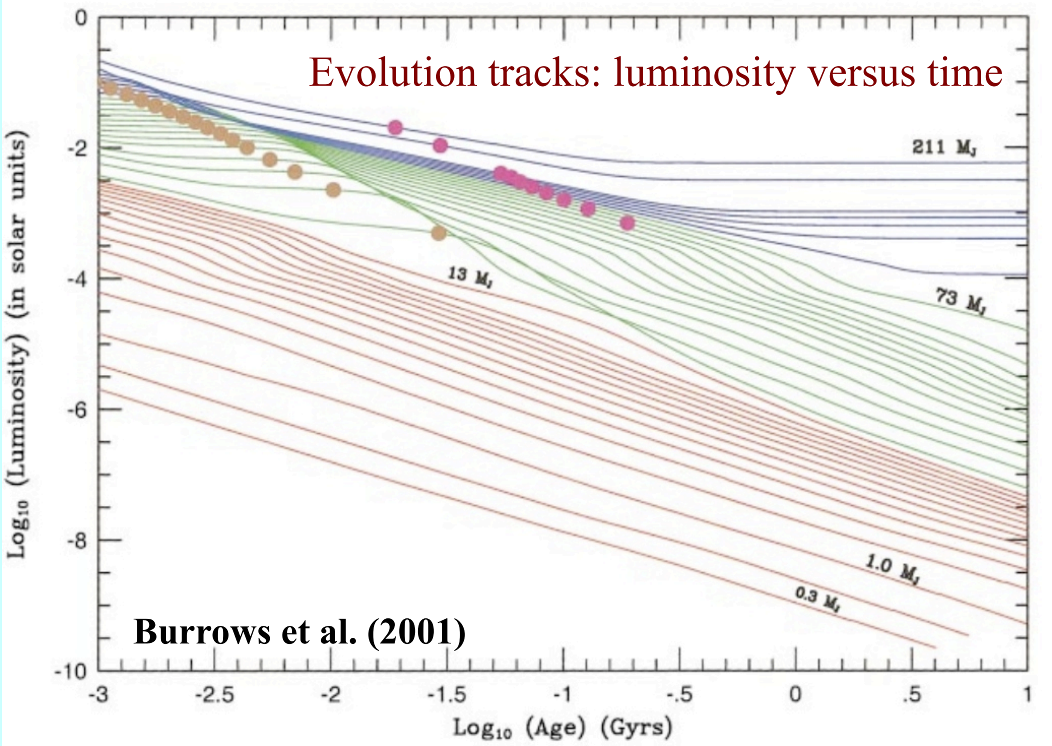
- Brown dwarfs are fluid hydrogen objects intermediate in mass between giant planets and stars. They are often free floating, though many also orbit stars.

- Presumed to form like stars (i.e., directly collapsing from a hydrogen cloud) but have masses too low to fuse hydrogen. Generally defined as objects with masses of 13 to ~80 Jupiter masses.

- Since they cannot fuse hydrogen, they cool off over time (like Jupiter). But massive brown dwarfs cool slowly and can still have surface temperatures >1000 K even after many billions of years

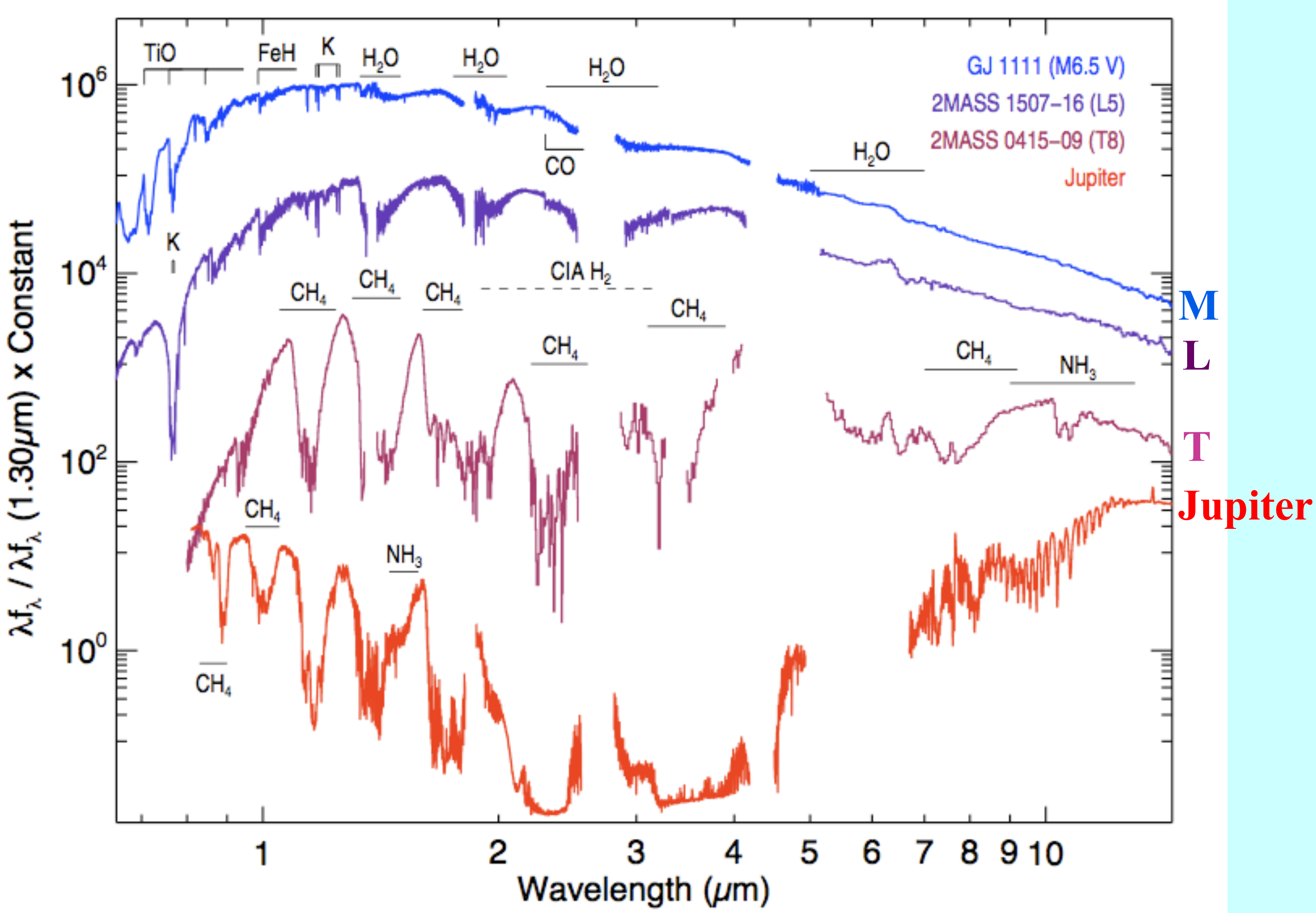
- Over a wide mass range (~0.3 to ~80 Jupiter masses), brown dwarfs and giant planets have radii very close to Jupiter's.

- >1000 brown dwarfs have been discovered, mostly with high temperature (>700 K) but now including objects as cool as ~300 K.


Evolution tracks: luminosity versus time

Burrows et al. (2001)

Typical brown dwarf infrared spectra

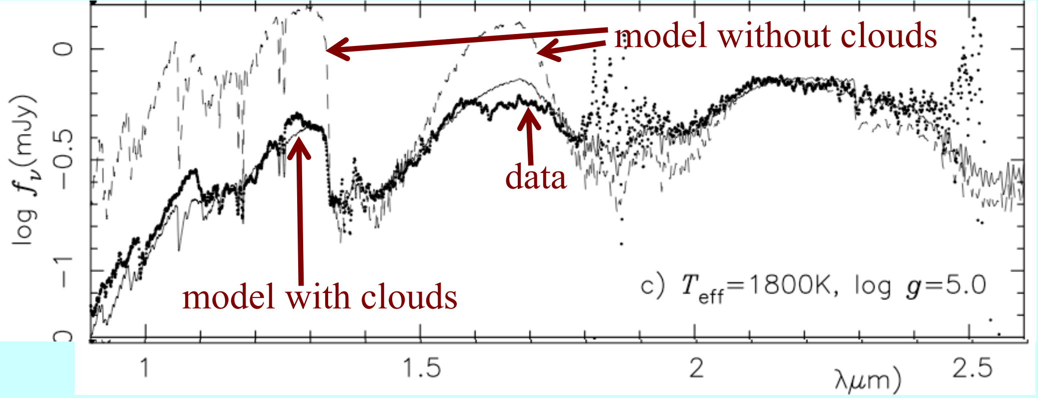


Burgasser (2009, "The brown-dwarf exoplanet connection")

Brown dwarfs are classified according to their IR spectra into M, L, T, and Y (from hot to cold). Unlike most stars, their spectra are dominated by molecular features. Dust (i.e., silicate clouds) affects the spectrum of M and L dwarfs, but not T dwarfs.

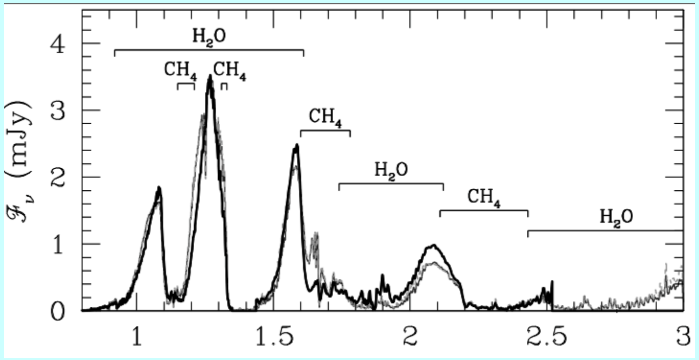
Brown dwarfs show evidence for condensate (dust) clouds

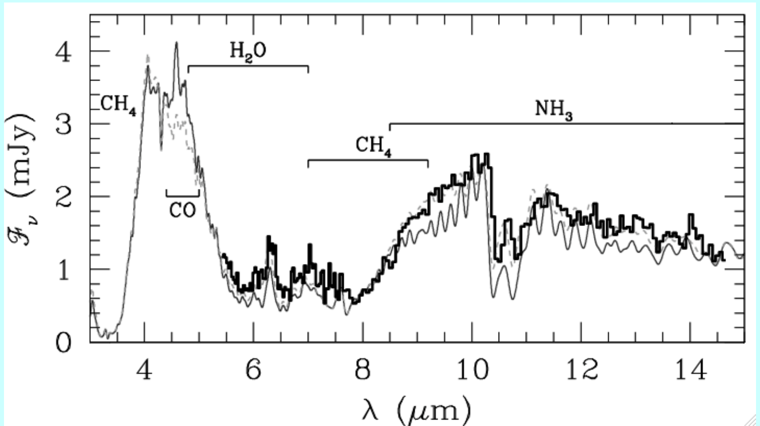
L dwarfs are cloudy, leading to flat spectral features:



Tsuji et al. (2004)

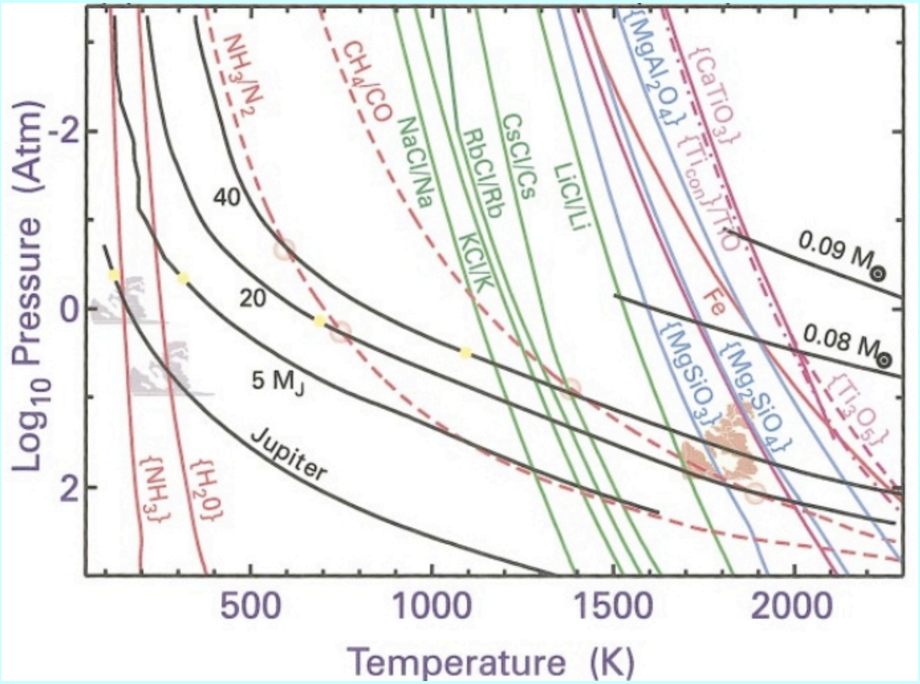
T dwarfs are generally cloud free:





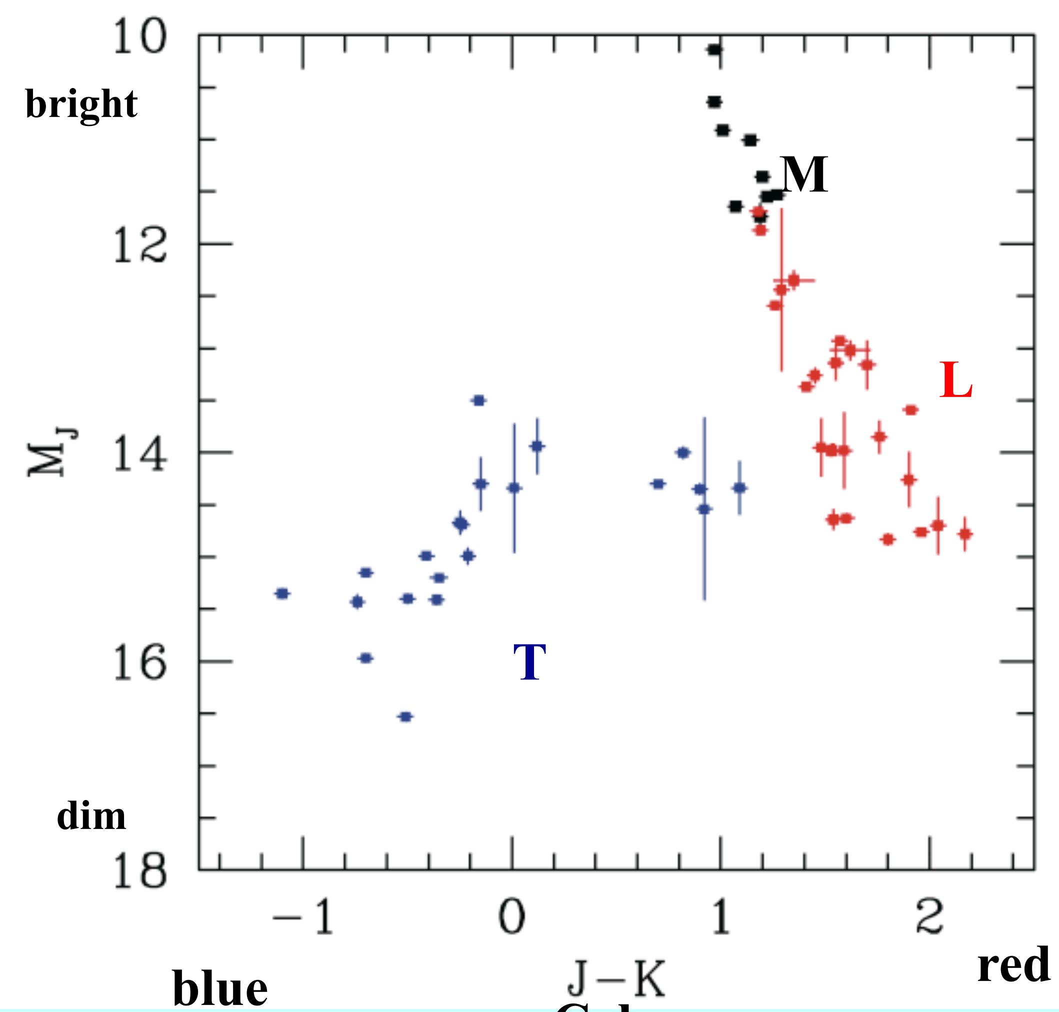
Saumon et al. (2006)

This behavior is explained by the fact that condensate levels lie in the atmosphere for hot objects (M, L dwarfs) but sink into the interior for cool objects (T dwarfs):



Burrows et al. (2001)

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



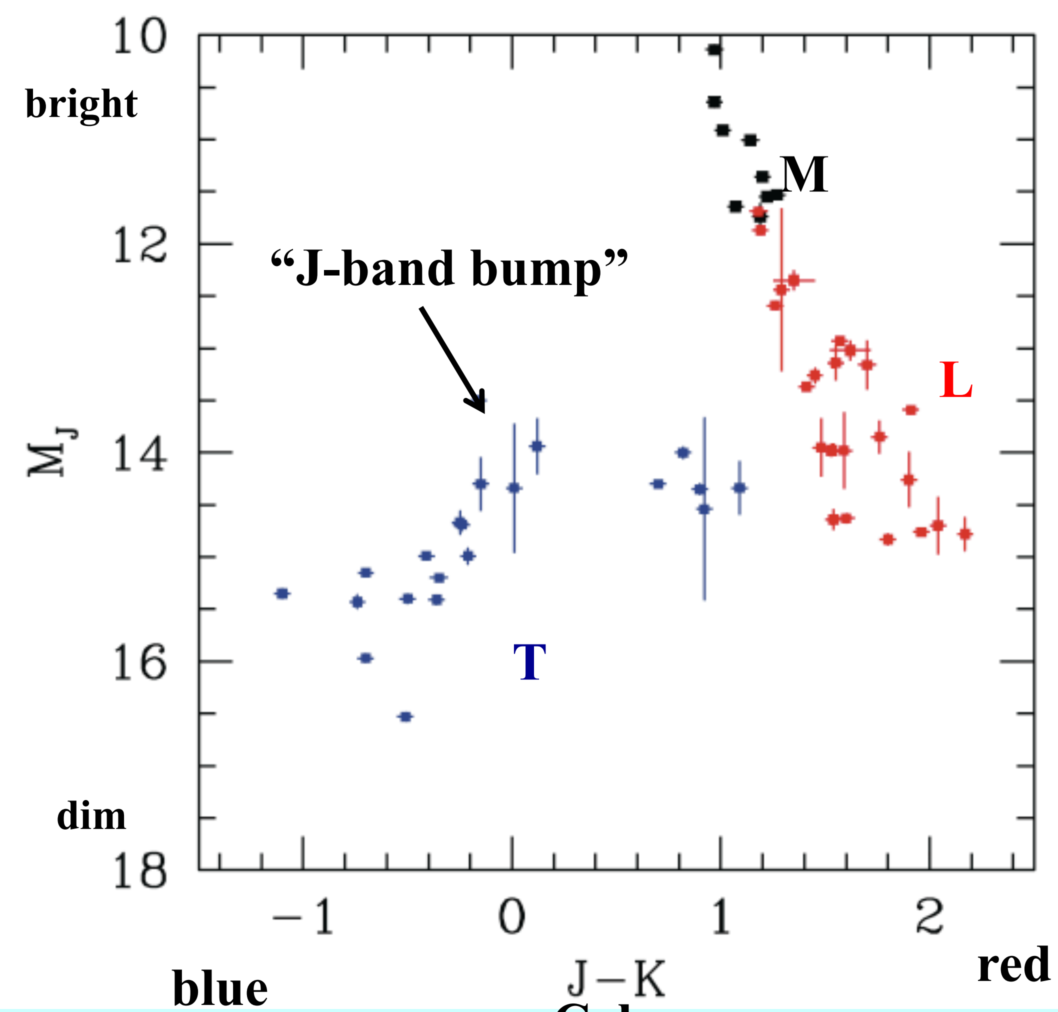
Magnitude (brightness) in J band, which is a spectral window

Color

Saumon & Marley (2008)

The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



Magnitude (brightness) in J band, which is a spectral window

Color

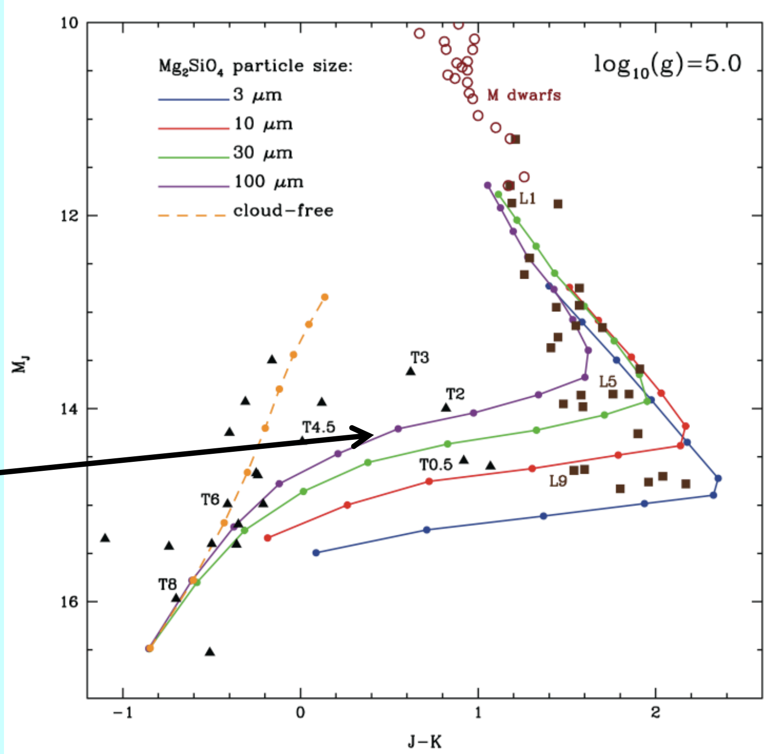
Saumon & Marley (2008)

The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.

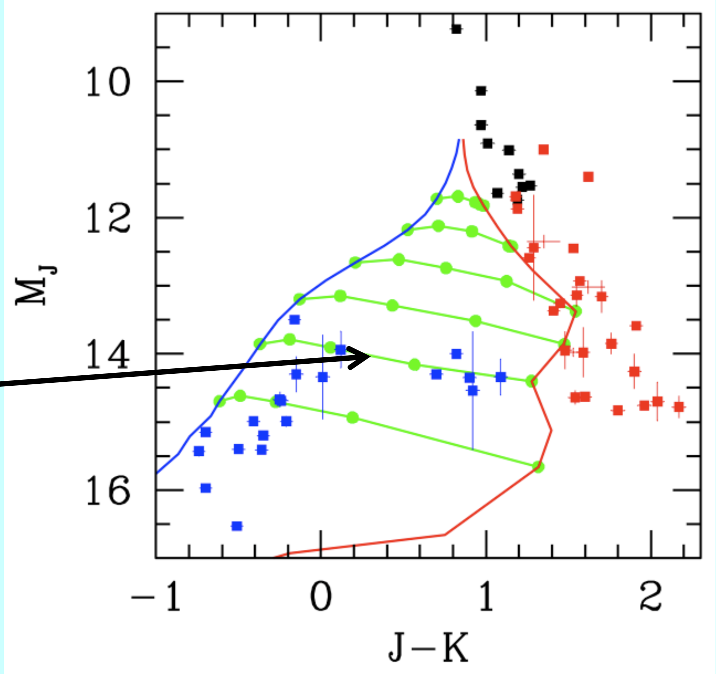
The L/T transition

- Although the loss of clouds across the L/T transition makes sense, the details are a puzzle: the transition occurs too fast.
  - 1D models of uniform cloud decks sinking into the interior predict that the J-band flux continually dims across the transition:
  - But in reality the J-band flux actually *increases* temporarily across the transition (the "J-band bump"), despite the fact that T dwarfs are cooler than L dwarfs
  - This suggests that the cloud decks are not simply disappearing from view, but becoming patchy or getting thin as they do so
- 1D models that assume the cloud deck gets patchy across the transition do a much better job of reproducing the "J-band bump"

This suggests a strong role for meteorology in controlling the transition



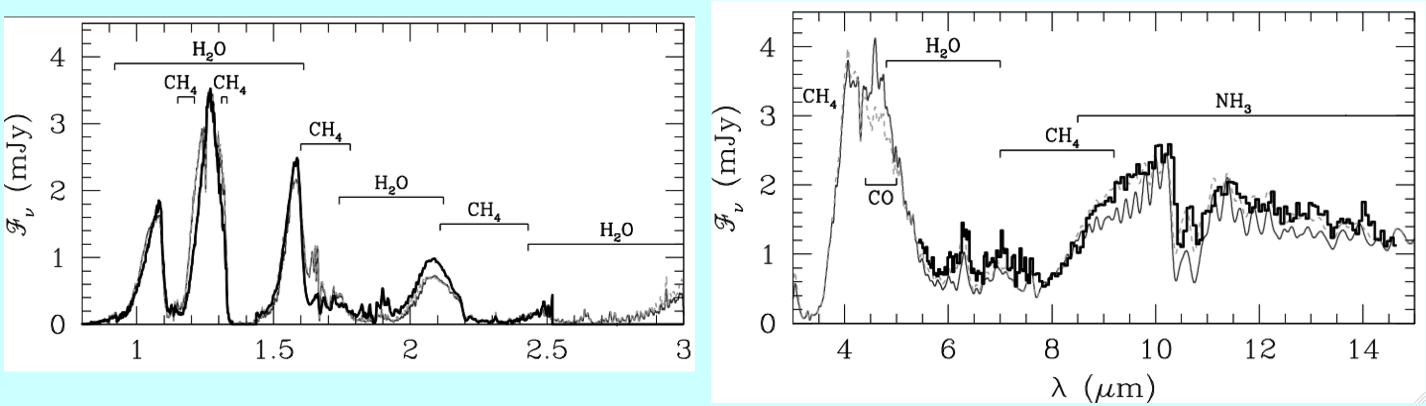
Burrows et al. (2006)



Marley et al. (2010)

Chemical disequilibrium

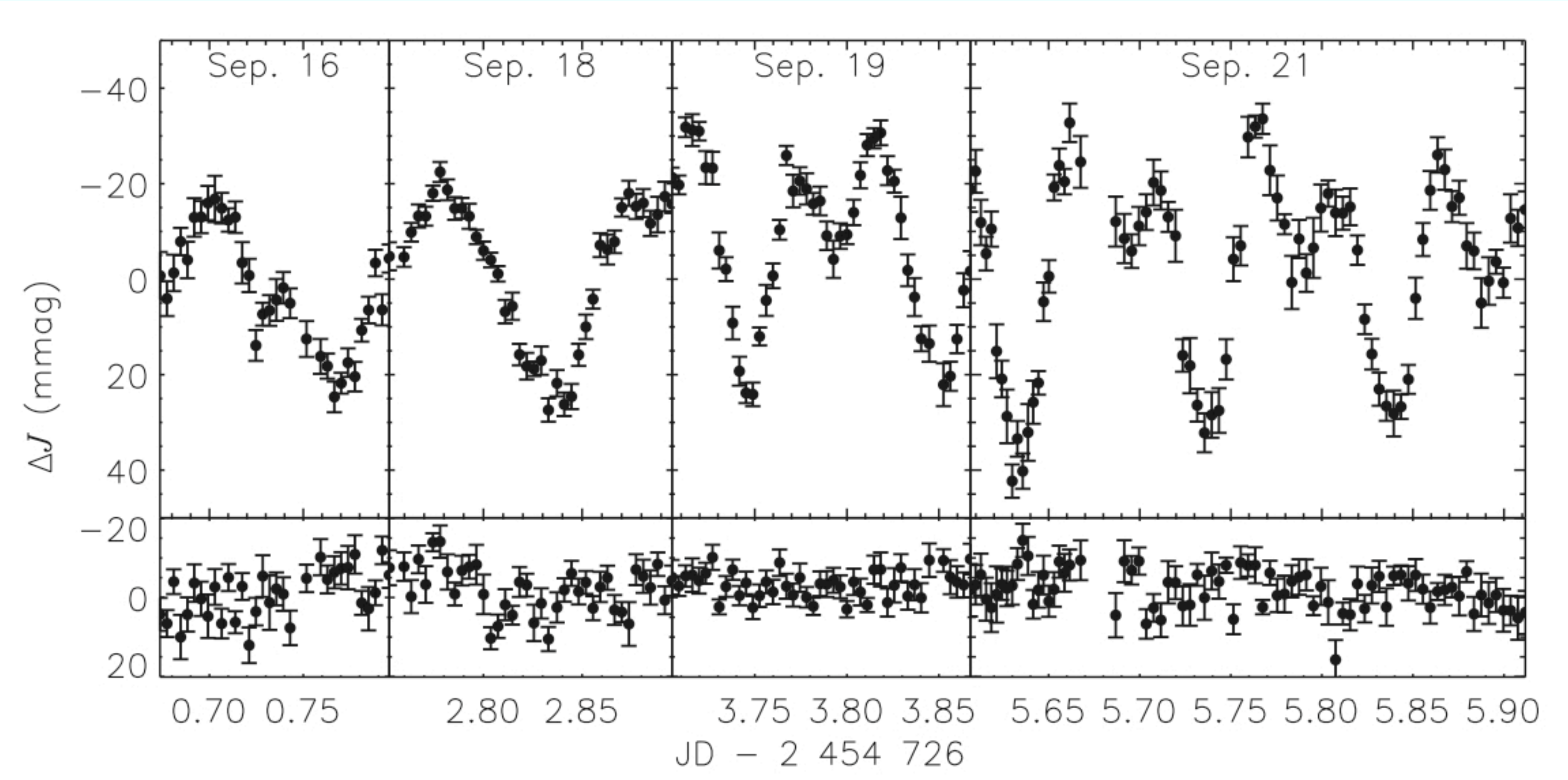
- In cool giant planets and brown dwarfs, the equilibrium form of carbon and nitrogen at the top are CH_4 and NH_3. The equilibrium form at depth are CO and N_2.
- In the absence of dynamics, equilibrium would prevail. But vertical mixing can dredge CO-rich, CH_4-poor, and NH_3-poor air from depth and mix it into the atmosphere.
- This will result in an excess of CO, and a deficit of CH4 and NH3, in the atmosphere
- Just such excesses and deficits are observed, and are interpreted as the result of vertical mixing. The observed abundances can be used to constrain the mixing rates



Saumon et al. (2006)

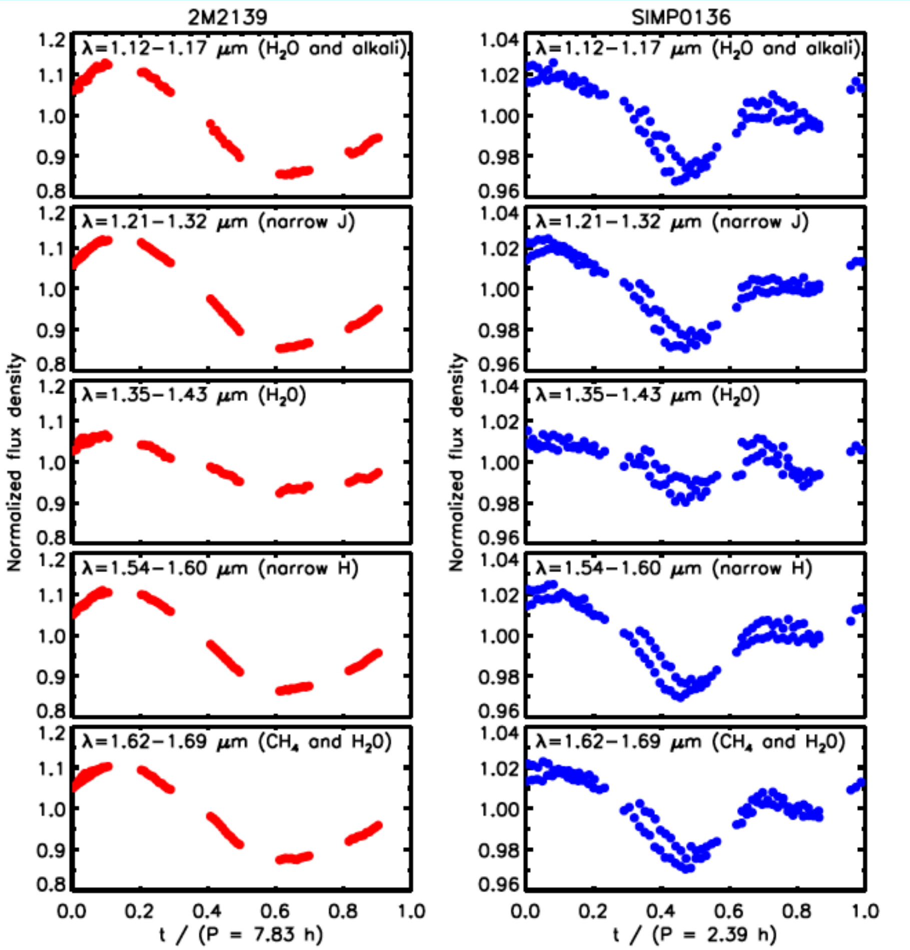
Thus, dynamics is required to explain the chemical disequilibrium

T2.5 brown dwarf SIMP 0136 shows weather variability

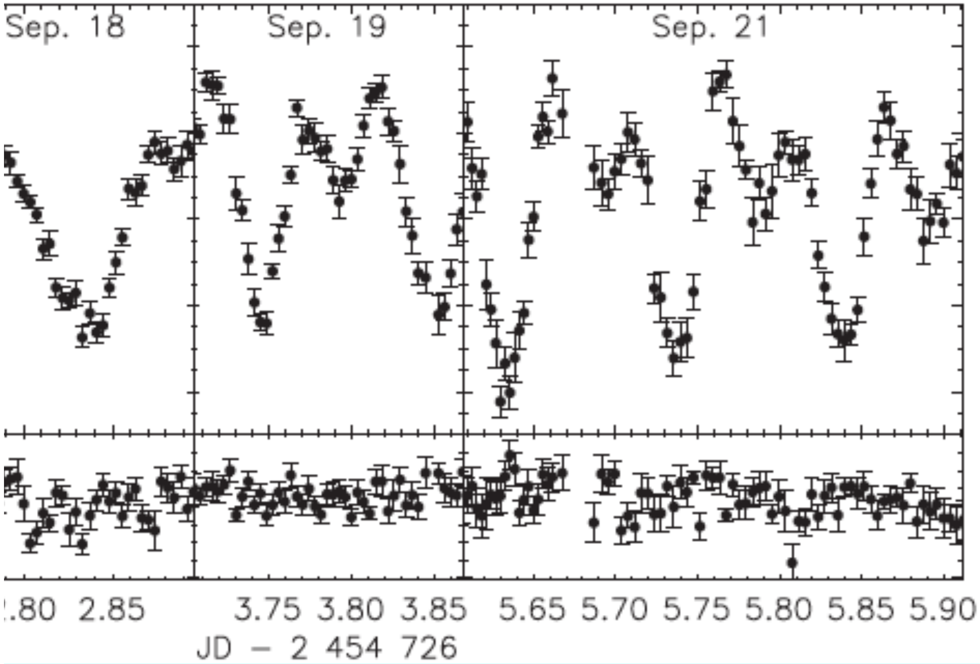


Artigau et al. (2009); see also Radigan et al. (2012), Buenzli et al. (2012), and many upcoming papers by Apai, Metchev, Radigan, Flateau, ….

Light Curves

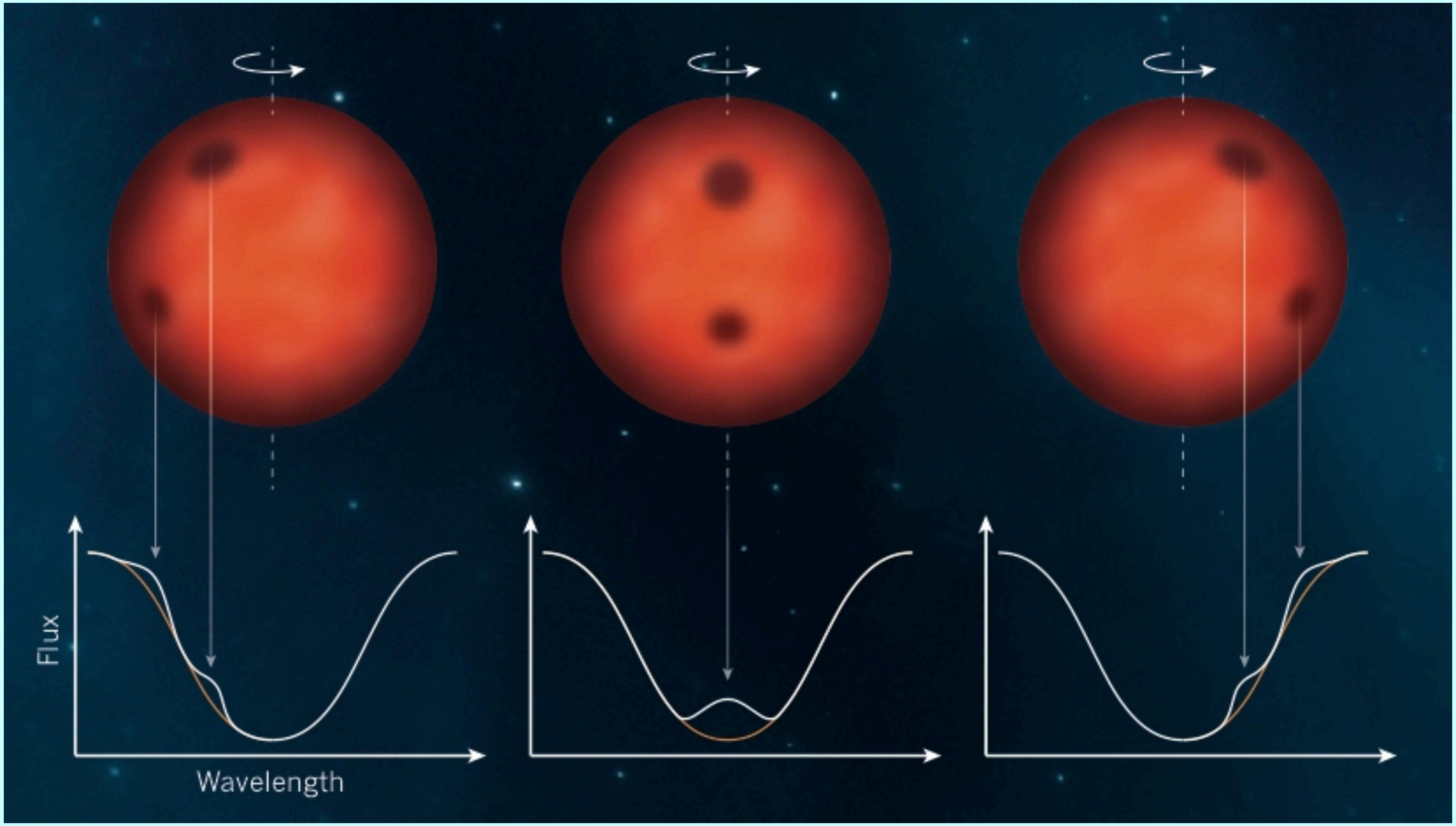


Apai et al. (2013)



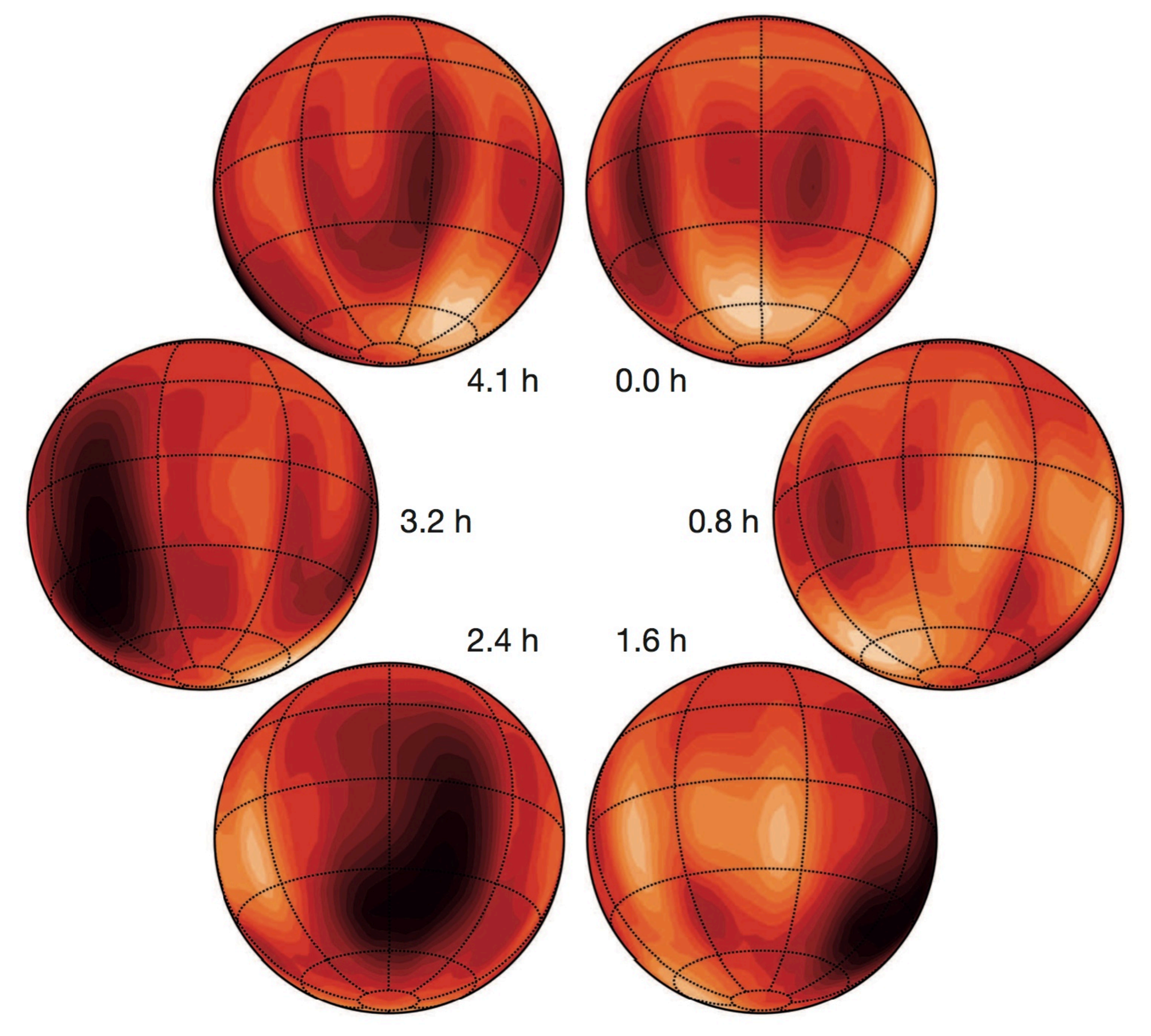
Artigau et al. (2009)

Doppler imaging technique: a method to map the surface patchiness of brown dwarfs



Showman (2014); see also Rice (2002)

Maps of Luhman 16B, the closest known brown dwarf to Earth



Crossfield et al. (2014, *Nature*), see also Showman (2014, *Nature*)

Summary of evidence for dynamics/weather on brown dwarfs

1) **Existence of clouds is required to explain spectra of many brown dwarfs.**

2) **Explaining the L/T transition requires change in cloud dynamics/physics, e.g., opening of holes in the clouds, as objects cool off over time.**

3) **Disequilibrium chemistry (quenching of CO, CH_4, NH_3) implies mixing from below, and allows mixing rate to be inferred if chemical kinetics are understood.**

4) **IR variability implies cloudy and cloud-free patches rotating in and out of view. Shape of lightcurves vary over time, implying that the *spatial pattern* of cloud patchiness evolves rapidly.**

5) **Doppler imaging allows global maps of surface patchiness to be inferred for the brightest brown dwarfs.**

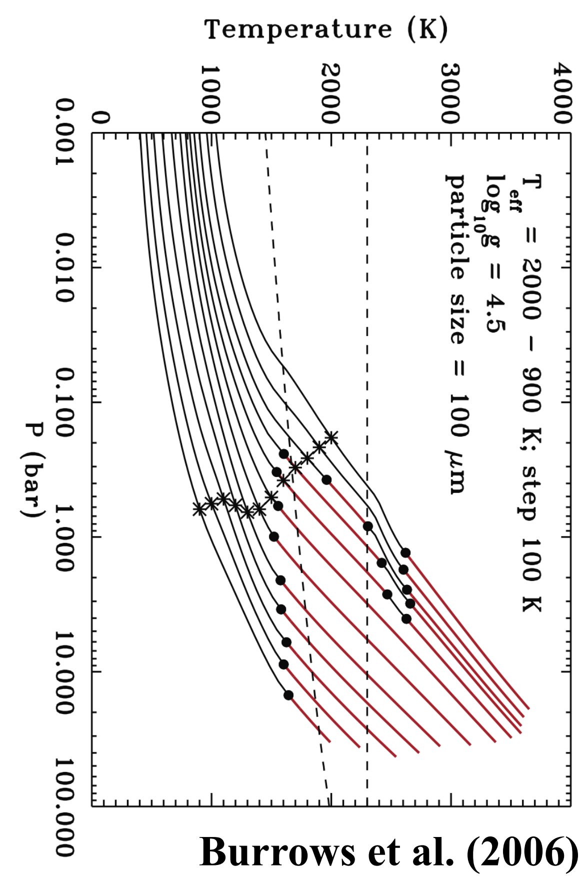
Dynamical Regime of brown dwarfs

- Rapid rotation (Period ~ 1.5-12 hours) implies rotational domination (Rossby numbers << 1)

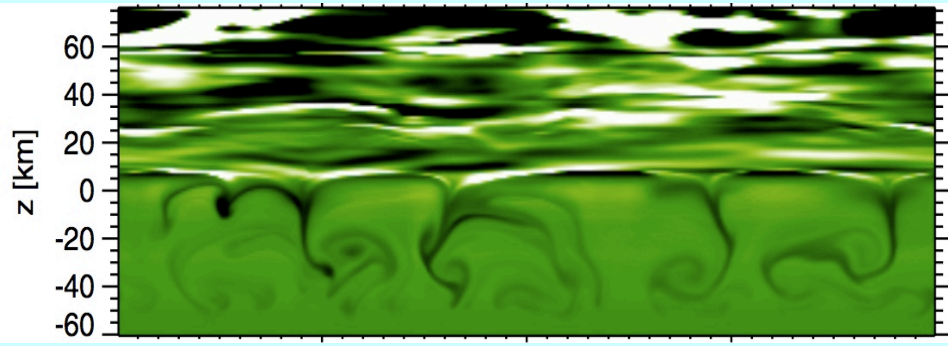
- Stably stratified atmosphere overlies vigorously convecting interior

- No external irradiation ⟹ no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)

- Wave generation will play a key role. Atmospheres may be mechanically driven, like stratospheres of Earth and Jupiter



Burrows et al. (2006)



Freytag et al. (2010)

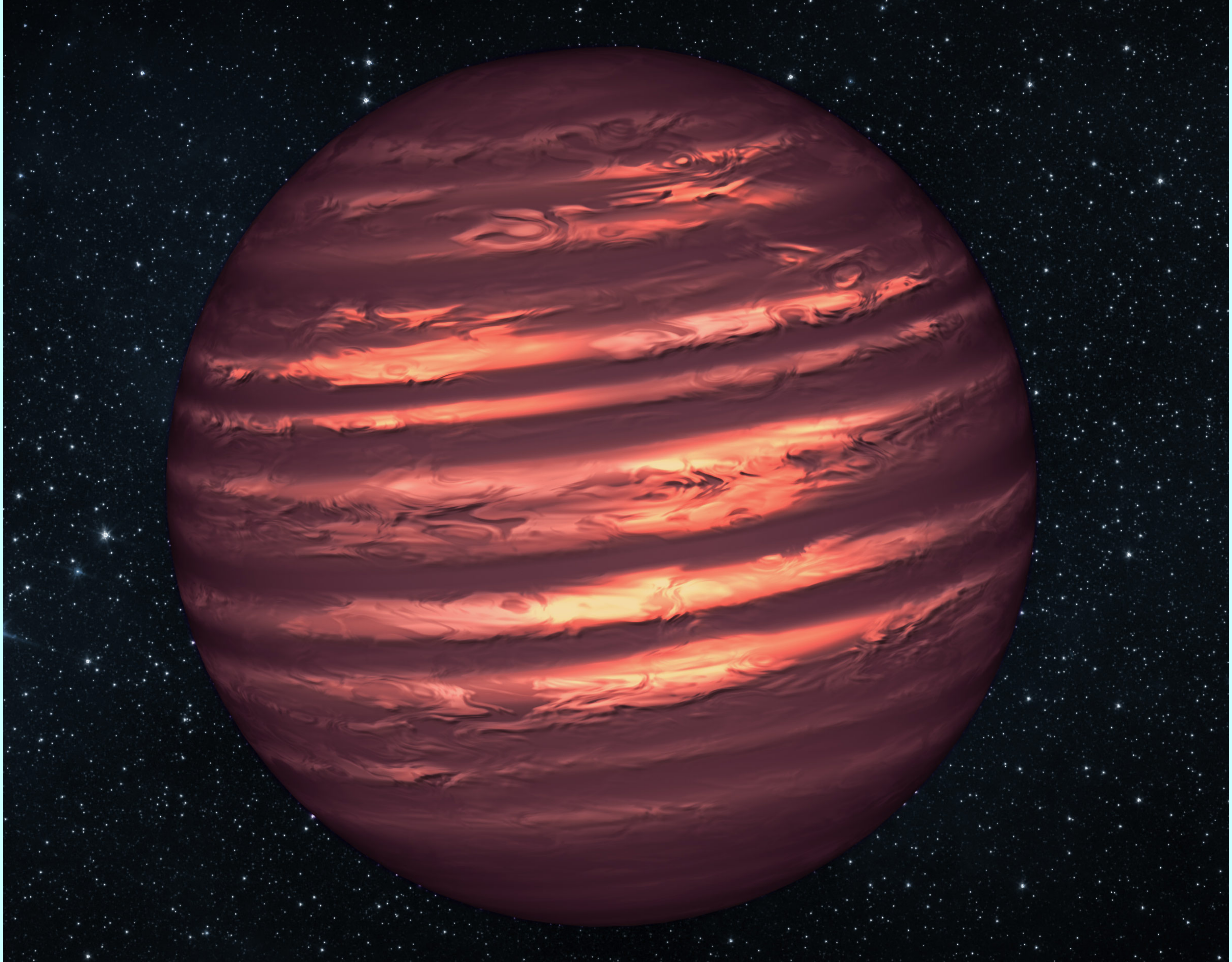
Some questions

- What is the atmospheric circulation like on brown dwarfs? Are there zonal jets? Large vortices? Fluctuating turbulence? What are the wind speeds, temperature fluctuations, and key length scales?

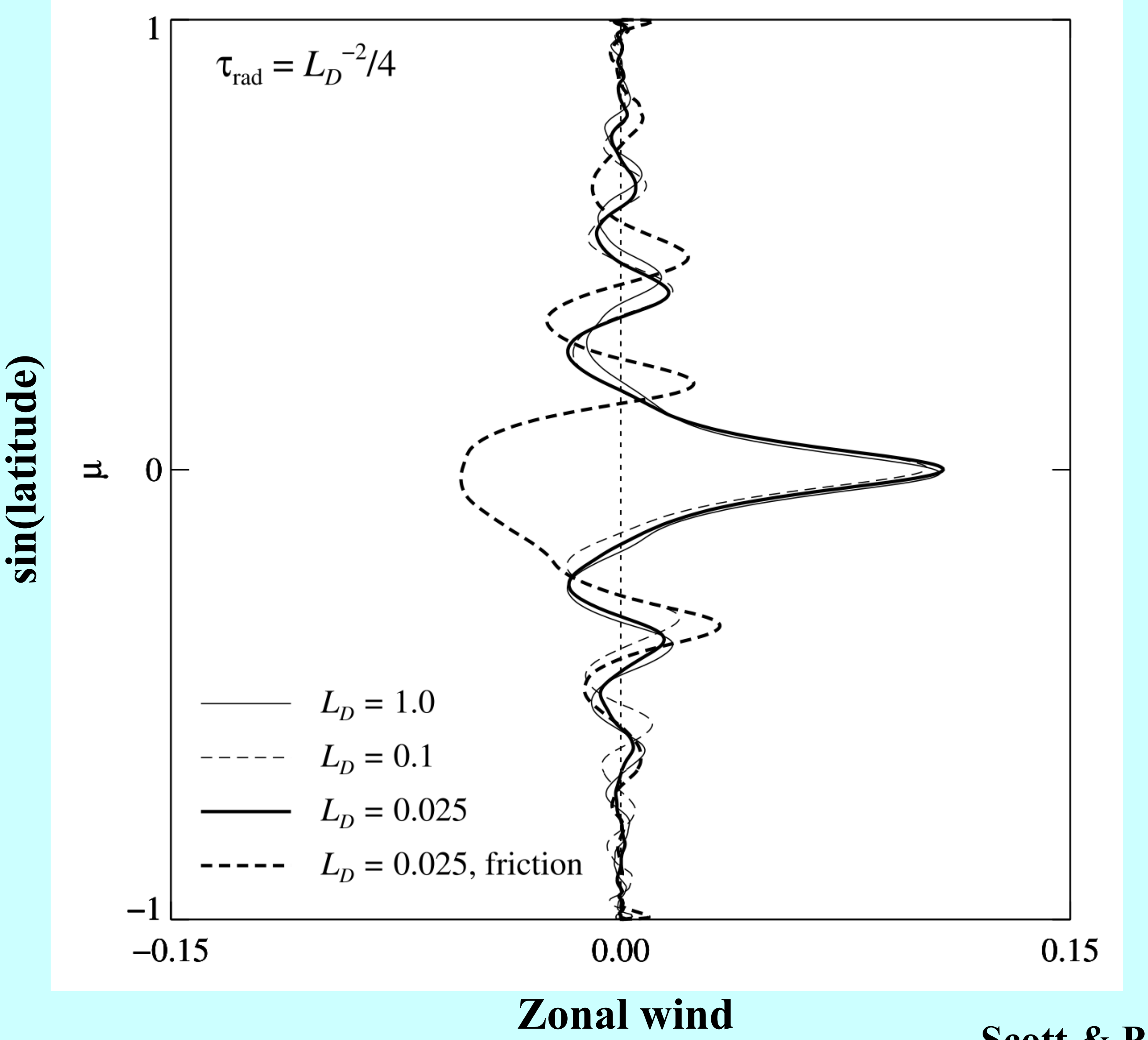
- How does the circulation work? What types of waves are generated by the convection, and by what mechanisms might they drive a circulation? How coupled is the atmosphere to the interior?

- What are the vertical mixing rates? To what extent is the mixing dominated by breaking gravity waves rather than large-scale overturning?

- How do clouds couple to the circulation? How patchy are the cloud layers?

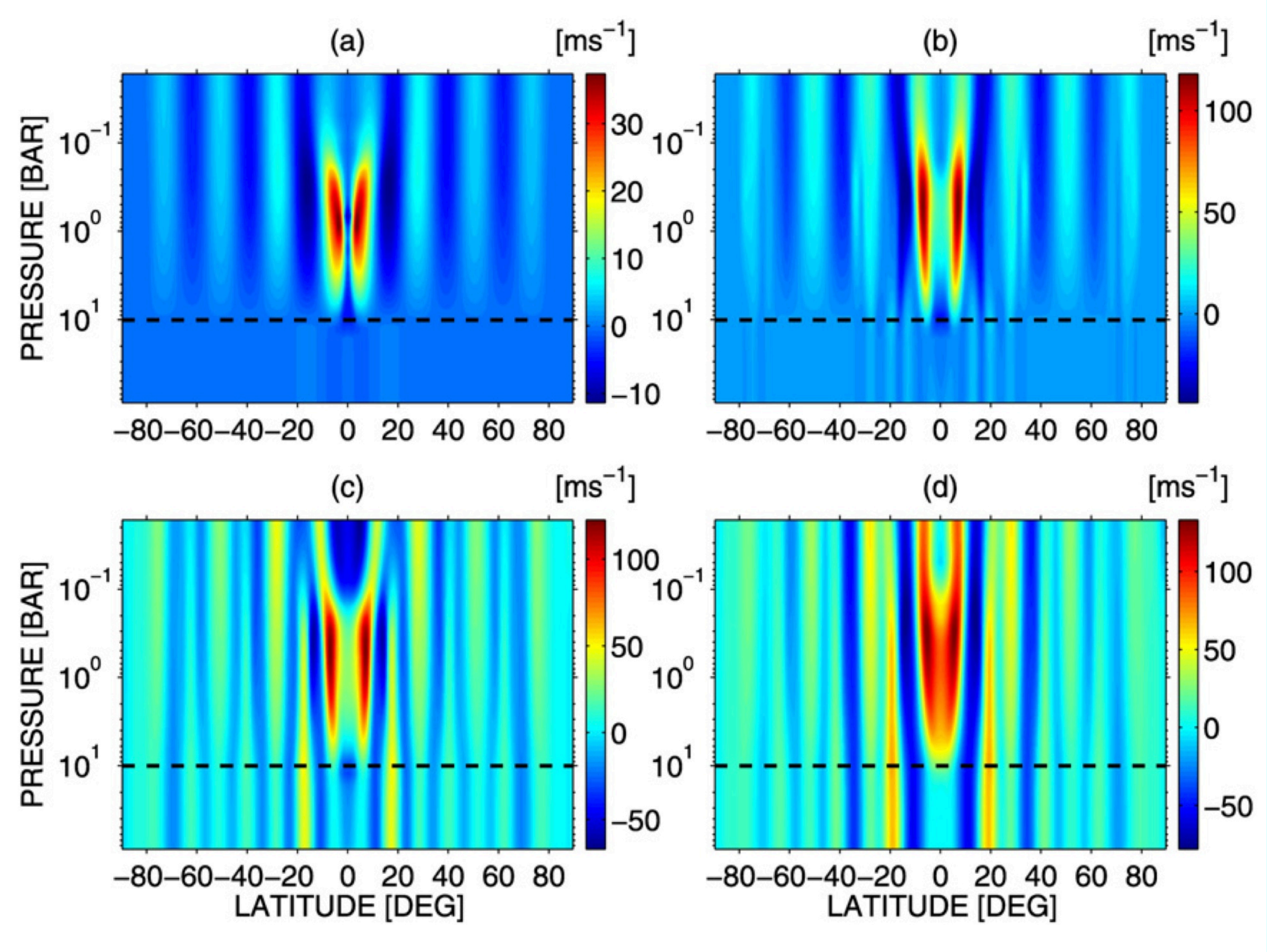


Superrotation in shallow-water models

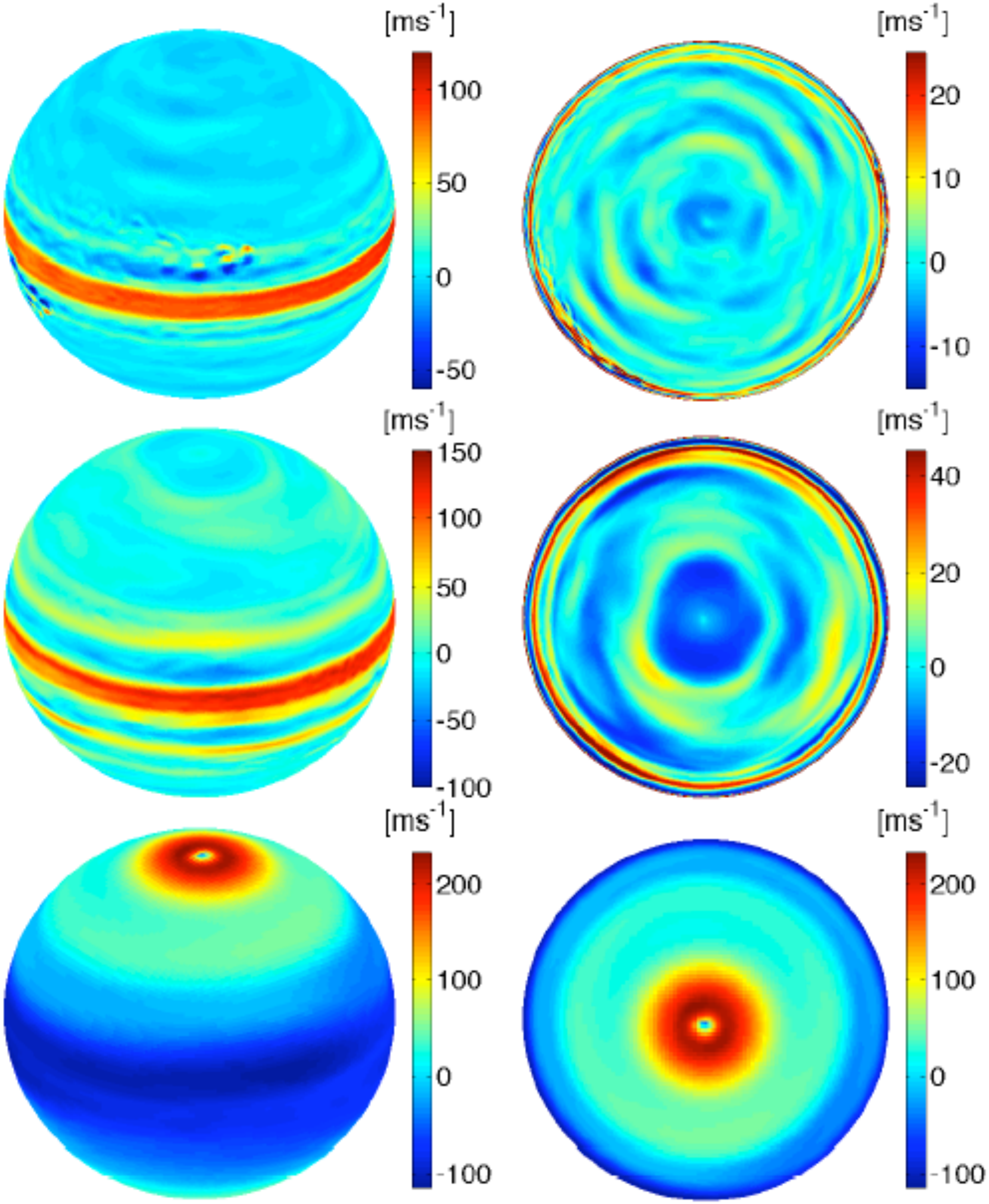


Scott & Polvani (2008)

3D atmosphere models show that multiple jets can occur, and that deep jets can arise from shallow forcing



Lian & Showman (2008)



Jupiter

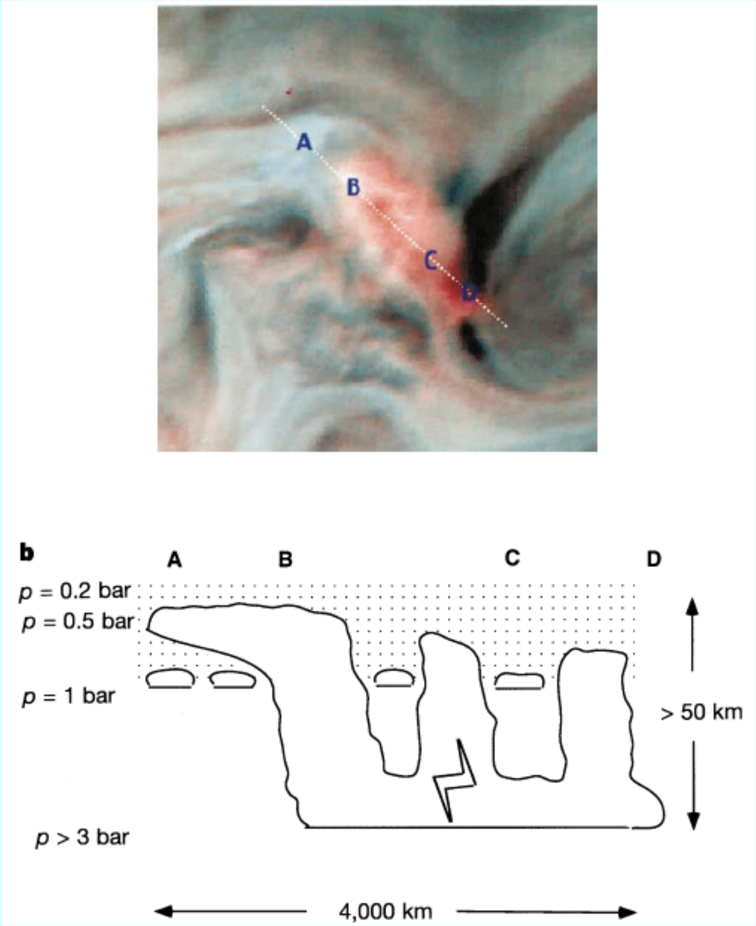
Saturn

Uranus/Neptune

Lian & Showman (2010)

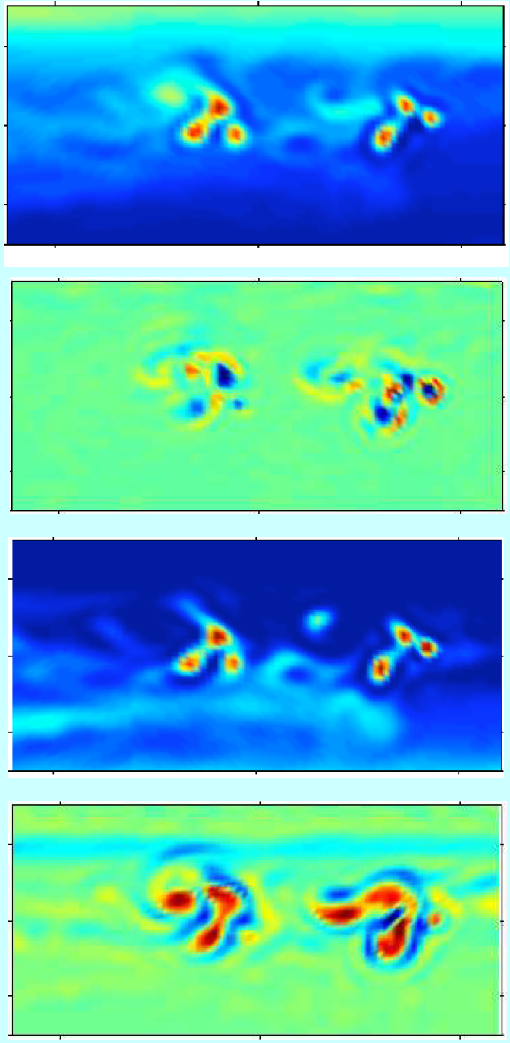
Storms

Observations (Galileo orbiter)



Gierasch et al. (2000)

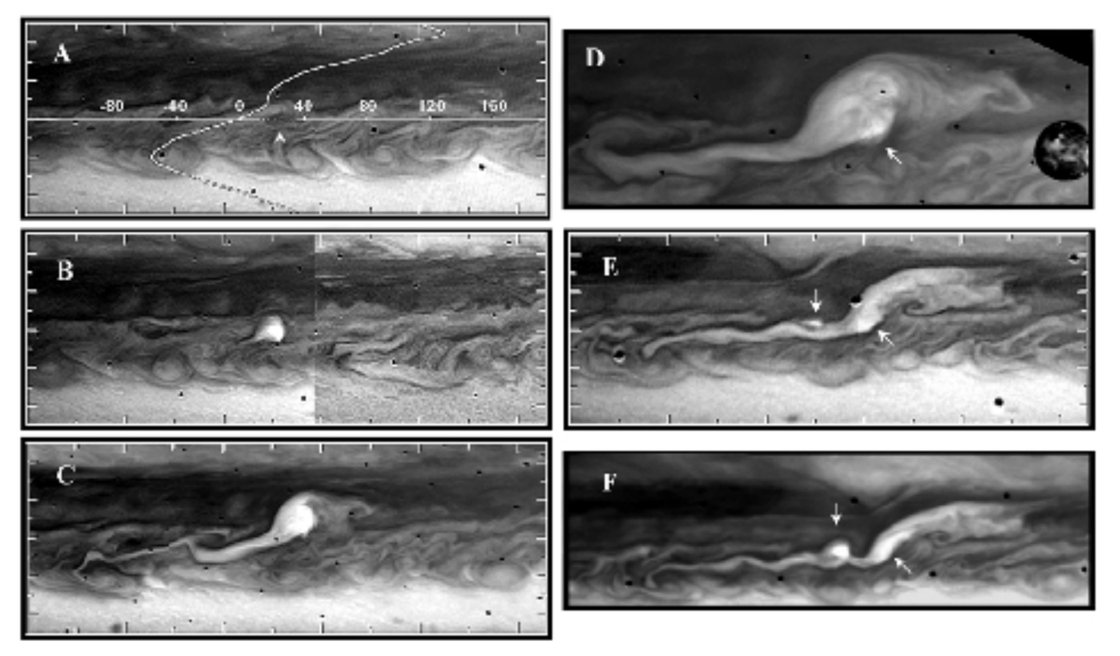
Global GCM with hydrological cycle



Lian & Showman (2010)

U3d_jup_1bar

Lian & Showman (2010)


A
-80
-40
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40
80
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B
C
D
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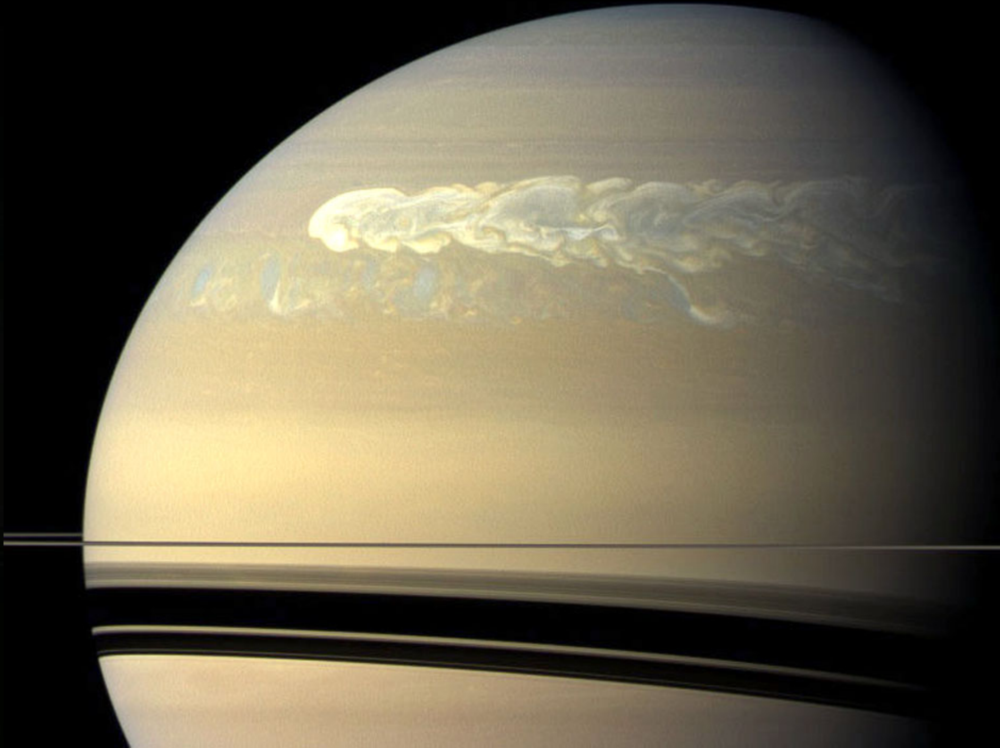
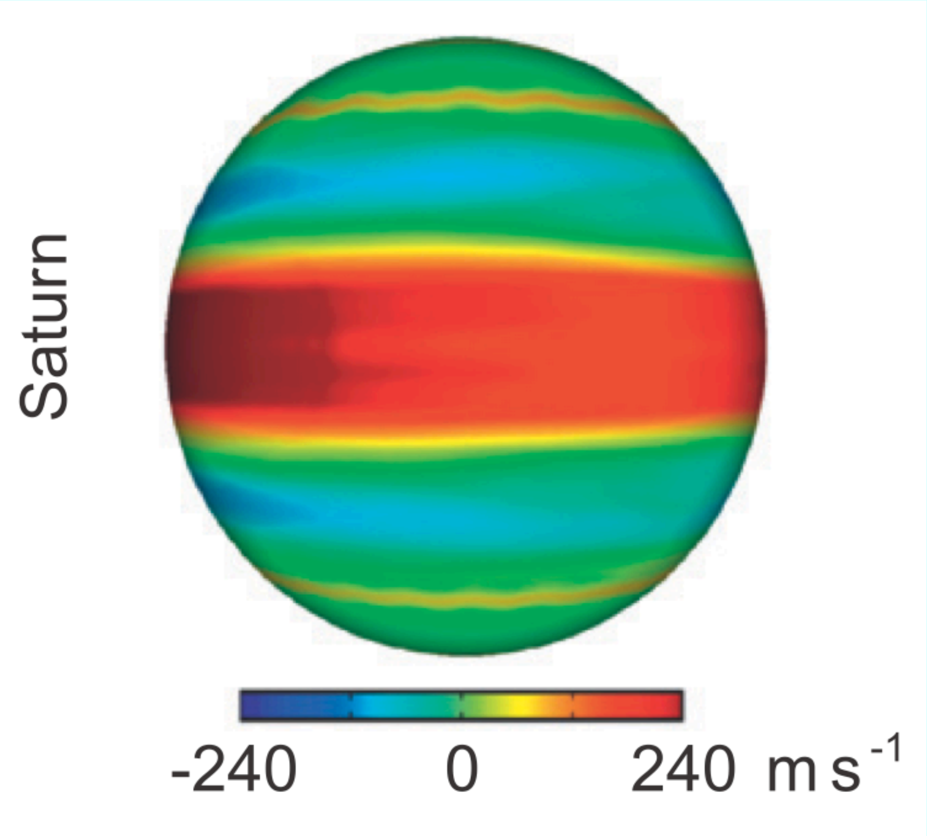
F

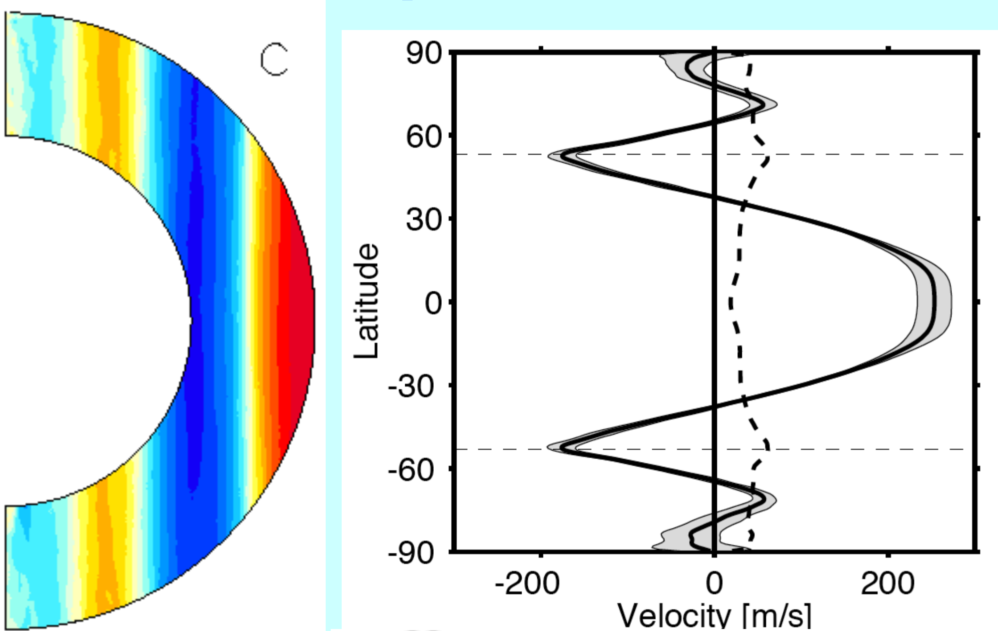


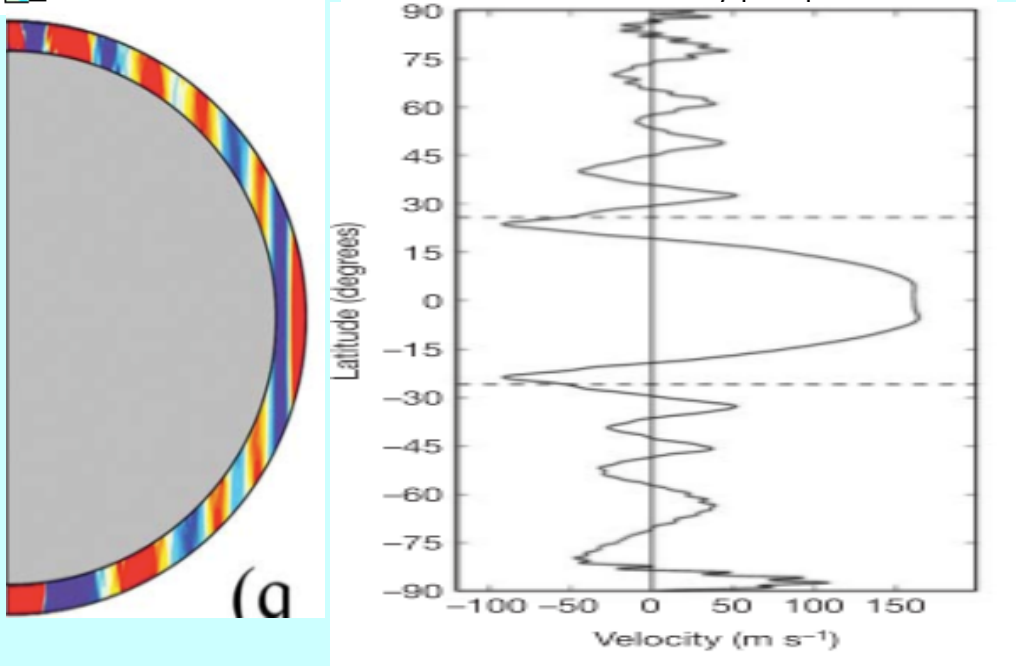


Liu & Schneider (2010)

Superrotation in these 3D atmospheric models seems to occur because convective divergence is greater at low latitudes, leading to preferential generation of Rossby waves at low latitudes, which propagate poleward and therefore transport angular momentum to the equator.

Deep convection models





Boussinesq models

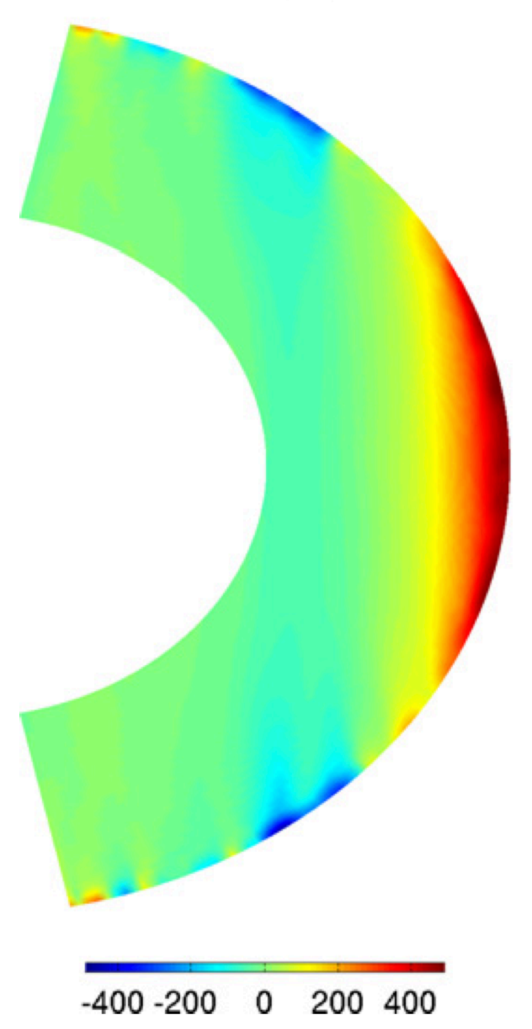
Thick shell

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

Thin shell

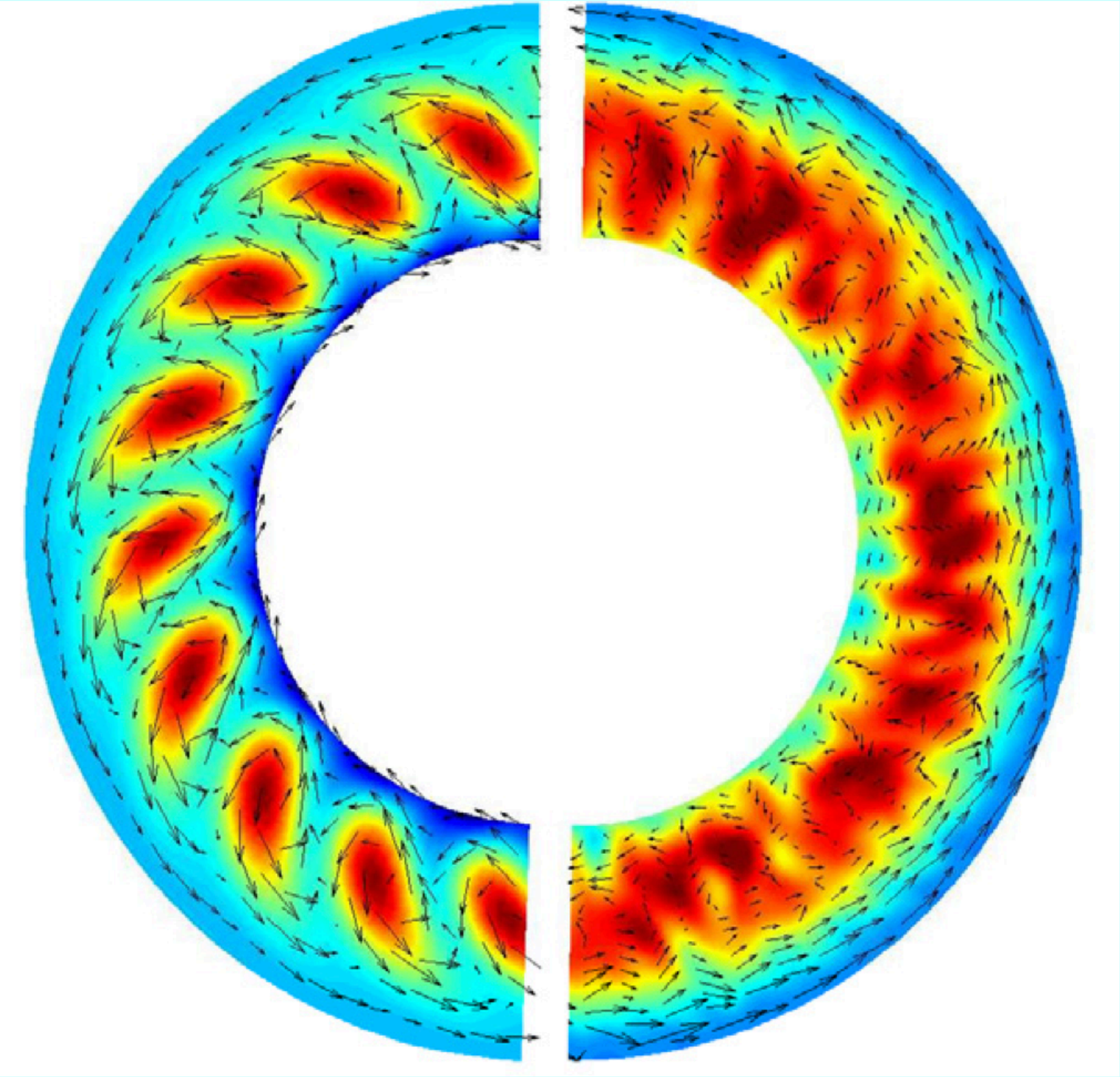
(Heimpel et al. 2005;
Heimpel & Aurnou 2007;
Aurnou et al. 2008)

Many deep models now include the radial density gradient



Kaspi et al. (2009);
Jones & Kuzanyan (2009);
Showman et al. (2011);
Gastine & Wicht (2012);
Gastine et al. (2013);
Radav et al. (2013)

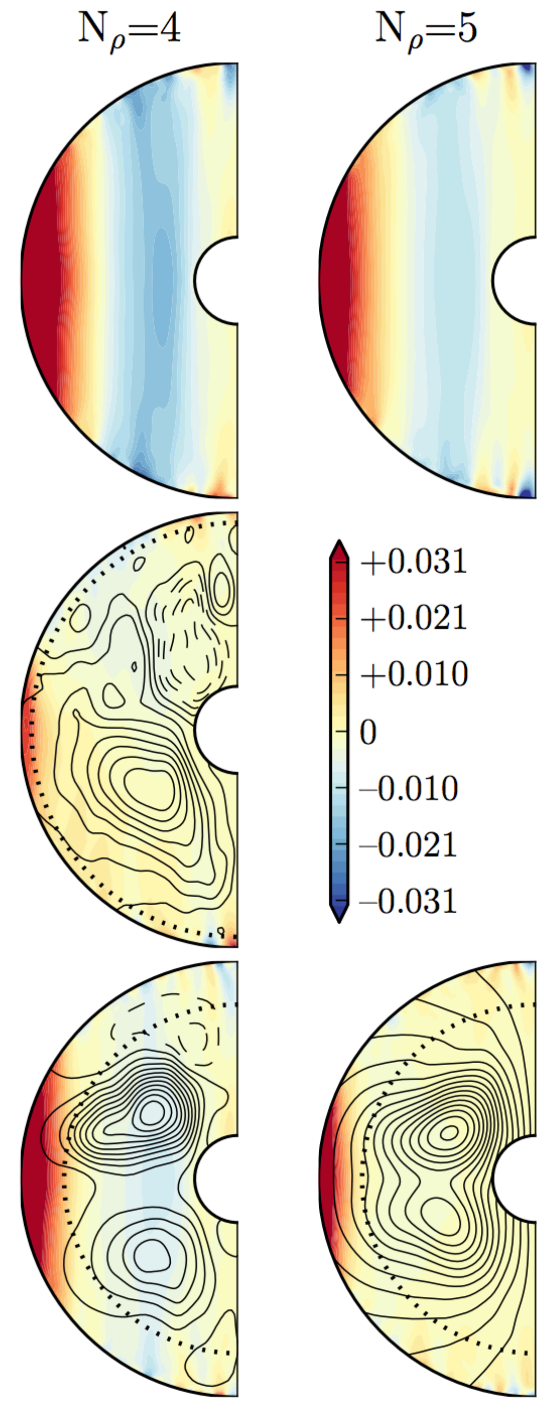
Superrotation in convection models results from correlations between zonal and (cylindrically) outward velocity components



Showman et al. (2011)

Models including radial gradient in electrical conductivity

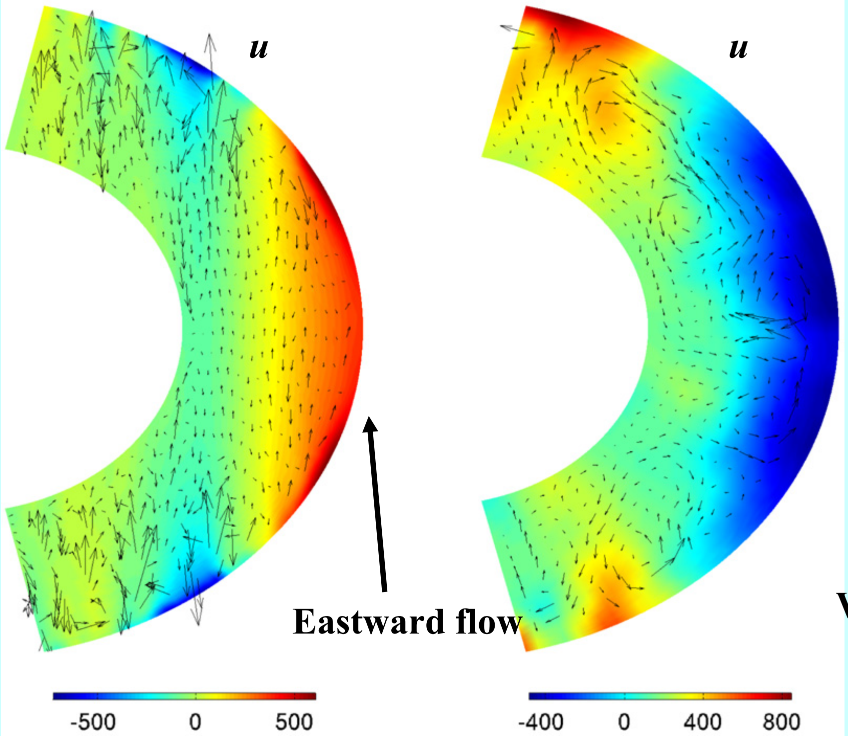
High-latitude jets are largely suppressed, but the equatorial jet still occurs



Duarte et al. (2013)

Deep convection models

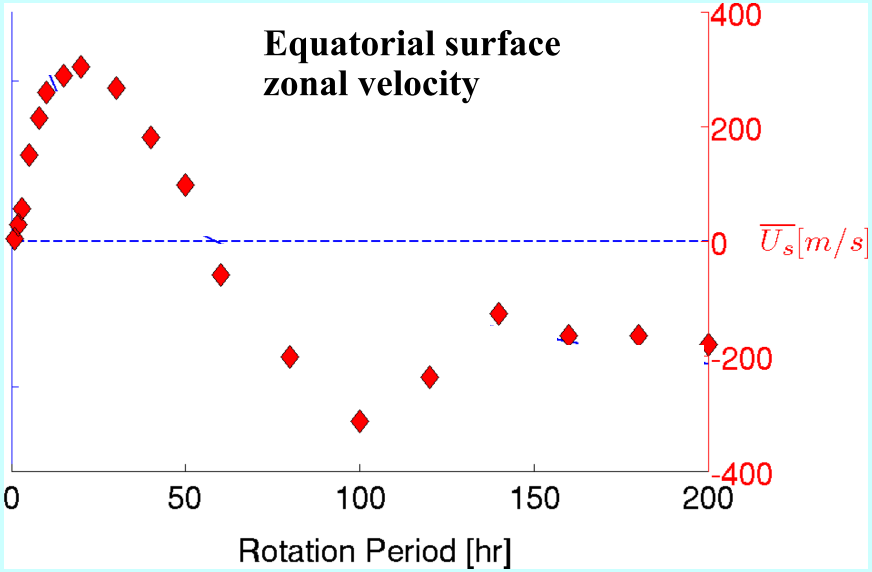
10 hr rotation period



100 hr rotation period

Eastward flow

Westward flow

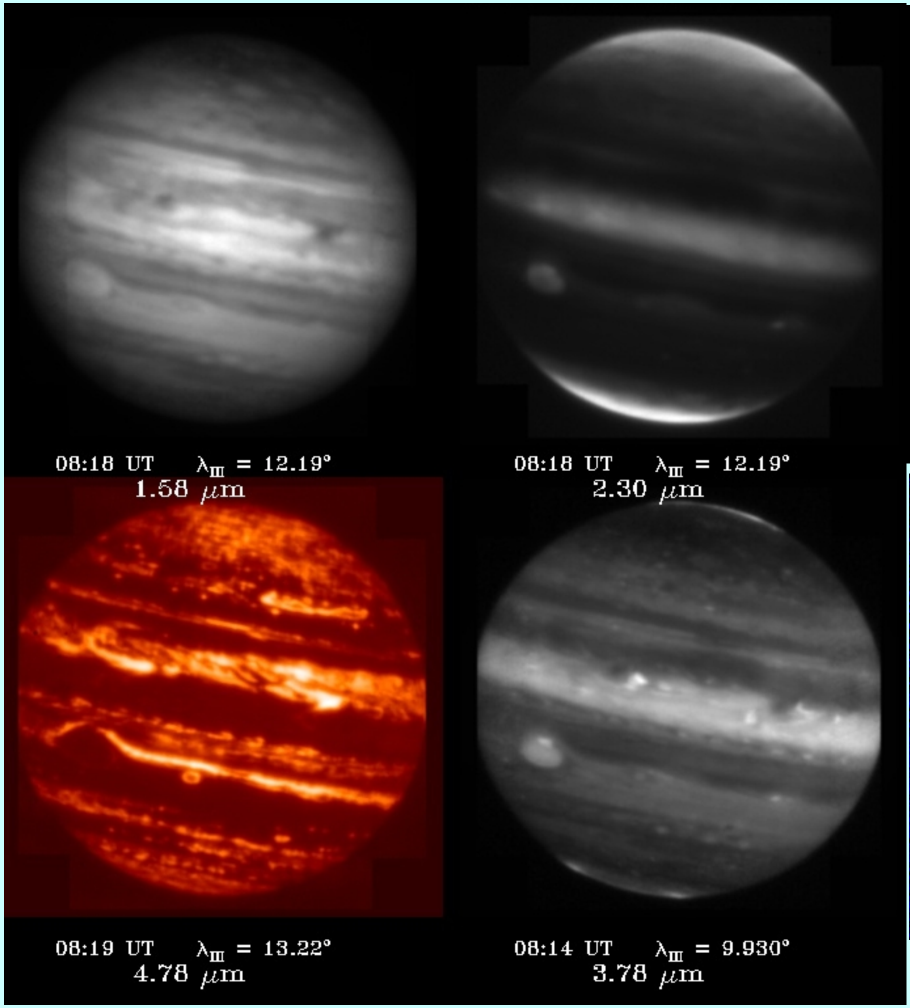


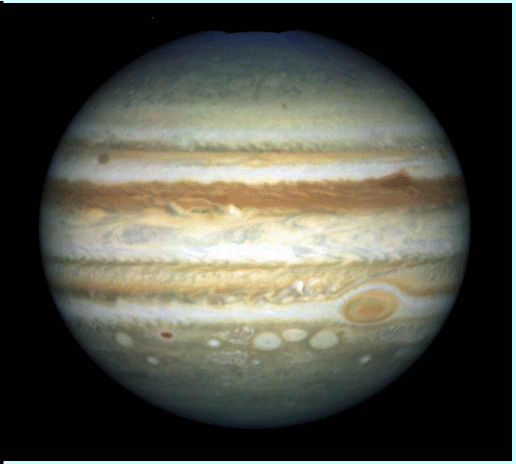
Equatorial surface zonal velocity

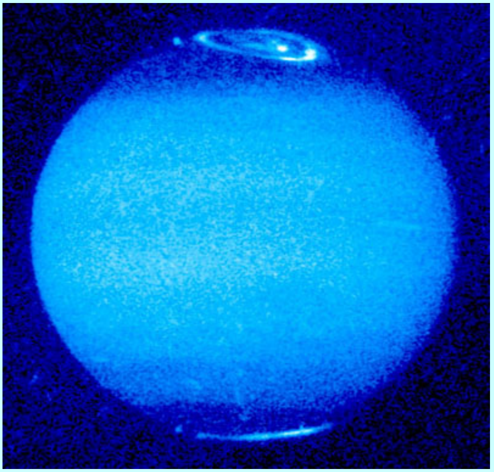
Kaspi, Flierl, & Showman (2009)

see also Aurnou et al. (2007), Gastine et al. (2013)

Jupiter at many wavelengths

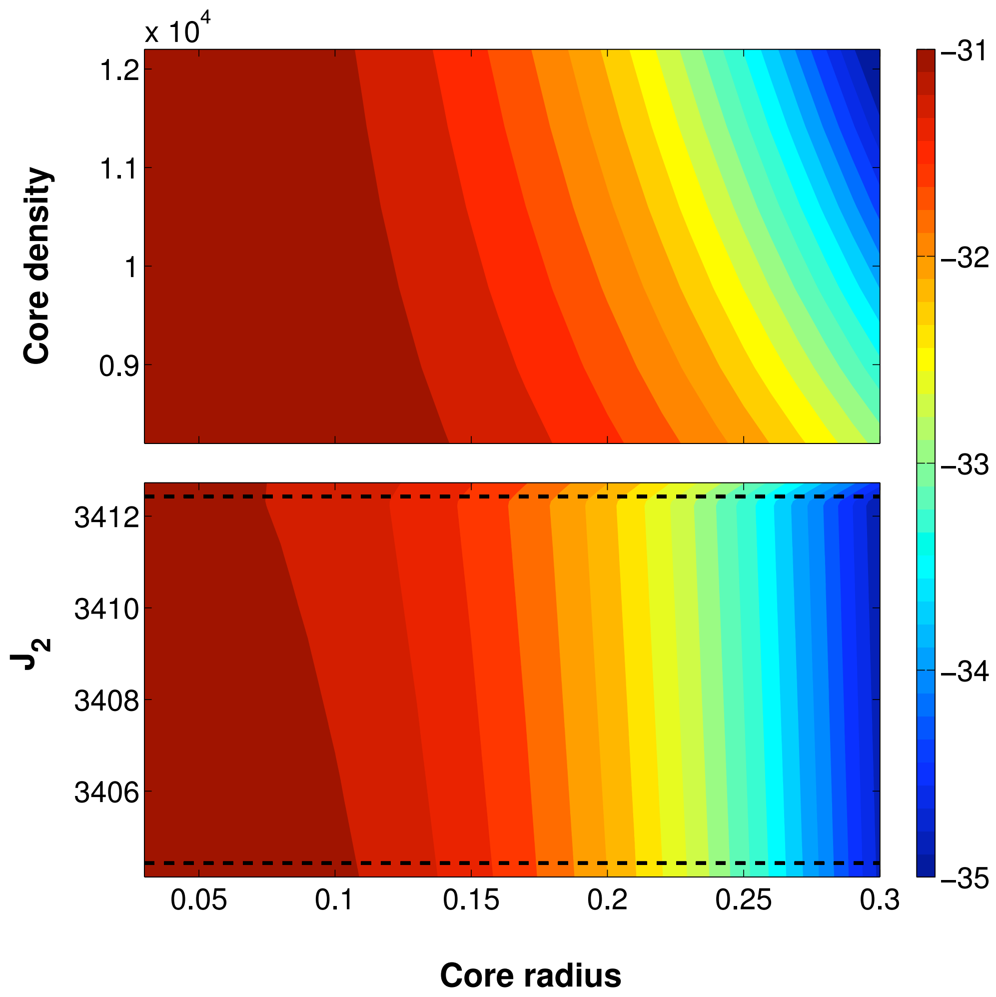




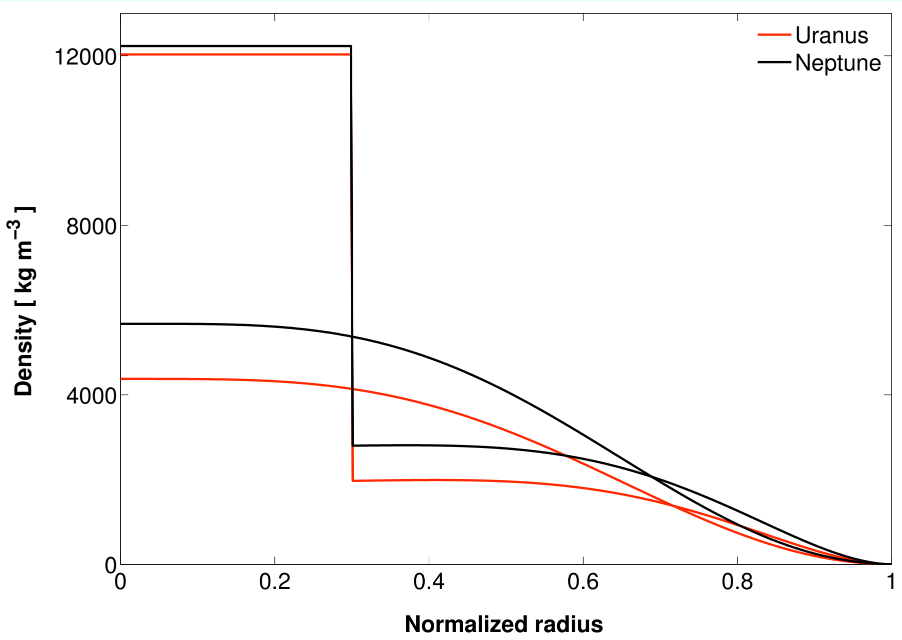


Interior models of Uranus and Neptune

Models constrained to match the mass, radius, atm. density, and J_2 allow this range of J_4 values:



…corresponding to radial density structures like these:



Kaspi, Showman, et al. (2013)

Observed J4 (Neptune): $(-33.4 \pm 2.9)\times 10^{-6}$

Procedure to infer depth of jets from J_4

- **Calculate the full suite of static, wind-free interior models that match all data—mass, radius, J_2, and atmospheric density—but without using J_4 as a constraint.**

- **Determine the J_4 values that these wind-free interior models imply.**

- **If the J_4 calculated for these wind-free models is consistent with observations, then winds are not needed to explain the data (i.e., winds are not strong enough to influence the gravity, implying jets are shallow).**

- **But if the J_4 calculated for these wind-free models differs significantly from the observed J_4, then the discrepancy must be explained by dynamics (which would require that the jets extend deep into the interior).**