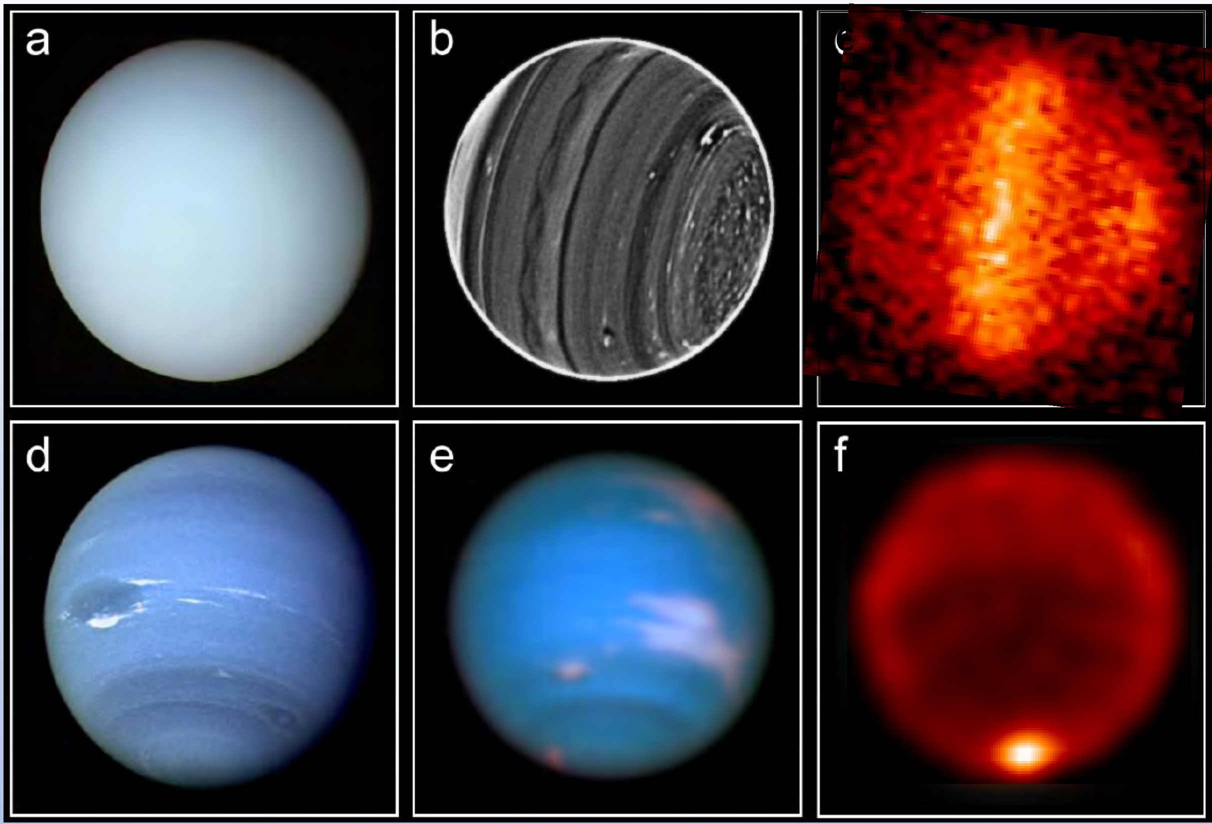
Ice giant atmospheres: clouds and dynamics



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With thanks to

Leigh Fletcher, Michael Roman, Pat Irwin…..

Plan

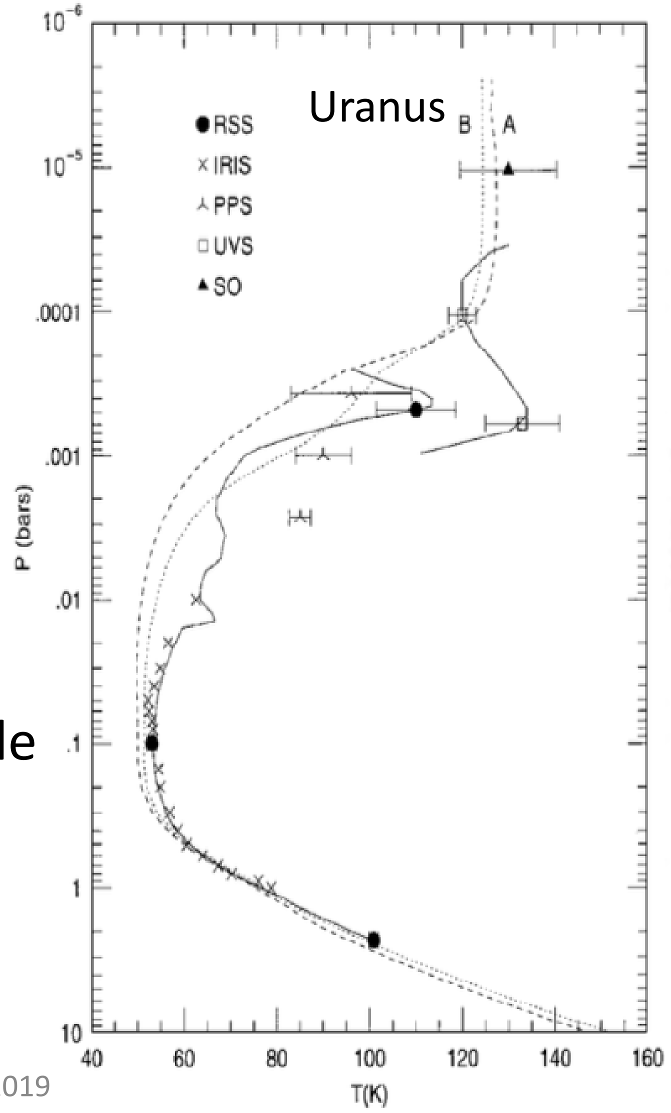
- Introduction
  - Overview of ice giants,
- Atmospheric structure
  - Sources of buoyancy, radiative-convective equilibrium models, clouds and condensibles
- Zonal mean circulation and dynamics
  - Simple models cf observations
  - Observed u, T, thermal winds and composition
- Waves and eddies
  - Convective storms, large vortices, large- and small-scale waves
  - 3D GCMs?
- Outstanding problems

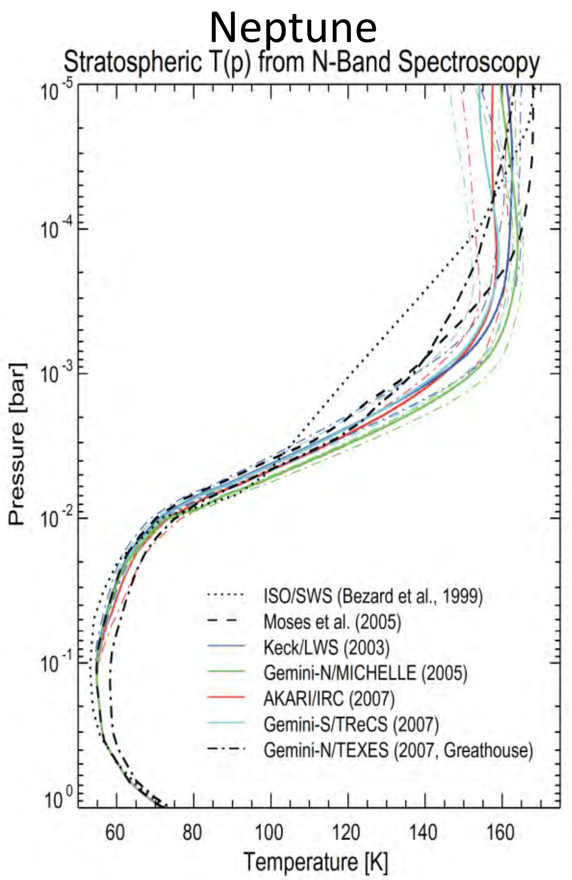
Some numbers

	Uranus	Neptune
Mean solar distance (AU)	19.2	30.2
Orbital eccentricity	0.046	0.009
Orbital period (yrs)	84.01	164.79
Northern summer solstice	1985.8	1913.7
Obliquity (degs)	97.77	29.32
Rotation period (hrs)	17h 14m	16h 06m
Equatorial radius (km/Earth radii)	25,559/4.01	24,764/3.88
g (m/s^2)	8.87	11.15
Emission/insolation	<1.06	2.52
Rossby radius of deformation (km)	3000-7000?	3000-7000?

Atmospheric thermal structure

- Radiative-convective equilibrium
  - Solar heating from above
  - Weak internal heat from below?
  - Model assuming dry convective adjustment (allowing for o-p H_2 conversion)
- RCE models (Marley & McKay 1999)
  - Near-adiabatic deep troposphere and ~isothermal stratosphere
  - B assumes no aerosols and uniform CH_4
  - A allows for aerosol absorption & variable CH_4
- Still some disagreement in stratosphere with observations…

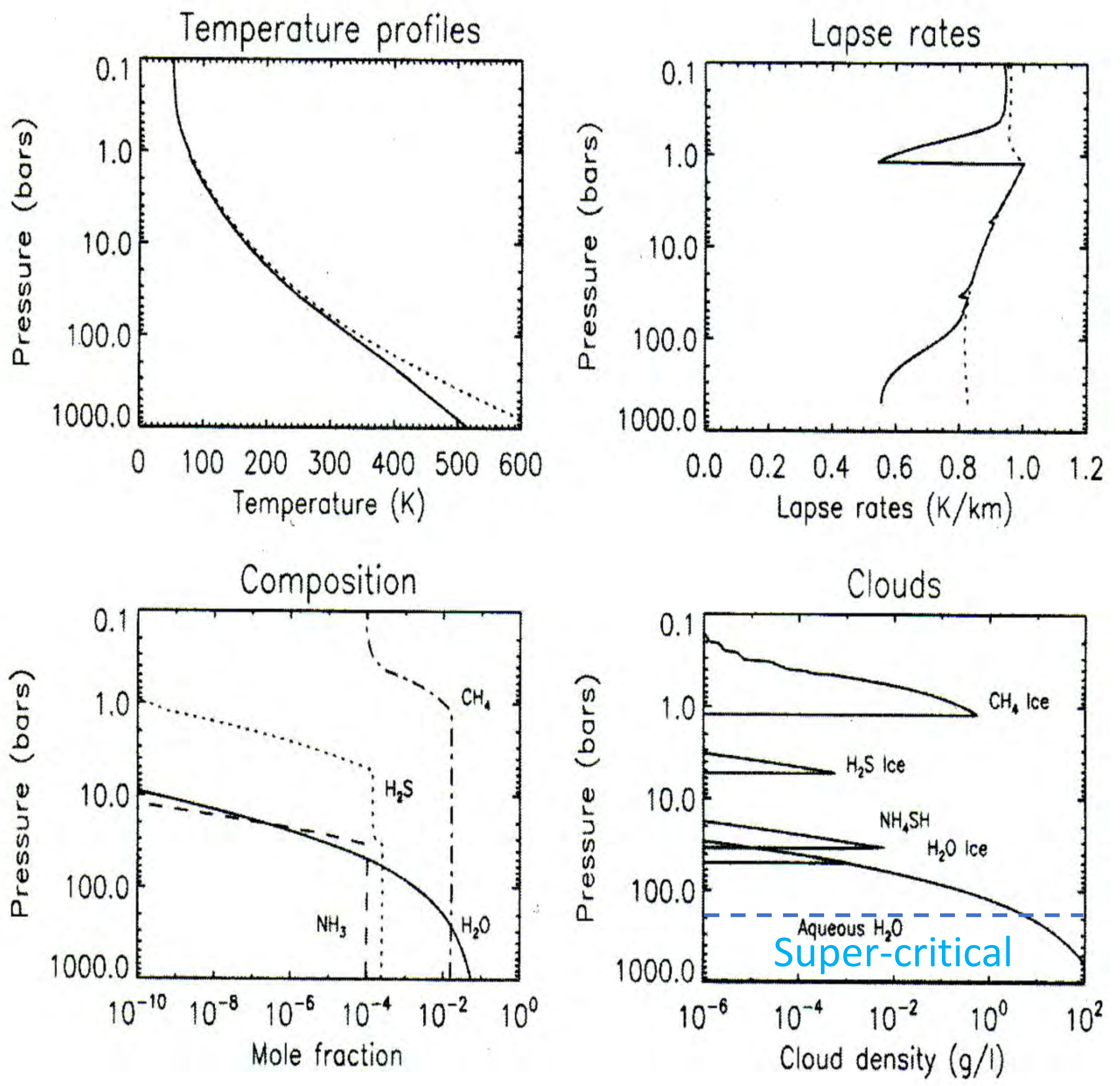




Cloud layers

- Model using equilibrium cloud condensation models
  - Adiabatic lifting of air parcel of prescribed composition from deep levels up to tropopause
- Composition assumed enriched in condensables
- Multiple cloud decks
  - No NH_3?
  - Probably dissolved in H_2O or combined with H_2S….
- Stratospheric hazes?
  - Higher hydrocarbons? [C_2H_6, C_2H_2 etc.]

Uranus



Irwin (2009)

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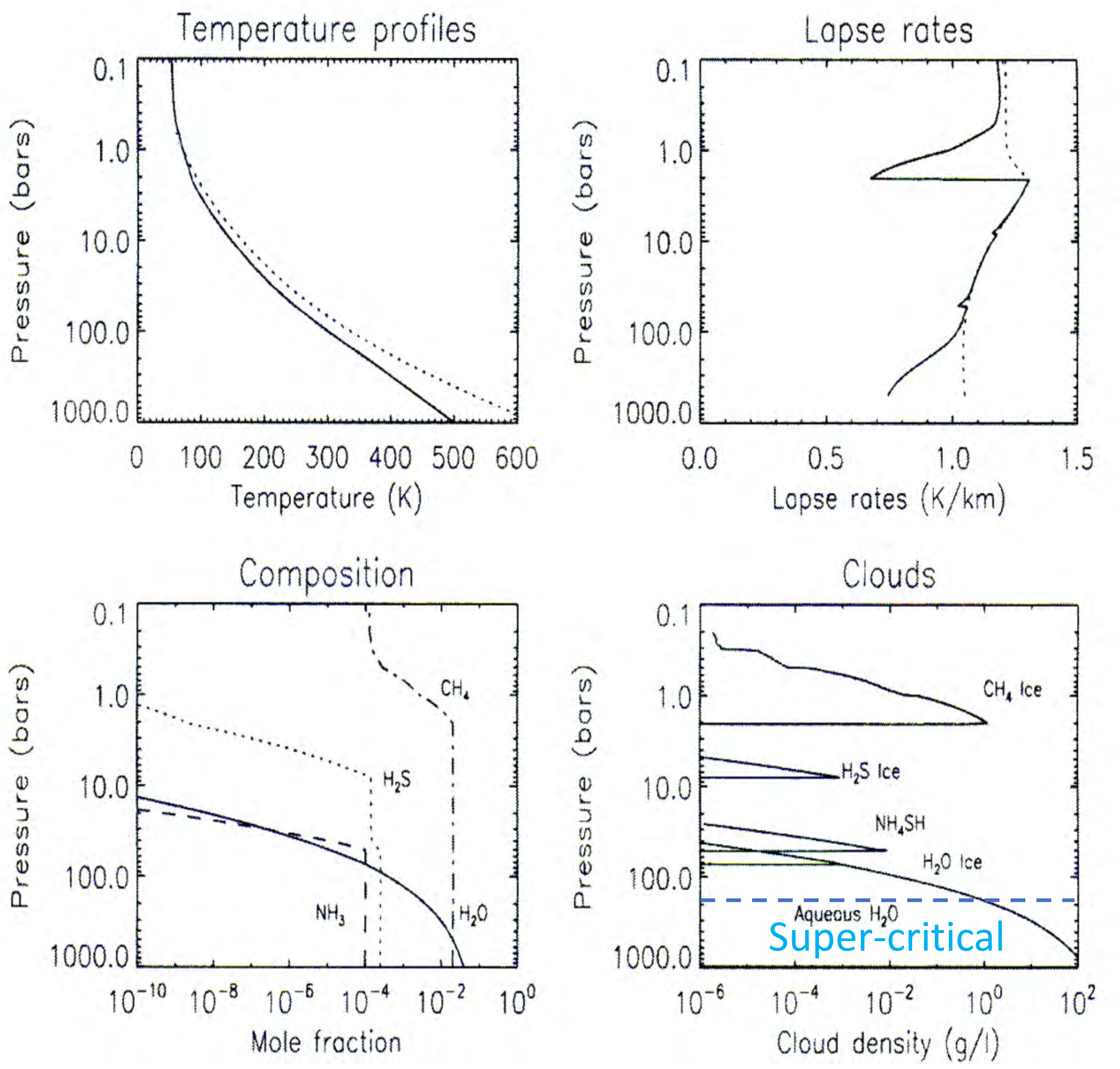
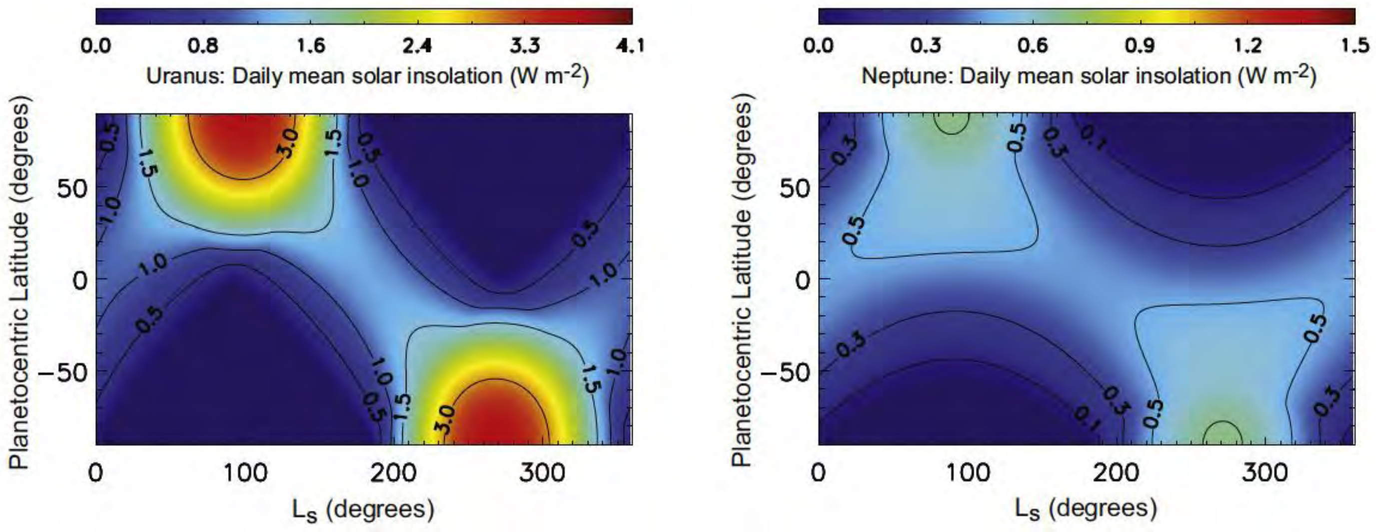
Neptune



Irwin (2009)

Incoming solar radiation

J.I. Moses et al./Icarus 307 (2018) 124–145



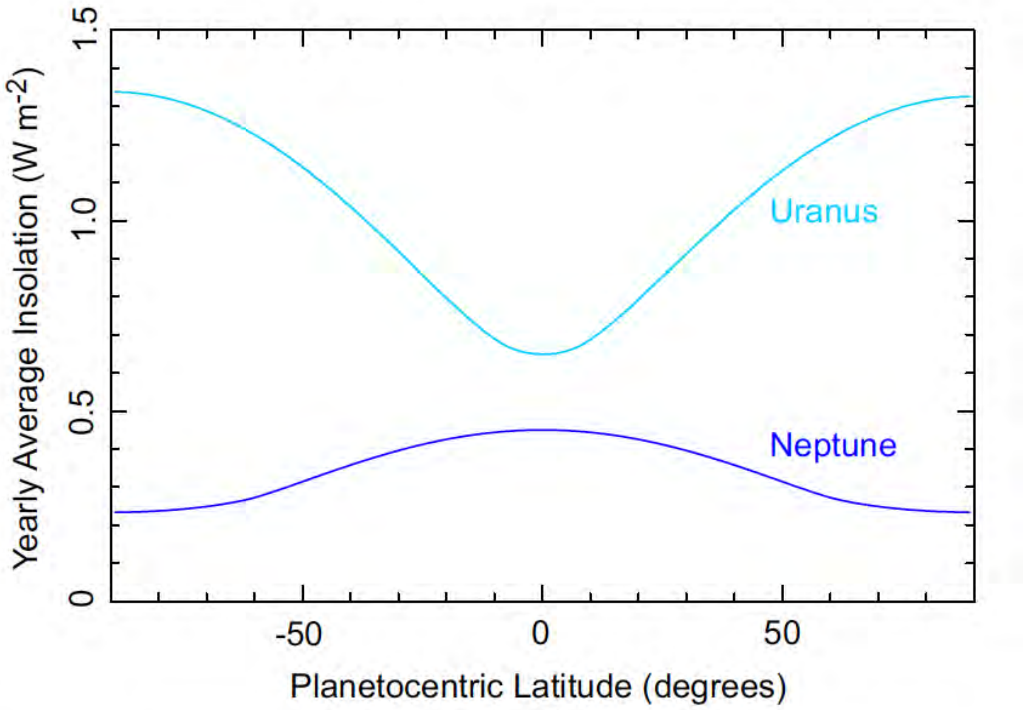


Fig. 2. Annual average solar insolation at Uranus and Neptune as a function of latitude. Unlike the situation on other planets in the solar system, the polar regions of Uranus receive a higher annual average insolation than the equatorial region.

- Solar heating varies with latitude and season
- Impact on zonal mean circulation?
  - Depends on radiative adjustment timescale

Radiative adjustment timescales?

CONRATH, GIERASCH, AND LEROY (1990)

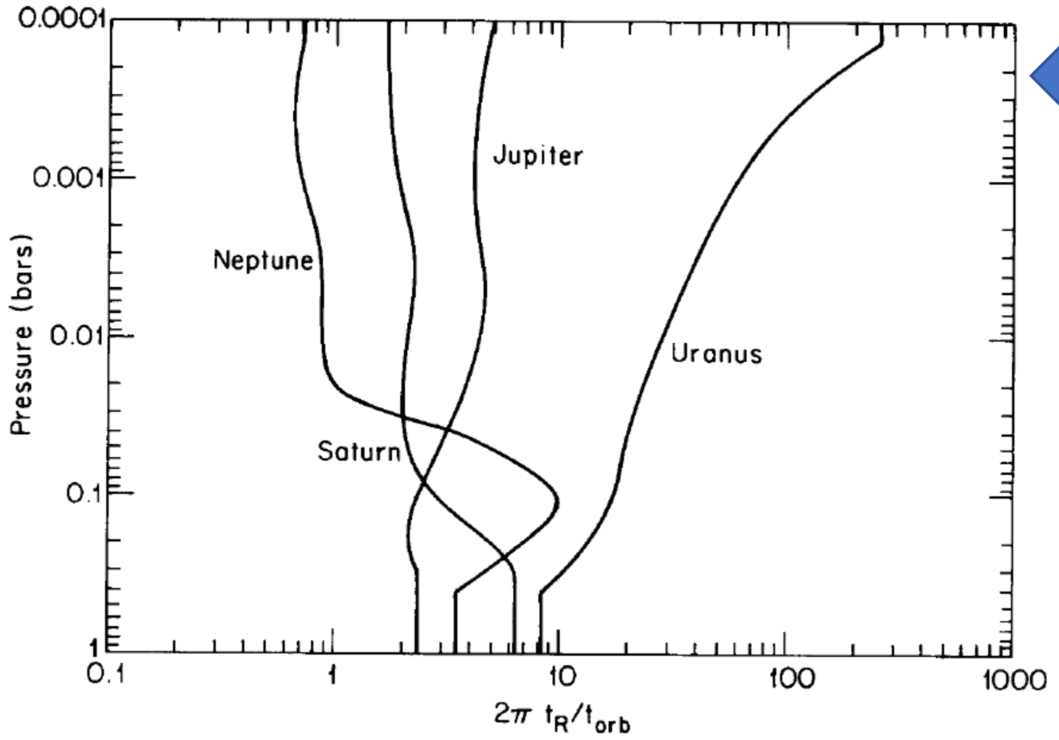


FIG. 2. Radiative time constant profiles based on the temperature profiles of Fig. 1, and on thermal disturbances uniform in height. Within the troposphere, taken constant where T_0 exceeds the effective temperature.

Li et al. (2018)

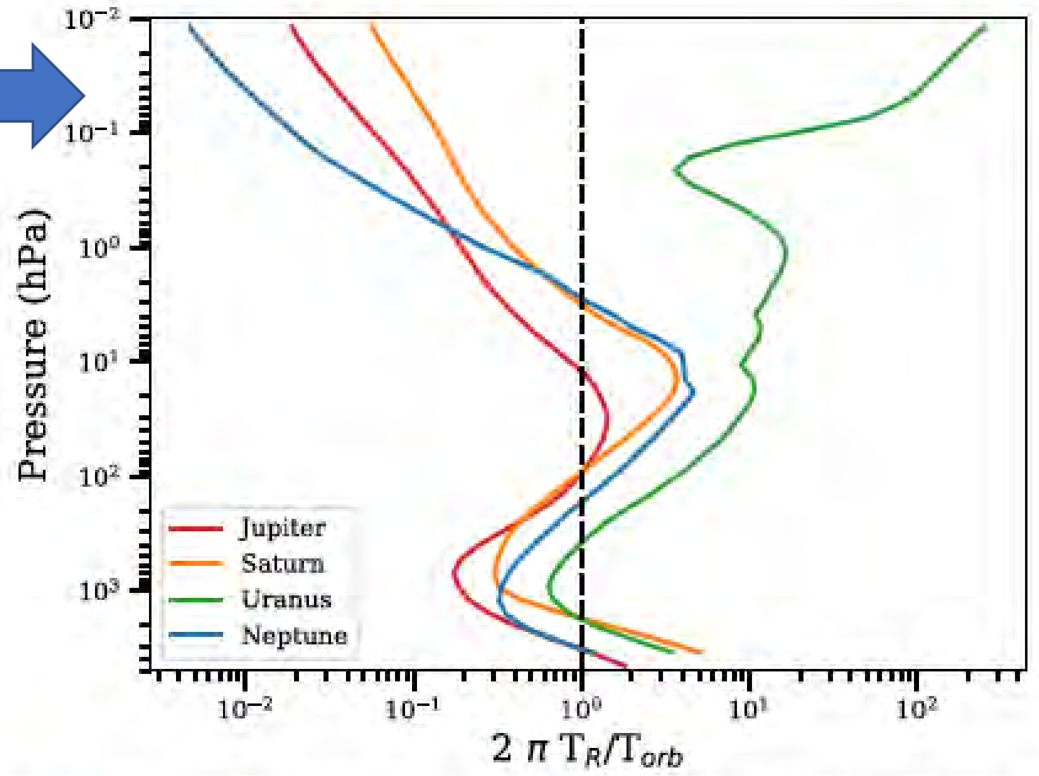
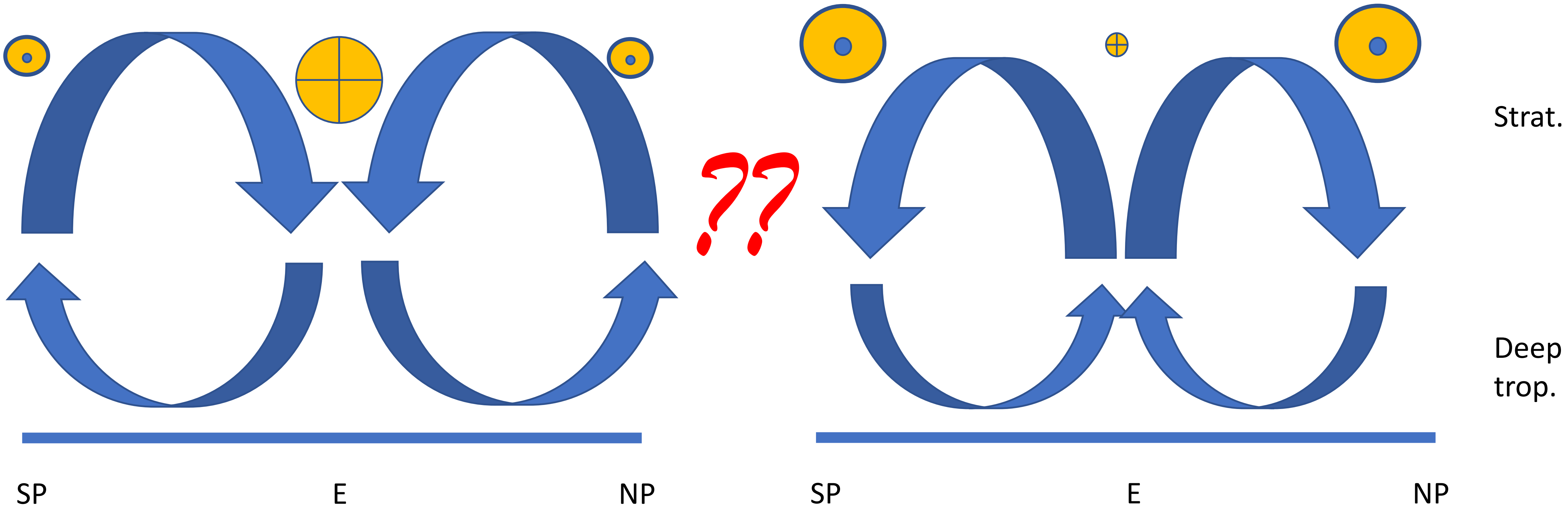


Fig. 7. Vertical profiles of radiative time constant based on the temperature profiles in Fig. 2 and the cooling rate profiles in Fig. 4. The radiative time constant T_R is normalized by the orbital period T_{orb}, which is 11.9, 29.5, 84 and 165 Earth years for Jupiter, Saturn, Uranus and Neptune, respectively.

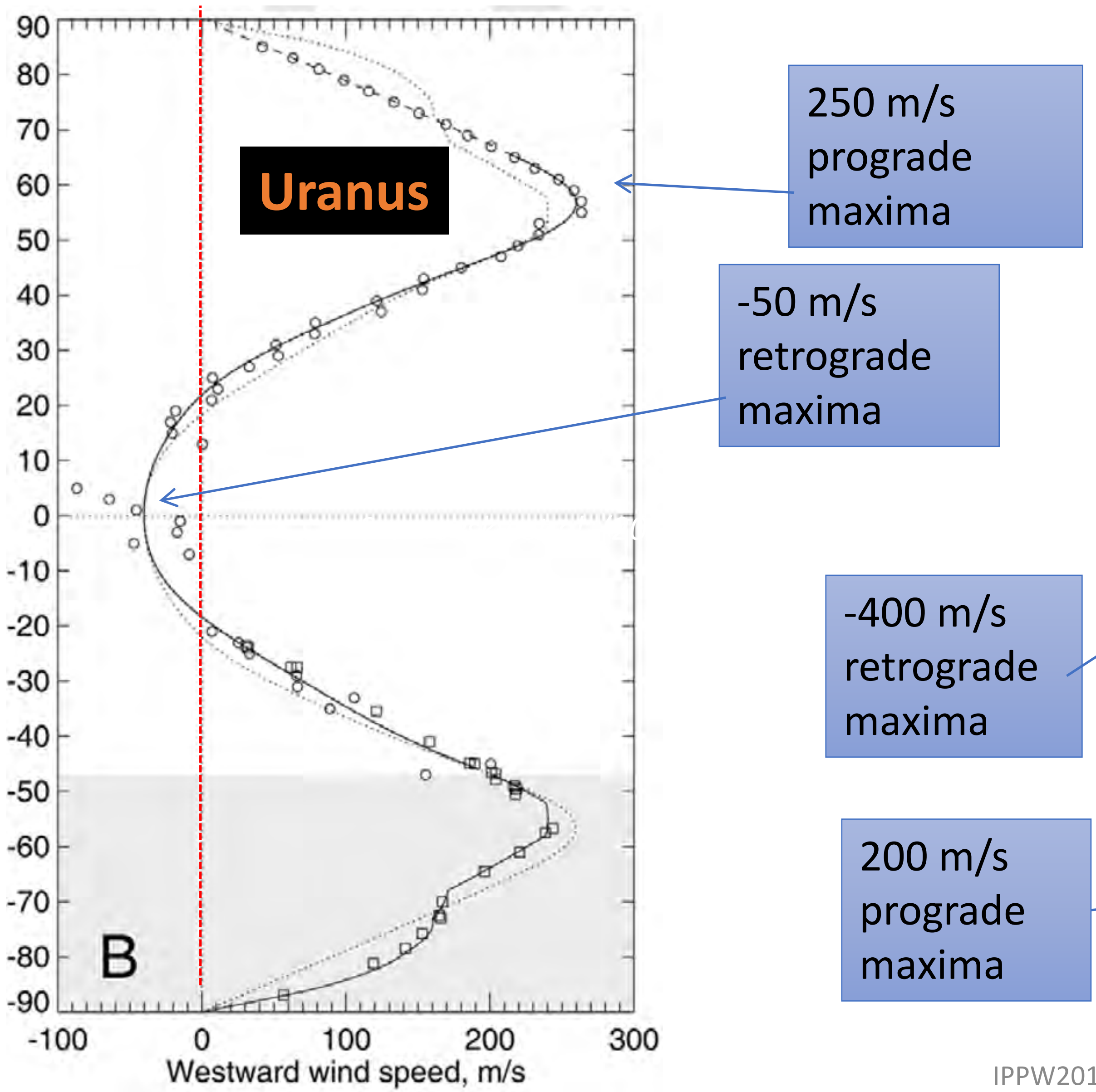
Schematic annual mean circulation driven by solar heating…?

• Uranus

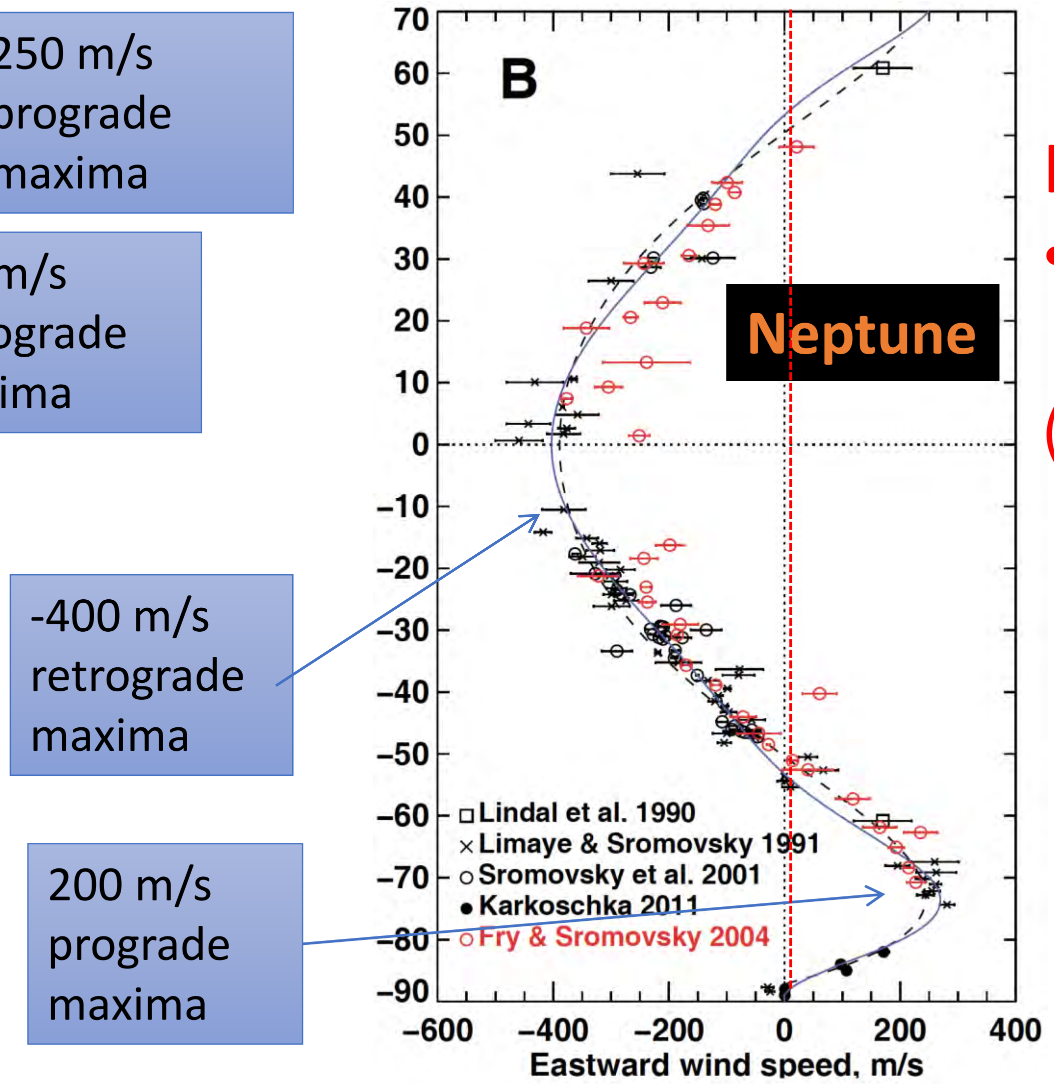
• Neptune



Observations: Ice Giant Winds



Sanchez-Lavega et al. (2018)



How deep?

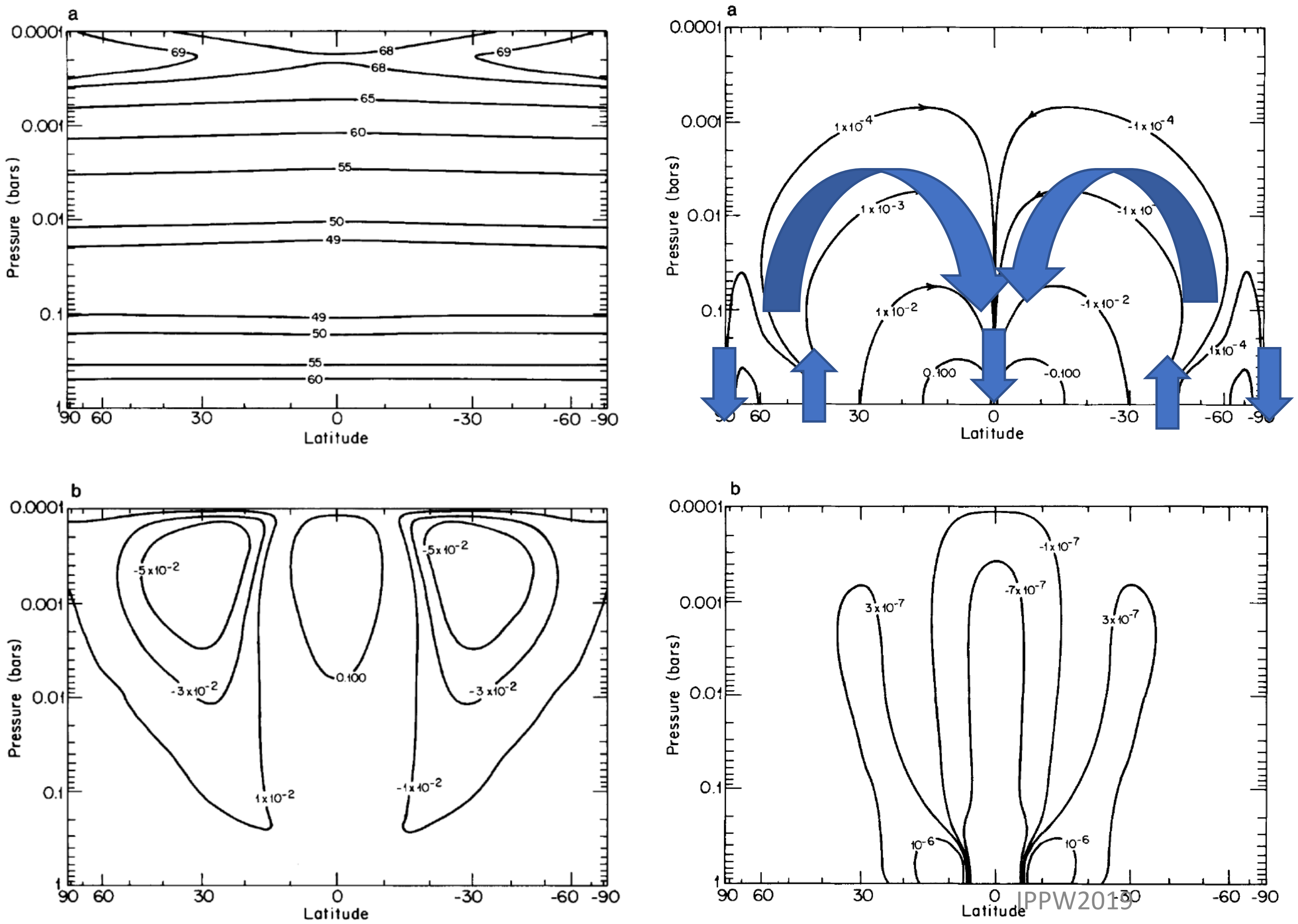
- <1000km or <3000 bars

(Kaspi et al. 2013)

Conserve angular momentum from latitude where u = 0

- Uranus: u(0)~-150 m/s
- Neptune: u(0)~-1200 m/s!
- **Implies dynamically active eddies…?**

Linear diagnostic 2D model (Conrath et al. 1990)



B. Equations of Motion

The linearized equations of motion are

$$\frac{\partial u}{\partial t} - fv = \frac{u_E - u}{t_F}, \tag{4}$$

$$fu + \frac{1}{a}\frac{\partial \Phi}{\partial \theta} = 0, \tag{5}$$

$$\frac{\partial \Phi}{\partial z} = RT, \tag{6}$$

$$\frac{1}{a \cos \theta}\frac{\partial}{\partial \theta}(\rho_0 v \cos \theta) + \frac{1}{H}\frac{\partial}{\partial z}(\rho_0 w) = 0, \tag{7}$$

$$\frac{\partial T}{\partial t} + \frac{N^2 H}{R} w = \frac{T_E - T}{t_R}. \tag{8}$$

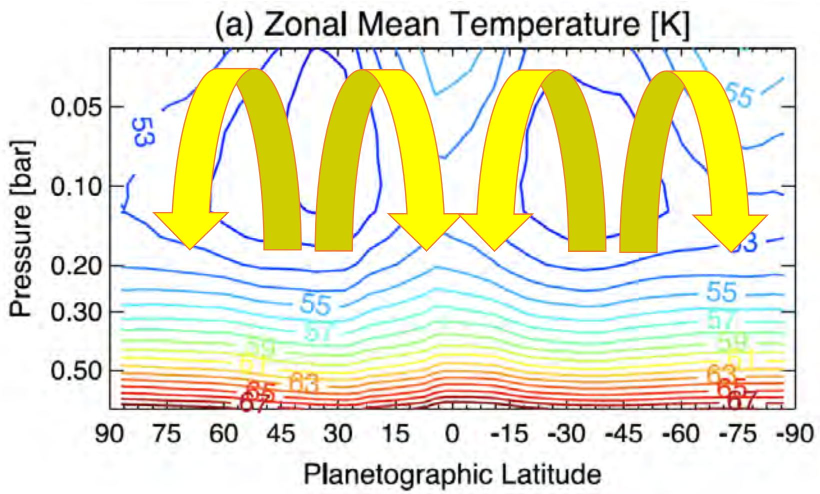
If data exist determining the latitudinal distribution of temperature at the base, then one would rearrange (8) to give

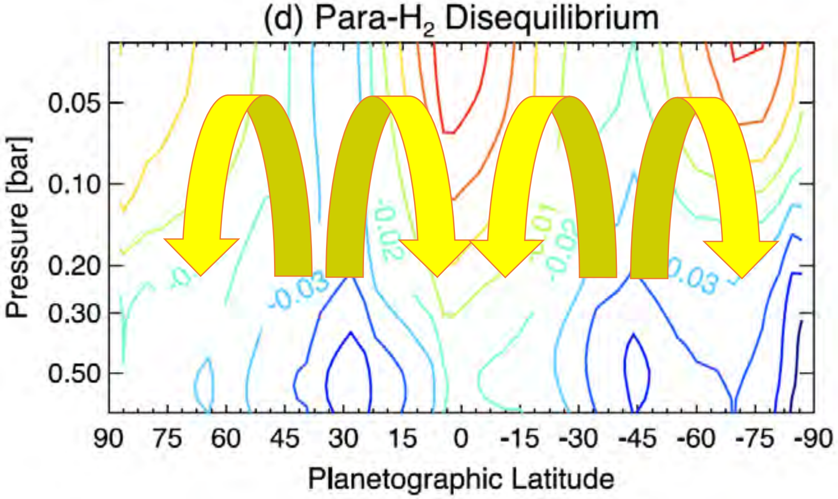
$$w(p_{base}, y, t) = \frac{R}{N^2 H}\left(-\frac{\partial T}{\partial t} + \frac{T_E - T}{t_R}\right).$$

or

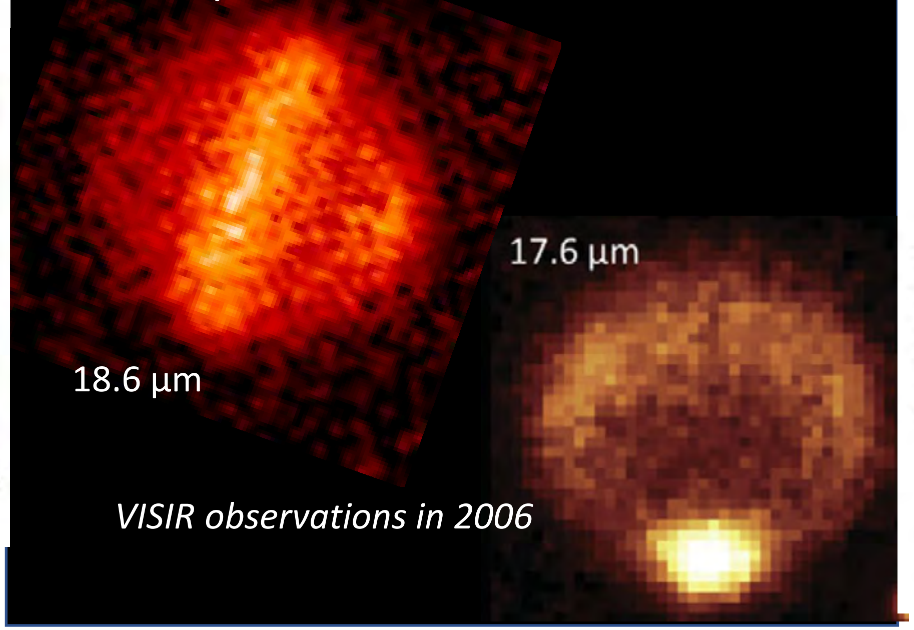
$$p\frac{\partial \psi(p_{base}, y, t)}{\partial p} = \frac{\rho_0 H \cos \theta}{f}\left(-\frac{\partial u}{\partial t} + \frac{u_E - u}{t_F}\right).$$

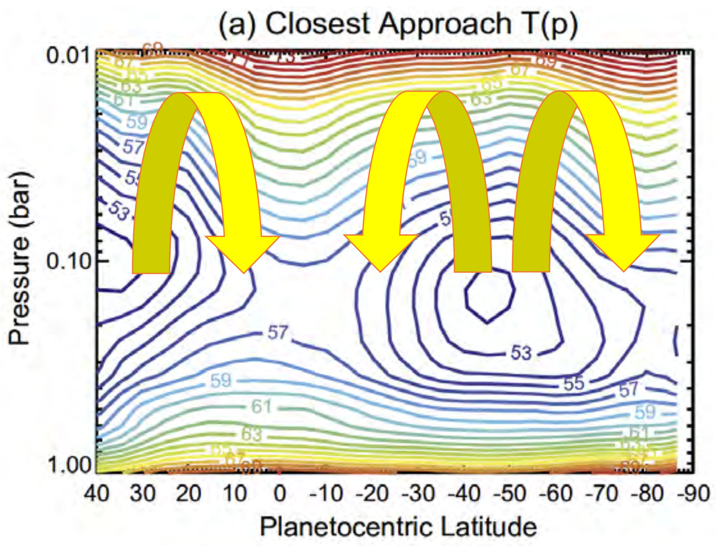
Observations: The Voyager Picture

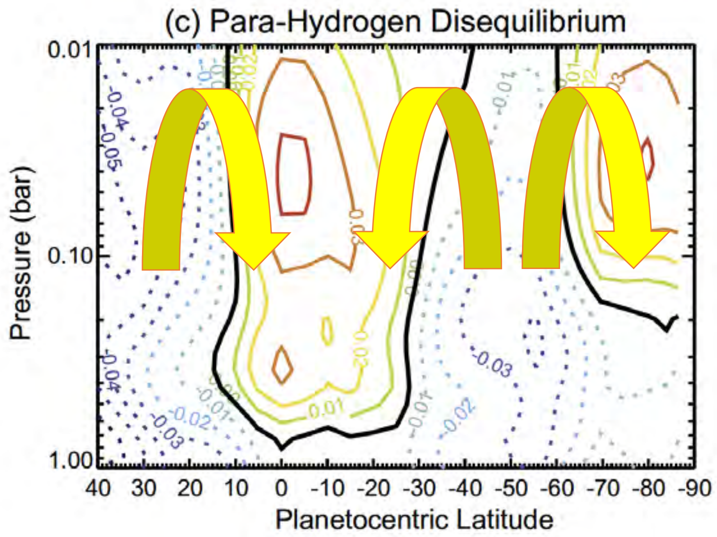




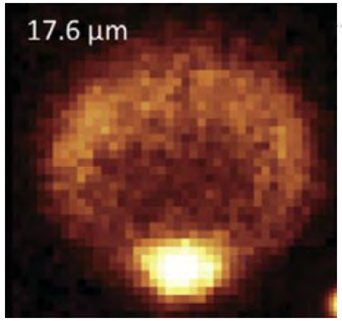
- 25-50 µm spectra (H_2-He continuum)
- Uranus 1986 (left, Orton et al., 2015)
- Neptune 1989 (right, Fletcher et al., 2014)
- 80-800 mbar only:
- Mid-latitude upwelling; warm equator; warm poles.

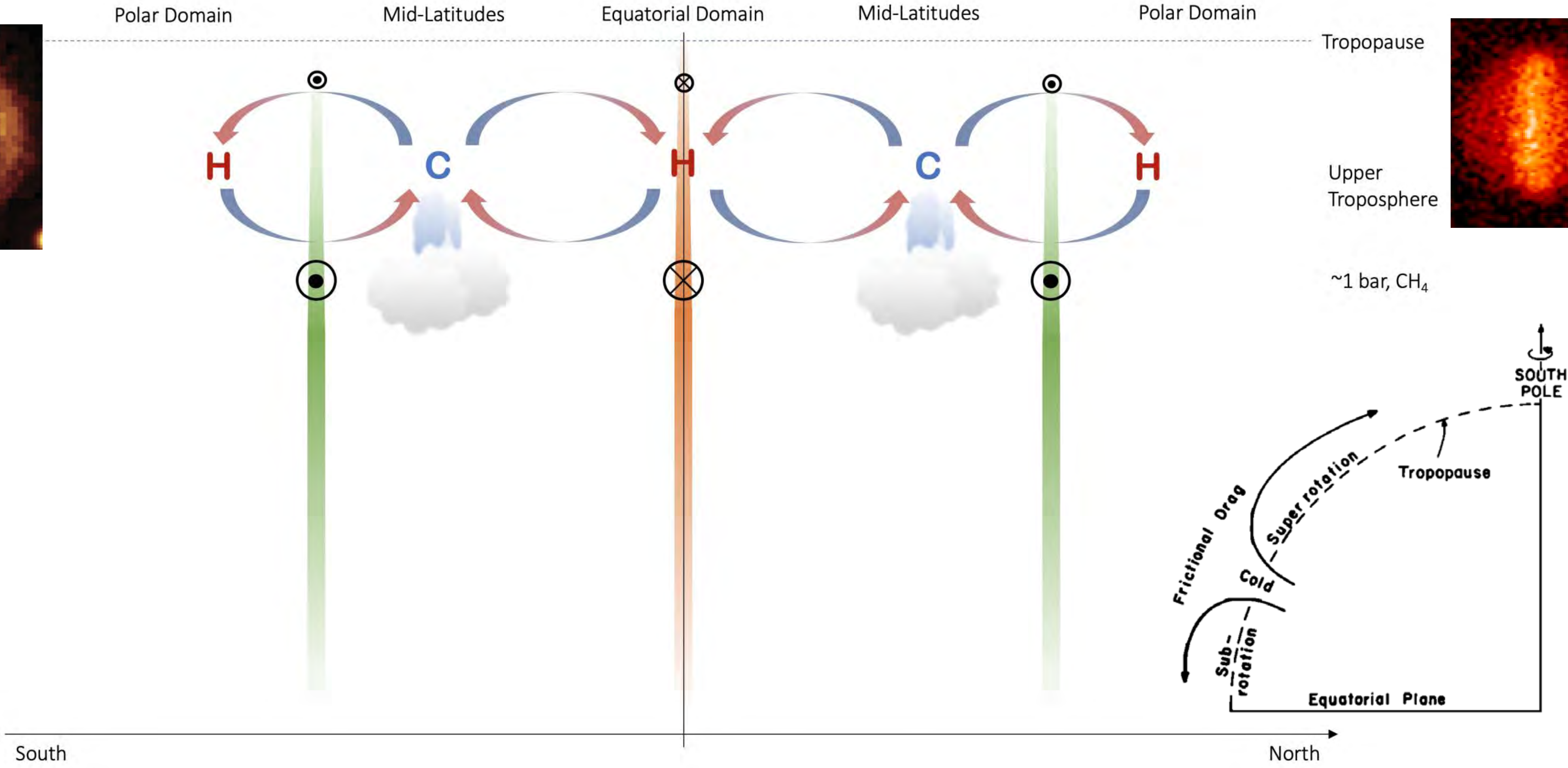


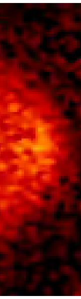




General Circulation of an Ice Giant - Schematic



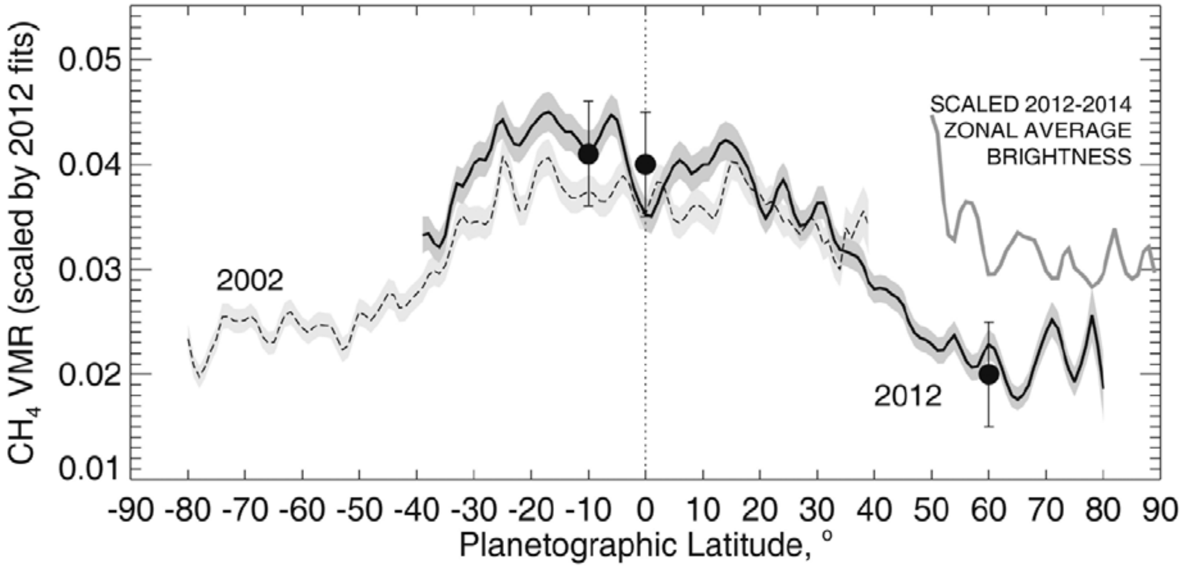


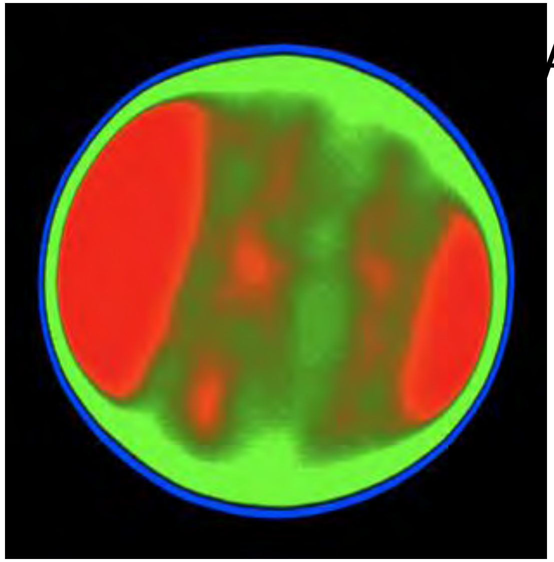


Flasar et al. (1987)

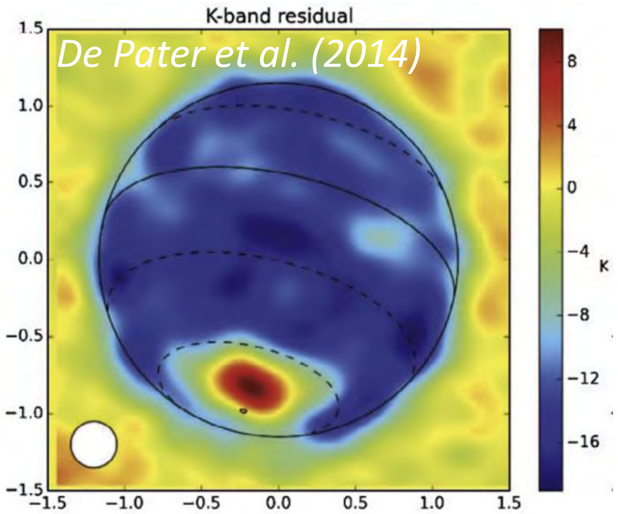
Equator-to-Pole Contrasts: Troposphere

- Schematic doesn't explain equator-to-pole contrasts in gaseous composition:
  - Methane (from near-IR reflectivity – Karkoschka, Irwin, Sromovsky, et al.) in 1-4 bar range
  - NH_3/H_2S (from microwave emission - Hofstadter, de Pater, et al.)
- Contrasts are likely to be at p>1 bar, potentially very deep.



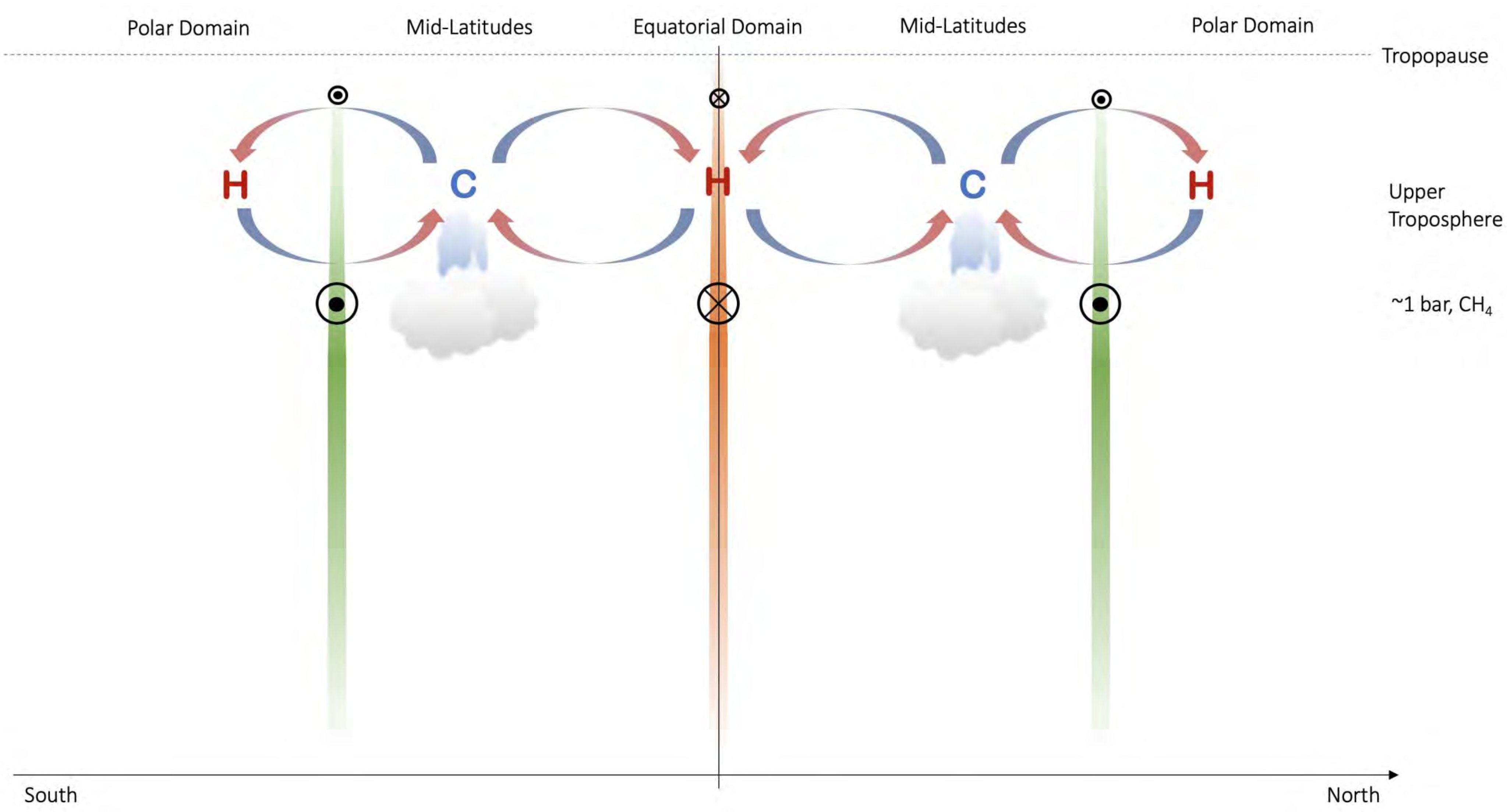


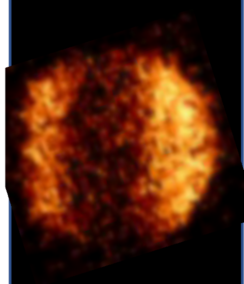
A

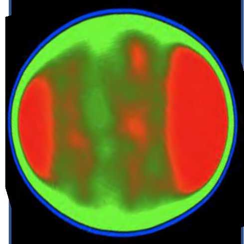


Hofstadter et al. (2003)

General Circulation of an Ice Giant - Schematic







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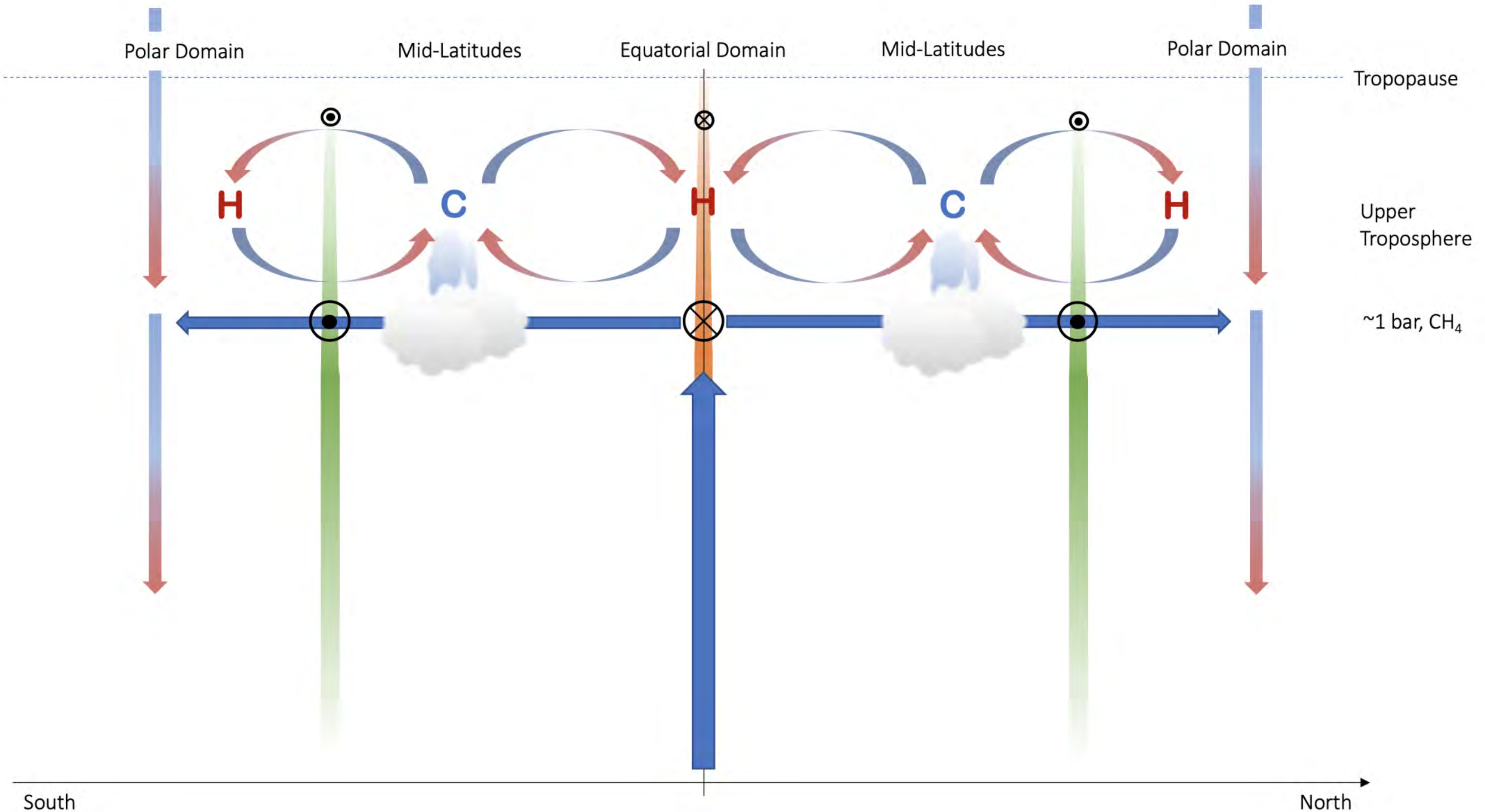
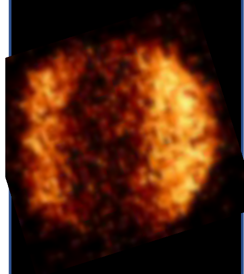
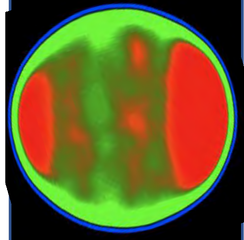
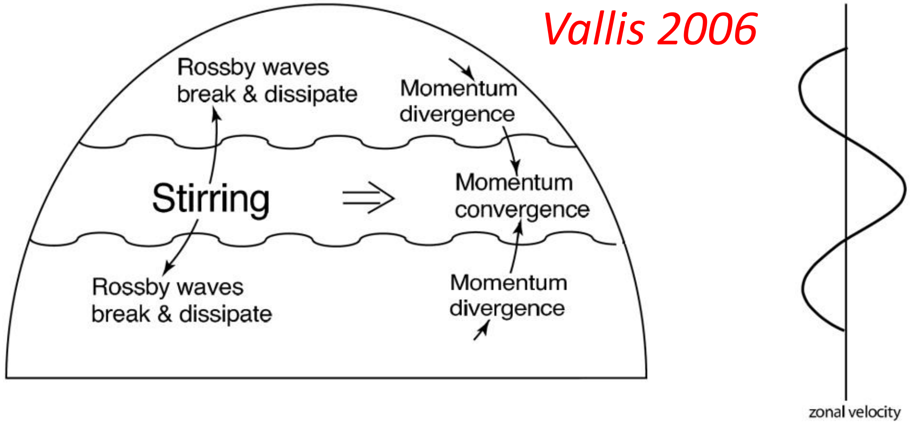






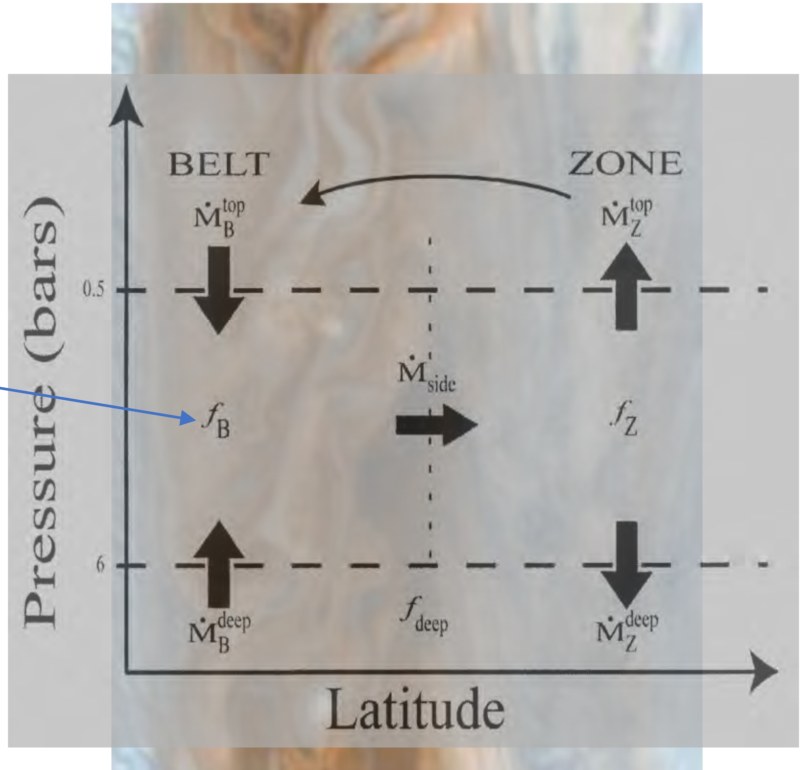
Gas Giant Prograde Jets

- …Are locations of eddy momentum flux convergence.
  - Balanced by Coriolis force on meridional flow, equatorward across prograde jet.
- **This is unknown for ice giants.**
- Would imply jets *strengthen* with height in mid-troposphere.
  - Warm mid-latitudes and cool equator.



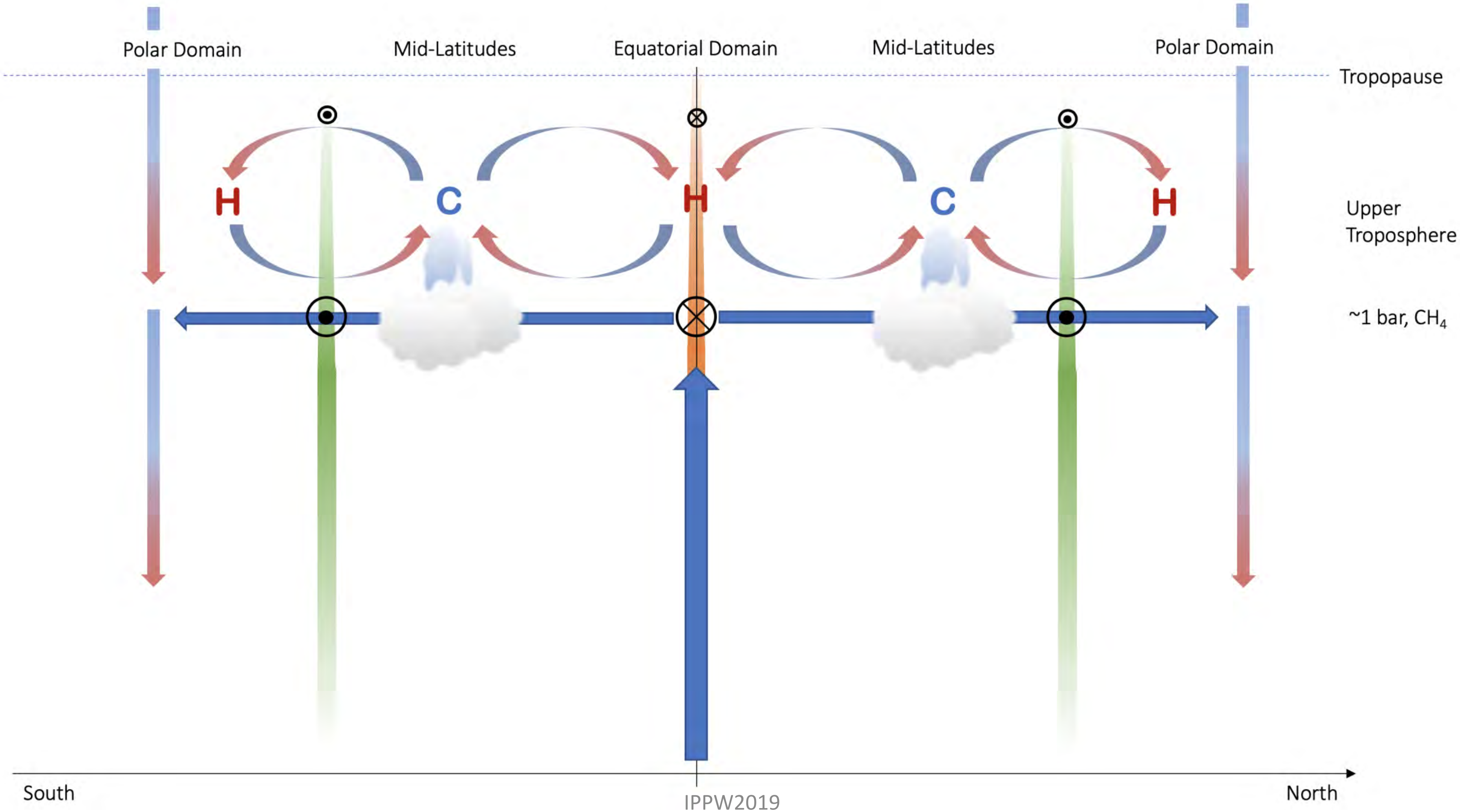
Vallis 2006

Flow convergence between two cells at cloud-tops in belts



Showman and de Pater 2005

General Circulation of an Ice Giant - Schematic



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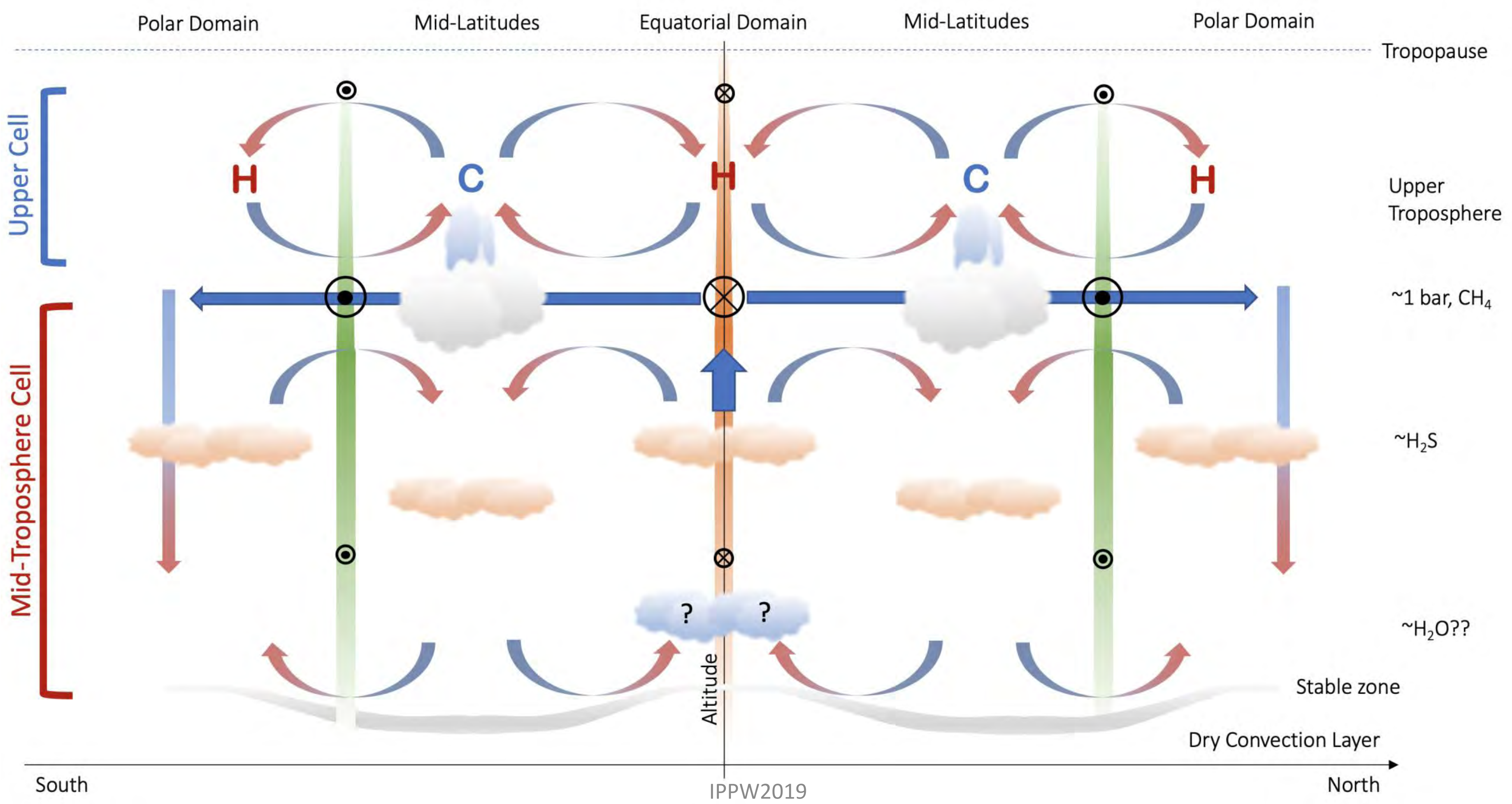
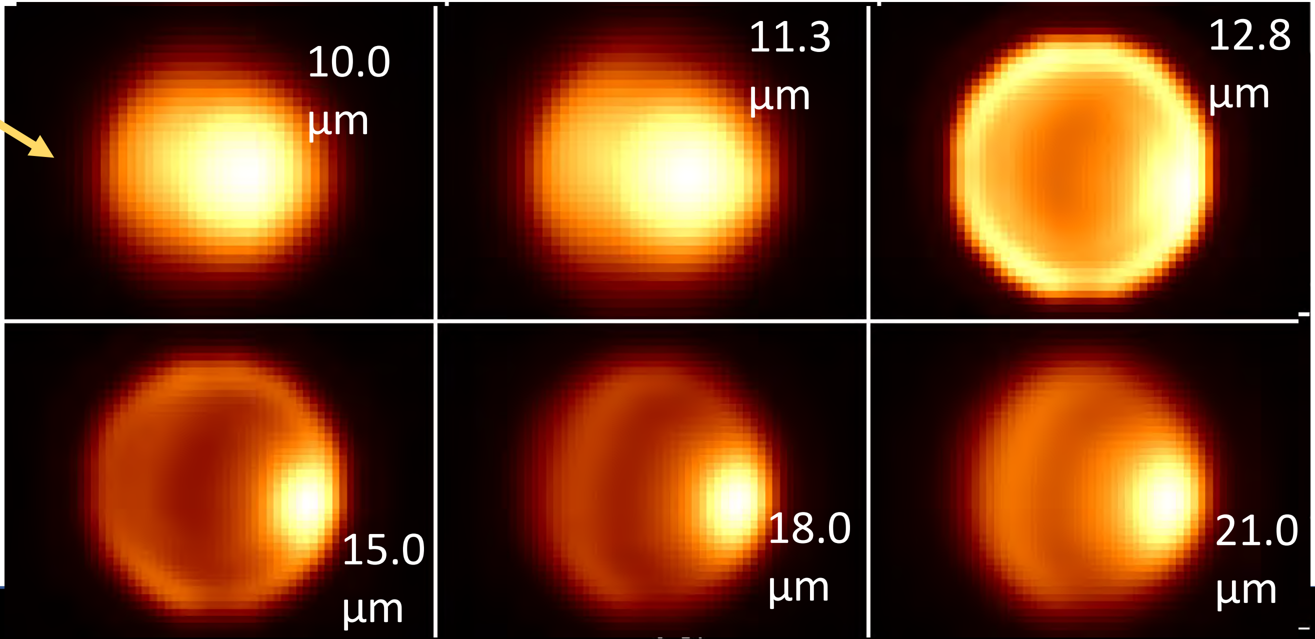
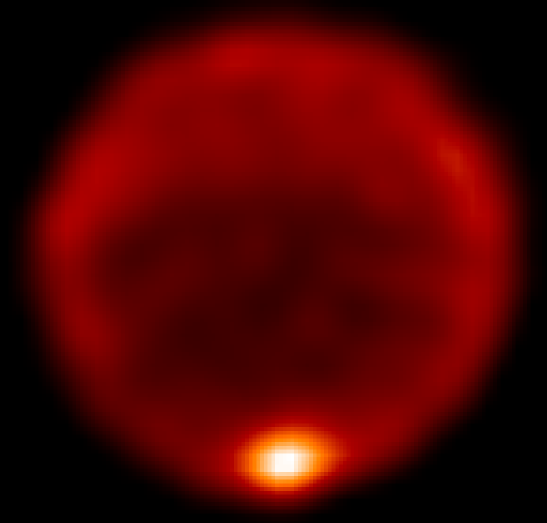


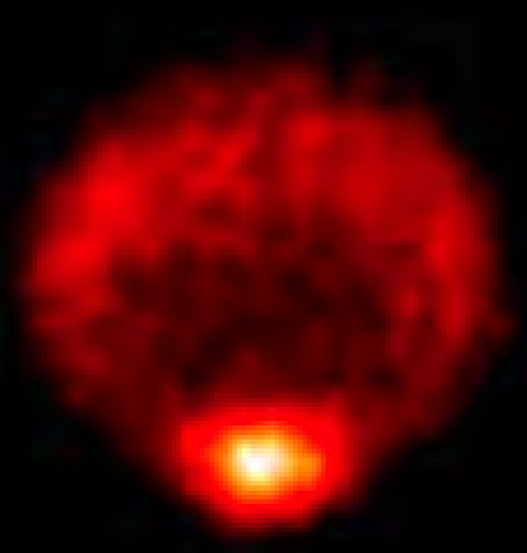
Neptune and Uranus polar vortices?



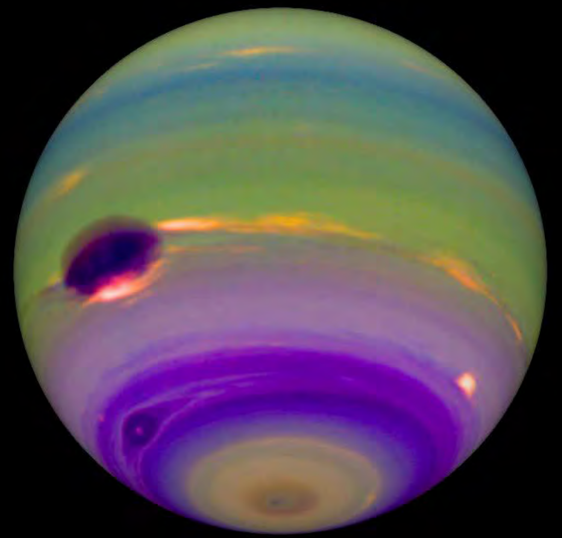
- Neptune has hot spot over south pole
- Compact polar vortex cf Saturn
- Uranus?
  - Not clear….?
  - Why not…?



Neptune, VLT/VISIR, 2008, 7.9 μm (Stratosphere)



Neptune, 2006 VLT/VISIR 17.6 μm (Troposphere)

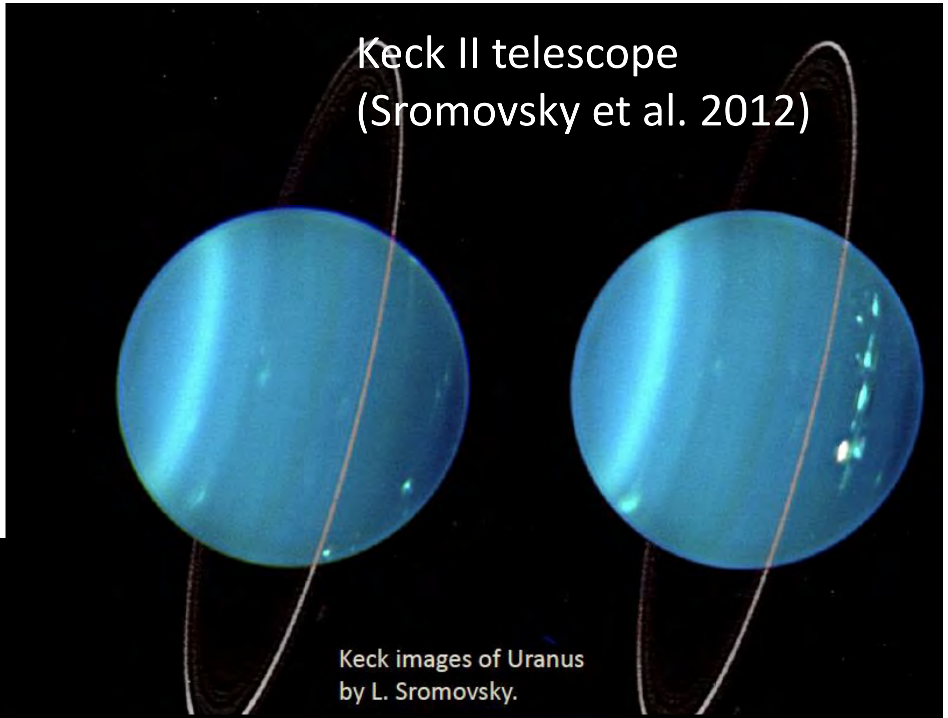


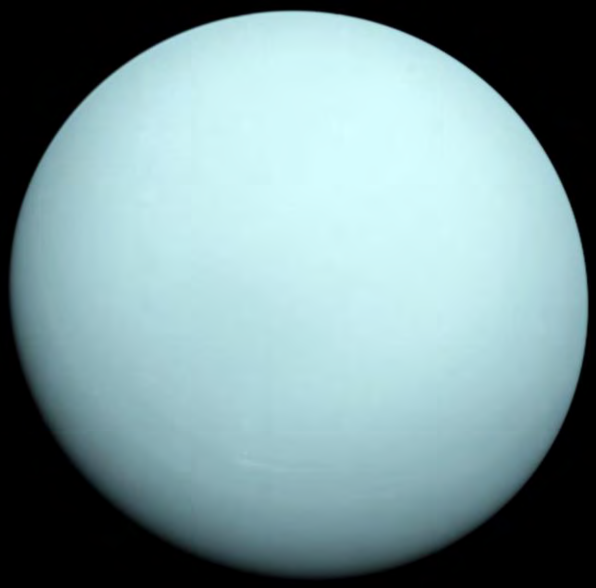
Ephemeral dark storms & Great Dark Spot seen by Voyager 2, Karkoschka (2011).

Eddies, waves and storms: Uranus

Keck Telescope in 2014
(De Pater et al. 2015)

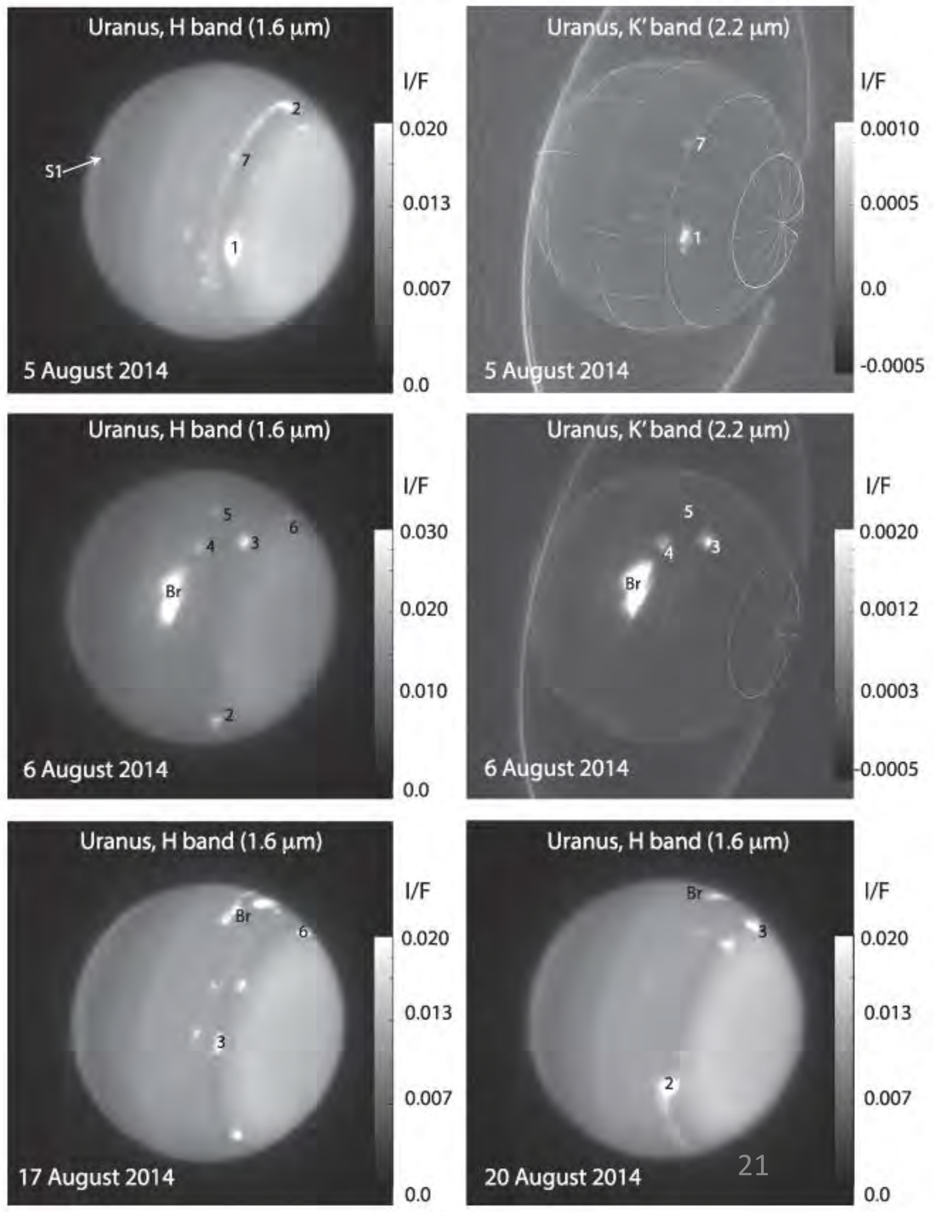
- Major changes recently from Voyager era (1986)
  - Seasonal shift from northern summer - autumn?
  - Induces convection around ~1-2 bar?



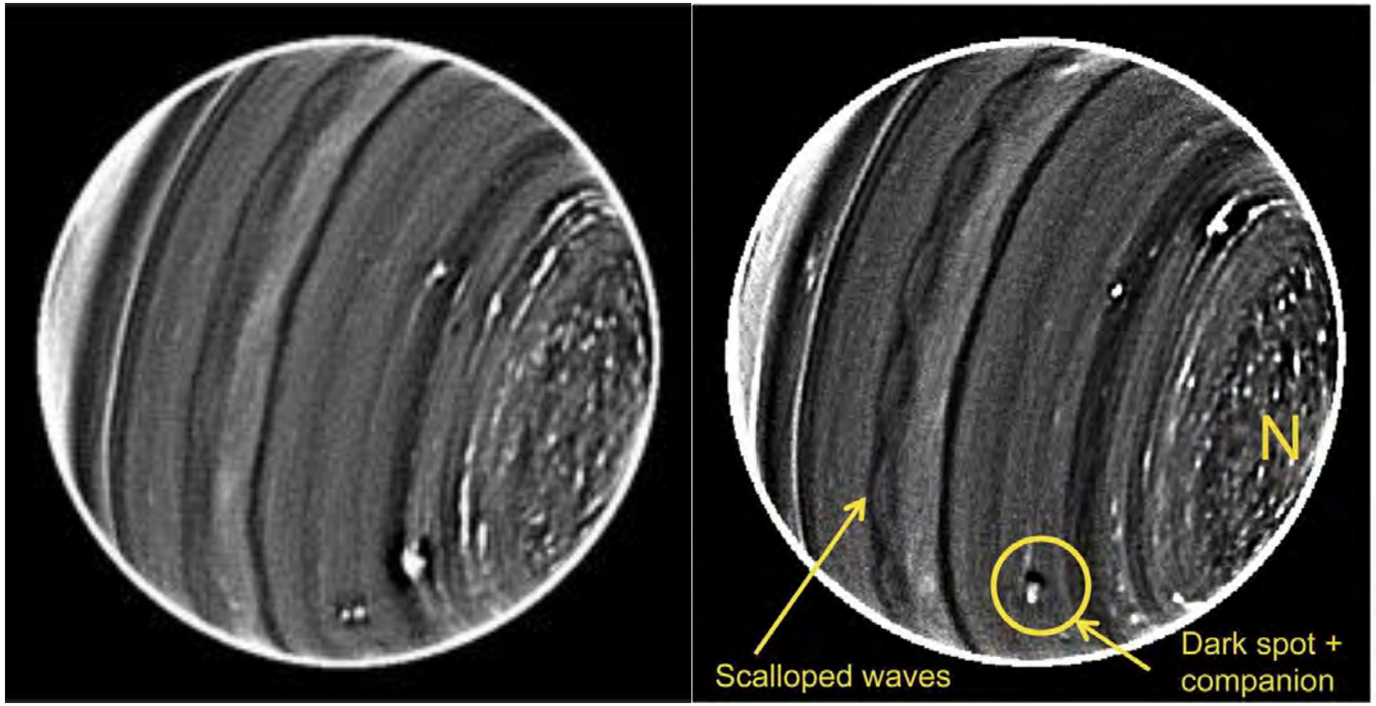


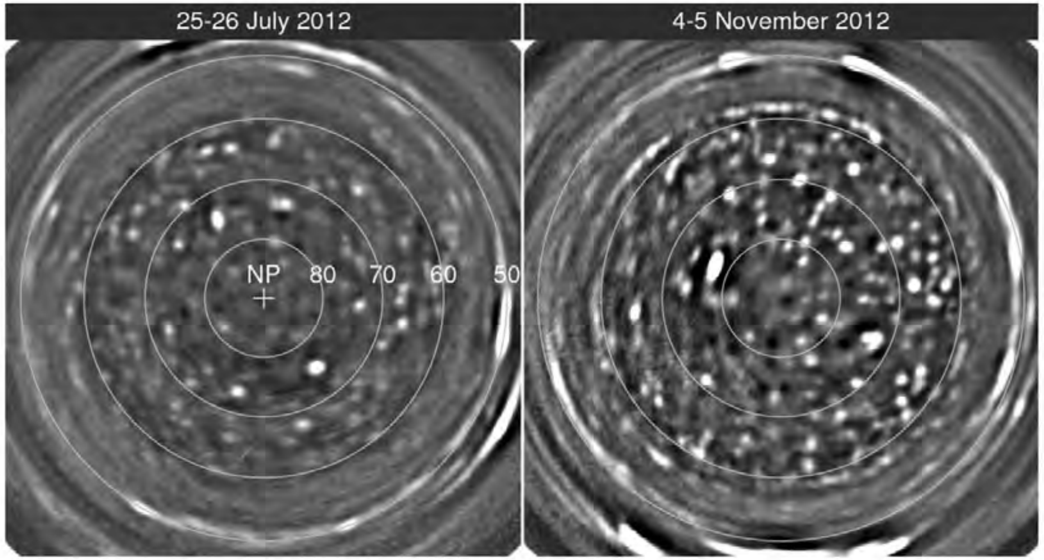
Voyager (1986)

HST (2018 – Amy Simon)



Eddies, waves and storms: Uranus



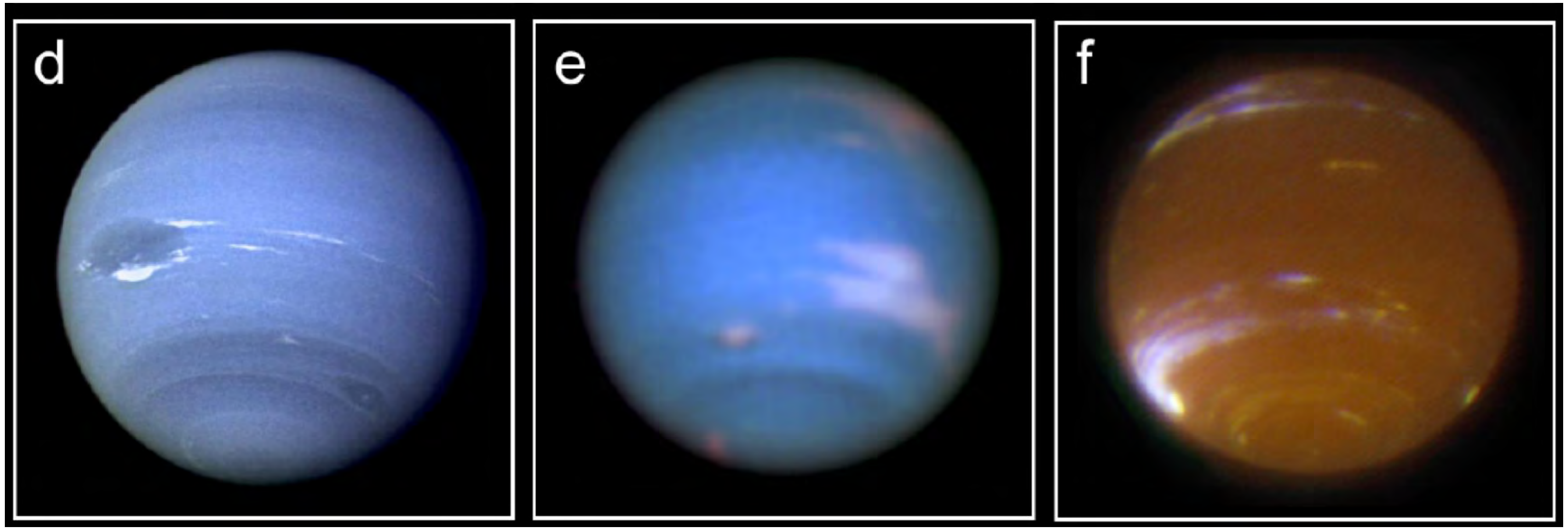


High S/N Keck II imaging of Uranus reveals unprecedented detail (left) and numerous discrete cloud features in the North polar region (above) where the atmosphere rotates about the pole like a solid body.

Sromovsky et al. (2015)

- Polar cap (convective?) spots (cf Saturn?)
- ”Scalloped” wave train just south of equator
  - Equatorial Rossby waves?

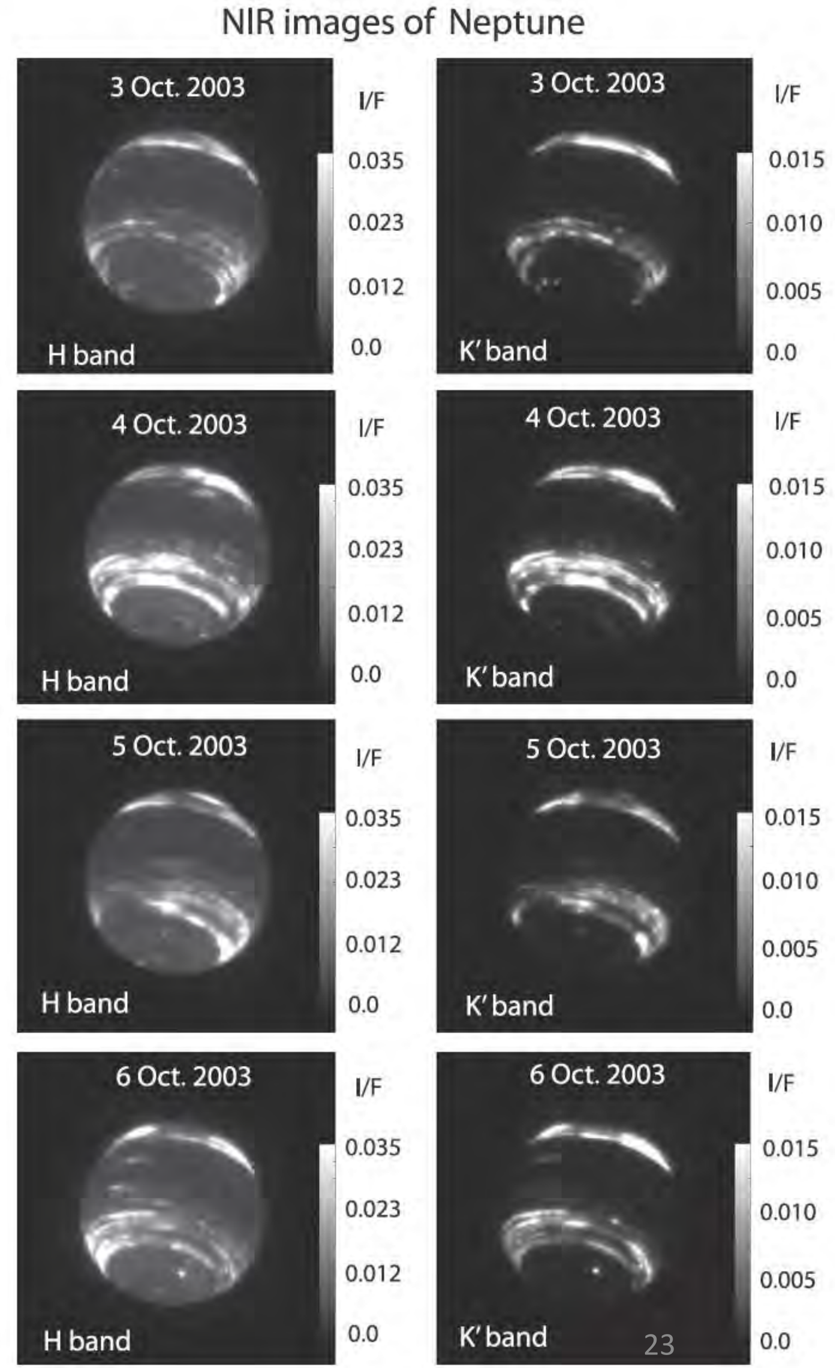
Eddies, waves and storms: Neptune



Voyager (1989)

- Transient dark spots with bright companion clouds (CH_4?)
- Convective streaks and spots (mainly midlatitudes)

De Pater et al. (2014)



Small-scale gravity waves (Neptune)

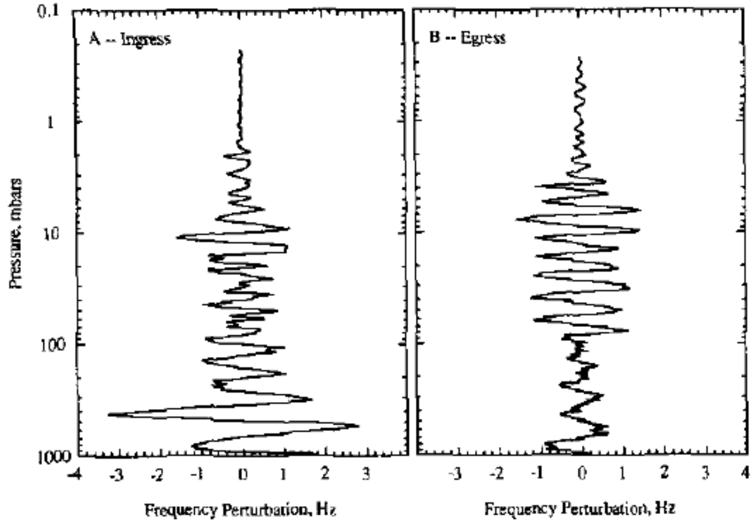


FIG. 6. Frequency perturbations, f_1', that result from atmospheric structure with vertical wavelengths of 4–16 km. Measurements exceed the noise level at pressures greater than 2–3 mbars.

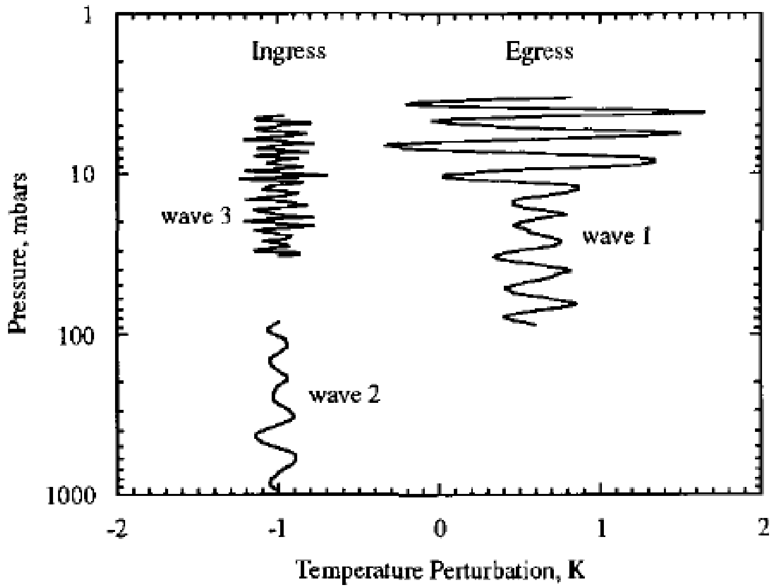


FIG. 11. Temperature perturbations from Figs. 8–10 superimposed on the same axes. Arbitrary temperature offsets have been introduced to avoid overlap.

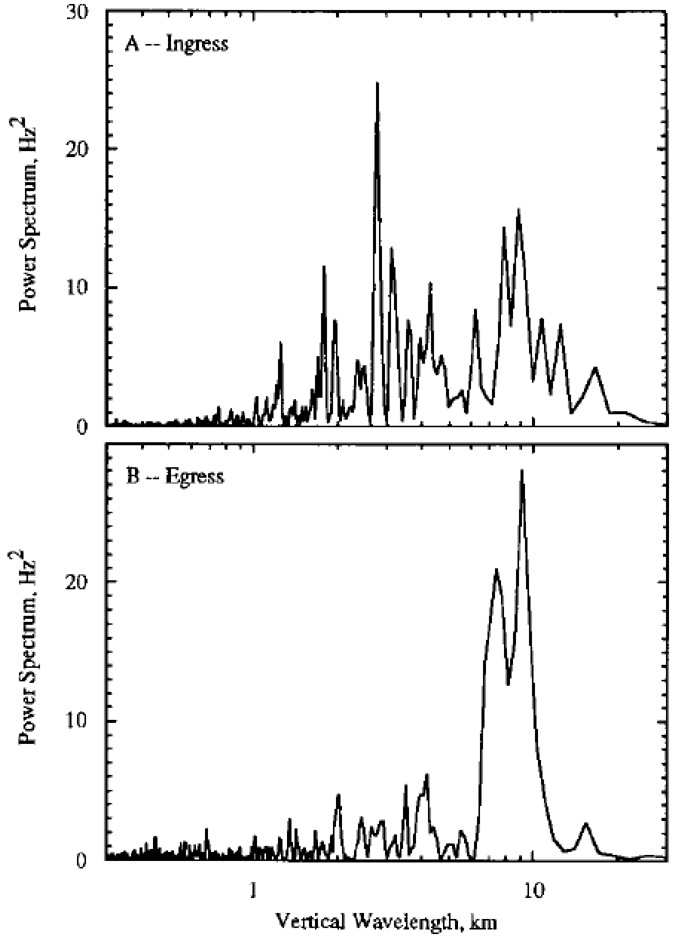


FIG. 5. Power spectra of frequency fluctuations, f', as a function of vertical wavelength. Results at both ingress and egress were obtained from data at pressures 1–1000 mbars. The dominant features in both spectra reflect structure in the atmosphere of Neptune. Random peaks caused by thermal noise should seldom exceed 1 Hz^2.

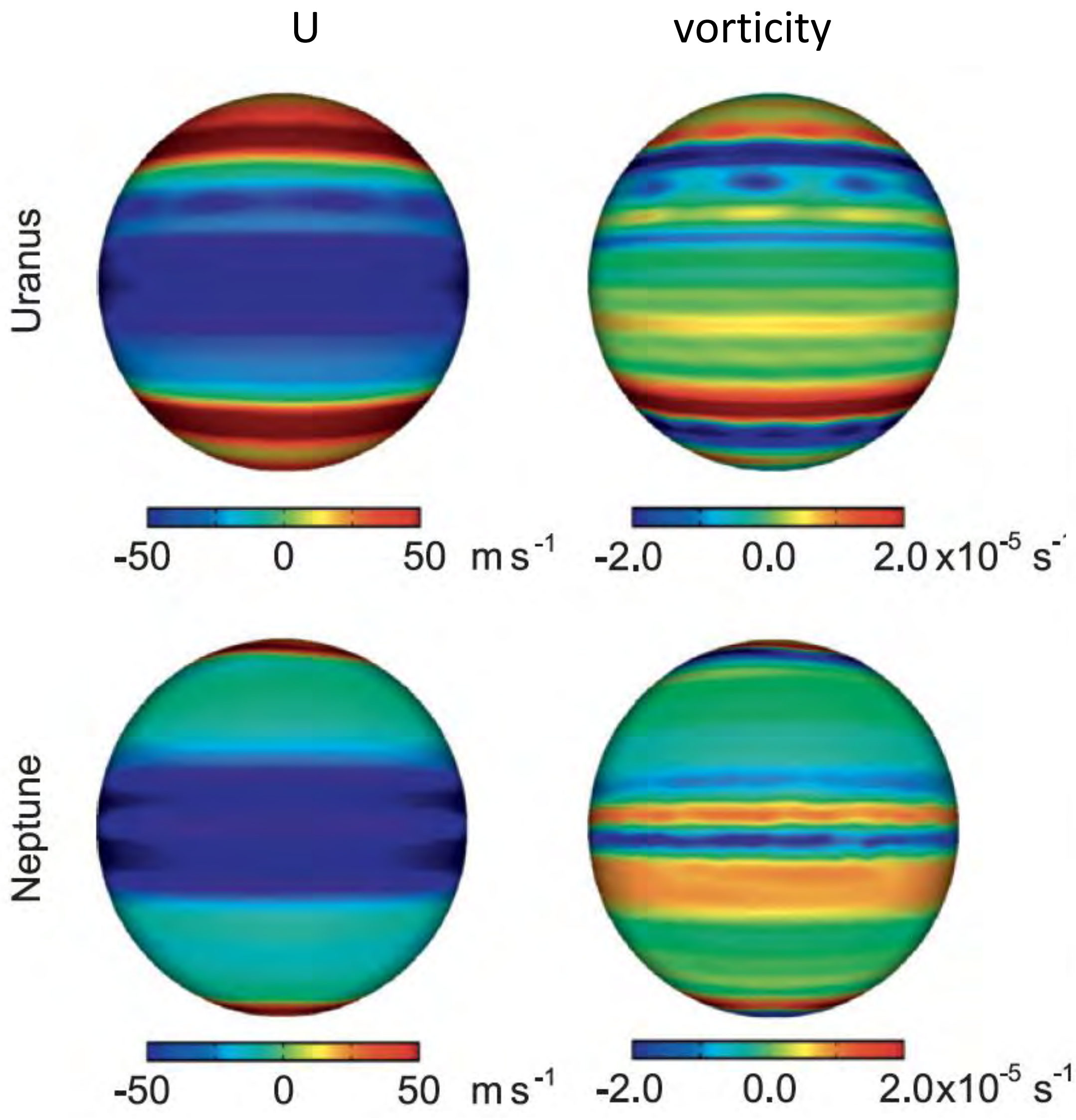
TABLE III
Measured Wave Properties

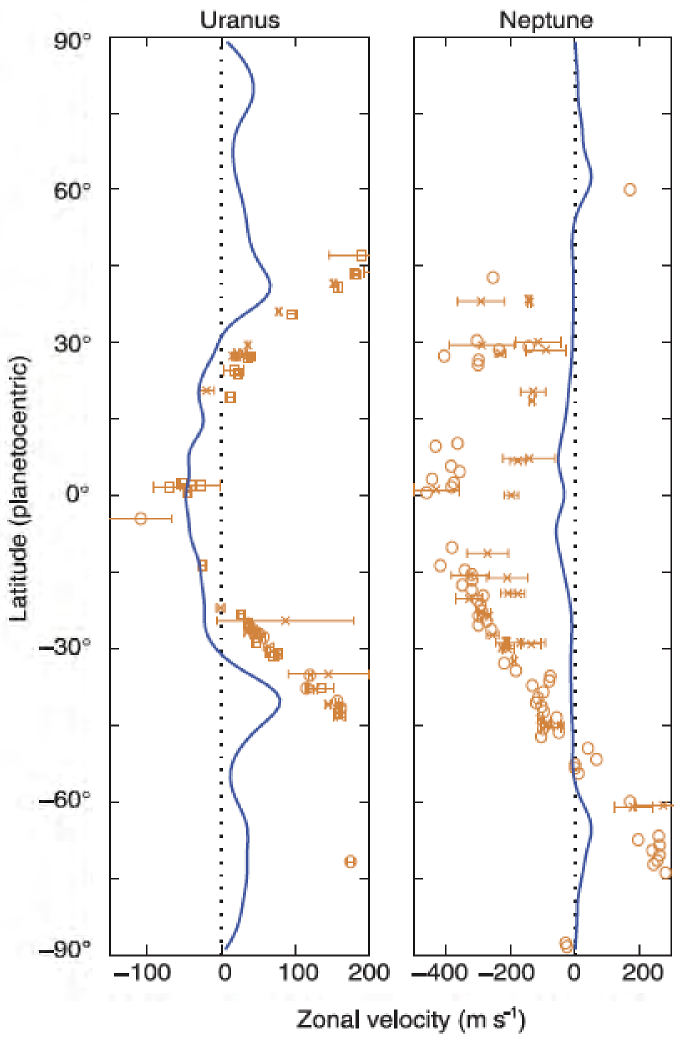
Parameter	Wave 1	Wave 2	Wave 3
Location:			
Latitude	45°S	61°N	61°N
Longitude	130°E	221°E	223°E
Pressure[a] (mbars)	3–90	80–1000	4–40
Average vertical wavelength[a] ($2\pi/m$) (km)	8	9	3
Amplitude in temperature[a] (K)	0.2–1	~0.1	~0.2
Figure showing vertical structure	8	9	10
Aspect ratio, m/k_1	>17	>20	>17

[a] Estimate based on neglect of horizontal structure of wave.

Voyager 2 (Hinson et al. 1993)

Uranus and Neptune in GCMs?





- Primitive equations in a ‘weather layer’ (Liu & Schneider 2010)
- Realistic (sort-of!) solar and internal heating, planetary radius and rotation rates
- BUT……
  - Base at only 3 bars!
  - “MHD” bottom drag
  - Earth-like obliquity….
  - Relatively weak zonal flows….
- Plenty of room for improvement!

Outstanding challenges for future probes? - many uncertainties!

- Zonal winds at depth
  - How do they vary (in space and time)?
  - Roles of solar insolation vs internal heating? – radiative fluxes…?
- Global transport circulations
  - How to reconcile thermal and compositional variations?
  - Widely different patterns in stratosphere and troposphere?
- Zonal bands
  - How are they driven and maintained?
  - Role of waves and eddies – local or non-local inverse energy cascades? Which kinds of eddy?
- Large vortices
  - Origin and maintenance, Life cycles?
  - Why only on Neptune?
- Seasonal storms
  - Origin and driving processes?
  - Moist convection? How deep?
- Small-scale processes?
  - Gravity waves?
  - Layered convection?

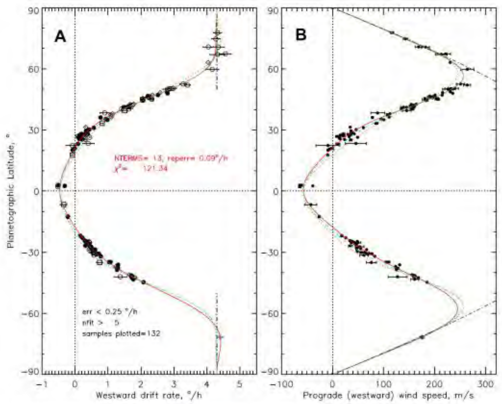


Fig. 11. As in Fig. 10 except that we here combined 1997–2005 HST and Keck observations with 2009 HST observations and 2007–2011 Keck and Gemini observations and carried out a 13-term Legendre polynomial fit. For this data set, Table 6 shows that the asymmetric fit is significantly better than the symmetric fit.