“Bending over backwards”?
- PV staircases or “hyper-staircases” in gas giant atmospheres

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Introduction

- Gas giant planets often cited as archetypal examples of PV staircases
  - Zonally banded clouds
  - Alternating parallel zonal jet streams
- Very different from Earth
  - Huge size: radius a = 71,400 km [Jupiter]
    a = 60,330 km [Saturn]
  - Composition: mainly H_2 + He
    [fluid throughout except for ”small” solid core]
  - Neutral convection/weather layer of depth
    D ~ 3000 km (~0.04a) [Jupiter]
    D ~ 9000 km (~0.15a) [Saturn]
  - Fast rotation:
    τ_r = 9.93 hours [Jupiter]
    τ_r = 10.57 hours [Saturn]

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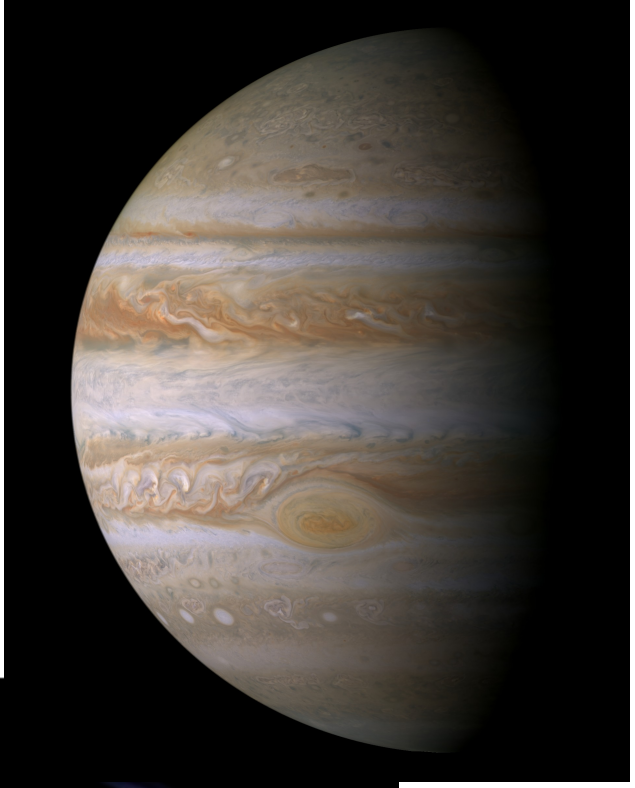
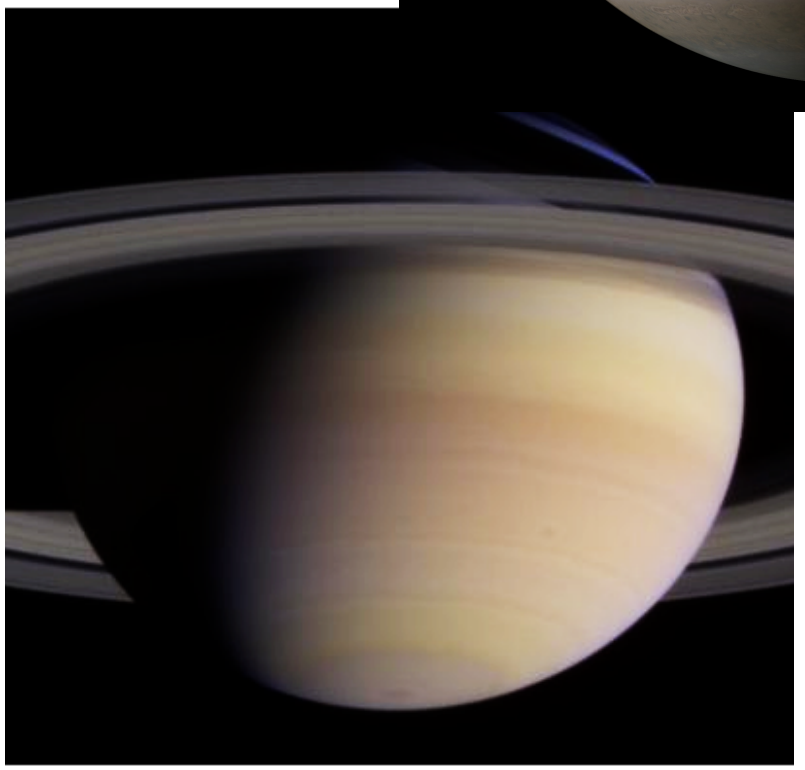
NASA/JPL Cassini ISS





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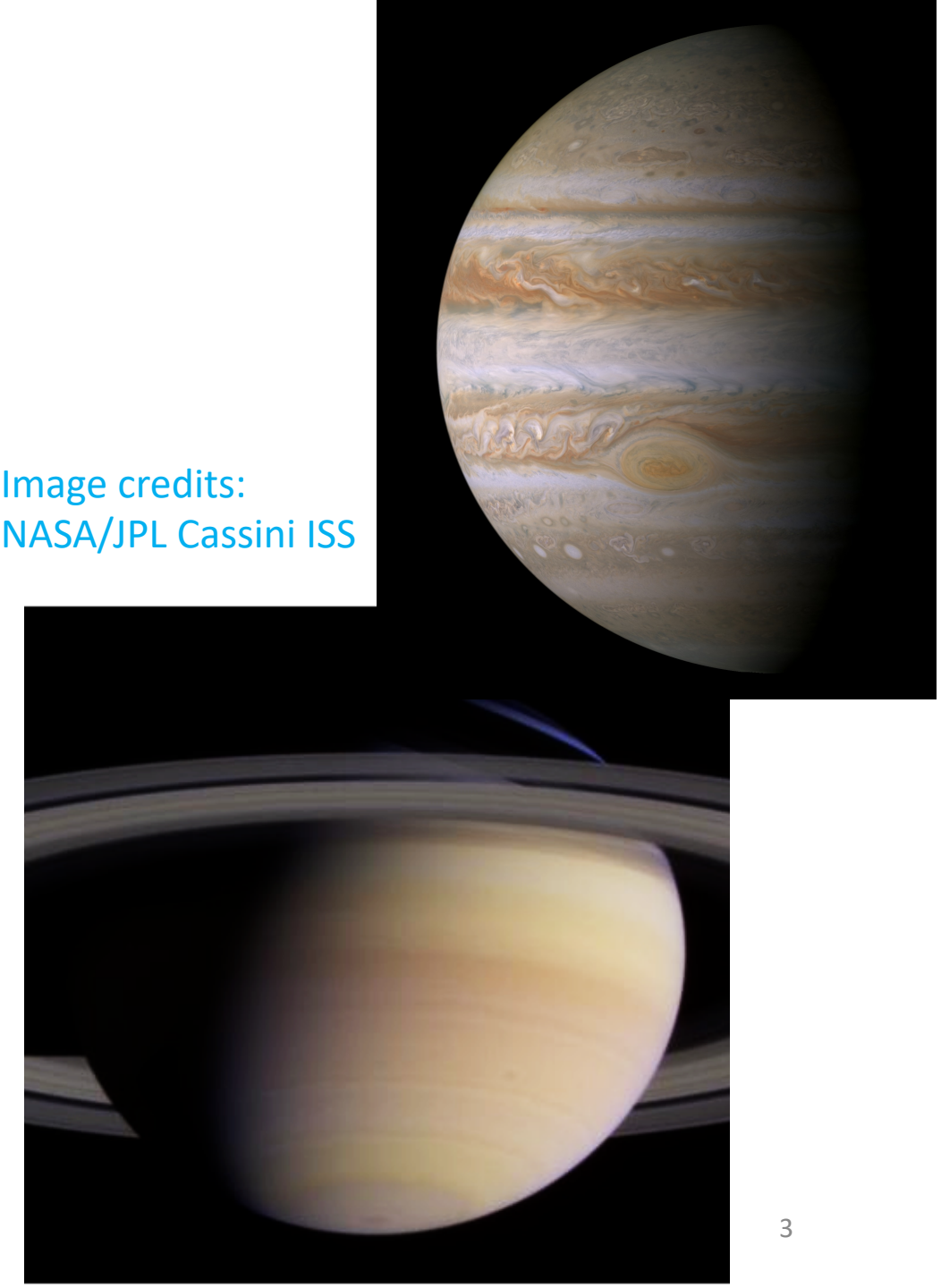
  - Composition: mainly H_2 + He
    [fluid throughout except for ”small” solid core]
- Key lengthscale parameters:

  Rhines $L_R \sim \left(\frac{u}{\beta}\right)^{1/2}$ ~ Jet scale;

  Anisotropy $L_\beta \sim \left(\frac{\varepsilon}{\beta^3}\right)^{1/5}$; L_R/L_β ~ 6;

  Rossby deformation (1st bc) $L_{D1} \sim \frac{ND}{2\Omega \sin\varphi}$ ~ 10^3 km;

  $L_R/L_{D1} \geq 10$; $L_{D1} \sim L_{forcing}$



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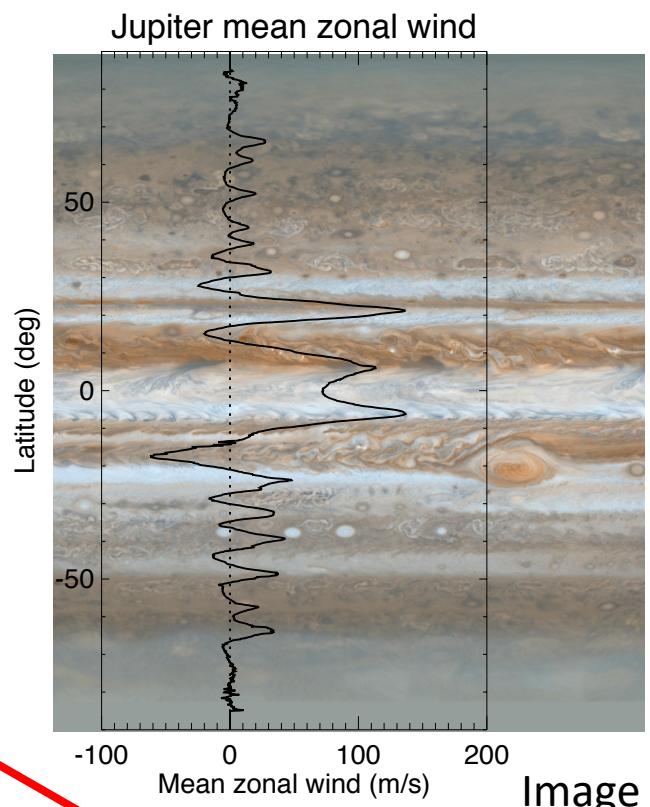
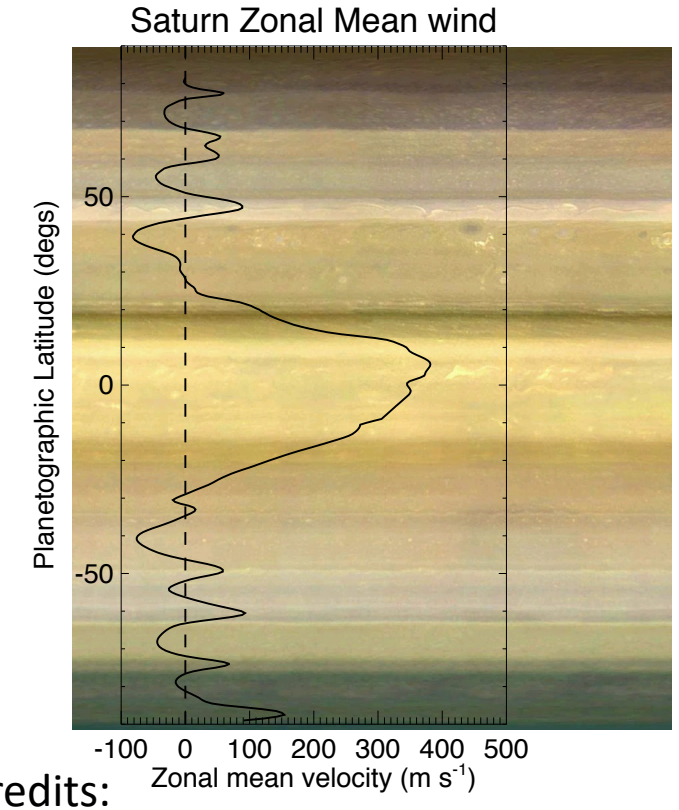
QUESTIONS:

- How good is a staircase as an interpretation of their PV structure?
- Staircase or “hyper-staircase” as asymptotic stable state?
- How is this layered structure in latitude generated and maintained?
  - Inhomogeneous mixing [Phillips, McIntyre etc.]
  - Roles of Rossby waves, barotropic and/or baroclinic instabilities, deep convection…..?





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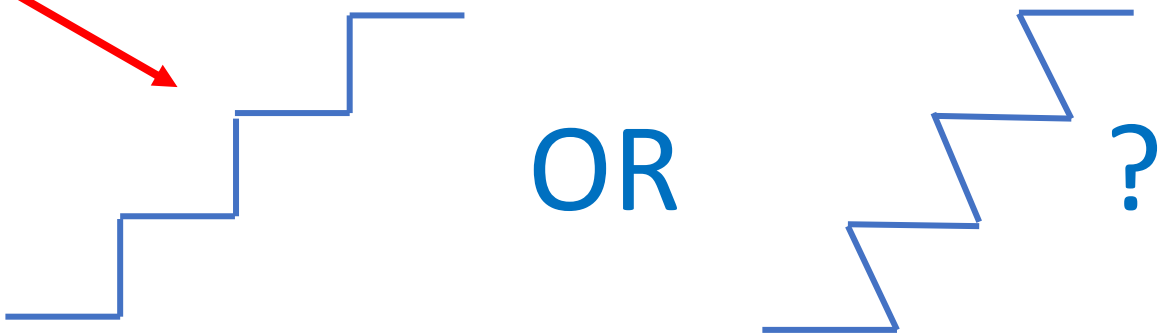


Jupiter: zonal flows as as PV staircase

- Idealise PV distribution as a perfect staircase (monotonic with latitude φ [Marcus 1993 ARAA; Marcus & Lee 1998 Phys. Fluids]
- Leads to very sharp eastward jets and broad, weaker westward flows
  - Are the real observed eastward jets this sharp….?
  - How valid is the perfect staircase as asymptotic state for real planets?

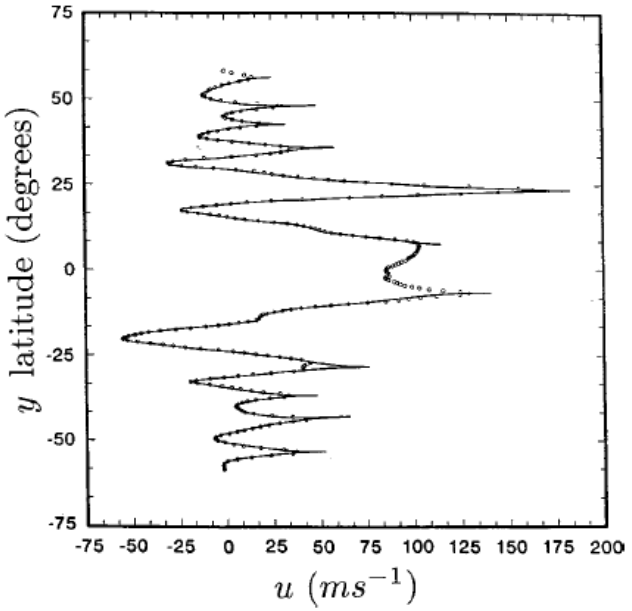


FIG. 1. Jovian east–west velocity u as a function of latitude y. The circles are the measurements[9] and the solid curve is a theoretical fit.[6] The velocity is not QG near the equator, so there is no QG fit.

simulate the flows to obtain information not readily available from experiments, c.f. instantaneous flow velocities **U** and potential vorticities q. (One point of this paper is that averaged values of **U** and q are misleading.) With this insight we construct a model that quantitatively reproduces the experiments. Most of this paper is devoted to validating our model and comparing it to a competing model based on a Bickley jet.[2,3,12] Determining which model is correct is important for several reasons. These laboratory flows have been used as examples of the Hamiltonian dynamics of passive Lagrangian tracers.[12] When seeded with tracers, the flows show re-

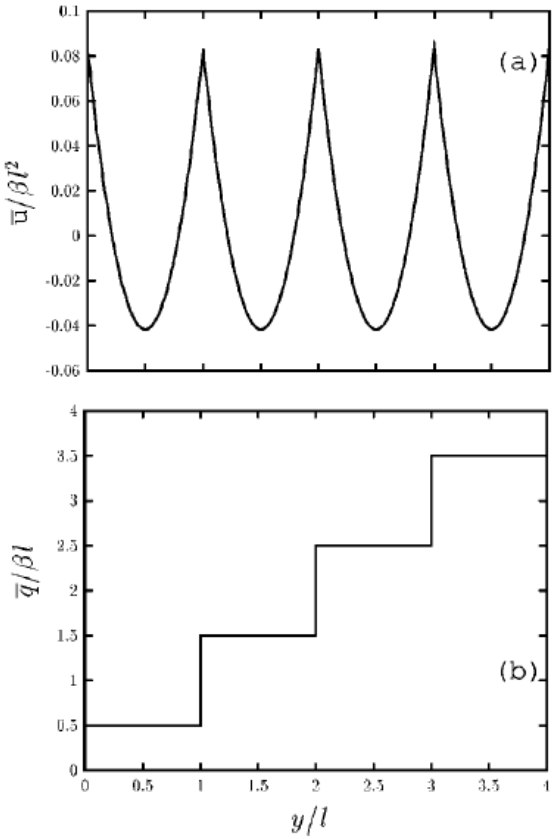


FIG. 2. (a) Model $u(y)$ as a function of latitude y for the jovian east–west velocity inferred from vortex dynamics.[6] Eastward (westward) jets have $u>0$ ($u<0$). The u is piecewise parabolic. (b) the $q(y)\equiv\beta y-du/dy$ for (a). This u and q also model the flow in an experiment with multiple slits in the bottom boundary (see section VII). Near each slit a region with uniform q grows in size until it runs into its neighbor. This creates a step function in q with step width l and step height $\Delta\bar{q}=\beta l$. As in the model in figs. 8 and 9, $q=\beta y$ when there is no pumping. In the model, eastward jets are always located at the maxima of $|\nabla q|$ and the westward jets at the minima.

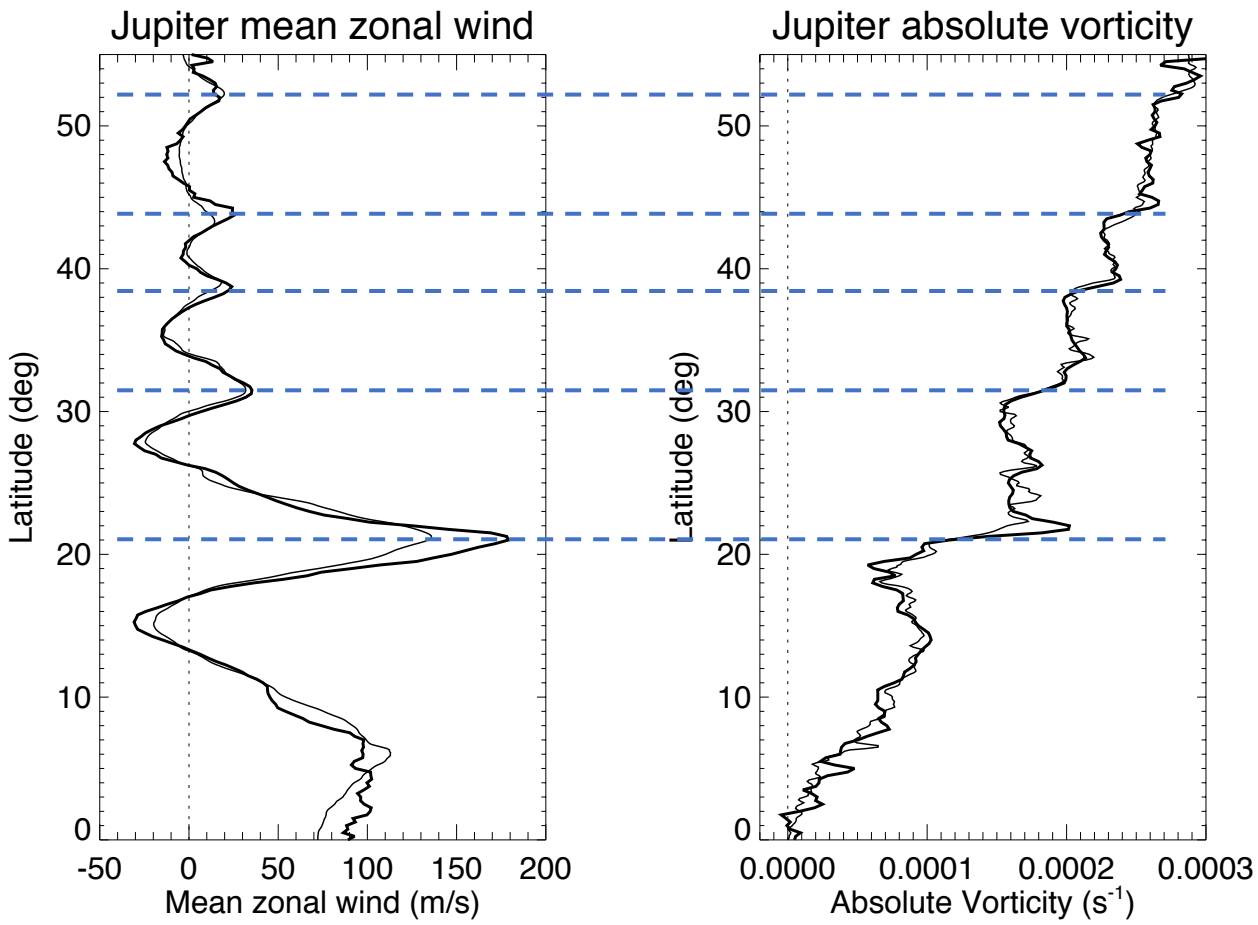
Jupiter: observed staircases in absolute vorticity

- Zonal mean zonal wind $\bar{u}$ measured from cloud tracking
  - Thick line = Voyager 1 & 2 [1979]: 0.25° resolution in latitude φ
  - Thin line = Cassini ISS [2000]: 0.1° resolution in φ
- Absolute vorticity computed as

$$\zeta_a = 2\Omega \sin\varphi - \frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}(\bar{u}\cos\varphi)$$

- Sharp eastward jets exhibit jumps in ζ_a
- Westward jets broader with weak (~negative) gradients in ζ_a
- **…..Hyper-staircase?**
  - Can it be a stable equilibrium…? OR
  - Perhaps it's just a transient effect [observations are snapshots!]? OR
  - Maybe unresolved vertical/thermal structure "straightens" backward-facing profile in **potential** vorticity…?

$$q = \frac{(2\Omega + \nabla \times \mathbf{u}) \cdot \nabla\theta}{\rho}$$

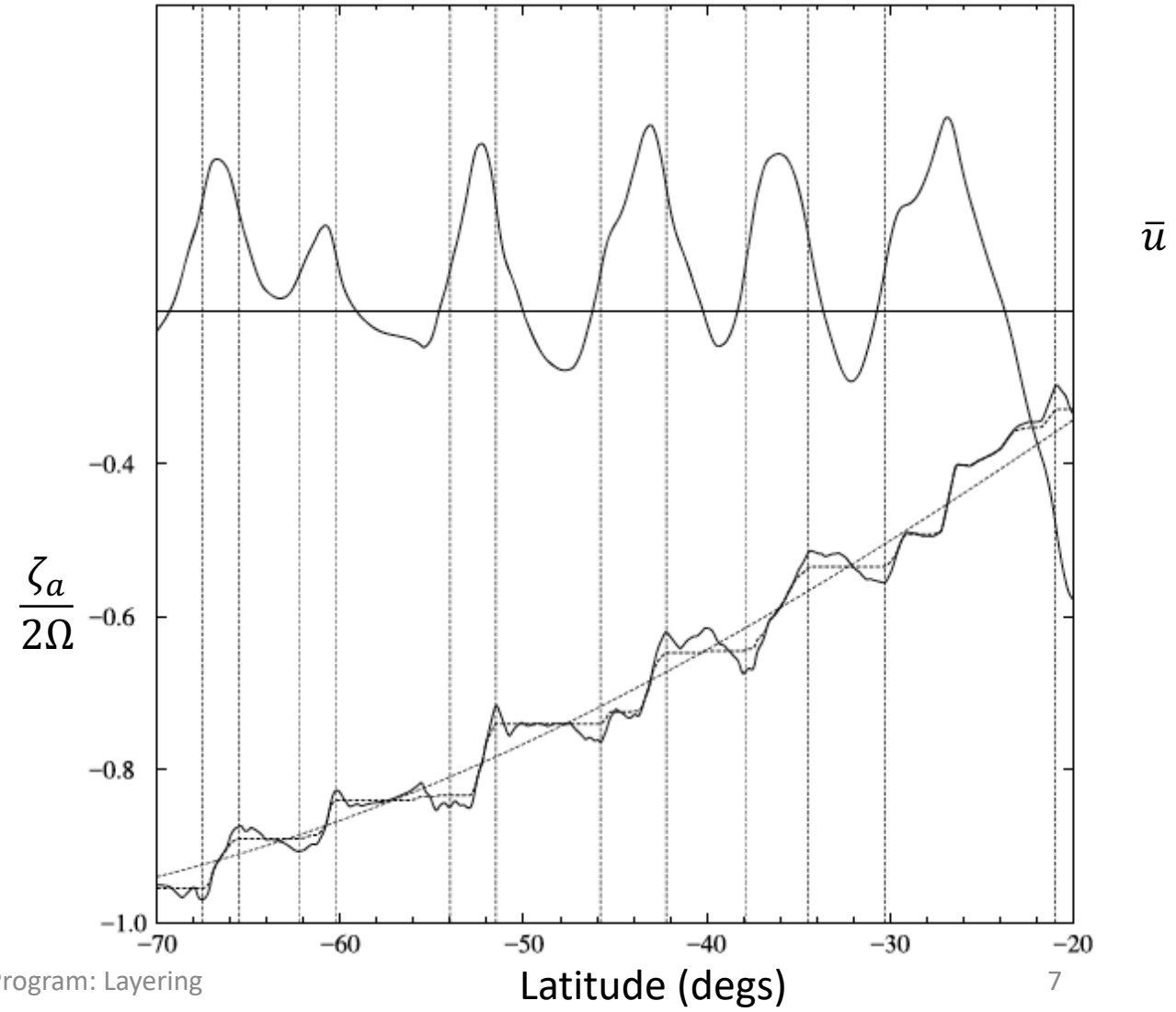


Smoothing a hyperstaircase: vertical structure?

- How might the vertical or thermal structure of the atmosphere allow a PV staircase look like a hyper-staircase in local absolute vorticity?
- E.g. solve for modified static stability

$$\alpha := \frac{\theta'_z}{\theta_{0z}} = \frac{\zeta_a^{\text{mon}}}{\zeta_a^{\text{obs}}} - 1.$$

  - Where ζ_a^{mon} is monotonic rearrangement of observed ζ_a^{obs} [Scott & Dunkerton 2017 GRL]
- Consistent with observations…?



Measuring PV on Jupiter and Saturn

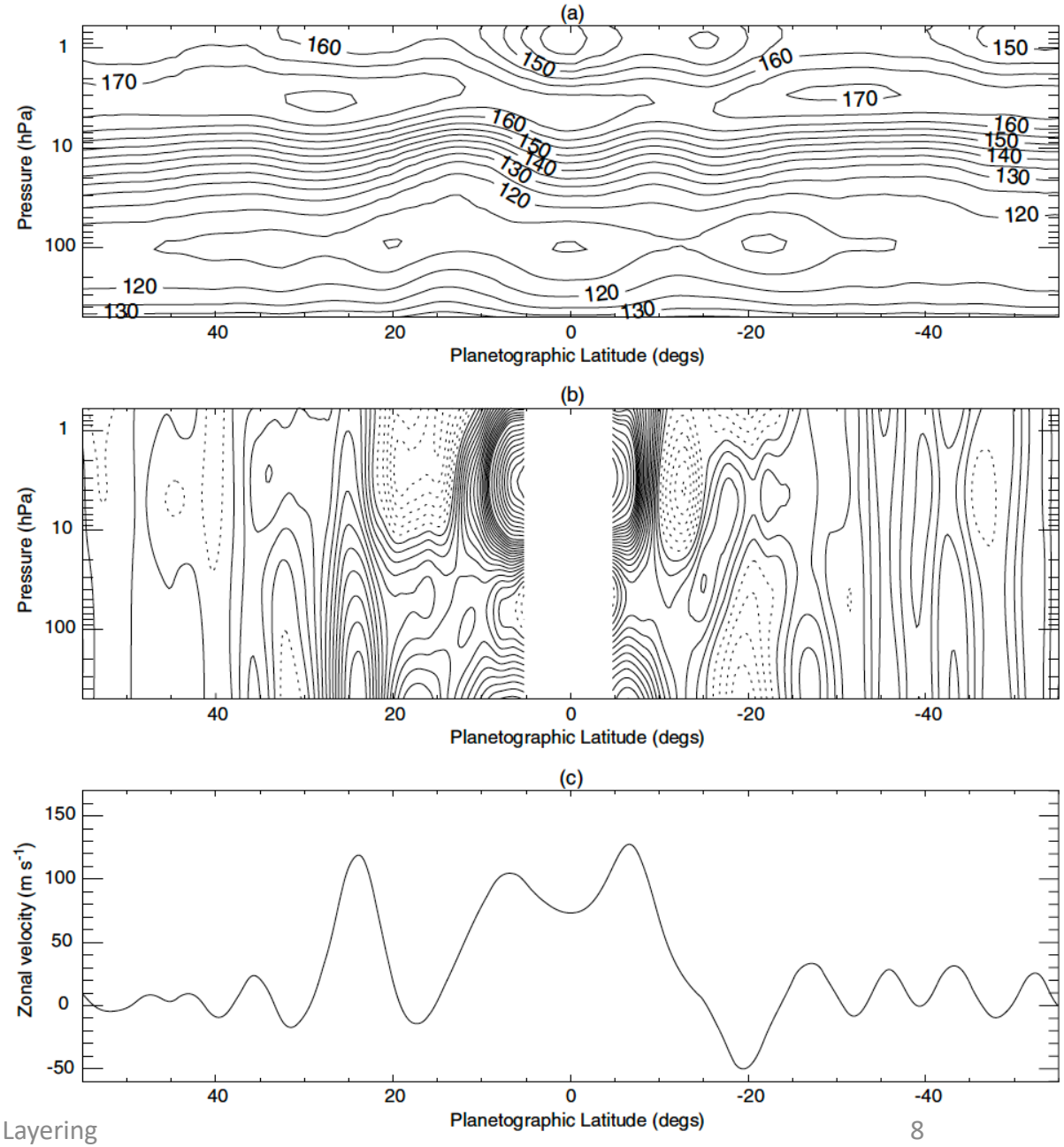
- Ertel PV defined by

$$q = \frac{(2\Omega + \nabla \times \mathbf{u}) \cdot \nabla\theta}{\rho} \simeq \frac{(f + \zeta_\theta)}{\rho}\frac{\partial\theta}{\partial z} \simeq -g(f + \zeta_\theta)\frac{\partial\theta}{\partial p},$$

- Approximated at large Ri to

$$q_{\mathrm{E}} \simeq -g(f + \zeta_p)\frac{\partial\theta}{\partial p},$$

- Derive q_E from measured temperature retrievals and thermal winds (using cloud-tracking) [Read et al. 2006 QJRMS]



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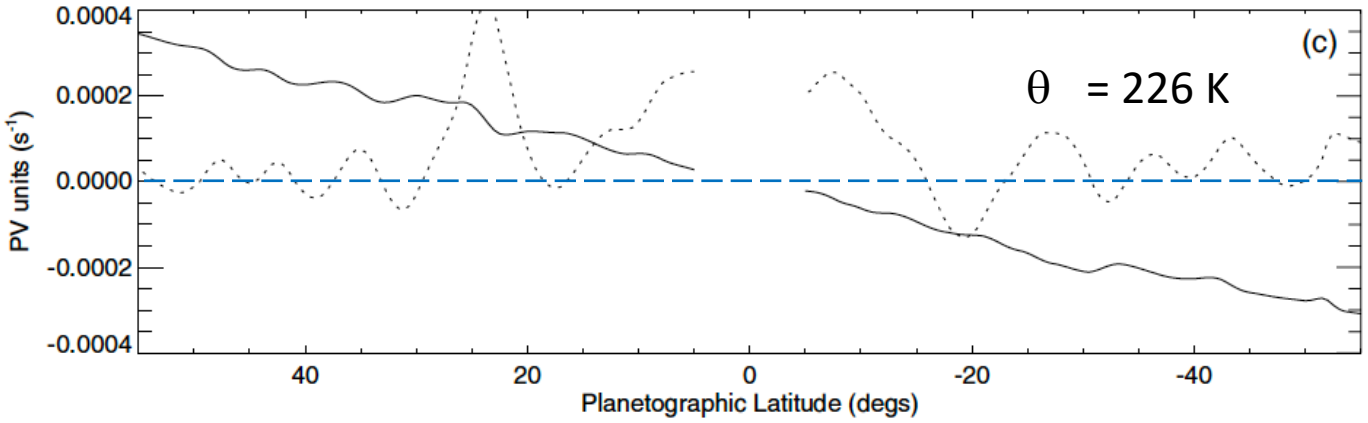
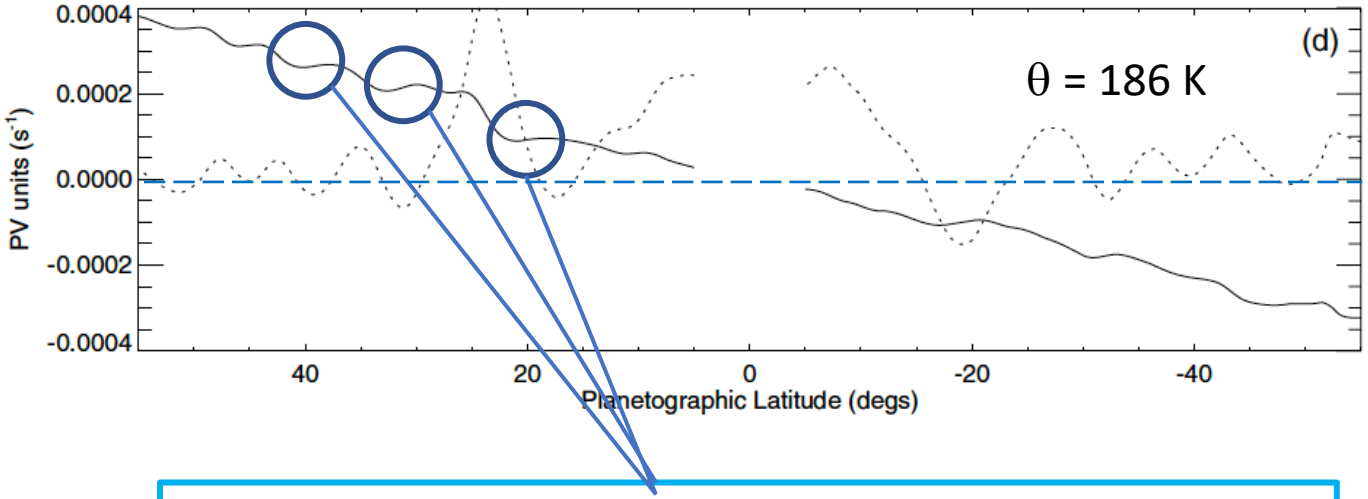


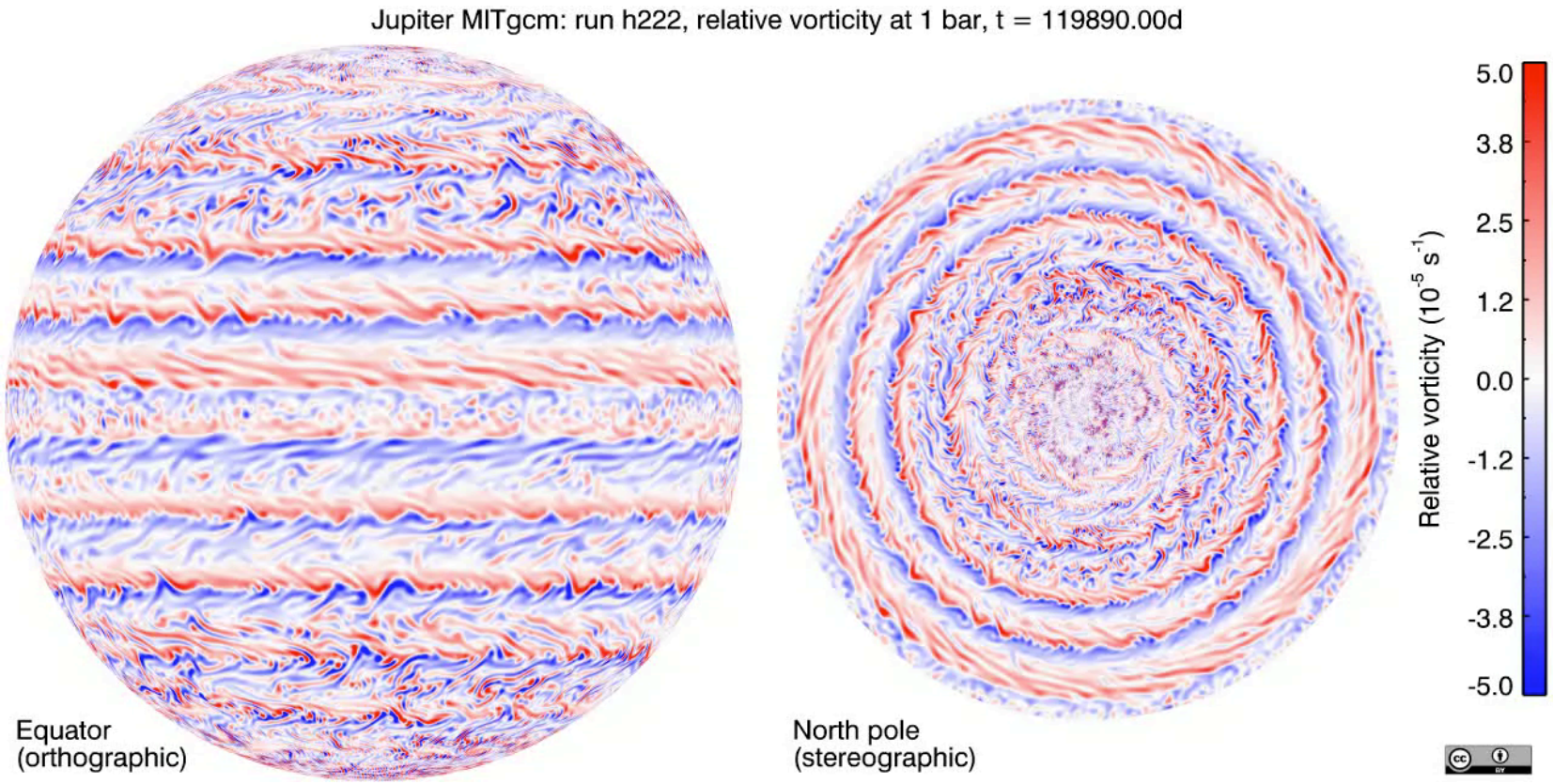


- Backward-facing overshoots in $q_E(\varphi)$ are still observed, despite measured variations in $\partial\theta'/\partial p$

[Run on UK STFC DiRAC supercomputer]

Oxford/MIT-gpm (JASON - Young et al. 2019 Icarus)

- Global atmospheric circulation model for Jupiter troposphere/stratosphere [~20bar –10mb]
- Based on MITgcm dynamical core
  - 0.7º x 0.7º to 0.3º x 0.3º x 33 vertical levels
  - Weak "MHD" drag at bottom
- 2-band "semi-gray" radiation scheme
- Interior heat flux (uniform w. latitude) = 5.7 W m^{-2}
- Passive condensible clouds
- Moist convection parameterization
  - Zuchowski et al. (2009 Icarus)

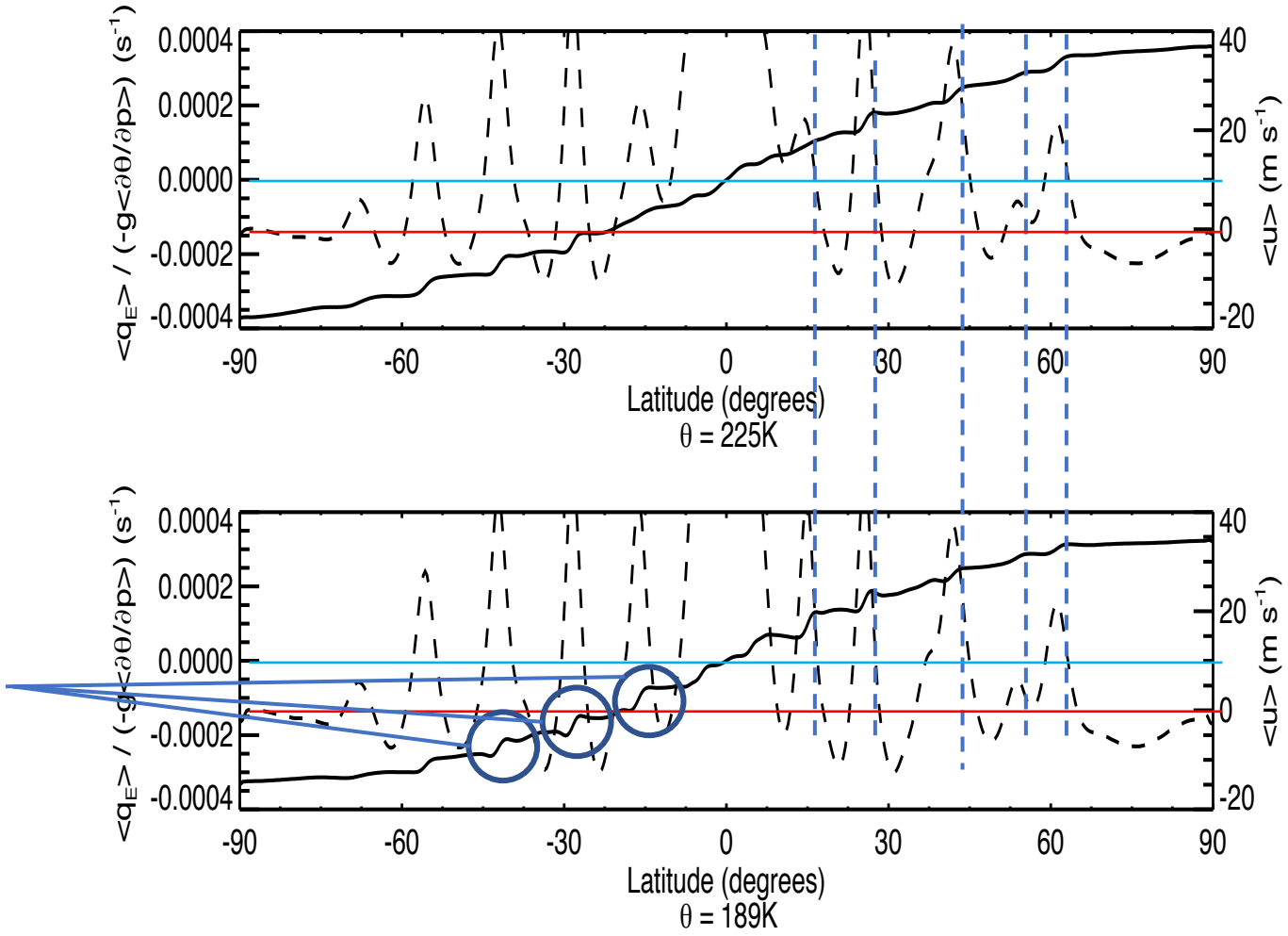


Jupiter simulated: staircases in PV?

- Compute zonal mean q_E from model fields at full spatial resolution using

$$q_{\mathrm{E}} \simeq -g(f+\zeta_p)\frac{\partial\theta}{\partial p},$$

- Take long time average [1000 days] to filter out transient variability
- **Over-shooting hyper-staircases persist!**
  - **But How….?**



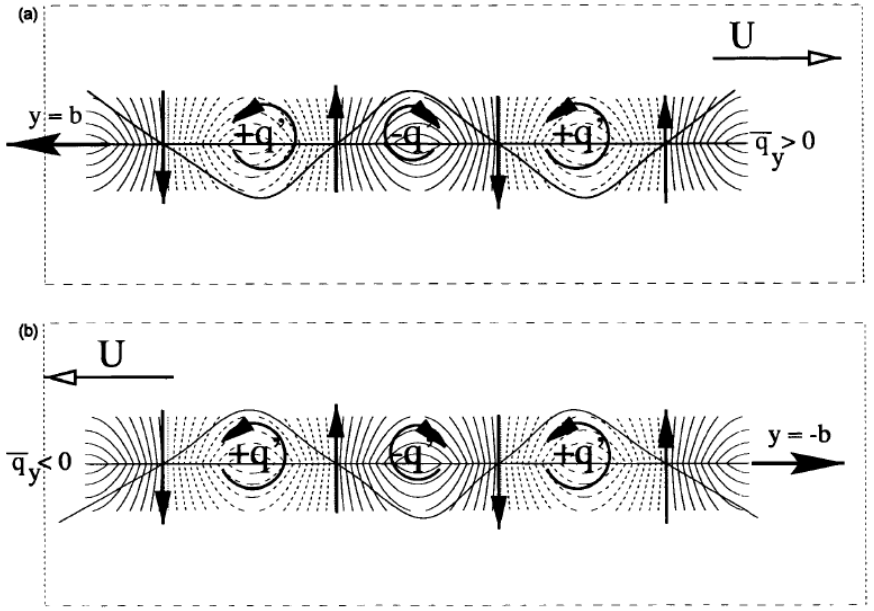
Counter-propagating Rossby waves & Arnol'd II stability

- Stability argument based on pseudo-energy $\mathcal{H}$: stability implied if $\mathcal{H}$ is negative-definite.
  - Leads to sufficient condition for stability (Arnol'd 1966 – known as "Arnol'd II")

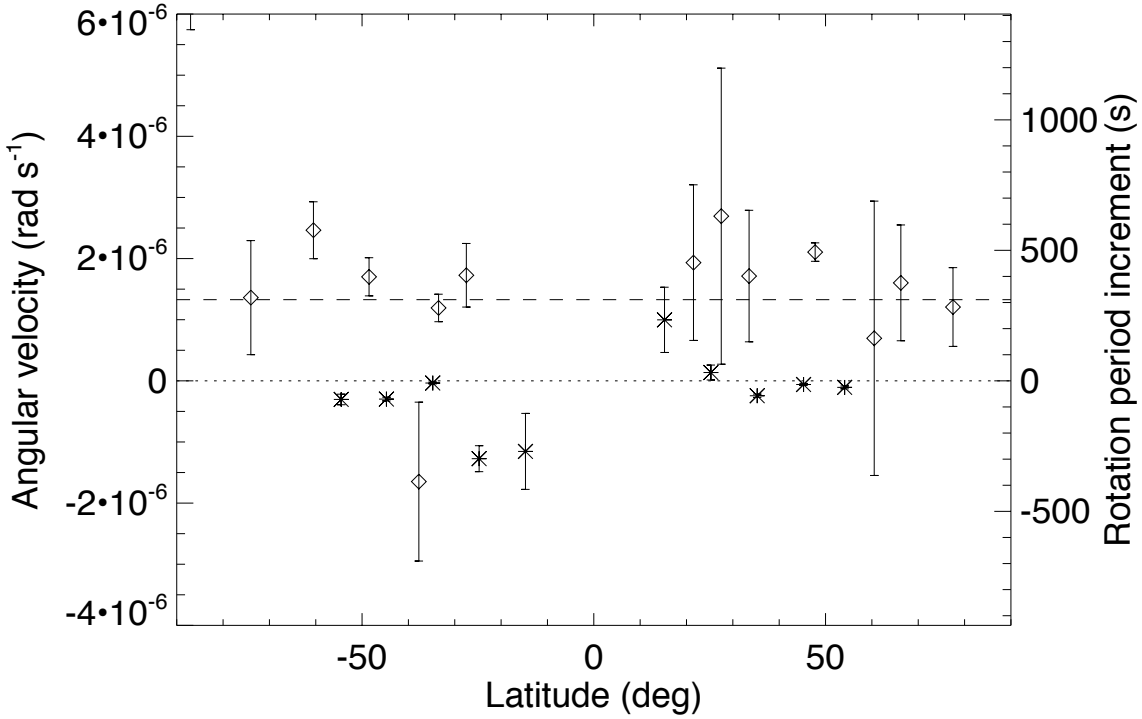
$$-\frac{d\Psi}{dQ} = -\frac{d\Psi/dy}{dQ/dy} = \frac{U-\alpha}{\frac{dQ}{dy}} \geq L_d^2$$

  - where α is a constant
- At marginal stability, $\geq \rightarrow =$ and α defines unique reference frame where the gravest edge waves (largest L_d) can just phase-lock….
- Barotropic adjustment as self-organized equilibrium state on Jupiter and Saturn….?
  - [Dowling 1993 *J. Atmos. Sci.;* Dowling 2020 *Plan. Sci. J.*]

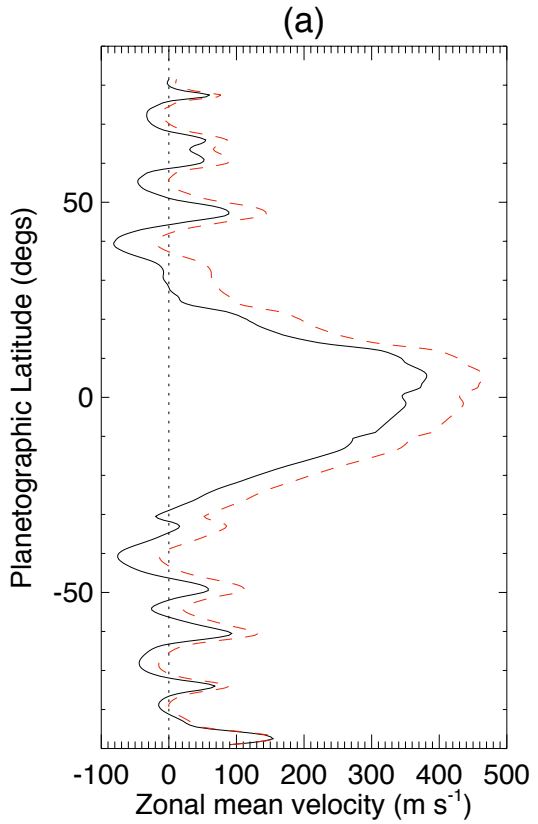
Rossby edge waves



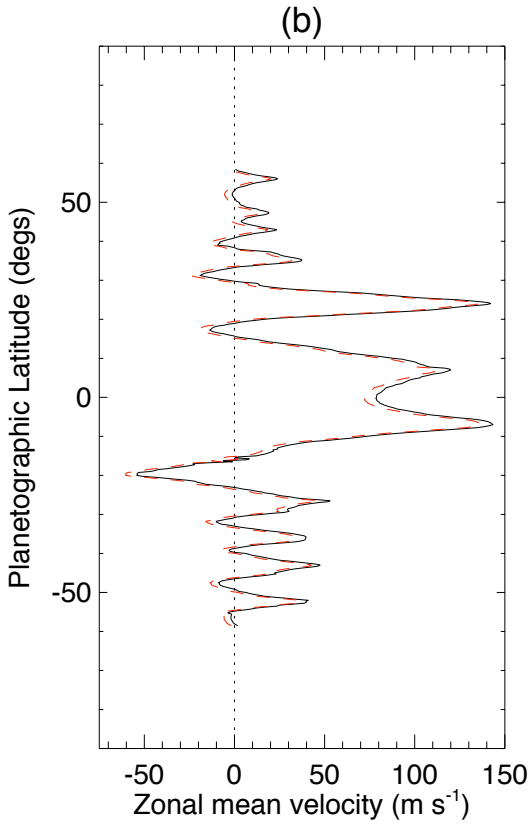
Application: measuring Saturn's interior rotation using hydrodynamic stability!



Voyager ------



Saturn

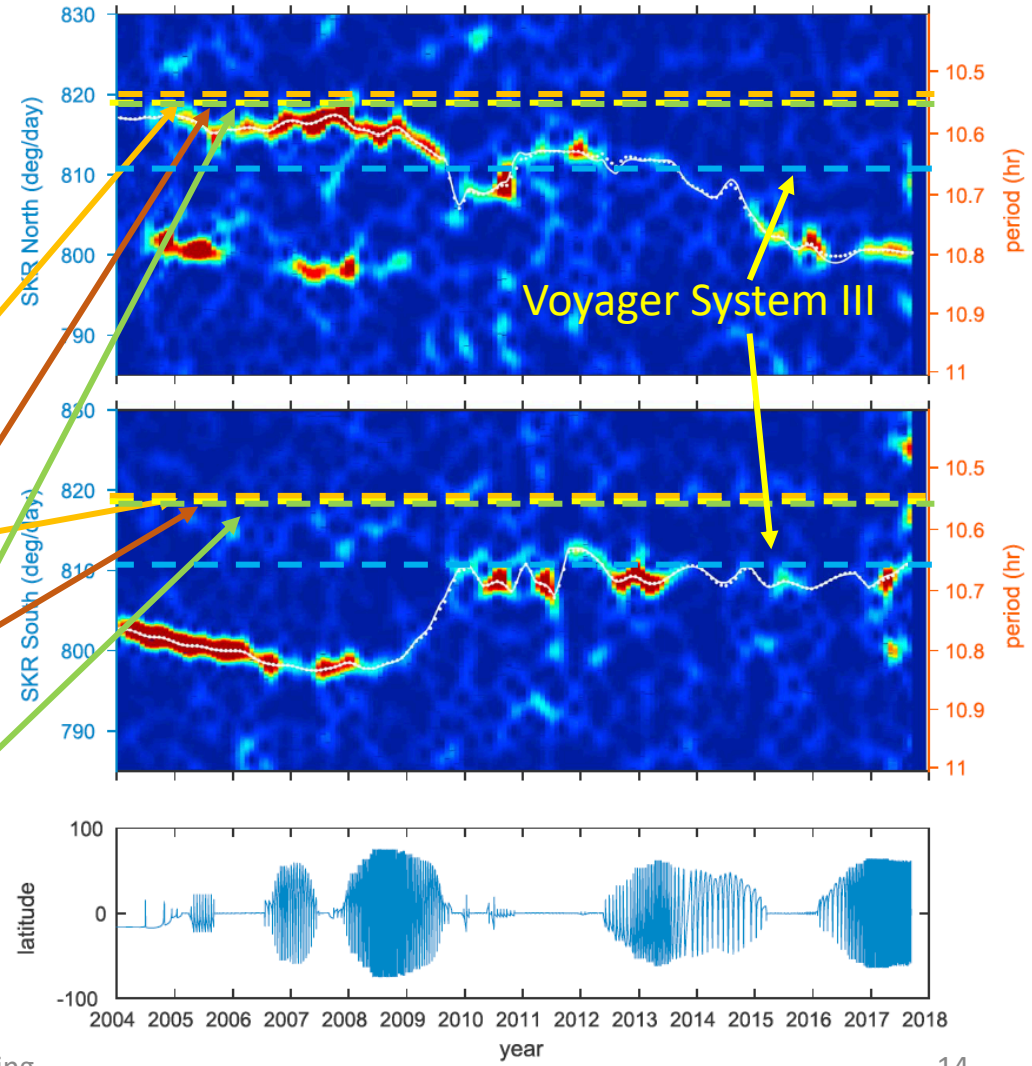


Jupiter

- Correlate $\bar{u}$ vs $d\bar{q}/dy$ in latitude bands to determine L_d, $\alpha(\phi)$ and corresponding $\Omega(\phi)$
- **Result: a unique Ω for each planet (to within statistical errors)!** [Read et al. 2009 Nature]

Saturn's interior rotation rate - a mystery?

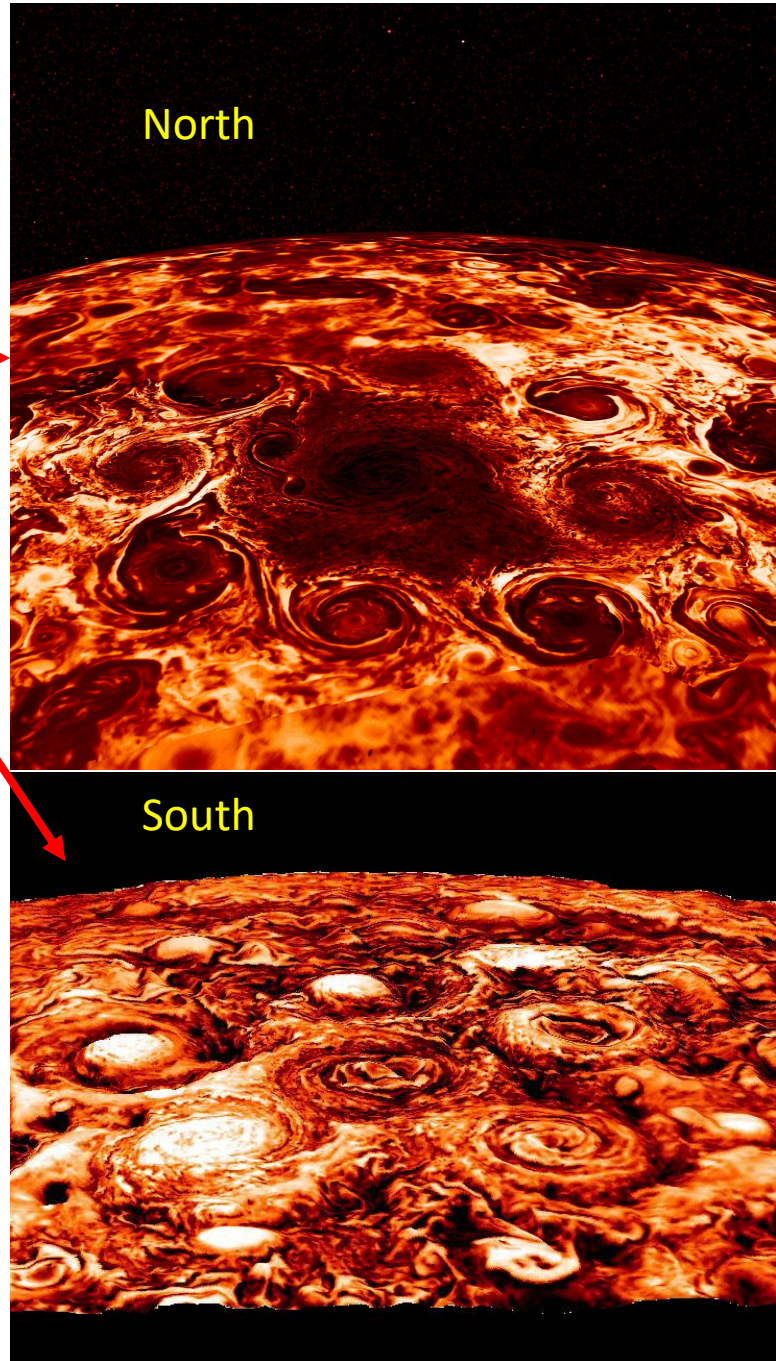
- Saturn's magnetic field dominated by a dipole aligned with its rotation axis (±<0.007°)!
  - Periodicity only in very low radio frequency emissions – locked to the interior…..?
  - First measured by Voyager fly-by in 1982
  - Monitored by Cassini orbiter from 2004-2017 and found to vary in time!!
  - Cf rotation period estimated from gravity field and oblateness (Anderson & Schubert 2007)?
- Hydrodynamic marginal stability value (Read et al. 2009 Nature)
  - agrees with Anderson & Schubert (2007)
- Recent confirmation from Cassini "ring seismology" (Mankovitch et al. 2019)



From Ye et al. (2018) GRL

Conclusions

- Jupiter (and Saturn) exhibit staircase-like structure in both absolute and potential vorticity, aligned with zonal jets near cloud-tops [except at high latitudes?]
- Staircases typically have overshoots with latitude –> hyper-staircases, which are apparently persistent
  - Zonal jets vary only weakly over timescales ~decades-centuries….
  - Hyper-staircase structure is consistent with near-neutral barotropic stability -> self-organized criticality?
- Mechanisms for maintaining (hyper-)staircase?
  - Weak Rossby wave breaking – cf “scouring”?
  - Baroclinic instability [forcing?]
  - Deep convection?
  - ……?



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