Saturn’s Polar Atmosphere

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Chapter Outline

1. Introduction (Kunio):

Review Voyager observation of north polar region (including the north-polar spot) by Voyager (there wasn't much except for Godfrey et al.) (1-2 pages)

2. South Polar Region (Ulyana, Kunio and Agustin):

South Polar Vortex has already been reviewed in the 2009 book, so the focus here will be to establish the context for the north polar vortex for comparison. (2 pages)

3. Northern Hexagon (Kunio, Agustin, Bob, Leigh, Peter and Kevin):

Morphology observed in multiple wavelengths (CIRS, VIMS and ISS), Thermal structure, and aerosol composition/structure. Numerical modeling and laboratory models (3-4 pages)

4. North Polar Vortex (Kunio, Bob, Leigh and Kevin):

Parallel structure to the hexagon section, but focusing on the polar vortex, and comparison to its southern counterpart. (3-4 pages)

5. Polar Atmospheric Dynamics (Kunio, Peter and ...?):

General review of the dynamics dynamics of polar vortices and hot spots, comparison between north and south polar vortices of Saturn, comparison to other polar vortices in the solar system. (3-4 pages).

6. Polar Stratosphere (Leigh, Bob, Peter and Kevin (?)):

Observation of stratospheric dynamics, thermal structure and aerosols by multiple Cassini instruments (CIRS, VIMS, ISS) (3-4 pages)

7. Discussions, Unanswered Questions (Everyone):

Discussion of yet to be answered questions -- theoretical/numerical model needs, future/proximal observations etc etc (2 pages)

Outline Today

1. Context of the Review

2. Observational Results
   - Polar-most jets and the Hexagon
   - Polar Vortices

3. Dynamical Modeling
   - Hexagon
   - Polar Vortices

Context of the Review

Del Genio et al. (2009) was Pre-equinox

State of the Polar Analyses in 2008:

North Pole:

- Hexagon and the pole not yet illuminated by sunlight
- Seen in IR (VIMS and CIRS) but not in visible (ISS)

North Pole Now Illuminated by Sunlight

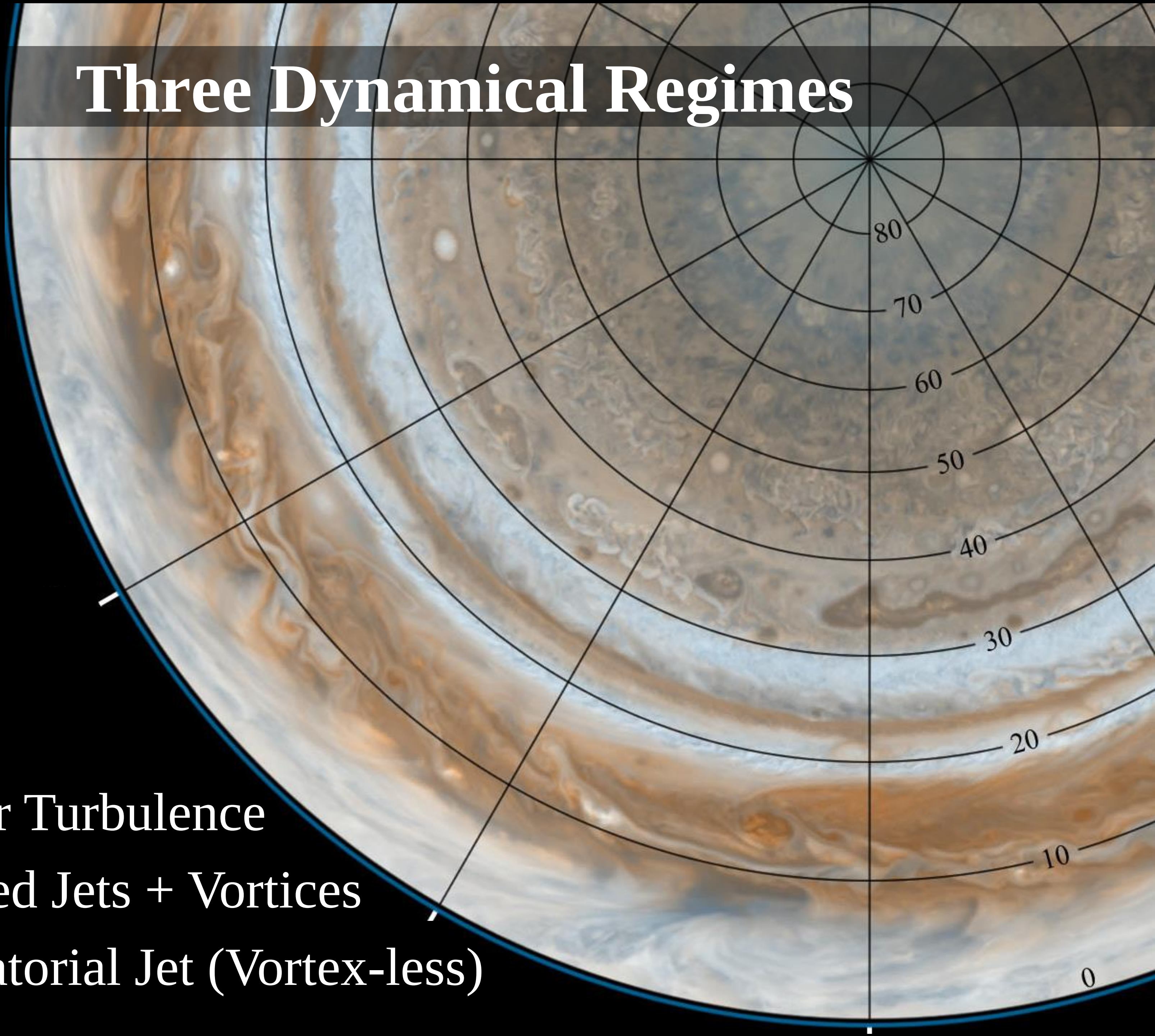
South Pole:

- Observations were done (ISS, CIRS, VIMS)
- Analyses were still under progress

More South Polar Analyses have been published

→ We Can Now Compare North and South Poles

Three Dynamical Regimes



1. Polar Turbulence
2. Mixed Jets + Vortices
3. Equatorial Jet (Vortex-less)

Dynamical Context: Transition to Polar Turbulence

Vasavada and Showman (2006) Review

Deformation Radius L_D:

$$L_D = H\,N/f$$

H ~ Characteristic Vertical Scale

N ~ Brunt-Vaisala Frequency (Gravity Wave Frequency)
$f = 2\Omega\sin\theta$ ~ Coriolis parameter.

→ L_D increases with N and decreases with f (and thus latitude θ)

Rhines Length:

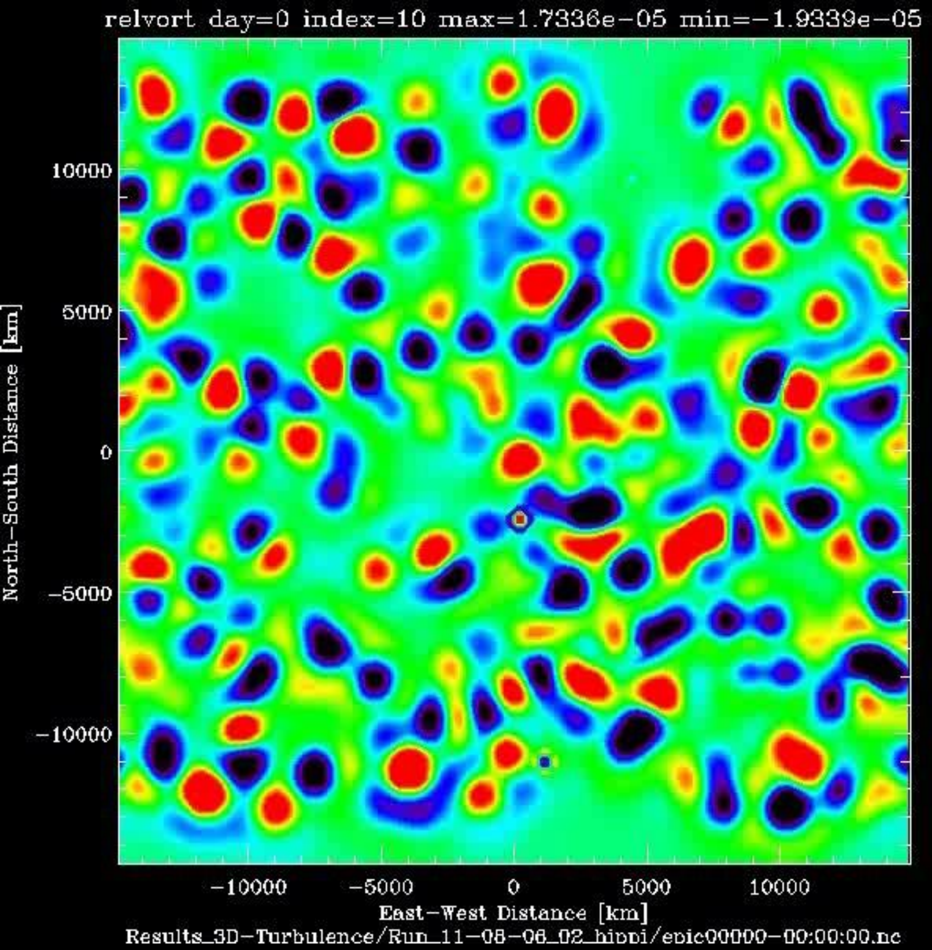
$$L'_\beta = \left(\frac{1}{L_\beta^{\;2}} - \frac{1}{L_D^{\;2}}\right)^{-1/2} = \left(\frac{\beta}{U} - \frac{1}{L_D^{\;2}}\right)^{-1/2}$$

$L_\beta = (U/\beta)^{1/2}$ ~ Rhines Length in 2D non-divergent flow (i.e., $L_D \sim \infty$)
U ~ characteristic flow speed
$\beta = 2\Omega a^{-1}\cos\theta$

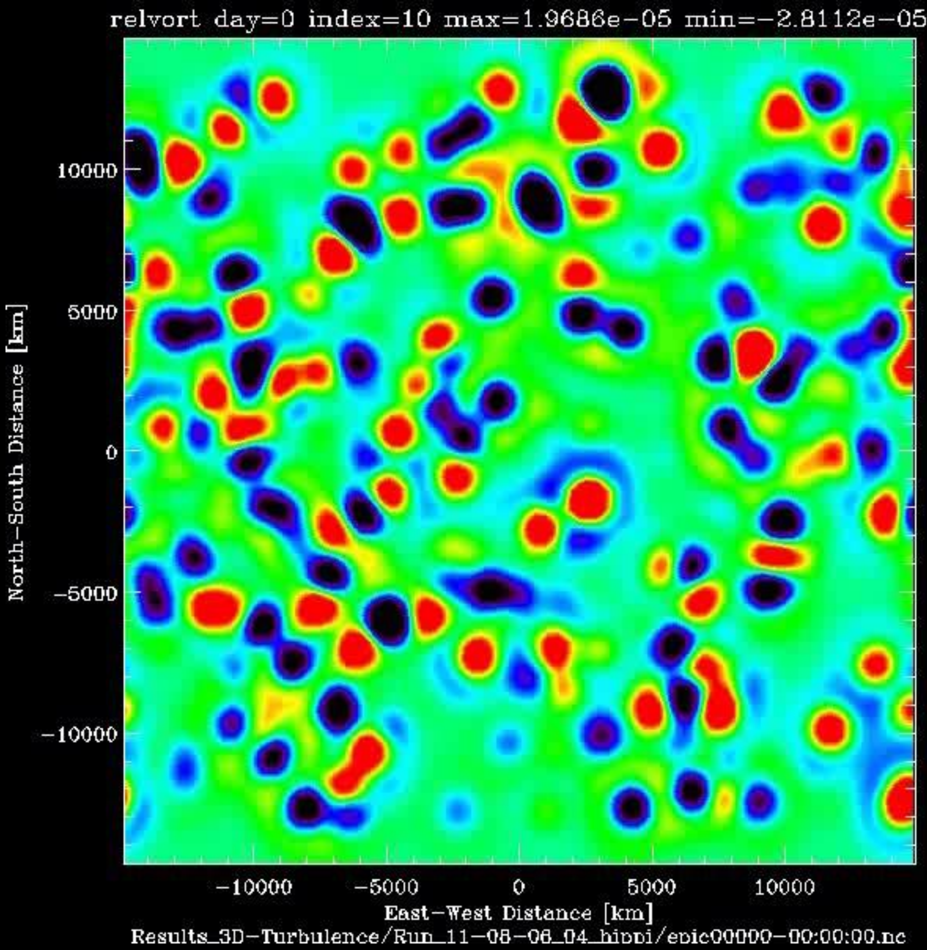
→ L_β decreases with N and β and increase with f (and thus θ)

Mid-Latitude Jets vs. Polar Turbulence

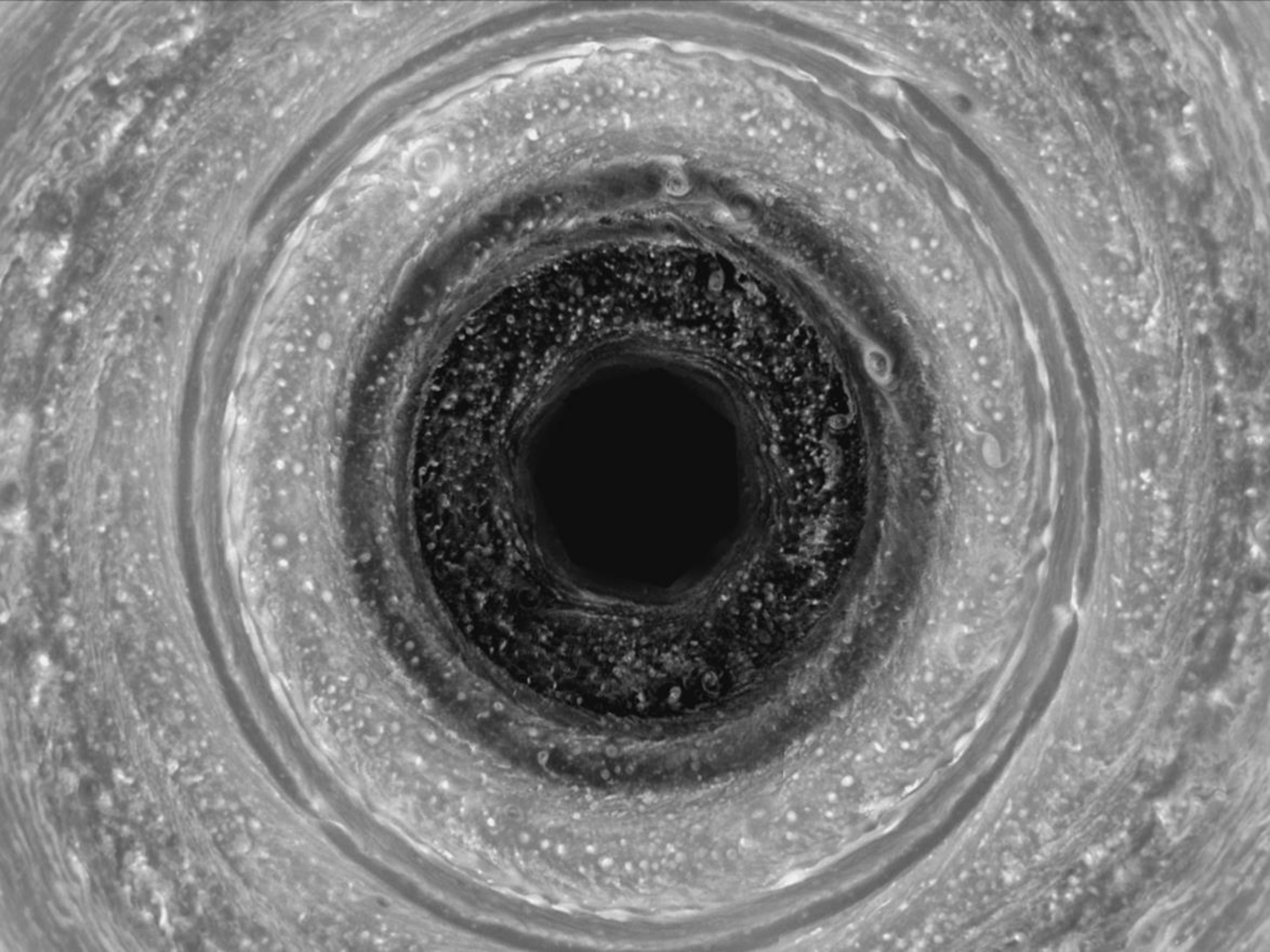
30degN Model



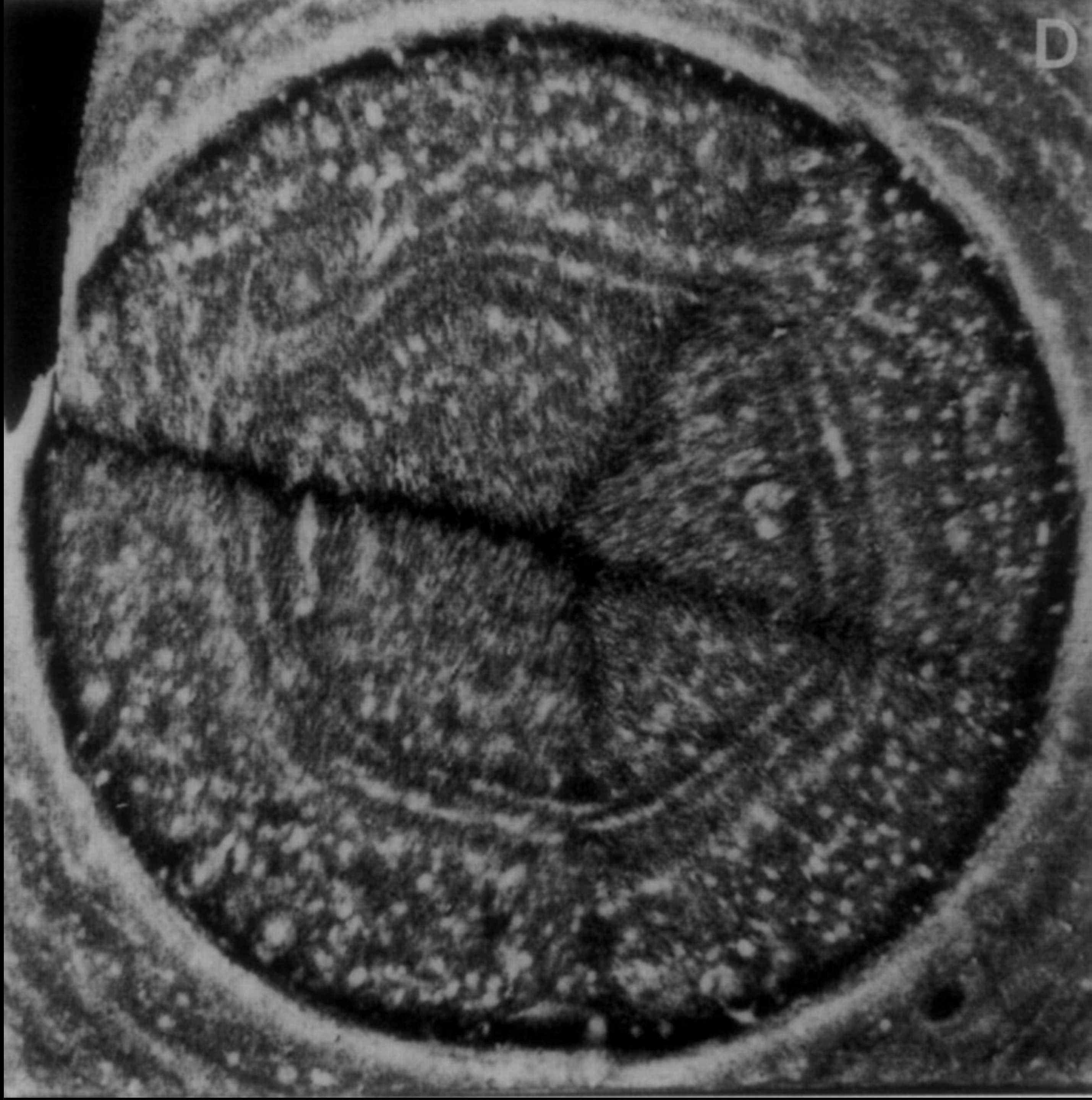
80degN Model



(Sayanagi et al 2008)



Voyager Hexagon Discovery

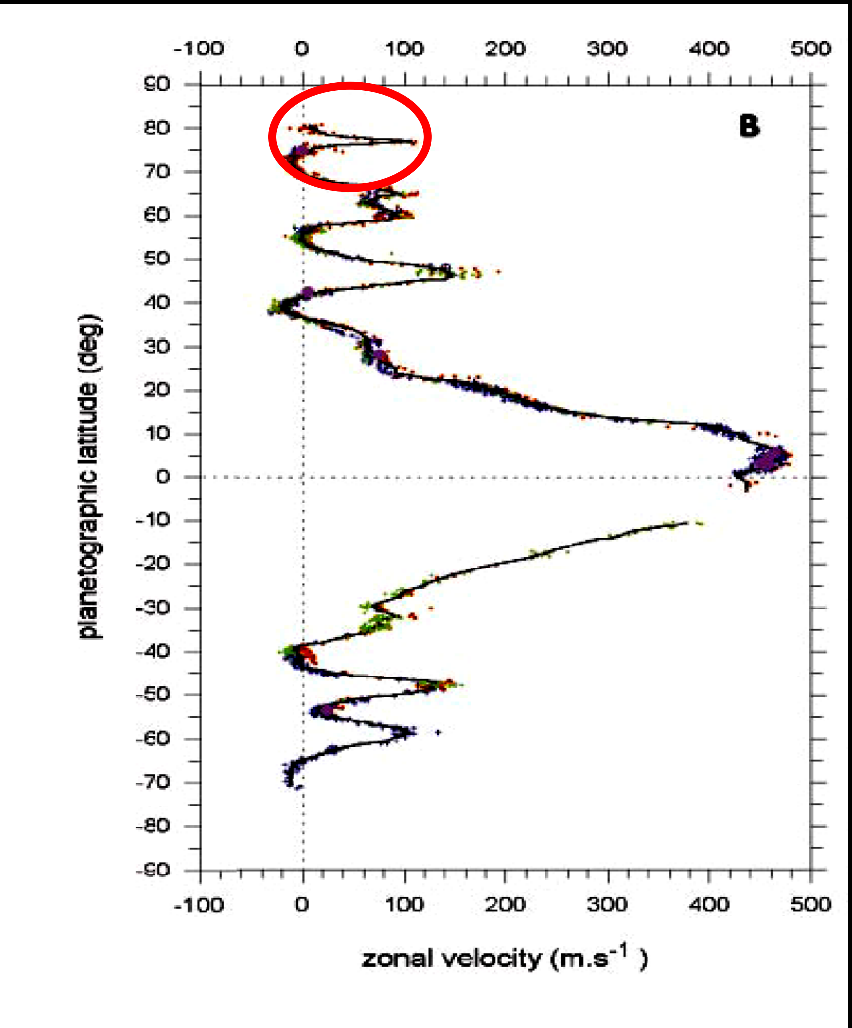


(Goddfrey, 1988)

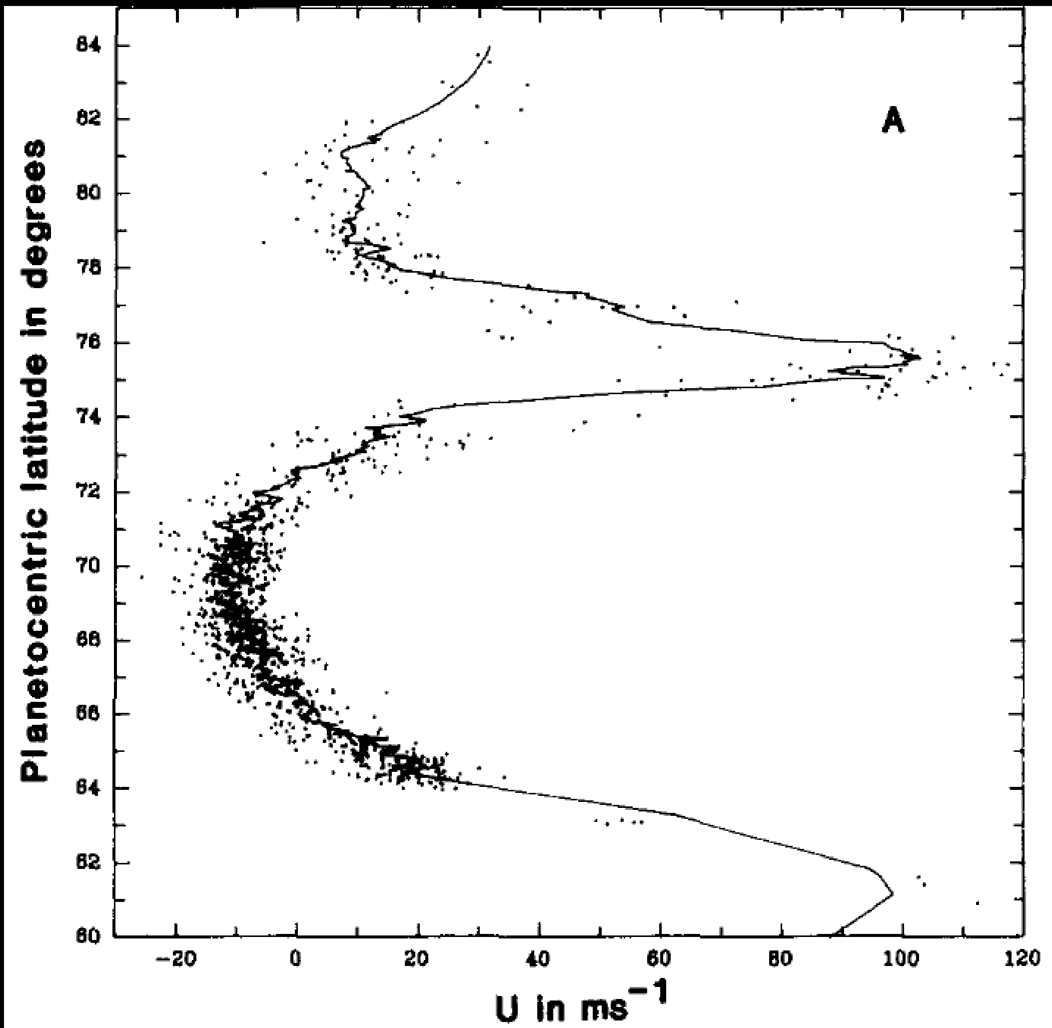
Hexagon: Northern-most Jet Stream

The hexagon is a feature in the 76ºN Jet:

Zonal wind speed on Saturn
(Sanchez-Lavega et al 2000)

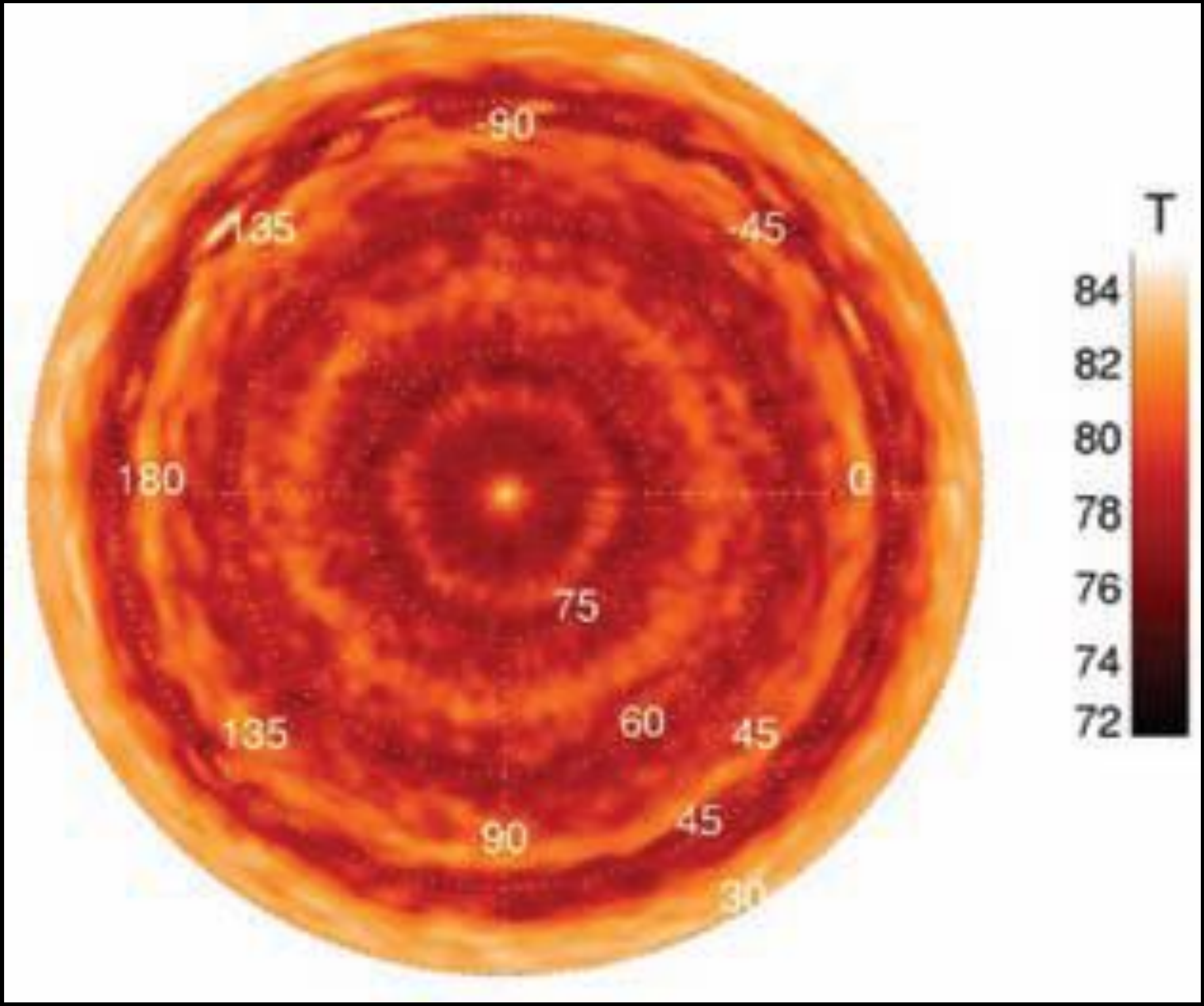


Northern High-Latitude Wind (Goddfrey, 1988)



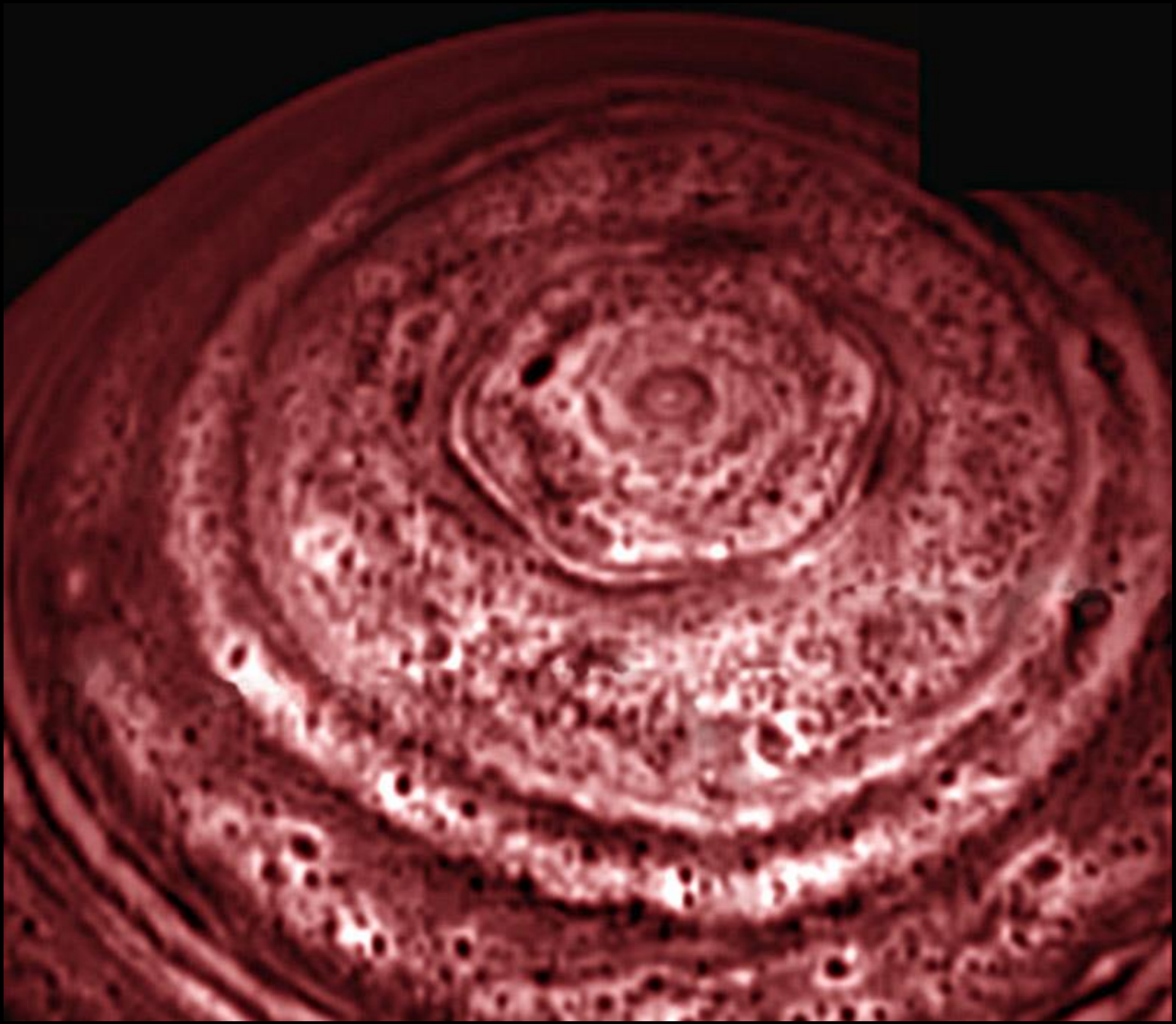
A Long-Lived Feature

The Hexagon has been observed by ground-based telescopes in 1990 (Sanchez-Lavega et al. 1993), and by multiple instruments on Cassini



Temperature Measurement using CIRS (Fletcher et al., 2008)

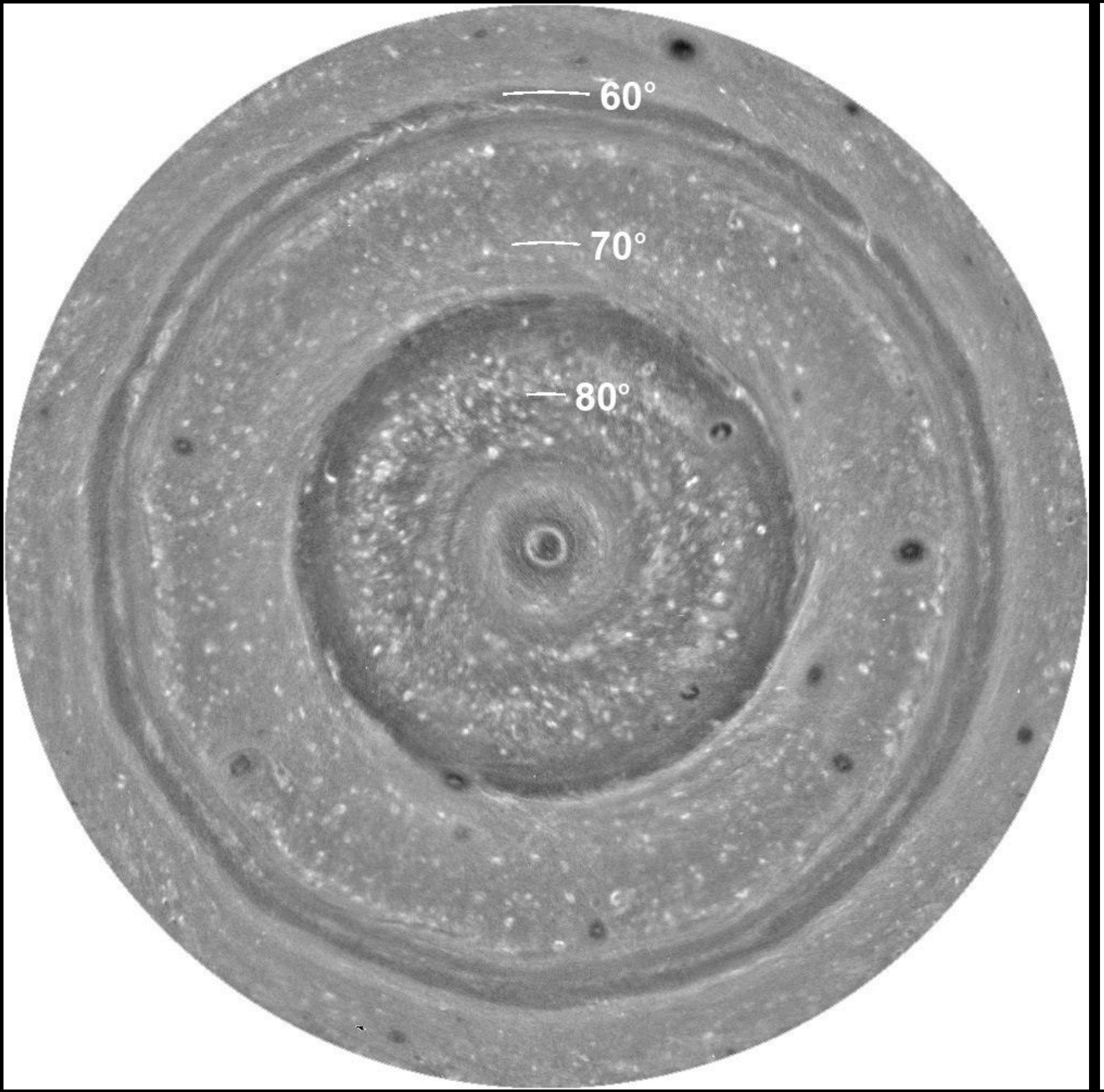
Cassini VIMS View

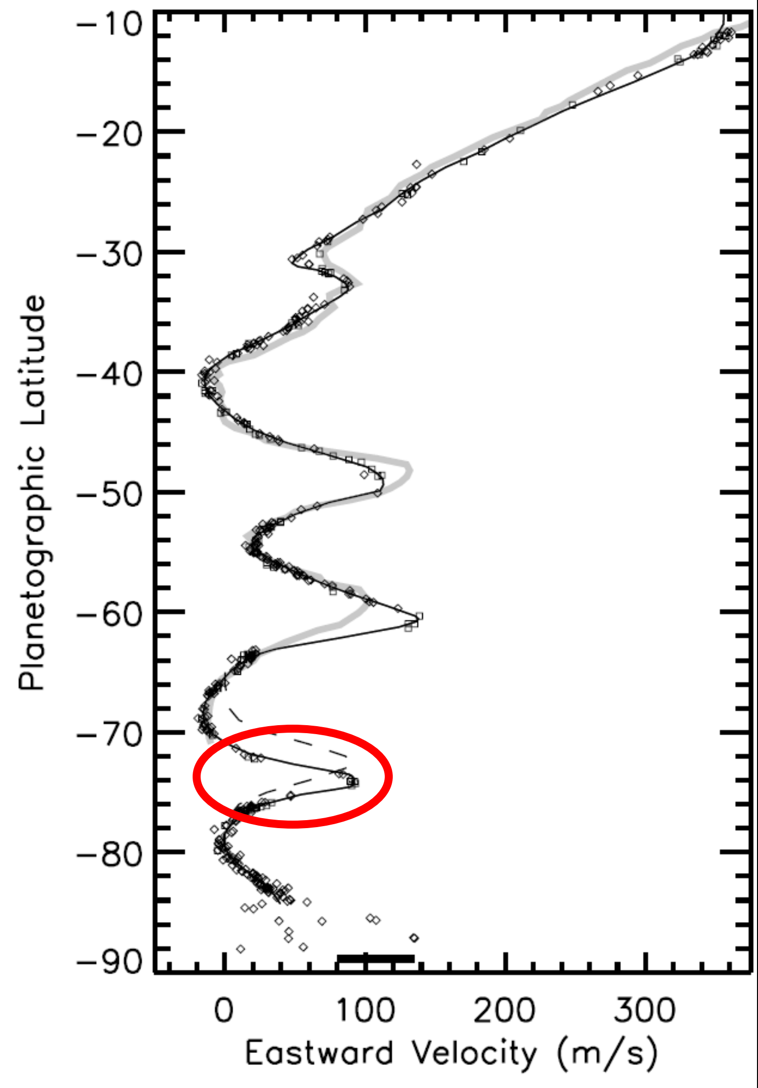


Southern Hemisphere – No Hexagon

Southern-most jet peaks at 74ºS

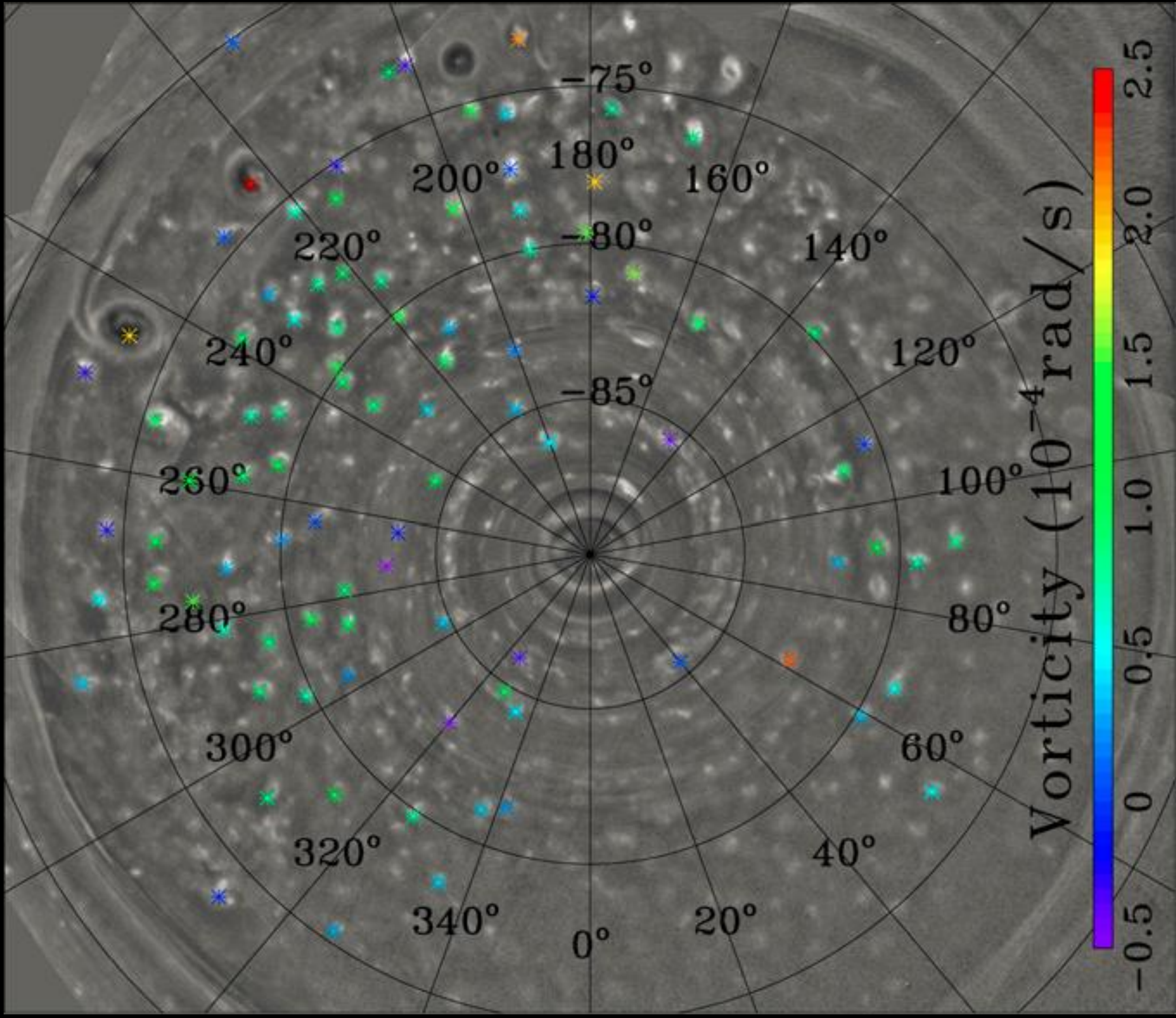
Vasavada et al (2006)





Southern High-latitudes – Vortices

Full of vortices

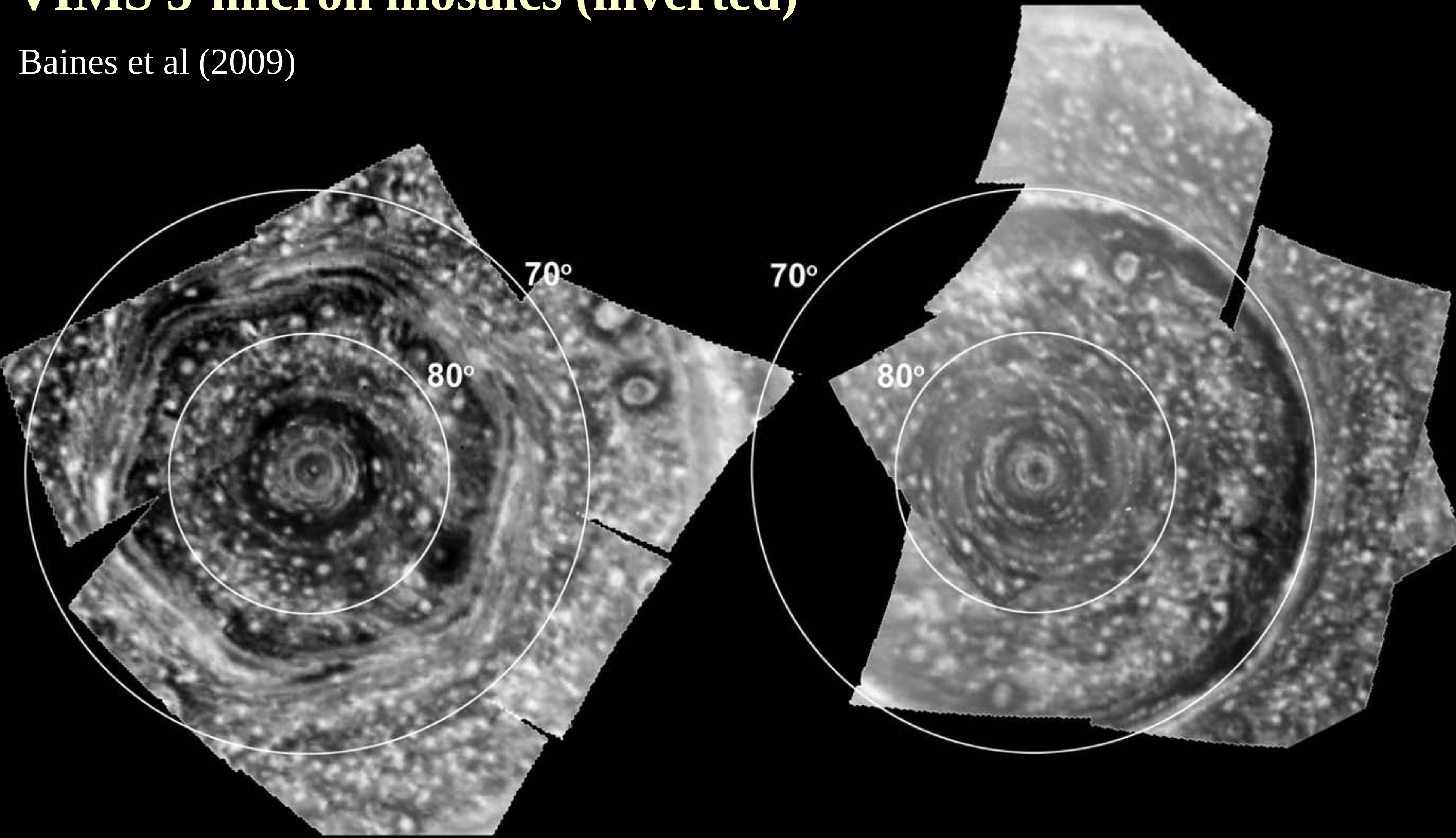


Dyudina et al (2009)

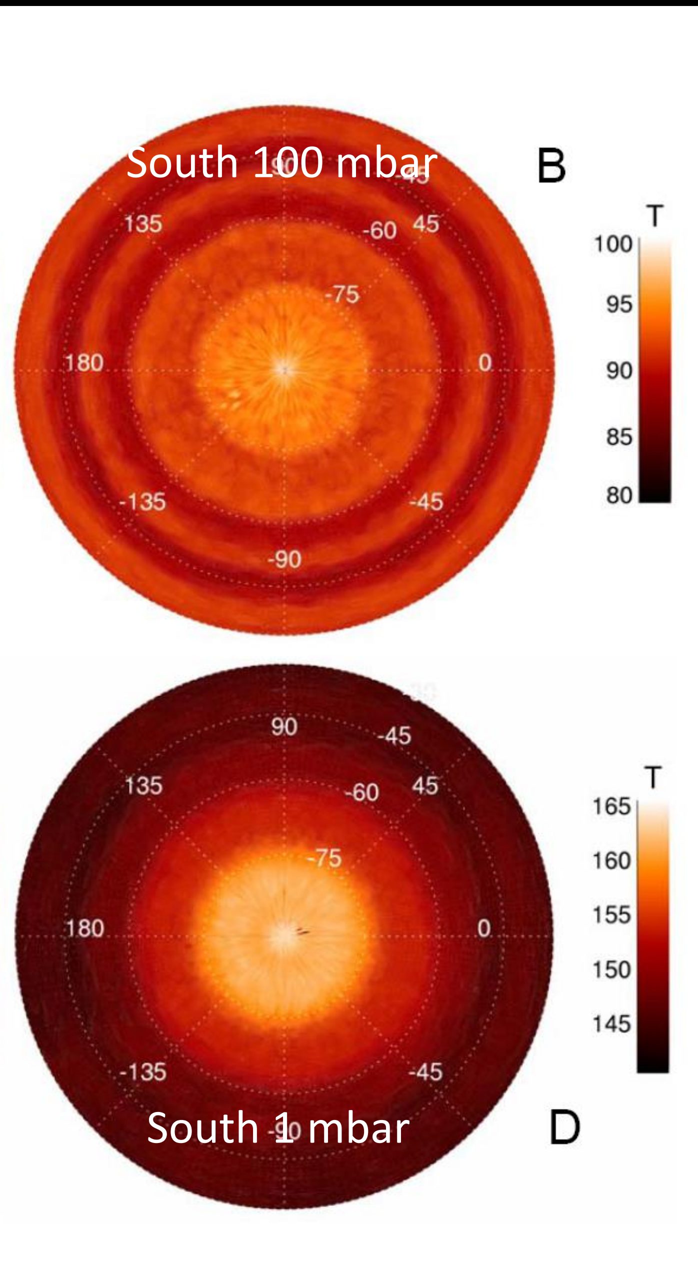
North-South Comparison

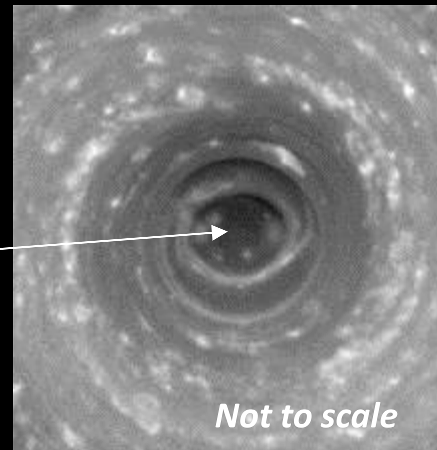
VIMS 5-micron mosaics (inverted)

Baines et al (2009)

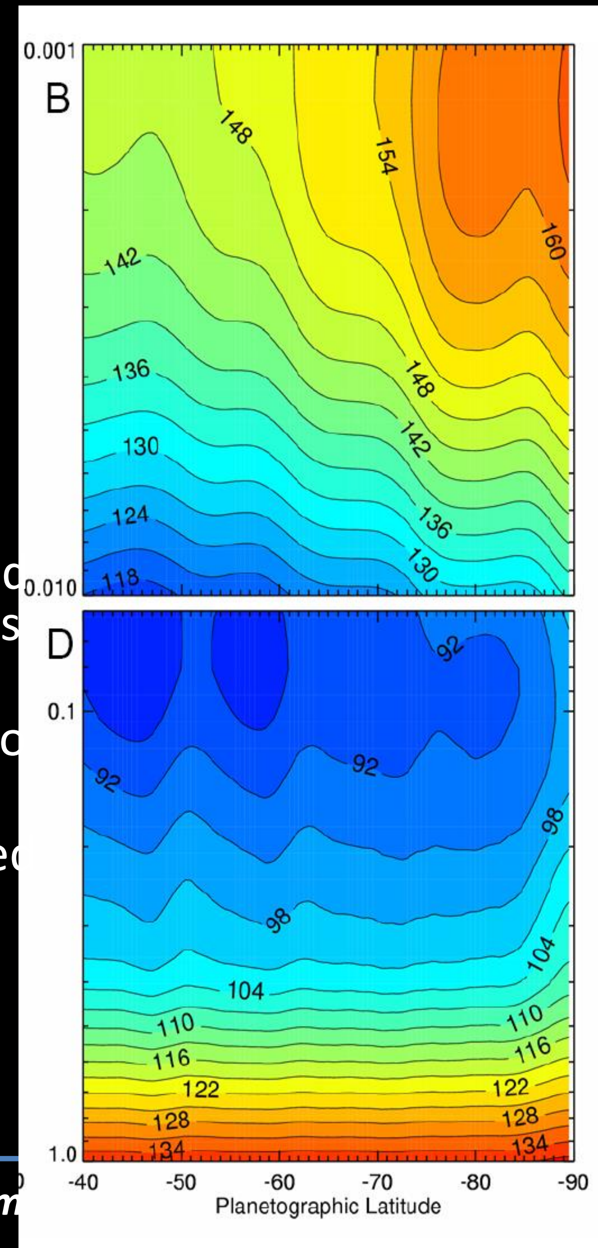


October 2006: CIRS at the South Pole

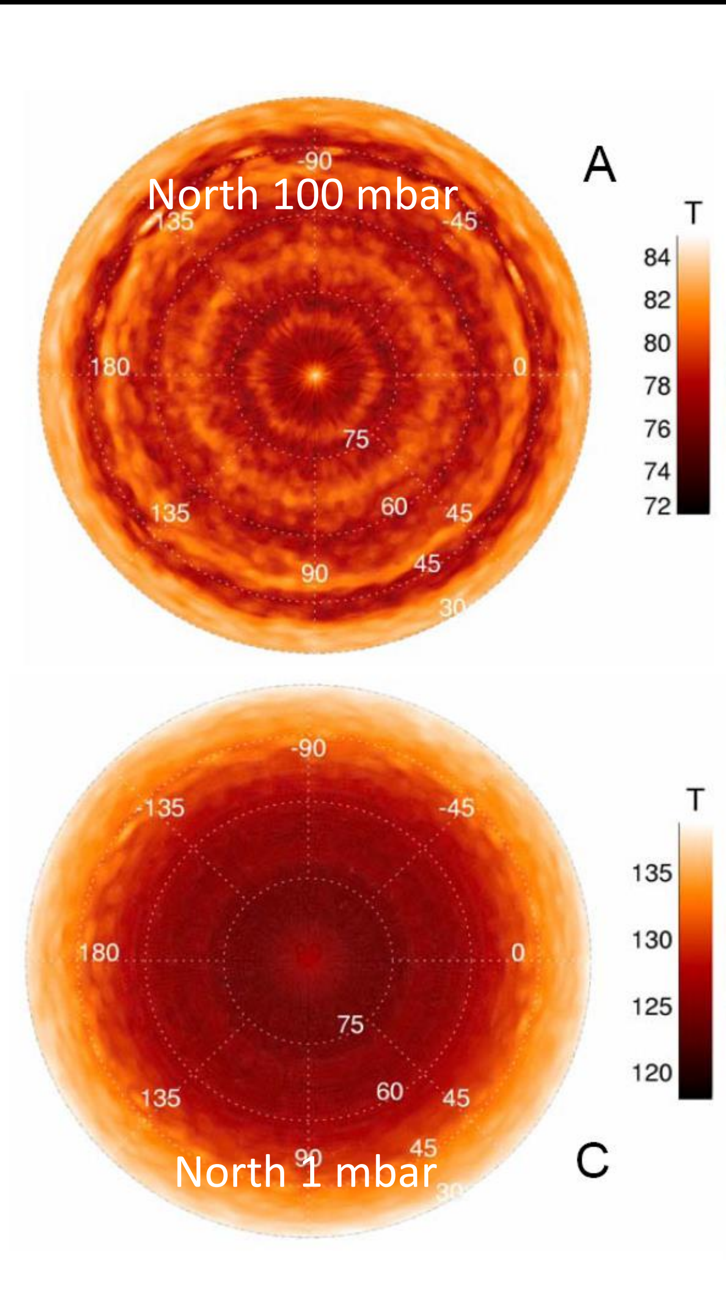


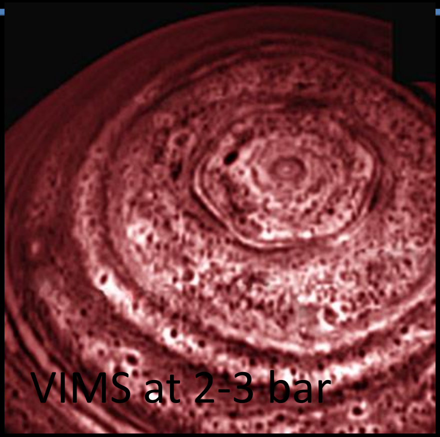


- Hot cyclonic vortex coincides with depressed cloud features surroundec by towering wall of clouds (eye wall).
- Belt/zone structure due tc upwelling/subsidence.
- Phosphine locally depletec within vortex core, enhanced in polar collar.

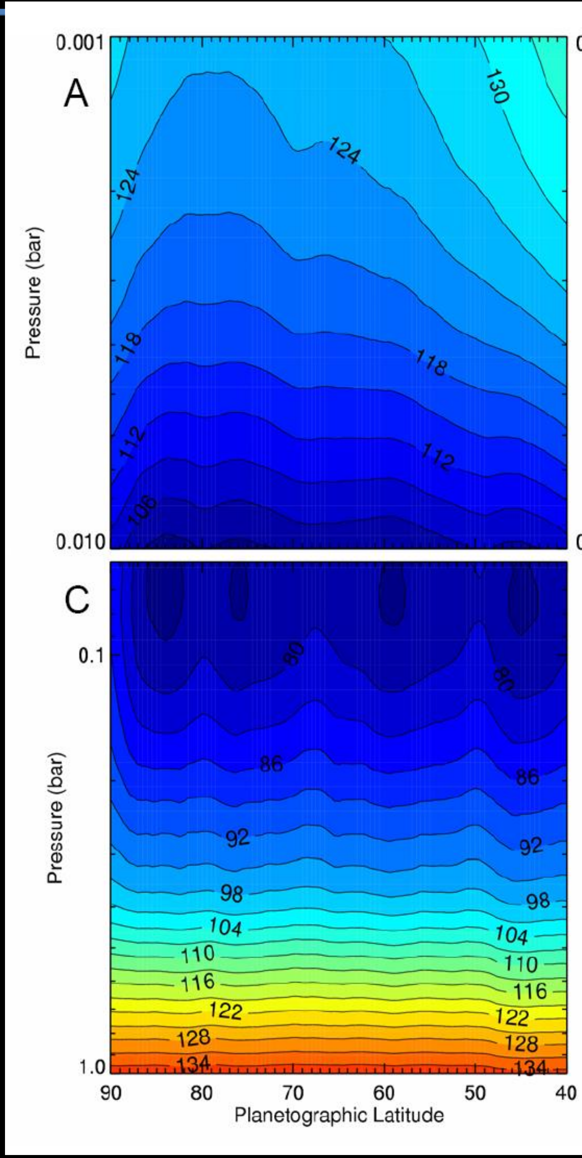


March 2007: First View of the Winter Pole

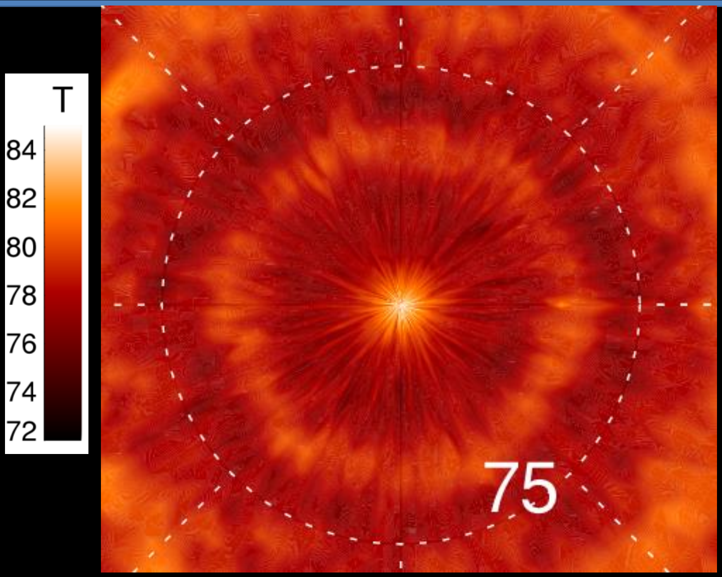


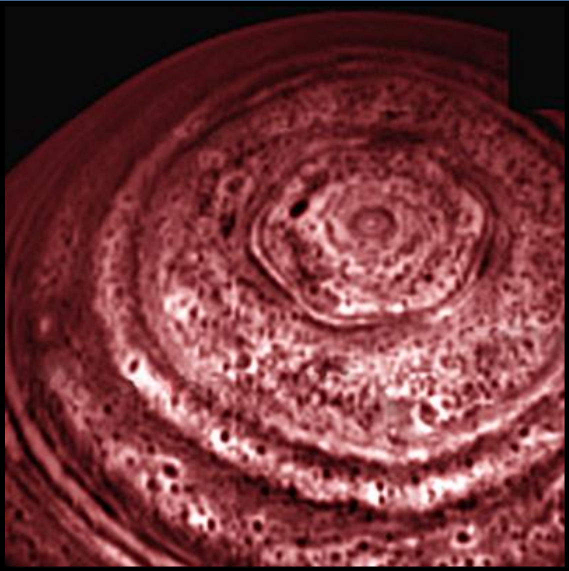


- Without sunlight for 14 years, we can exclude radiative effects at the winter pole. Features are dynamically generated.
- No stratospheric polar hood.
- Hot cyclonic vortex at north pole mirrors that at the south pole (Fletcher *et al*., 2008).
- Hexagonal wave!!



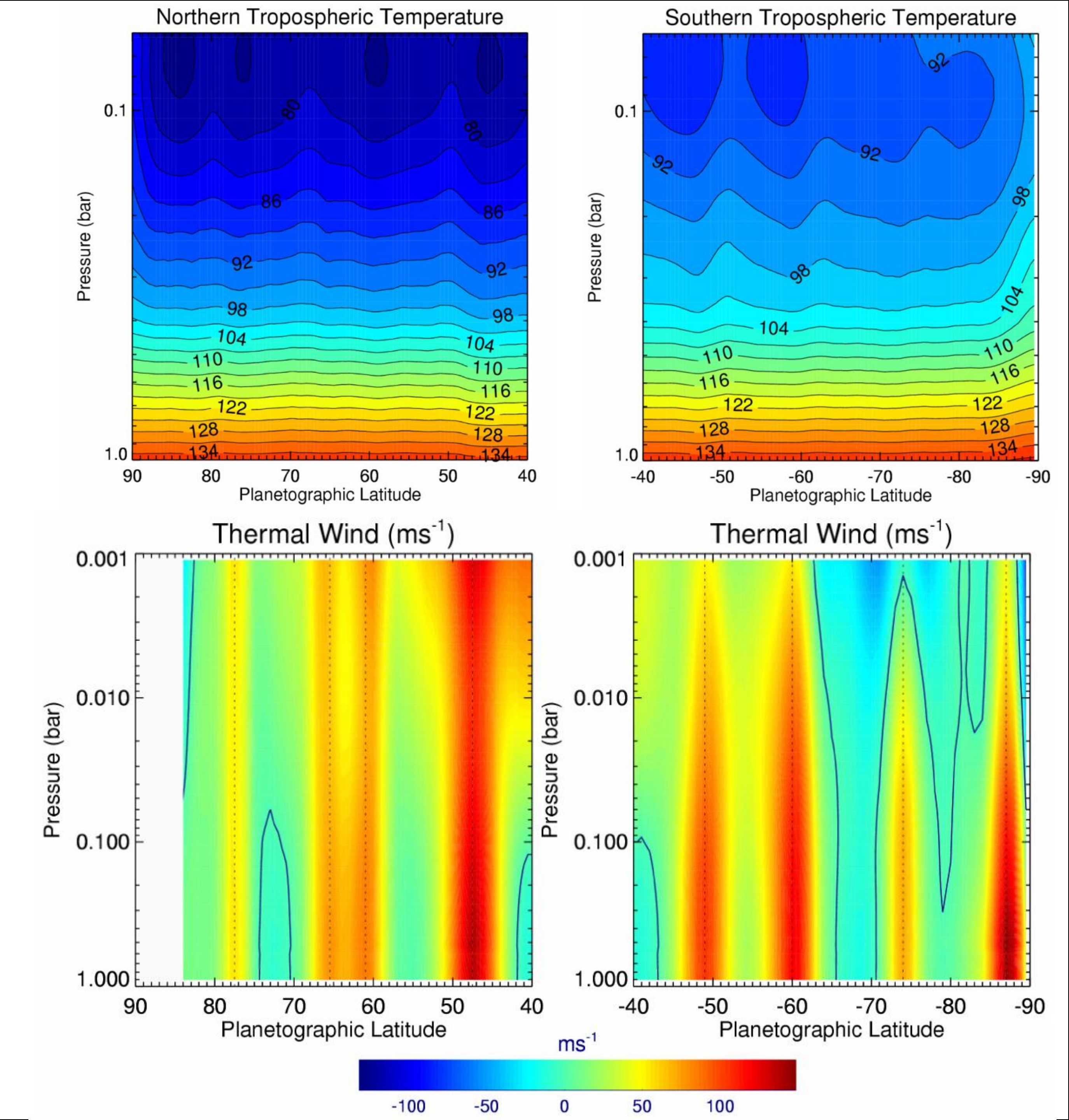
Hexagon





- Only present in the north, no such feature in the south – why?
- Example of collaboration between instrument teams, show hexagon present from tropopause down to 2-3 bar level.
- Warm CIRS hexagon coincides with cloud-free VIMS hexagon at 2-3 bar – subsidence to north of zonal jet at 77N, upwelling to the south.
- But the hexagon is not a new feature – discovered in Voyager images from 1981, long-lived feature.

Vertical Wind Structure

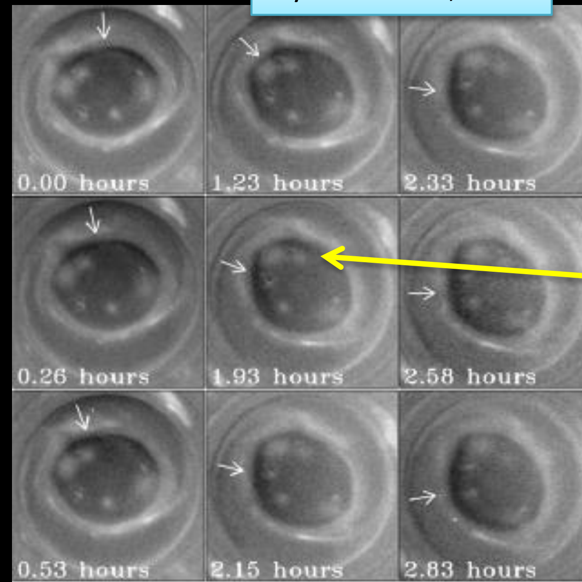


Fletcher et al (2008)

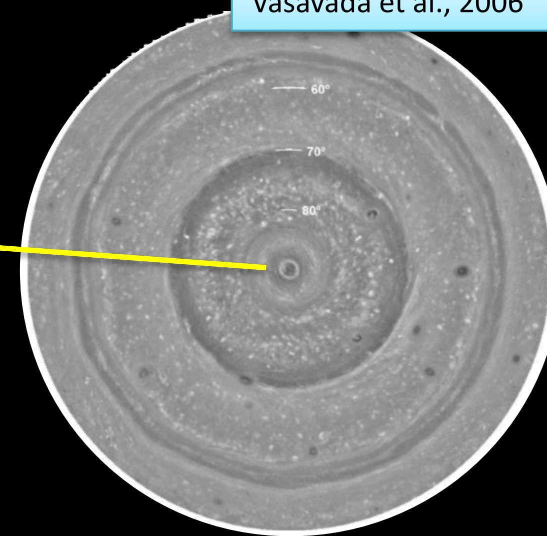
Poles during Cassini Prime Mission

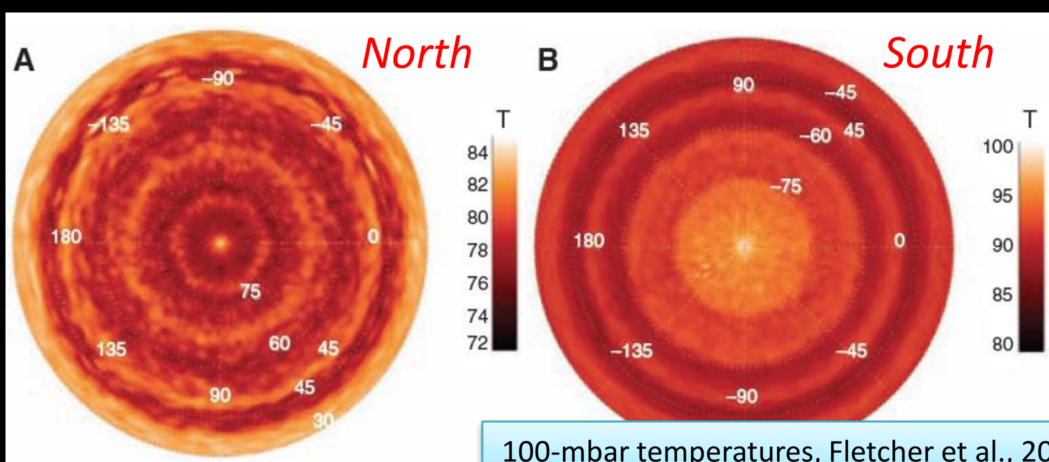
- First high inclination phase **compared summer and winter poles;** north in darkness
  - Hot cyclones at both poles, 2-3 degrees wide.
  - Peripheral prograde jets at 88.3N and 87.5S encircle hot poles.
  - Well defined eye-wall in south.
  - Hexagon at north; ephemeral polygonal waves at south.
  - Hexagon seen in darkness, extends from tropopause to deep 2-3 bar clouds.
  - Warm stratospheric hood over southern summer pole.

Dyudina et al., 2009

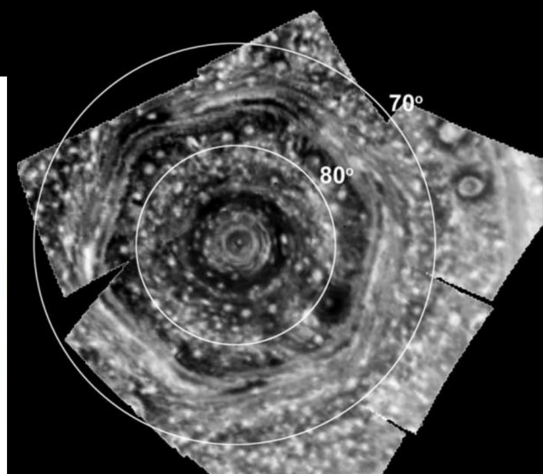


Vasavada et al., 2006





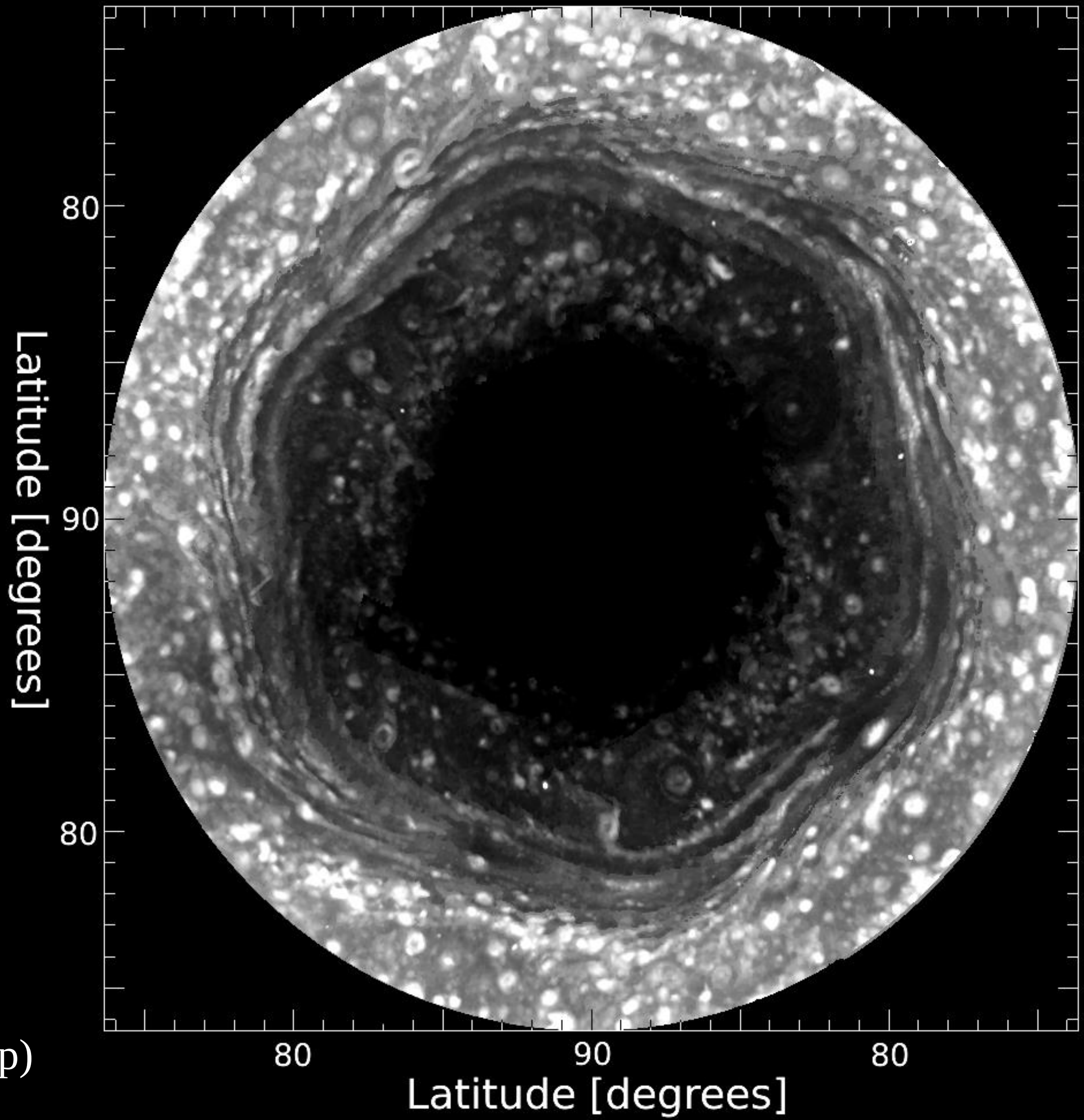
100-mbar temperatures, Fletcher et al., 2008



5-µm emission, Baines et al., 2009

Hexagon

(Jan 2009)

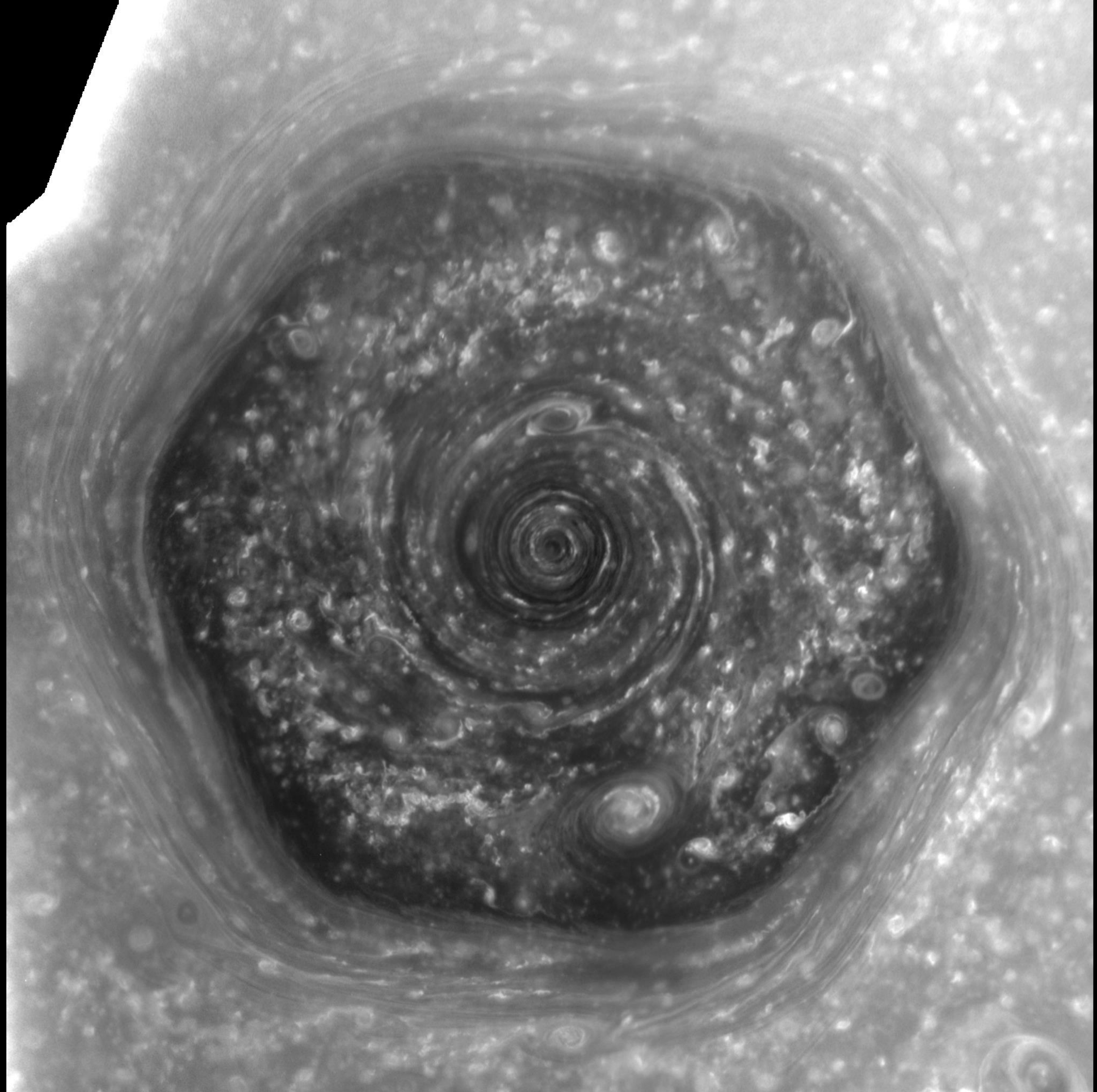


Sayanagi et al (in prep)

Hexagon

Dec 2012

CB2 Filter



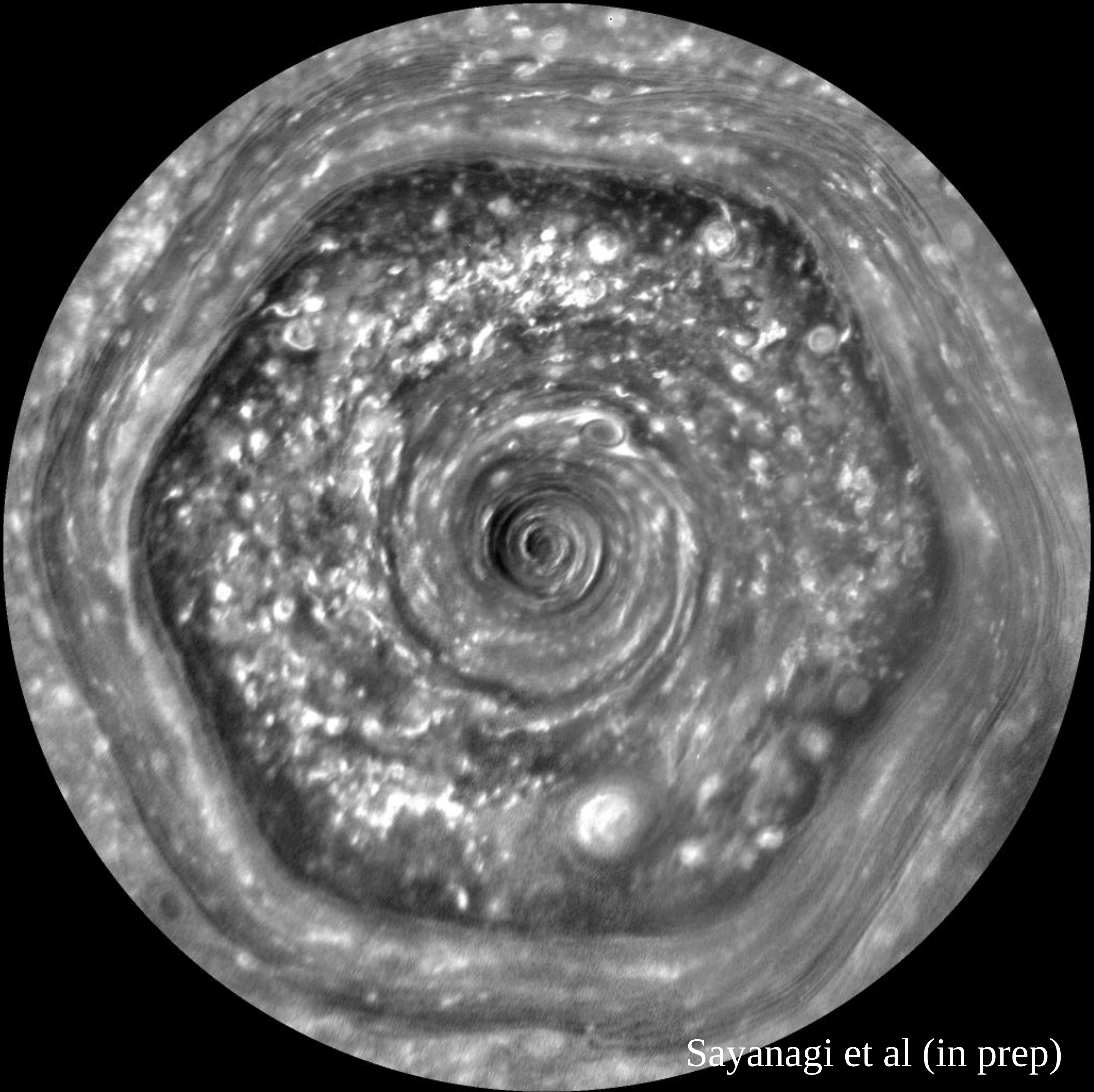
Hexagon

Dec 2012

(Movie)

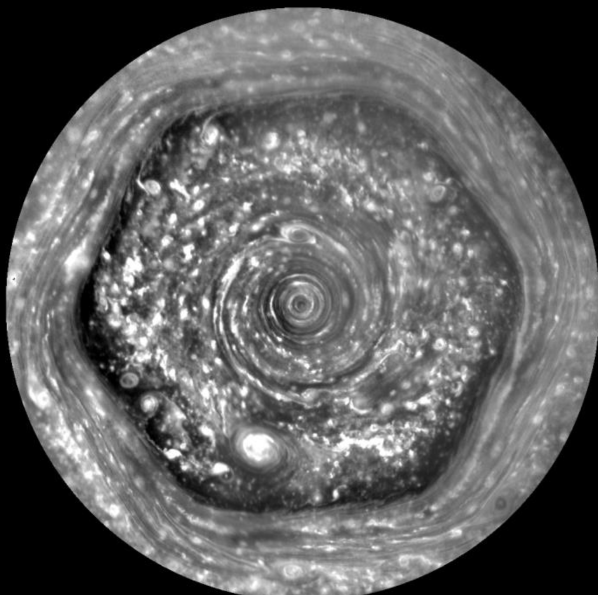
CB2 Filter

8 mosaics over 10 hours

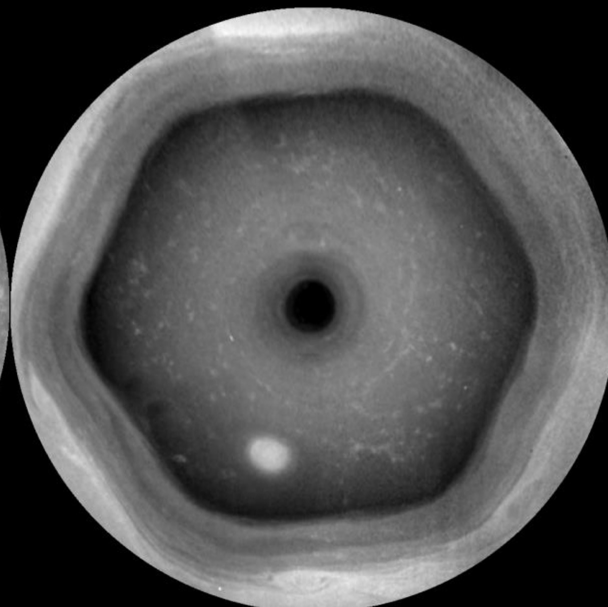


Hexagon Color View

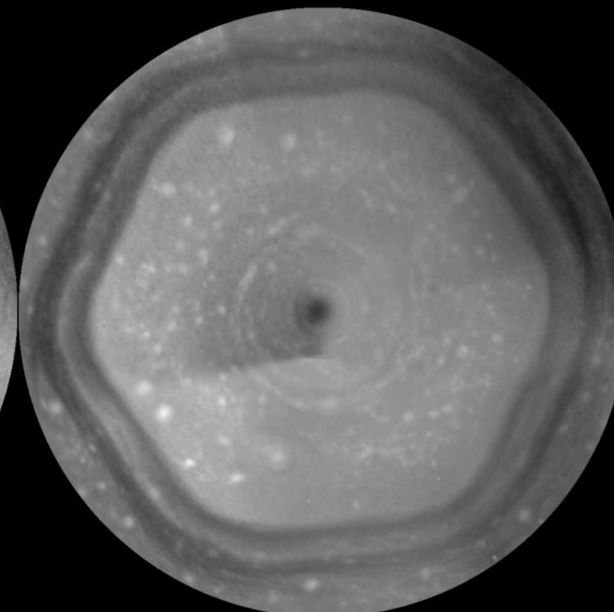
CB2 (750nm)



MT2 (728nm)



BL1+VIO (<450nm)



Sayanagi et al (in prep)

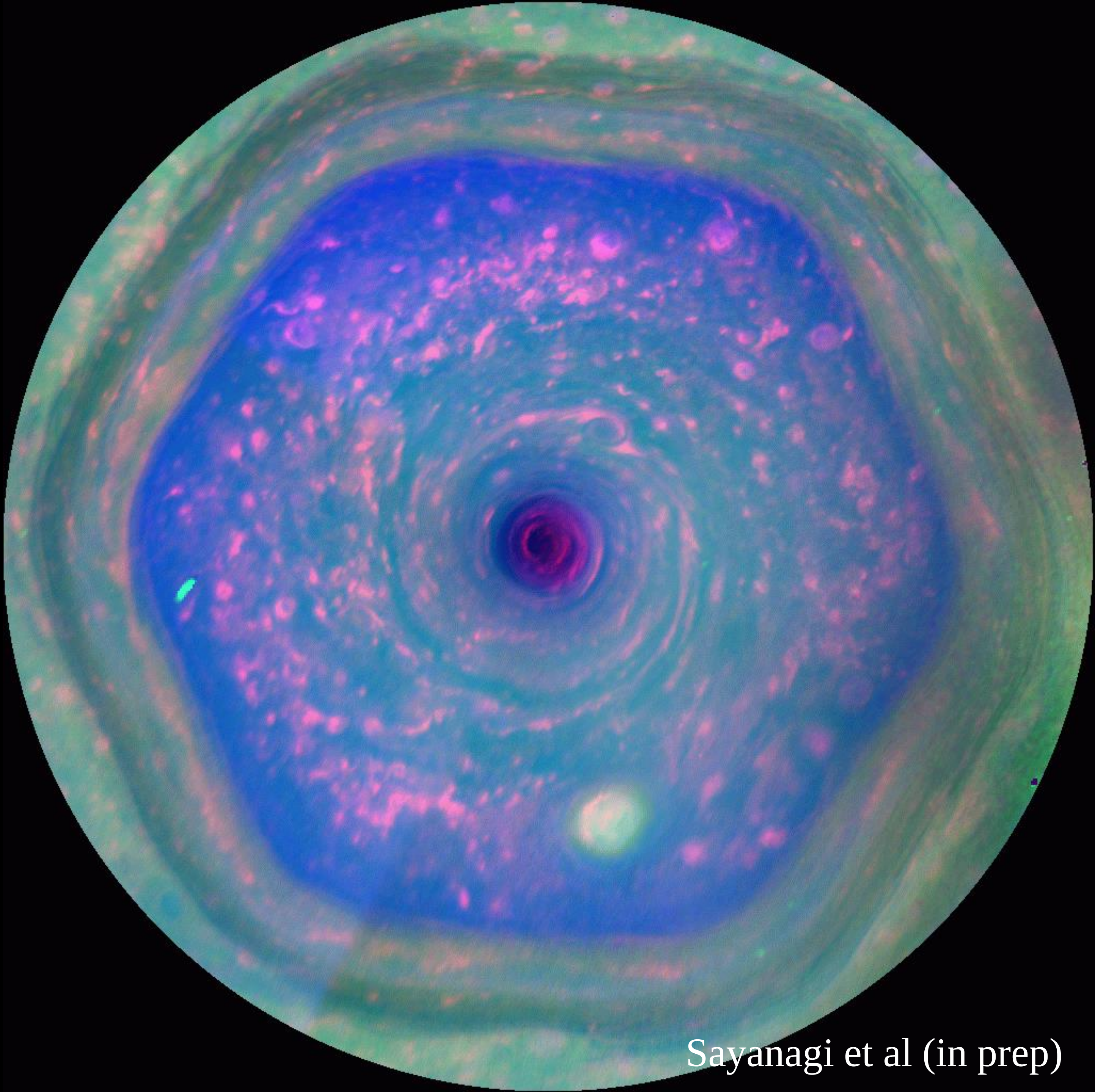
Hexagon

Dec 2012

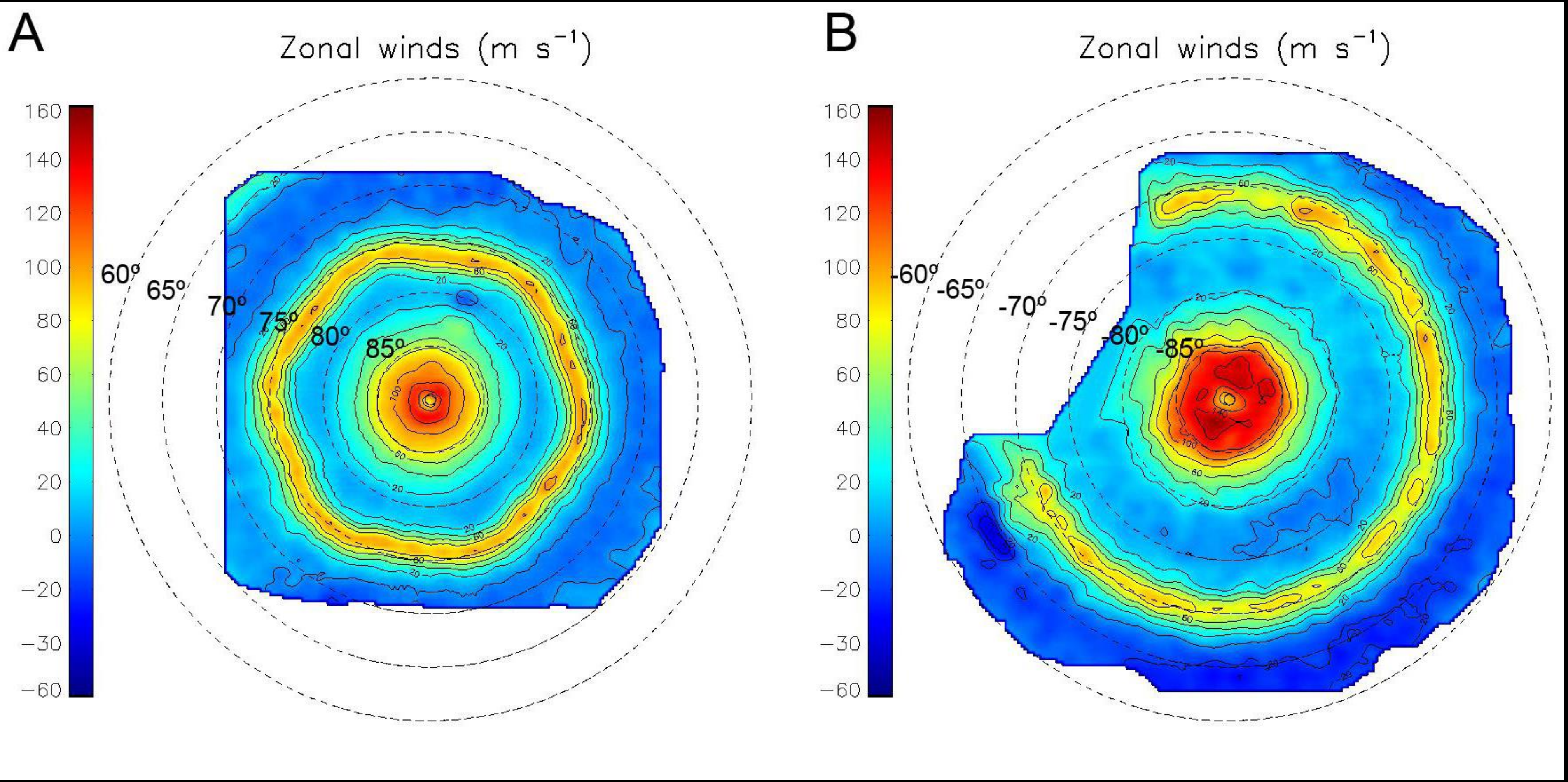
(Movie)

RGB = CB2, MT2, MT3

8 mosaics over 10 hours

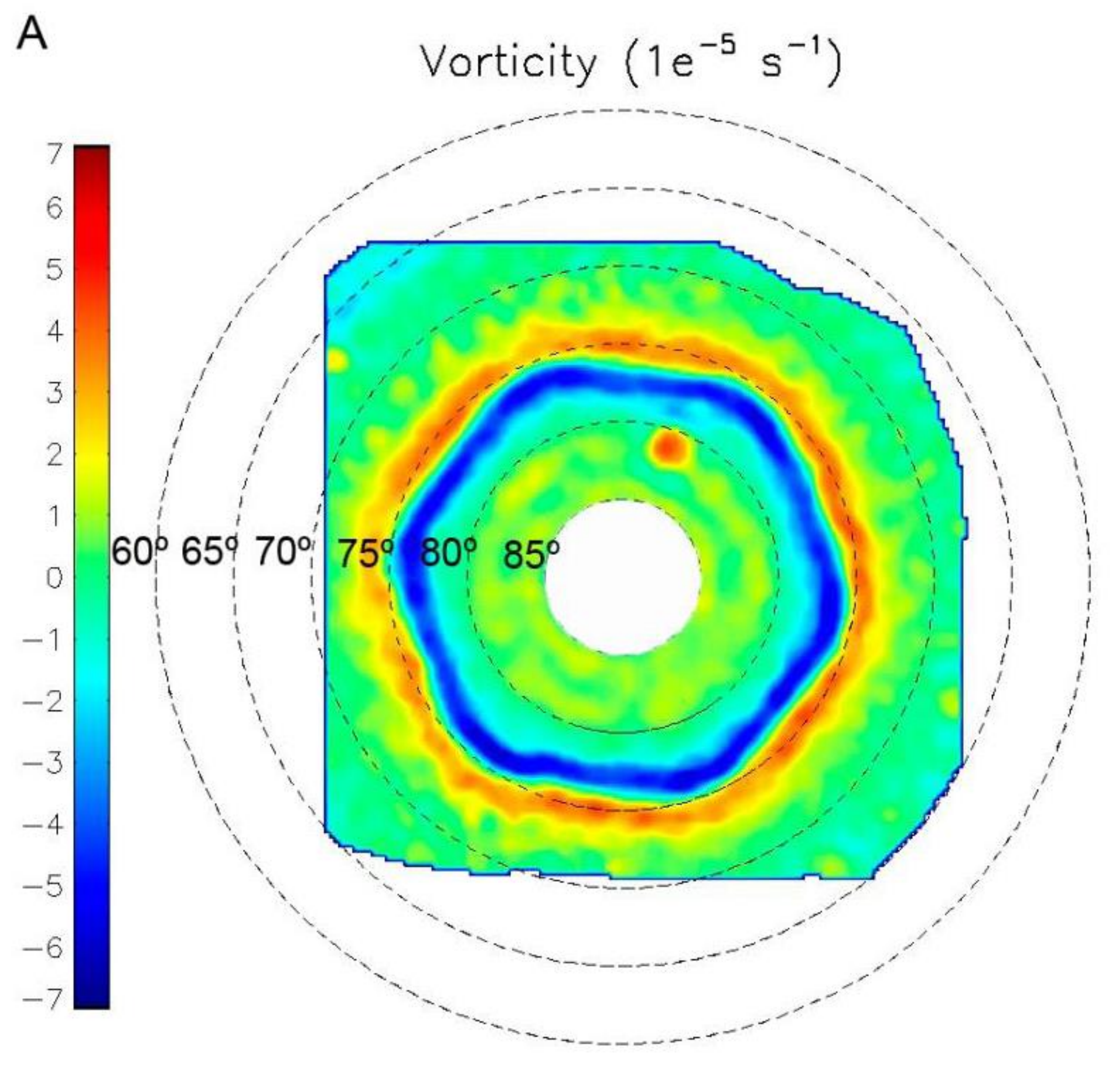


Hexagon = Jet Stream



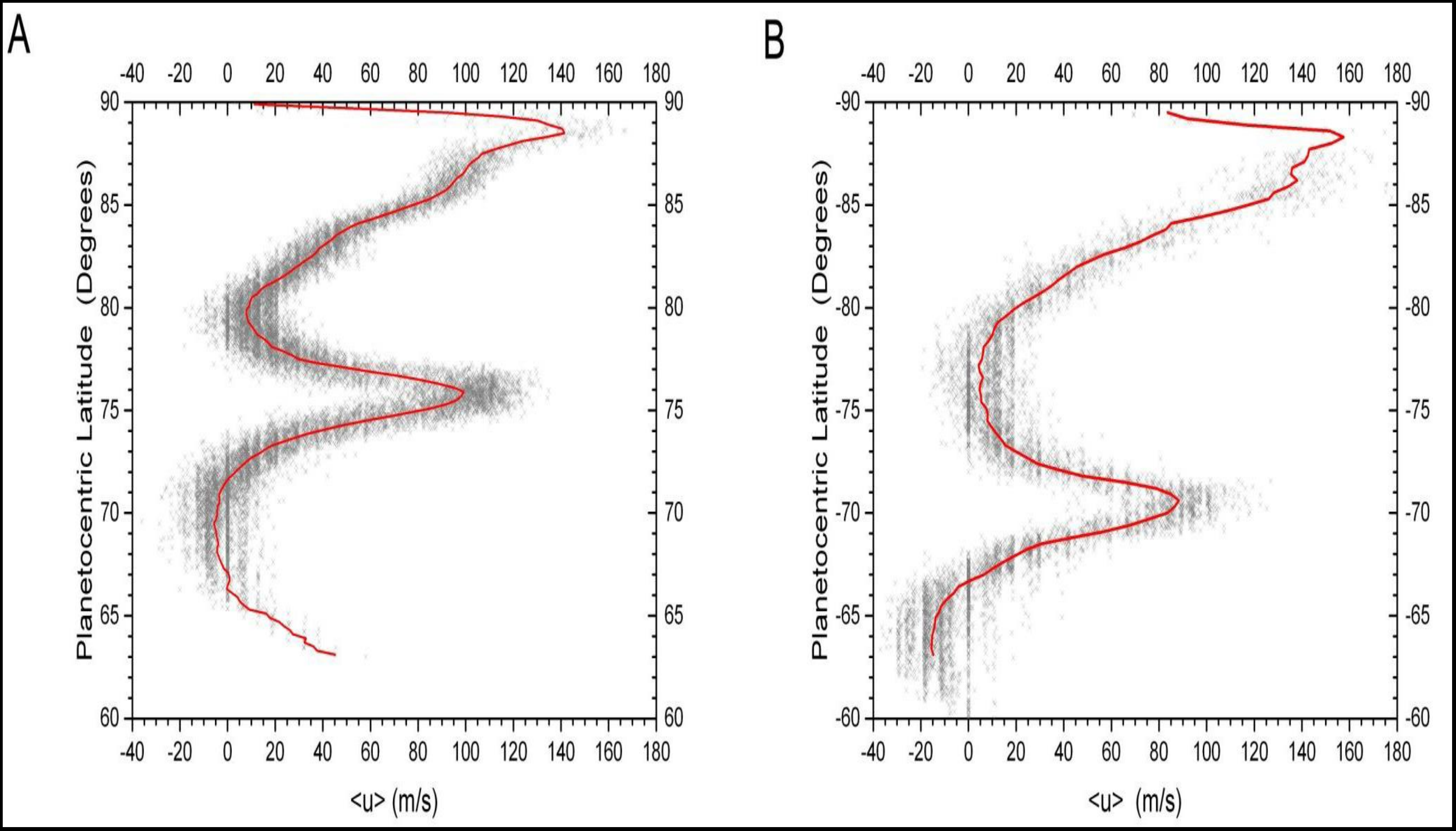
Arrate et al (in prep)

Hexagon ≠ Vortex Street



Arrate et al (in prep)

Hexagon Zonal Wind



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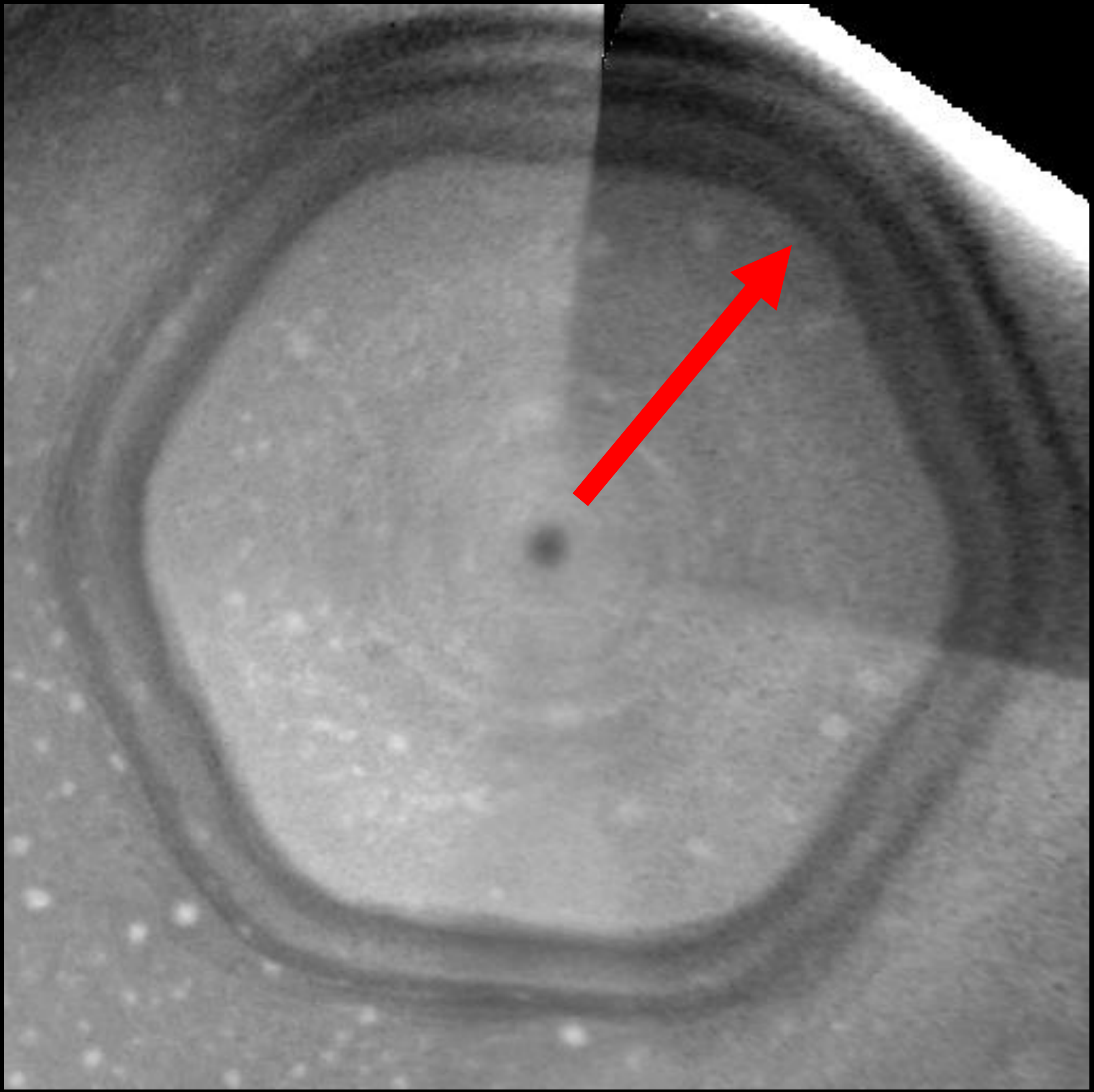
Hexagon Shadow

BL1+VIO

Arrow
= direction of sunlight



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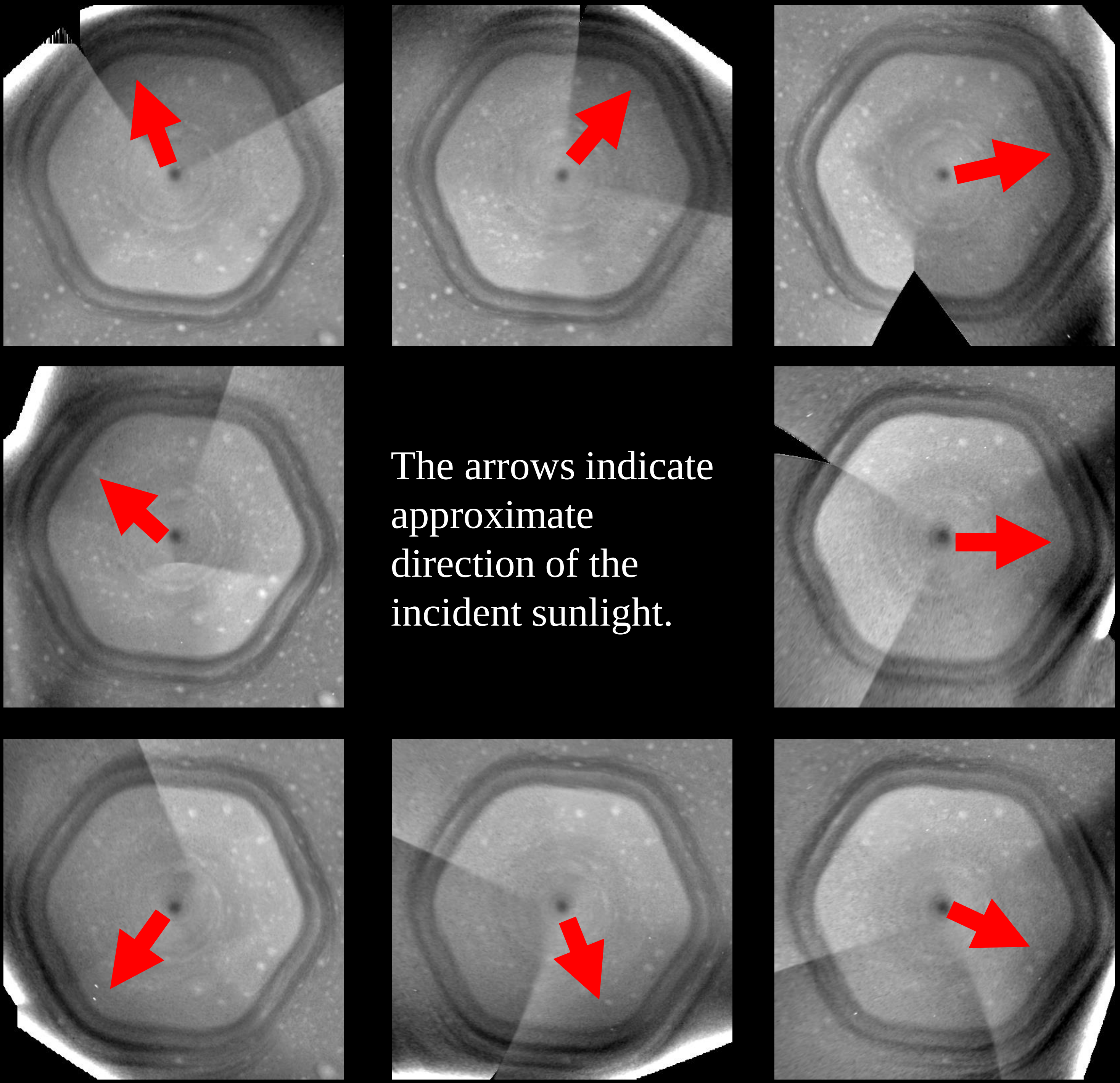
Hexagon Shadow



The arrows indicate approximate direction of the incident sunlight.

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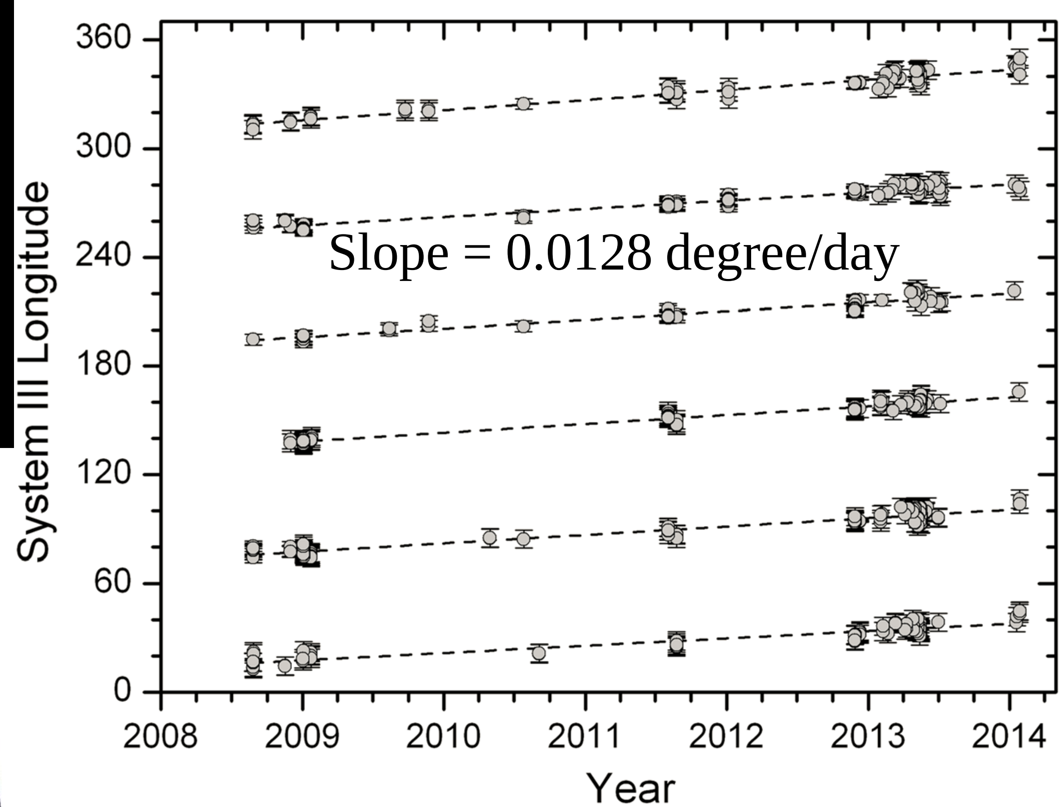
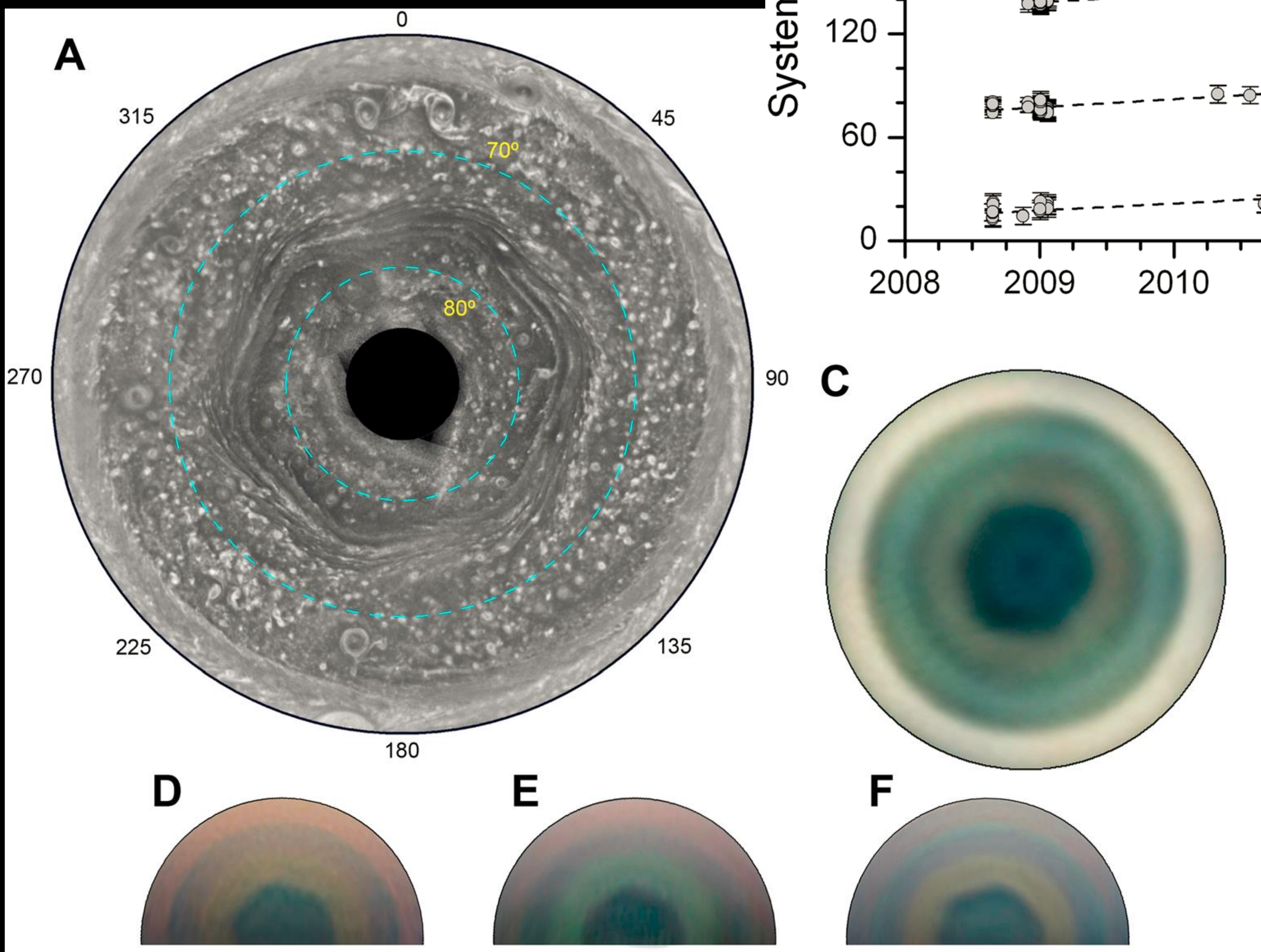
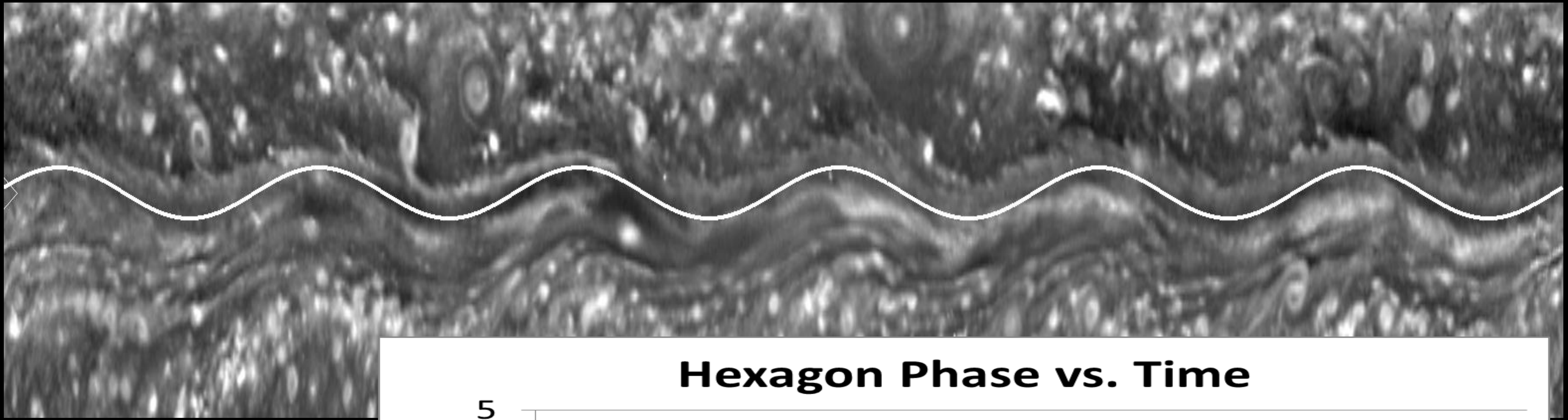
Hexagon Propagation Speed

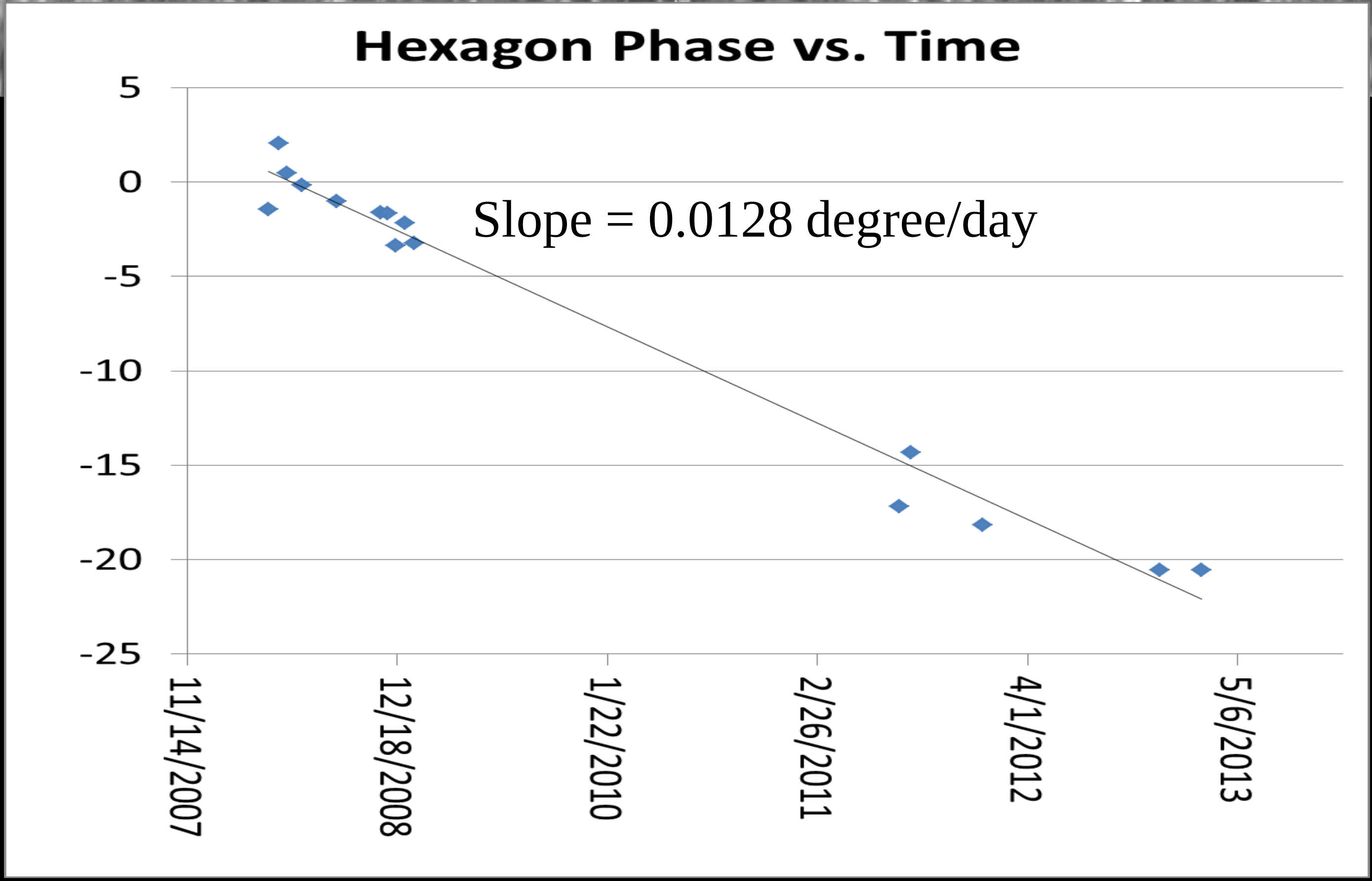




Sanchez-Lavega et al (2014)

Hexagon Propagation Speed





Sayanagi et al
(in prep)

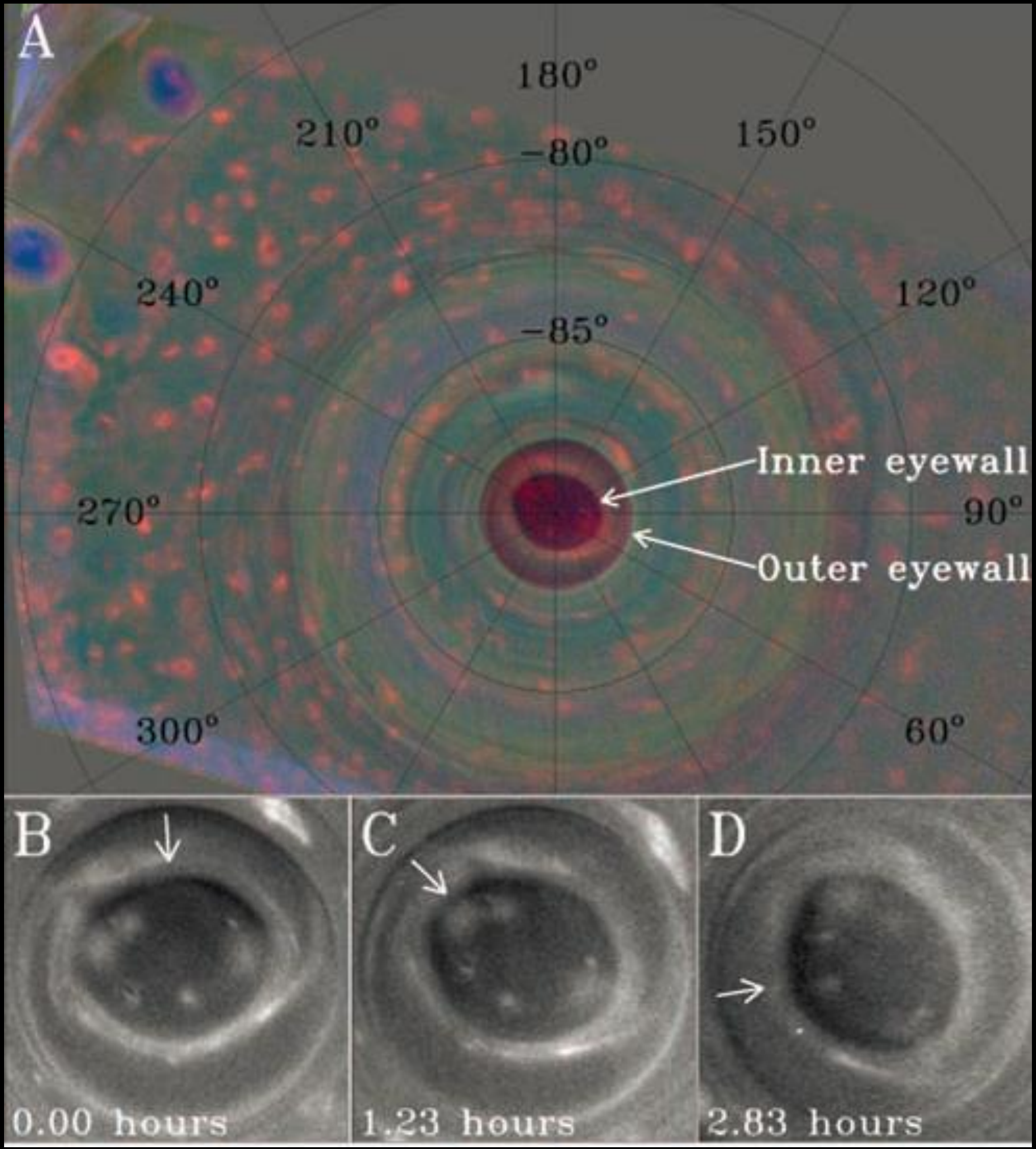
Summary -- Hexagon Observation

- Hexagon = 77deg N Jetstream
- Survives Seasonal Changes
- Jetstream follows Hexagon’s outline
- It is a meandering jetstream, and not a vortex street.
- Slow Propagation (but non-zero in System III)
- Acts as a transport barrier.

Polar Vortices

South Polar Vortex Clouds

R = 750 nm (CB2)
G = 727 nm (MT2)
B = 889 nm (MT3)

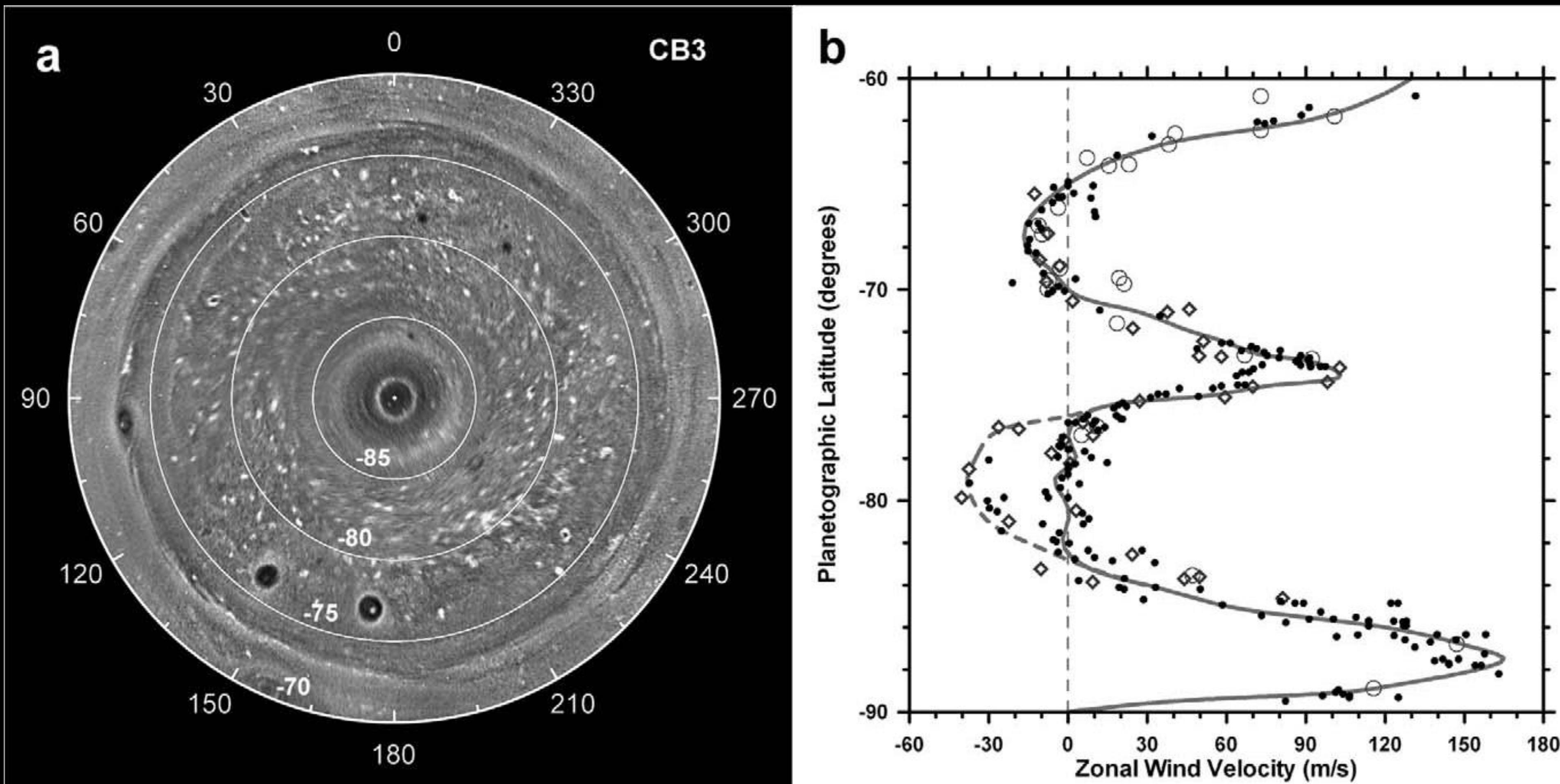


Dyudina et al (2008)

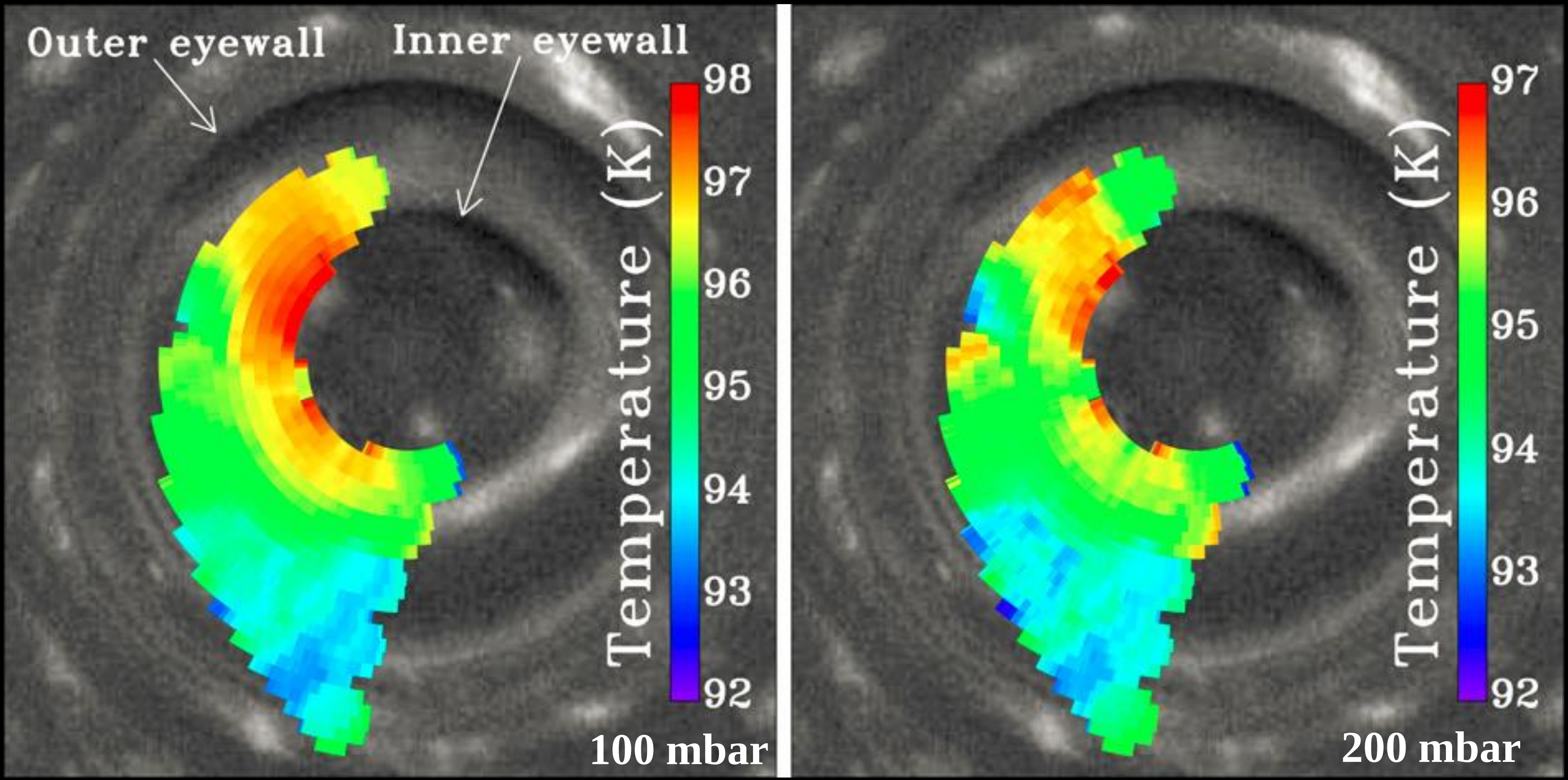
South Polar Vortex

South Polar Cyclone ("Hurricane," "Polarcane" …)

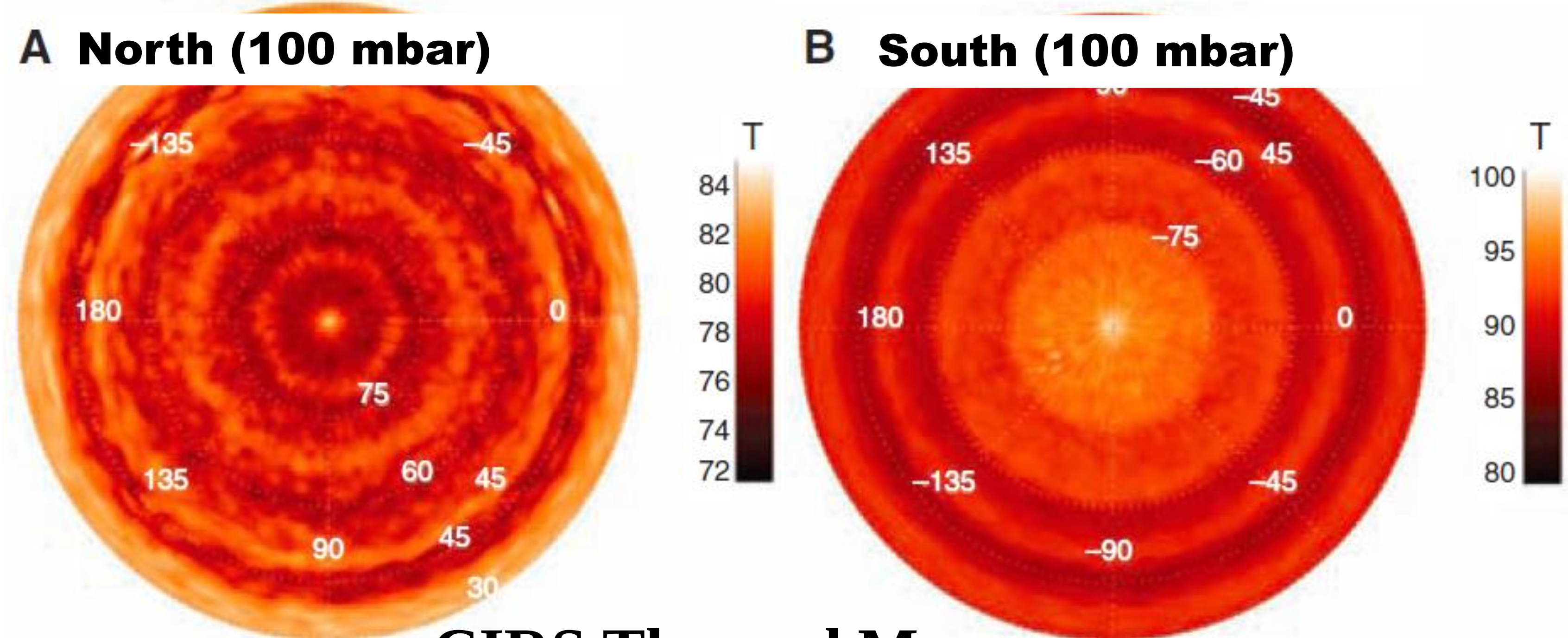
Sanchez-Lavega et al (2006)



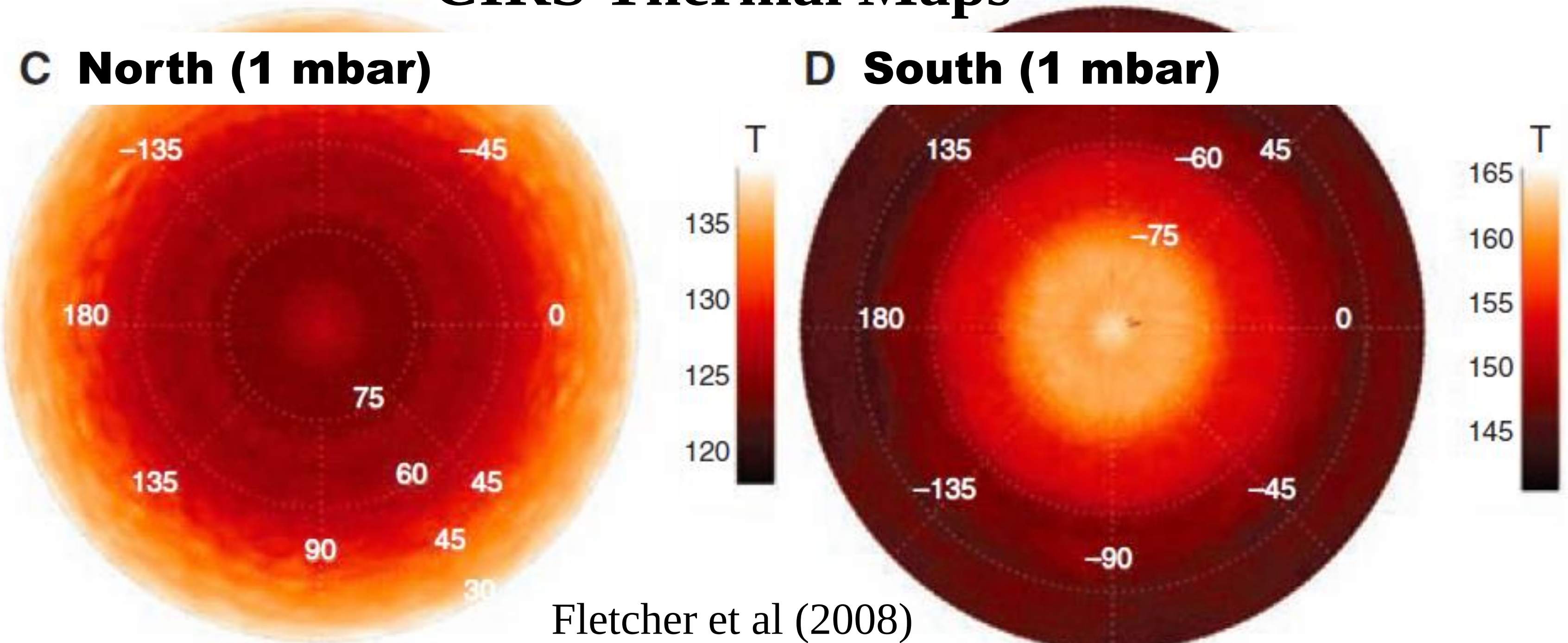
South Polar Vortex Warm Core



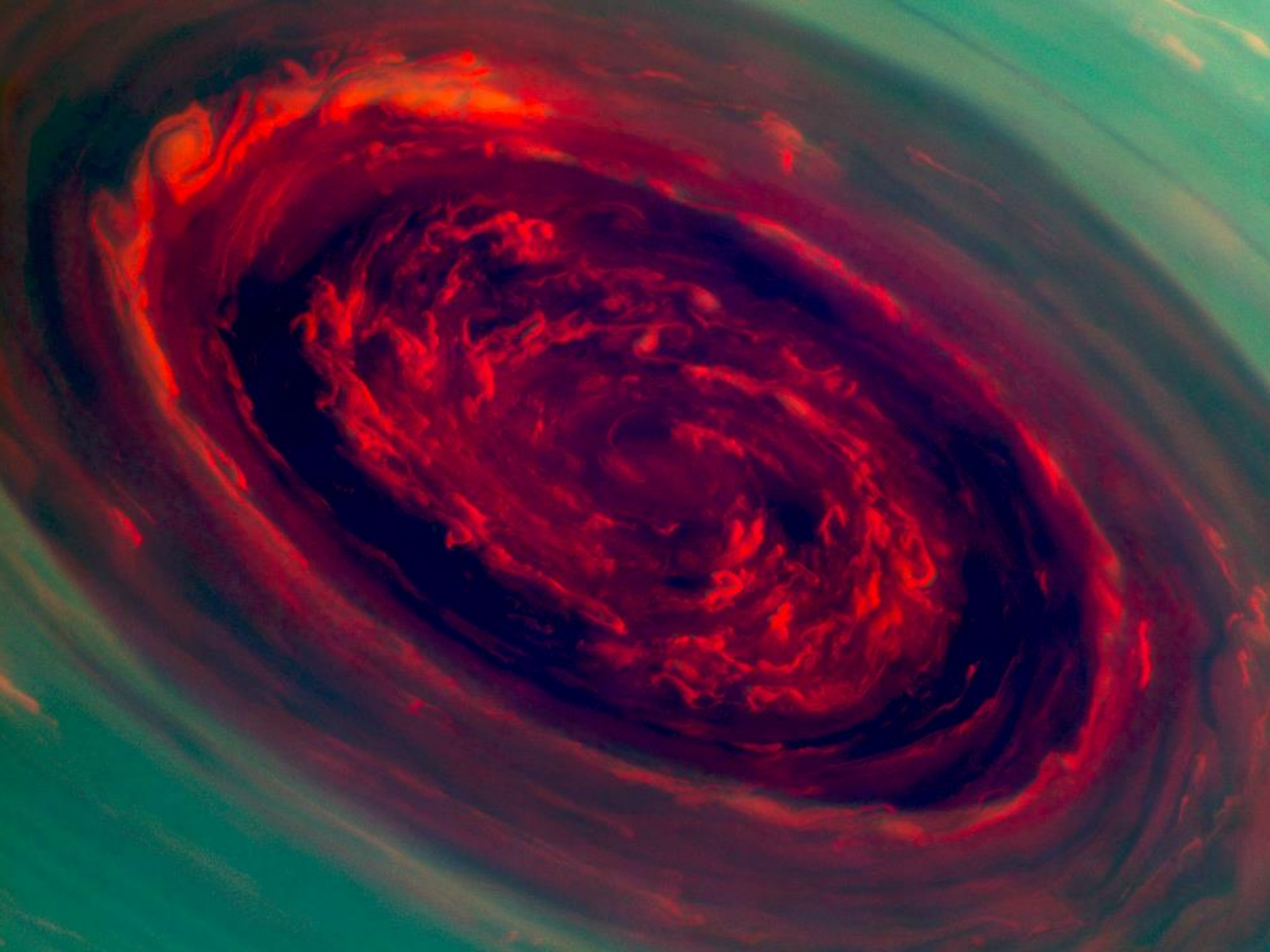
Dyudina et al (2009)

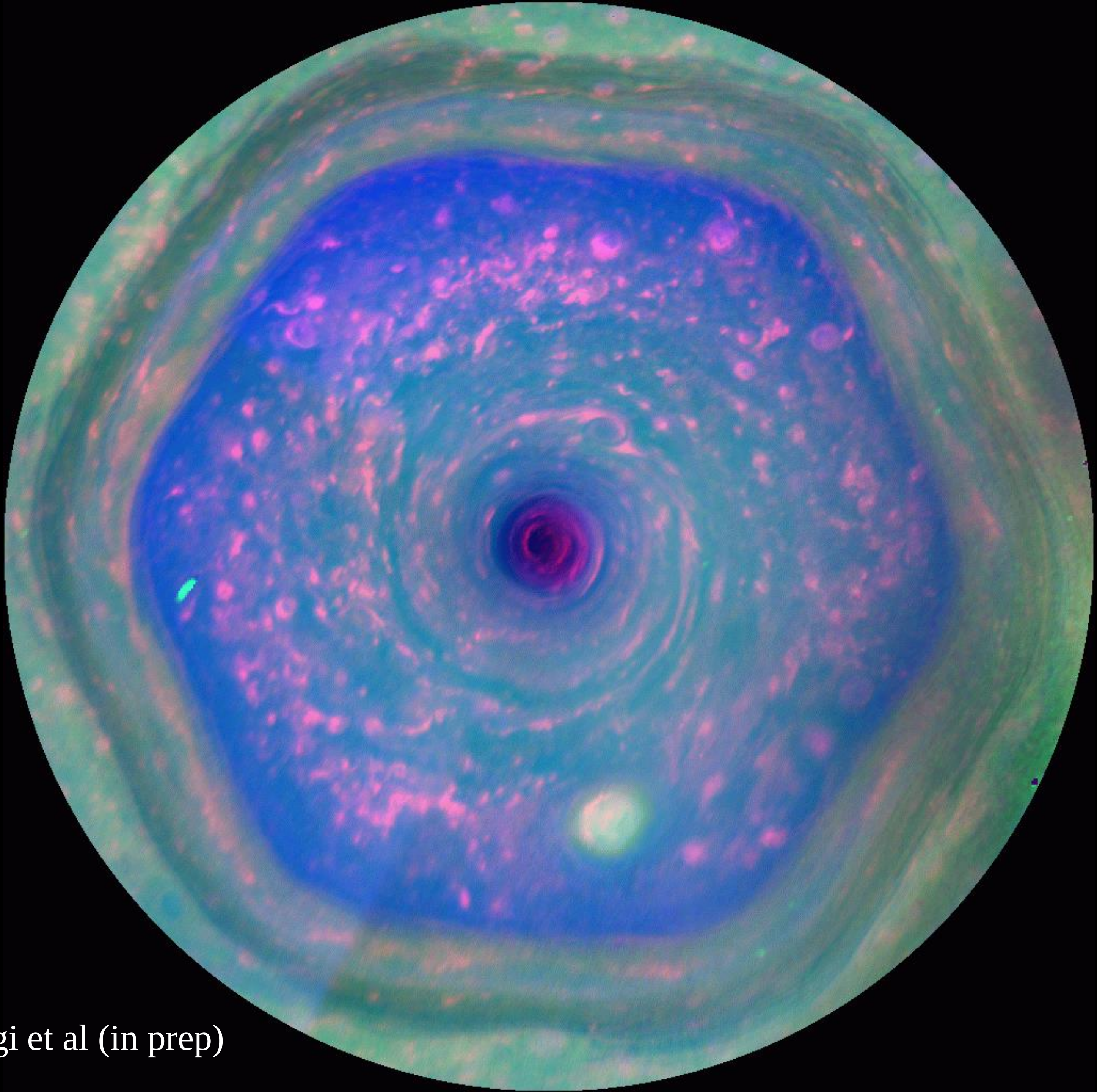


CIRS Thermal Maps



Fletcher et al (2008)



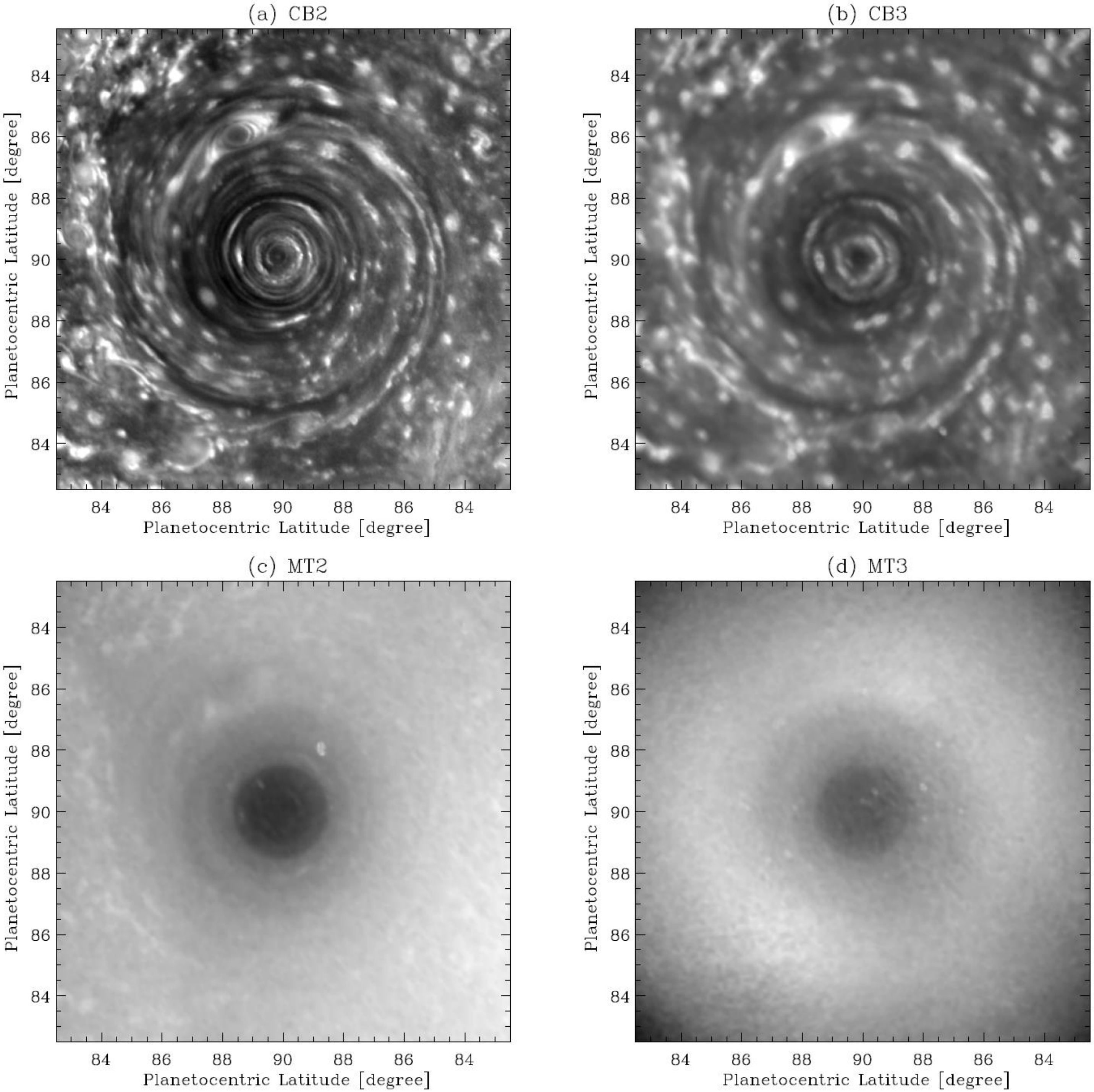


Sayanagi et al (in prep)

North Polar Vortex

Dec 2012

NIR Filters

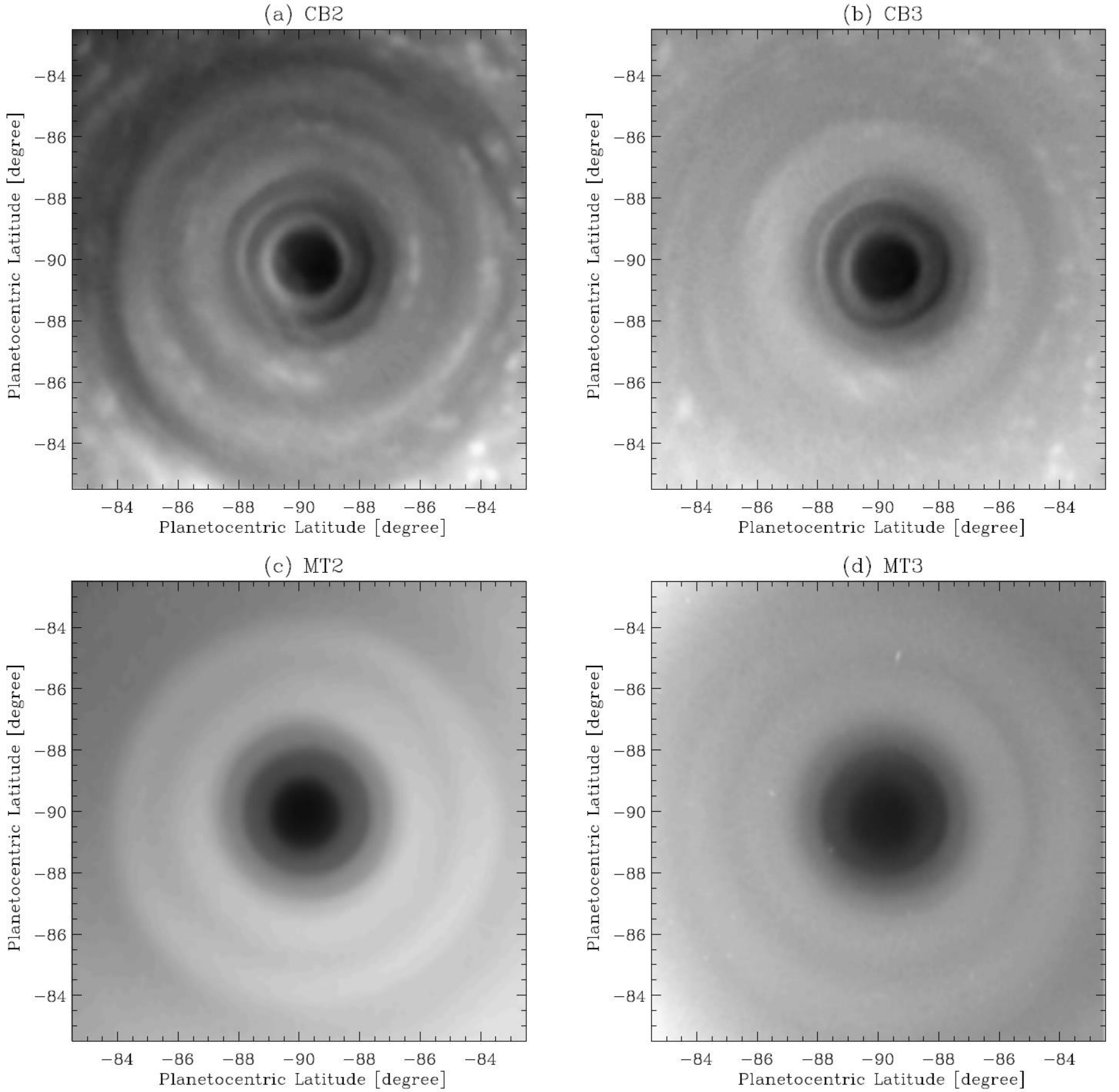


Sayanagi et al
(in prep)

South Polar Vortex

Jan 2007

NIR Filters



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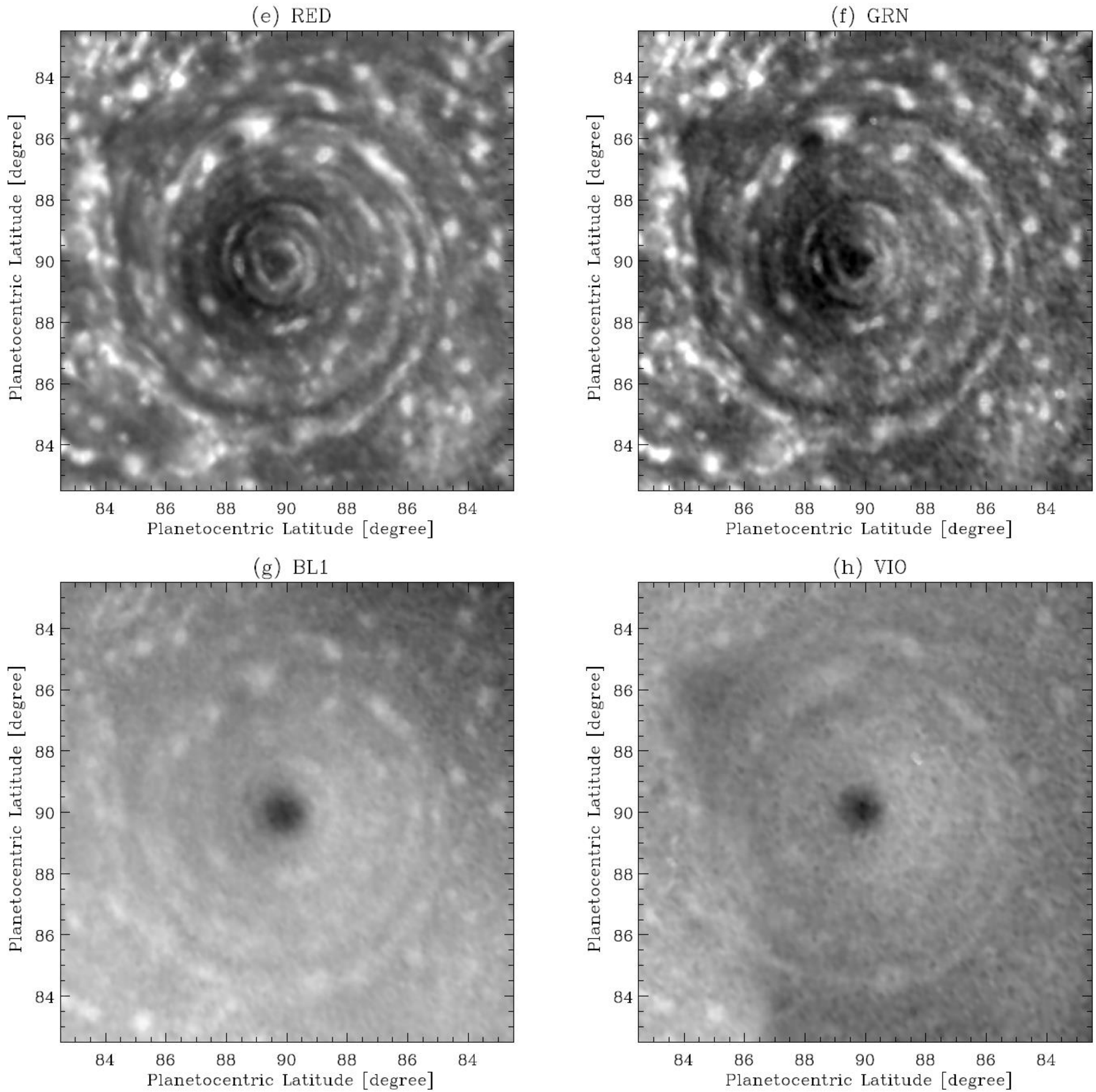
North Polar Vortex

Dec 2012

VIS/UV



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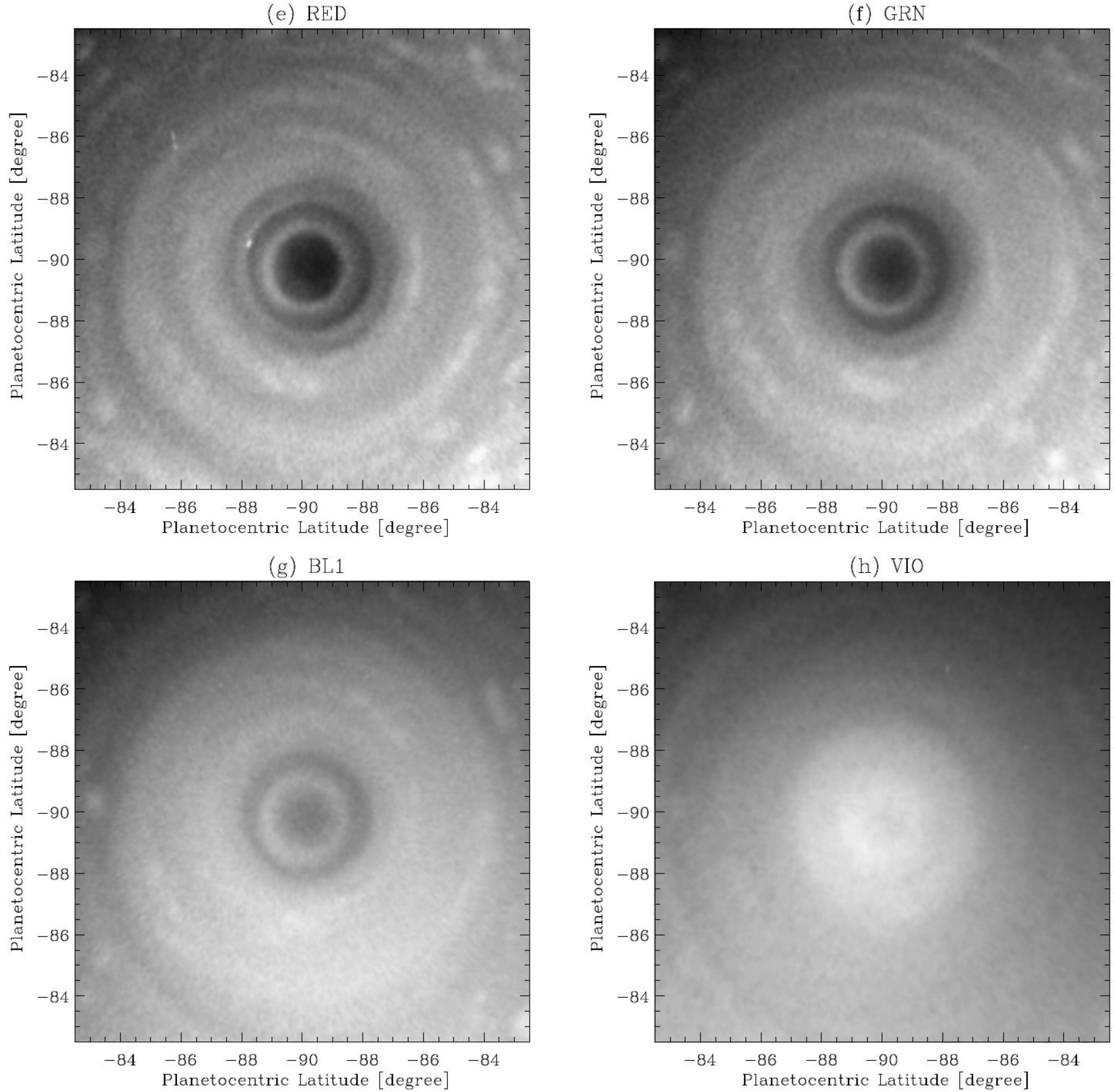
South Polar Vortex

Jan 2007

VIS/UV



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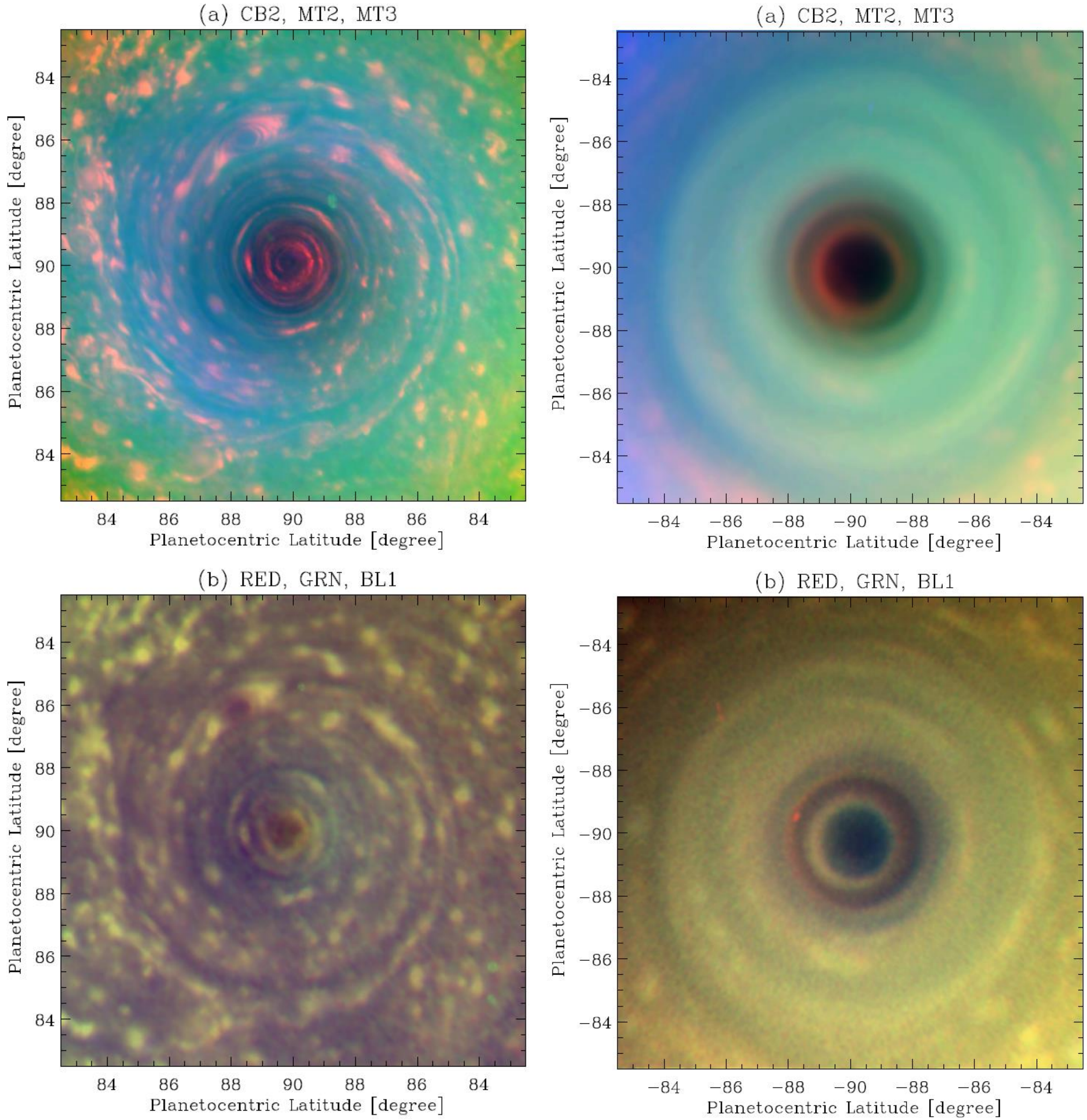
North/South Comparison

Color Composites



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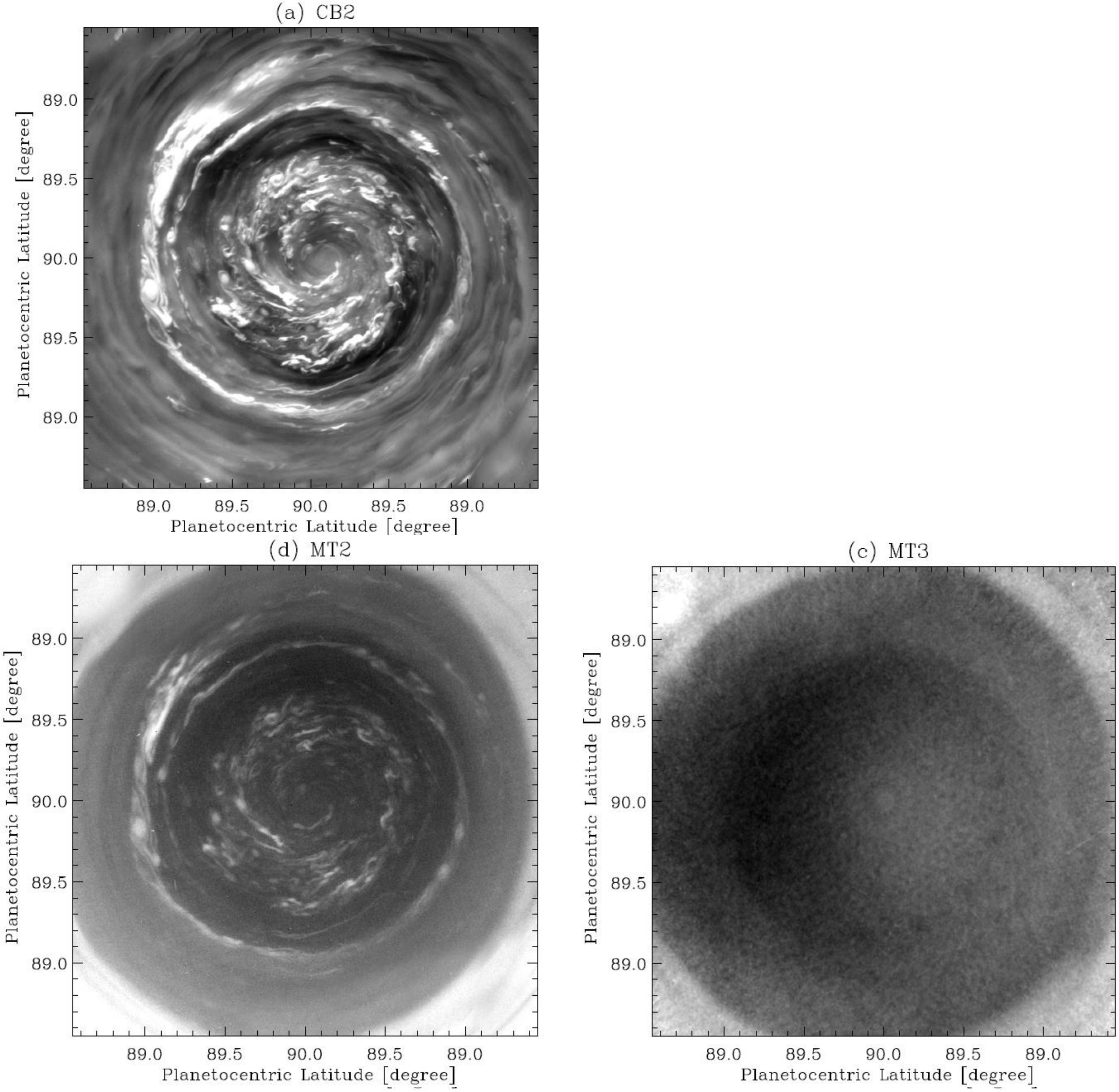
North Polar Vortex Core

Nov 2012

NIR View



Sayanagi et al
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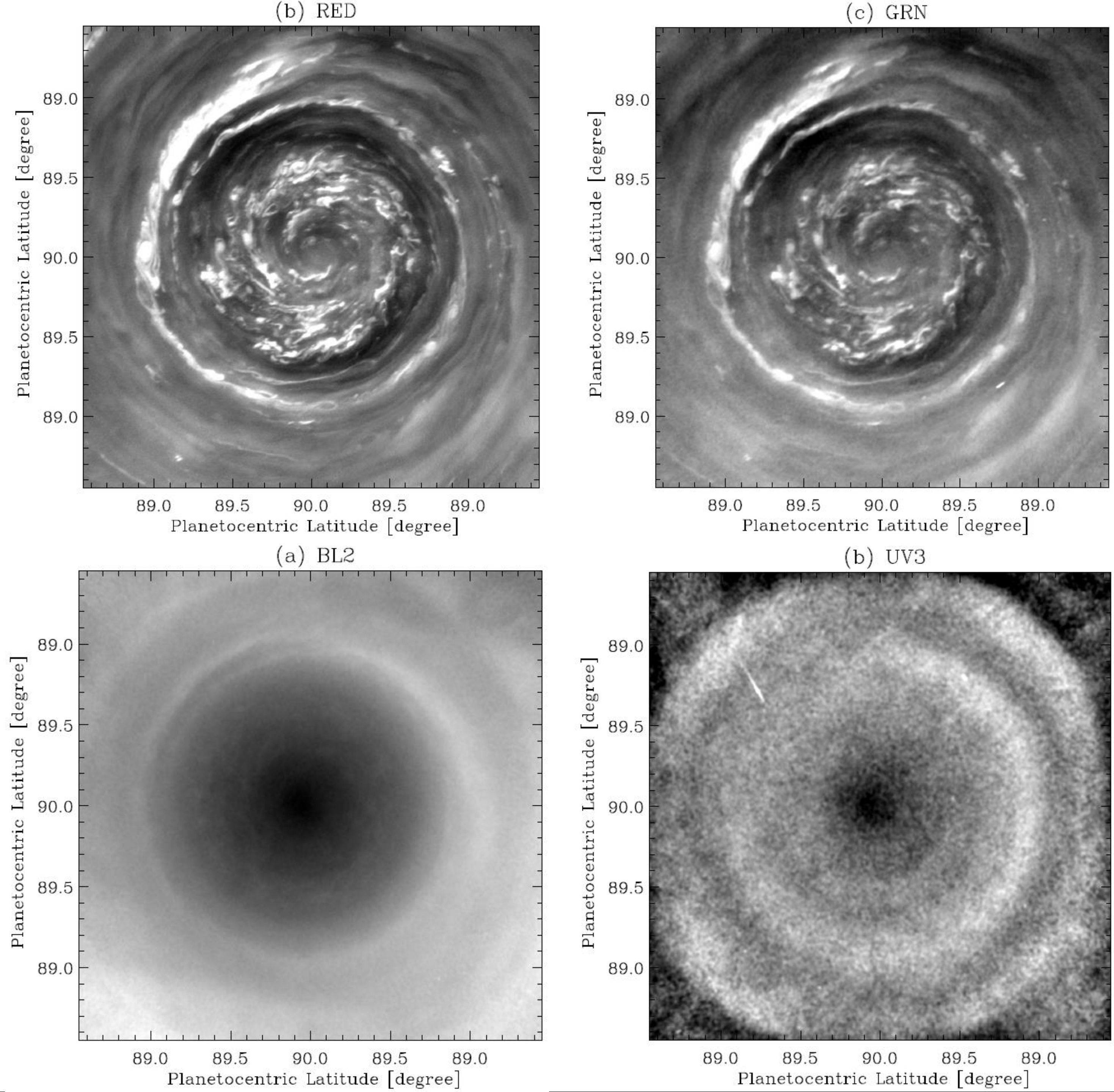
North Polar Vortex Core

Nov 2012

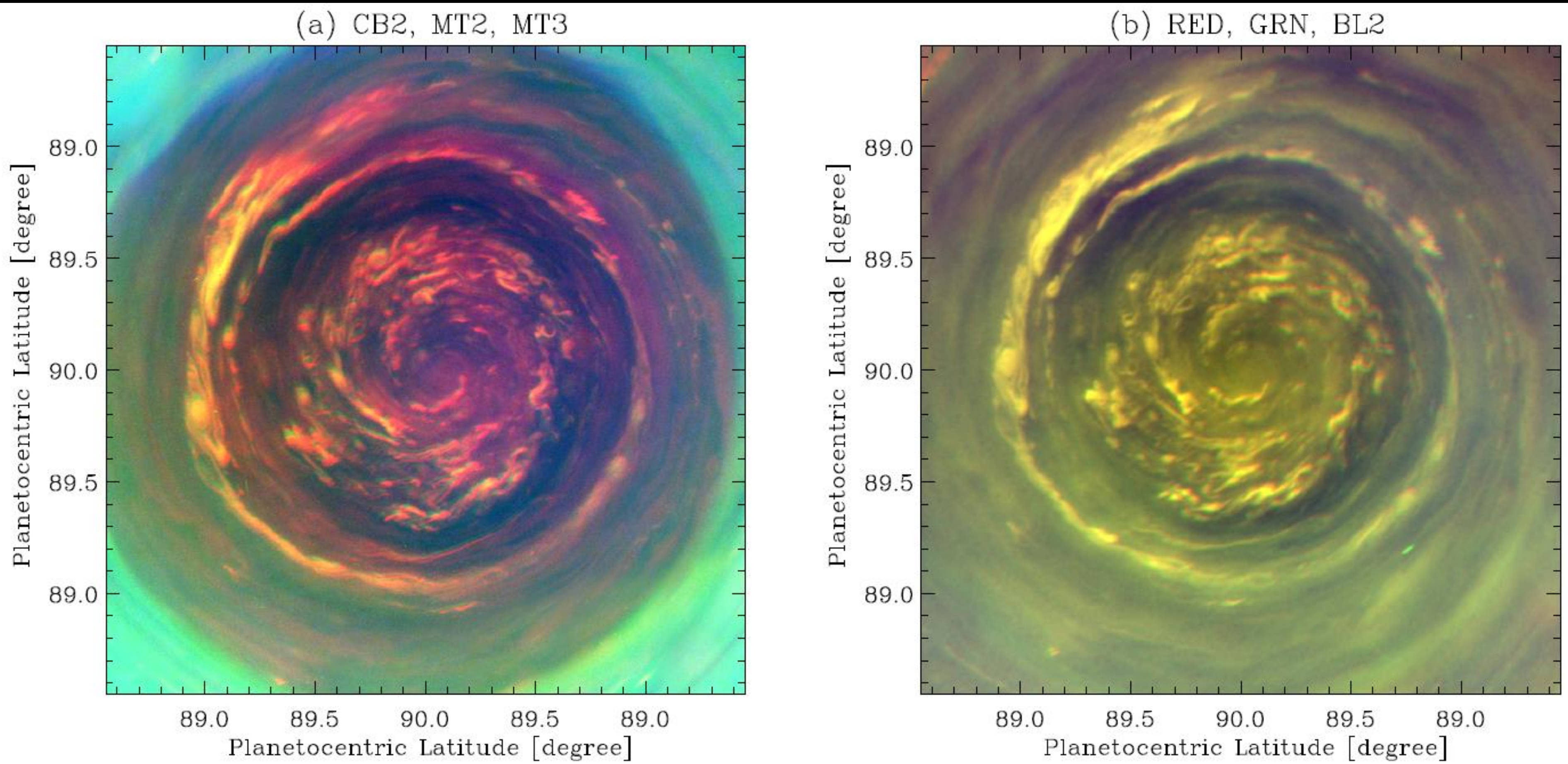
VIS/UV



Sayanagi et al
(in prep)

North Polar Vortex

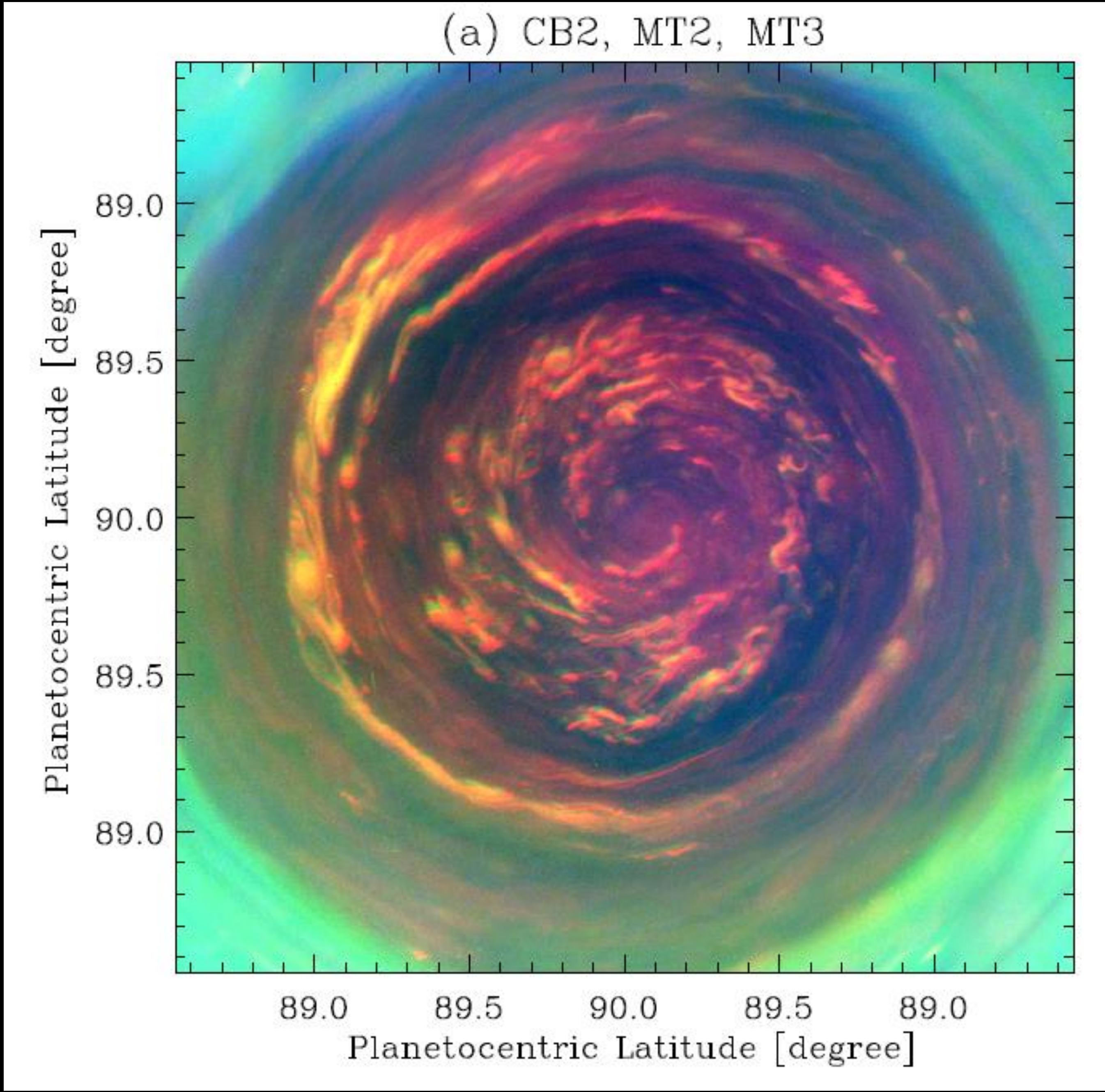
Color Composites



Sayanagi et al (in prep)

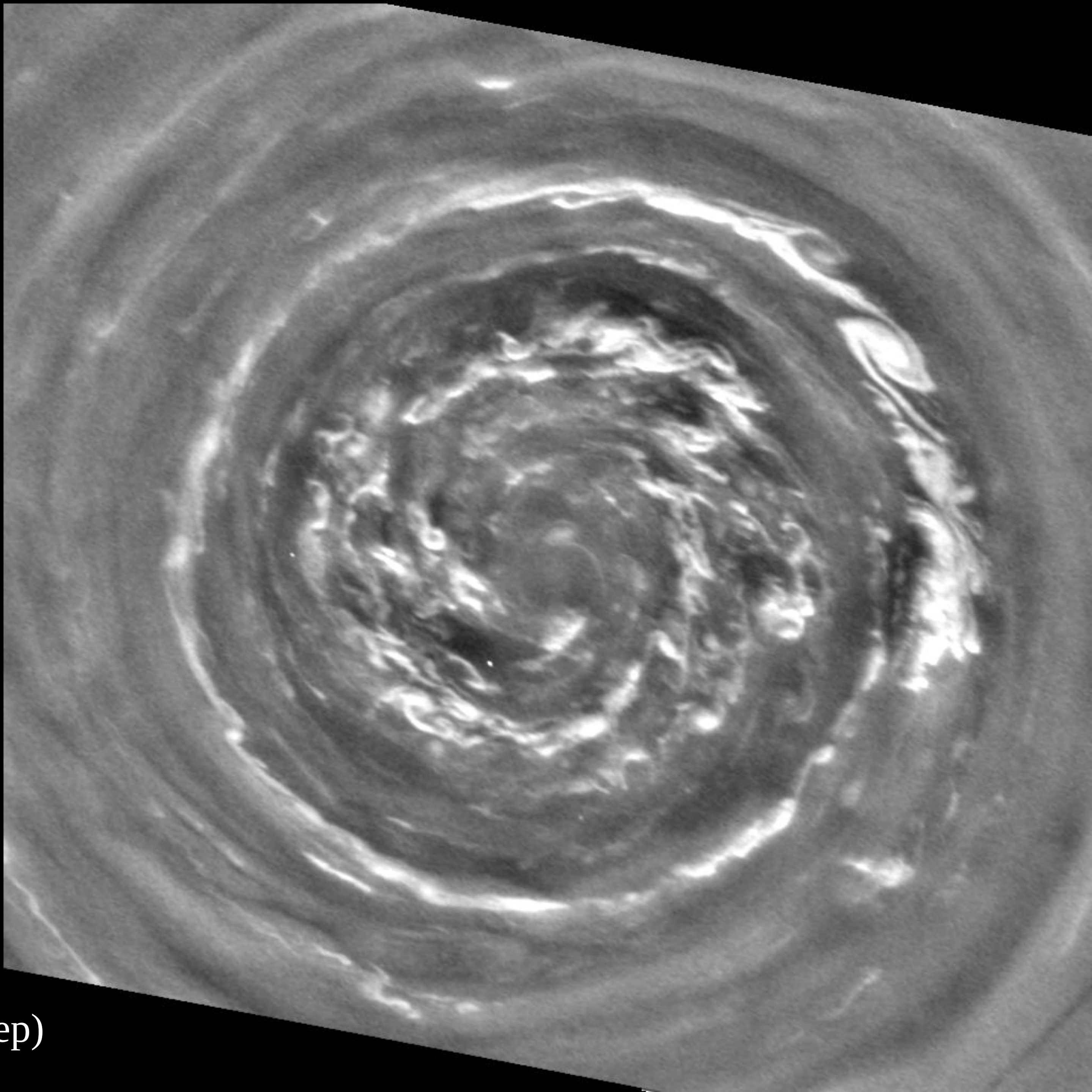
North Polar Vortex

Color Composites



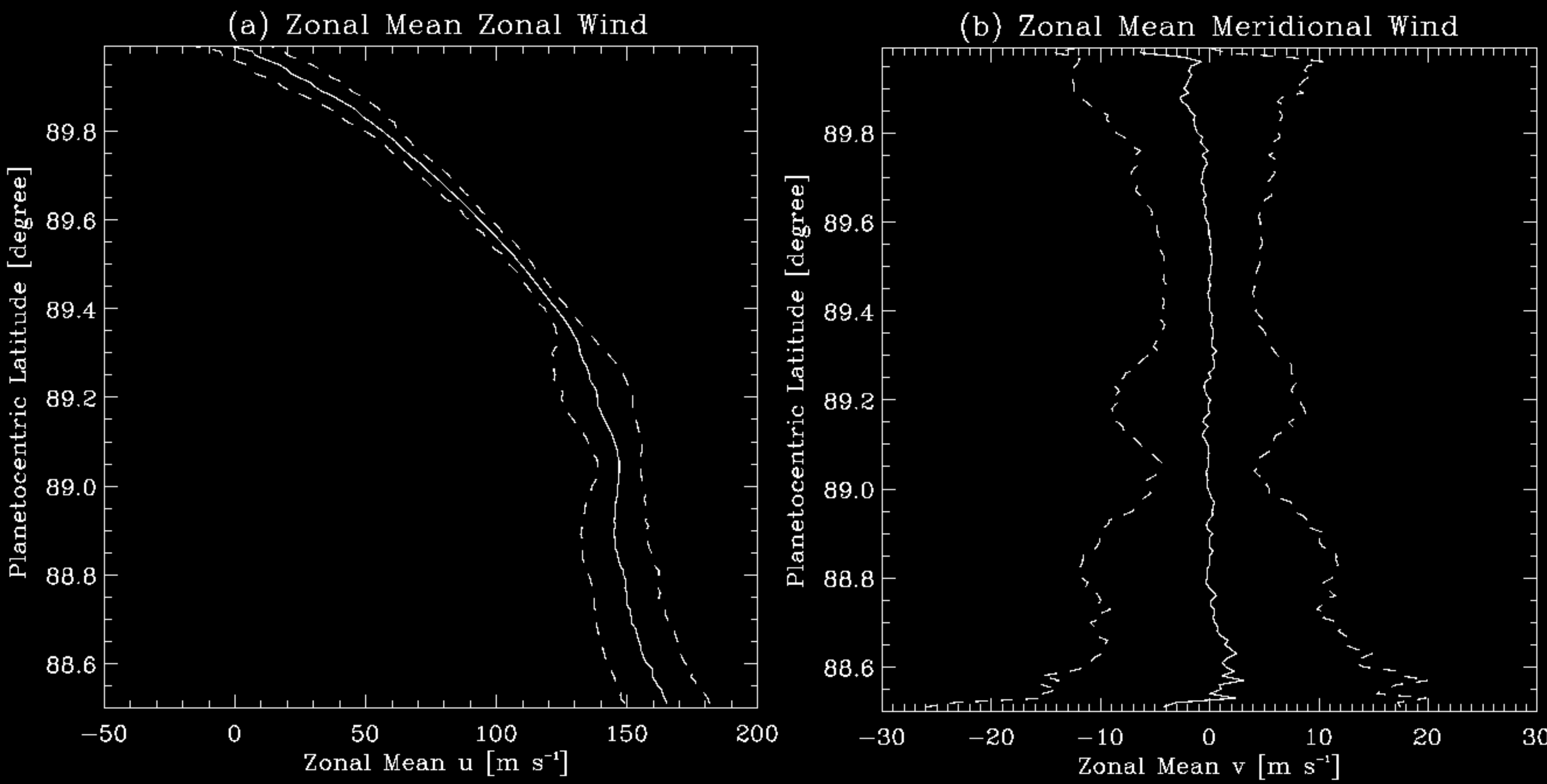
Sayanagi et al (in prep)

North Polar Vortex Movie



Sayanagi et al (in prep)

North Polar Vortex Wind

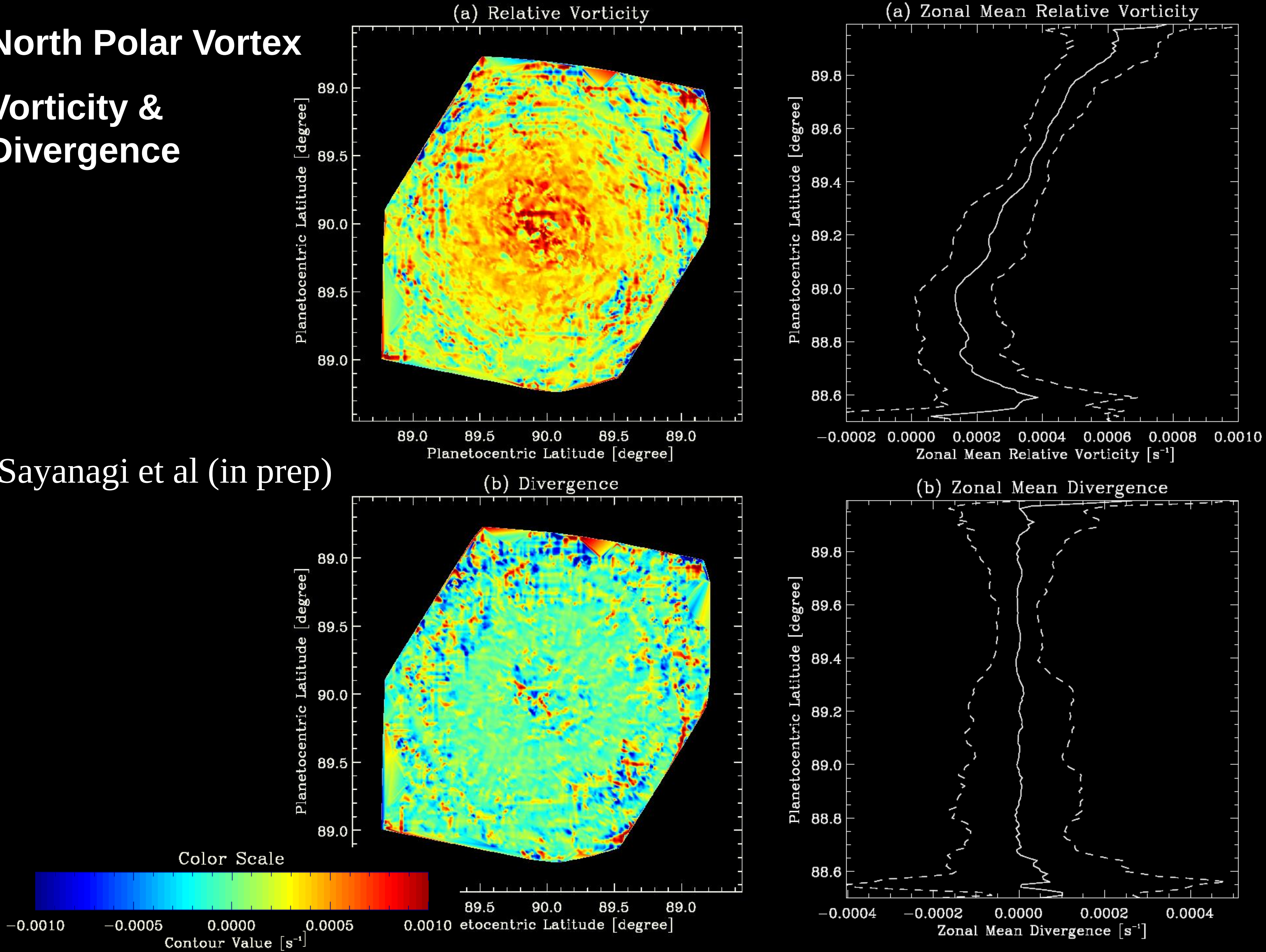


Sayanagi et al (in prep)

North Polar Vortex

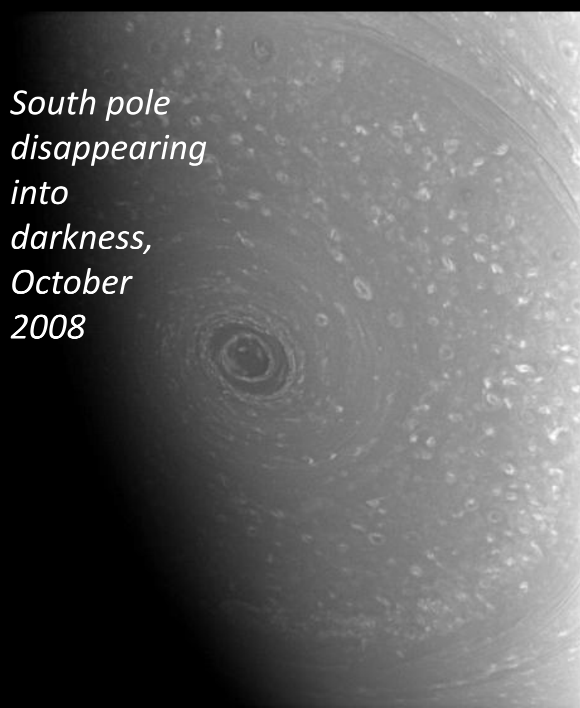
Vorticity & Divergence

Sayanagi et al (in prep)

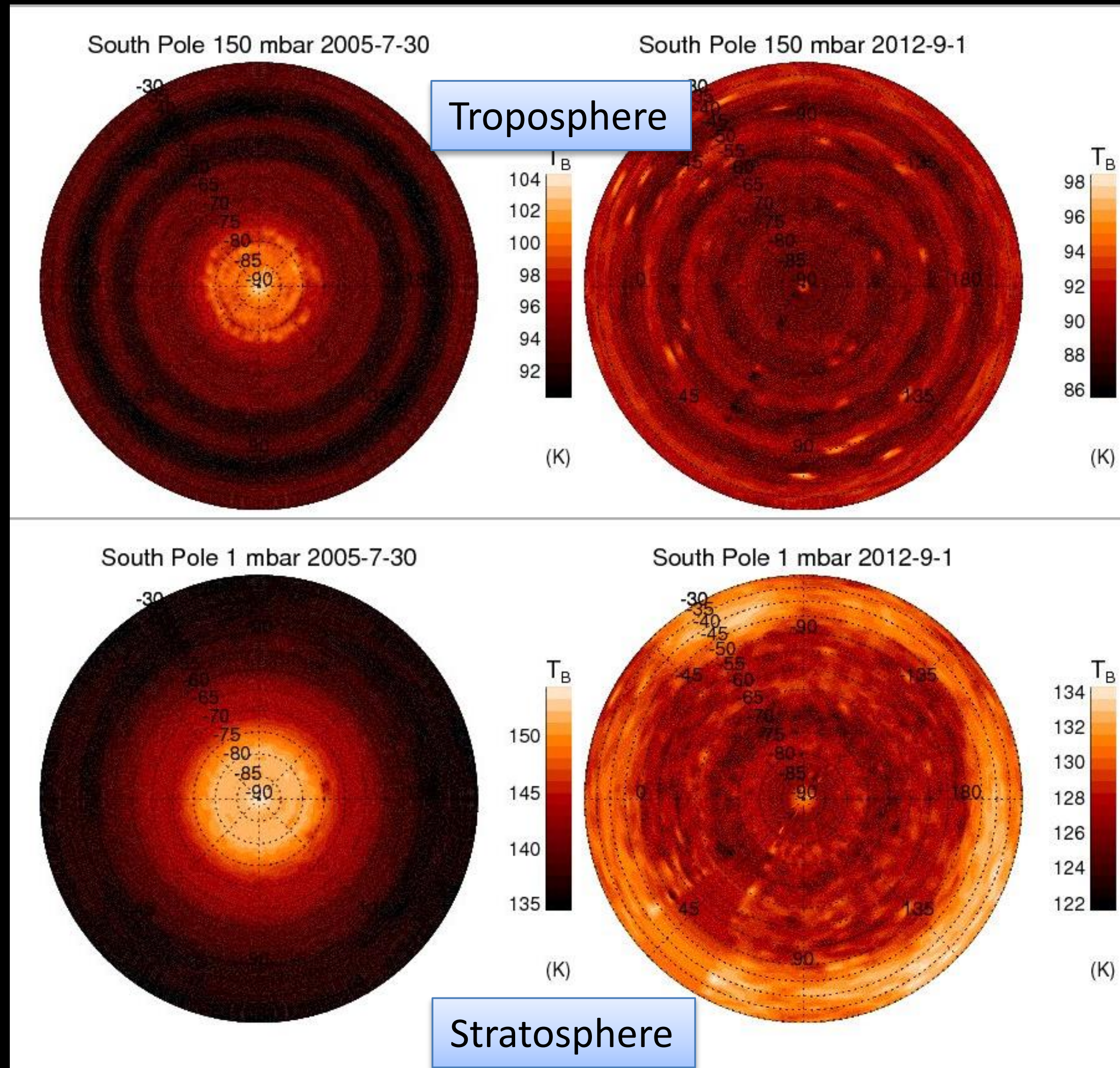


Seasonal Change: South Polar Vortex still Present but Cooling in Autumn

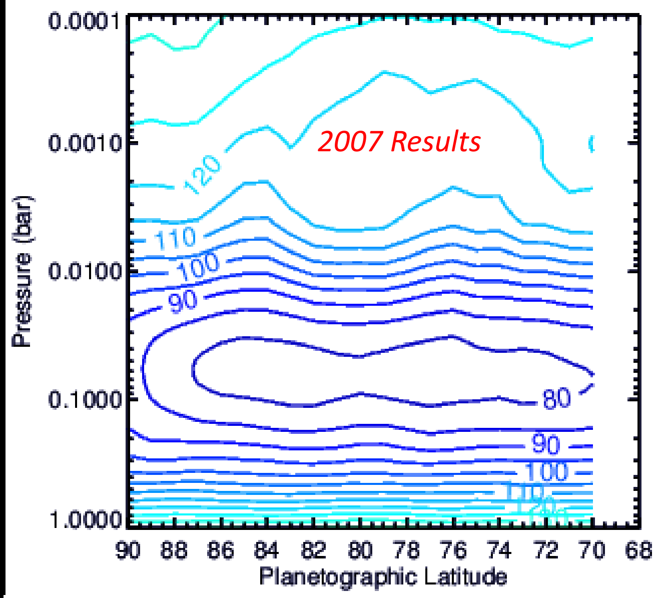
- Low 15 cm^{-1} resolution maps provided good south polar coverage.
  - South pole in 2005 (summer) and 2012 (autumn) from CIRS.
- Tropospheric and **stratospheric polar hoods (70-90S) dissipated** (breakdown of polar vortices?); cyclonic hotspot still present.
- Generally cooler than in 2005, seasonal radiative cooling.

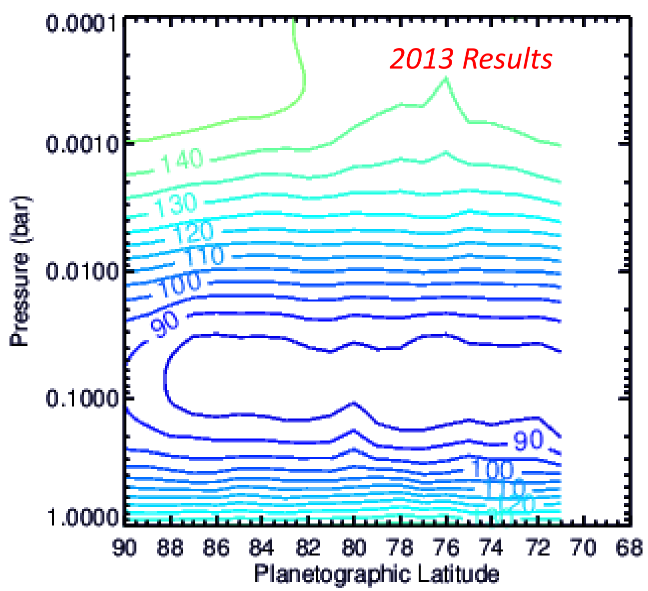


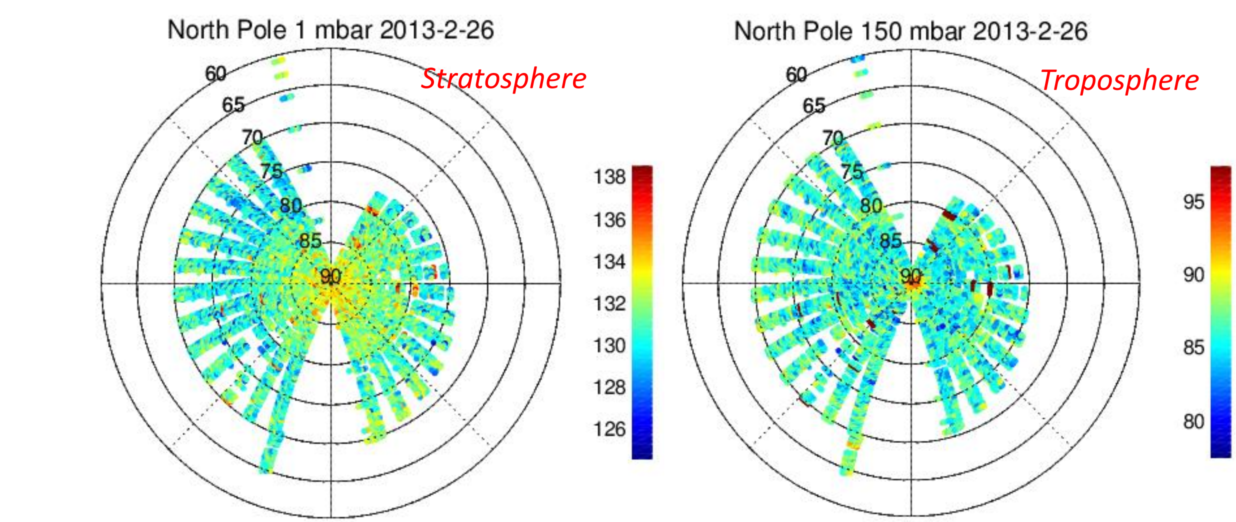
South pole disappearing into darkness, October 2008



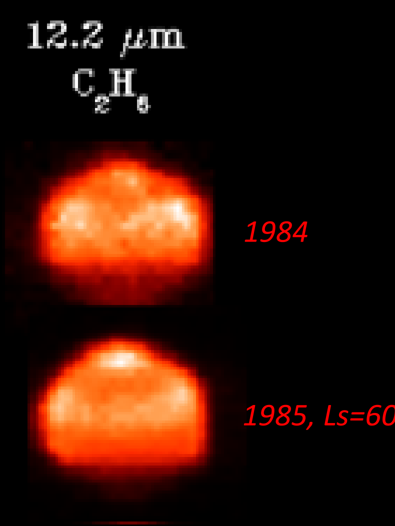
Seasonal Change: North Polar Warming in Spring, Onset of Warm Stratospheric Hood







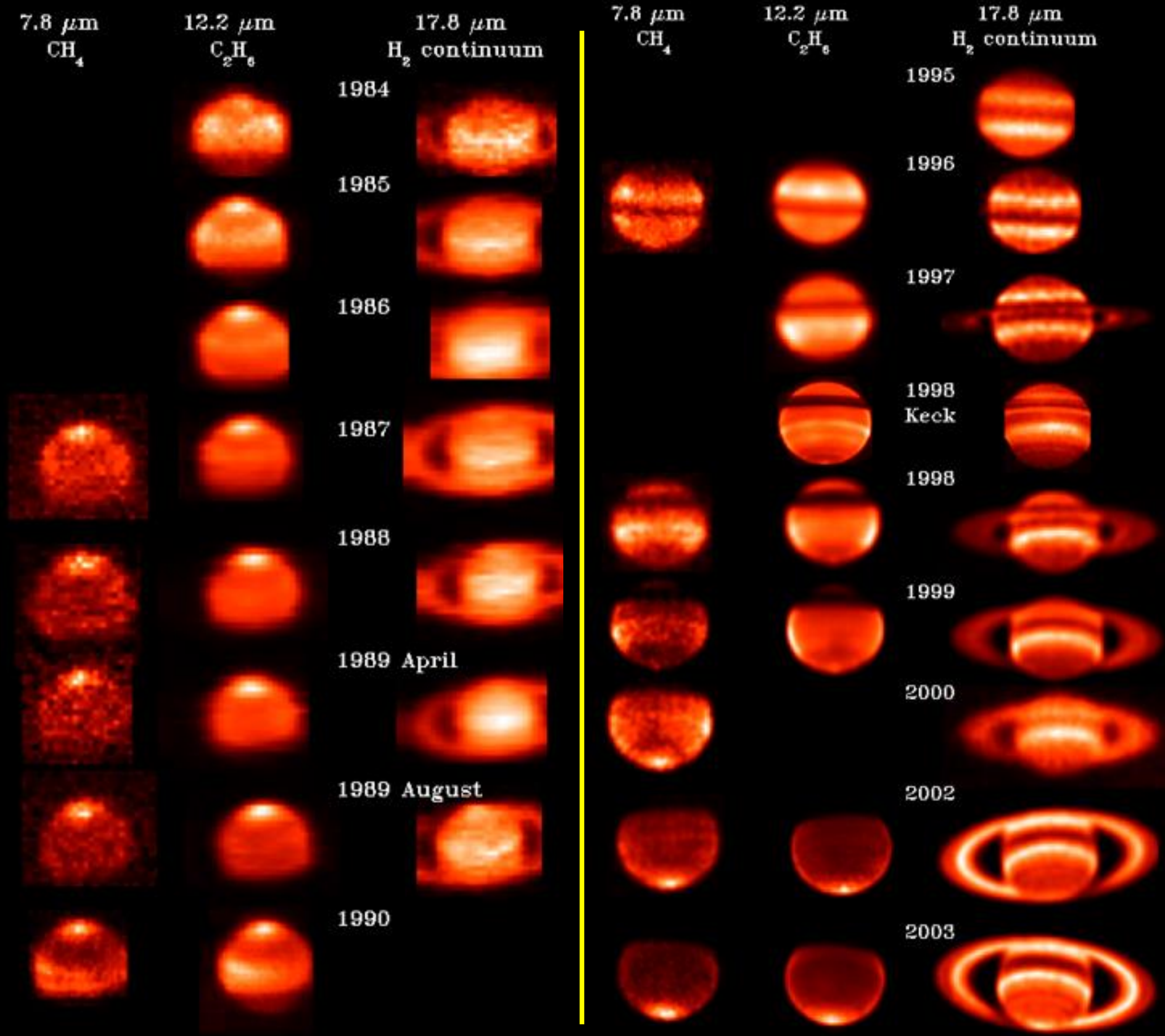
- Moderate 2.5 cm^{-1} resolution scans allow zonal mean retrievals of T(p) and composition.
- **North polar cyclone also remains present as it emerges into sunlight**.
- Tropospheric cyclone has warmed 2-3 K.
- **Stratospheric polar hood warmed 123-144 K at 1 mbar** (dT=21 K)
  - Onset of new polar hood occurred before Feb 2013 (Ls=42), mirroring results in 1984-1985.
  - Gradual radiative heating? Or forced subsidence?
  - Implication for zonal jet strength in stratosphere.



Historical Record 1984-2003 (IRTF)

Northern spring equinox, March 1980

Northern summer solstice, Dec 1987

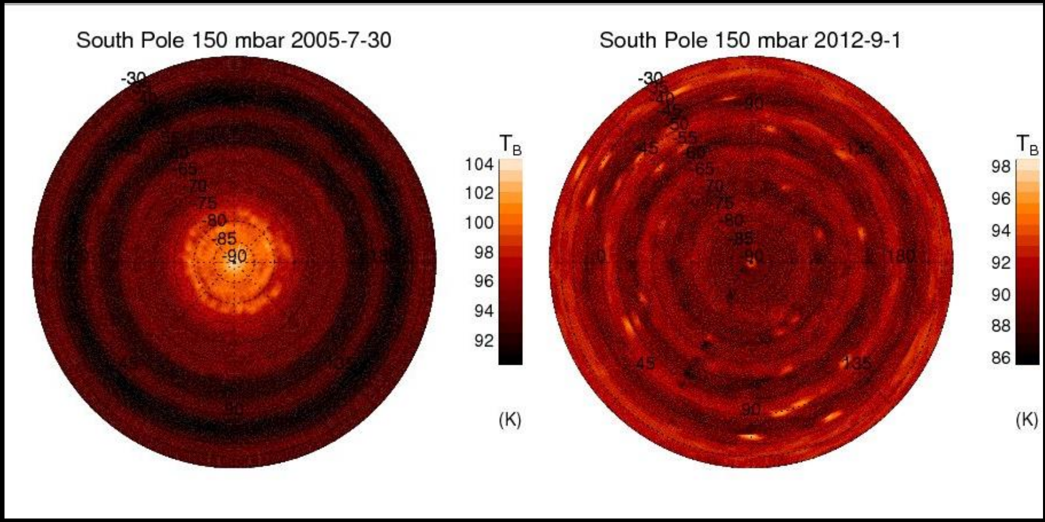


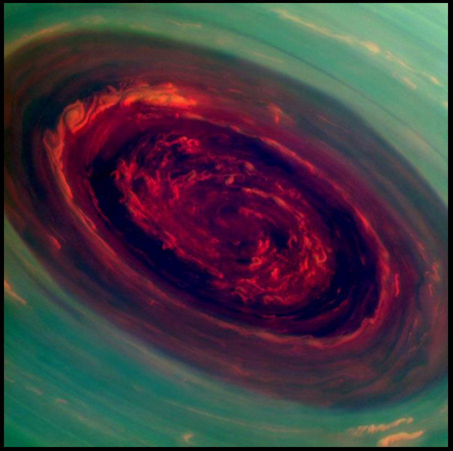
Northern autumnal equinox, Nov 1995

Northern winter solstice, Oct 2002

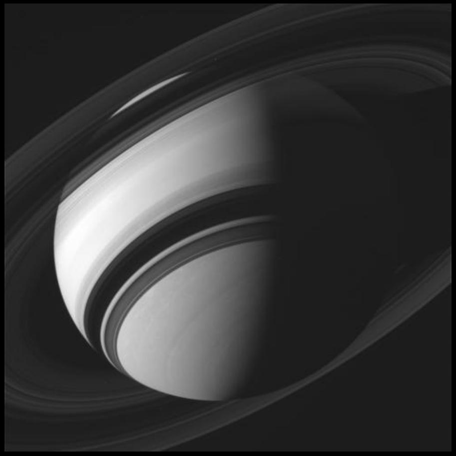
Summary: Seasonal Change at Saturn's Poles

- **Hot polar cyclones (87-90°) still present** 6 years after discovery; associated with vortices in visible light
  - Present in every season; permanent feature?
- **North polar spring stratosphere now warmer than the southern autumn**.
  - Temperatures follow expectations of radiative heating/cooling,
- **Warm stratospheric hood (70-90°) weakening in south; strengthening in north**
  - Hydrocarbons still entrained in south but weakening.
  - Hydrocarbon gradient strengthening in north.
- **Warm north pole present from Ls=40 onwards** (mirrors 1984/1985).
- **Vertical temperature structures very different**
  - Influence of waves and/or aerosol heating in the south at 0.5 mbar?





North emerges into spring sunlight



South disappears into winter darkness

Summary – Polar Vortex

- Strong Cyclonic Vortex at North Pole
- Stratospheric haze has a hole over the pole
- North-South dichotomy
  = Probably seasonal difference

Hexagon Models

The models should reproduce:

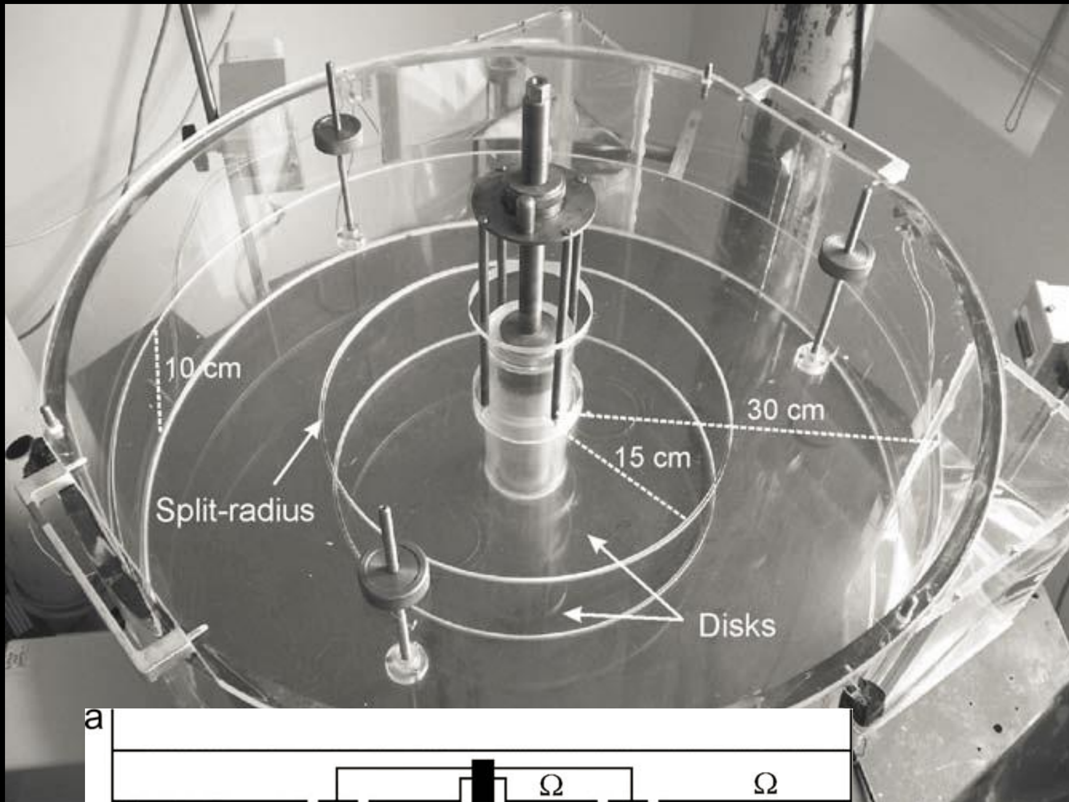
- **Hexagon = 77deg N Jetstream**
- **Jetstream follows Hexagon's outline**
- **It is a meandering jetstream, and not a vortex street.**
- **Slow Propagation (but non-zero in System III)**
- **Hexagon acting as a Transport Barrier**

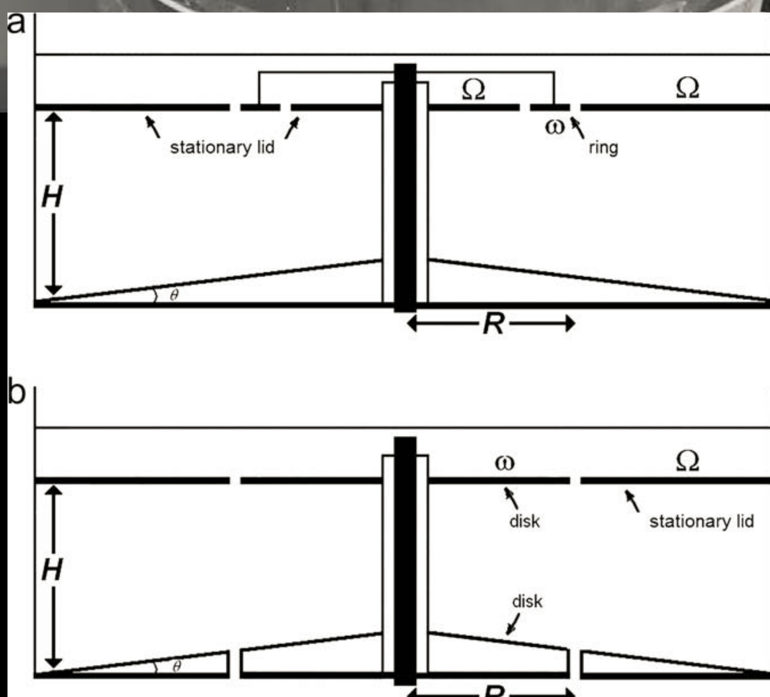
"Obviously, it's a Rossby Wave."

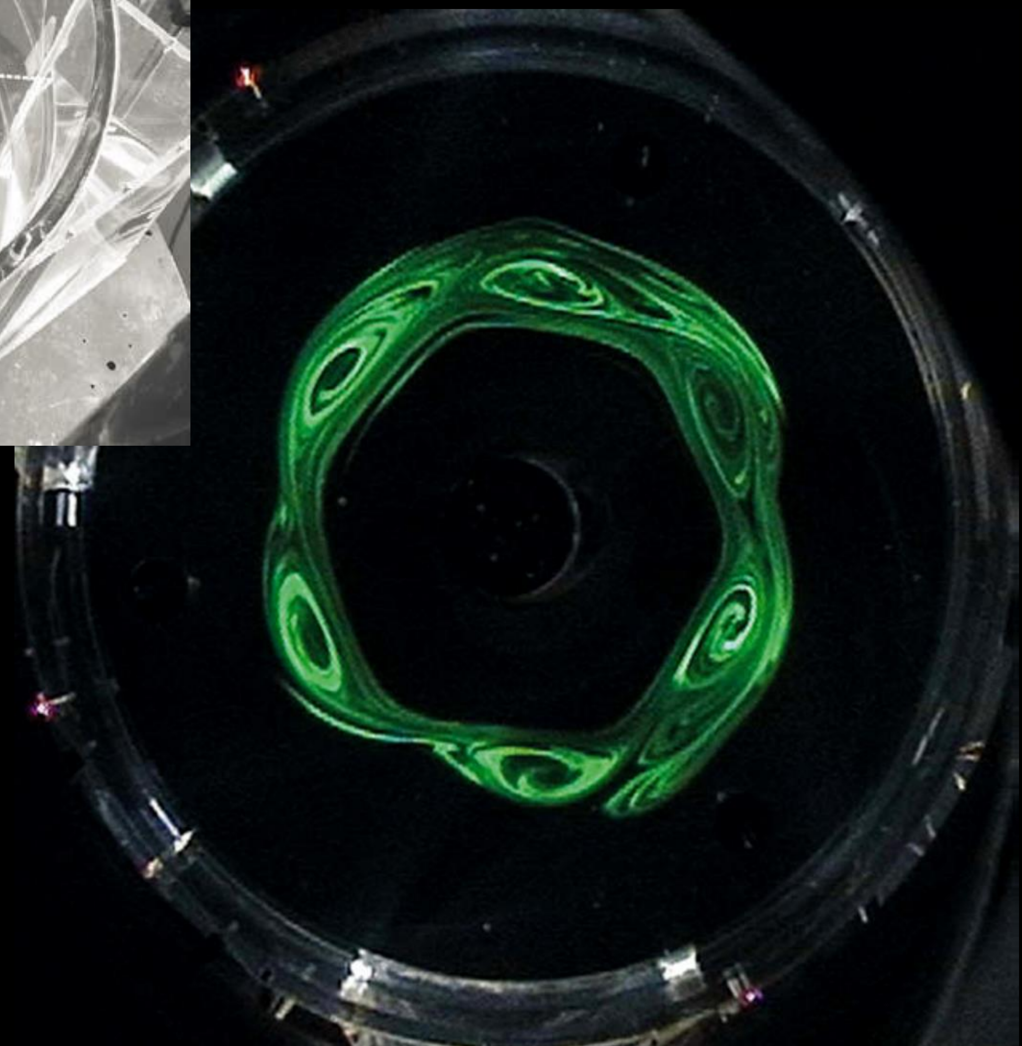
→ Its propagation rate, wavelength, and excitation mechanism still need to be explained.

Lab Experiments

Barbosa-Aguiar et al. (2010)

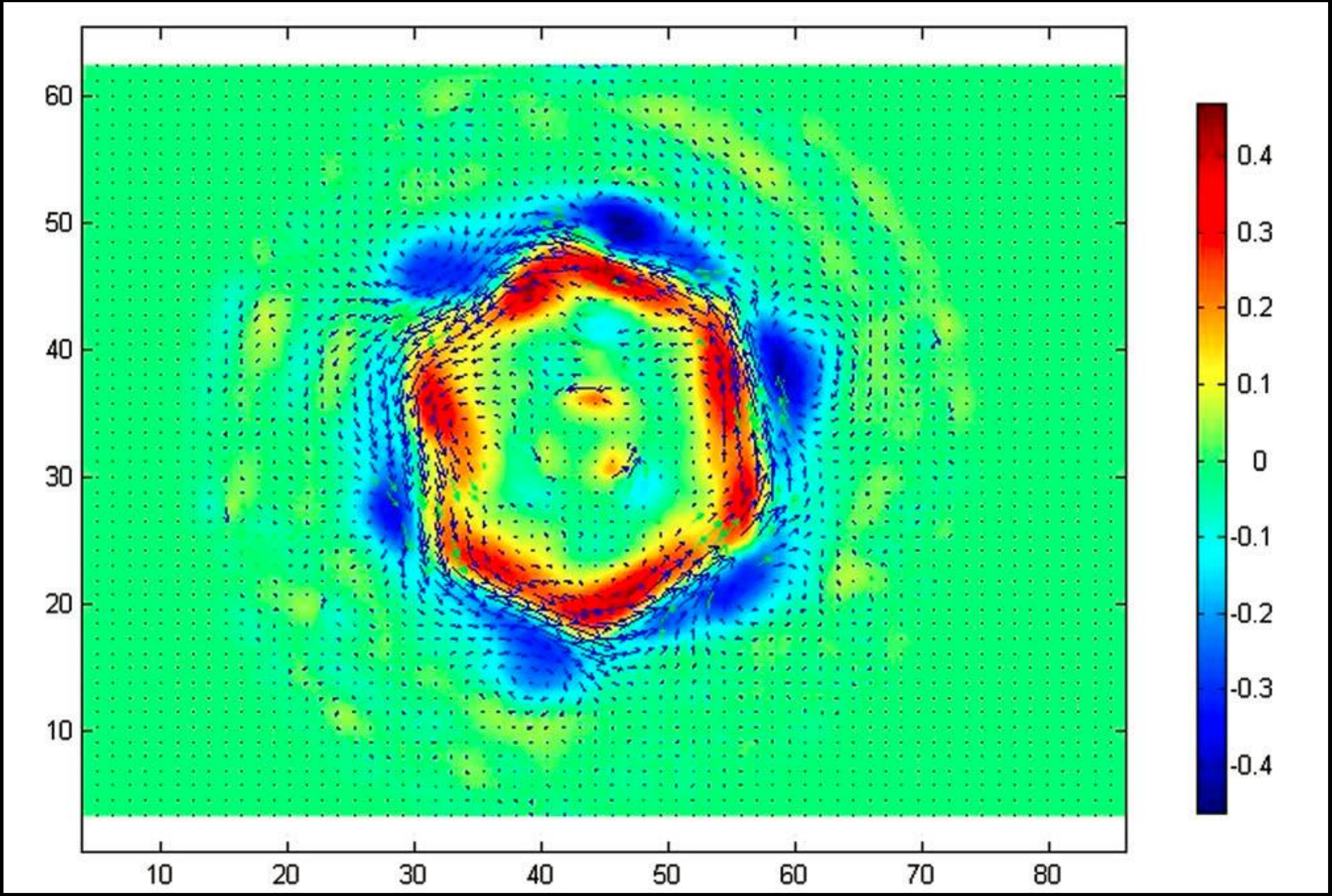






Lab Experiment

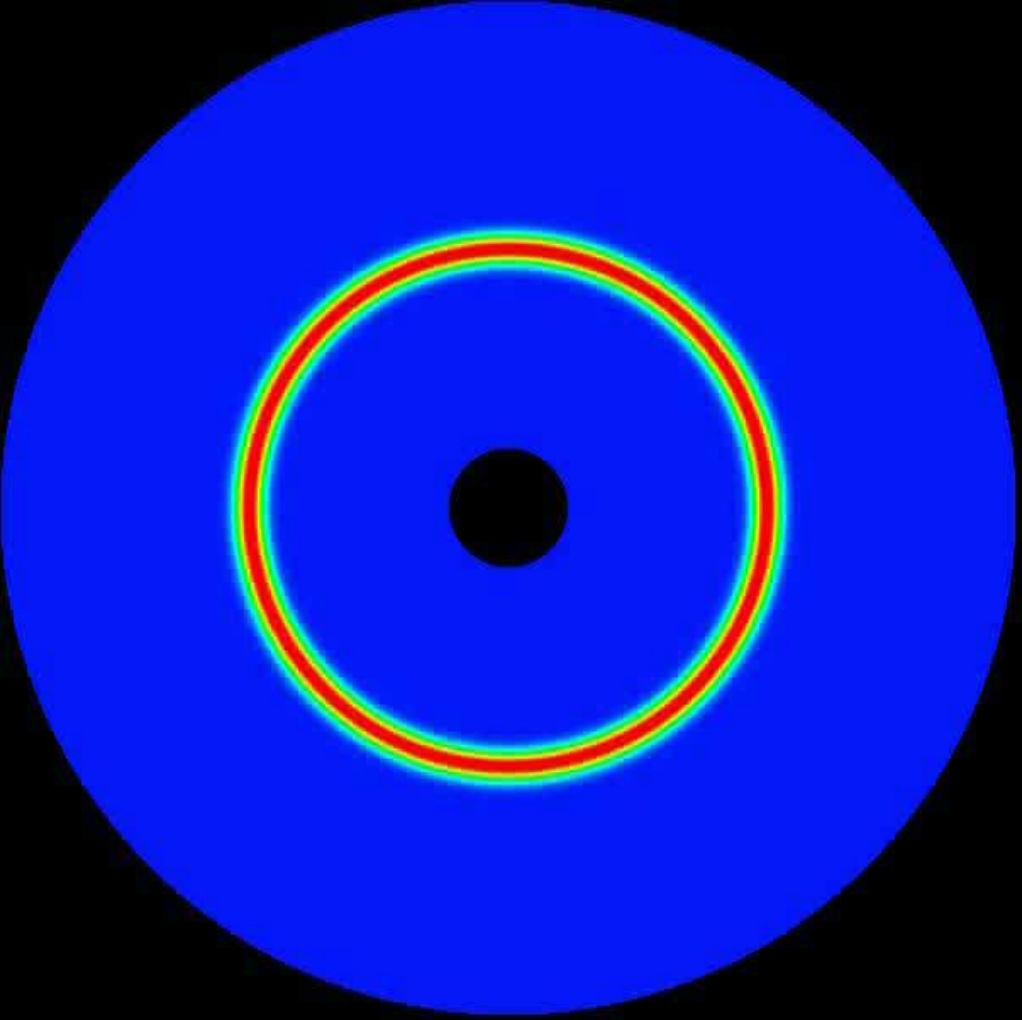
Hexagonal flow produced by interlocking set of vortices, i.e., a Vortex Street



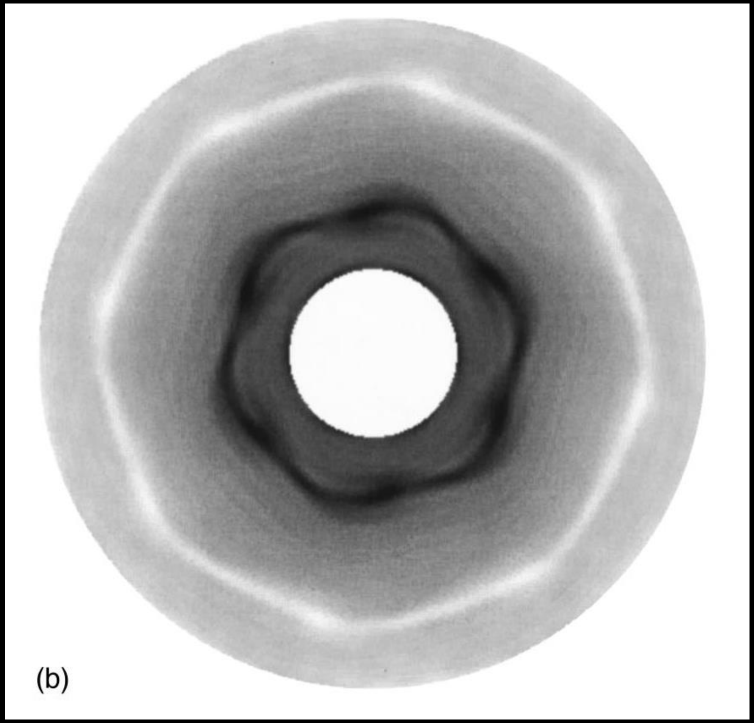
Barbosa-Aguiar et al. (2010)

Numerical Models

Hexagonal flow caused by interlocking set of vortices, i.e., a Vortex Street

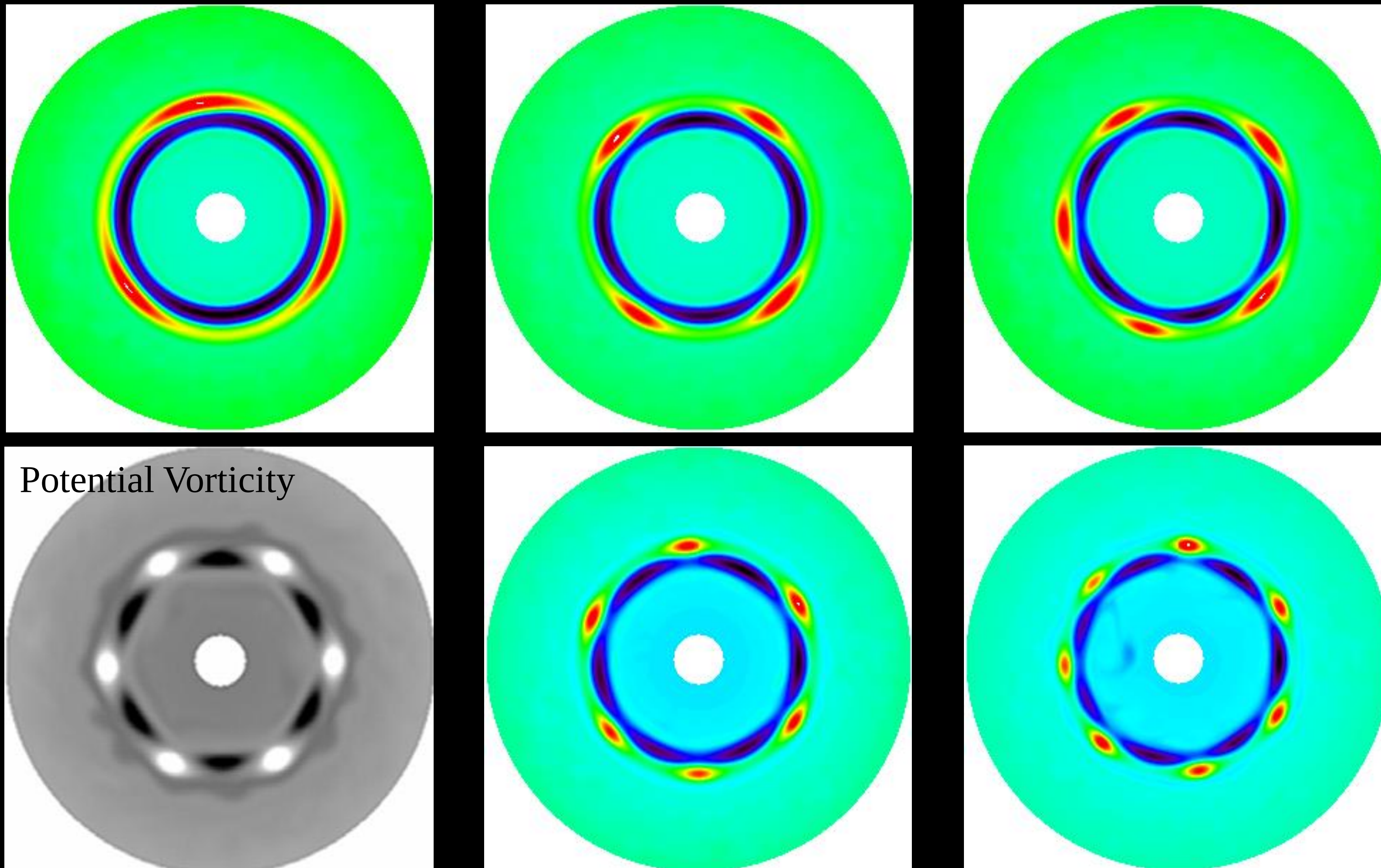


Morales-Juberias et al. (2011)



Marcus and Lee (1998)

Jet Width controls the Dominant Wavenumber

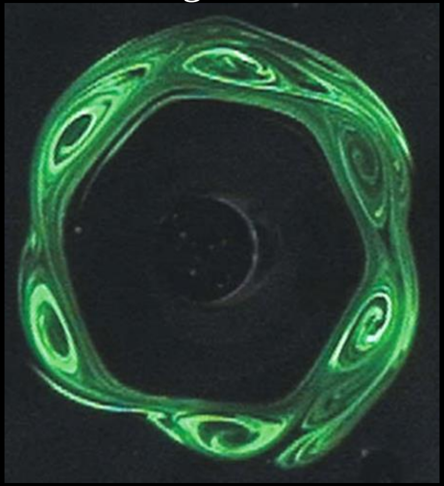


Relative Vorticity: Red = Anticyclonic Blue = Cyclonic Green = Zero

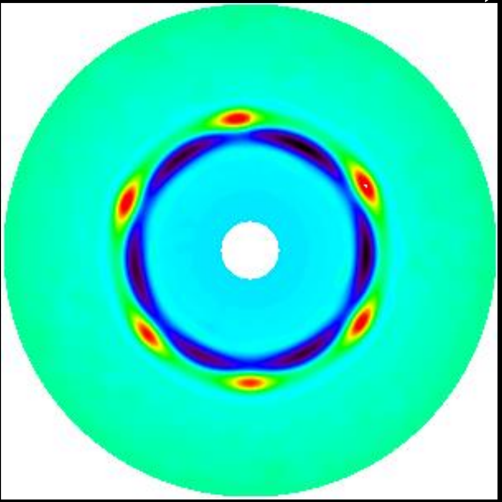
Morales-Juberias et al. (2011)

Hexagon – Vortex Street or Meandering Jet?

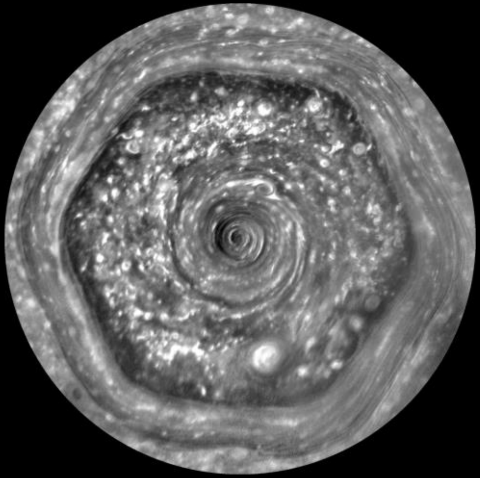
Lab Experiment
(Barbosa-Aguiar et al. 2010)



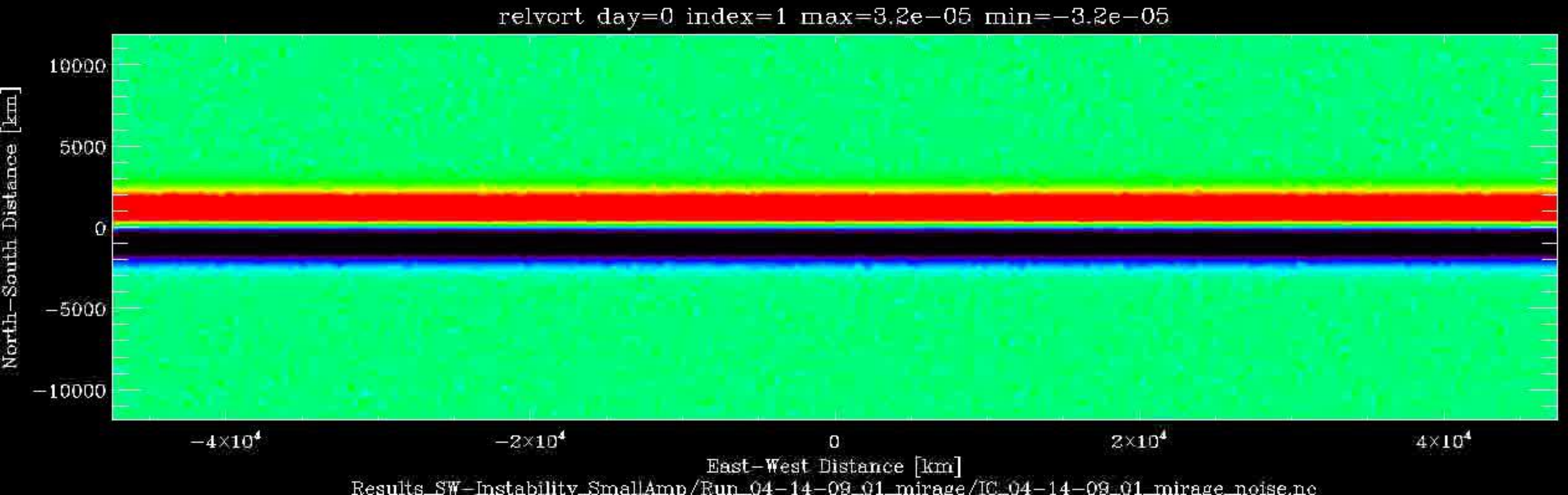
Simulation
(Morales-Juberias et al, 2011)



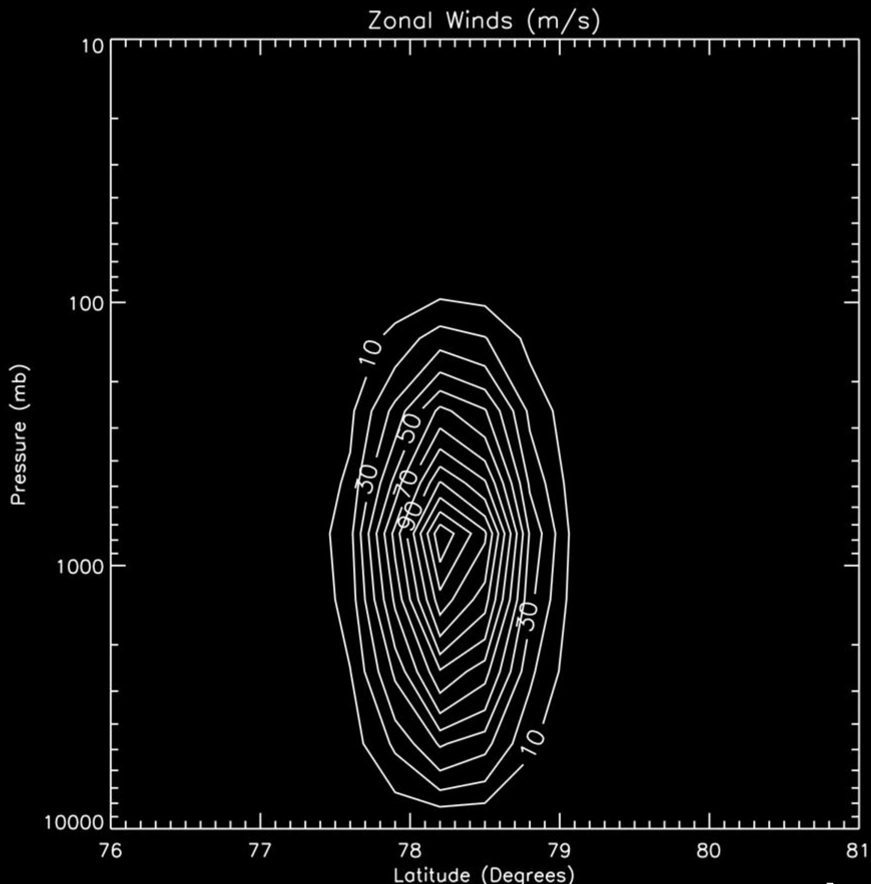
Observation
Sayanagi et al. (in prep)



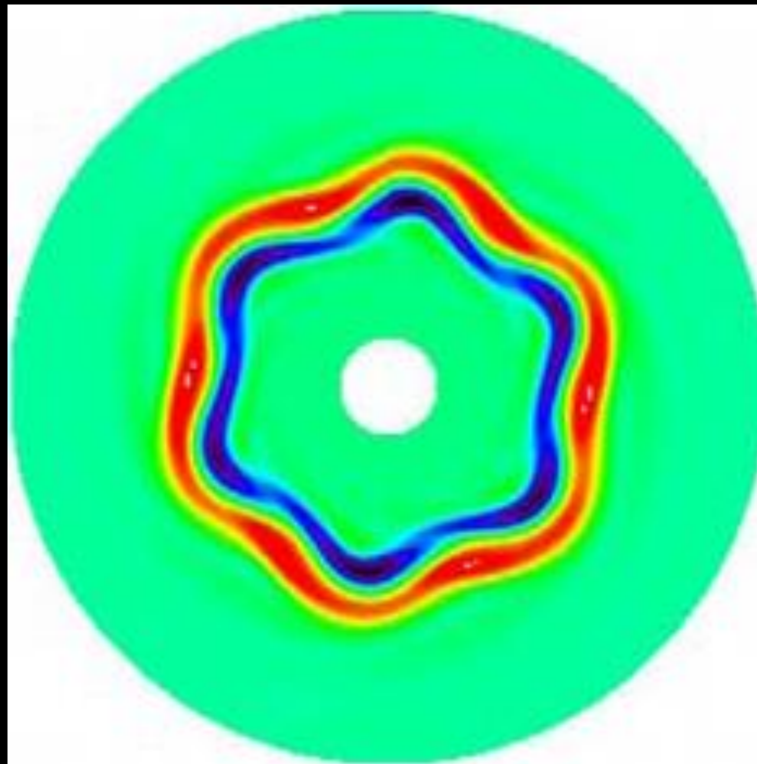
Preliminary Simulation of a Meandering Jet by Sayanagi et al. (in prep)



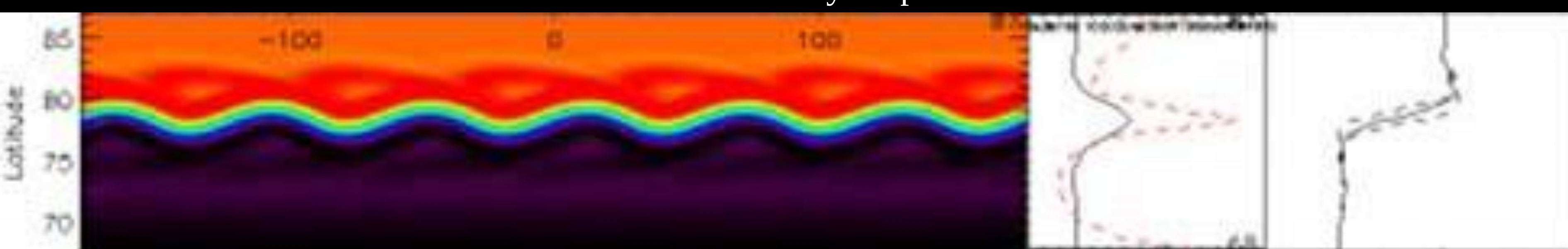
Hexagon as a Shallow Meandering Jet (Preliminary!)



Relative Vorticity Map



Potential Vorticity Map



Morales-Juberias et al. (in prep)

Polar Vortex Model

Observational Constraints:

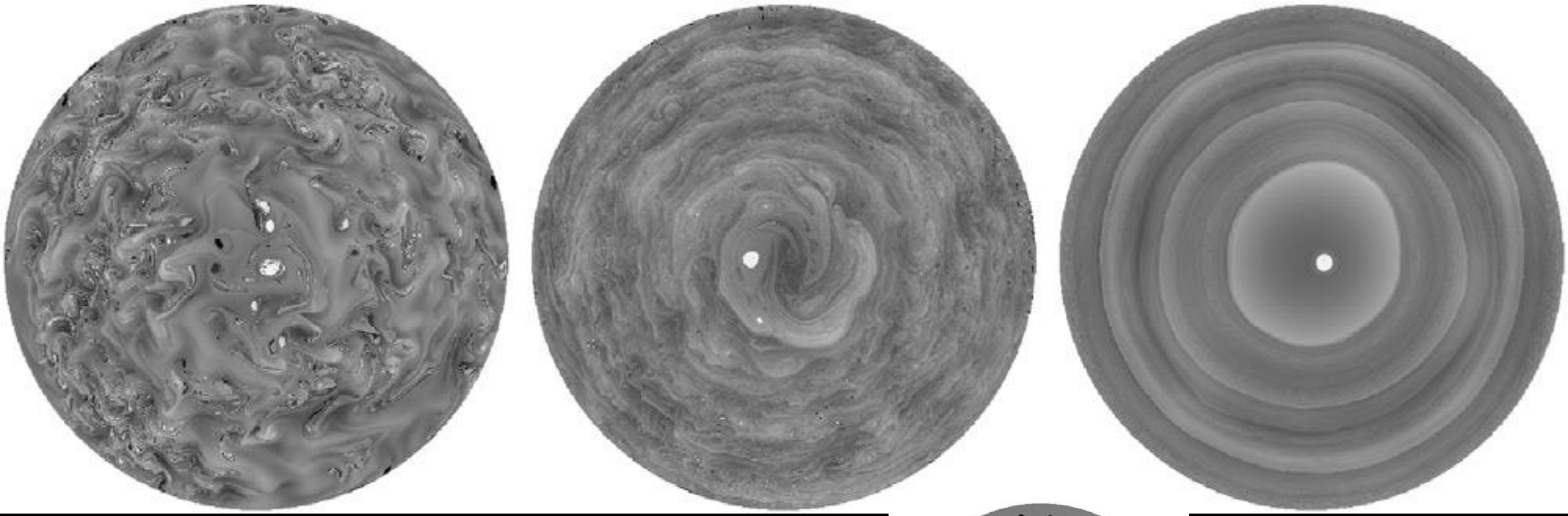
- Strong Compact Cyclonic Vortex at North Pole
- Stratospheric haze has a hole over the pole
- North-South dichotomy
  = Probably seasonal difference

Is the analogy with a terrestrial hurricane a good one?

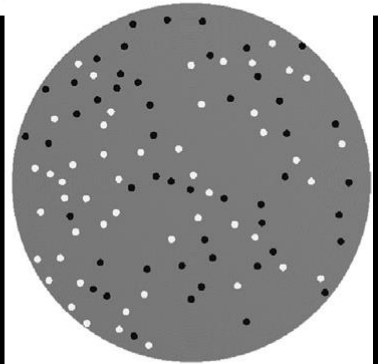
Polar Vortex Model

Scott (2011):
<u>Beta-drifting Cyclones Accumulate at the Pole</u>

Relative Vorticity Map

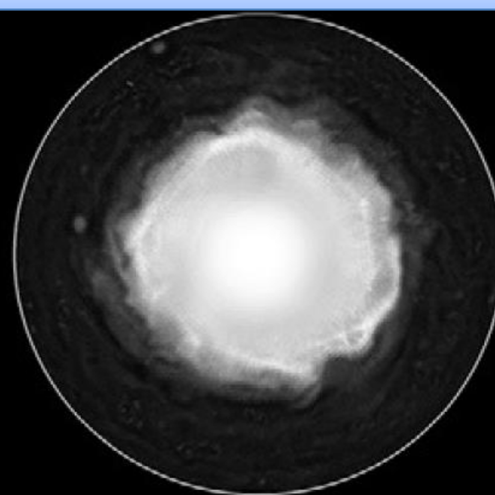


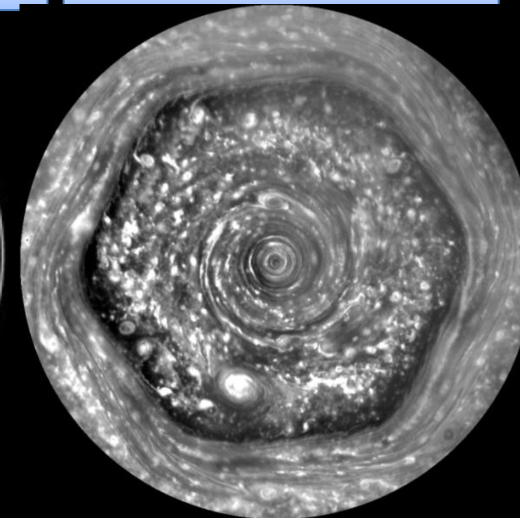
Relative Vorticity Initial Condition:

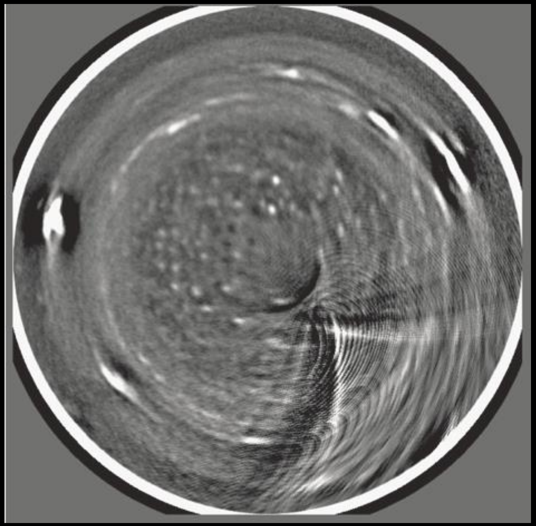


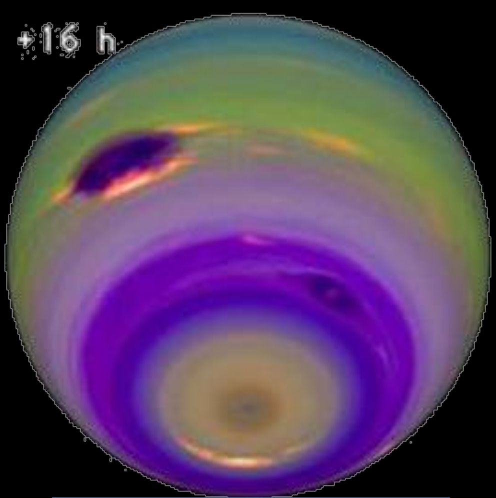
Giant Planet Poles

- Polar atmospheres provide an **extreme test of our understanding of circulation, clouds and chemistry**
  - Apex of planet-wide circulation
  - Unique connection between atmosphere and charged particle environment
  - Extremes of seasonal contrasts.
- Giant planet **poles appear different to banded mid-latitudes**
  - Long lived polar vortices.
  - Planet-encircling waves
  - Mottled appearance of convective events
- **Cassini reconnaissance** revealing seasonal evolution of Saturn's poles from 2004 to 2013.
  - Third of a Saturnian year.


Jupiter (Cas/ISS Barrado-Izagirre etal. 2008)


Saturn's Hexagon (Cassini/ISS)


Uranus (Keck, Sromovsky et al.)



Neptune (Voyager, Karkoschka et al., 2011)

Polar Chapter: Summary

Main Progress since Del Genio et al (2009):

- **Fuller comparison between North and South Polar Regions (cloud morphology, thermal structure).**

- **Atmospheric Dynamics of the poles revealed.**

- **Temporal changes in clouds and thermal structures are visible.**

- **Dynamical models continue to identify key dynamical processes.**

Saturn Polar Science Outlook

Cassini until 2017:

- Continued Observation of Seasonal Changes
- Higher Resolution Images and Wind Measurements?

Theoretical/Modeling Priorities:

- What separates polar turbulence from mid-latitude jets?
- Hexagon: Vortex Street or Meandering Jet?
- Polar Vortex: Do we need heating? Meridional Circulation/Transport Model?

Final Conclusion