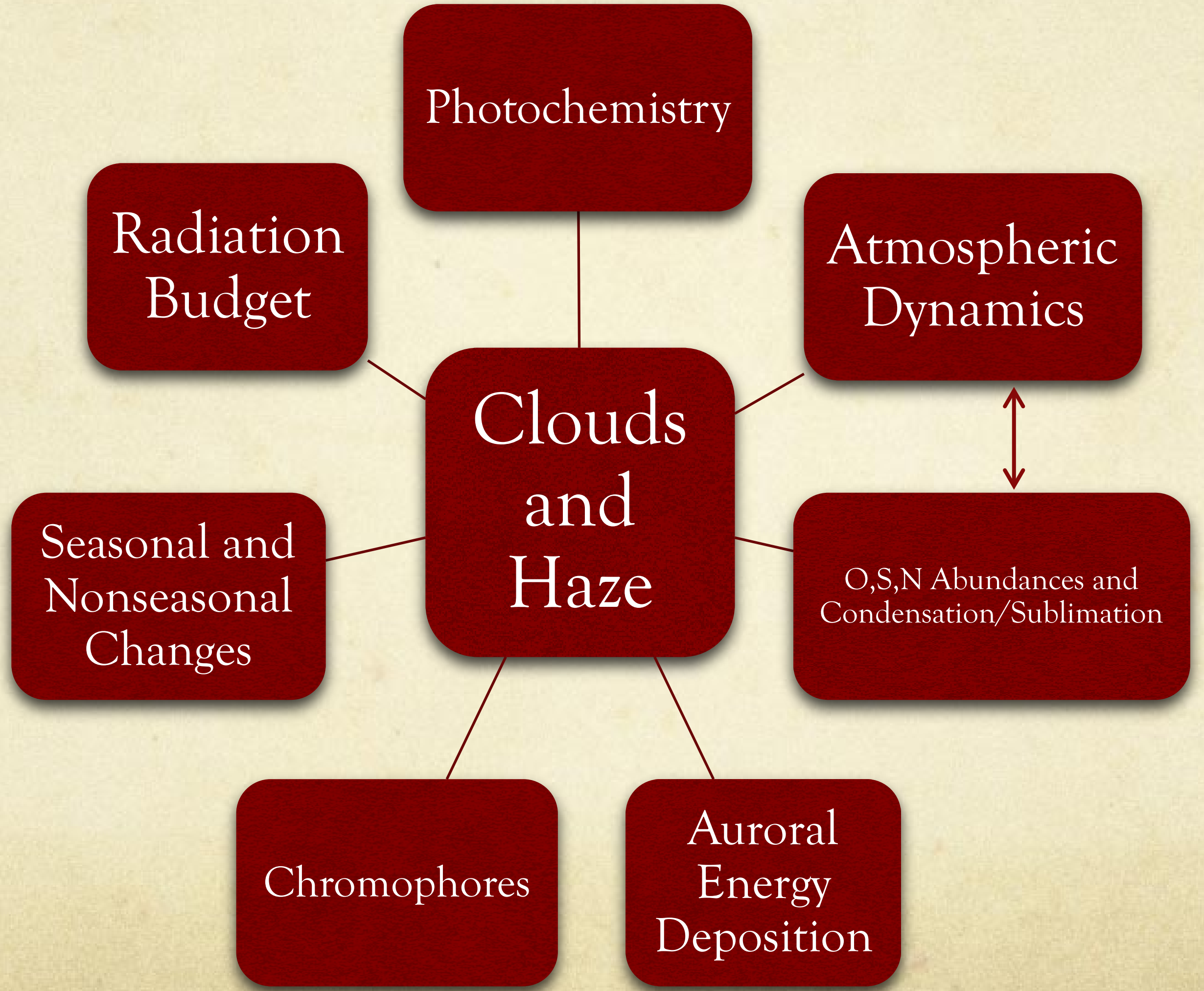
Clouds and Aerosols in Saturn's Atmosphere

Robert West JPL/Caltech

Causal and Diagnostic Relationships



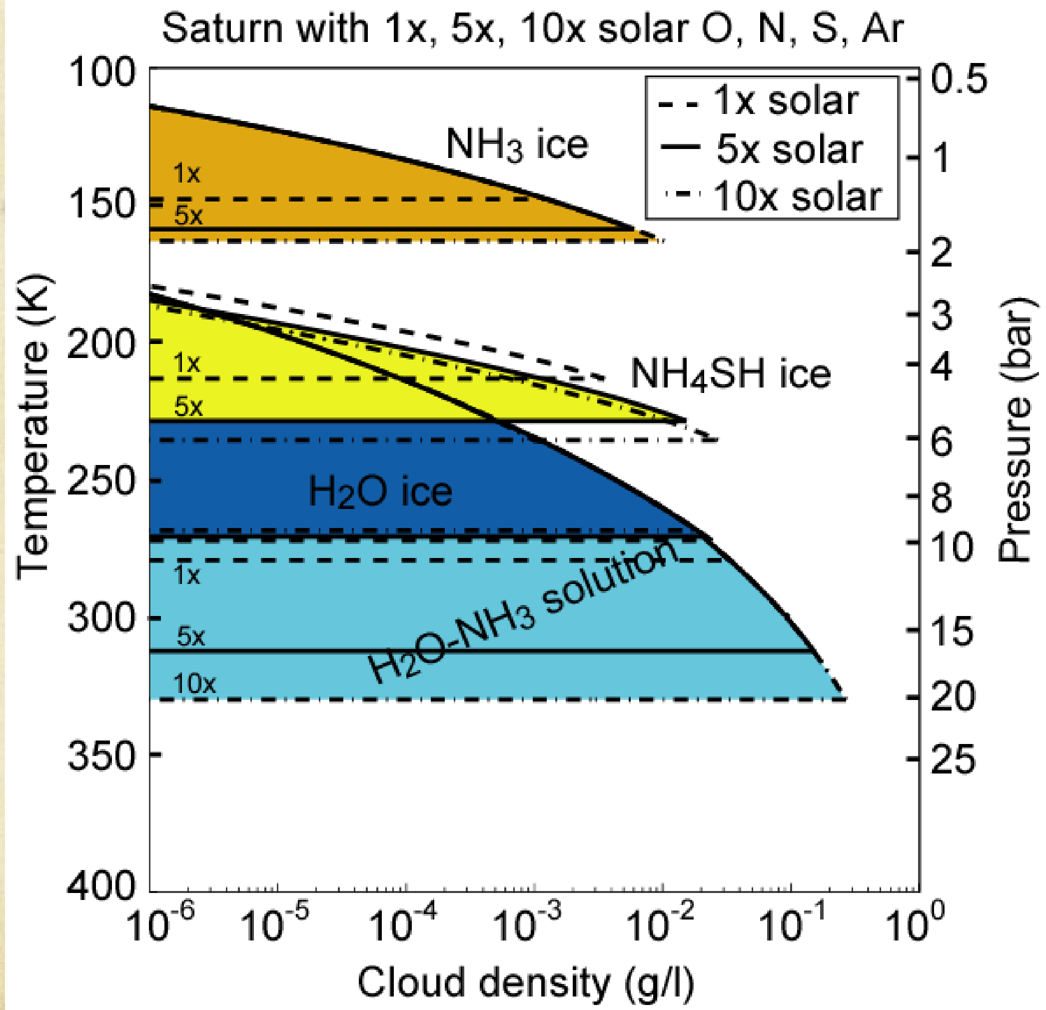
Principal Cloud/Haze Regimes Probed by Remote Sensing of Saturn

- Stratospheric haze outside of the polar regions, probably photochemical in origin. Organics? P_2H_4 ice? Mixtures and coatings are possible.
  - P ~0.01-50 mb,
  - Layers seen on the limb in ISS images at some latitudes.
  - Particle radius ~ 0.1 μm
  - Optically thin down to UV wavelengths
- Polar stratospheric haze, probably generated by auroral energy deposition. Probably hydrocarbons.
  - Principal UV absorber; highly polarizing.
  - Aggregates of small 'monomers'.
- Ubiquitous upper-tropospheric cloud/haze (composition unknown).
  - Longitudinally symmetric, banded structure in the visible.
  - Larger particles; provide IR opacity.
- Small-scale cyclones/anticyclones/other visible at 5 μm and near-IR continuum.
- Lightning storms and giant storms (latest in 2010-2011) (some ices identified).

II. O,S,N Abundances and Condensation/Sublimation

- Thermochemical Equilibrium Condensate Models
- Tropospheric Clouds: Composition
- Vertical Structure

Thermochemical Equilibrium Condensation Models



Note: the cloud density profiles are meant to be illustrative. The model does not include atmospheric dynamics which will have a profound influence on cloud structures. The base levels of cloud formation are robust but depend on constituent deep mixing ratios and the P/T profile.

Graphic (updated) from S.K. Atreya and A. S. Wong, *Space Sci. Rev.*, 116, Nos. 1-2, pp 121-136, 2005.

Compositional Information from Observation

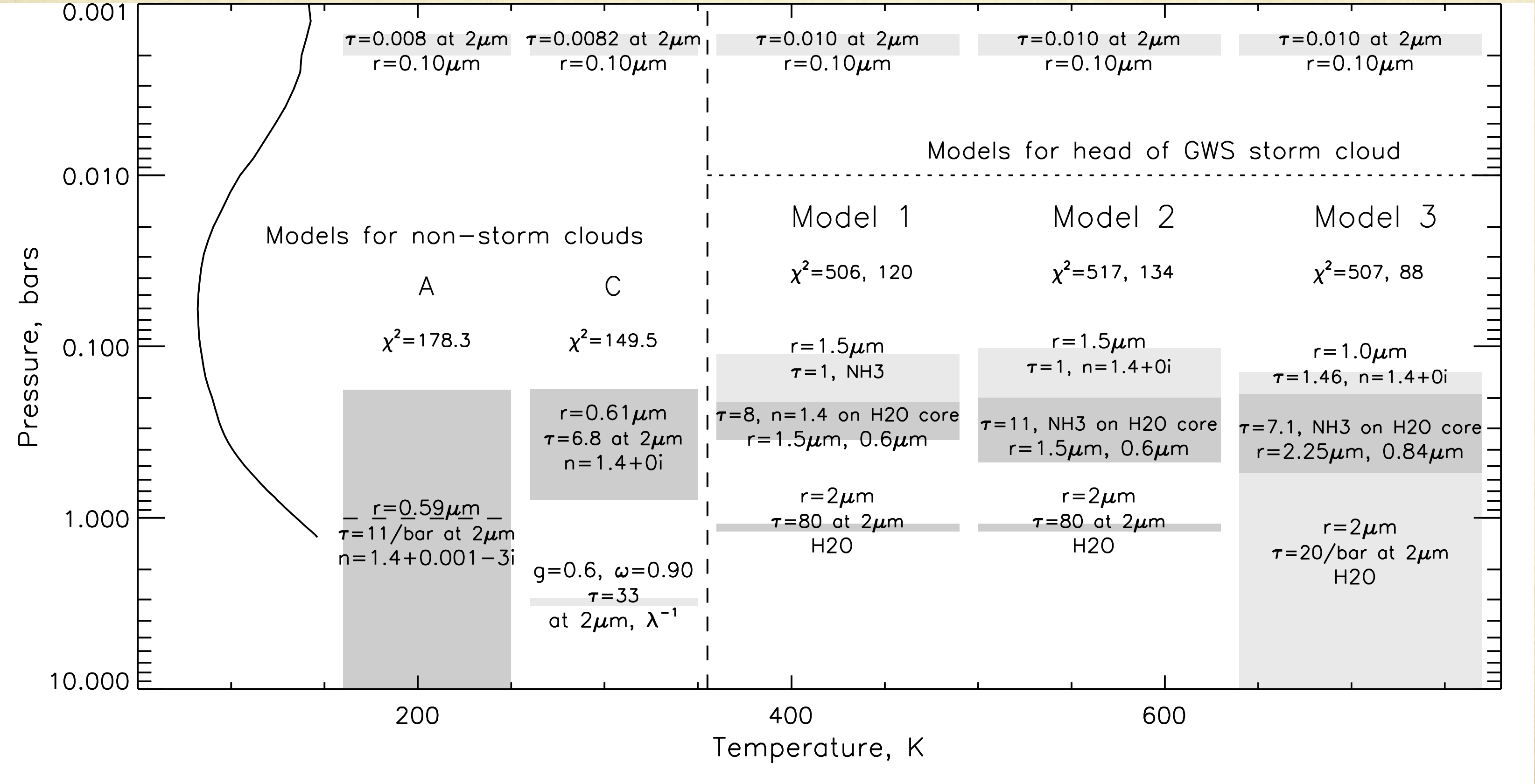
- Jupiter has a spectral feature at 3 μm.
  - Brooke et al. *Icarus* **136,** 1–13, 1998 interpreted this to be a signature of NH_3 ice
  - Using updated NH_3 gas absorption coefficients, Sromovsky and Fry re-interpreted it to be a mixture of NH_4SH ice and NH_3 ice.
  - "The best fits are obtained with a layer of small ammonia-coated particles (r ~0.3 μm) overlying but often close to an optically thicker but still modest layer of much larger NH_4SH particles (r ~ 10 μm), with a deeper optically thicker layer, which *might* also be composed of NH_4SH." Sromovsky and Fry, Icarus 210 (2010) 230–257.
- "Saturn lacks the broad 3-μm absorption feature, but does exhibit a *small absorption* near 2.965 μm, which resembles a similar jovian feature and suggests that both planets contain upper tropospheric clouds of sub-micron particles containing ammonia *as a minor fraction*." Sromovsky and Fry, *Icarus* **210** (2010) 230–257.
- What is the major fraction??? Water and ammonia ices now detected in the great storm of 2010/2011 – described next.

VIMS Images and Spectra

L. A. Sromovsky et al., *Icarus* **226**, 402-418 2013

Cloud Structures for Three Models

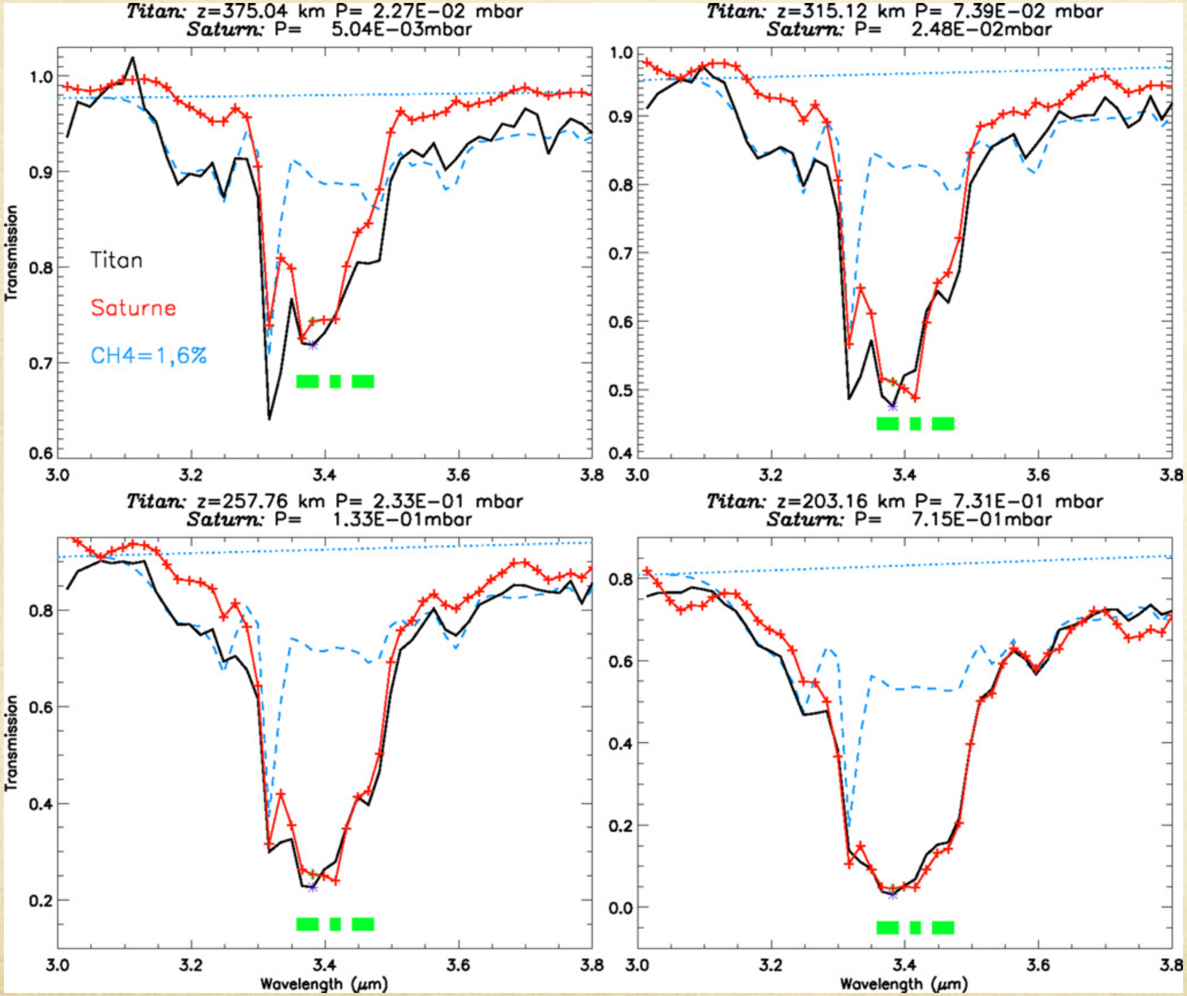
013) 402–418



Results from the Sromovsky et al. 2013 Study (condensed)

- “Outside the storm-affected regions, there is no evidence for particulate absorption at 3 lm, further confirming the peculiar result that at least the upper several optical depths of Saturn’s main visible cloud layer is not made of NH_3, NH_4SH, or N_2H_4”.
- Clear detection of H_2O ice and NH_3 ice inside the storm region.
- Evidence for NH_4SH ice is ambiguous and depends on the model. A spectrally neutral component (modeled as a particle with refractive index n = 1.4) is an equally good candidate depending on model ‘homogeneous’ or not.

Hydrocarbon Feature in a VIMS Stellar Occultation Spectrum



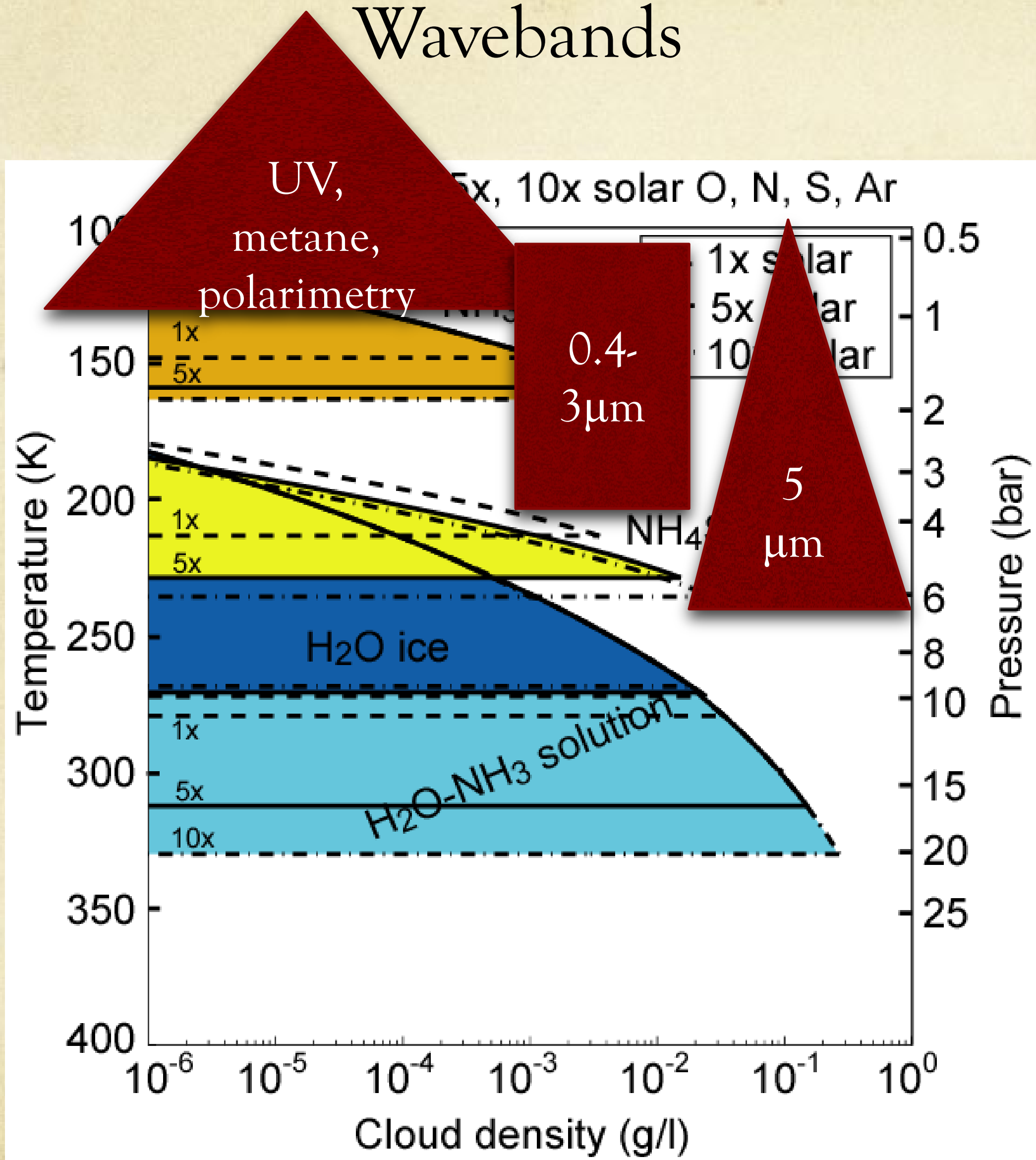
Red curves: VIMS spectrum occultation by Saturn. Graphic from A. Bellucci et al., *Icarus* **201** (2009) 198–216, based on a DPS presentation by P. Nicholson et al., 2006, Probing Saturn's atmosphere with Procyon. *Bull. Am. Astron. Soc.* **38**, 555.

This spectrum sampled the stratospheric haze at 55 N. latitude, outside of the polar latitudes, at pressures indicated.

III Cloud and Haze Vertical Structure

- Regions sensed by different techniques
- Direct Inversion of single scattering in the strong methane bands
- Multiple scattering models
- The Roman et al. technique
- Fletcher et al. 2011

Aerosol Sensitivity in Different Wavebands



In addition, limb images probe aerosols in the mb range (recent work by K. Rages).

Note that thermal radiation is sensitive to all opacity at altitudes above the altitude of the emission, but is insensitive to micron or sub-micron particles. There is an additional dimension to this – sensitivity to particle size

Note that aerosols themselves modify the contribution function (unlike for longwave radiation where it is fixed by the gas opacity). However, if the aerosol opacity is very small the gas opacity will determine the contribution function.

Cloud Structure Modeling: Caveats and Recommendations

- Contribution functions are introduced by the properties (wavelength, spectral resolution, spatial resolution, Stokes parameter I and/or P, angular sampling and range, and types of features selected – limb images, belts and zones, small clouds) of the observations and of the technique.

- Aerosols and nonuniformly-mixed gases themselves modify the contribution function.

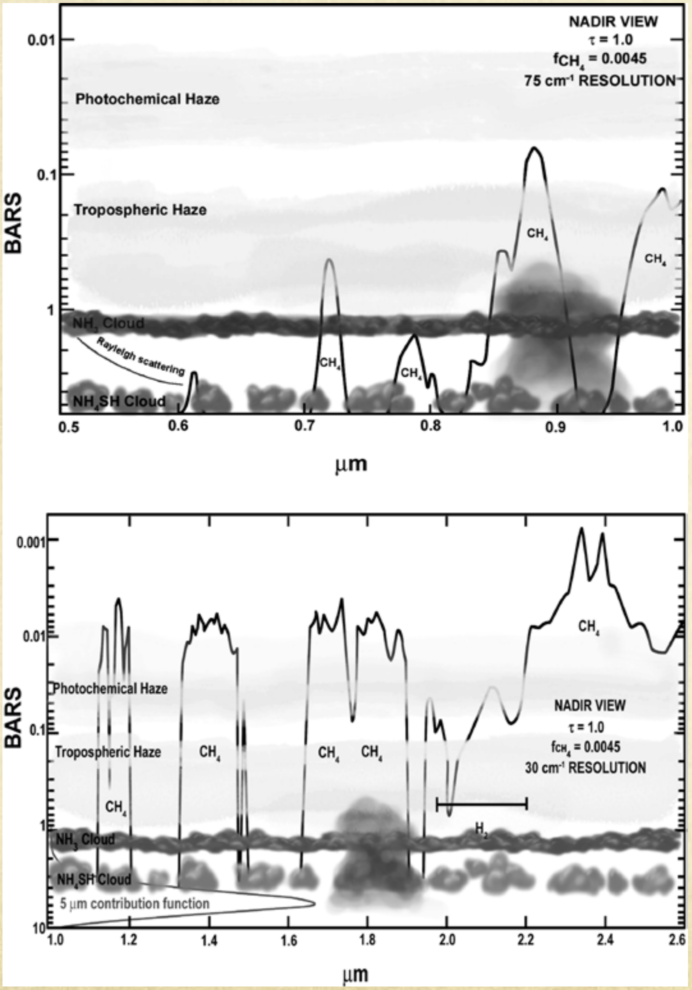
- Simplifying assumptions (plane-parallel geometry, quantization into a few layers, use of Mie theory, use of priors, others) couple with the above to produce a retrieval product that can be biased or have results that depend more on assumptions than retrieved information.

- The best strategy is to take a wholistic approach – the more data of different types incorporated into the model the better.

- Recognize dependencies (e.g. a poor choice of the particle scattering phase function will give an incorrect value for the optical depth). Avoid simplifying assumptions where possible (e.g. use a synthetic phase function retrieved from observations instead of Mie theory).

- Look at a statistically large sample when possible.

Cloud Vertical Structure Retrievals



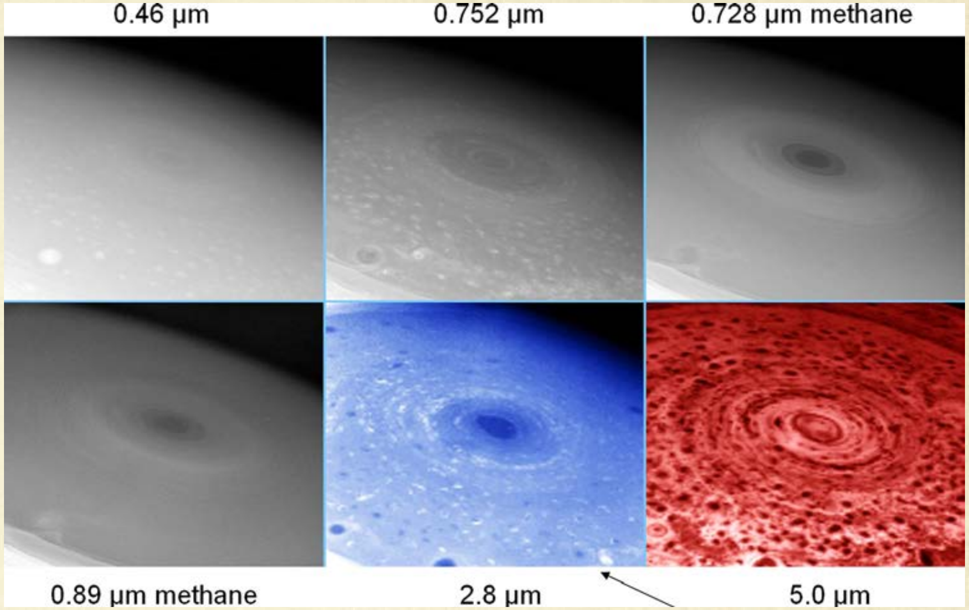
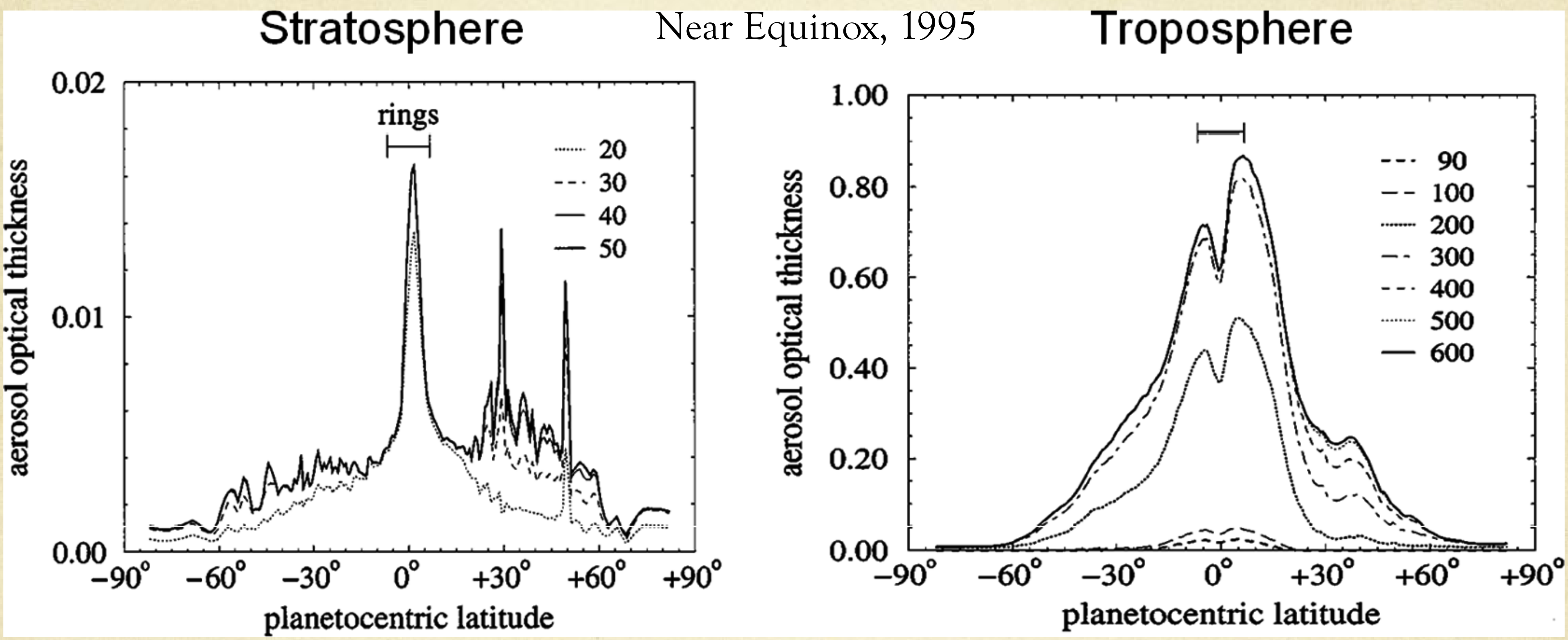


Figure on the left adapted from Baines et al., *Earth Moon Planets* **96**, 119–147 (2005). Above figure from West, R. A., K. H. Baines, E. Karkoschka and A. Sanchez-Lavega. Clouds and Aerosols in Saturn's Atmosphere", in Saturn from Cassini/Huygens, M. Dougherty et al. Eds., Springer, 2009.

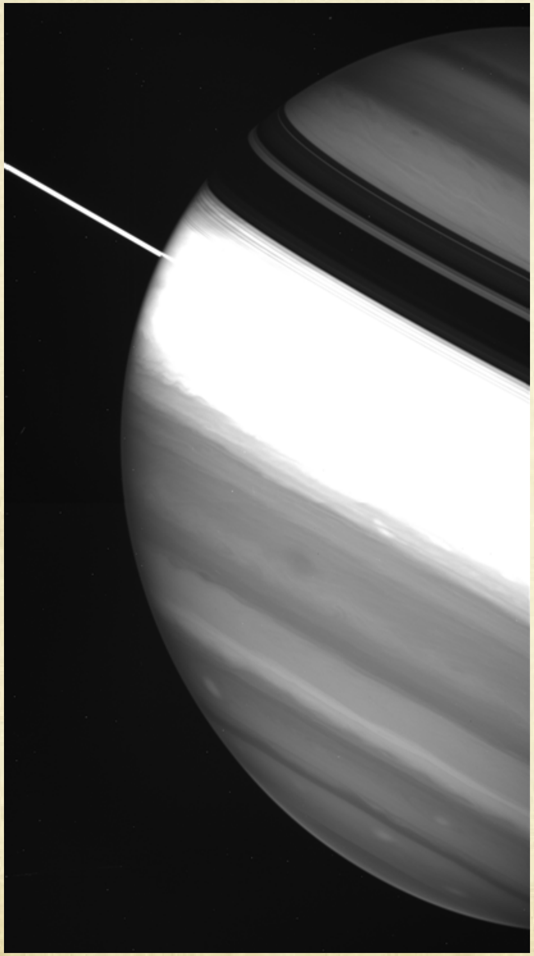
Spectral Inversion Via Strong Near-IR Methane Bands

Near Equinox, 1995



Graphic from Stam, D.M., Banfield, D., Gierasch, P.J., Nicholson, P.D.,Matthews, K., Near-IR Spectrophotometry of Saturnian Aerosols—Meridional and Vertical Distribution, *Icarus* **152**, 407–422 (2001).

Upper Tropospheric Cloud
Cassini ISS 890-nm (MT3) Methane Filter



To first order this image shows relative cloud-top altitudes (brightest is highest) of the upper tropospheric cloud. Ignore the ring shadow just north of the equatorial zone. Note the banded structure, hemispheric asymmetry (deeper clouds in the north) and limb haze at high southern latitudes. Image from West, R. A., et al., Clouds and Aerosols in Saturn's Atmosphere", in Saturn from Cassini/Huygens, M. Dougherty et al. Eds., Springer, 2009.

Saturn at 5μm

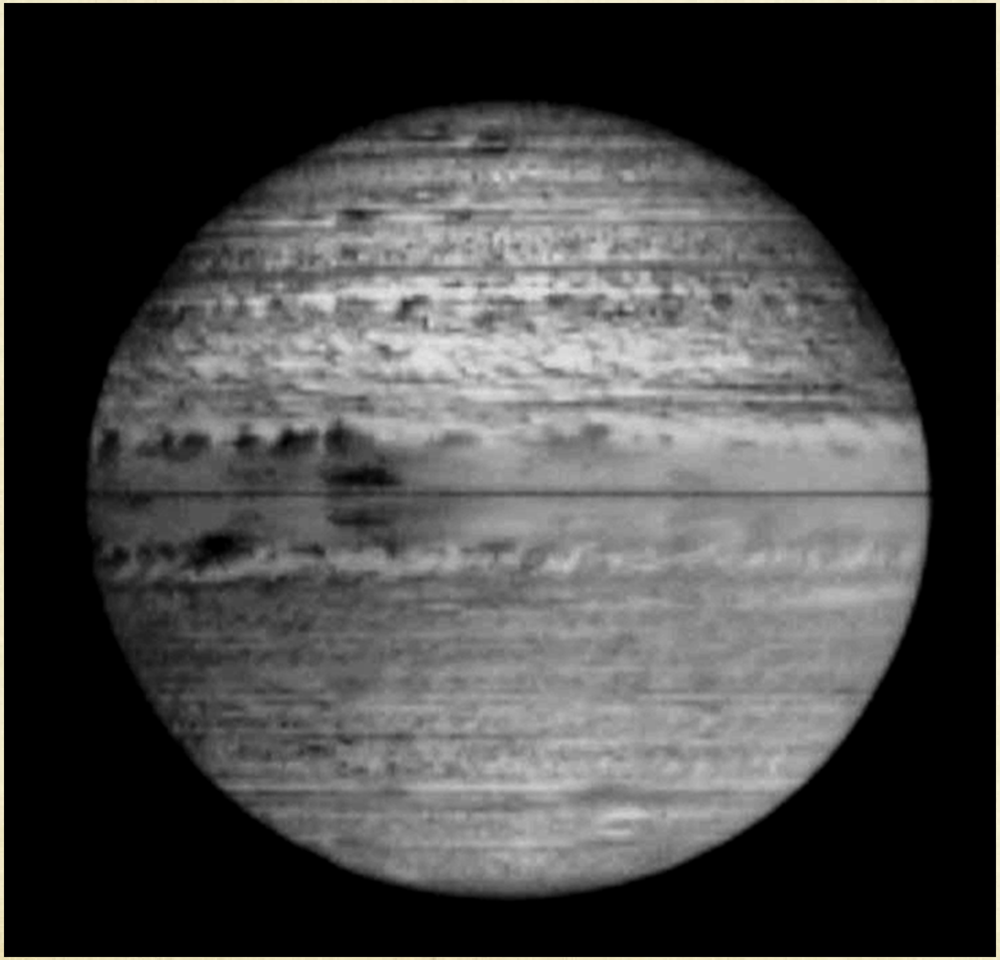
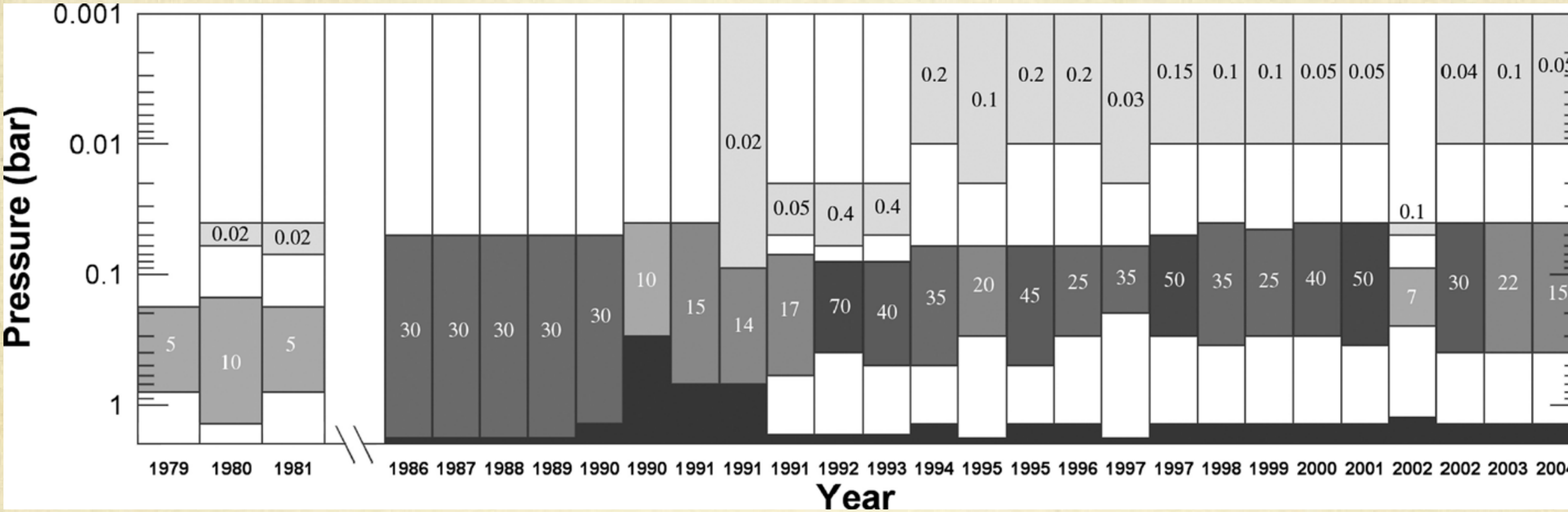


Figure from West, R. A., K. H. Baines, E. Karkoschka and A. Sanchez-Lavega. Clouds and Aerosols in Saturn's Atmosphere", in Saturn from Cassini/Huygens, M. Dougherty et al. Eds., Springer, 2009.

Equatorial Zone Cloud Structures

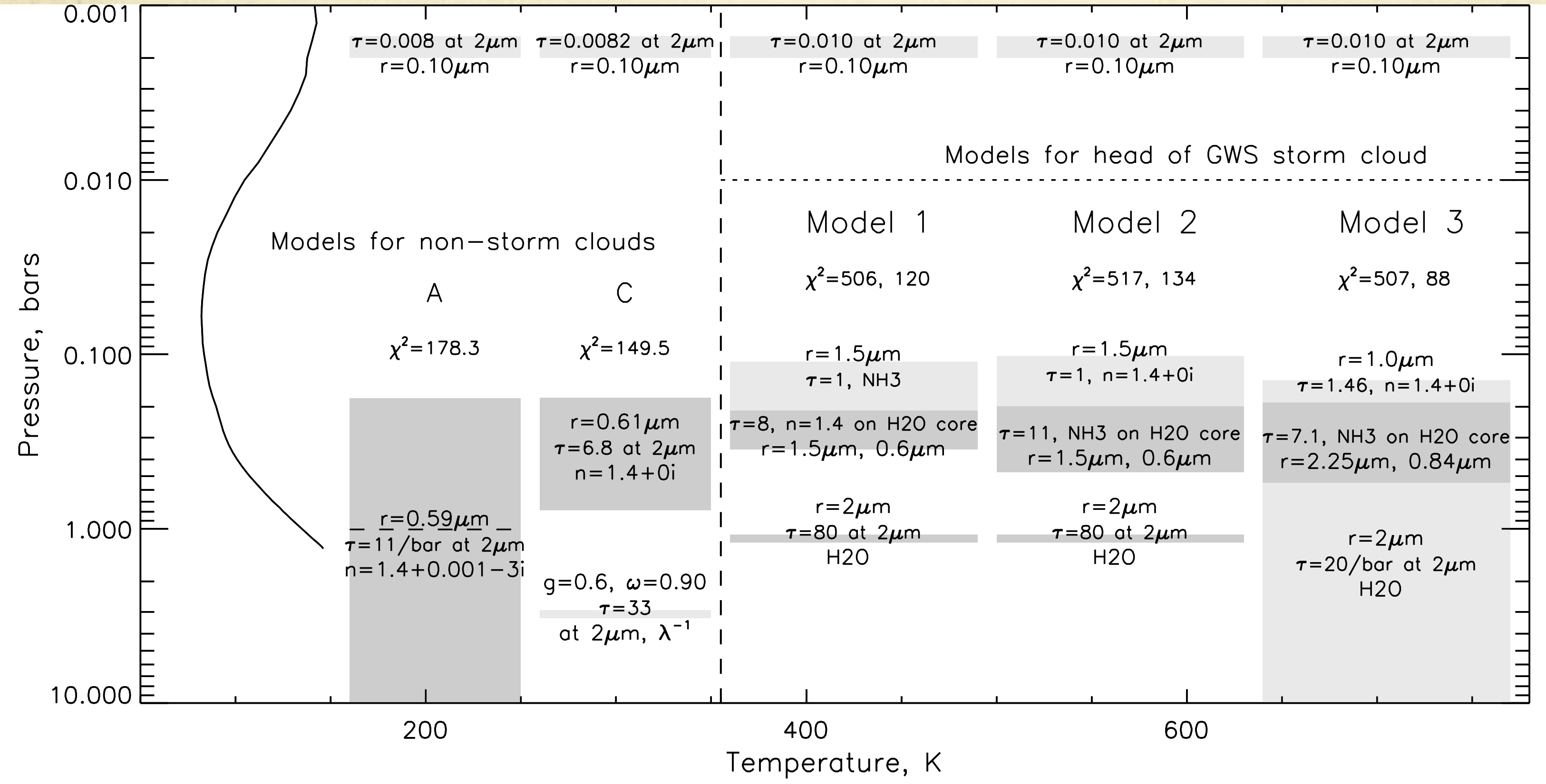


Numbers in boxes are optical depths. Models from various authors/publications are gathered together here.

Graphic from Pérez-Hoyos, S., and Sánchez-Lavega, A. On the vertical wind shear of Saturn's equatorial jet at cloud level. *Icarus* **180**, 161–175 (2006).

Cloud Structure Models of the 2010-2011 Great Storm and Surroundings from VIMS Data

013) 402–418



Analysis of the Small-Scale Clouds

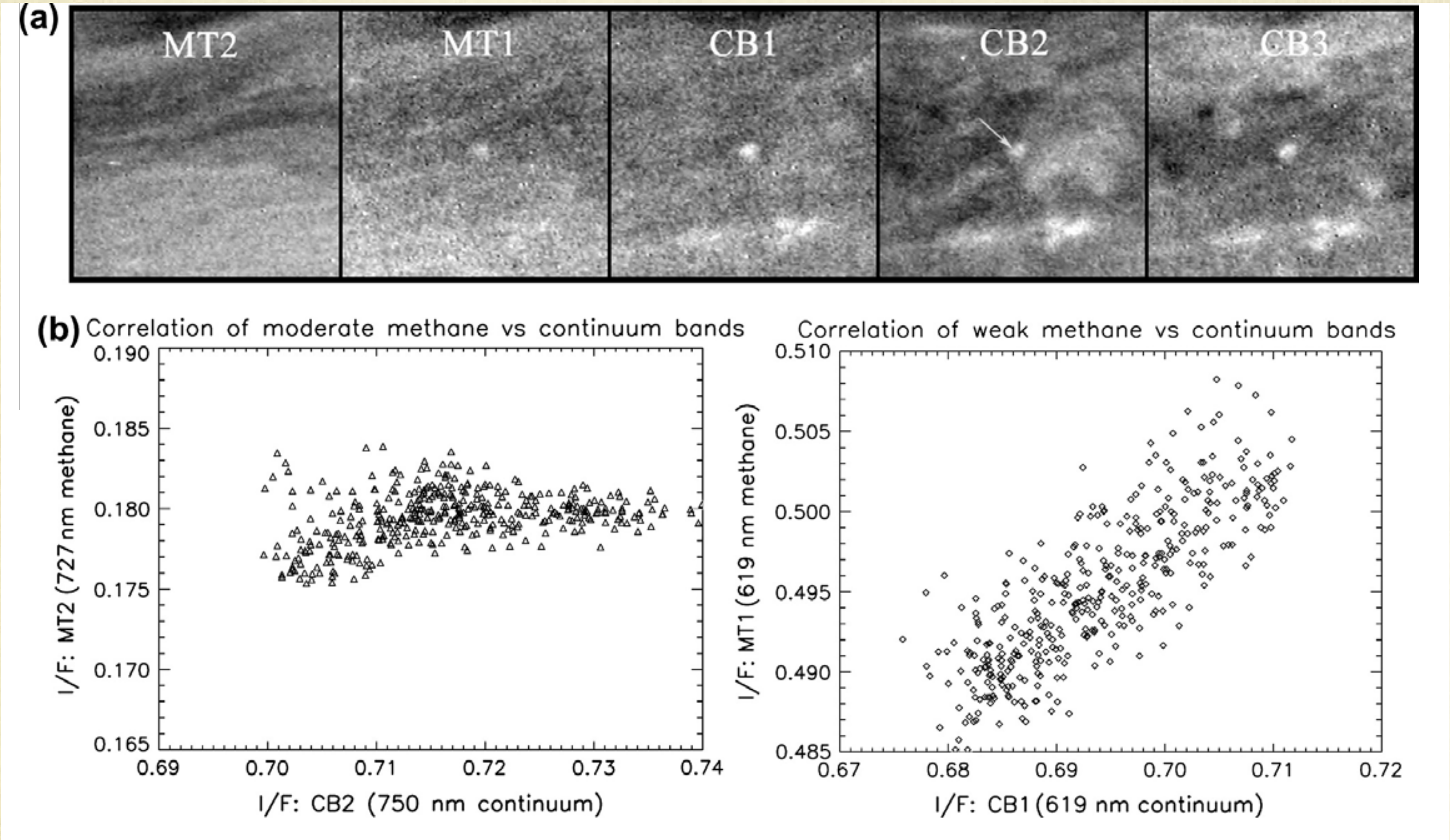


Figure from Roman et al., Saturn's cloud structure inferred from Cassini ISS, *Icarus* **225** (2013) 93–110.

The Roman et al. Analysis

- Used mostly ISS MT1, CB1 pairs – same central wavelengths (619 nm) eliminates wavelength variations in particle optical properties between the methane and continuum filters.
- Analyzed white spots, justifying(???) the assumption that particles in both the spots and their surroundings have the same single-scattering albedo. Then the contrast is attributed to vertical structure differences via differential methane absorption.
- This approach is the same method used by Banfield et al. for Jupiter. It is difficult to get agreement with analysis of Galileo NIMS data (See West et al. chapter in the 2004 Jupiter book for a review). Possibly the two methods are both 'correct' but are limited to the features used in the analysis (Banfield et al. analyzed small-scale features)
- "The tropospheric haze is optically thickest and extends to the greatest heights (40 mbar) over the equator; its top surface is at significantly greater depths (150 mbar) at mid-latitudes. The height of the haze correlates well with position of the tropopause as indicated by the temperature field."
- "Beneath this haze, we find a scattered denser cloud responsible for small-scale contrasts at an average depth of 1.75 ± 0.4 bar, with some features as deep as 2.5 bar or greater."

Analysis of VIMS Spectra at 5μm

Results from Fletcher et al., *Icarus* **214** (2011) 510–533 (condensed)

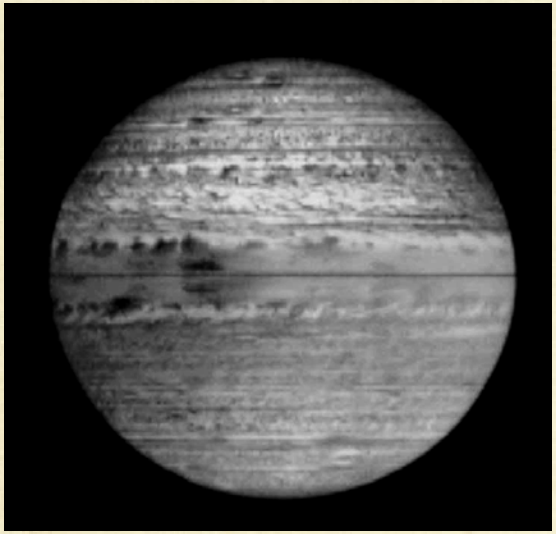


Figure from West, R. A., et al., Clouds and Aerosols in Saturn's Atmosphere", in Saturn from Cassini/Huygens, M. Dougherty et al. Eds., Springer, 2009. Permission obtained from the authors to reproduce this figure.

- The VIMS spectra are rich in features, providing information on gas vertical profiles (NH_3, PH_3, AsH_3) where they are photolytically destroyed ($p < 1.4$ bar).
- VIMS data reveal latitudinal gradients in gas profiles, with enhancements at some latitudes due to upwelling. Specific values of the retrieved abundances depend on the aerosol model.
- Two cloud/dynamical regimes are apparent in VIMS 5μm spectral cubes: an upper-troposphere 'homogeneous' cloud but with N/S hemispheric asymmetry, and a deeper population of small clouds in the pressure range 2.5–2.8 bar.

IV. Photochemistry and Chromophores

- What is the state of knowledge? Who are the candidates?
- The small dark spots.
- Polar UV absorbers and auroral energy deposition
- Fractal aggregate particles at high latitudes
- The N. polar hexagon
- Phosphine and Diphosphene

Chromophores

- A muted yellow-brown color has a global distribution but is concentrated at some latitudes. It is not well correlated with the zonal jet structure as is color on Jupiter, and there is a season hemispheric asymmetry. Photochemistry and atmospheric dynamics are implicated.

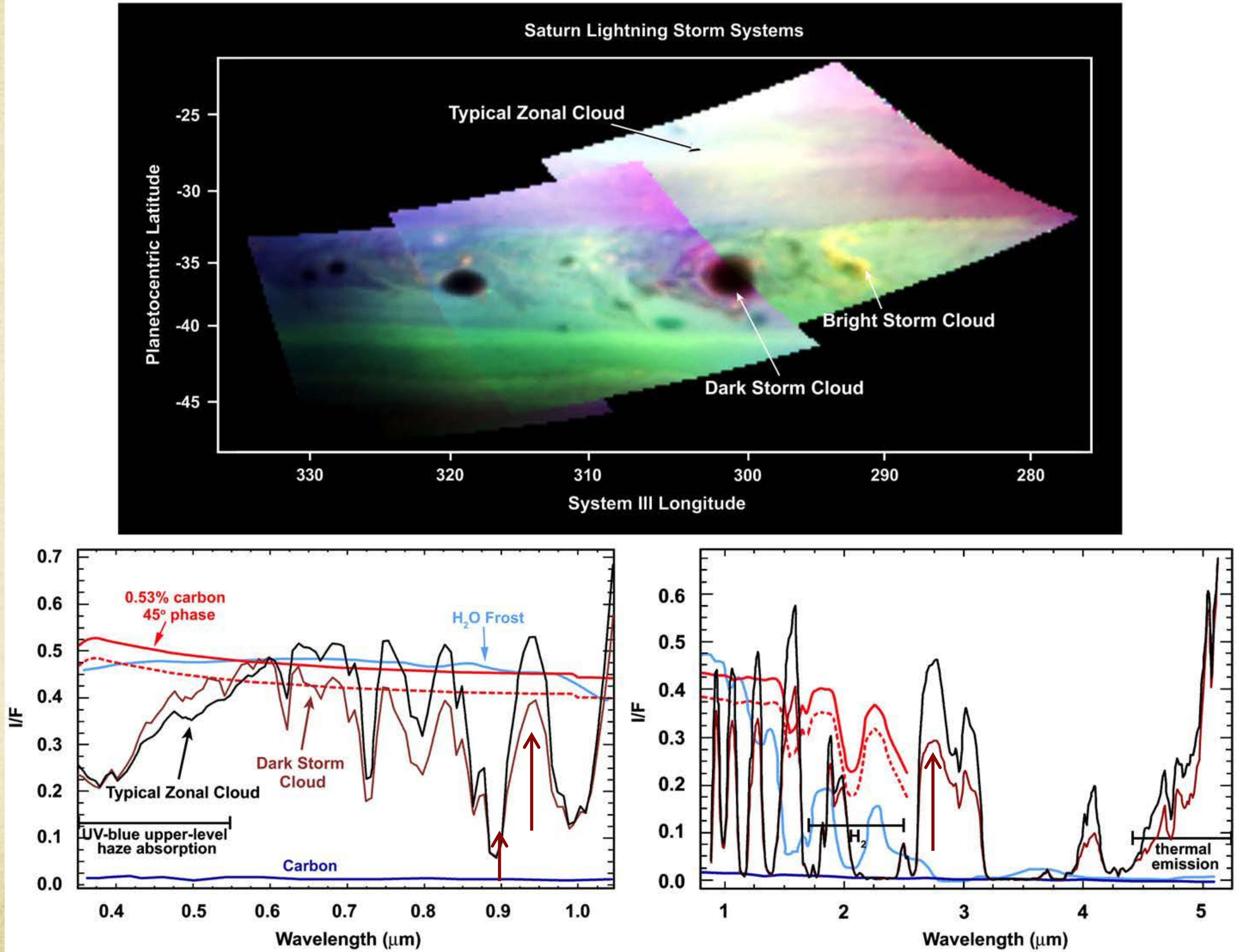
- Diphosphine ice is a candidate for the stratosphere but has never been confirmed spectroscopically. Optical constants are lacking.

- A separate class of dark and more spectrally flat aerosol shows up in some small spots. Baines et al. 2009 suggested a lightning production mechanism. Some other mechanism is responsible outside of 'storm alley'.

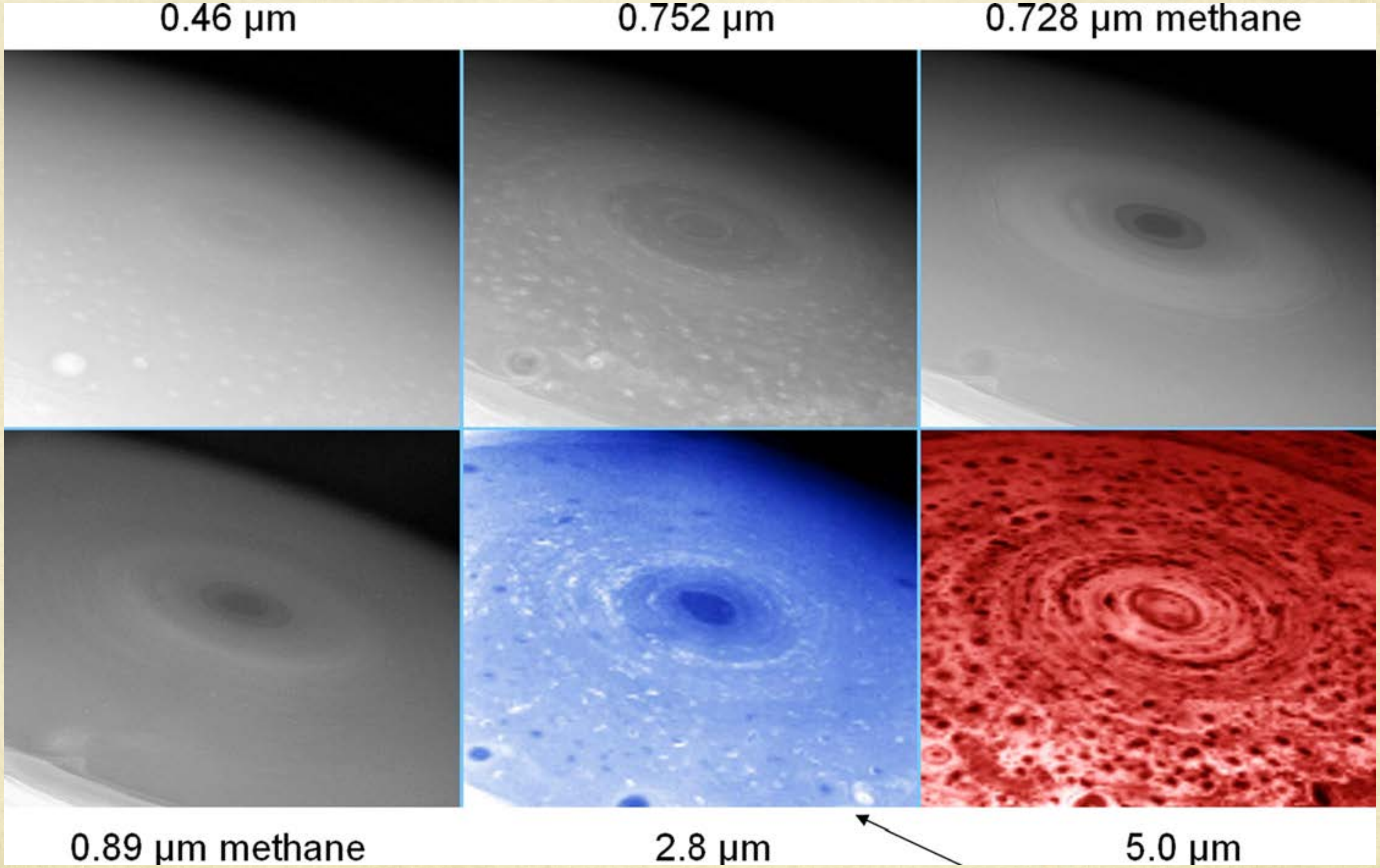
- Photochemistry involving sulfur, a popular hypothesis for Jupiter, is problematic for Saturn because the NH_4SH cloud is many optical depths from the top of the atmosphere.

- A recent hypothesis (organic coating on NH_3 ice cores) for Jupiter from Carlson et al., Chromophores from photolyzed ammonia reacting with acetylene: application to Jupiter's Great Red Spot, Icarus, submitted, 2014 could be attractive for Saturn.

From Baines et al., Storm clouds on Saturn, *Planetary and Space Science*, **57**, 2009, Pages 1650-1658.



Small Dark Spots at High Southern Latitudes



Auroral Energy Deposition, The North Polar Hexagon and Polar Vortices

Voyager Photopolarimeter Meridional Scans at 240 nm and 265 nm

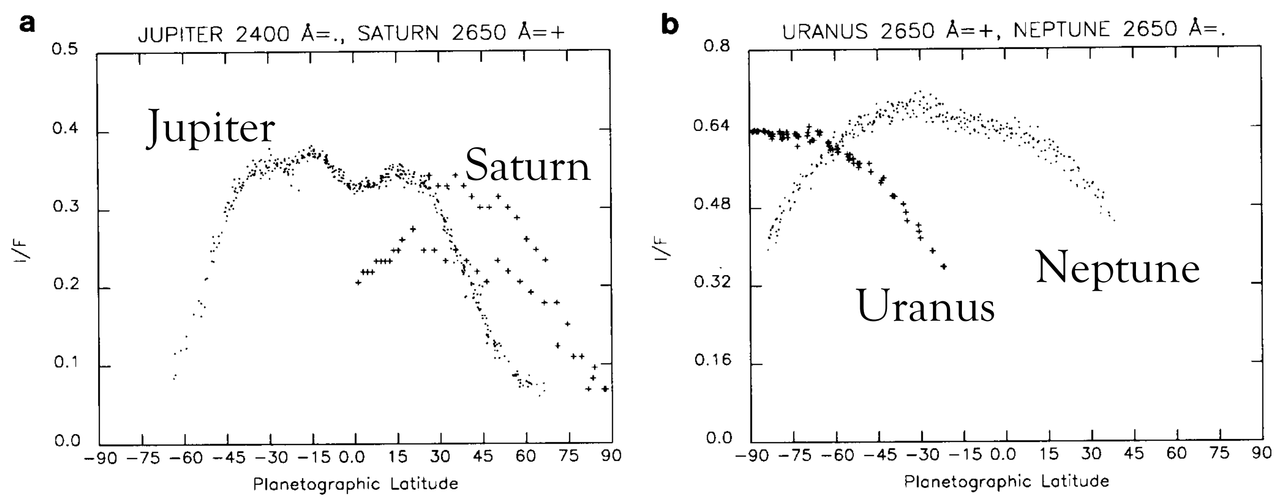
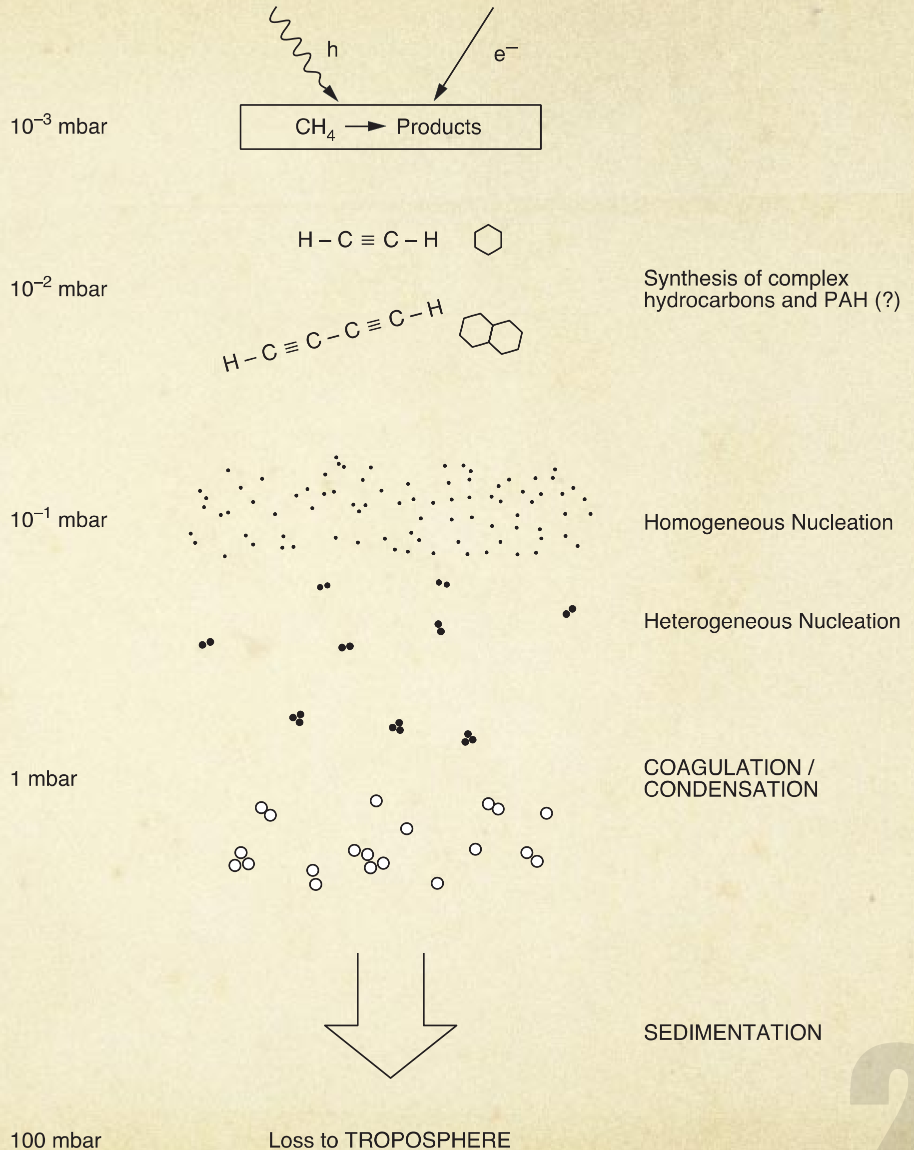


FIG. 2. PPS ultraviolet *I/F* versus latitude for (a) Jupiter and Saturn and (b) Uranus and Neptune. Saturn has two curves because two swaths (Vpol1, Vpol2) were made at different phase angles (49–54°, then 54–59°).

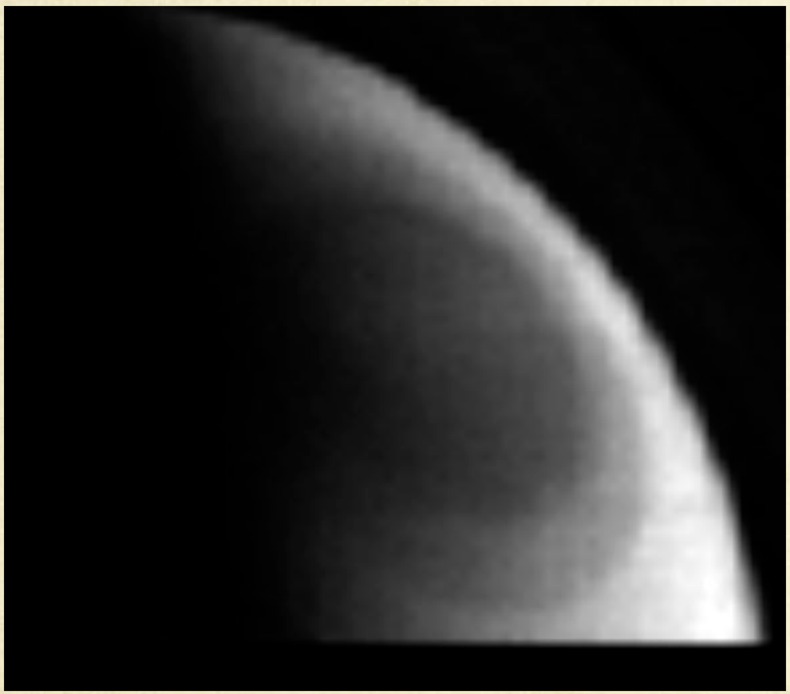
Pryor and Hord, *Icarus* **91**, 161-172 (1991)

Haze Formation – Auroral Chemistry on Methane and Acetylene

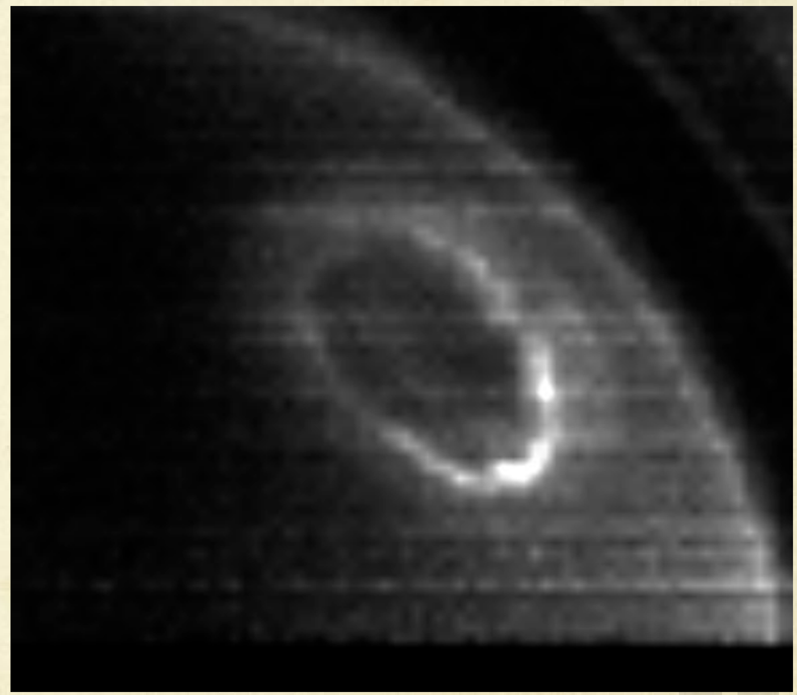


Friedson et al., *Icarus* 158, 389–400 (2002)

Saturn's North Polar Regions Observed by Cassini/UVIS

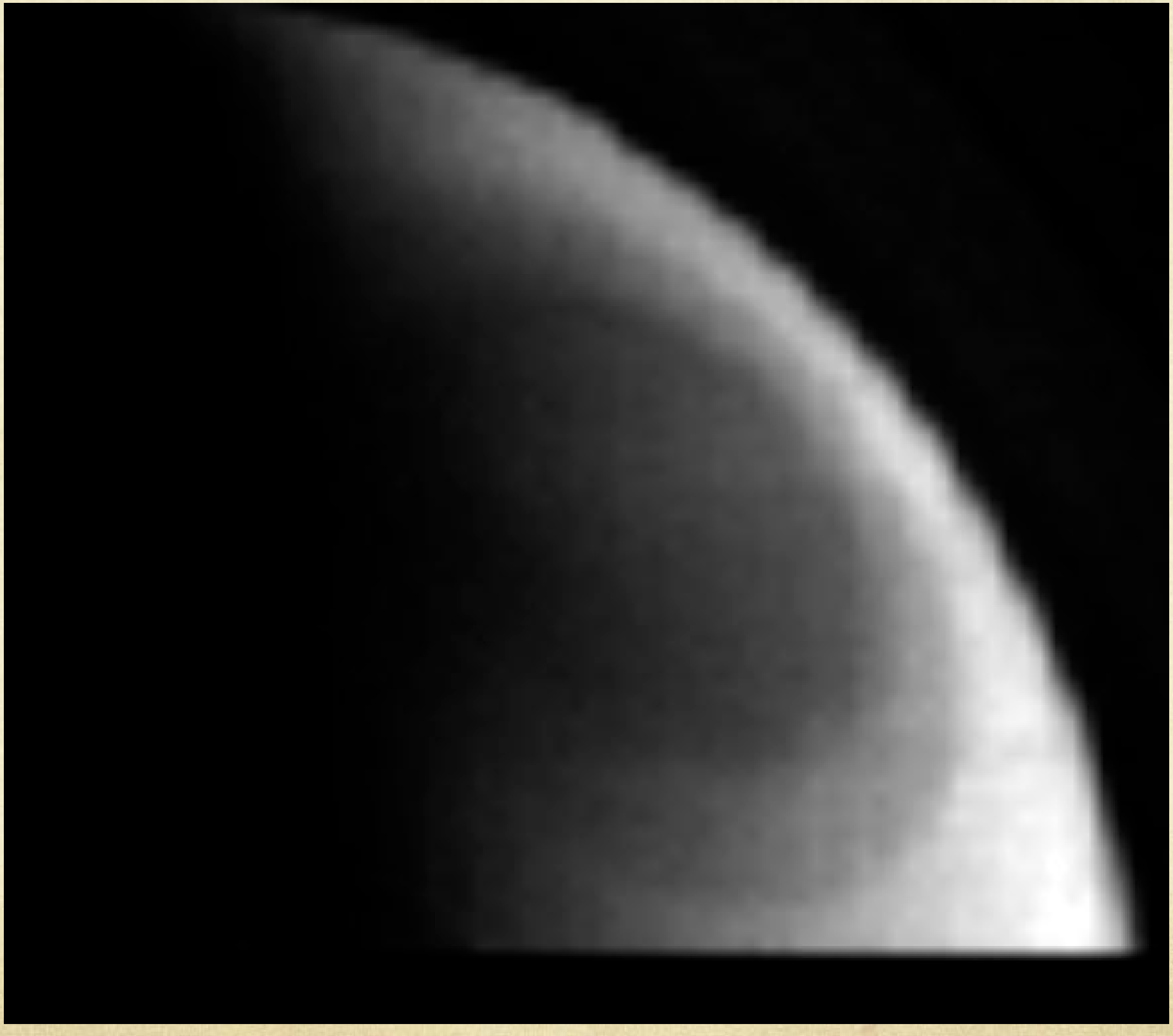


171.2-191.0 nm

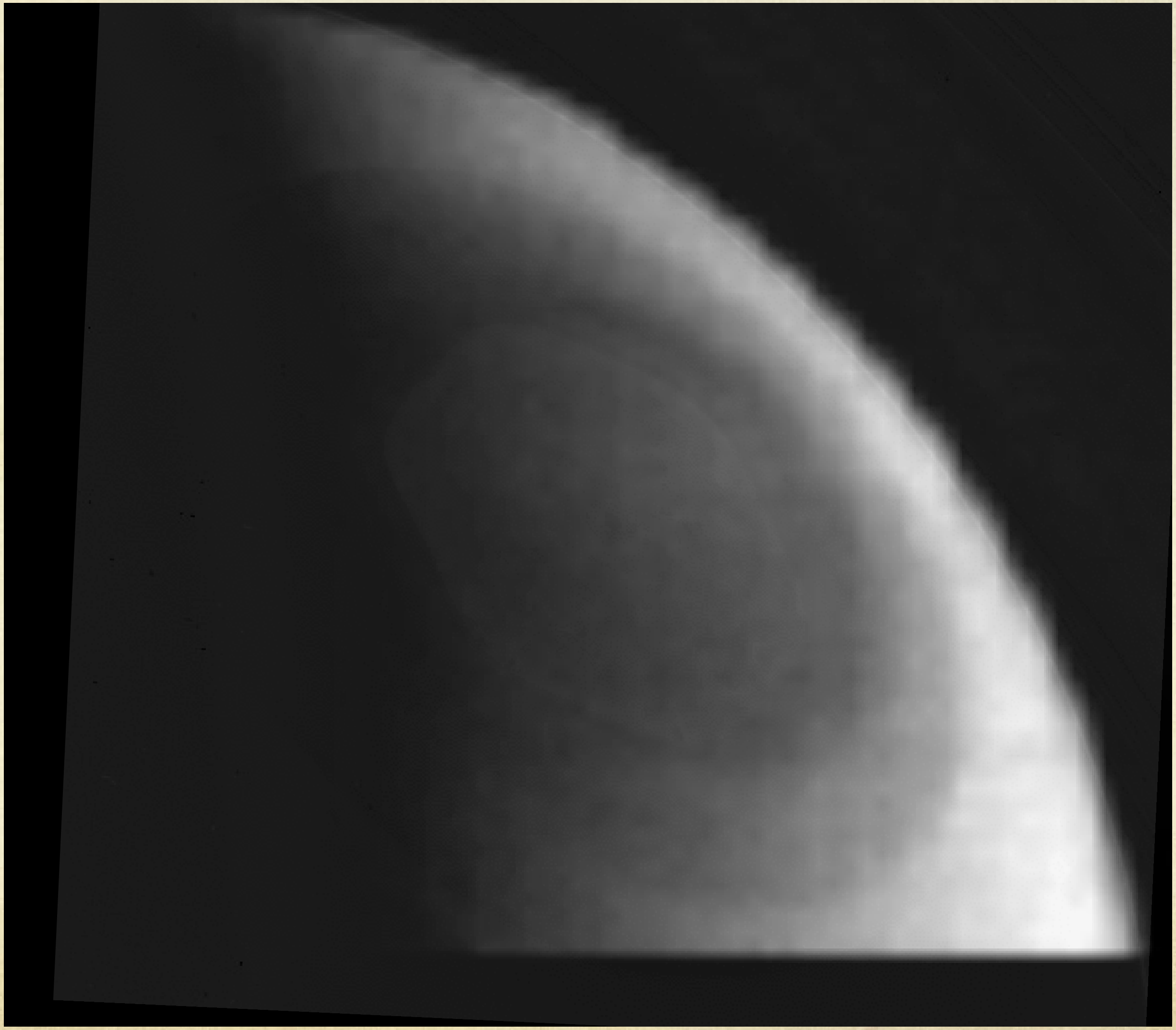


Ly-α

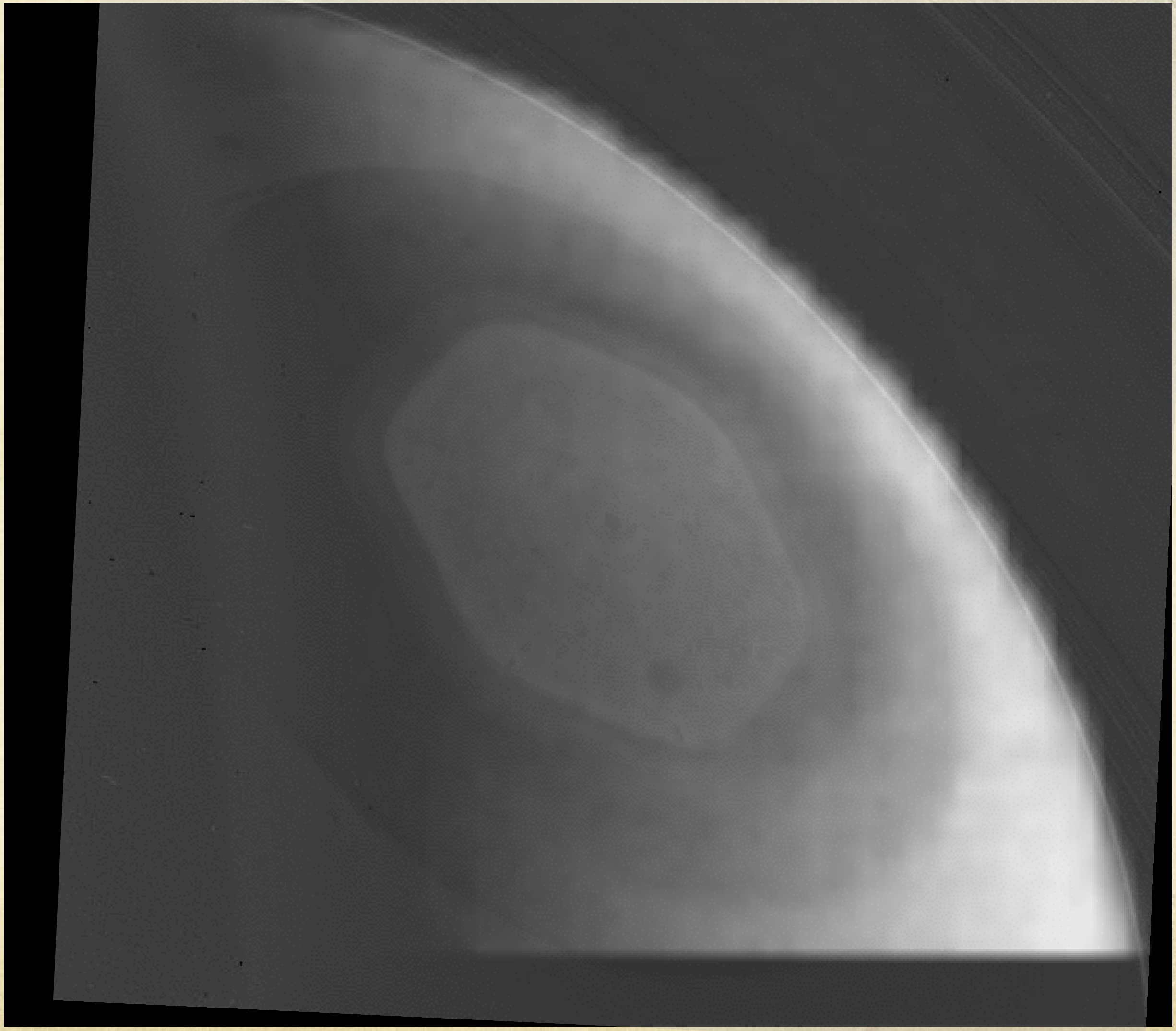
UVIS FUV + Polarization Observed by ISS



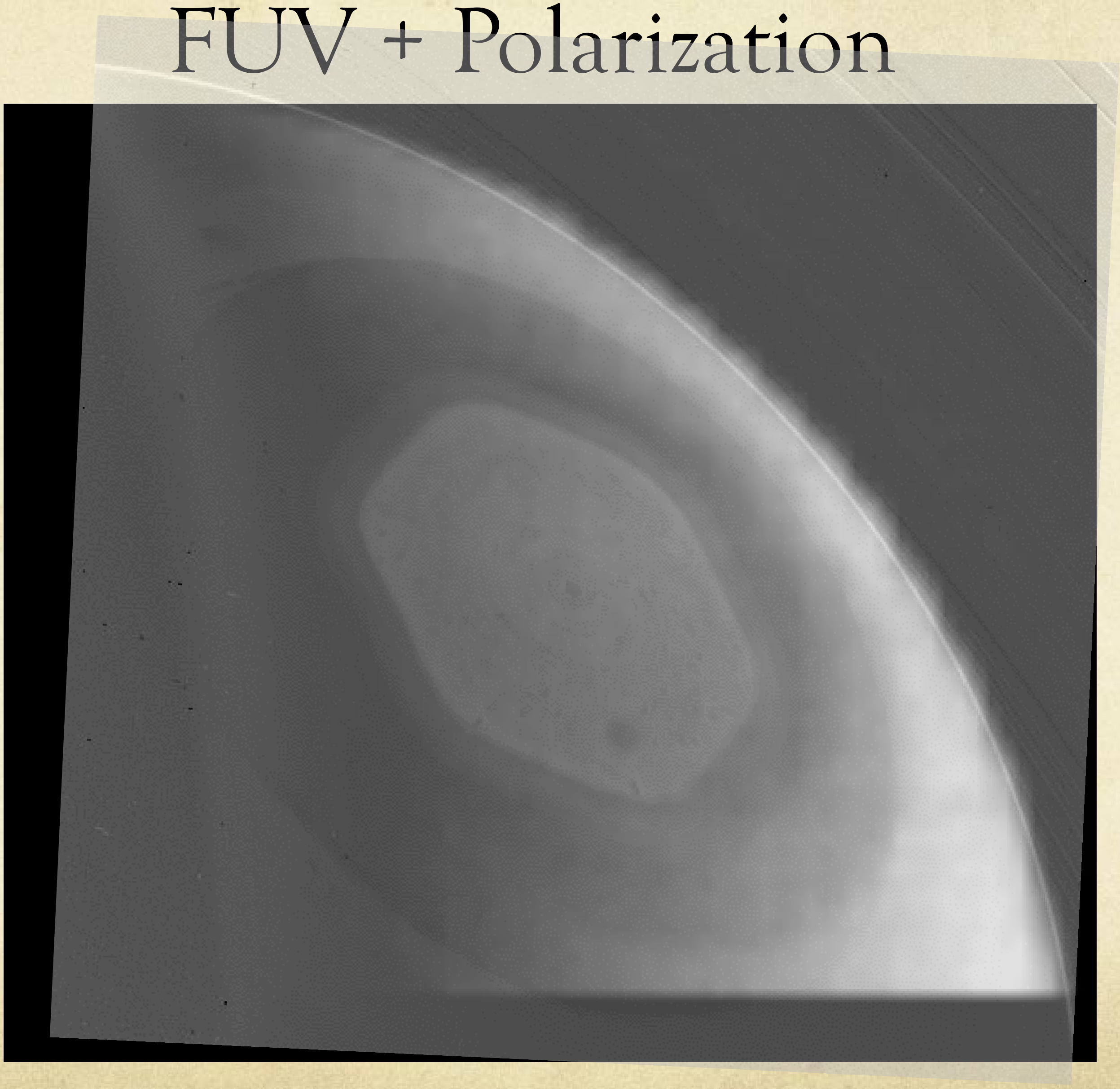
FUV + Polarization



FUV + Polarization

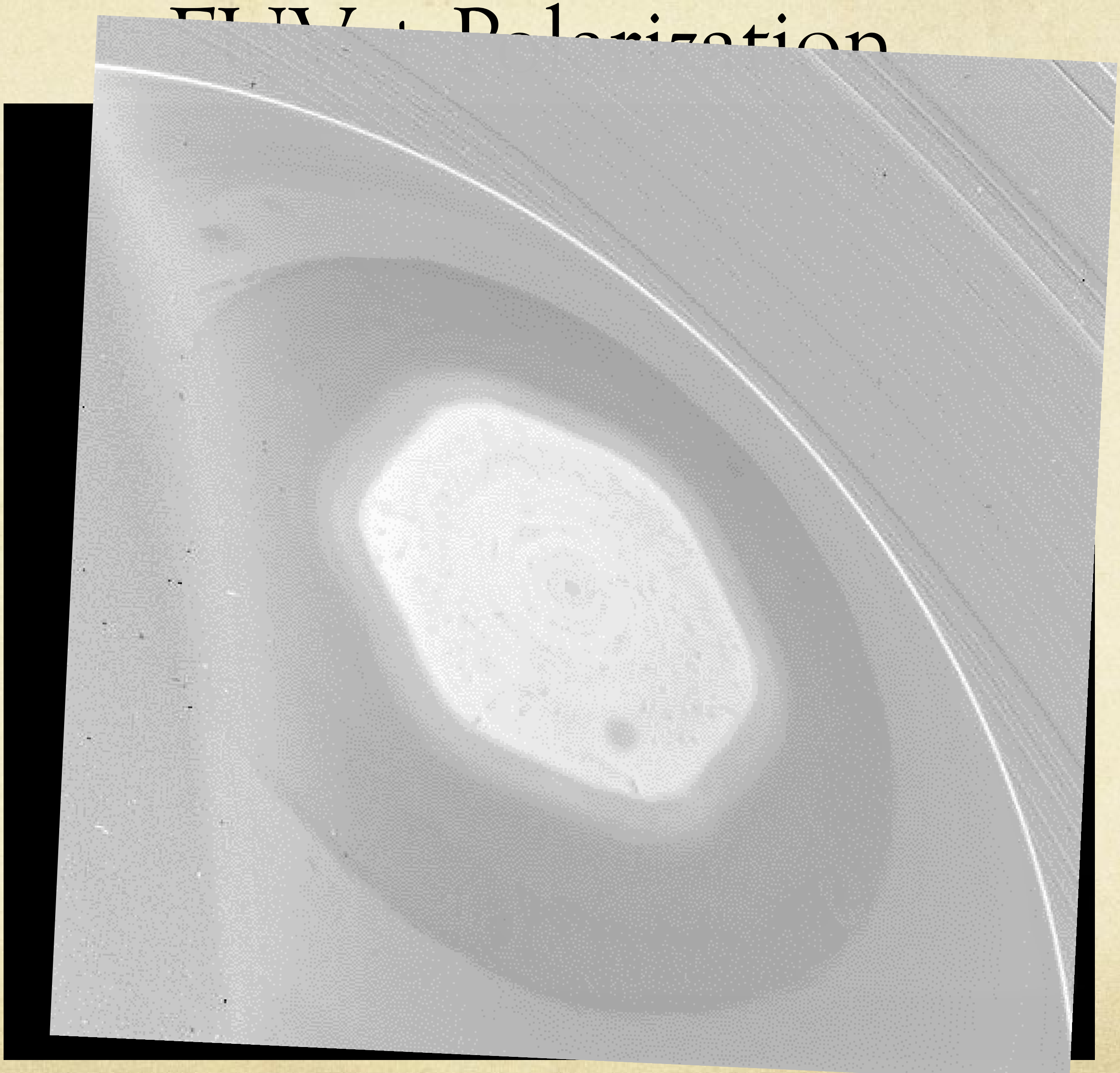


FUV + Polarization

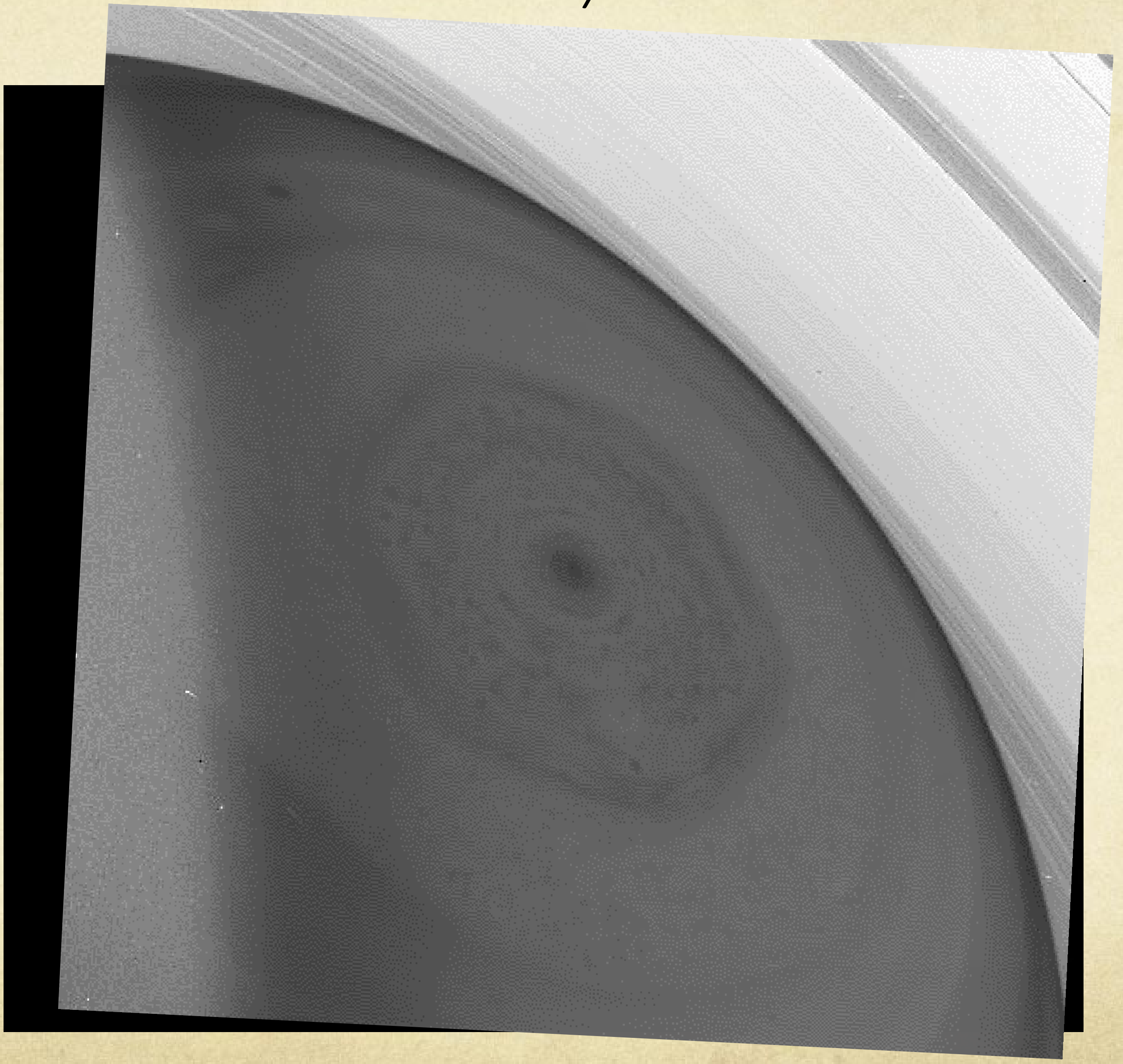


FUV + Polarization

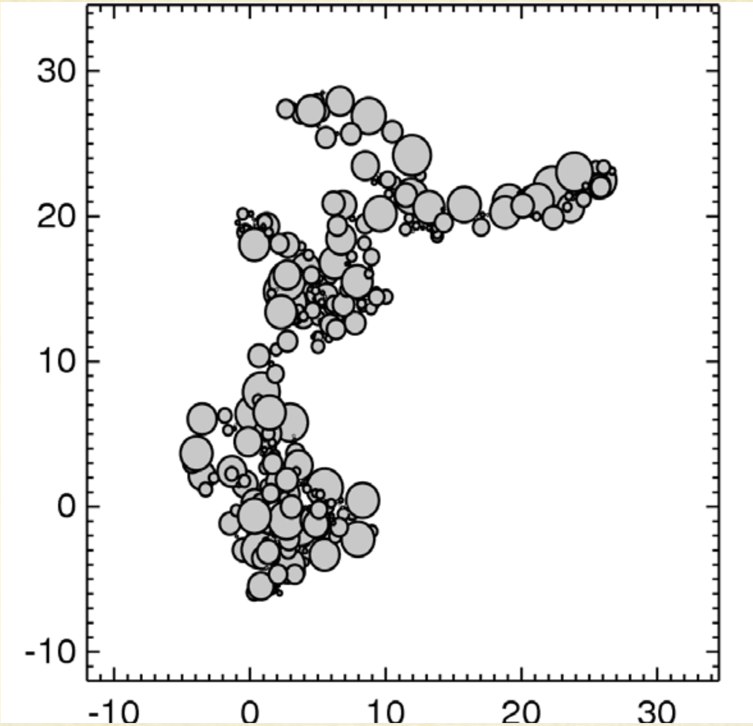
FUV + Polarization



FUV + Methane/Continuum



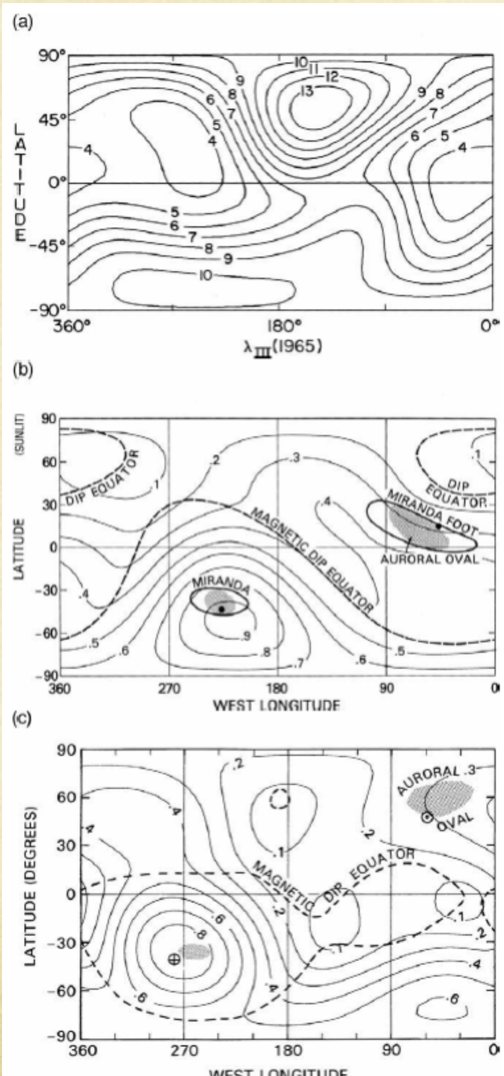
Polar Haze Particles are Aggregates



West and Smith, 1991, *Icarus*, **90**, 330-333, proposed an aggregate structure for Jupiter's polar haze based on polarization and photometry.

R. West

Magnetic Field/Auroral Zones/Jets



Jupiter

Uranus

Neptune

Note the **<u>hemispheric asymmetry</u>** of the magnetic field configurations for Jupiter, Uranus and Neptune. The polar haze on Jupiter is also asymmetric in the same sense. The high-latitude **<u>jets may also provide a confinement mechanism</u>** as they do for ozone in the terrestrial polar winter. The auroral zones on Uranus and Neptune are too near the equator to overlap the high latitude jets, and no UV-absorbing polar hazes are seen on Uranus or Neptune. The **<u>ability of energetic particles to penetrate to the methane homopause</u>** can also be a key factor (greatest on Jupiter, negligible(?) on Uranus and Neptune).

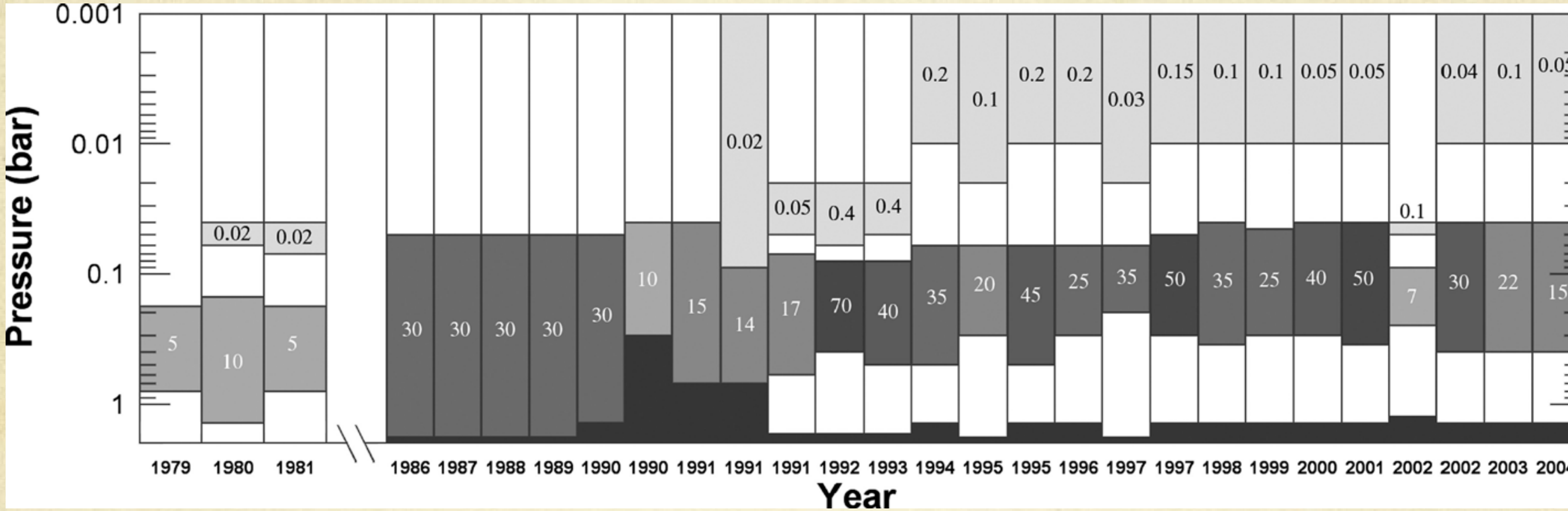
Auroral Energy Deposition - Summary

- UV hazes on Saturn are concentrated at high latitudes.
  - In the north the regions of strong UV absorption and strong polarization is bounded by the hexagon.
- Auroral energy deposition appears to be the dominant energy input leading to UV-absorbing aerosol formation on Saturn as well as on Jupiter.
- Differences between UV-absorbing haze optical thickness for Jupiter, Saturn, Uranus and Neptune and the asymmetry for Jupiter are probably due to
  - Energetics of auroral impacting particles: Jupiter > Saturn > Uranus
  - Latitude distribution of the auroral input coupled with confinement within the polar vortex and transport to lower latitudes (Uranus' auroral zone is at low latitude). Most apparent on Jupiter.
  - On Saturn the polar hexagon appears to be a confining mechanism
- High polarization is a diagnostic of aggregates of small 'monomers'.

V. Seasonal and Nonseasonal Changes

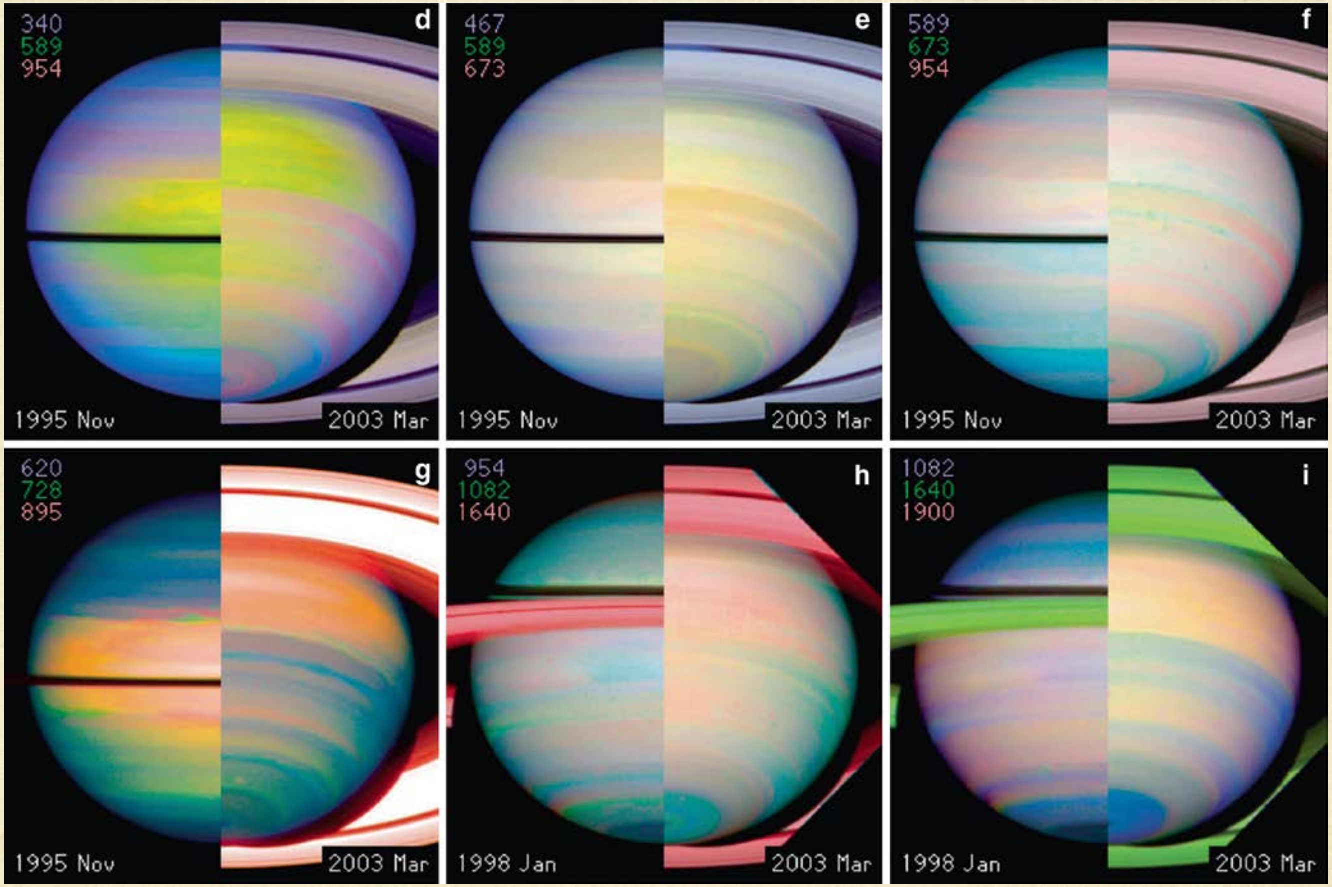
- 30+ years of observation
- Karkoschka and Tomasko – A several year study from HST
- Blue northern latitudes from Cassini in 2004. A hemispheric asymmetry is apparent also in 5μm.
- Discrete latitude changes seen via polarimetry suggests stepwise change rather than smooth with latitude.

Temporal Changes - Equatorial



Graphic from Pérez-Hoyos, S., and Sánchez-Lavega, A. On the vertical wind shear of Saturn's equatorial jet at cloud level. *Icarus* **180**, 161–175 (2006).

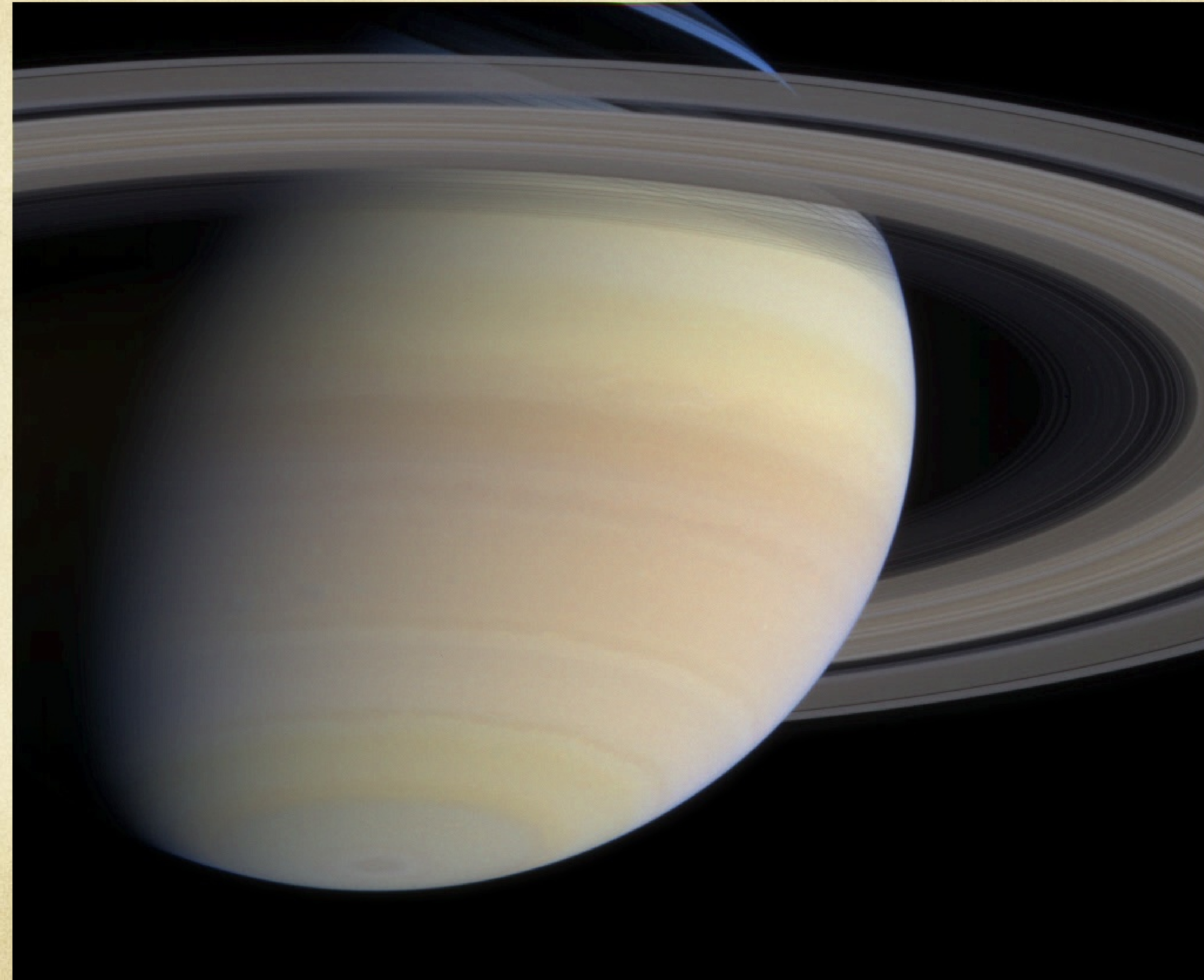
14 Years of Hubble Images



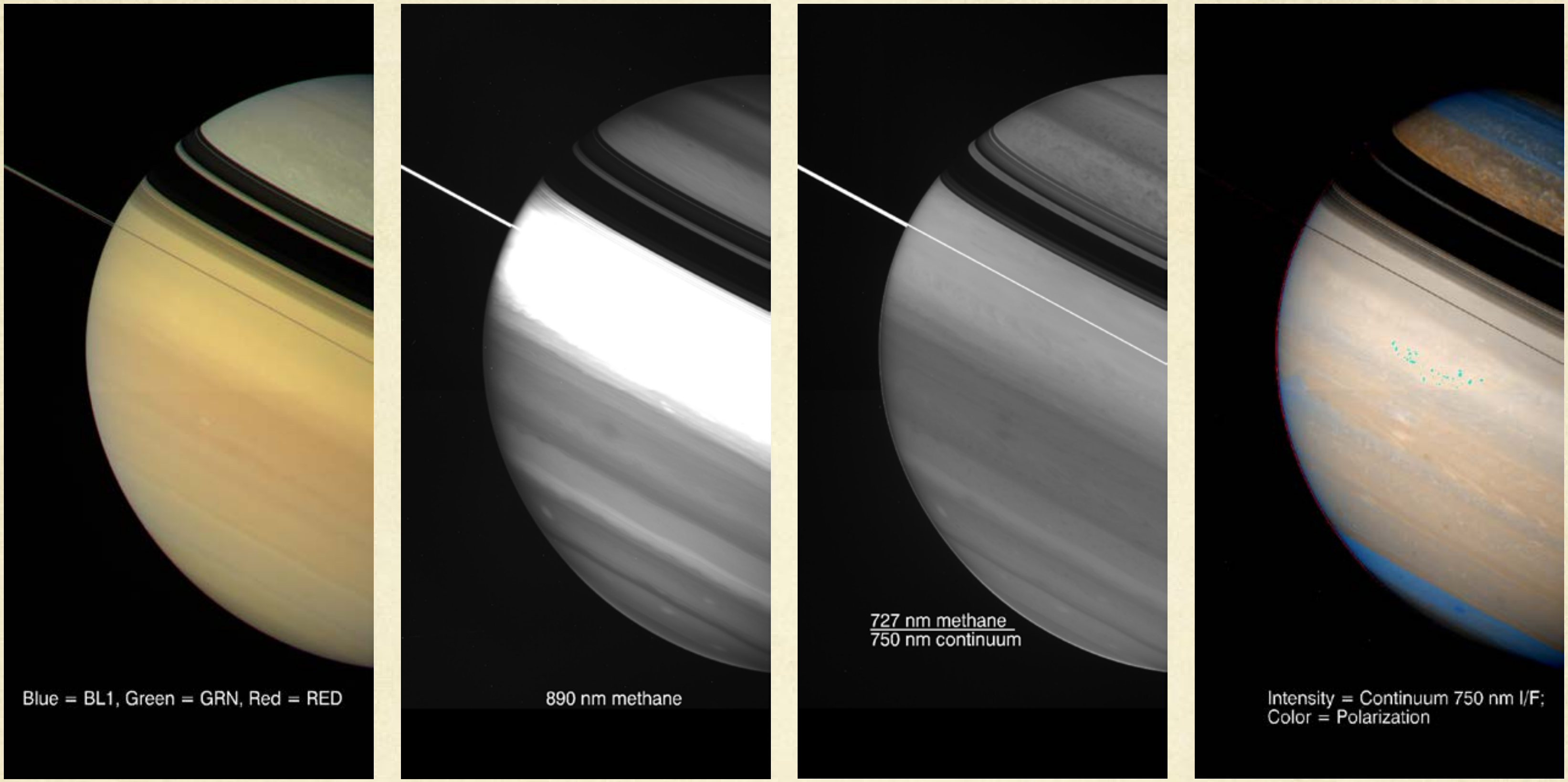
Credit: Karkoschka, E., and Tomasko, M. Saturn's vertical and latitudinal cloud structure 1991–2004 from HST imaging in 30 filters. *Icarus* **179**, 195–221 (2005).

Principal Components from the HST Study

- A strong latitudinal variation of the aerosol optical depth in the upper troposphere.
  - This structure shifts with Saturn's seasons, but the structure on small scales of latitude stays constant
- A variable optical depth of stratospheric aerosols.
  - The optical depth is large at the poles and small at mid- and low latitudes.
  - This structure remains essentially constant in time.
- A variation in the tropospheric aerosol size, which has only shallow gradients with latitude, but large seasonal variations
  - Aerosols are largest in the summer and smallest in the winter.
- A feature of the tropospheric aerosols with irregular latitudinal structure and fast variability, on the time scale of months.



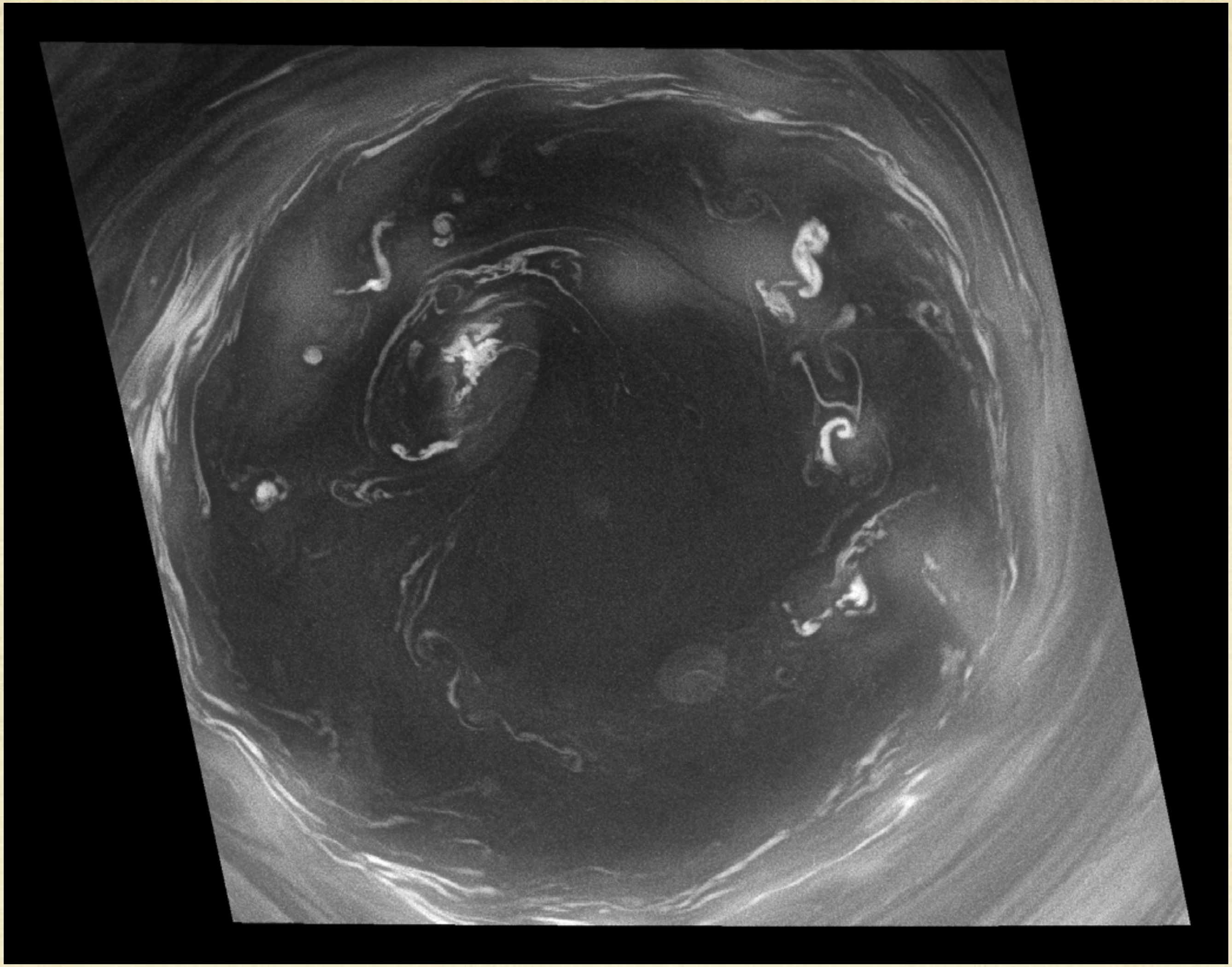
Evidence for Step-wise Seasonal Change (?)



A color composite (from Blue, Green, Red filters) of Saturn in 2007 day 35 phase angle 31° appears in the left panel. The right panel shows the linear polarization at 750 nm in the continuum between methane bands (red is negative, blue is positive, and the intensity is from the 750-nm intensity image). Other panels show reflectivity in the strong and moderate methane bands at 889 nm and 727 nm.

VI. Clouds Expose Atmospheric Dynamical Regimes – Some Examples

- The polar vortex clouds
- The Great Storm of 2010-2011
- Latitude and altitude distributions of smallclouds.

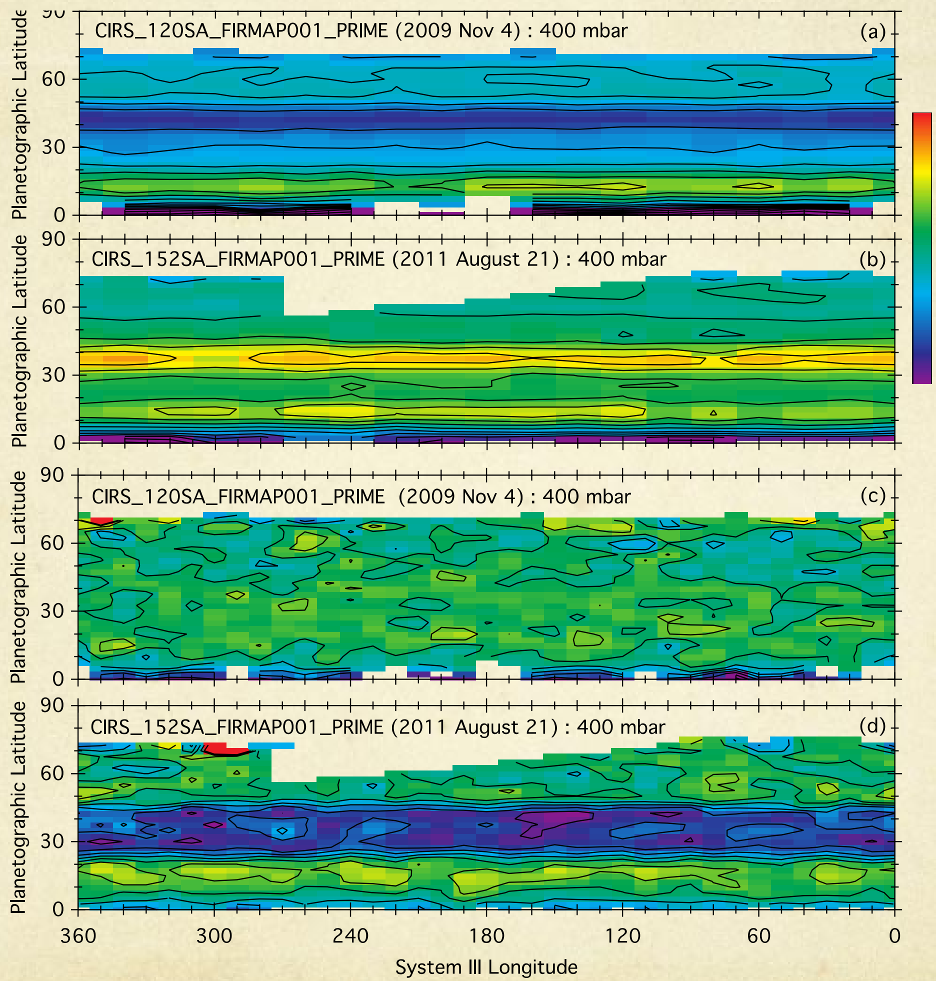


Cassini NAC image PIA11104 of Saturn’s south polar vortex at 2 km/pixel. The ring of clouds is at 89°S. Convective features exist at the equator too. See Dyudina et al., Saturn's south polar vortex compared to other large vortices in the Solar System, *Icarus* **202**, 240-248 (2009).

PIA14921 of Saturn’s giant storm at 20 km/pixel. The NAC happened to capture a lightning flash when the shutter was open for the blue filter. The figure on the right shows the same cloud 30 minutes after the first image was taken.

Temperature and Para Fraction

Achterberg et al., The Astrophysical Journal, 786:92, 2014



Analysis of Spot Locations and Albedo

Choi t al., J. GEOPHYS. RES., **114**, E04007, doi:10.1029/2008JE003254, 2009

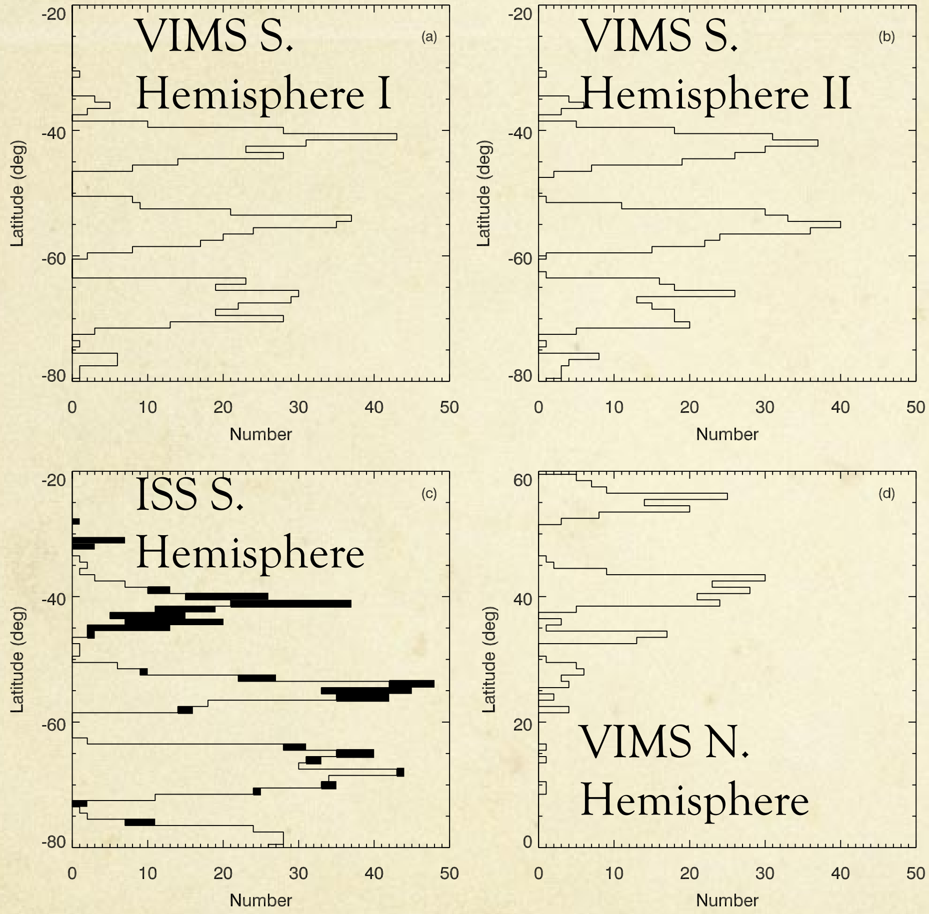


Figure 6. Histogram of the number of spot features as a function of latitude (planetographic). (a) VIMS southern hemisphere mosaic I. (b) VIMS southern hemisphere mosaic II. (c) ISS southern hemisphere mosaic, captured during the first orbit of Cassini around Saturn in 2004. The unfilled areas are light spots analyzed in this current study, whereas black bars are dark, low-albedo spot features analyzed by *Vasavada et al.* [2006]. (d) VIMS northern hemisphere mosaic.

"… the equatorial jet reaches speeds exceeding 450 m/s, similar to speeds obtained during the Voyager era. This suggests that recent inferences of relatively slower jet speeds of 275–375 m/s are confined to the upper troposphere and that the deep (>1 bar) jet has not experienced a significant slowdown."

"…numerous dark, spotted features seen in the VIMS mosaics reveals that most of these features have diameters less than 1000 km and reside in confined zonal bands between jet stream cores."