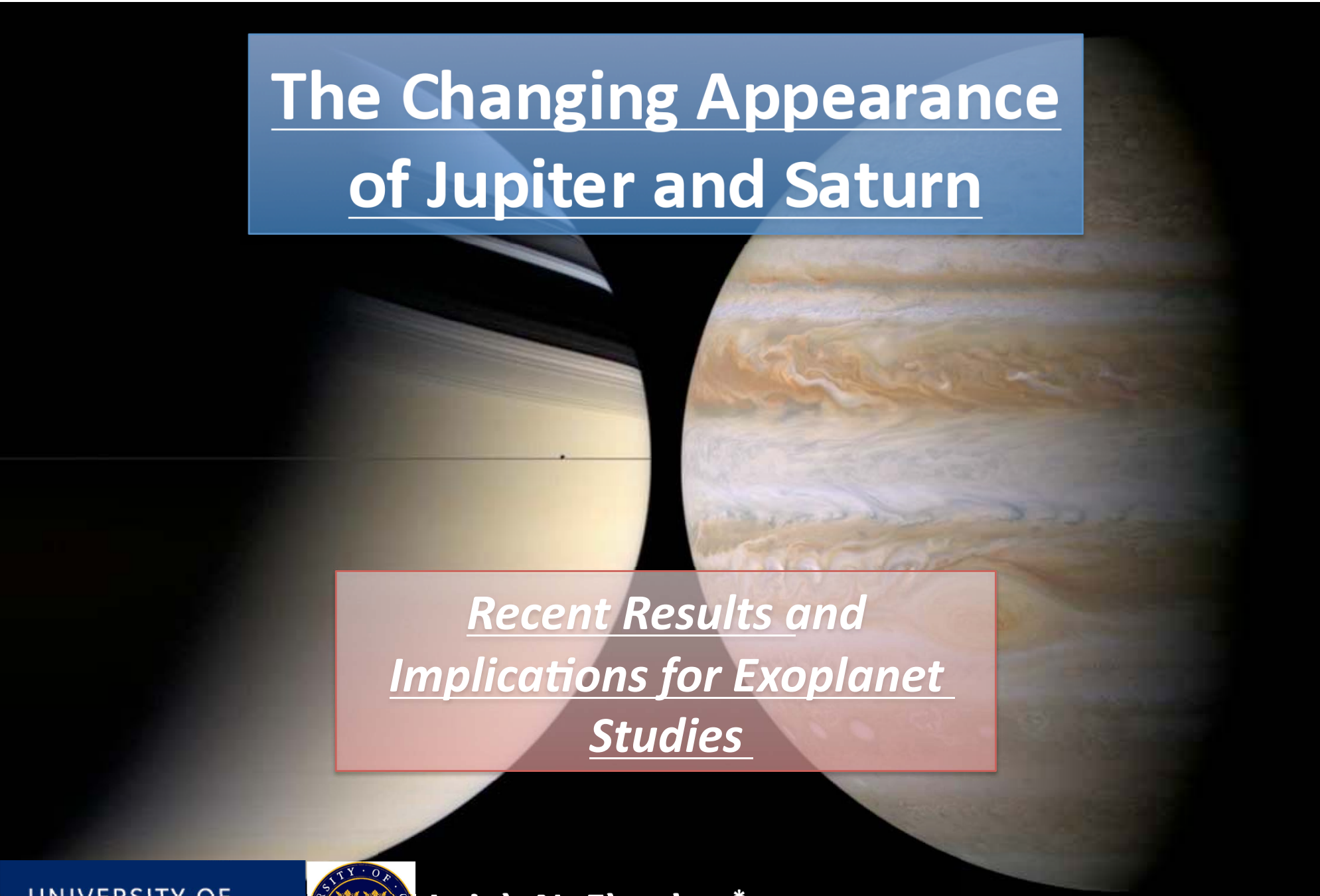
# The Changing Appearance of Jupiter and Saturn



## *Recent Results and Implications for Exoplanet Studies*

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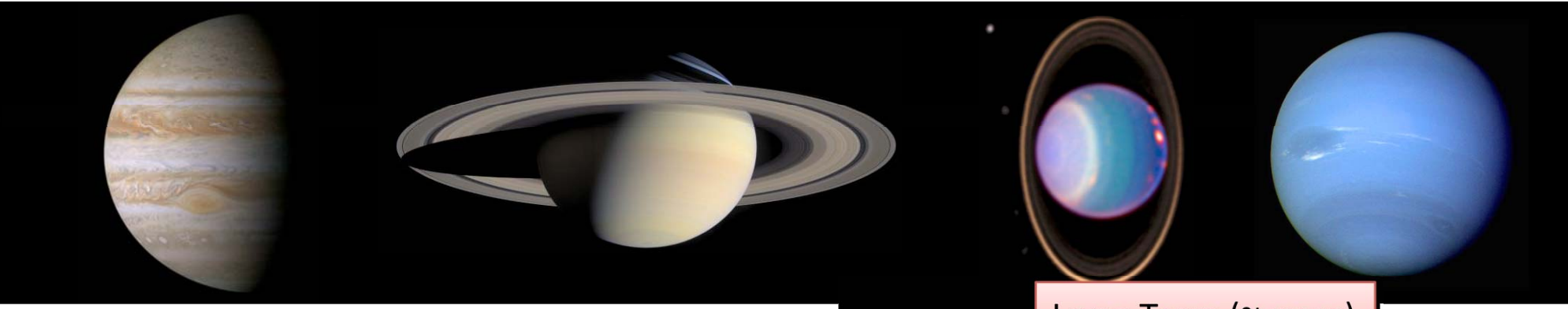
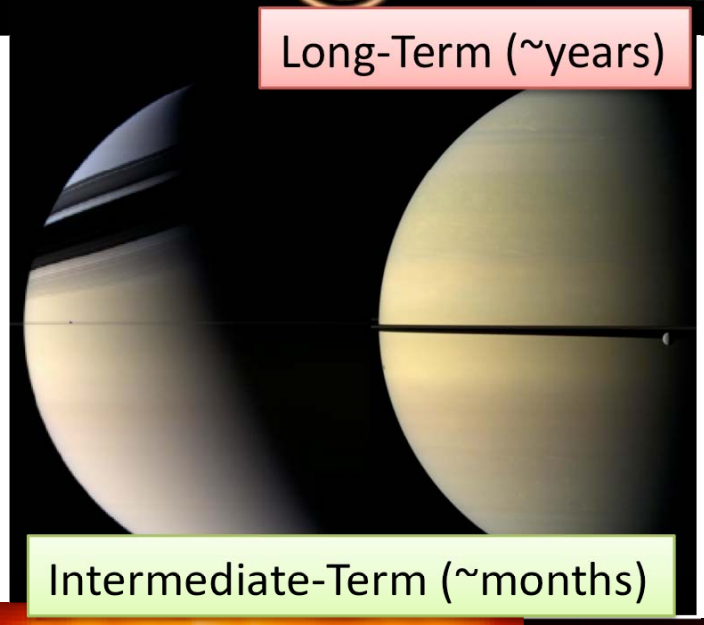
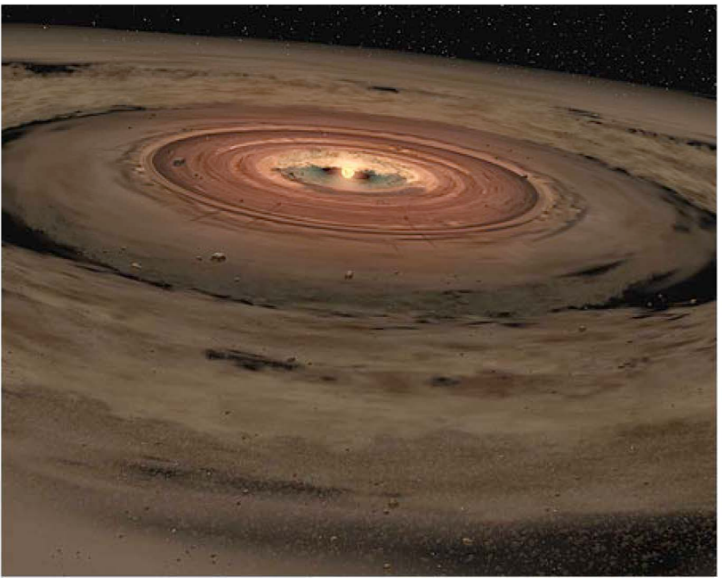


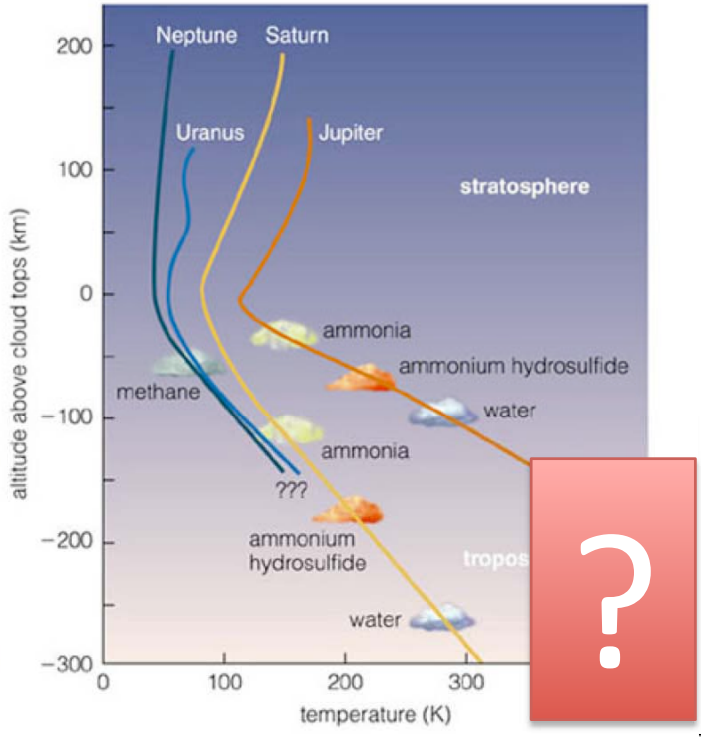
- Despite decades of intense research and observation, our understanding of the giant planets of our solar system remains incomplete.
- Yet the origins, evolution, dynamics and composition of Jupiter and Saturn serve as the paradigm for the interpretation of exoplanetary spectra.
- Recent results on the spatial and **temporal variability** of these atmospheres.

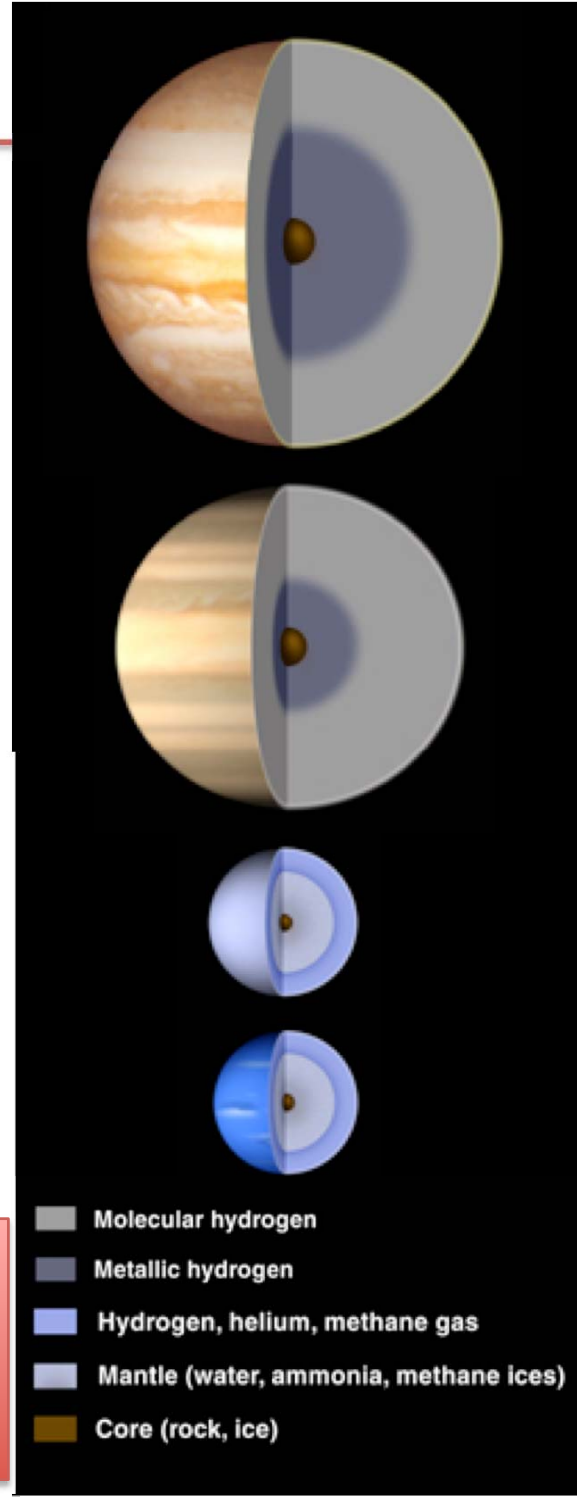


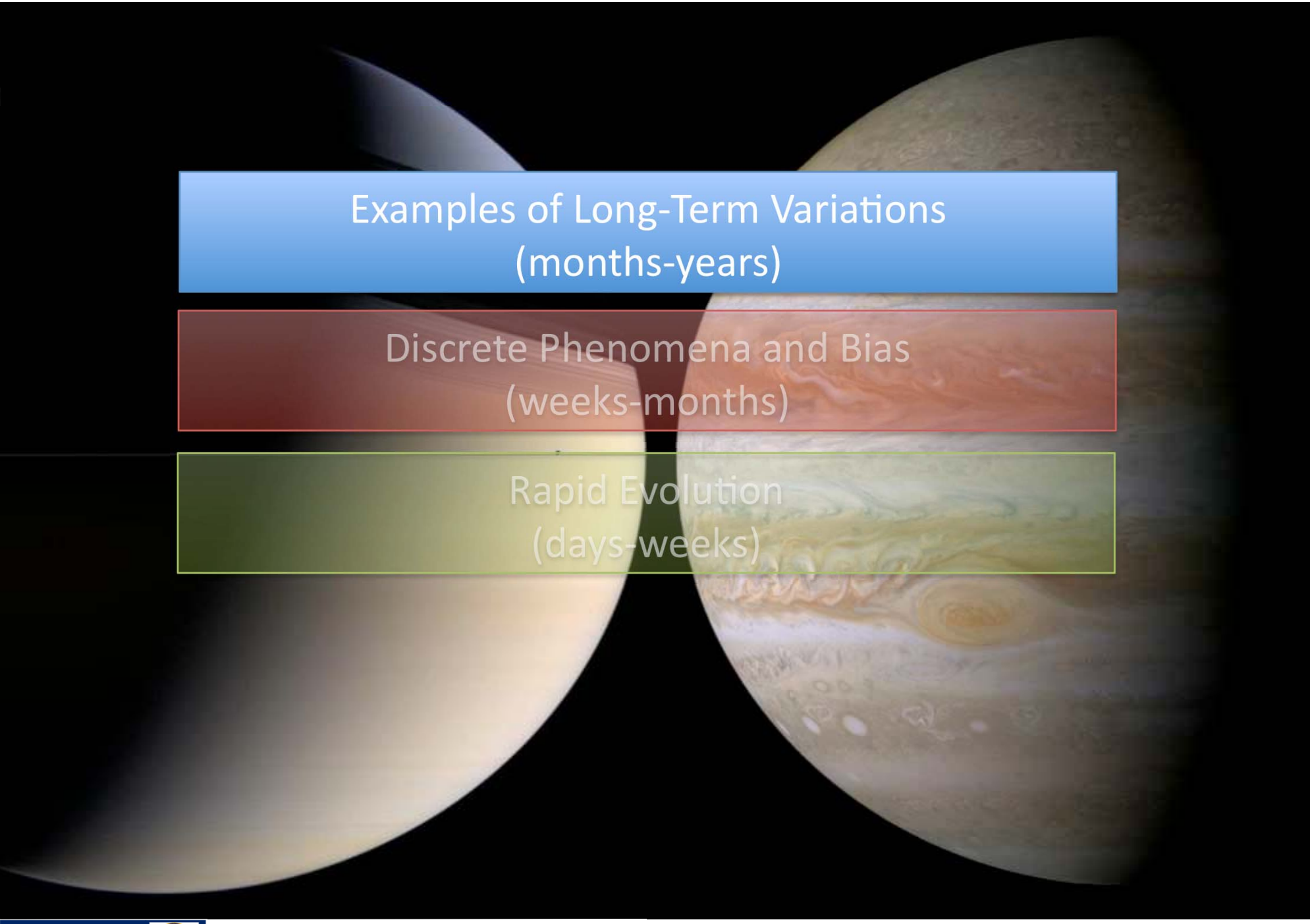
# The Trouble with Remote Sensing

- Characterisation of the giant planets remains incomplete
  - Remote sensing struggles to penetrate the cloud tops, deep interior composition and dynamics inferred indirectly.
- Composition provides a window onto solar system evolution
  - Yet there are multiple degeneracies/solutions (e.g. temperatures, clouds, gases).
- Weather layer variability makes interpretation of bulk composition difficult!



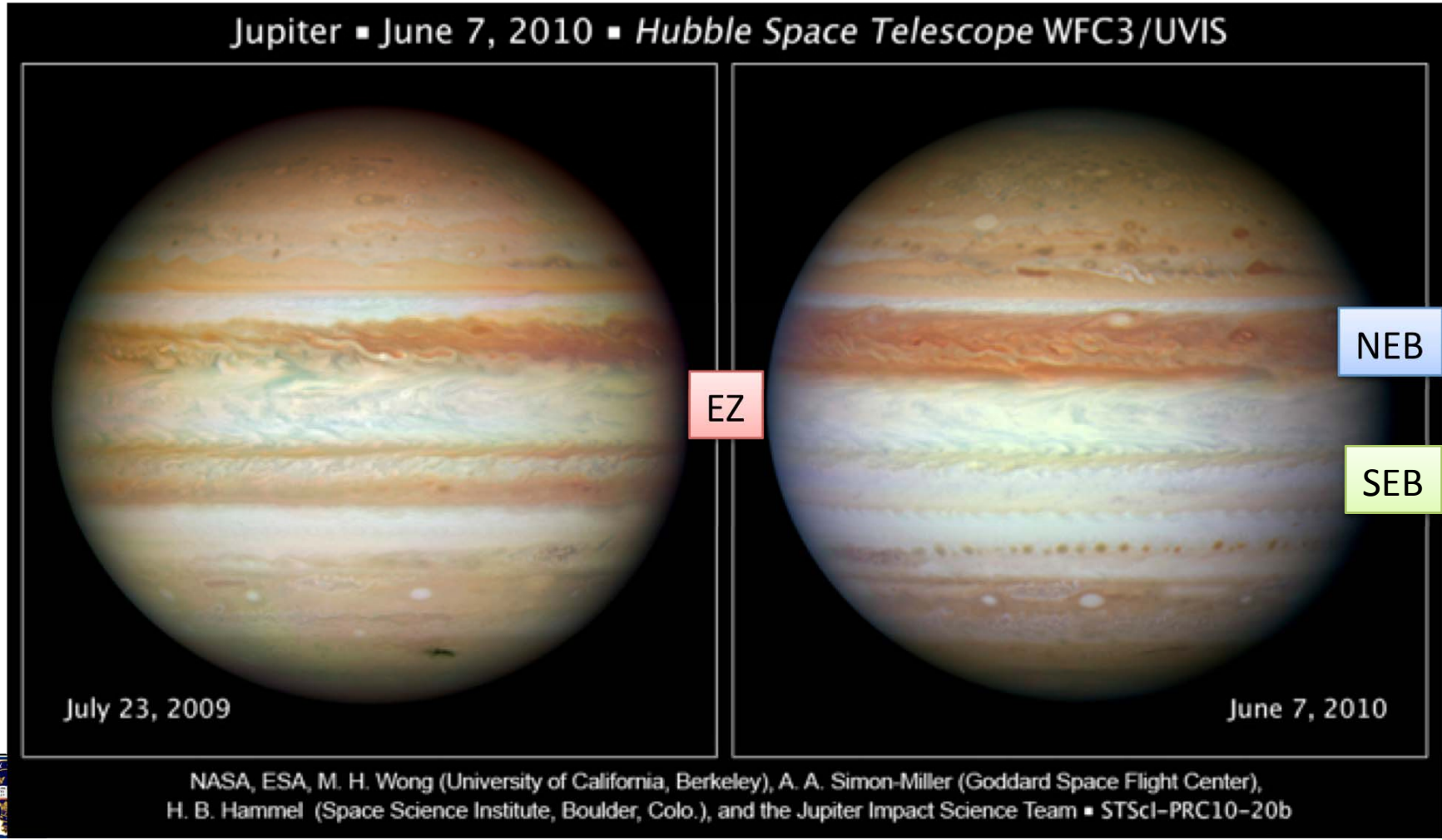



Examples of Long-Term Variations
(months-years)
Discrete Phenomena and Bias
(weeks-months)
Rapid Evolution
(days-weeks)

# Large-Scale Jupiter Variations

- Jupiter's axisymmetric structure experiences periodic 'upheavals'
  - Outbreaks of plumes, disturbances, albedo changes
  - Can significantly alter the appearance of the planet.
- Present unusual state of South Eq. Belt (SEB) – Missing stripe!



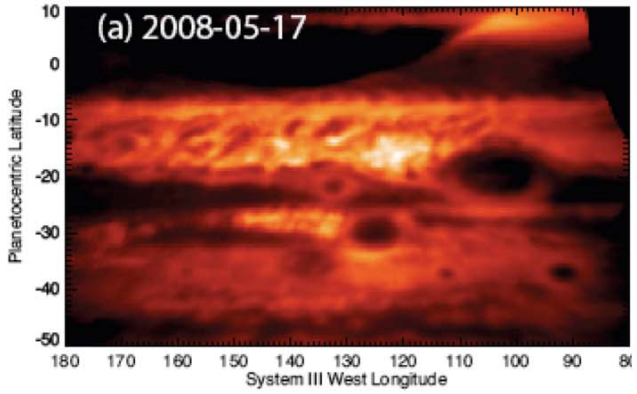
© Anthony Wesley, June 2010

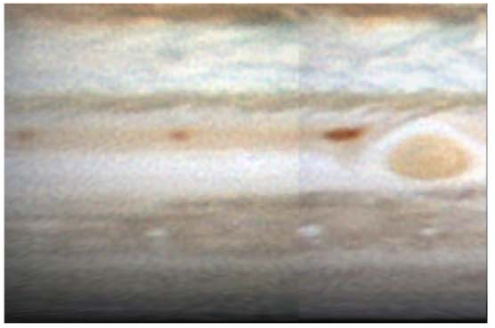
Jupiter, 23 July 2010

# Life Cycle of an SEB Fade

VLT/VISIR Thermal imaging 2008-2010

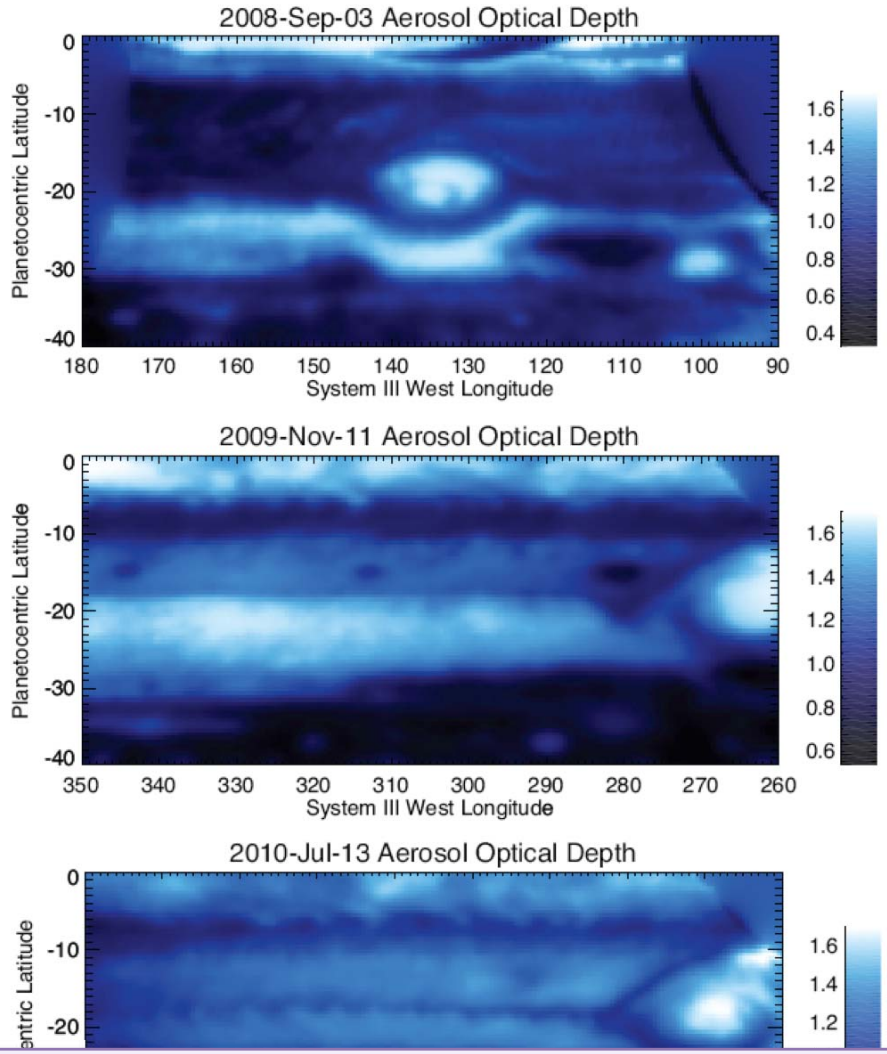
- Cessation of turbulence NW of the Great Red Spot
- SEB appears more diffuse, darker @8.6µm.
- Series of dark brown barges forms, bright at 8.6 µm.
- By April 2010, SEB appears pale and white, zone-like.
- Presently awaiting disturbance that will revive the typical brown colour of the SEB (1-3 years?).

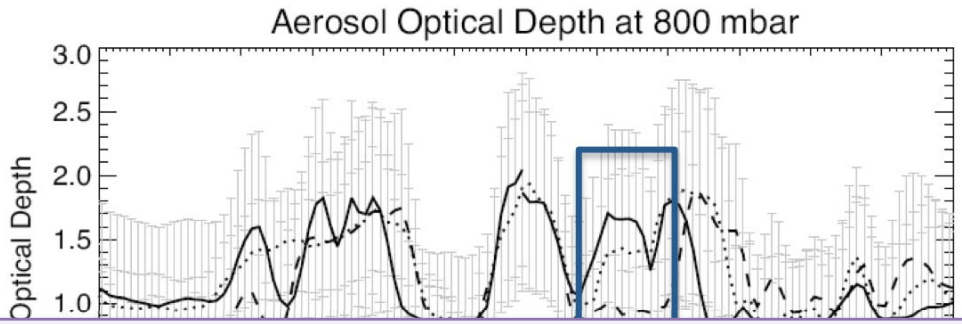


# Jovian Haze Variability

- Optimal estimation retrievals show whitening corresponds with (a) cooling at depth and (b) increased haze opacity
  - $NH_3$ ice condensation on blue-absorbing chromophore?
  - Barges were cloud-free, $NH_3$ ice evaporation?
  - Revival should exhibit warming in localised subsiding regions.
- But underlying physical mechanism for cessation of turbulence, onset of fade and instability leading to revival are all unknown.

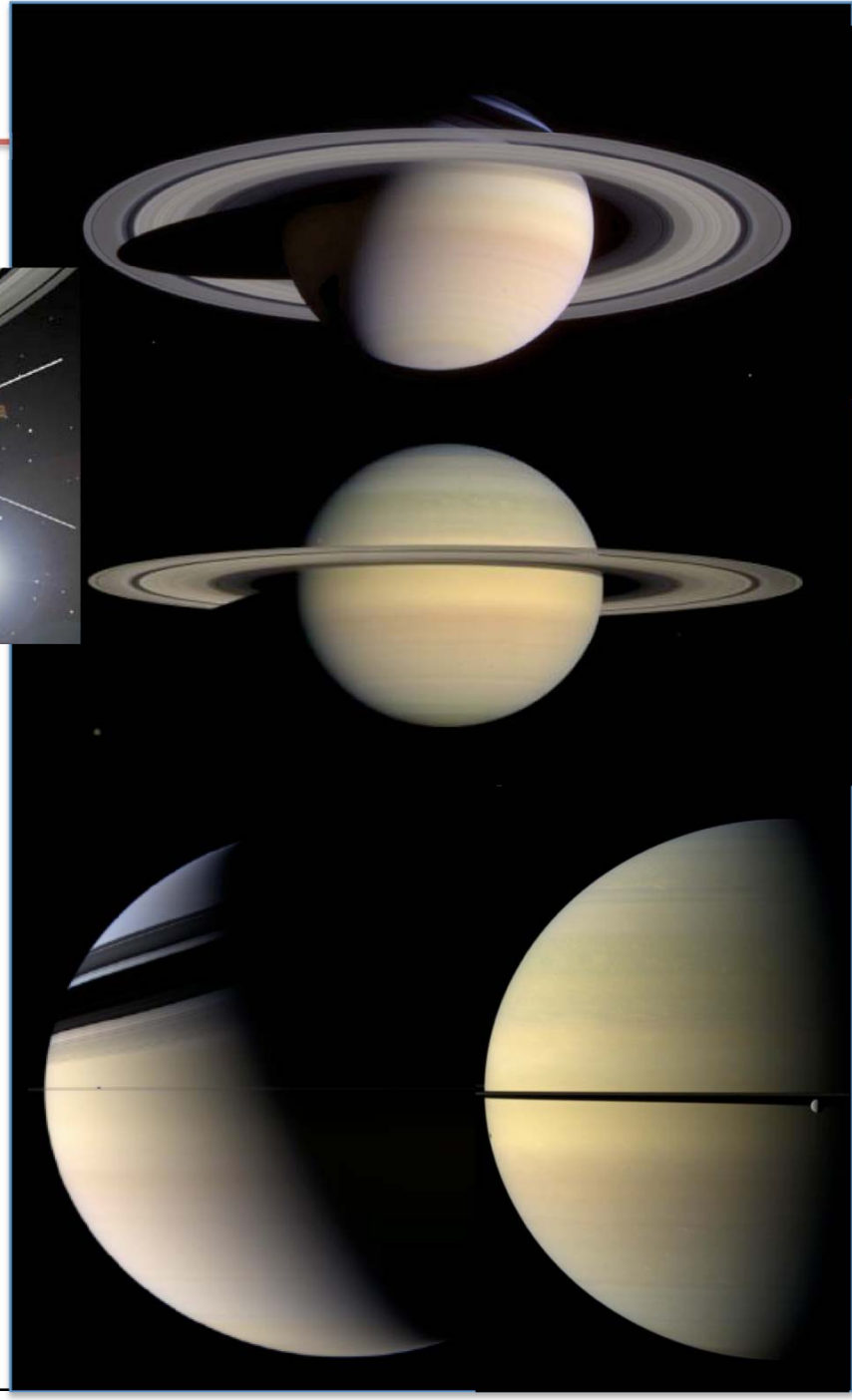


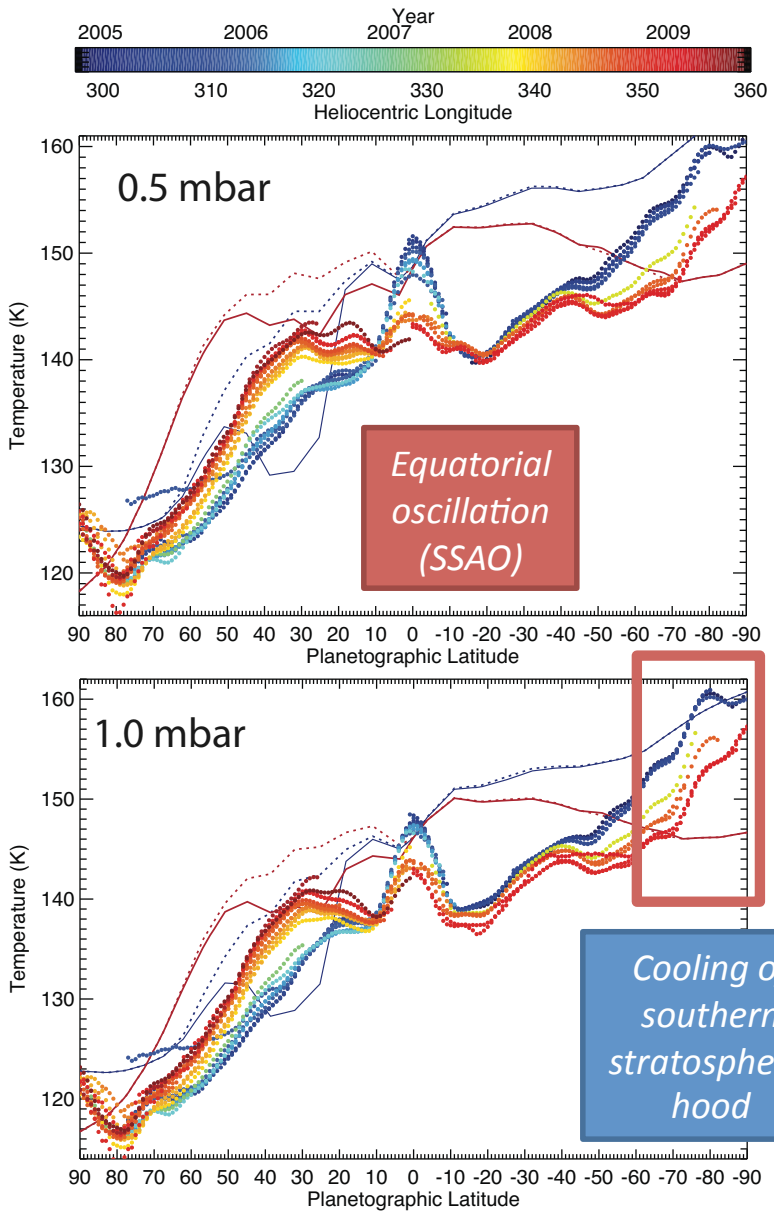

*Dynamical/chemical causes of 'global upheavals' are unknown, but have a substantial effect on aerosol content, thermal emission spectra and VNIR albedo*

# Saturn's Seasonal Variability

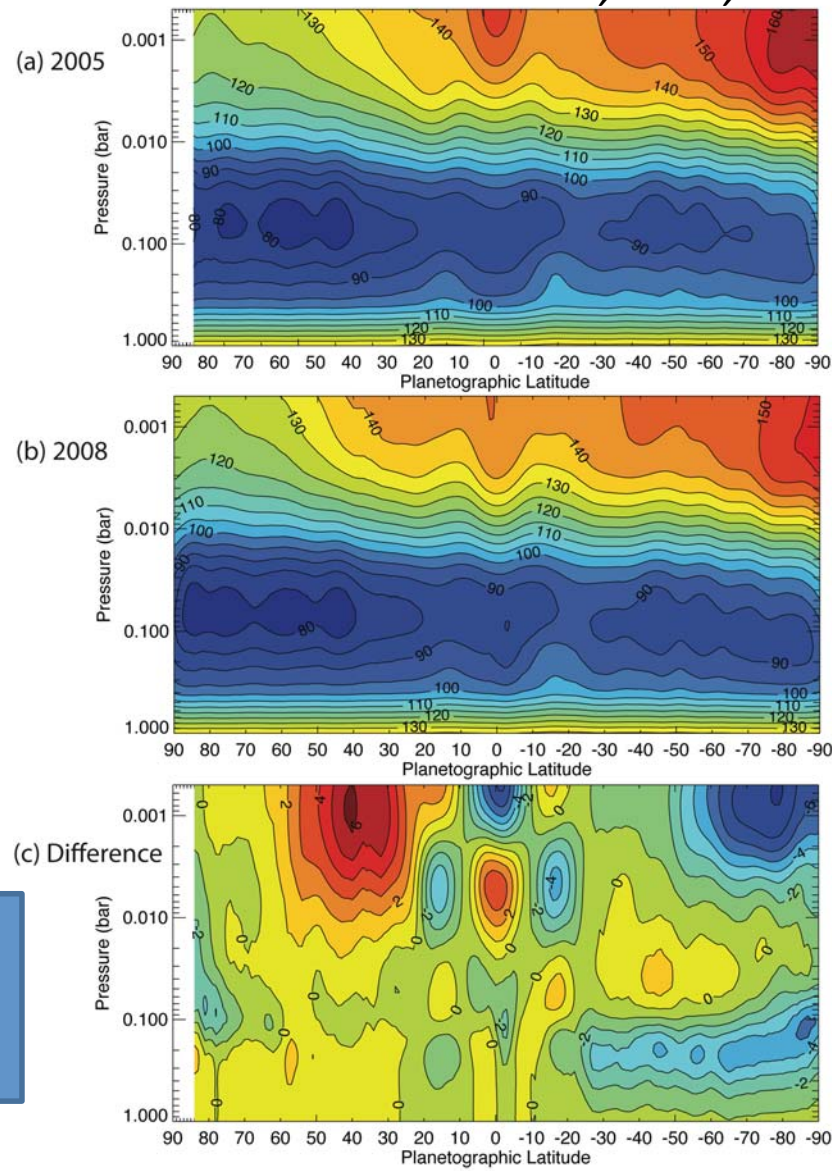
- Second example of long term trend:
  - Saturn's 26.7° orbital obliquity leads to hemispherical temperature, aerosol and composition asymmetries.
- Blue northern hues observed early in Cassini mission have been replaced by typical yellow-ochre colouration.
  - Growth of aerosol particles in response to springtime?
  - Cassini IR studies revealed enhanced opacity of southern hemisphere.
- Tropospheric and stratospheric temperatures respond to variation of insolation.
  - Slow 29 year trend



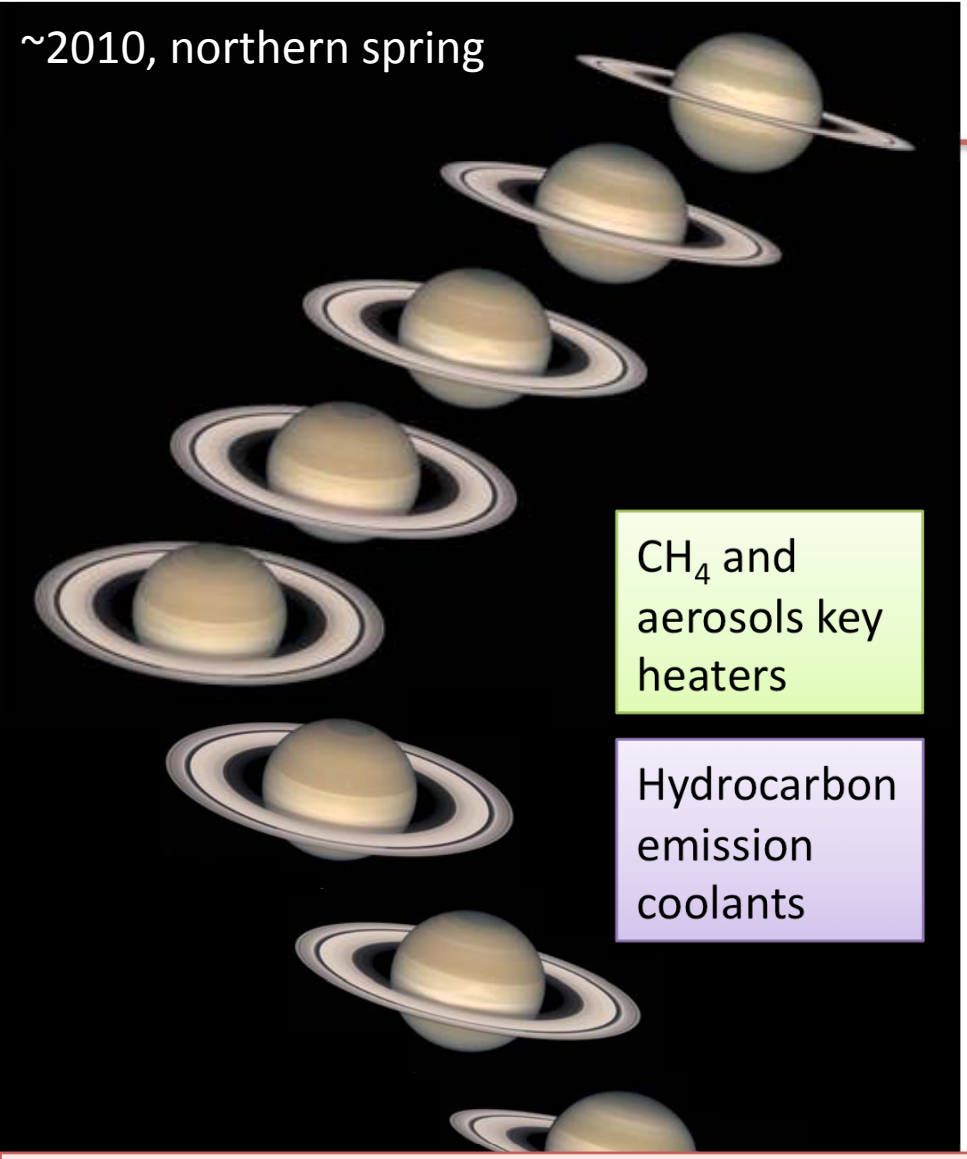
# Temperature Changes 2004-2009



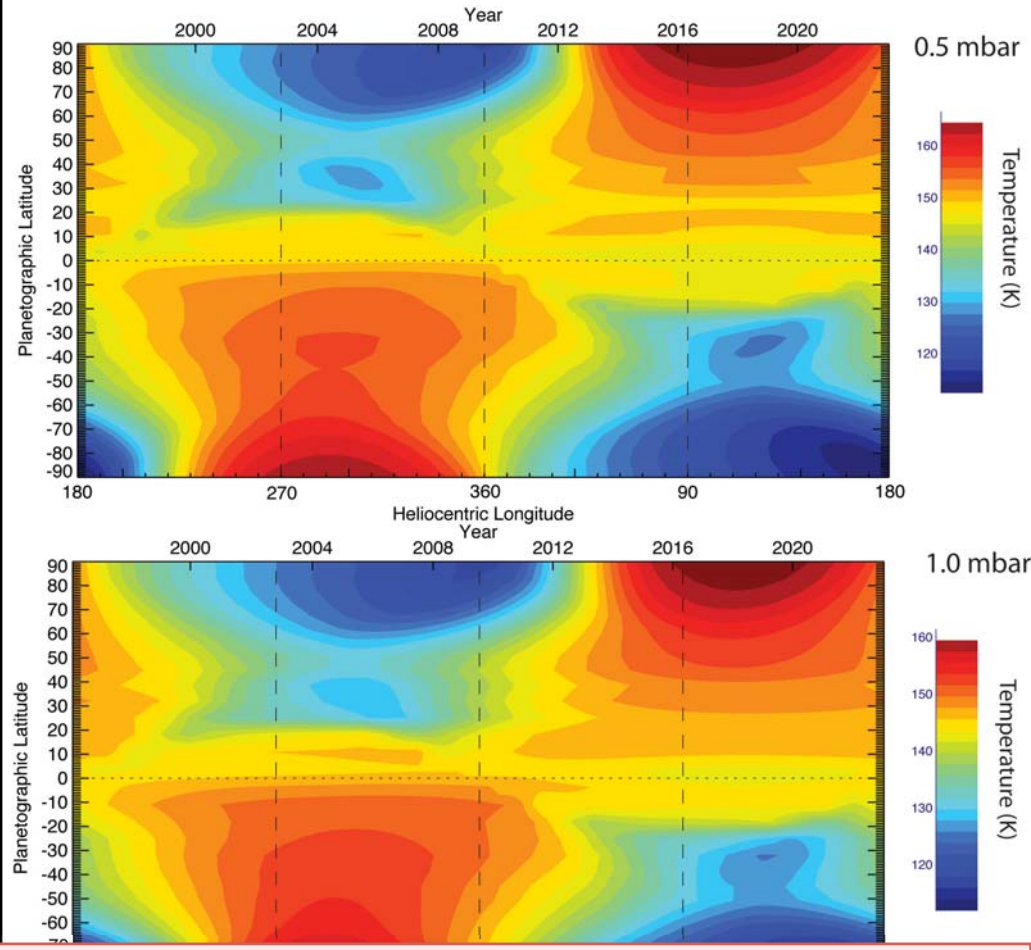

*Fletcher et al., 2010, Icarus*



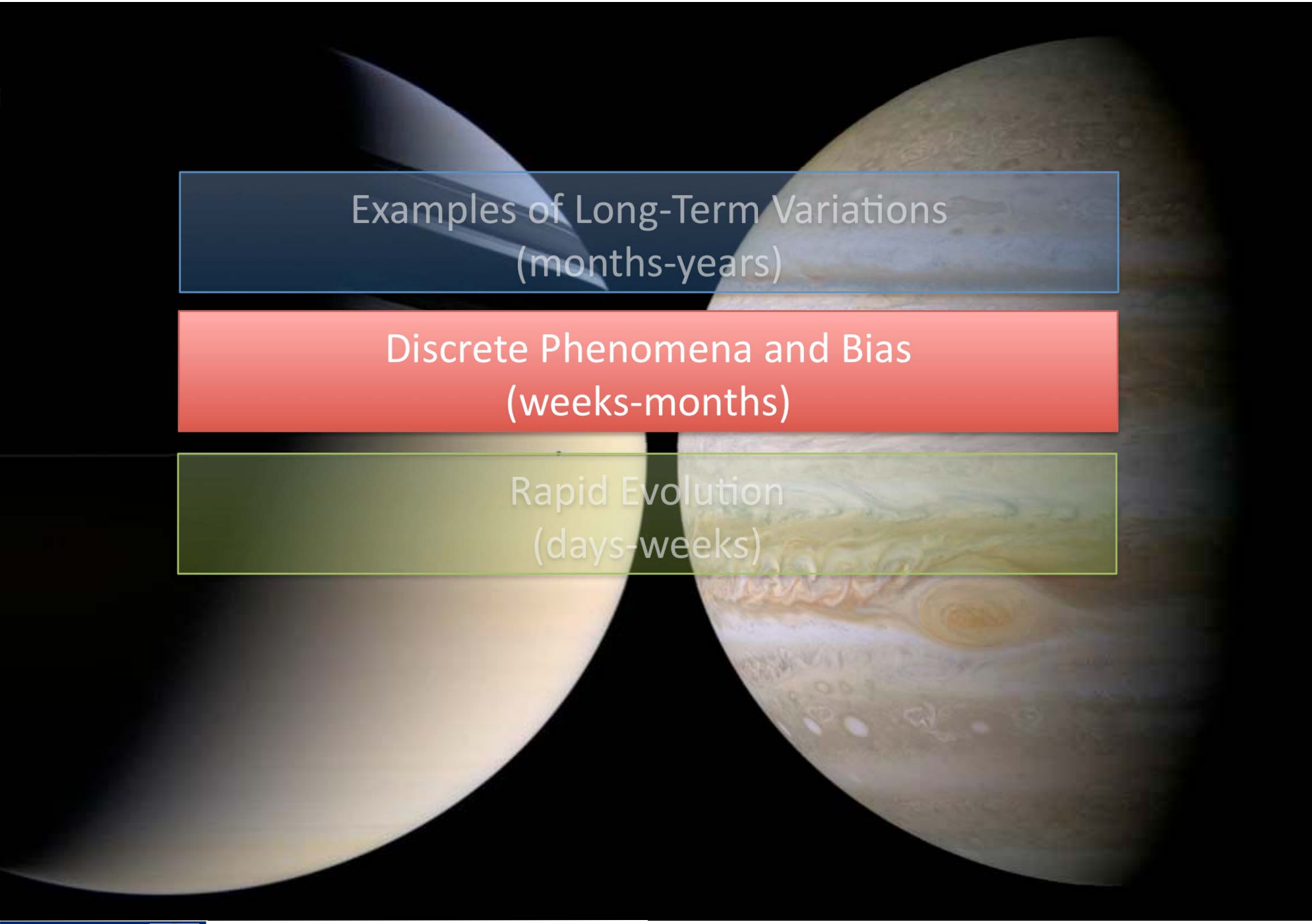

*Warming of northern mid-latitudes associated with haze production?*




# Predictability

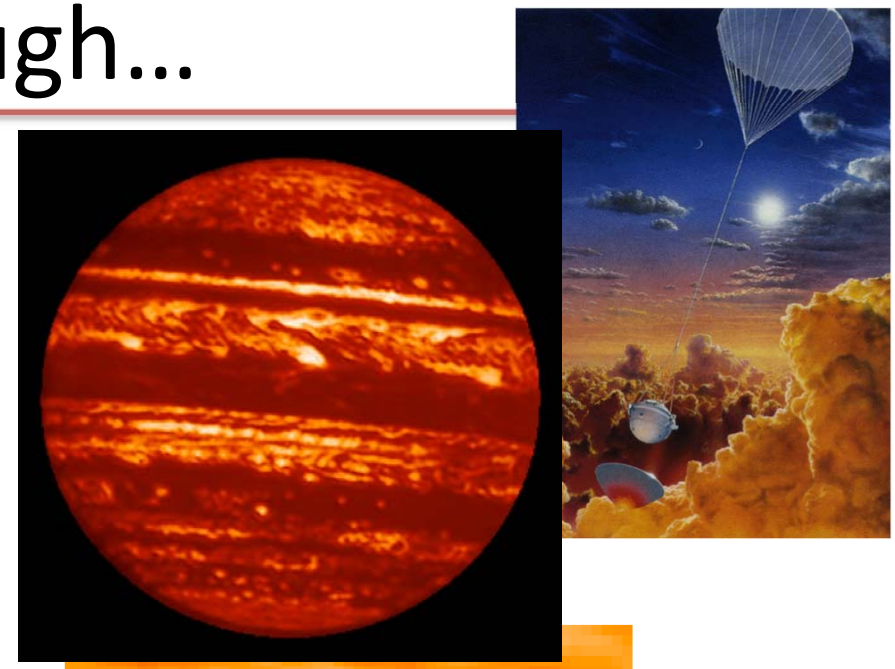


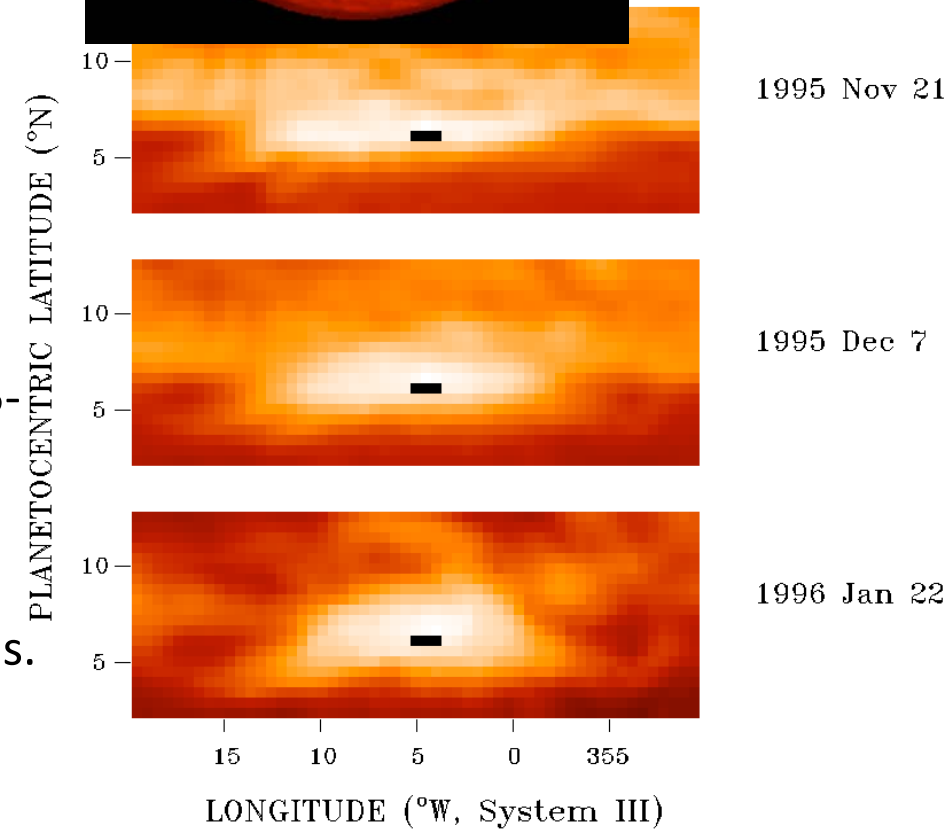

*Any planet with an axial tilt will experience substantial radiative modification of the weather layer (photochemistry, heating and cooling, aerosol production) so that thermal emission and reflectivity vary during the orbit.*


Examples of Long-Term Variations
(months-years)
Discrete Phenomena and Bias
(weeks-months)
Rapid Evolution
(days-weeks)

# Spectroscopy isn't Enough…

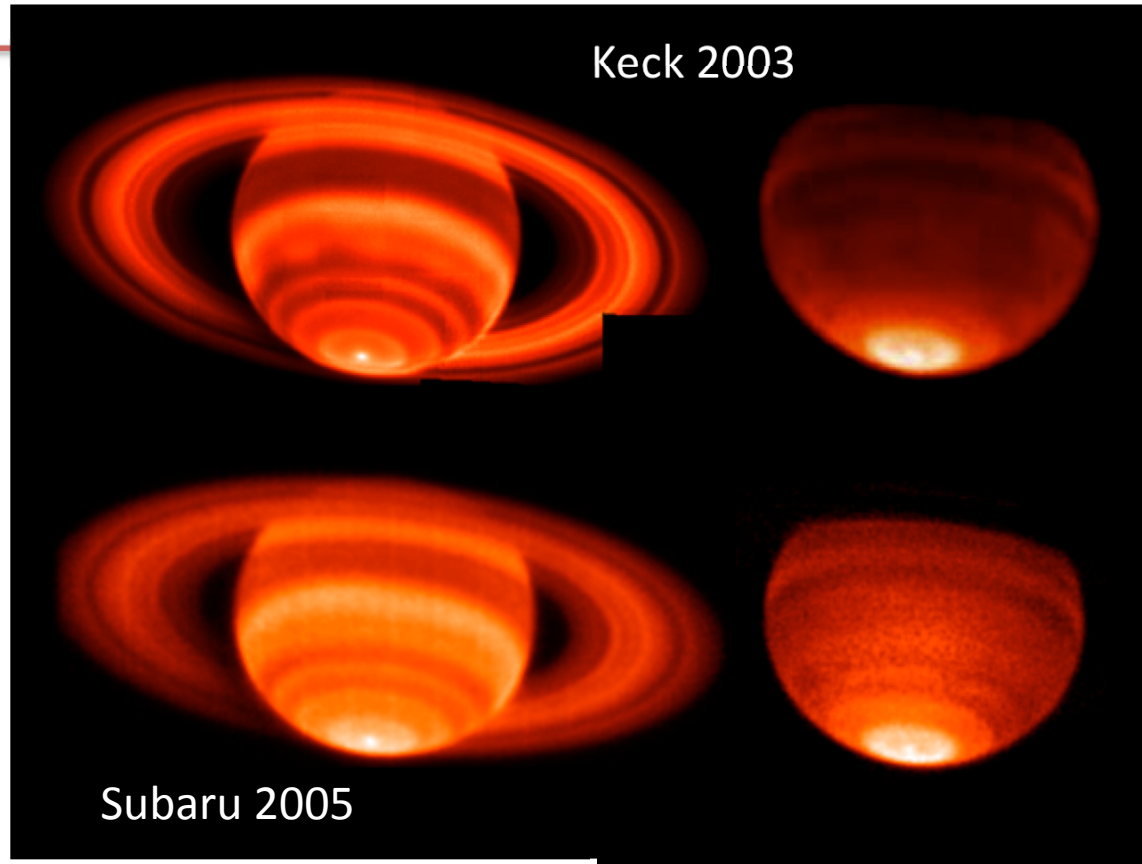
- Presence of discrete structures in planetary atmospheres can alter disc-averaged spectra.
  - Giant vortices, wave phenomena, polar dynamics, rapidly evolving cloud systems.
  - These can bias compositional measurements to the warmest/ brightest/most reflective regions.
- Example: Galileo Probe (1995)
  - Discovered atmosphere unexpectedly depleted in volatiles.
  - O/H abundance much lower than expected.
  - Orton et al. (1998): Probe entered a 5-μm hotspot, depleted in volatiles.
  - Roos-Serote et al. (2004): Bright 5-μm hotspots depleted in $H_2O$ but come to dominate the disc-average.
  - Not representative of global conditions.



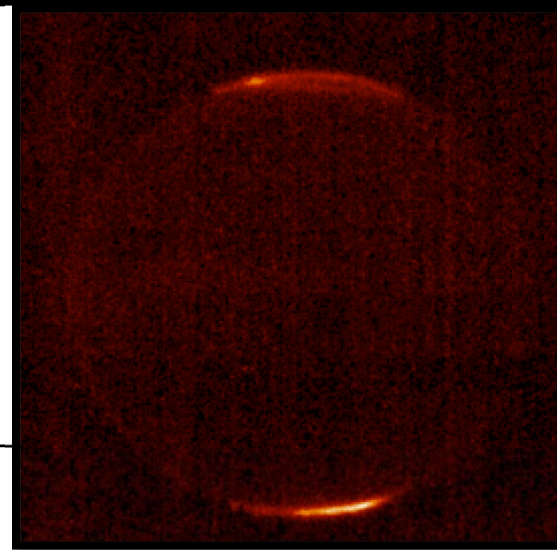


# Polar Dominance

- Polar atmospheres:
  - Apex of a planet-wide circulation
  - Unique connection to external planetary environment via mag. field/aurora.
- Polar emission can dominate disc-average, leads to spurious results
  - Anomalous UV-absorbing hazes, high CxHy abundances, depletion of tracers due to subsidence.

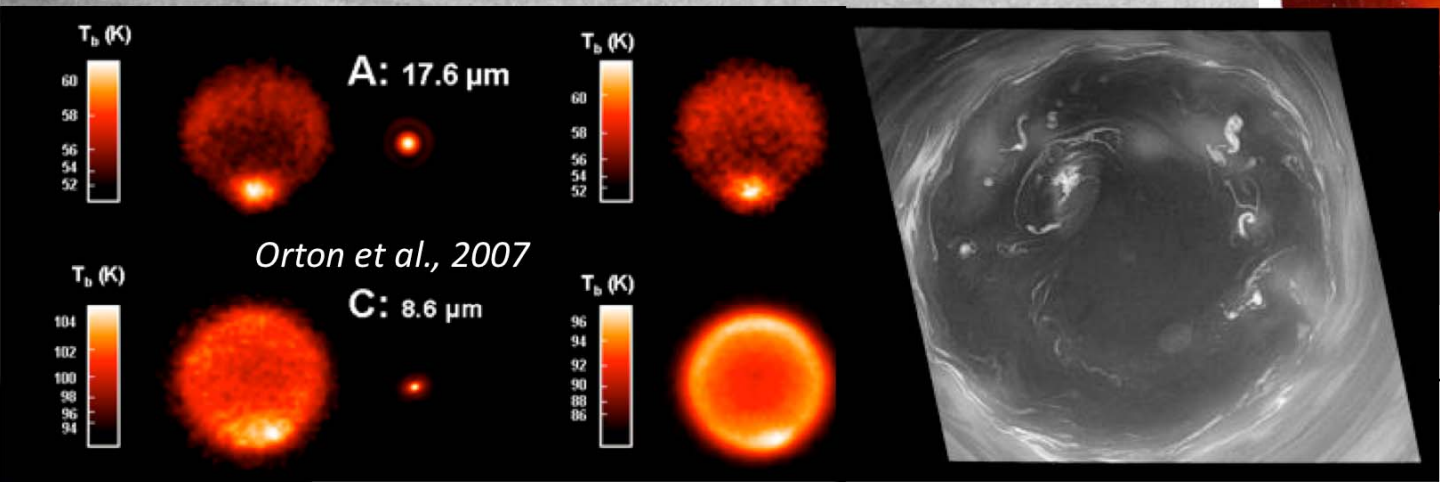



*IRTF/NSFCAM2 3.43 μm $H_3^+$ Emission from auroral regions of Jupiter.*



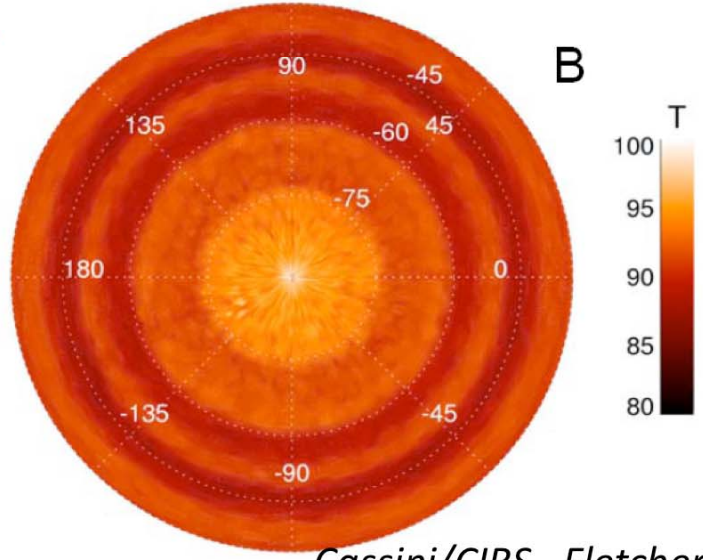
# Unique Activity at Poles

- **Globally averaged spectra from Earth are sensitive to the summer hemisphere**
  - **Saturn: Polar subsidence in cyclonic vortices, surrounded by prograde jet, depleted in aerosols and $PH_3$, enhanced in hydrocarbons.**
  - **Neptune: warm pole permits $CH_4$ to leak through cold trap.**
- **NOT representative of global conditions.**

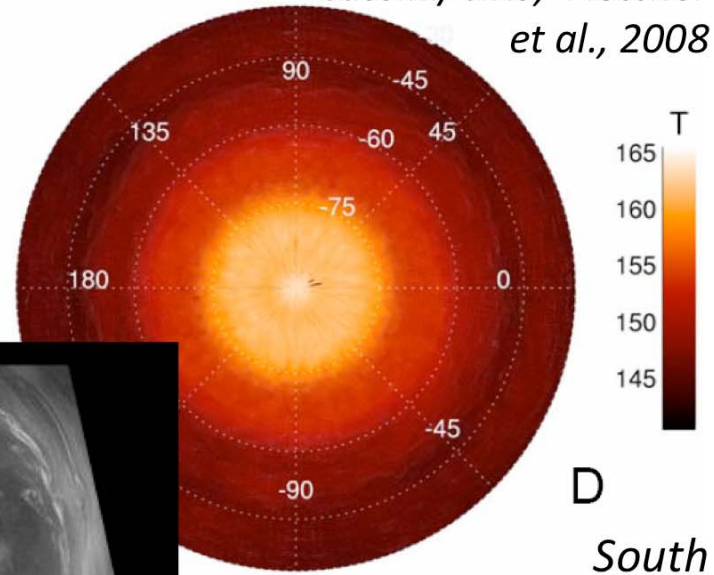



*Orton et al., 2007*

*South Troposphere 100 mbar*



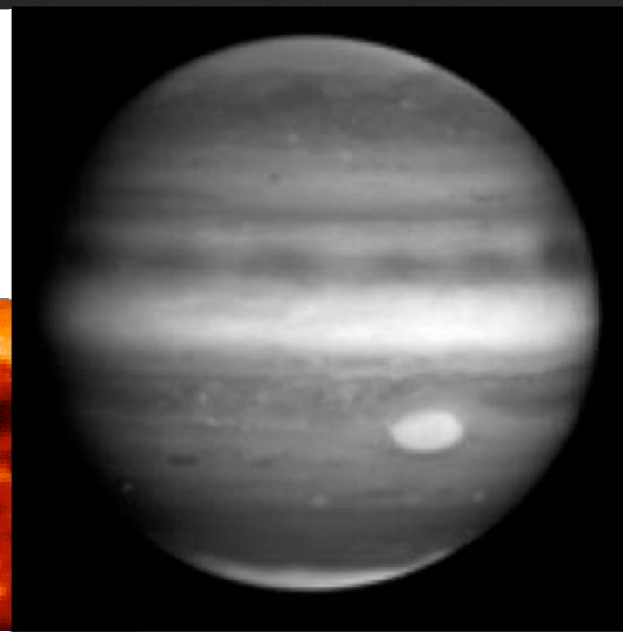

*Cassini/CIRS, Fletcher et al., 2008*



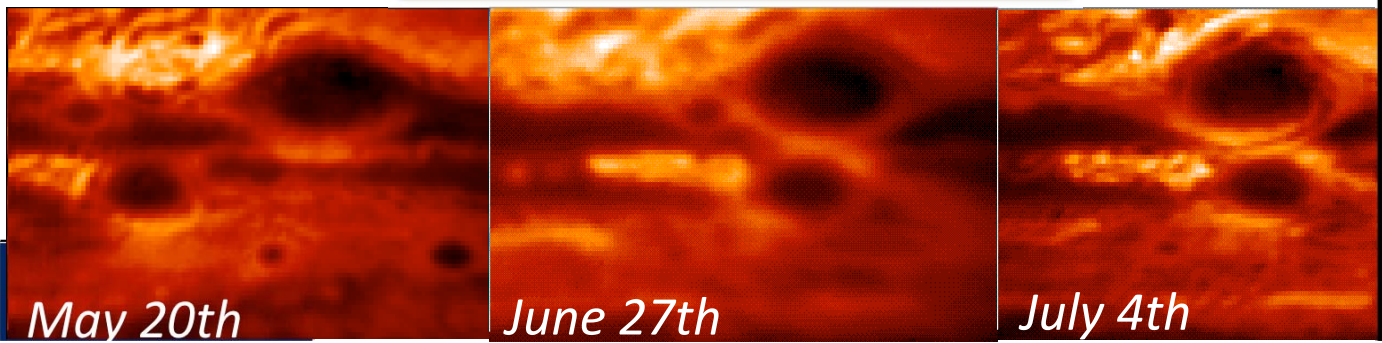

*South Stratosphere 1 mbar*

# Importance of Giant Vortices

- Jupiter's giant anticyclones dominate the visible appearance
  - High near-IR reflectivity
  - Low mid-IR thermal emission
  - Unique visible spectrum (i.e. red)
- Large vortices would modulate radiance as planet rotated (although GRS influence is relatively small).
- T(p) and composition of vortex could also dominate disc-average, unique chemistry.

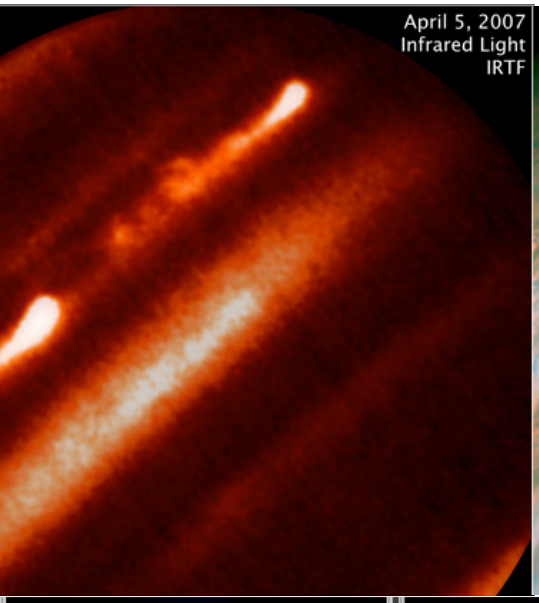



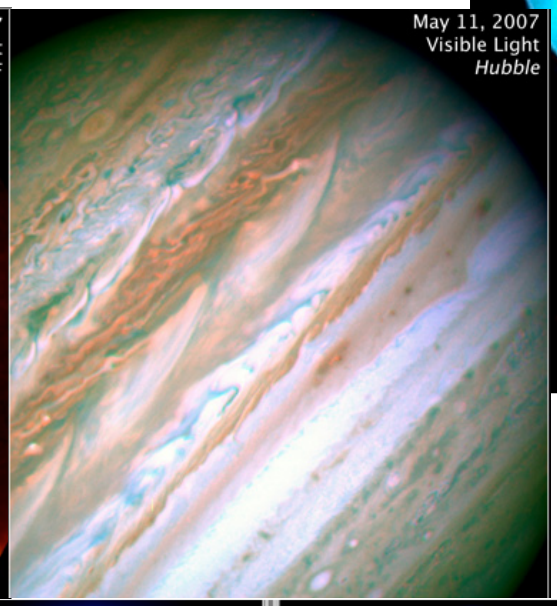
**Thermal Imaging (VLT) in 2008**

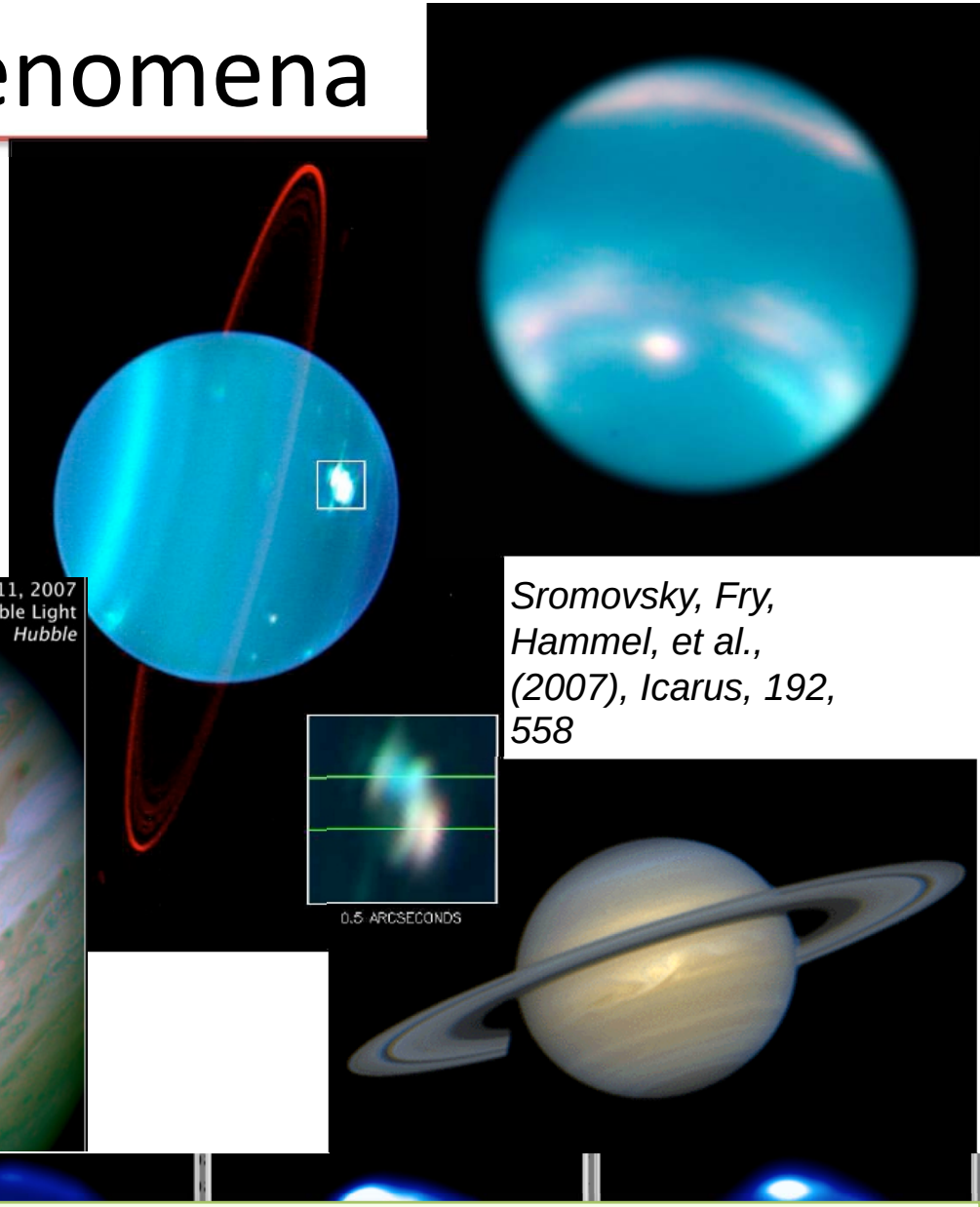


# Discrete Weather Phenomena

- Plumes, outbreaks of clouds, instabilities can dominate near-IR wavelengths for short periods of time



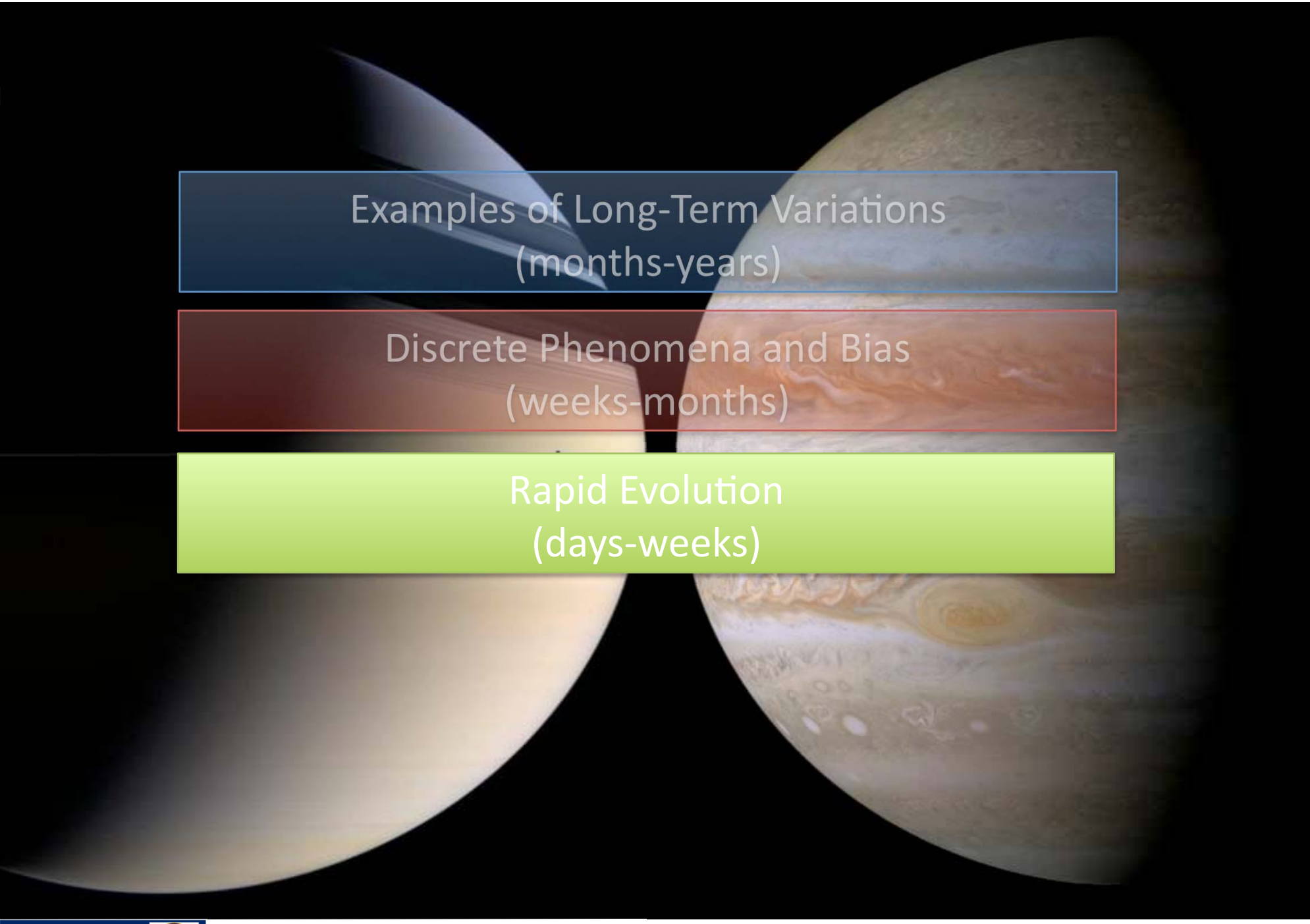






*Sromovsky, Fry, Hammel, et al., (2007), Icarus, 192, 558*



*Weather-layer phenomena – hotspots, polar vortices, plumes, storms – significantly affect planetary brightness at UV to IR wavelengths, and cannot be ignored when assessing variability in disc-averaged spectra.*


Examples of Long-Term Variations
(months-years)
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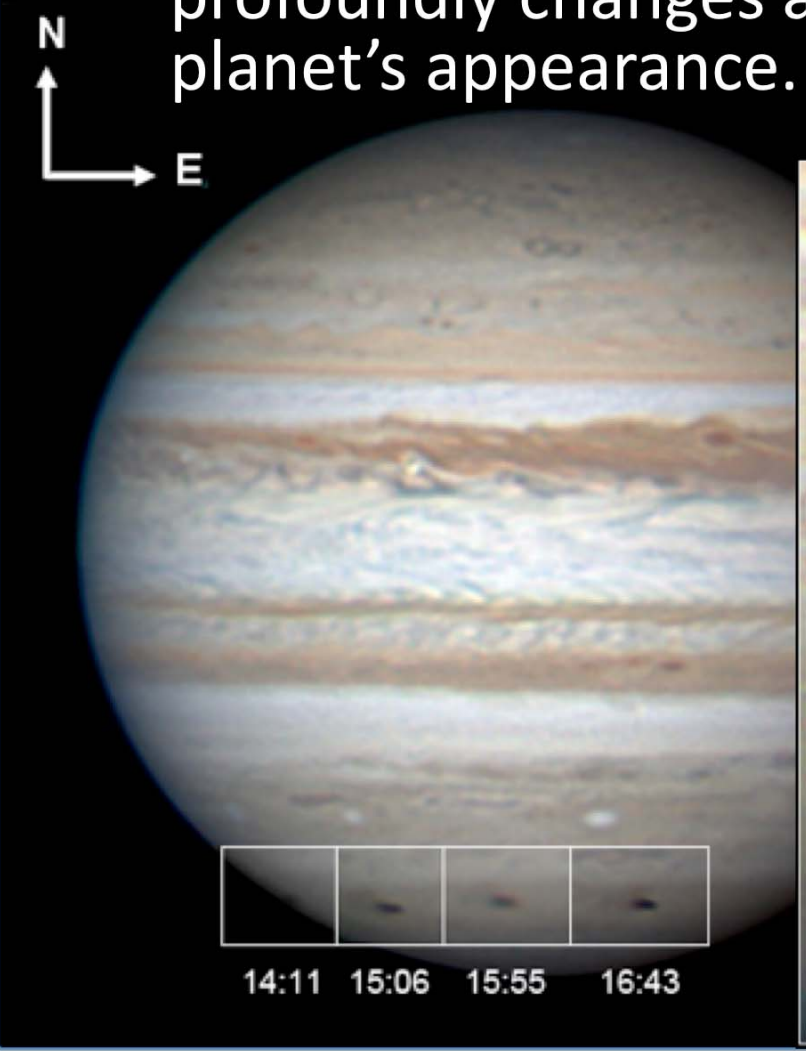
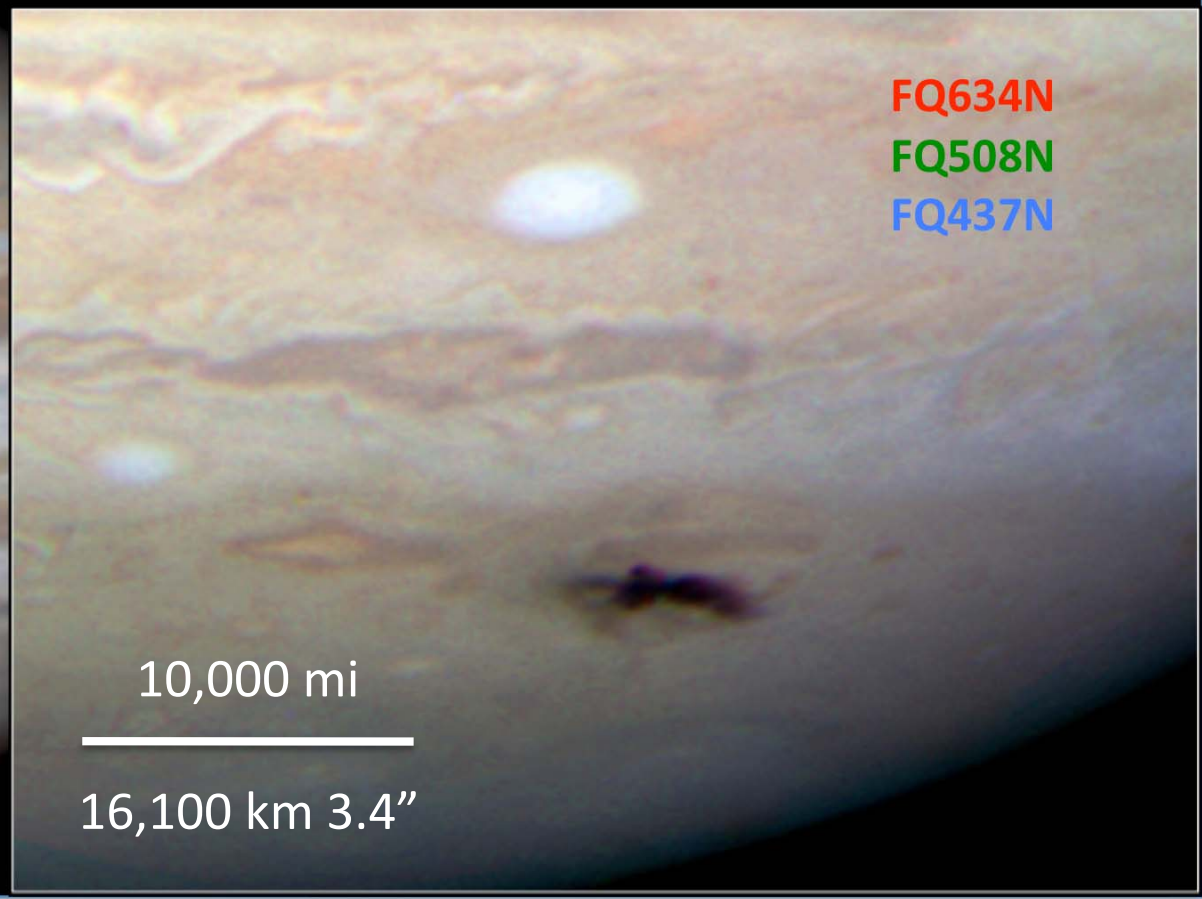
# Summer 2009: Jupiter Impact

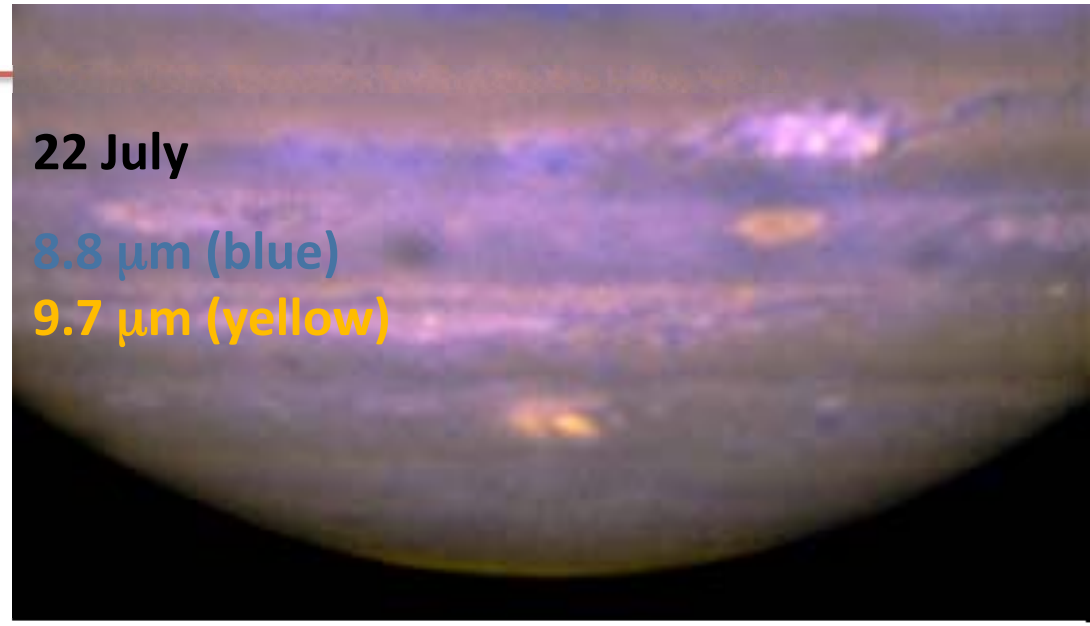
- Recent impacts on Jupiter are a perfect example of short-term variability that profoundly changes a planet's appearance.
  - Near-IR reflected sunlight from high altitude haze.
  - Visibly dark debris field
  - High mid-IR emission from excess heating

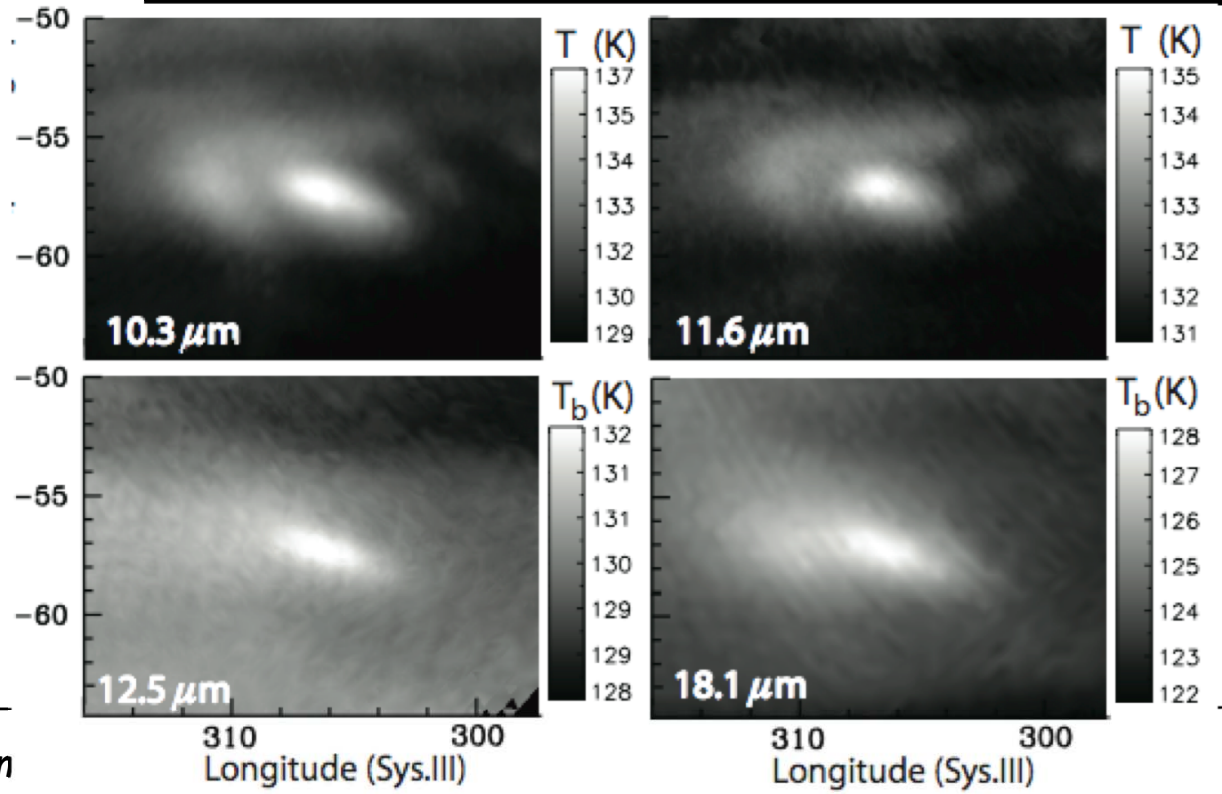


# Mid-IR Imaging

- Gemini and VLT 7-25 μm spectroscopy vital for diagnosing atmospheric response
  - Impact core and ejecta were bright across much of the thermal-IR
  - Chemical differences between 'streak' and 'crescent' reveal the processes at work

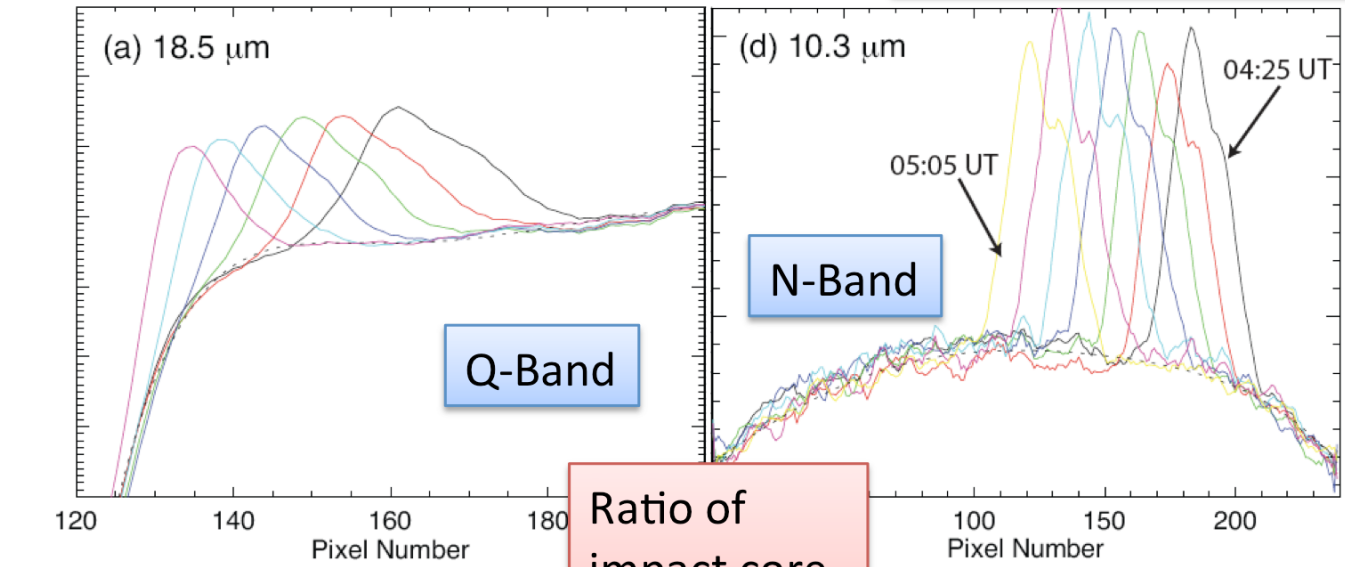


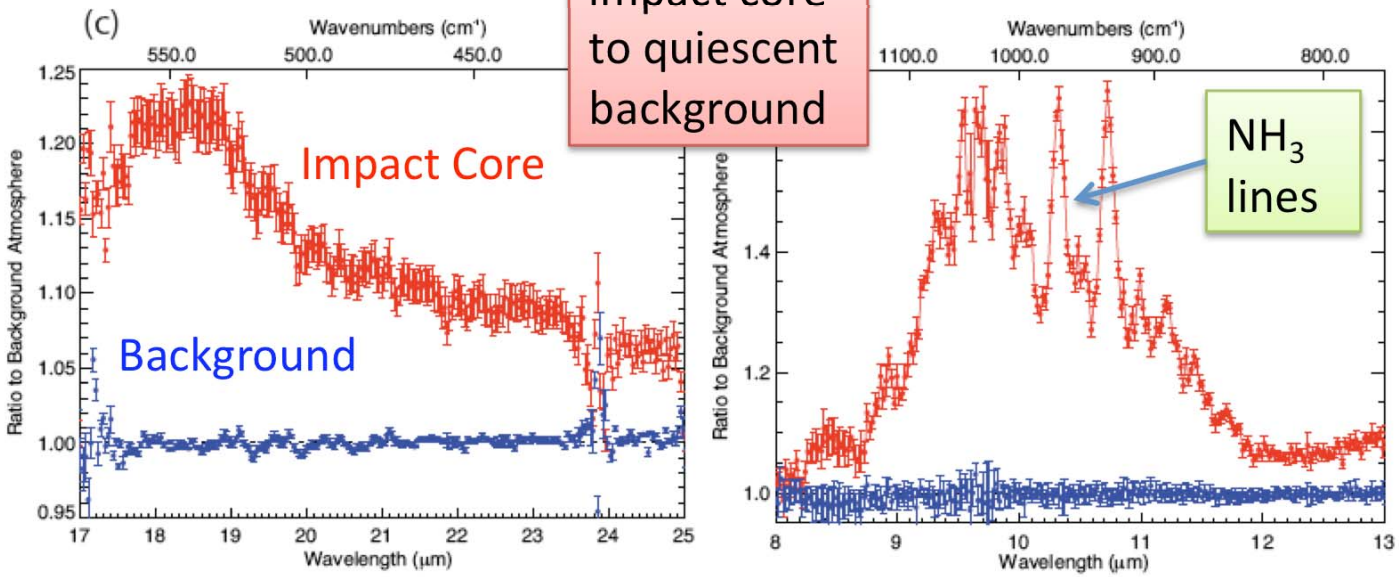
# Brightest Feature on the Planet?

Enhanced emission @ nearly all wavelengths

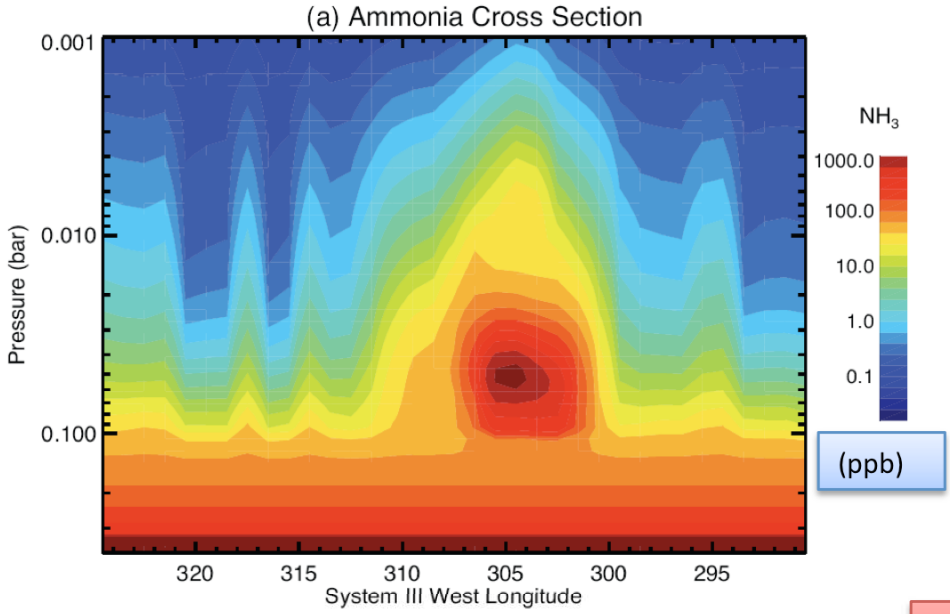
- Gemini-TReCS spectroscopy 5 days post-impact
- Jovian rotation moved debris field through multiple emission angles.
- Polynomial curves for background radiance.
- Q-band enhanced ~20%
- N-band enhanced ~60%
- Spectra used to retrieve atmospheric properties…

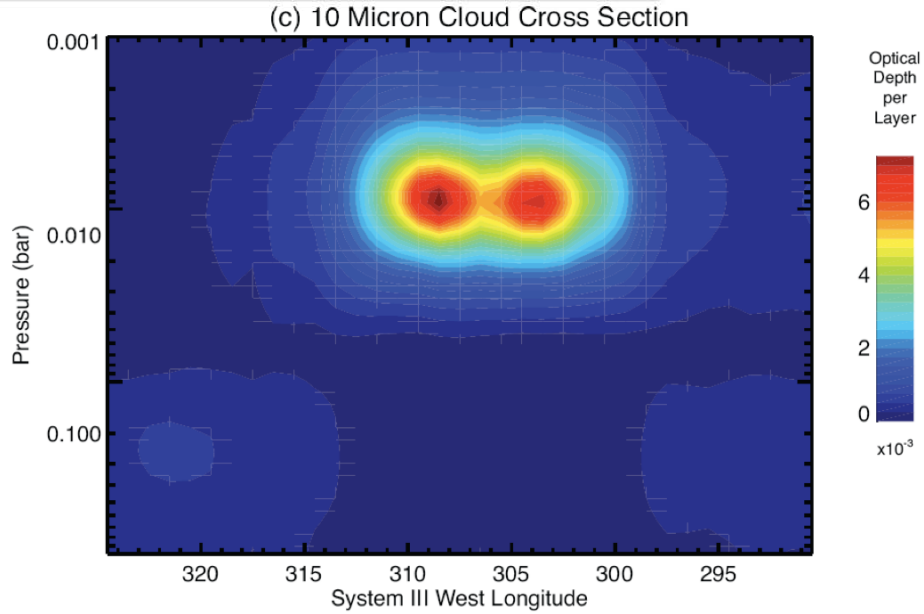


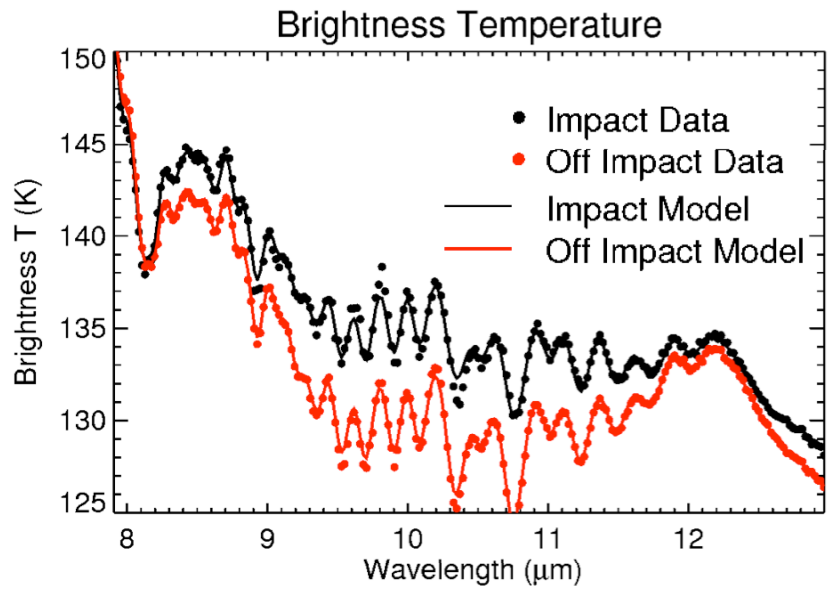

Ratio of impact core to quiescent background



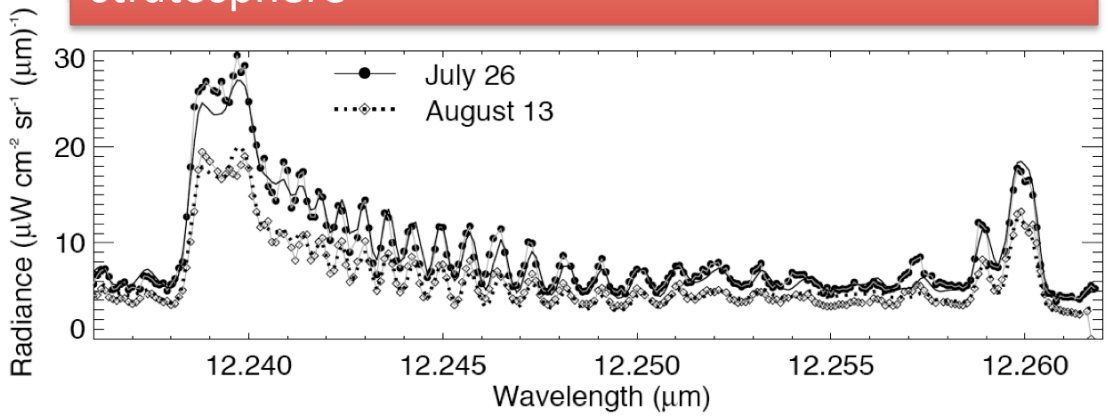
# Atmospheric Response



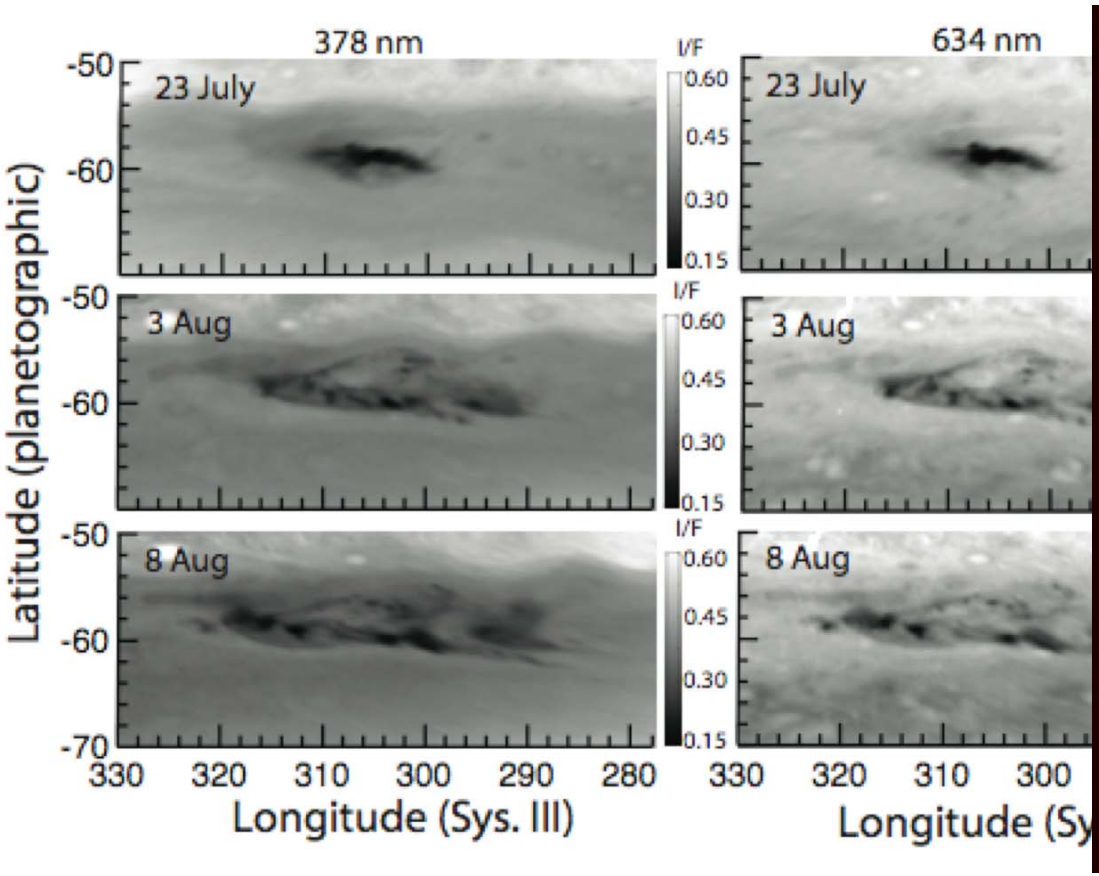



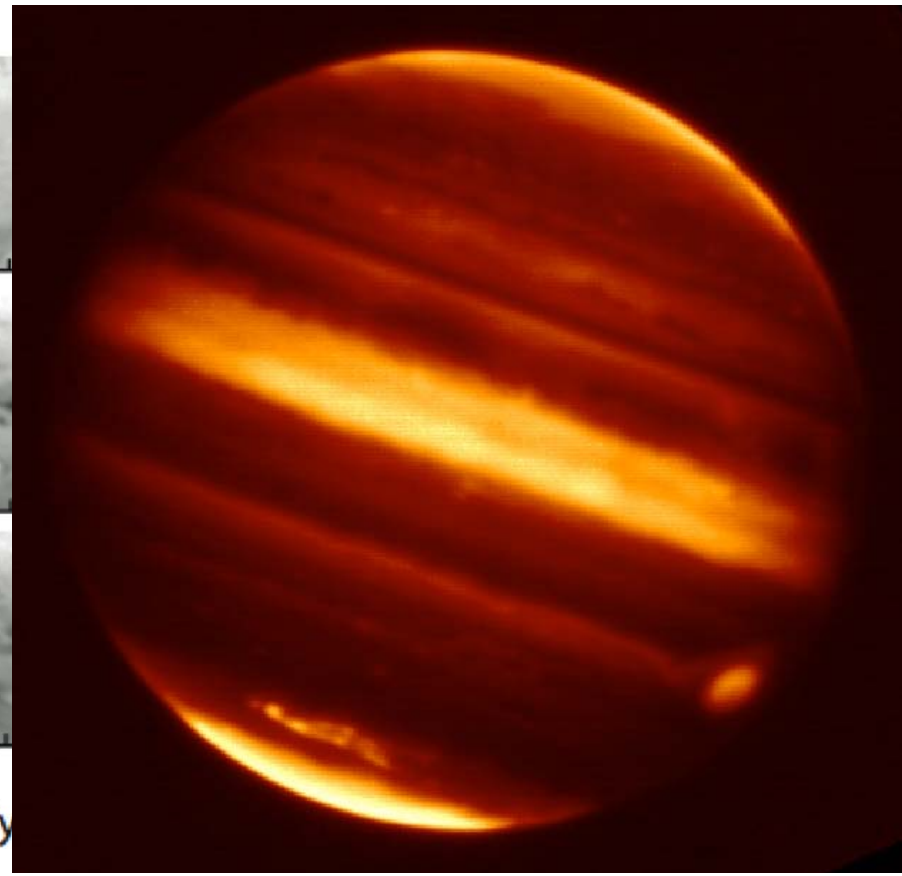




$NH_3$ lofted into stratosphere; high altitude silicate debris; excess hydrocarbons; heating of stratosphere



# Evolution of the Impact Scar

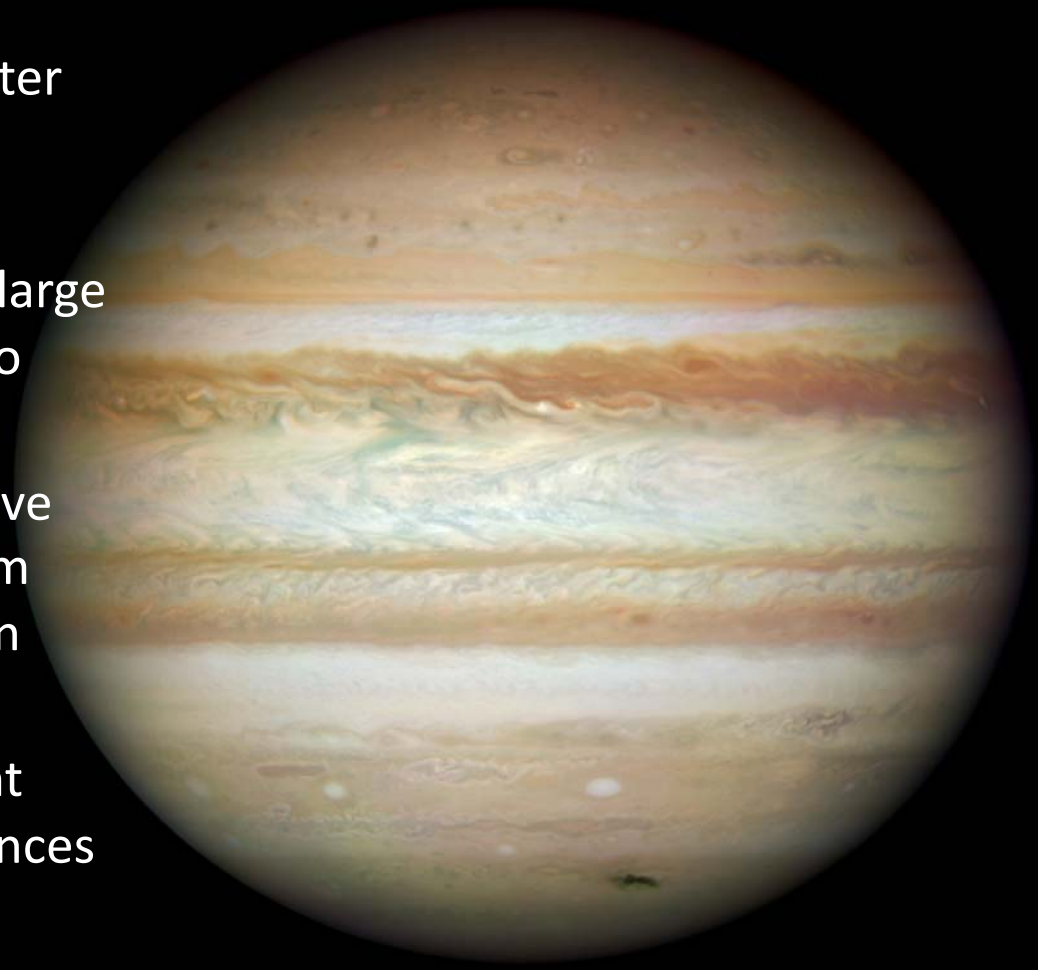


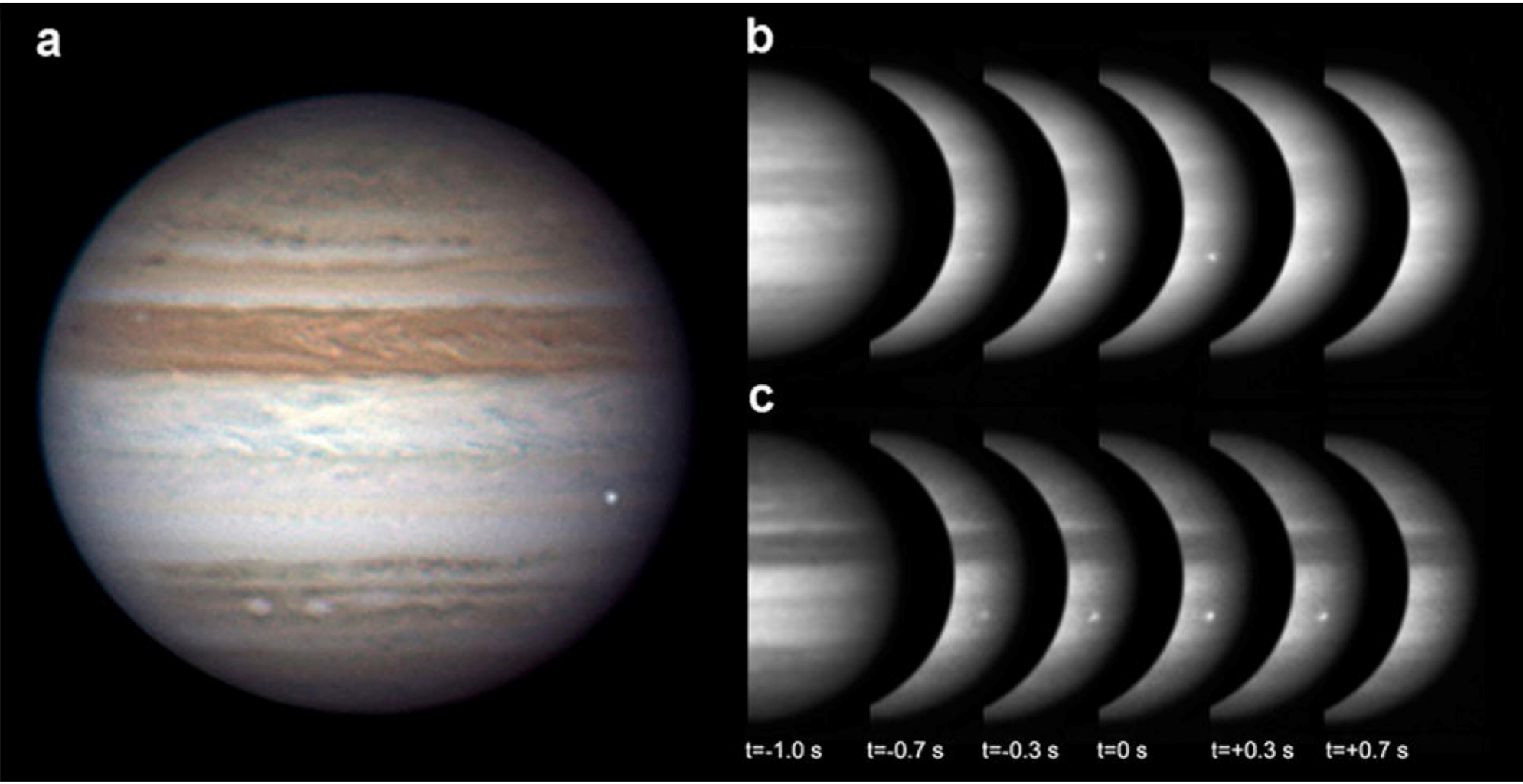
- Aerosols redistributed by zonal winds, some meridional transport.
- Emission from $NH_3$, silicate debris and CxHy decreased as it was mixed/ diluted with unperturbed jovian air.
- Debris still detectable in December 2009, 5 months after impact.

# Rare Glimpse of Planetary Evolution

- Impacts perturb stratospheric composition for years
  - HCN is only observable on Jupiter after SL9 (1994), still present, spreading meridionally.
  - CO production in SL9 supplied large quantities of stable molecule to stratosphere.
- Many stratospheric compounds have exogenic sources (e.g. $H_2O$, CO from interplanetary dust, rings, icy moon interactions).
- Accretion of small objects in distant past raised heavy element abundances in giant planets.
- Thought 1994 and 2009 collisions were 'chance of a lifetime' events, until….

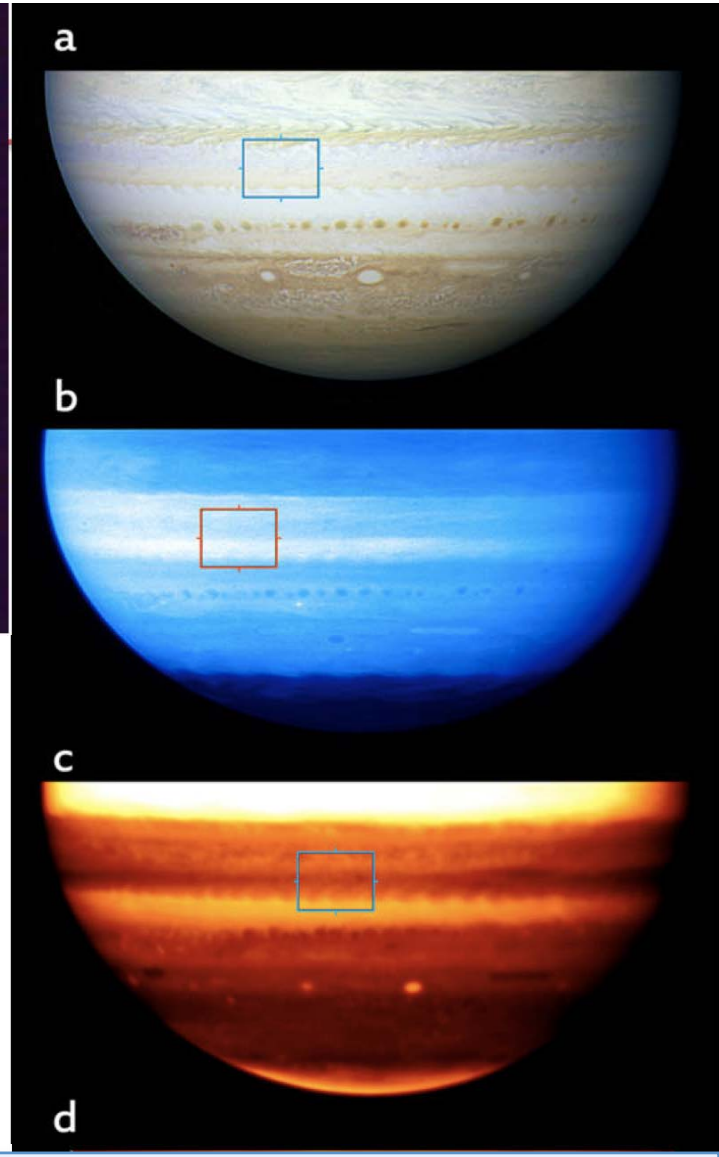


# …Jupiter got hit, again (June 3, 2010)




- A. Wesley and C. Go independently observed optical flash in SEB on video.
- 2-second fireball, Hueso et al. (2010, accepted) suggest 8-13 m object, much smaller than 2009 (250-500 m).
- Described as a 'super-bolide'

# …and again!

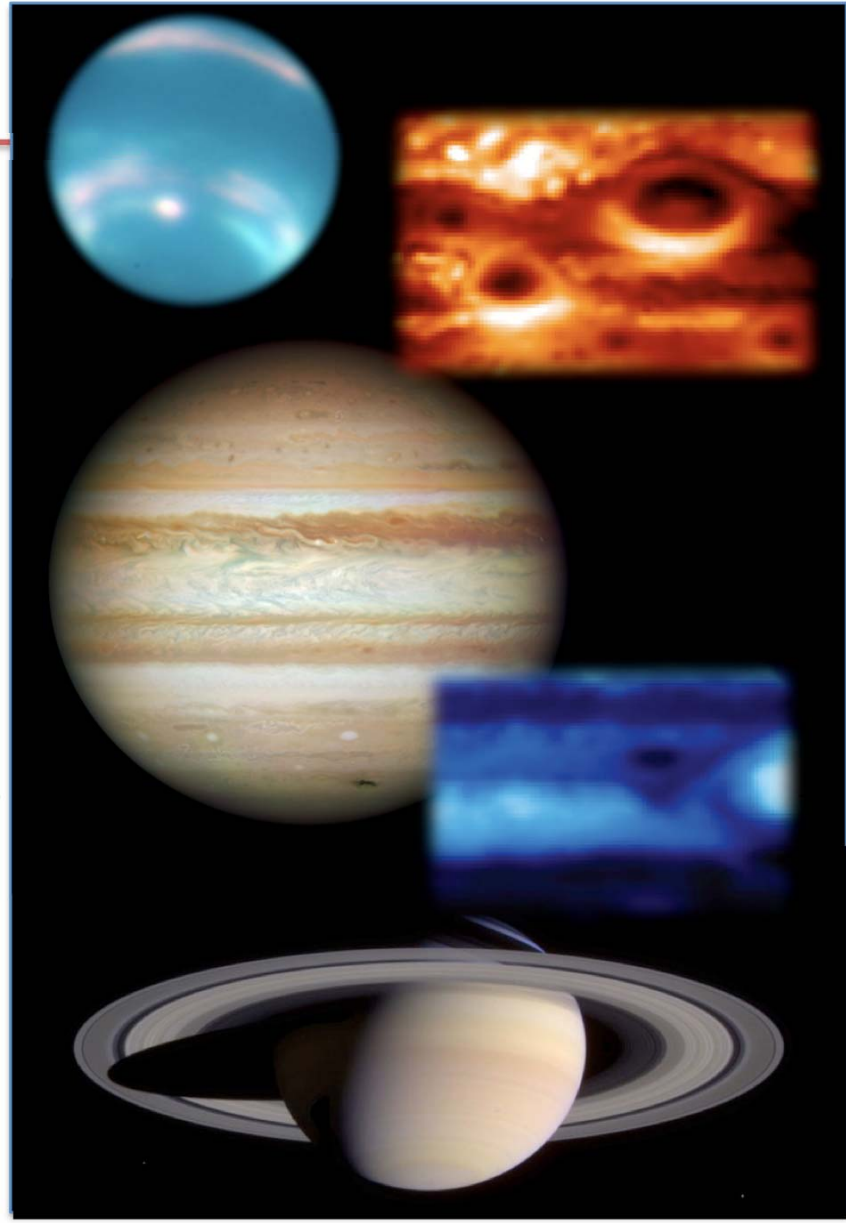



- … on August 20, 2010 in NEB, detected by the amateur Japanese astronomers Masayaki Tachikawa and Aoki Kazuo.
- Flashed for about 1.5 seconds.
- Hubble, Keck, Gemini and VLT searched for any debris from 2010 impacts, but none observed.

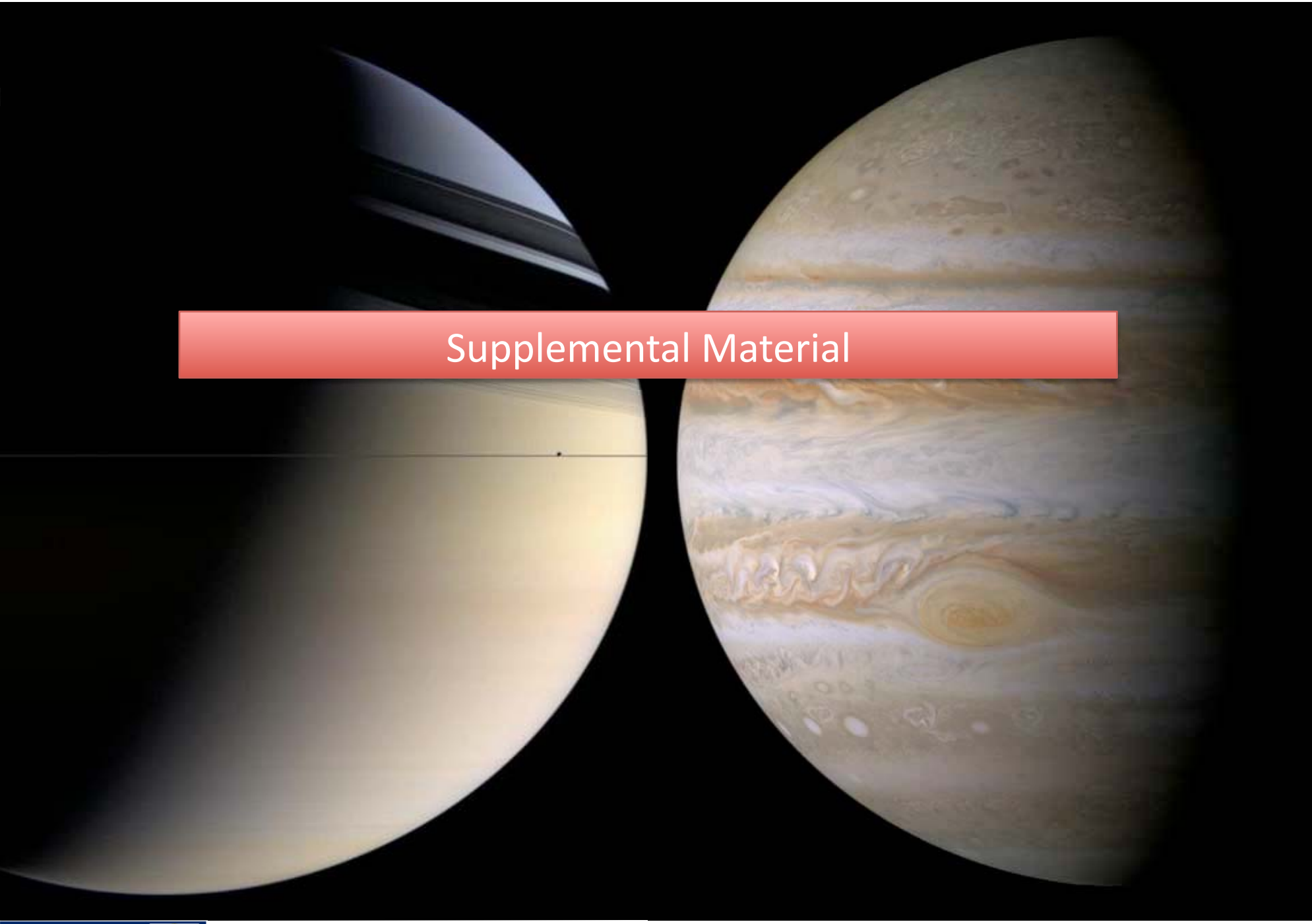
*Impacts and other rapidly-evolving phenomena can briefly dominate planetary radiance, and provide insights into mechanisms supplying heavy elements to upper atmospheres. Dramatic example of complex activity within our solar system!*

# Conclusions

- Remote Sensing in our own solar system has left many open questions
  - Deep structures inferred indirectly; degenerate solutions; evolving atmospheric weather layer.
- Long-term variations occur on giant planets
  - Jupiter's global upheavals and changing belt/ zone structure (e.g. SEB fade); Saturn's seasonal asymmetries.
- Discrete features can dominate planetary brightness and bias results.
  - Anticyclonic vortices, polar circulations, plumes, instabilities, convective clouds, impacts.
- Impacts provide a glimpse of planetary accretion in action
  - Substantial perturbation to atmospheric structure & chemistry;
  - Briefly outshines the rest of the planetary disc.



*Above all, the planetary atmospheres of our Solar System are complex and continually evolving, and we should expect nothing less as we explore exoplanetary systems!*


Supplemental Material