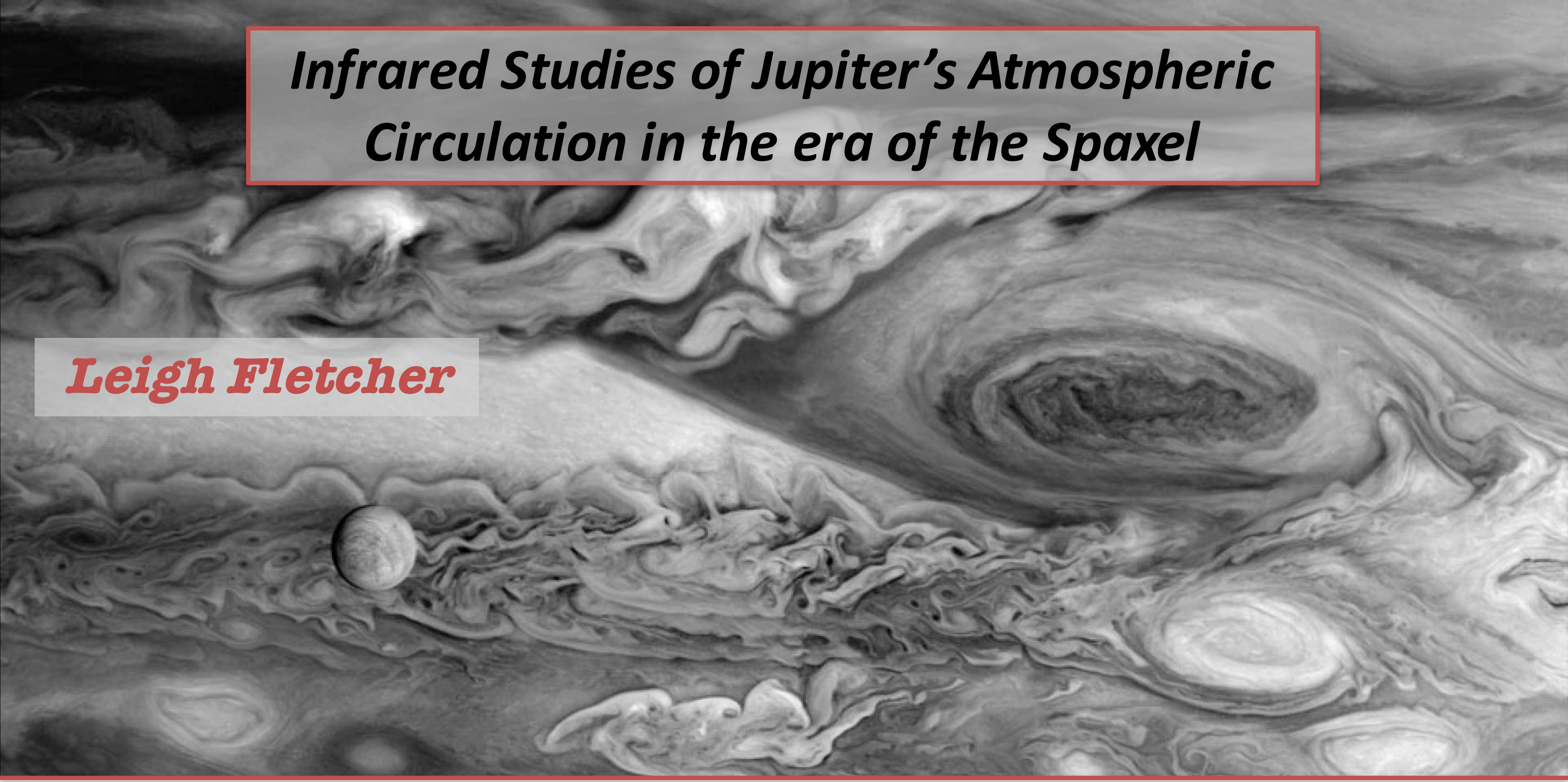
Infrared Studies of Jupiter's Atmospheric Circulation in the era of the Spaxel

Leigh Fletcher



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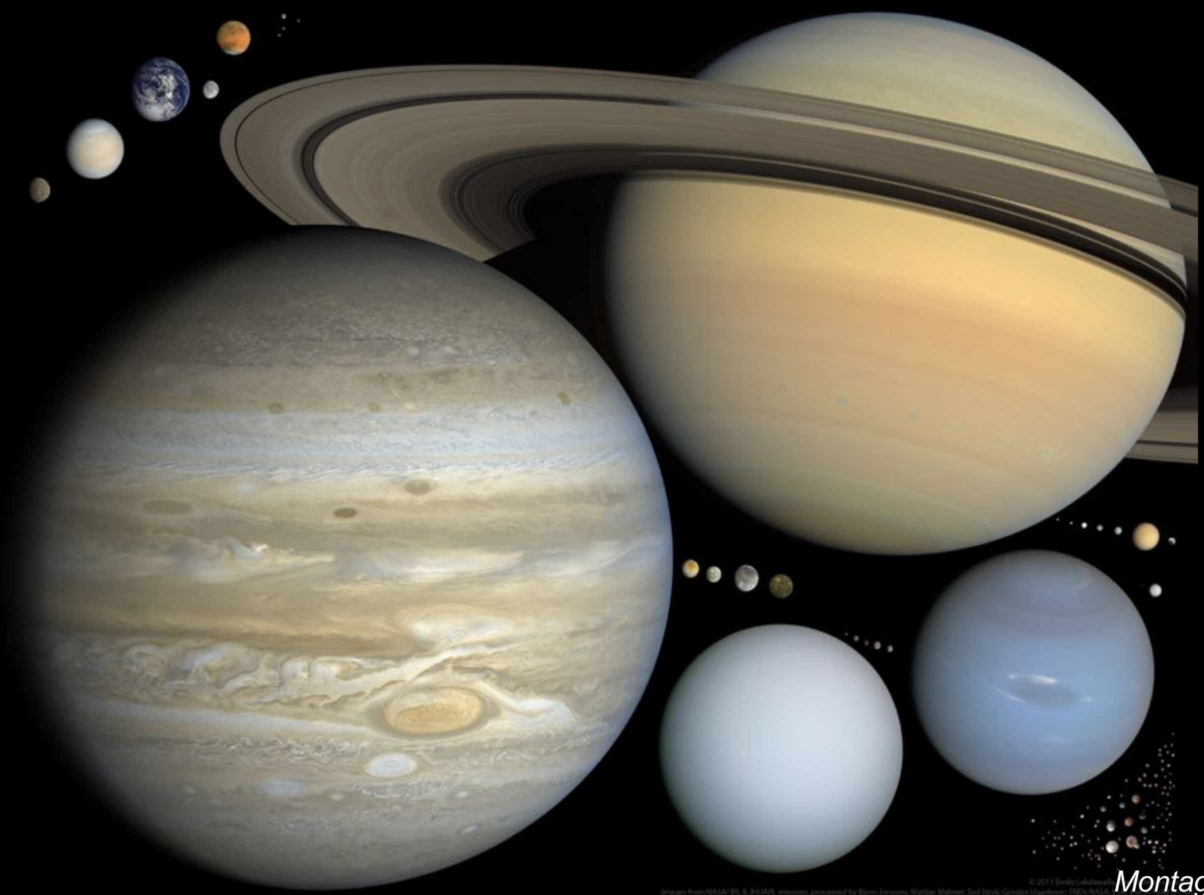
Beyond the Clouds…



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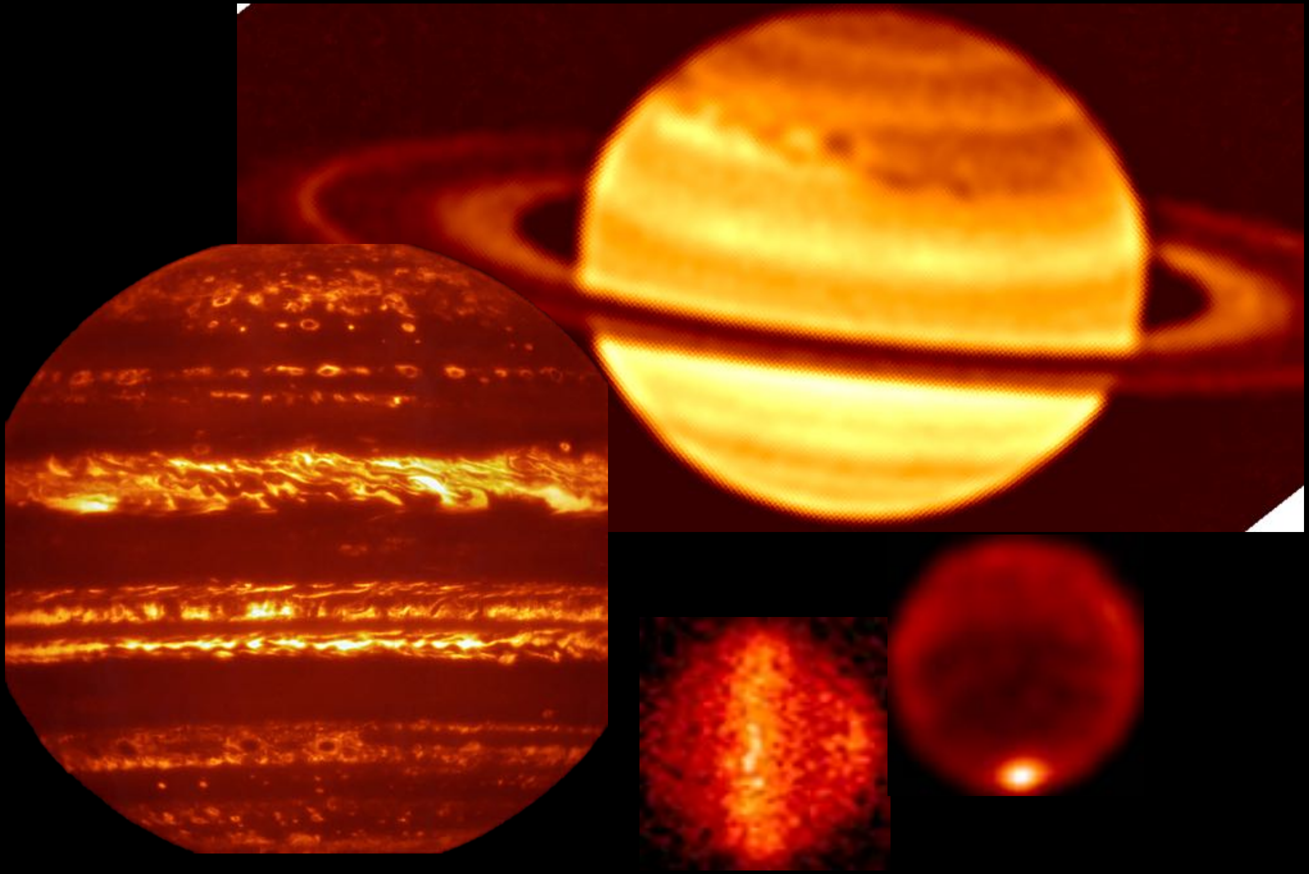
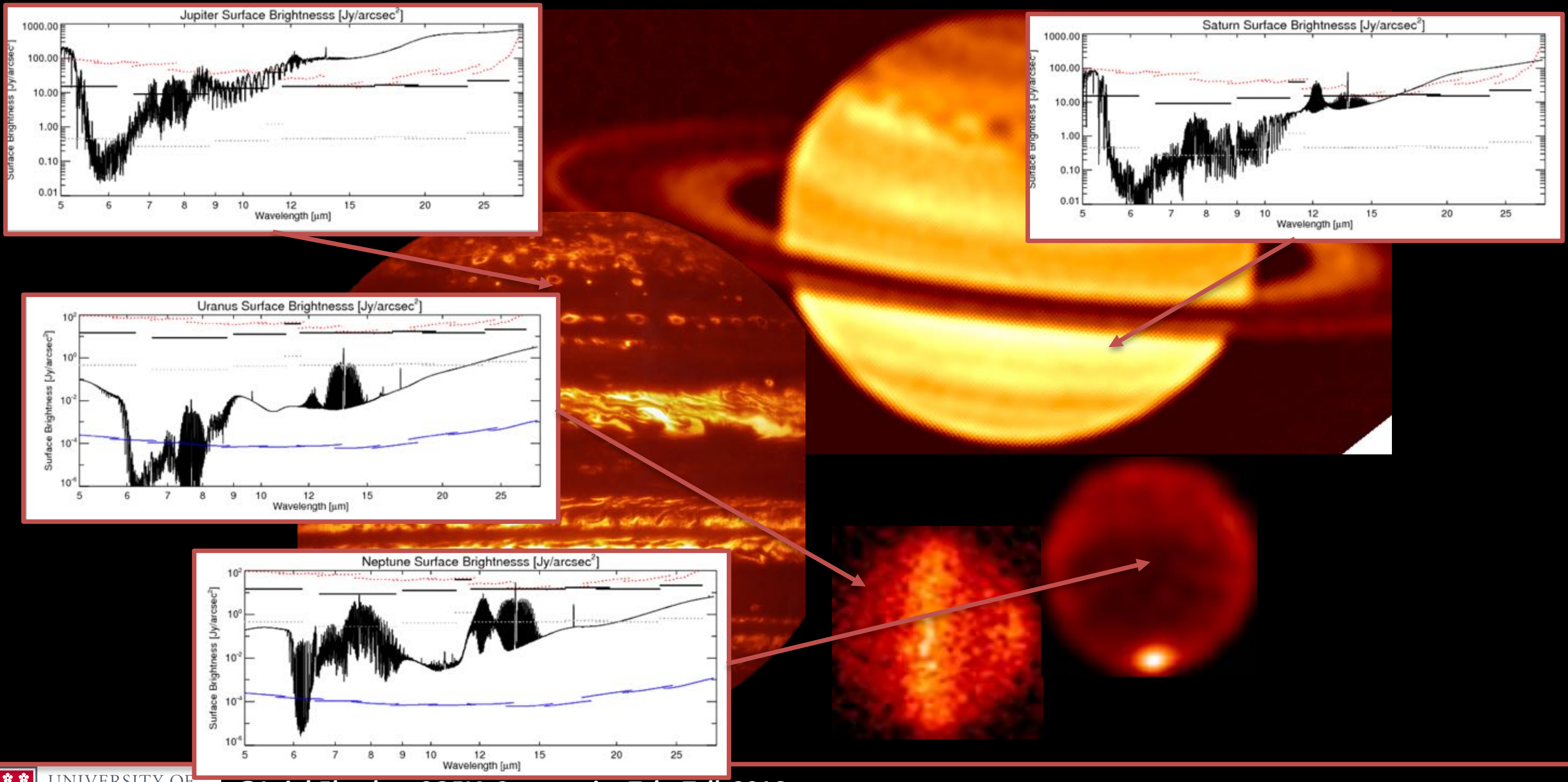
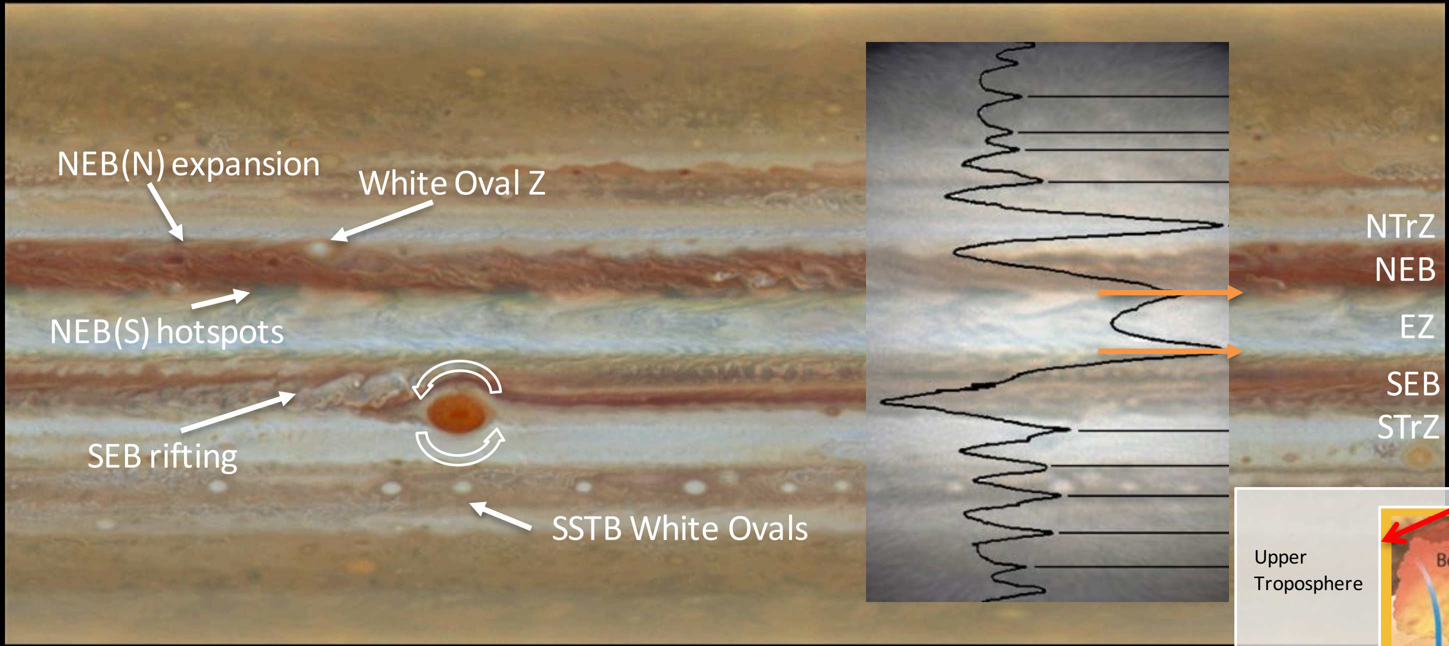
…to 3D atmospheric sounding



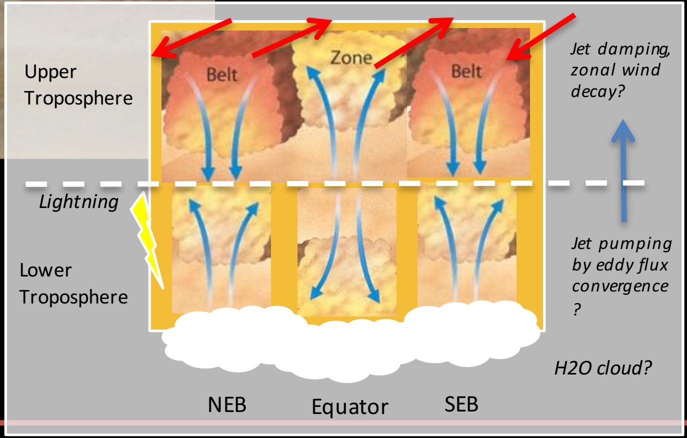
...to 3D atmospheric sounding



The Anatomy of a Giant



Jupiter in 2016 from Hubble/OPAL project



- Visible-light maps are a 2D representation of 3D circulation.
  - Top-most cloud decks; radiative-convective boundaries.
- All giants exhibit banding, of various widths depending on rotation.
- Storms, vortices, waves drive ever-shifting patterns.

Planetary Skydiving

UV-IR spectroscopy required to understand the vertical.

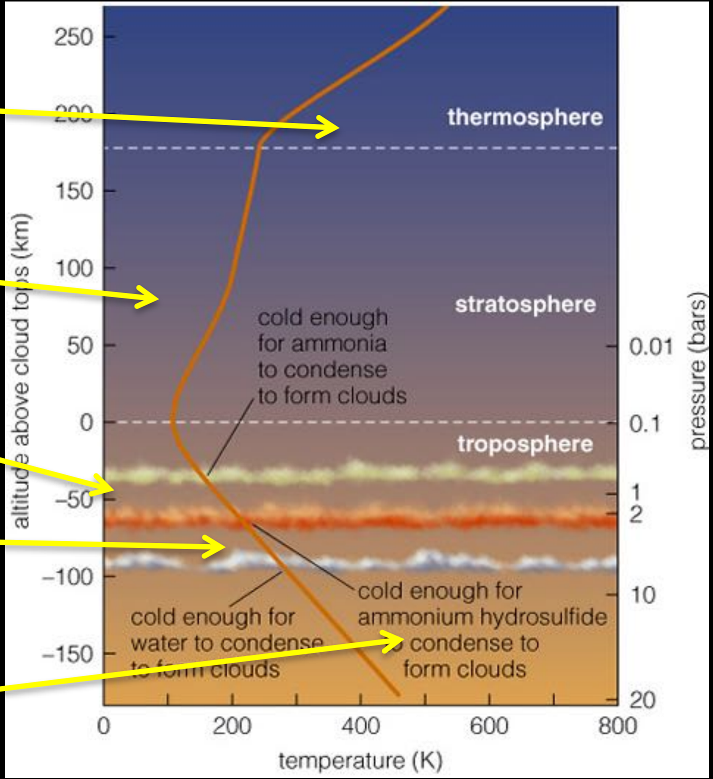
Upper Atmosphere:
Auroral energy deposition, ionosphere, exogenic sources…

Stratosphere:
Photochemical soup; hydrocarbon hazes; radiative control & waves.

Upper Troposphere:
NH3/PH3 photolysis & hazes; zonal winds; belt/zone structure.

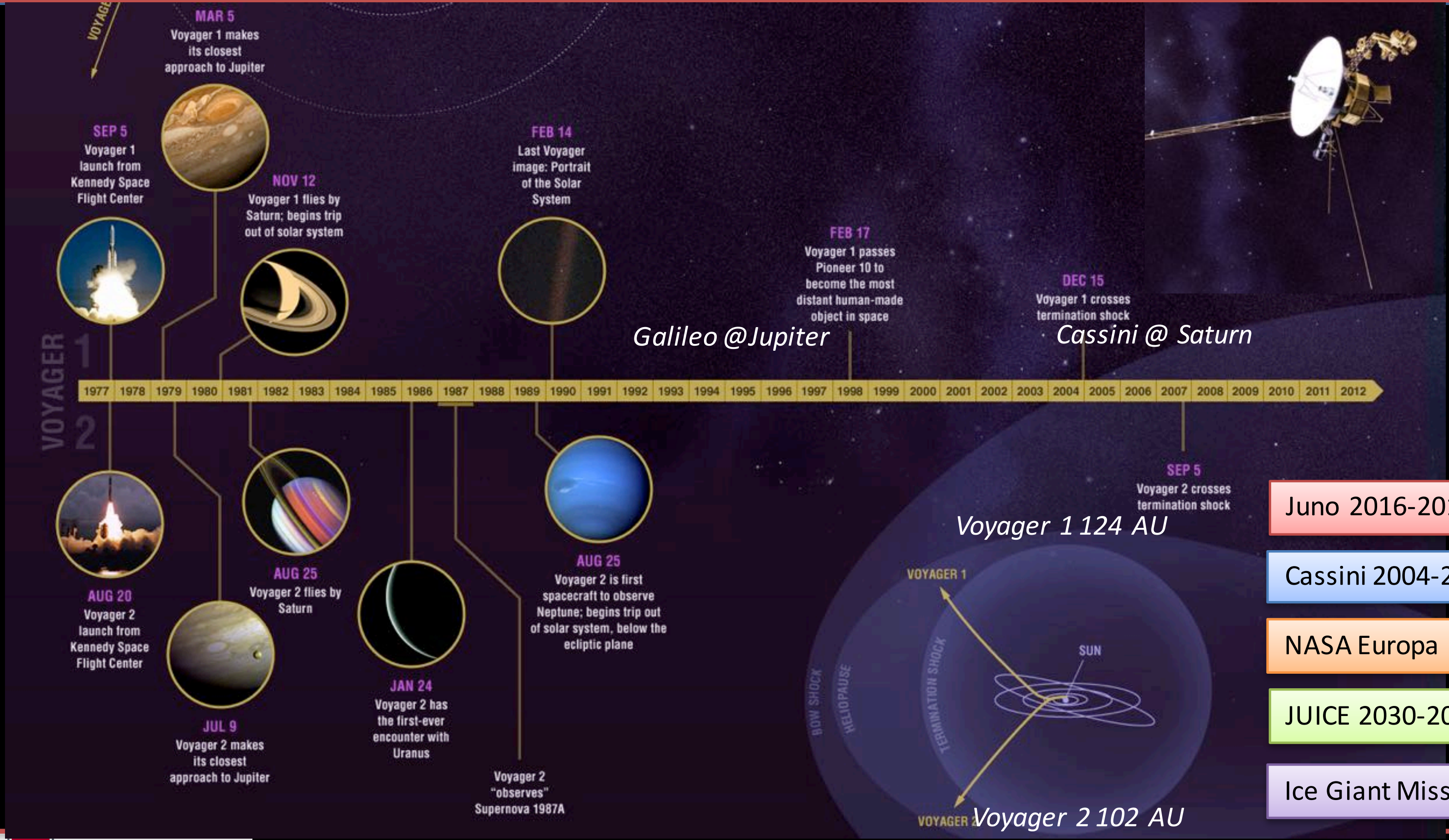
Cloud-Layer:
Condensable species; rising plumes; vortices; moist convection?

Sub-Cloud Troposphere:
Dry convection? Taylor Proudman columns? MHD drag & metallic H2? Smooth transition or discrete core?



Energy, momentum, material exchange

Challenge of Outer Solar System Exploration



- Extreme challenge of outer solar system exploration = opportunity for Earth-based observers!

Juno 2016-2019

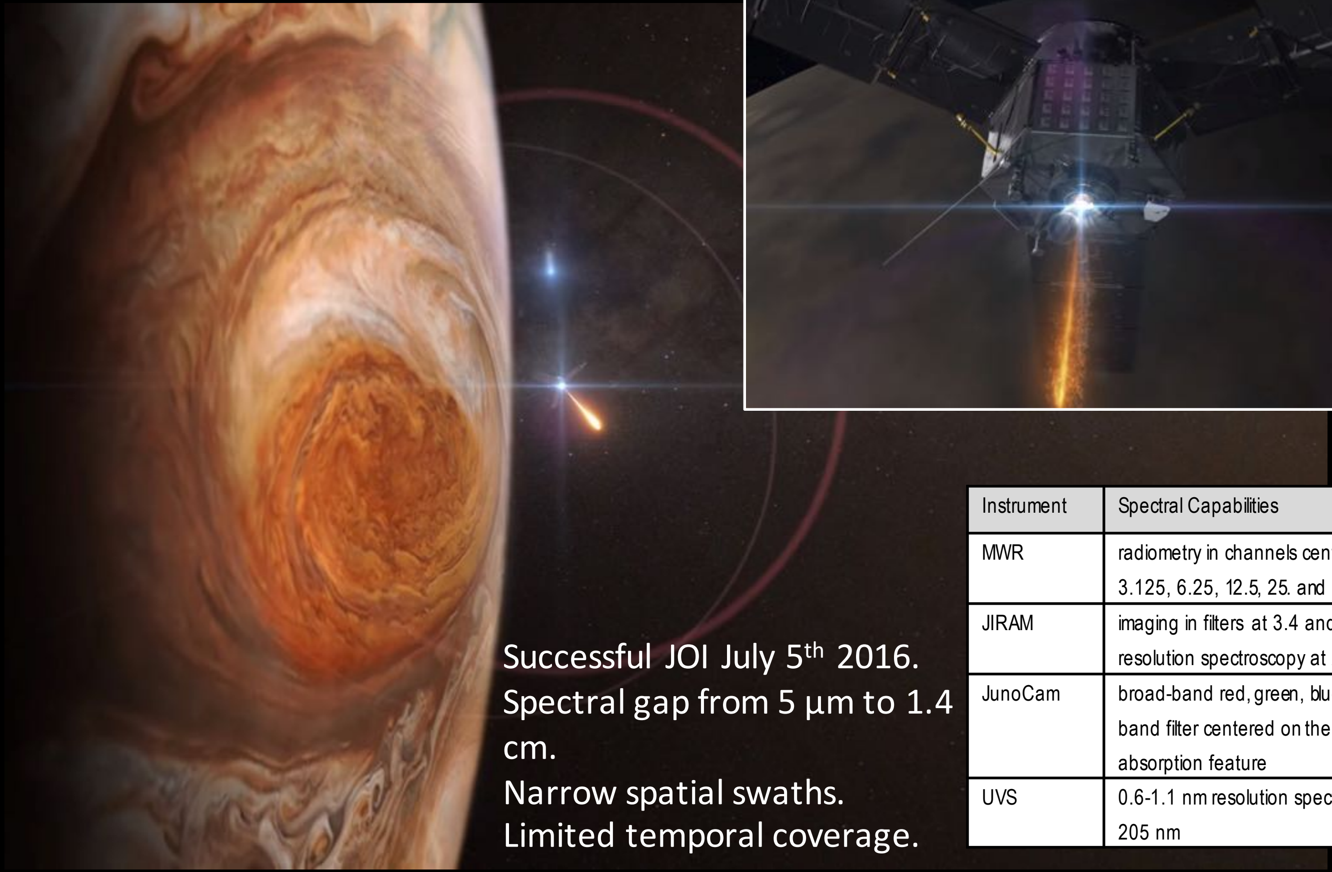
Cassini 2004-2017

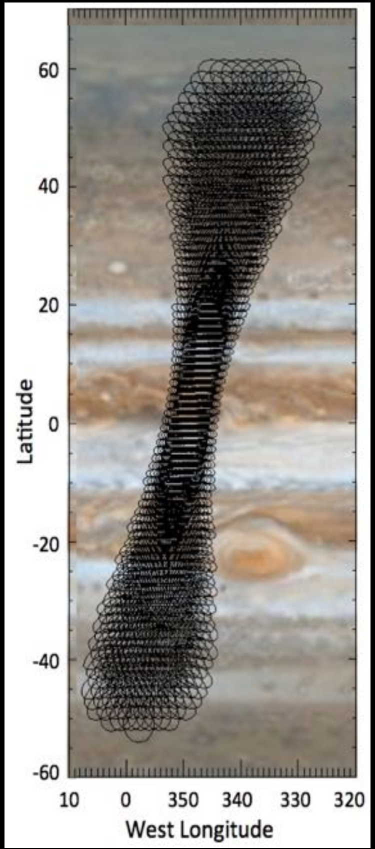
NASA Europa Mission 2025+?

JUICE 2030-2033

Ice Giant Mission 2040+?

Rationale: The Juno Mission

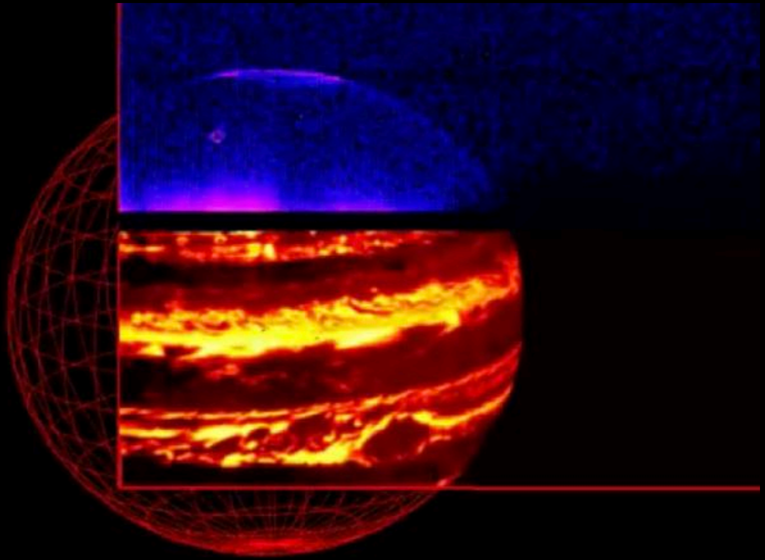




Successful JOI July 5th 2016.
Spectral gap from 5 μm to 1.4 cm.
Narrow spatial swaths.
Limited temporal coverage.

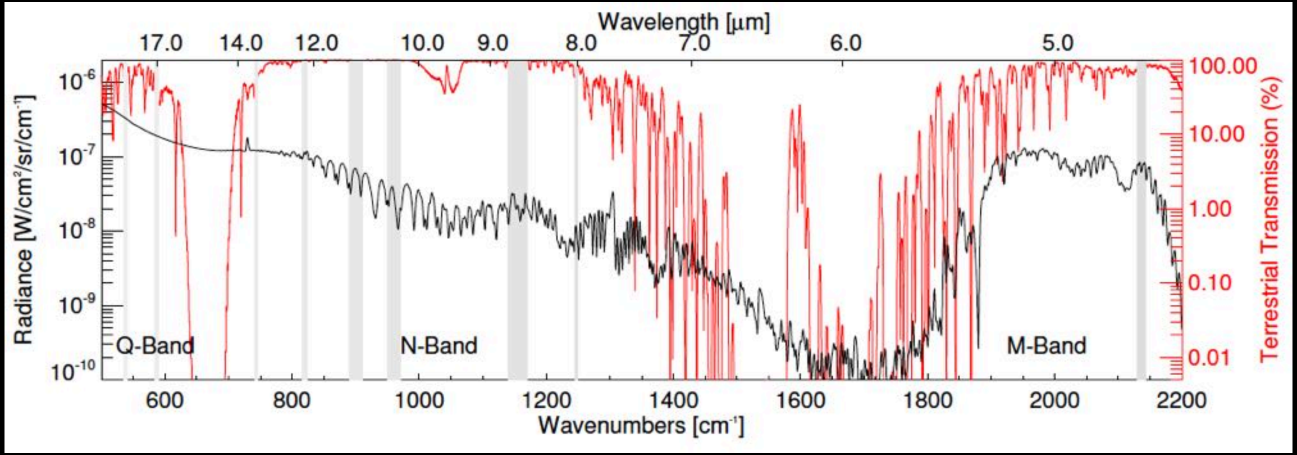
Instrument	Spectral Capabilities
MWR	radiometry in channels centered at 1.3, 3.125, 6.25, 12.5, 25. and 50 cm wavelength
JIRAM	imaging in filters at 3.4 and 5.0 μm; 9-nm resolution spectroscopy at 2.0-5.0 μm
JunoCam	broad-band red, green, blue filters; medium-band filter centered on the 890-nm CH_4 absorption feature
UVS	0.6-1.1 nm resolution spectroscopy at 70-205 nm

First Results from Juno – August 2016

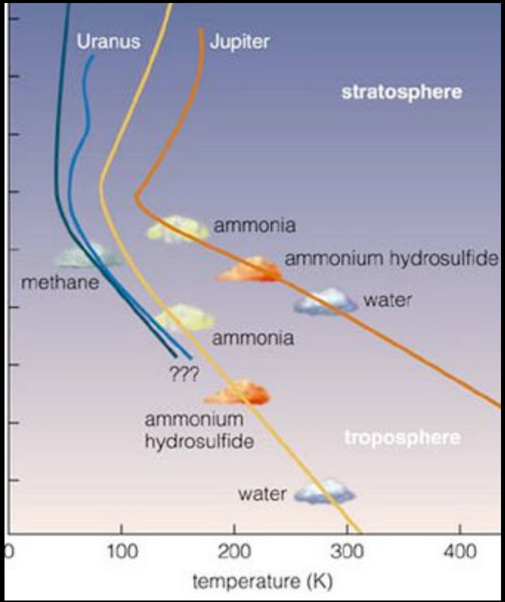


- First close-up views of poles.
- Mapping of aurora and deep internal emission.
- Microwave mapping of sub-cloud layers.
- Gravity mapping of internal structure.
- Plasma and radio waves in magnetosphere.

Why the Thermal-IR?

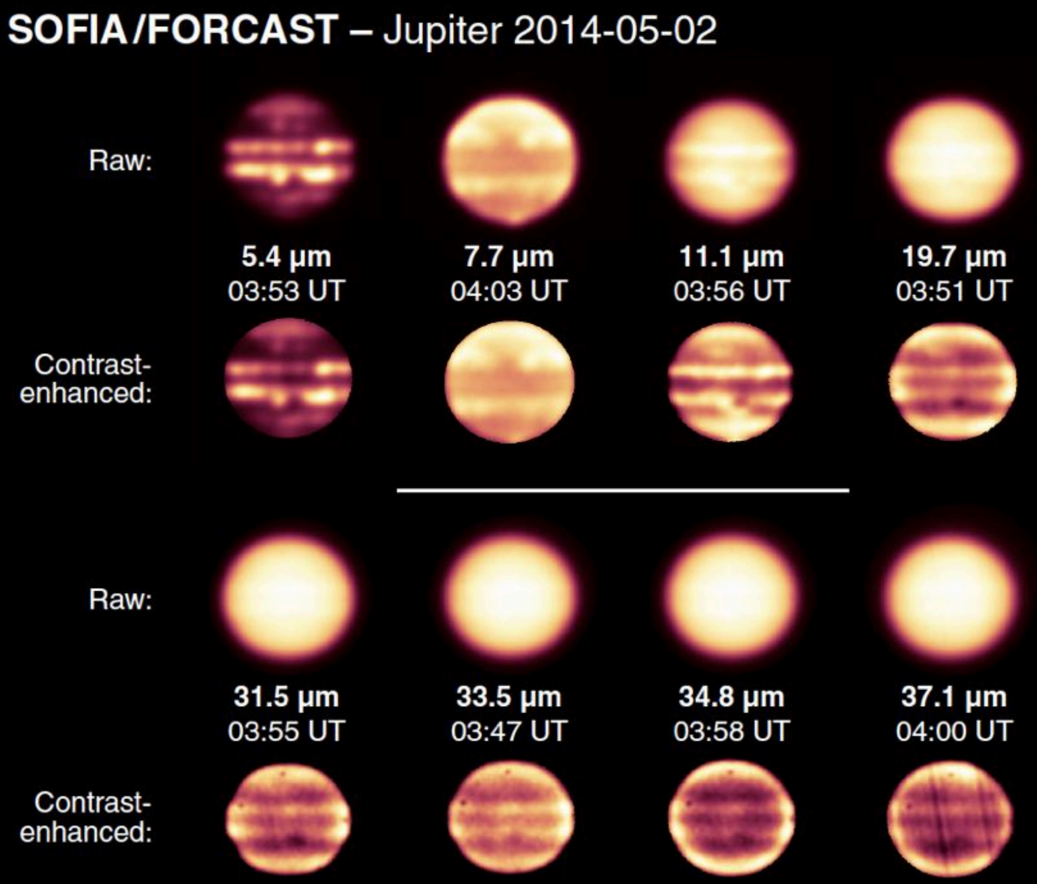


1. **Spatial context for close-in perijoves.**
   - Exploit simultaneity with amateurs & other facilities
2. **Long-term temporal context for Juno science.**
   - IRTF Spectroscopic mapping since 2012.
   - Photometric imaging from 8-m observatories since 2006.
3. **Plug IR Gap in Juno remote sensing**
   - Only method of determining environmental conditions associated with dynamic phenomena from the cloud-forming region into the middle-atmosphere.

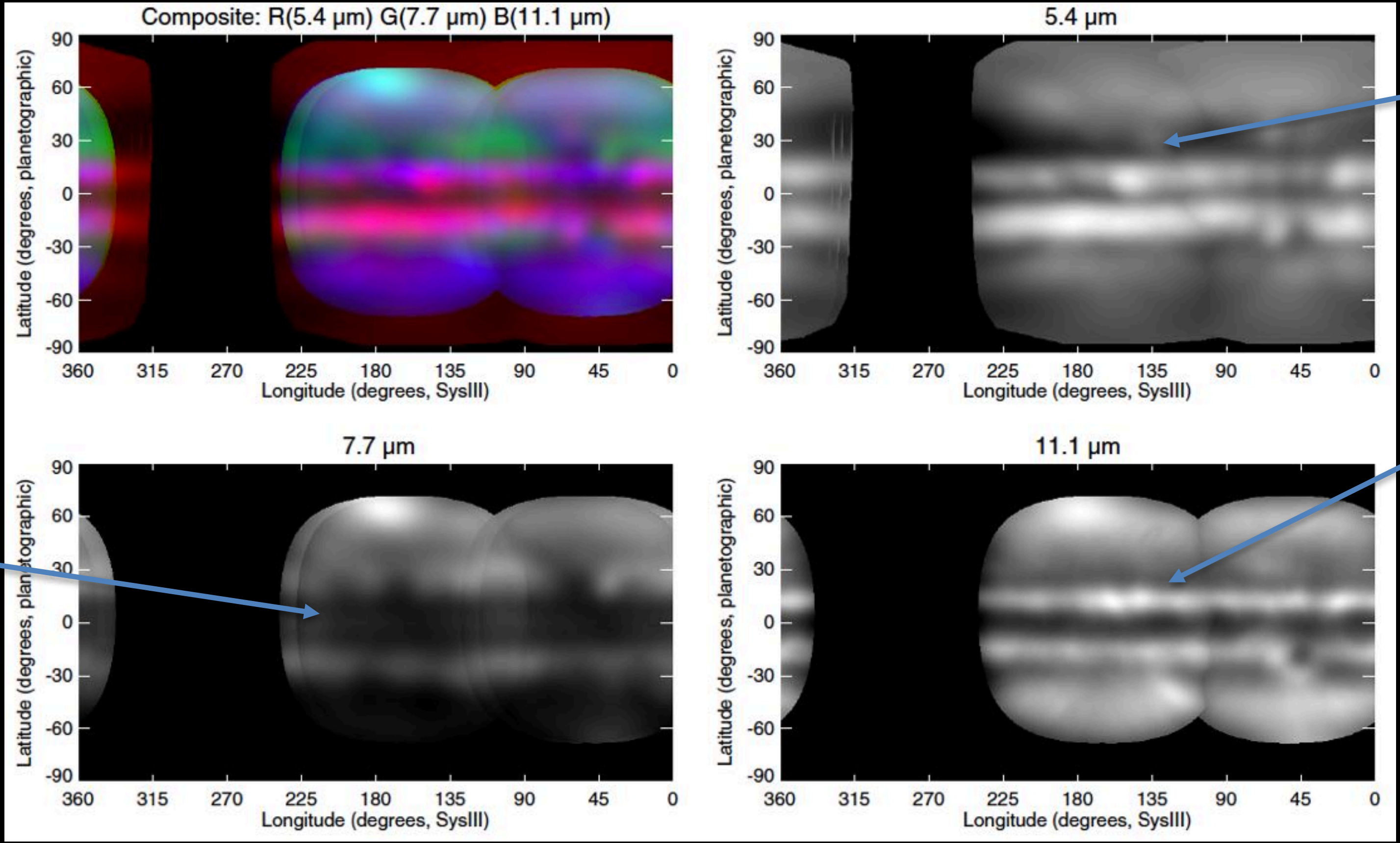


SOFIA Observations of Jupiter

- Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST)
- 256x256 array translates to a wide 191” field of view
  - More than sufficient to capture Jupiter’s 40” disc.
  - Angular resolution ranges from 2-4”, depending on wavelength
- Eight Filters, plus G227 (17.5-27.3 μm) and G329 (28.7-36.7 μm) grisms.



Mapping FORCAST Data

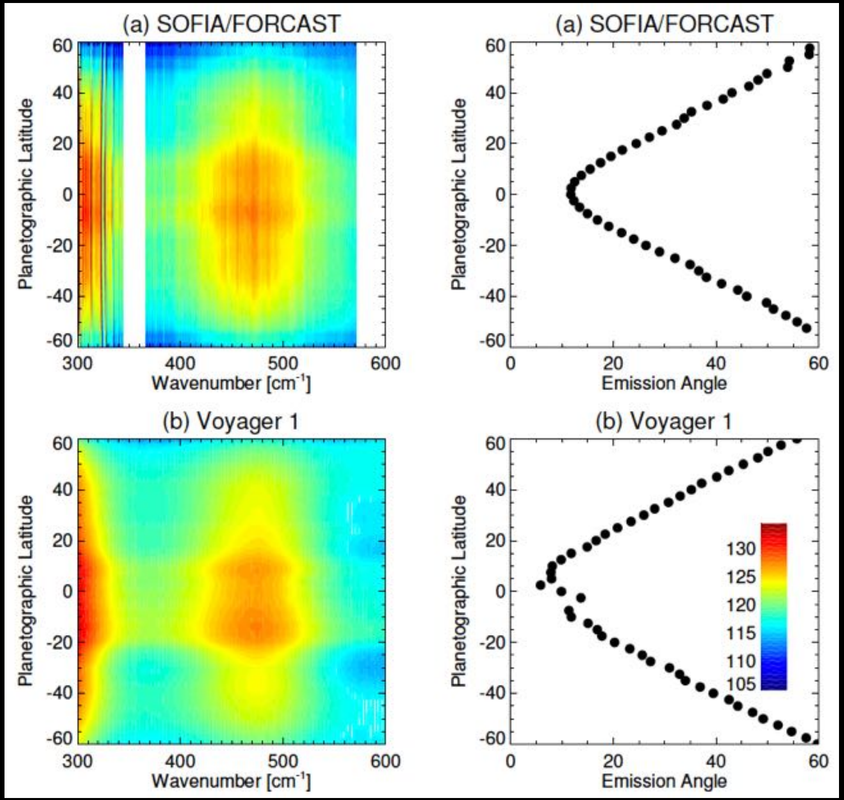


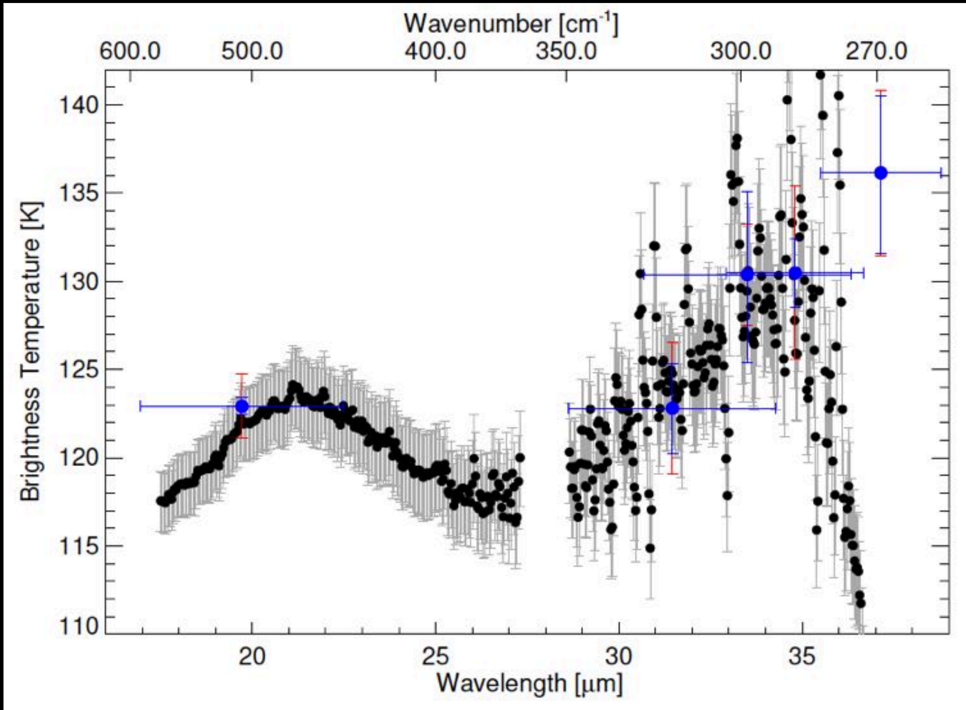
Thermal radiance from gaps in deep clouds.

Stratospheric temperatures, including auroral heating

Tropospheric temperatures and NH3 above clouds.

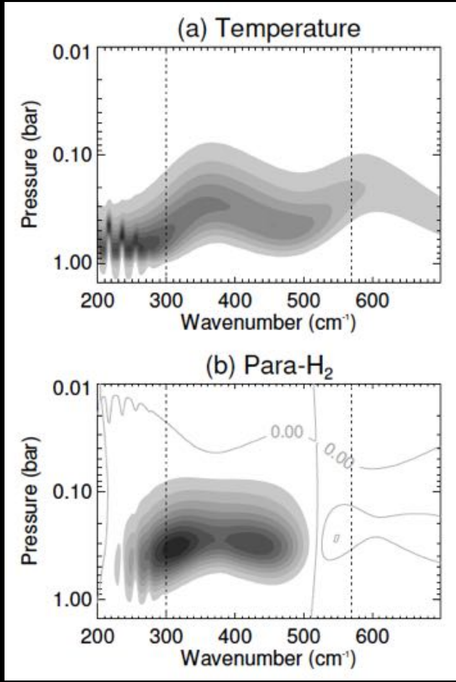
Grism Spectroscopy

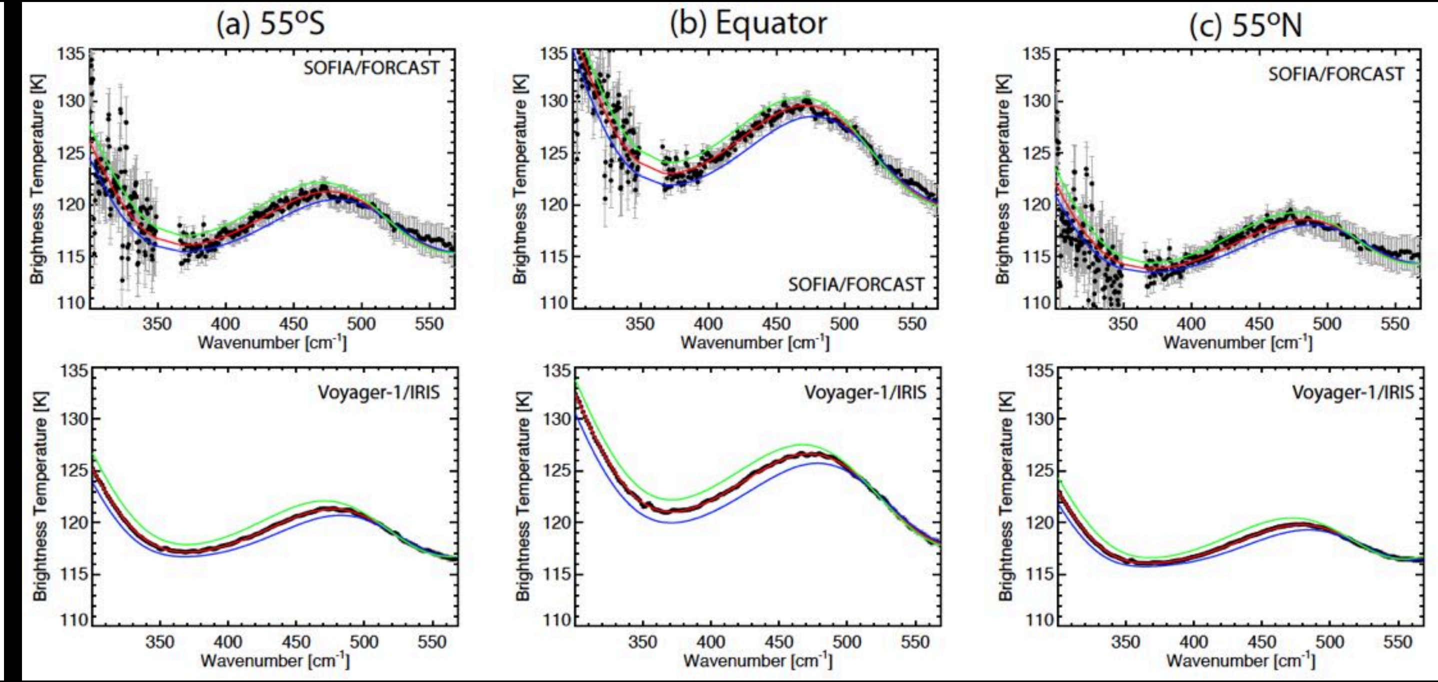




Grism	wavelength range	$R = \lambda/(\Delta\lambda)$	UT time range	Longitude range	Latitude	Integration time	Chop freq.
G227	17.50-27.30 μm	140	05:36-05:45	265-270°	1.67°	5.66 s/scan	3.97 Hz
G329	28.65-36.66 μm	220	05:26-05:35	259-264°	1.67°	6.19 s/scan	2.49 Hz

Jovian Para-Hydrogen

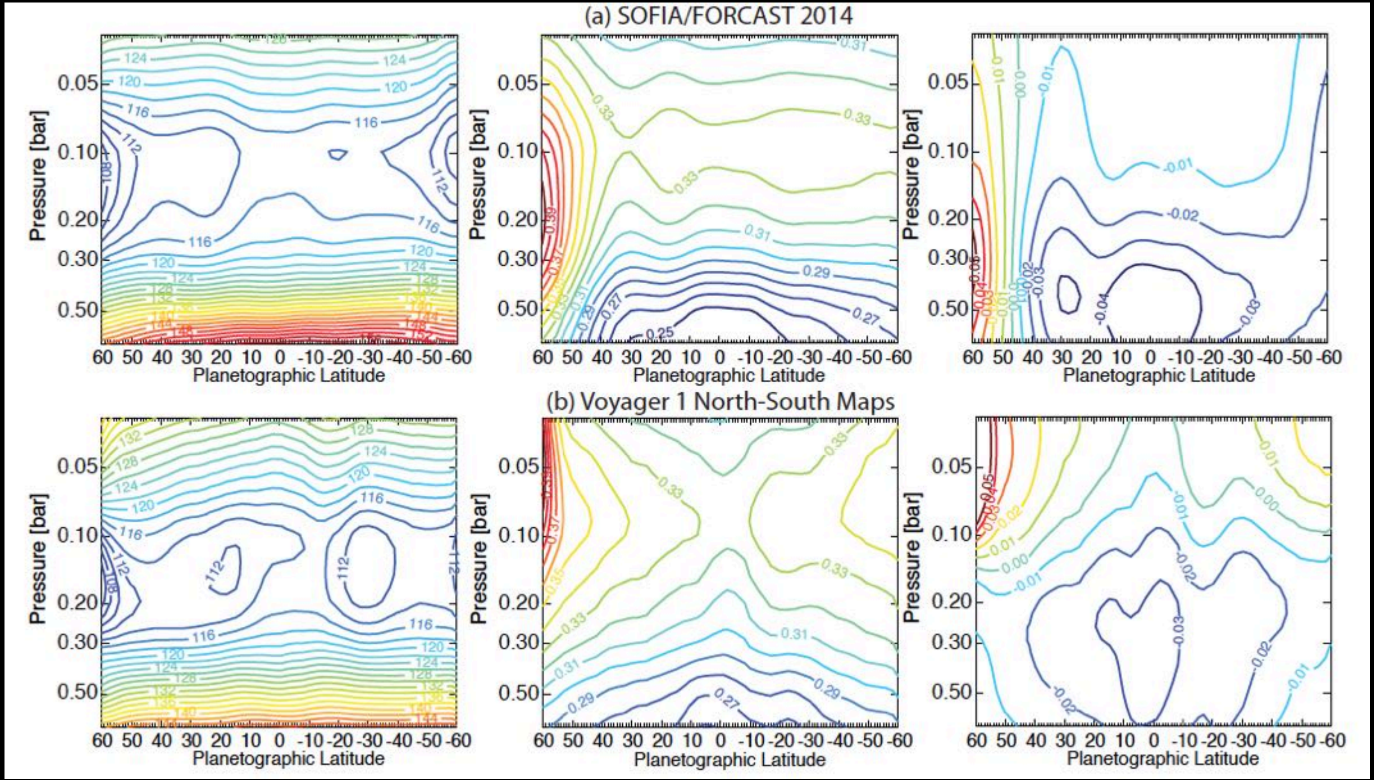




- Comparing FORCAST and Voyager/IRIS spectra – similar spatial resolution, different noise quality, but both constrain temperature and para-H2 fraction.
- Only previous measurements of Jupiter's para-H2 fraction from Voyager (1979).

Tracing Atmospheric Motion & Chemistry

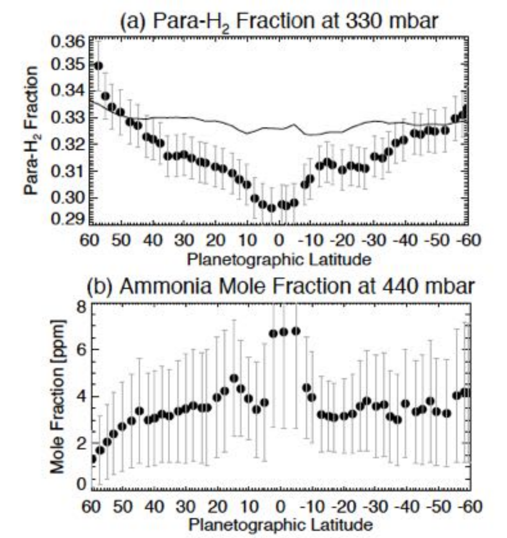
- **Temperature:**
  - Low T = rising, adiabatic expansion, cooling.
  - High T = falling, adiabatic compression, heating.
- **Para-H2:**
  - Low fp (sub-equilibrium) = rising.
  - High fp (super-equilibrium) = sinking
- **Complication**:
  - Radiative heating/cooling
  - Aerosol catalysis of para-ortho conversion.

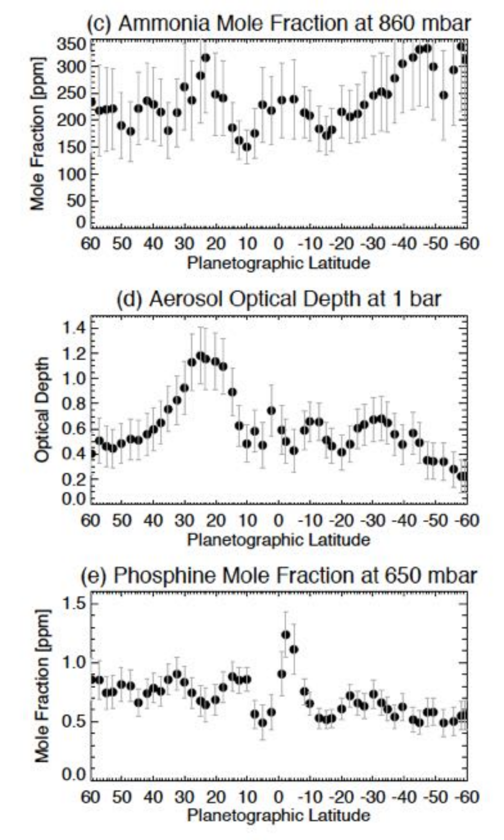


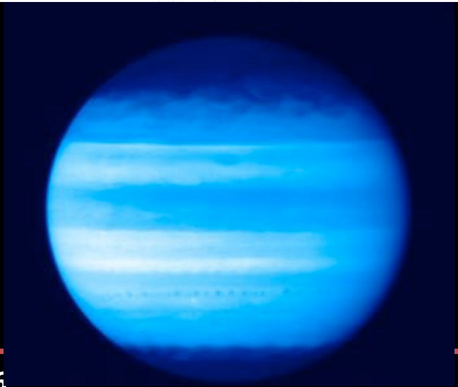
Conclusions from SOFIA

- **Further comparison of SOFIA to Voyager:**
  - Para-H2 is unlike PH3, NH3, or tropospheric clouds.
  - Looks most like upper tropospheric haze measurements.
- **Conclusions from SOFIA:**
  - Poles close to equilibrium due to efficient aerosol catalysis.,
  - Tropics sub-equilibrium due to upwelling.
  - Possible polar enhancement due to sinking & seasonal asymmetry?
- Take home:
  - ***We can now do from SOFIA what was only previously possible from Voyager!***

L.N. Fletcher, I. de Pater, W.T. Reach, M. Wong, G.S. Orton, P.G.J. Irwin, R.D. Gehrz (2016), Jupiter's Para-H2 Distribution from SOFIA/FORCAST and Voyager/IRIS 17-37 μm Spectroscopy, Icarus, in press (http://dx.doi.org/10.1016/j.icarus.2016.10.002) (http://arxiv.org/abs/1610.01304)

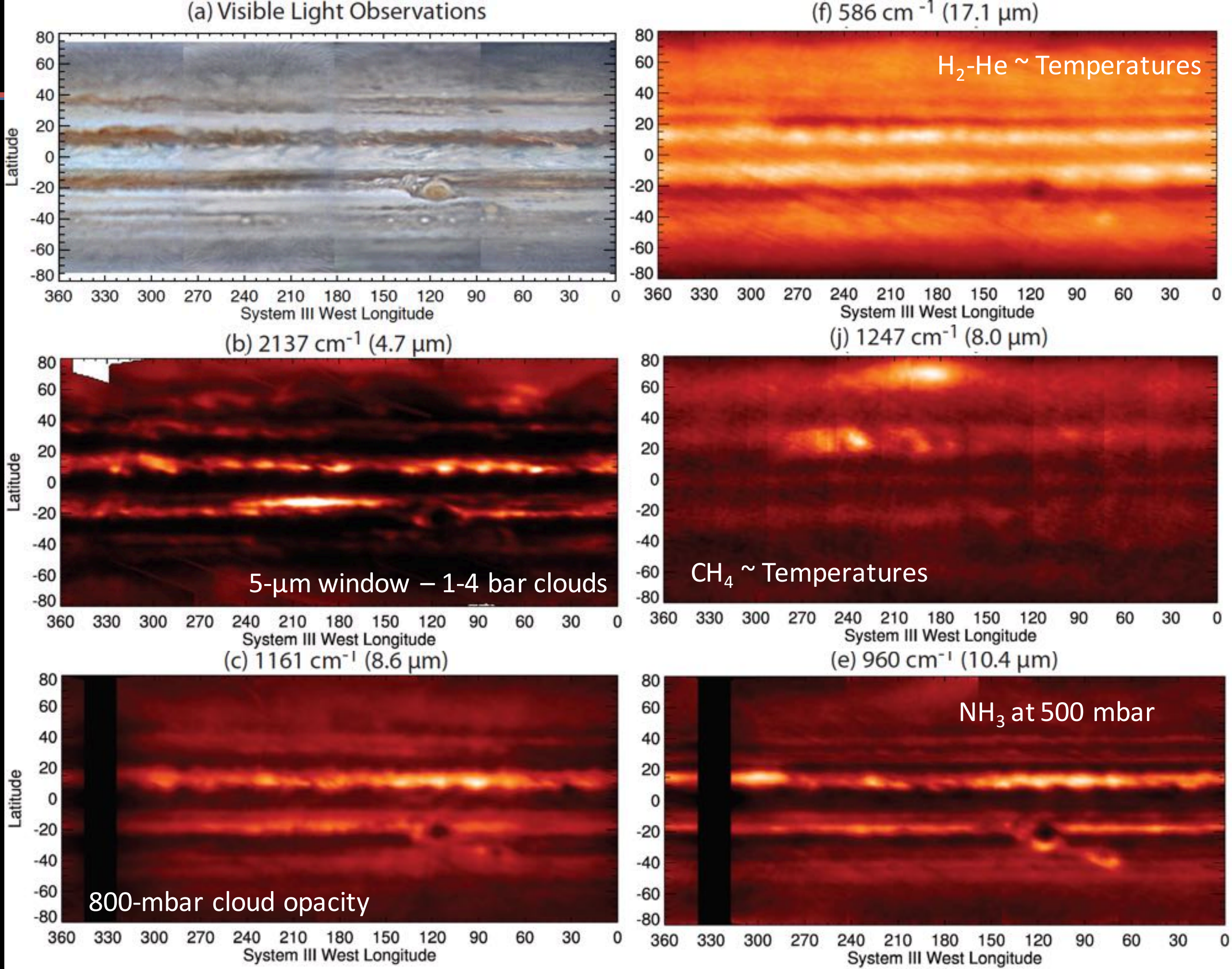






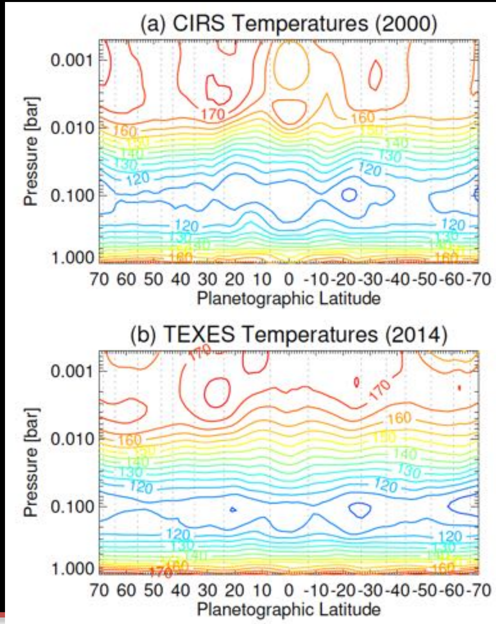
IRTF Mapping

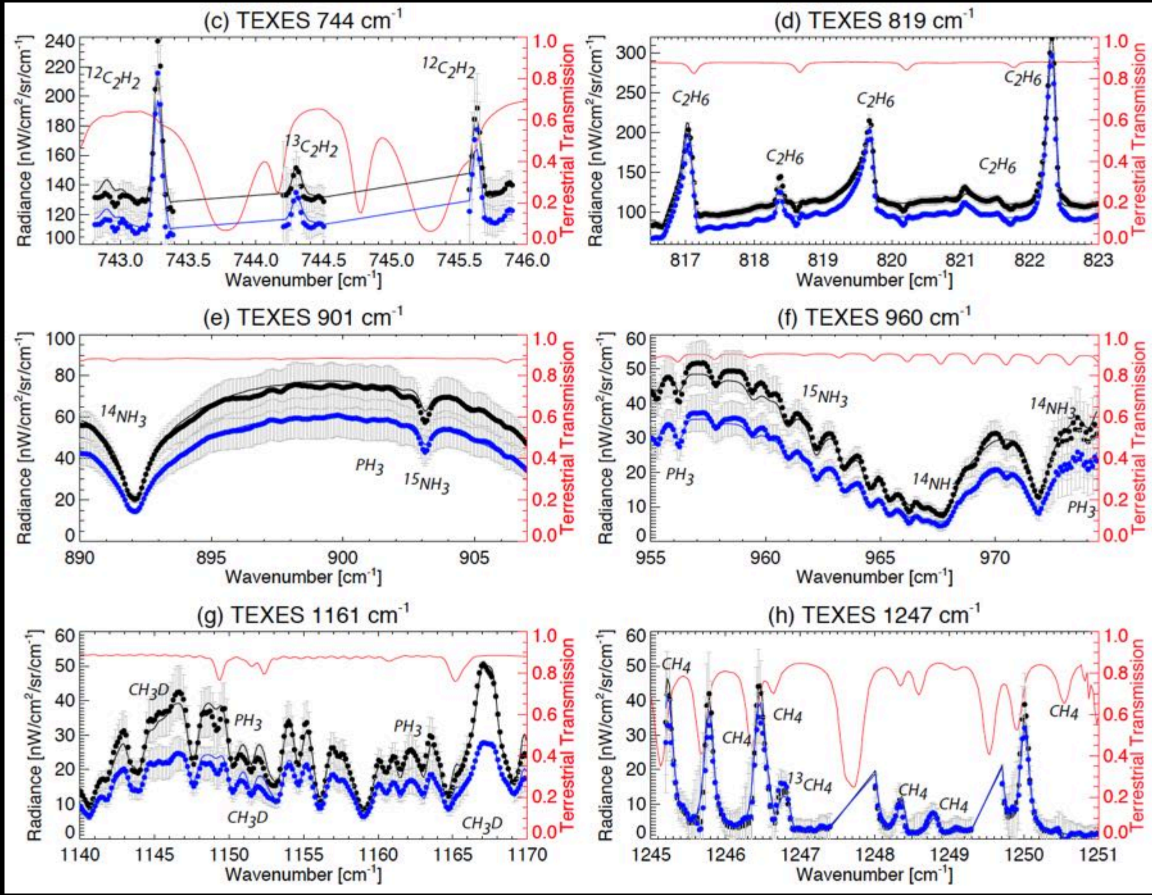
- Shorter wavelengths than FORCAST 5-20 μm.
- Programme to track jovian climate over full year.
- Global spectroscopic mapping for 1st time with TEXES.
- Only possible with ~10 hours of good conditions, challenge for EXES.



TEXES Spectroscopy

- Spectra in multiple channels inverted simultaneously.
- NEMESIS optimal estimation retrieval code (Irwin et al., 2008).
- Map 3D temperature structure and windshears, NH3, PH3, aerosol opacity, stratospheric hydrocarbons.

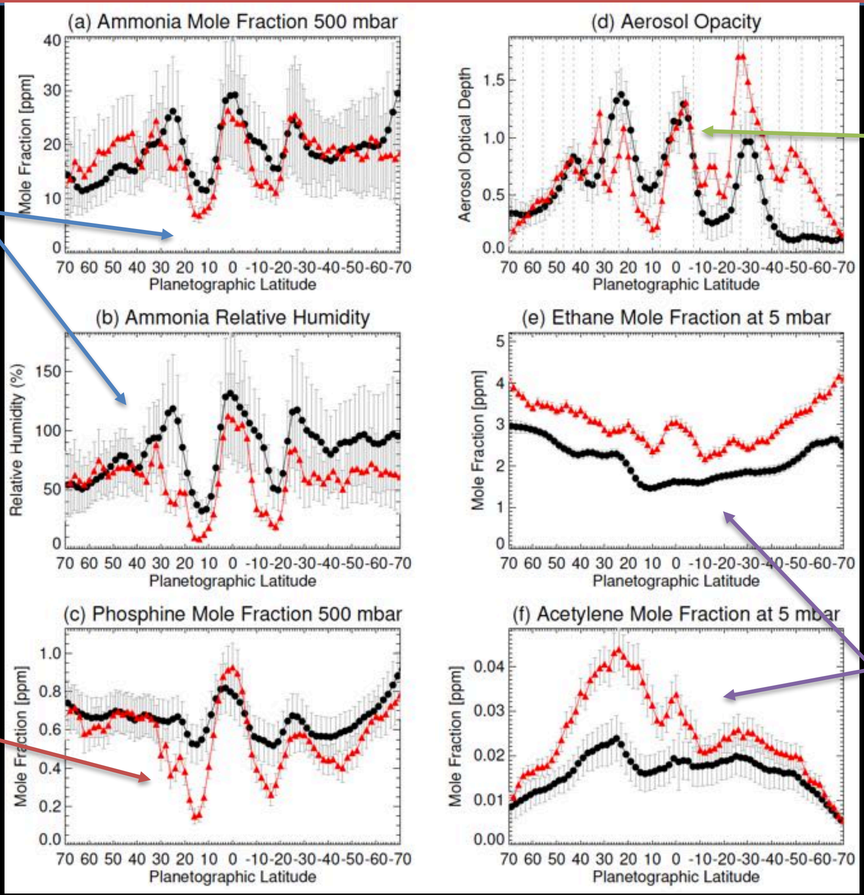




Jupiter's Gaseous Composition

Ammonia contrasts at 500 mbar set upper boundary for deeper microwave mapping by Juno/MWR

Phosphine traces tropospheric mixing, sets Juno/JIRAM spectra in global context.



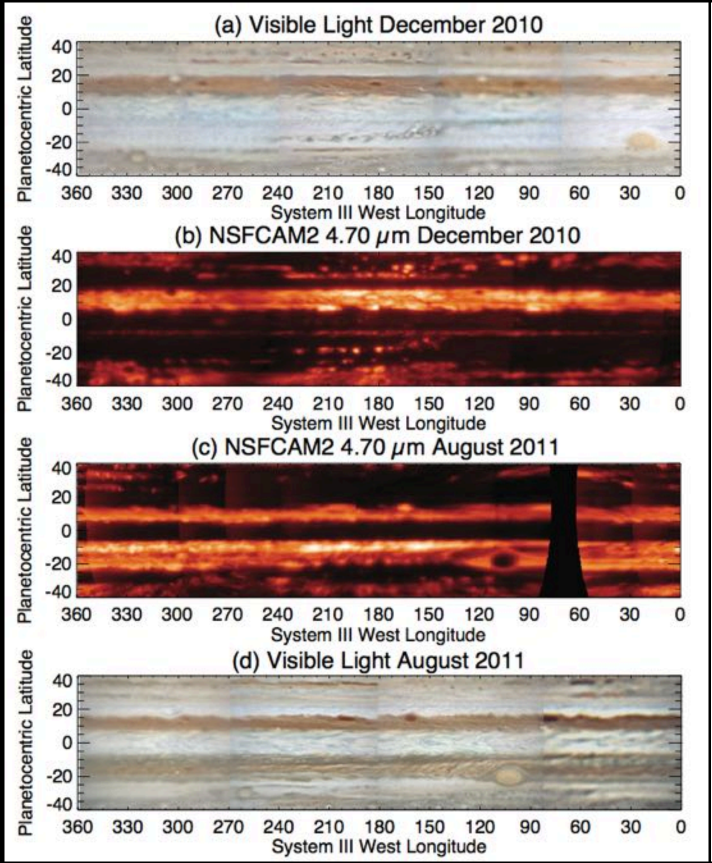
Infrared aerosol opacity contrasts with visible structure & colours from JunoCAM.

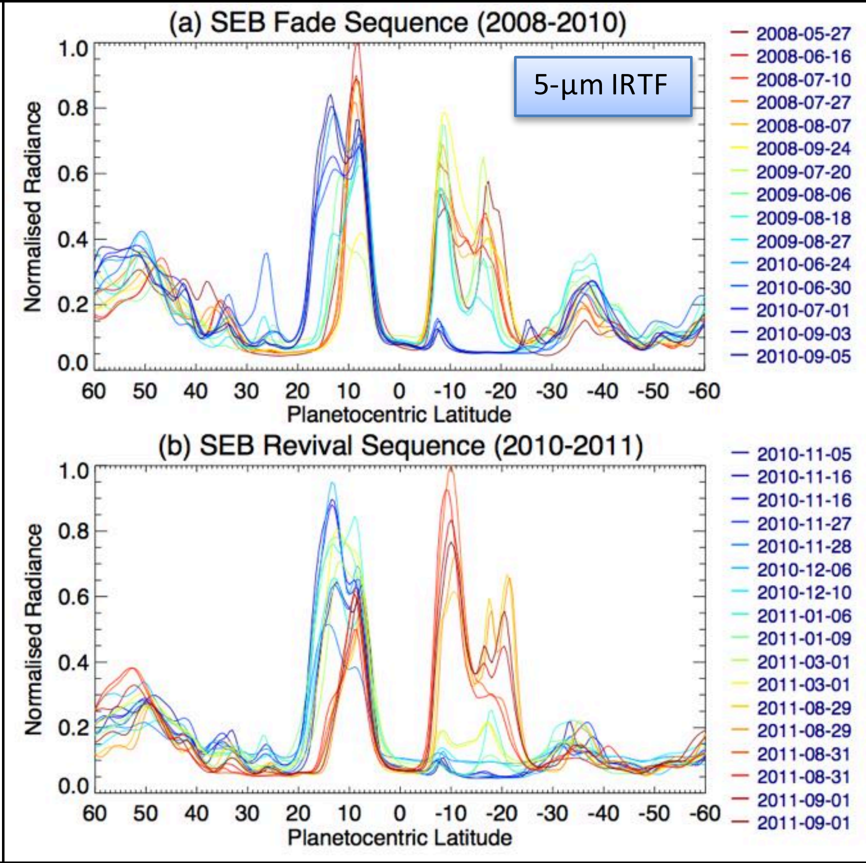
Ethane & acetylene trace stratospheric dynamics (waves, overturning), match to Juno/UVS hydrocarbon maps.

- Comparison of Cassini (red) and TEXES (black).
- As with SOFIA, ***we can now do from Earth what was only previously possible from space***.
- …opens up the possibility for temporal studies!

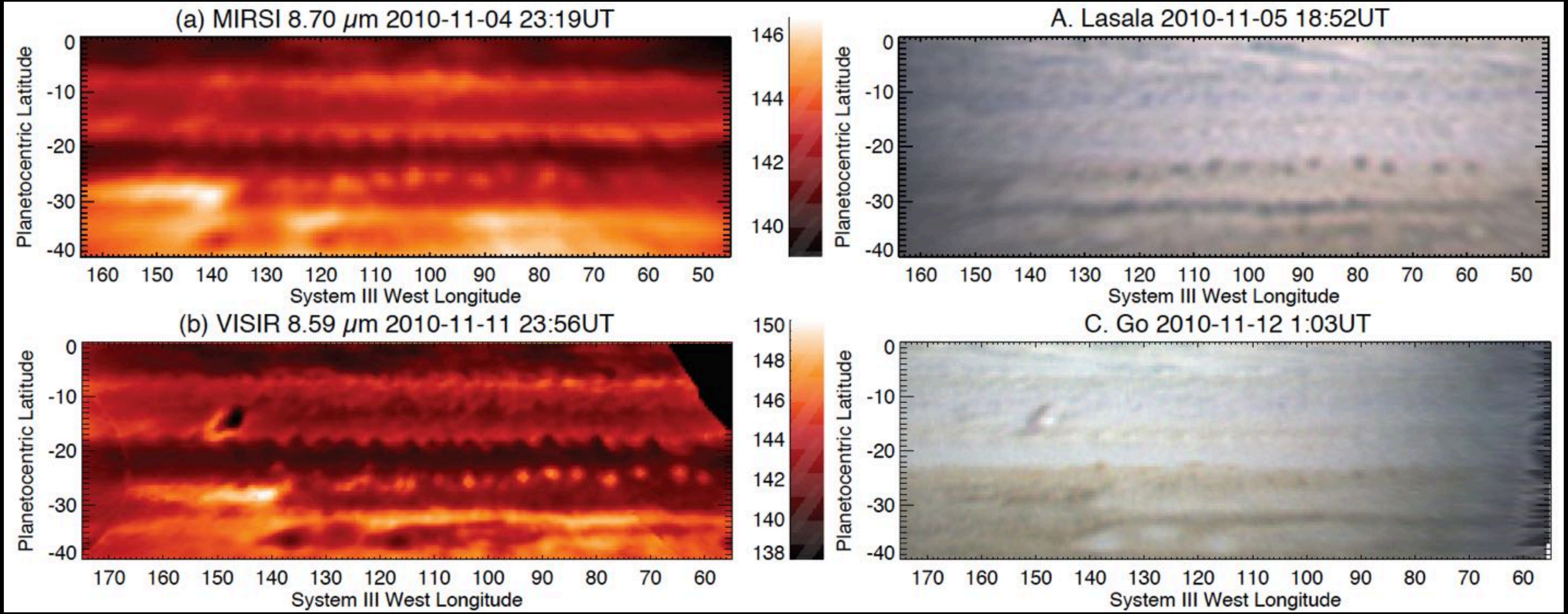
Temporal Changes in Jupiter's Tropics

- "Breathing" of Jupiter's most prominent belts.
- **SEB fade and revival cycle** (2009-2011), 2-14 yr timescales, cessation of GRS rifting; triggered convection.
- **NEB expansion (2015-2016),** 3-5 yr timescales, wave activity on NEBn, prominent cyclonic barges.

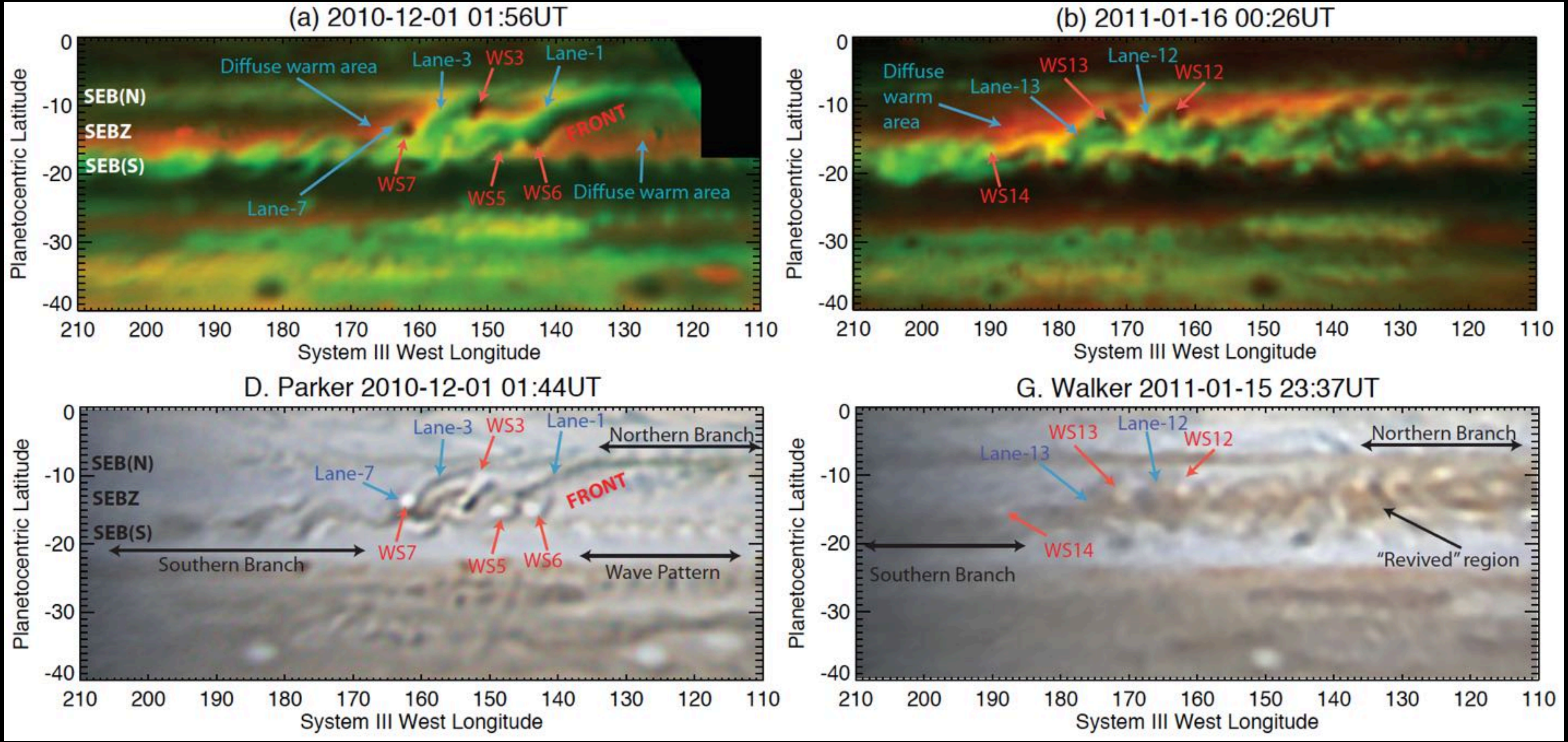




SEB Revival Plume Evolution



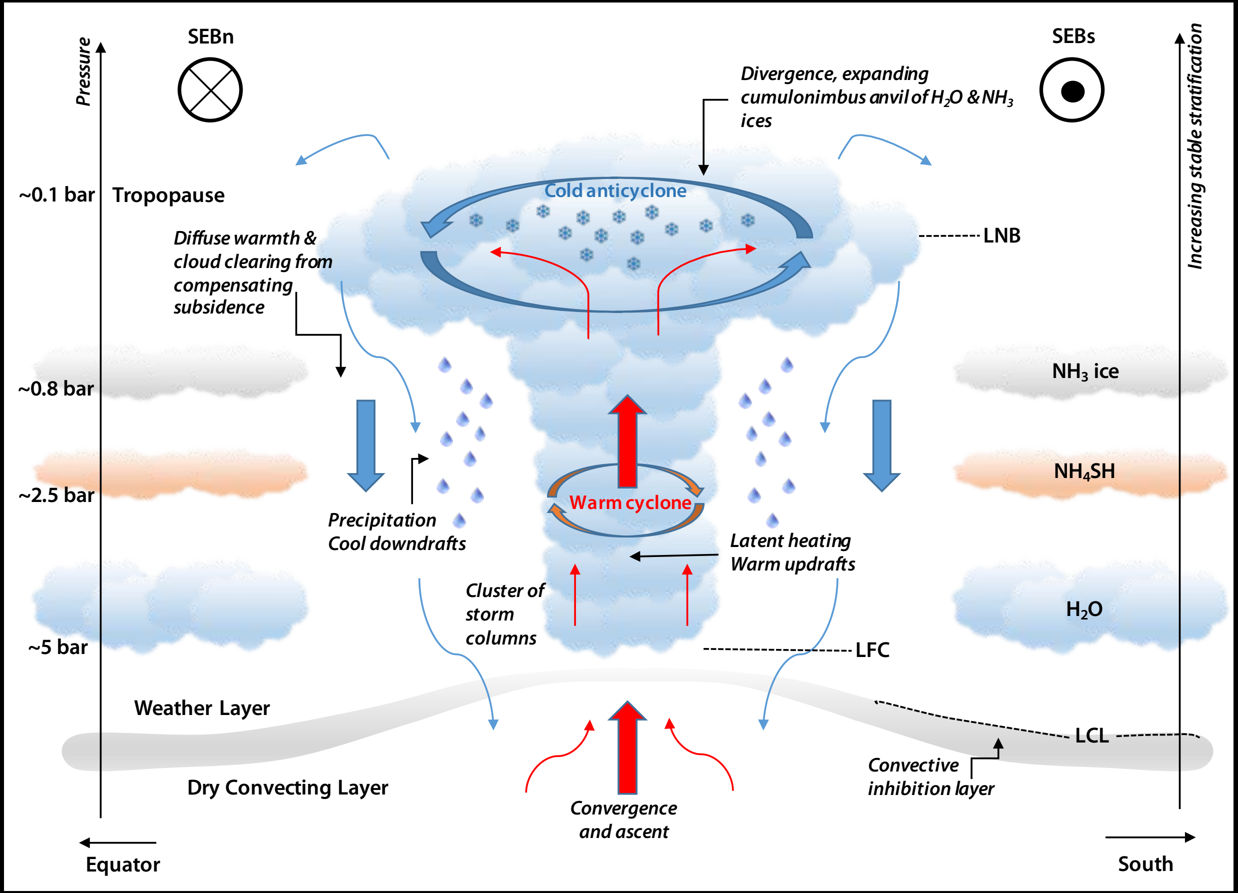
SEB Revival and Plume Evolution



Triggered Moist Convection?

- Plumes punch through convective inhibition layer to LCL/LFC.
- Cyclone/anticyclone pair.
- Cold plume tops.
- Cloud-free peripheral subsidence revives belt.

This work is mostly from imaging. Desire temporally-resolved spectral mapping of plumes.



Summary: Era of the Spaxel

- Infrared spectroscopy reveals 3D ***temperature, composition, clouds*** underlying visible changes.
- Spatio-spectral mapping only previously possible from space (Voyager, Cassini).
- **IRTF/TEXES** (5-20 μm) and **SOFIA/FORCAST** (17-37 μm) providing Earth-based maps to support Juno.
- Large database to **study temporal evolution** (natural cycles) on Jupiter as archetype for giant planets.