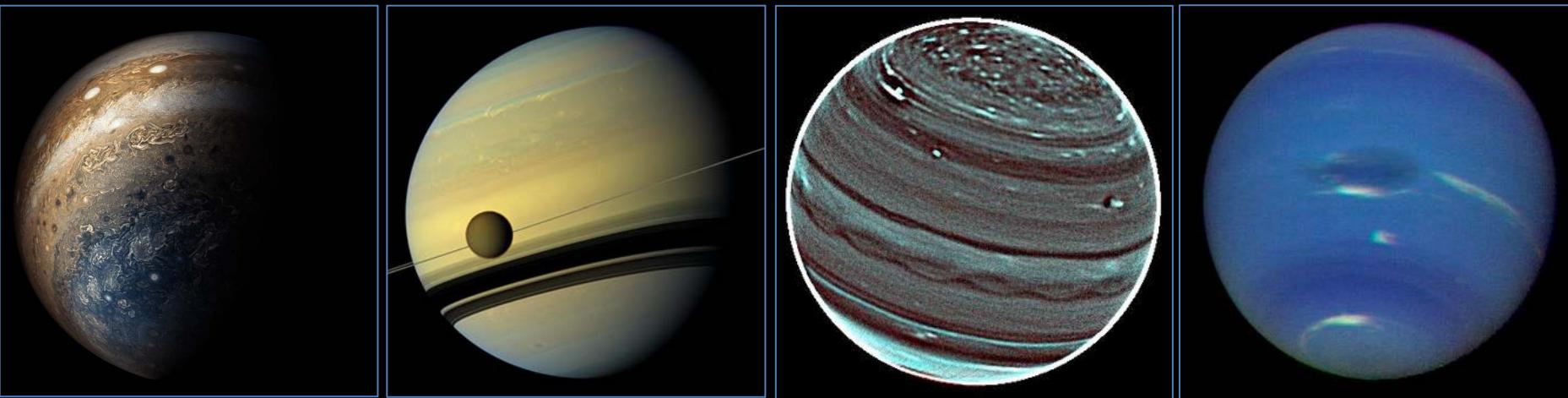
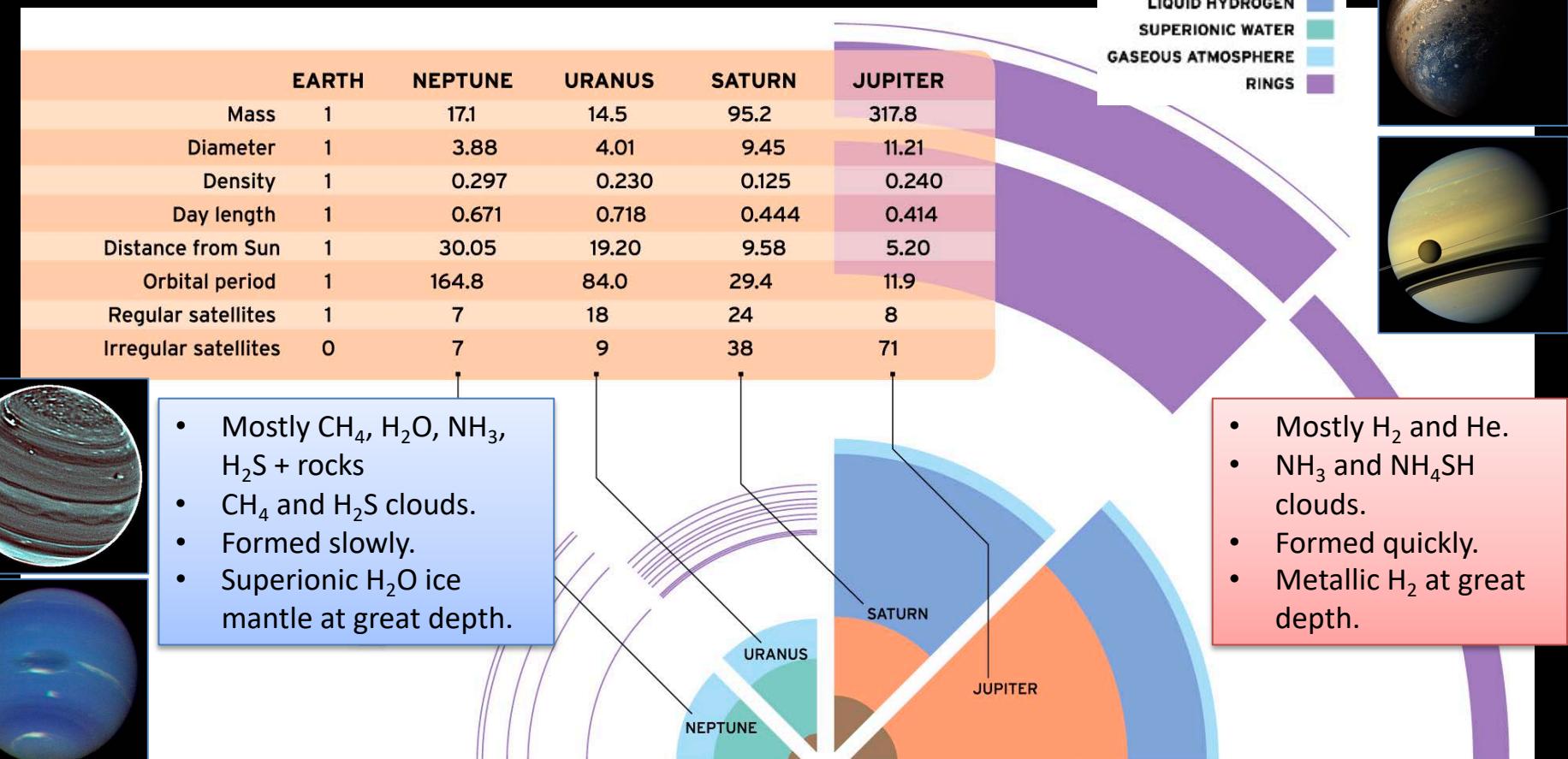


# Giant Planet Science Opportunities with SOFIA

Building the SOFIA 2020-2025 Instrument Roadmap



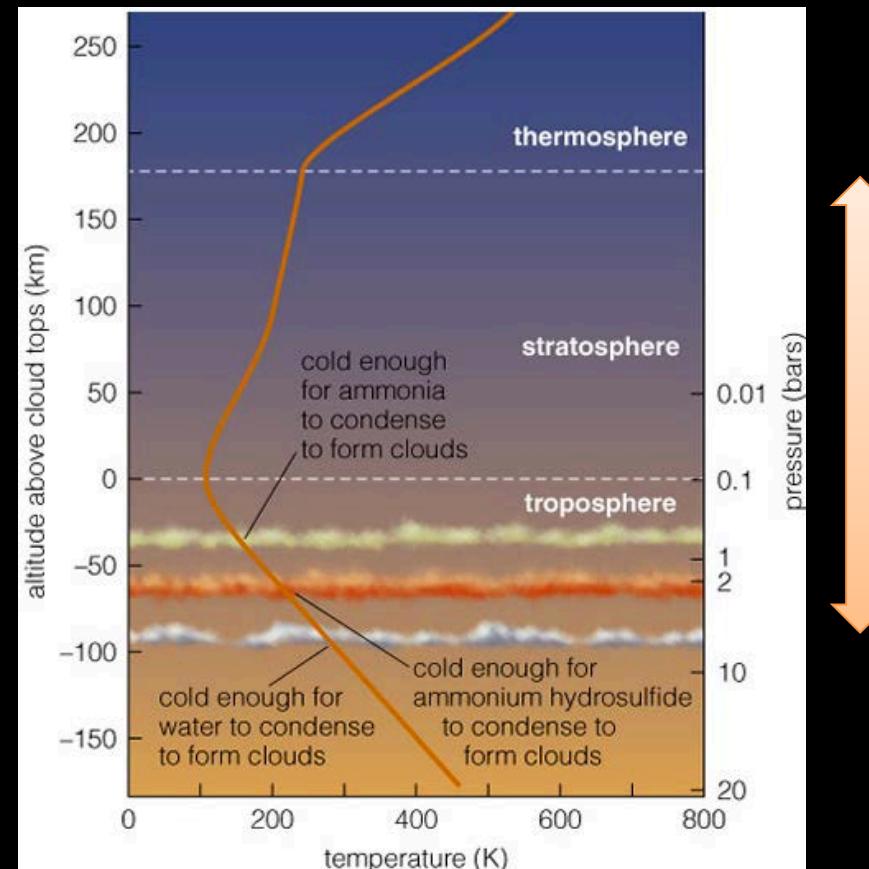
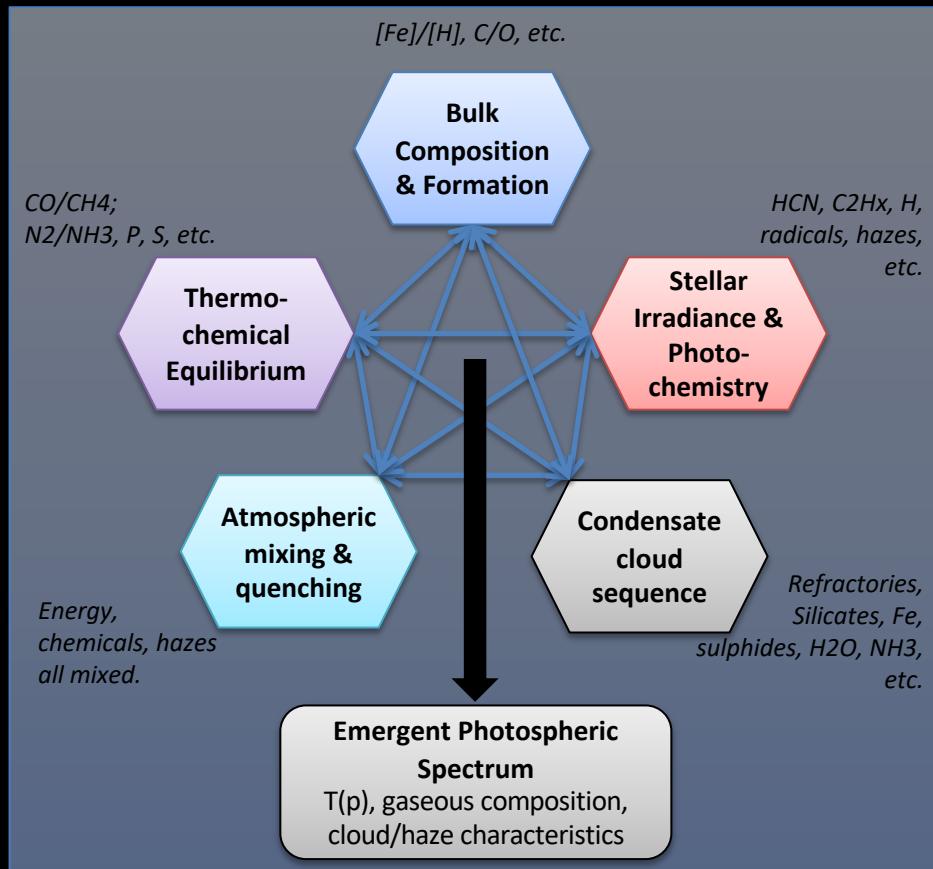
# Comparative Planetology



- Mostly CH<sub>4</sub>, H<sub>2</sub>O, NH<sub>3</sub>, H<sub>2</sub>S + rocks
- CH<sub>4</sub> and H<sub>2</sub>S clouds.
- Formed slowly.
- Superionic H<sub>2</sub>O ice mantle at great depth.

- Mostly H<sub>2</sub> and He.
- NH<sub>3</sub> and NH<sub>4</sub>SH clouds.
- Formed quickly.
- Metallic H<sub>2</sub> at great depth.

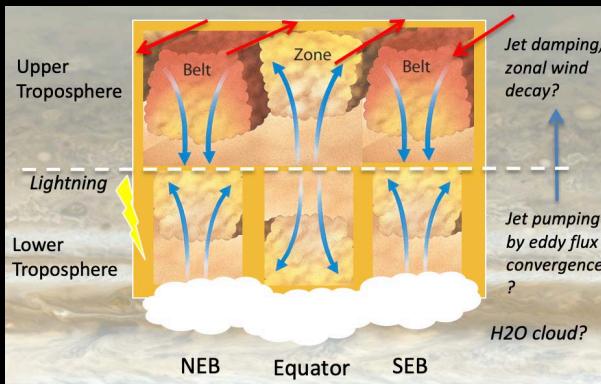
# Orientation: Infrared Sounding of Giant Planet Atmospheres



## **Key Questions for SOFIA**

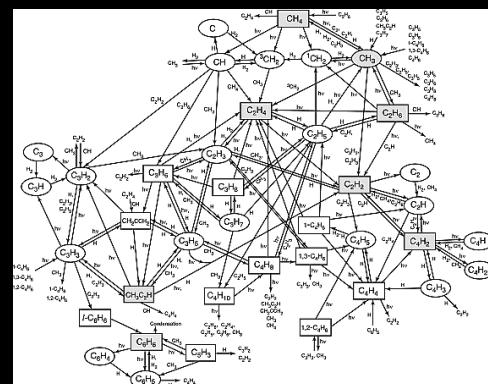
## DYNAMICS:

# How does planetary circulation differ from gas to ice giants?



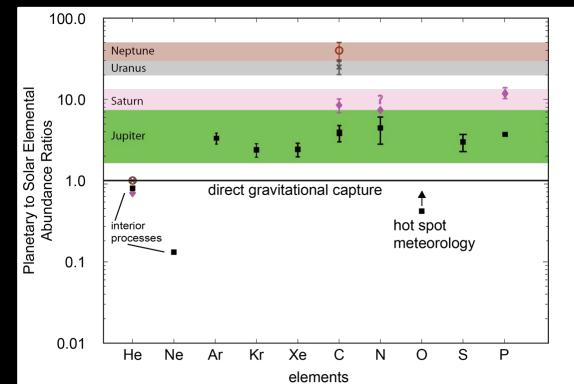
# **CHEMISTRY:**

# How do photochemistry, aurora, and exogenic material shape planetary stratospheres?



## ORIGINS:

What does the bulk composition reveal about planetary origins?



# Key Questions for SOFIA

## DYNAMICS:

How does planetary circulation differ from gas to ice giants?

## CHEMISTRY:

How do photochemistry, aurora, and exogenic material shape planetary stratospheres?

## ORIGINS:

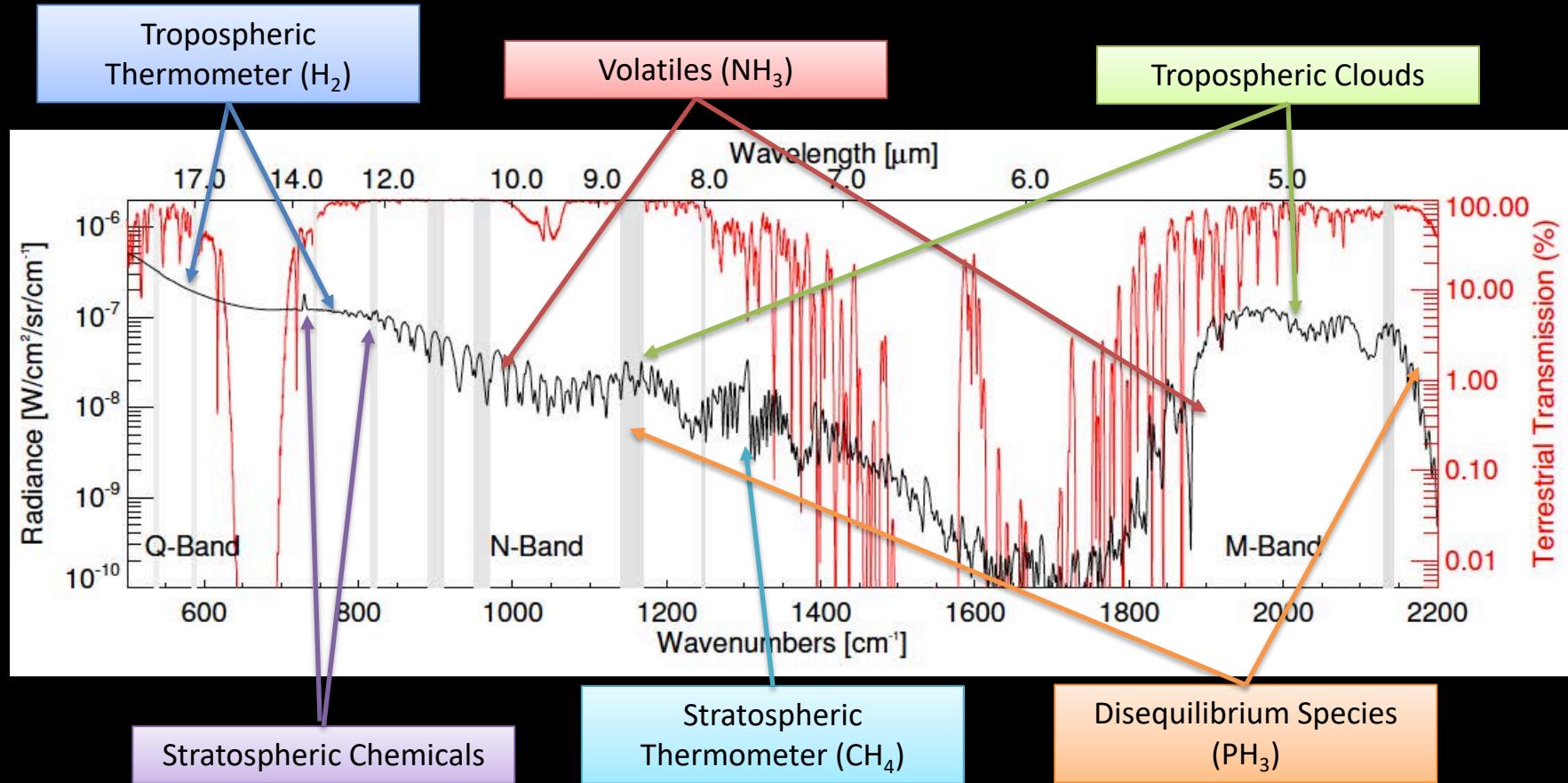
What does the bulk composition reveal about planetary origins?

*Spatially-resolved low- $R$  thermal-IR spectra/images of H<sub>2</sub>-He continuum (>16  $\mu\text{m}$ ) to measure spatial contrasts in temperature & composition.*

*Spatially-resolved moderate- $R$  thermal-IR spectra to measure stratospheric emission (esp. @poles) & tropospheric chemicals.*

*Disc-integrated high- $R$  far-IR spectra of HD, CH<sub>4</sub>, CO, H<sub>2</sub>O features inaccessible from the ground.*

# Mid-Infrared Observations



# Mid-IR Highlights from VLT/VISIR



*Natural cycles in jovian belts and zones at 8.6 and 10.8  $\mu\text{m}$  – temporal variability (Fletcher et al., 2017).*



*Giant storms and seasonal change at 18  $\mu\text{m}$  on Saturn (Fletcher et al., 2011).*

*Stratospheric circulation at 13  $\mu\text{m}$  (acetylene) on Uranus (Roman et al., 2020).*

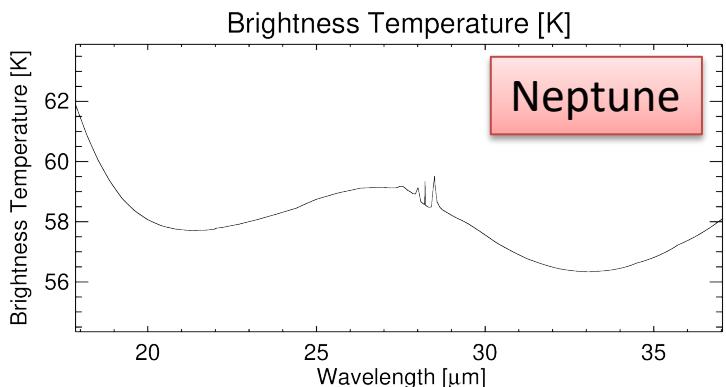
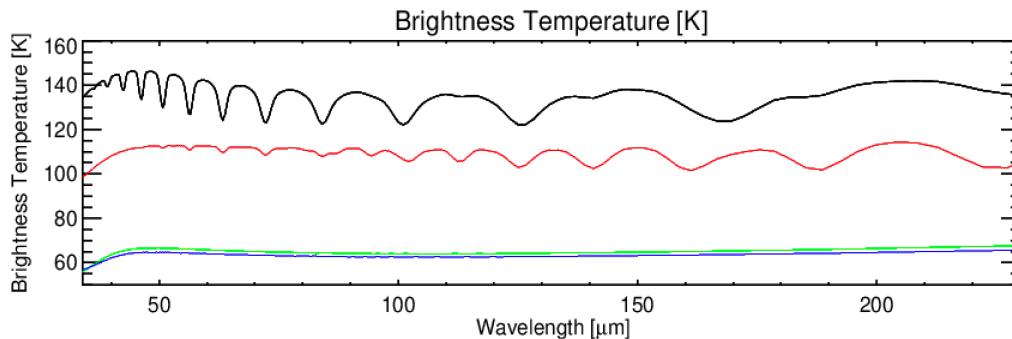
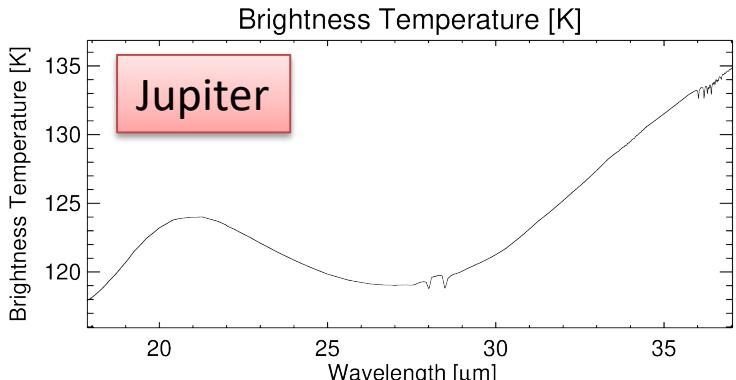


*Polar vortex and stratospheric bands at 7.9  $\mu\text{m}$  (methane) on Neptune (Sinclair et al., 2020)*

Giant Planets observed from 8-m facilities in telluric windows.

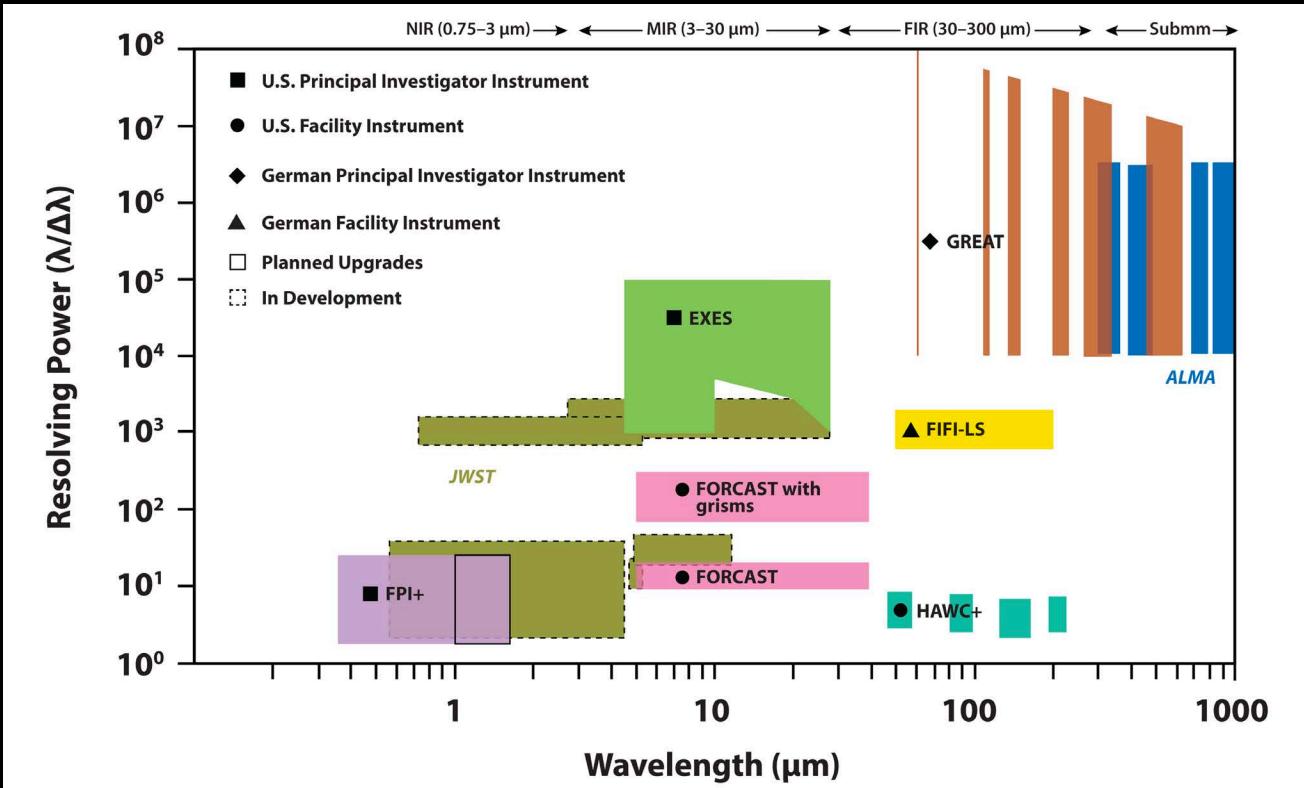
SOFIA and space telescopes won't be able to match this, but can access regions invisible from the ground.

# SOFIA Access to the Far-IR



- Synthetic calculations of brightness temperature (low-R).
- H<sub>2</sub>-H<sub>2</sub> and H<sub>2</sub>-He collision-induced absorption (plus dimers) reveal tropospheric T(p) and para-H<sub>2</sub> (e.g., **circulation**).
- Rotational features of PH<sub>3</sub> and NH<sub>3</sub> (e.g., **clouds/chemistry**).
- Rotational features of HD and CH<sub>4</sub> for D/H and C/H measurements (e.g., **origins**).

# Assessing SOFIA's Current Instruments

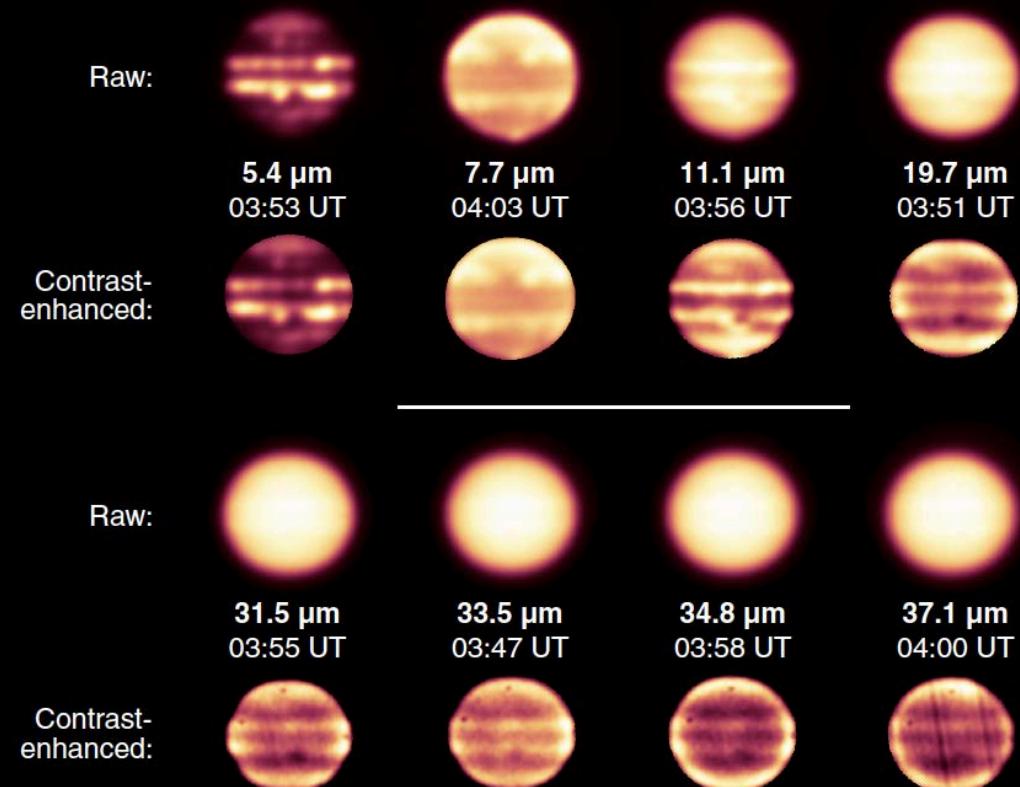


- **Dynamics:** FORCAST H<sub>2</sub>-He observations in MIR/FIR.
- **Chemistry:** EXES observations of stratospheric emission.
- **Origins:** GREAT observations of narrow features?
- FIFI, FPI+, HAWC+ don't contribute.

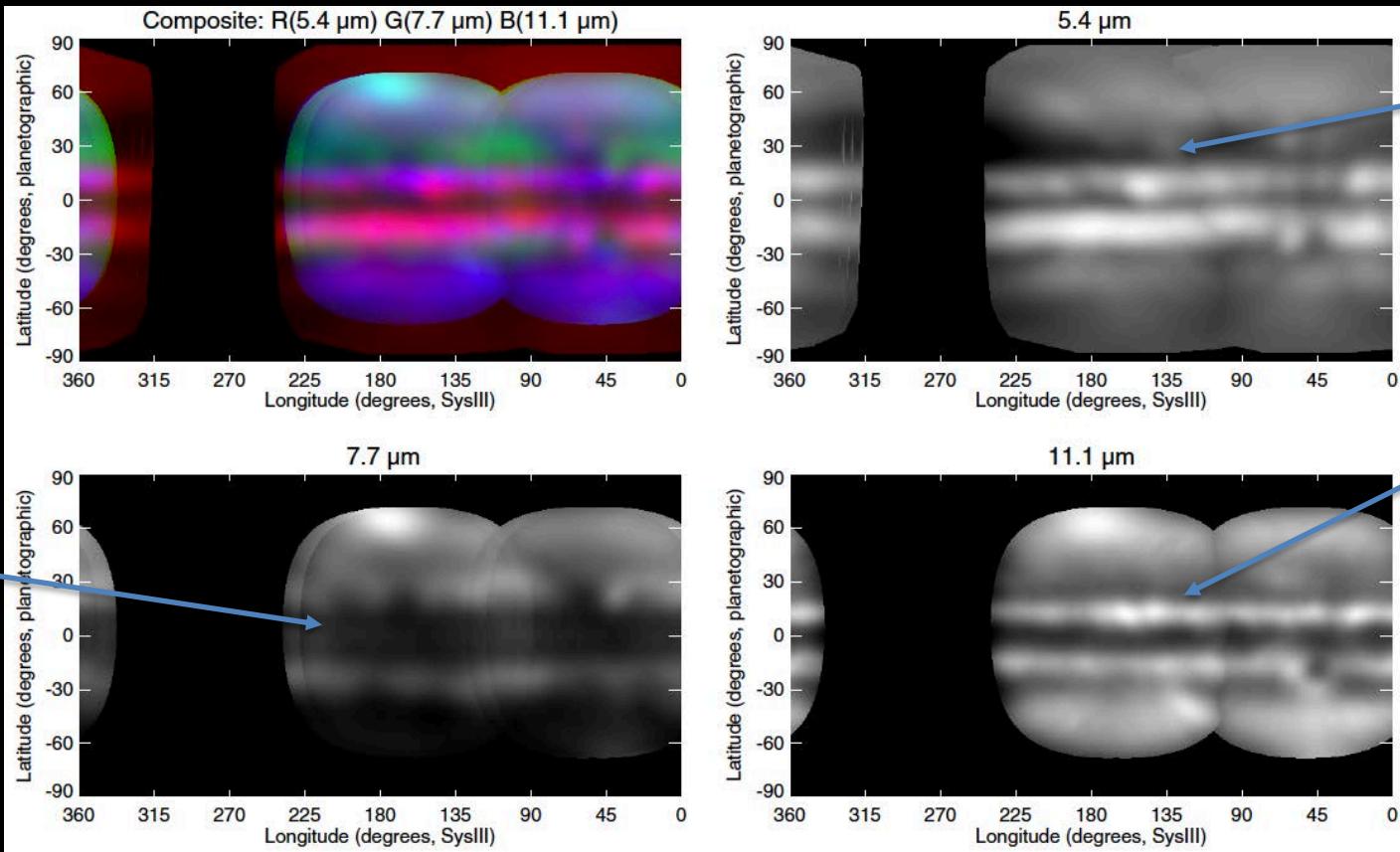
# FORCAST Observations of Jupiter - Dynamics

SOFIA/FORCAST – Jupiter 2014-05-02

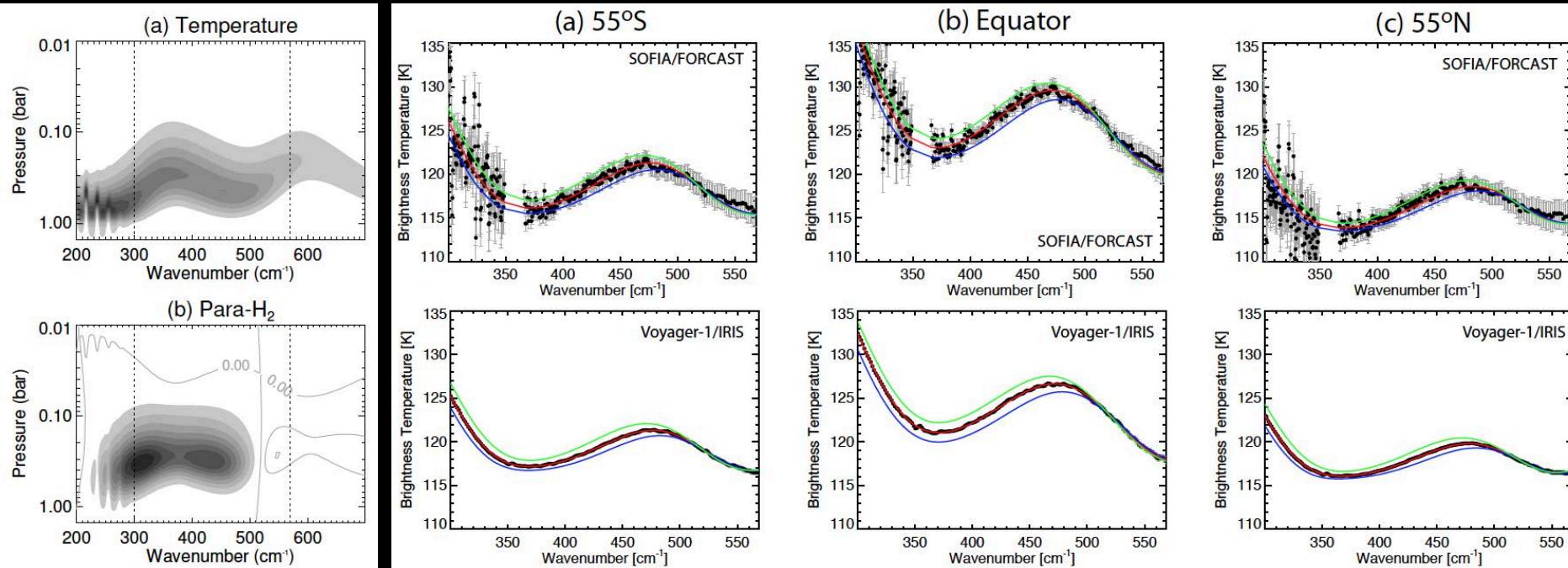
- Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST)
- 256x256 array translates to a wide 191" field of view
  - More than sufficient to capture Jupiter's 40" disc.
  - Angular resolution ranges from 2-4", depending on wavelength
- Eight Filters, plus G227 (17.5-27.3  $\mu\text{m}$ ) and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



# Mapping FORCAST Data



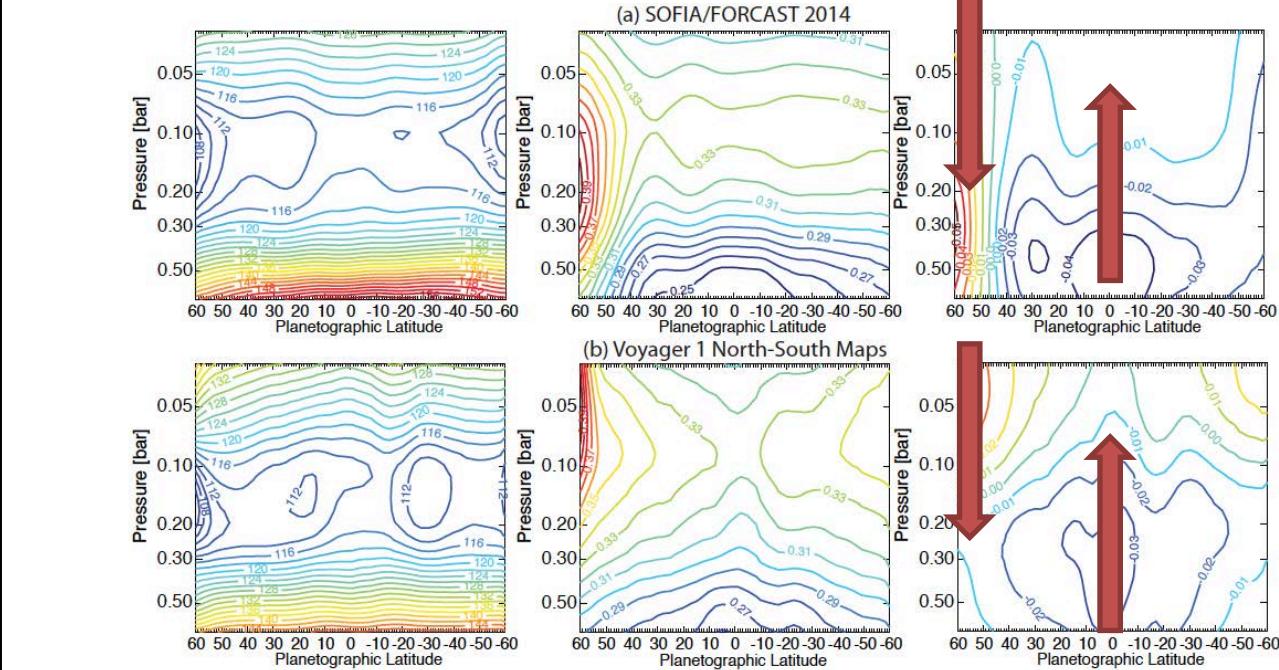
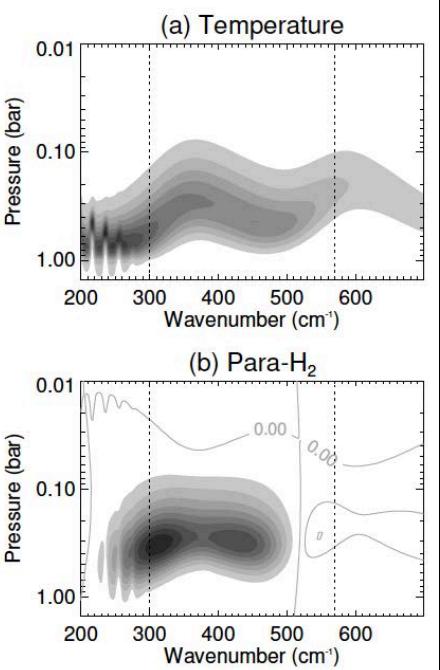
# FORCAST Spectroscopy: Jovian Para-Hydrogen



- Comparing FORCAST and Voyager/IRIS (1979) spectra: both constrain temperature and para-H<sub>2</sub> fraction.
- Constrain atmospheric circulation, and repeat for temporal variability.***

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-H<sub>2</sub> Distribution from SOFIA/FORCAST and Voyager/IRIS 17-37  $\mu\text{m}$  Spectroscopy, *Icarus*, in press (<http://dx.doi.org/10.1016/j.icarus.2016.10.002>) (<http://arxiv.org/abs/1610.01304>)

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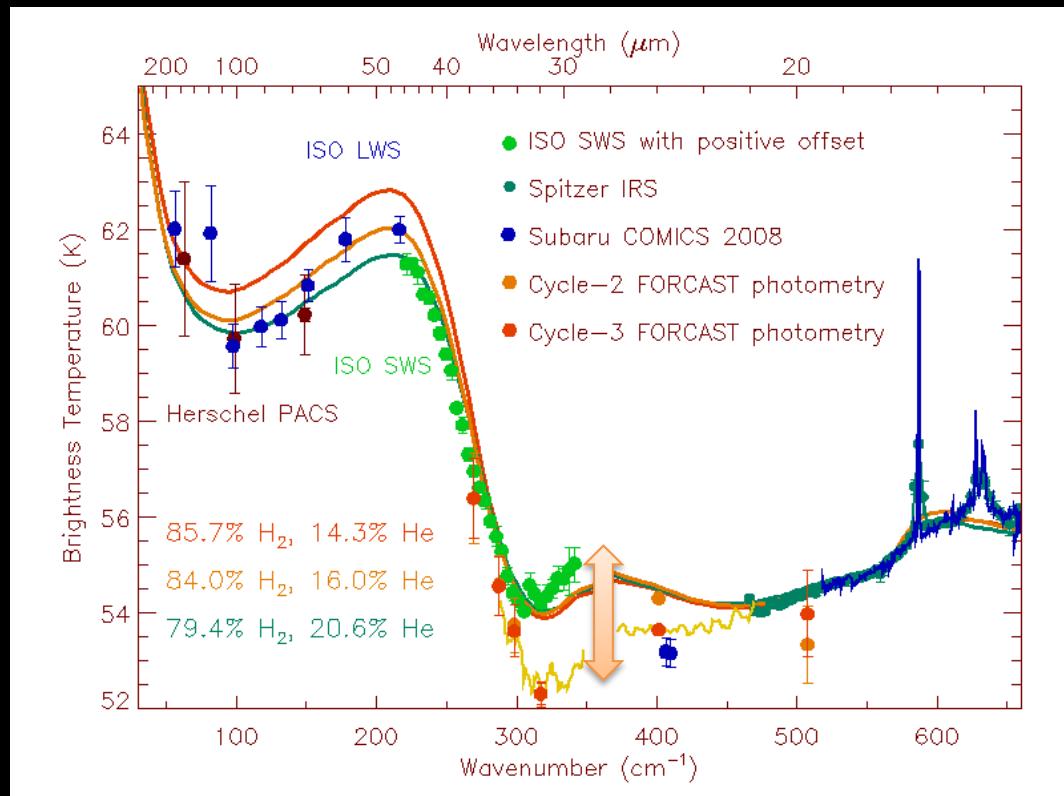


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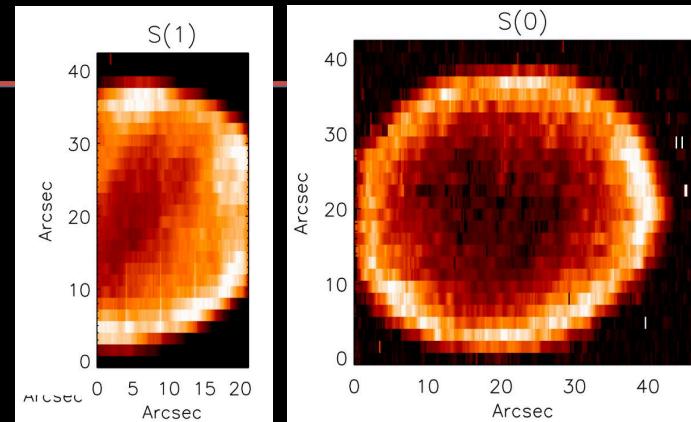
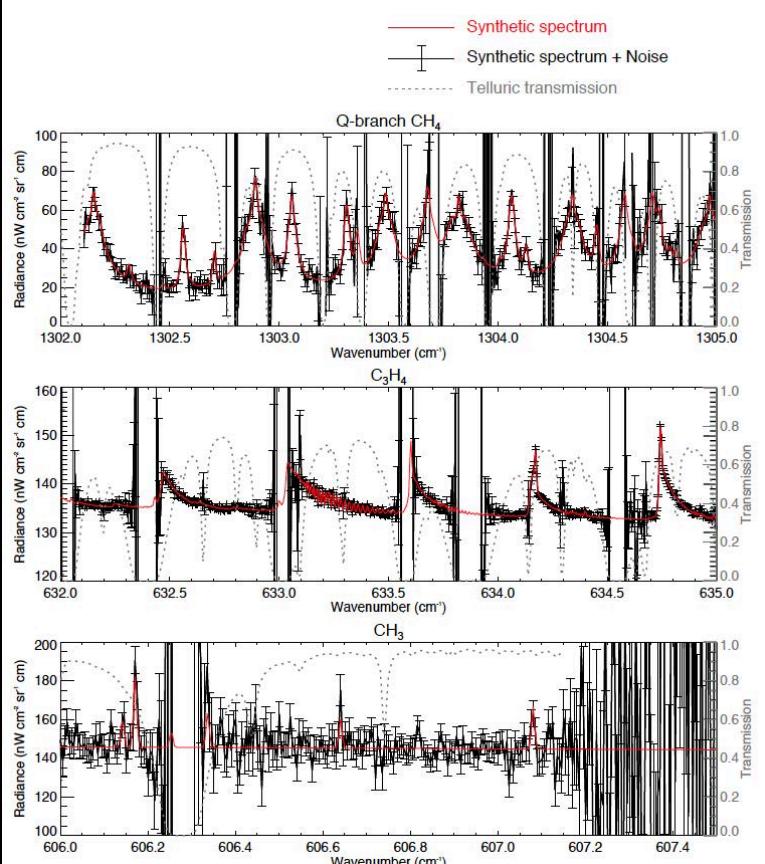
# FORCAST Uranus – Ice Giant Origins

- Attempt to cross-calibrate Spitzer/IRS, SOFIA, Subaru, and ISO/SWS observations.
  - Much deeper than expected near  $300\text{ cm}^{-1}$ .
- Fitting constraints on para- $\text{H}_2$  and He/ $\text{H}_2$  ratio (poorly known for Ice Giants)
  - Key to achieving a unified physical model for structure, chemistry and their spatial variability.
- *Careful new FORCAST measurements/calibration required to pin this down.*



*Credit: Orton et al.*

# EXES Jupiter - Gas Giant Chemistry

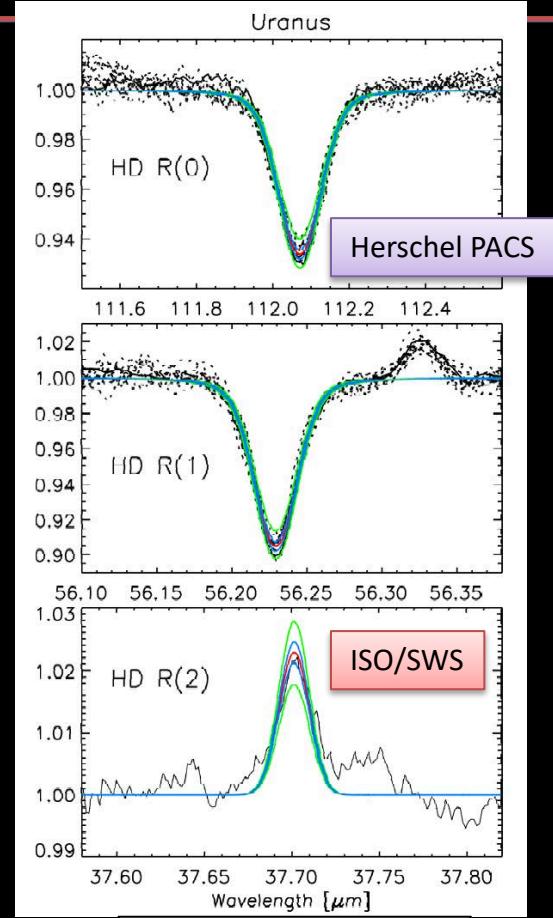
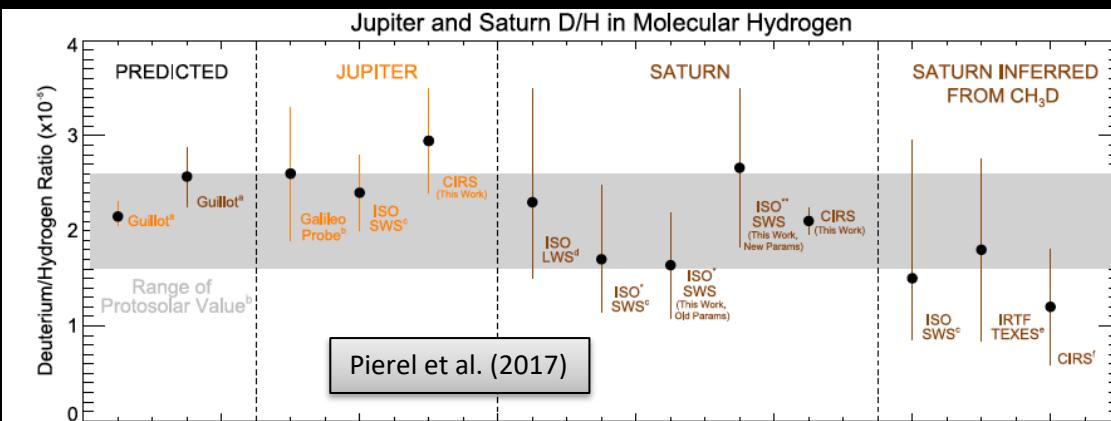


- EXES Provides access to spectral regions inaccessible from the ground.
  - 2014 EXES spectral maps of H<sub>2</sub> emission on Jupiter at 17.0 and 28.3 microns.
  - Simulated emission from methane, methyl-acetylene and methyl, key species in the photochemistry of stratospheres.
  - Could also use EXES at 5 microns for water humidity in Jupiter/Saturn cloudy zones (challenging from ground).
- *A comprehensive EXES spectral survey would provide new insights into atmospheric chemistry.*

Credit: Sinclair et al.

# GREAT – Planetary Origins

- Possible new mode of GREAT (not implemented): D/H on all 4 outer planets.
- HD R(0) line at  $112.07 \mu\text{m} = 2.676 \text{ THz}$ .
  - Currently 4GREAT 2.54THz works only 2.49 to 2.59 THz, missing HD.
  - Independent constraint on stratospheric T would come from CH<sub>4</sub> in existing M Channel.
- 4GREAT 1.37THz could be used for CO/HCN (not tried).
- 4GREAT 1.00THz could be used for CO/CS (not tried).



# Returning to the Key Questions

## DYNAMICS:

How does planetary circulation differ from gas to ice giants?

## CHEMISTRY:

How do photochemistry, aurora, and exogenic material shape planetary stratospheres?

## ORIGINS:

What does the bulk composition reveal about planetary origins?

*FORCAST spectroscopy of continuum to constrain vertical  $T(p)$ , para- $H_2$ , and variation with location.*

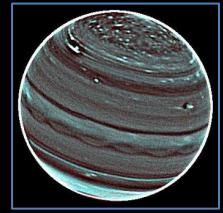
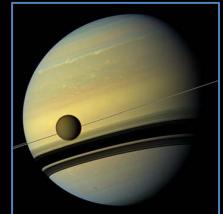
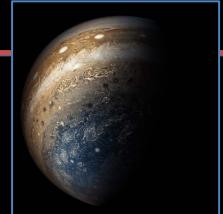
*EXES spectroscopy of stratospheric chemicals, tropospheric condensables inaccessible from ground.*

*FORCAST spectroscopy to constrain He/H<sub>2</sub>. Adaptation of GREAT to allow comparative planetology for HD.*

*Note: Identified upgrades to FIFI-LS, FPI+, HAWC+ will not necessarily assist the Giant Planet community.*

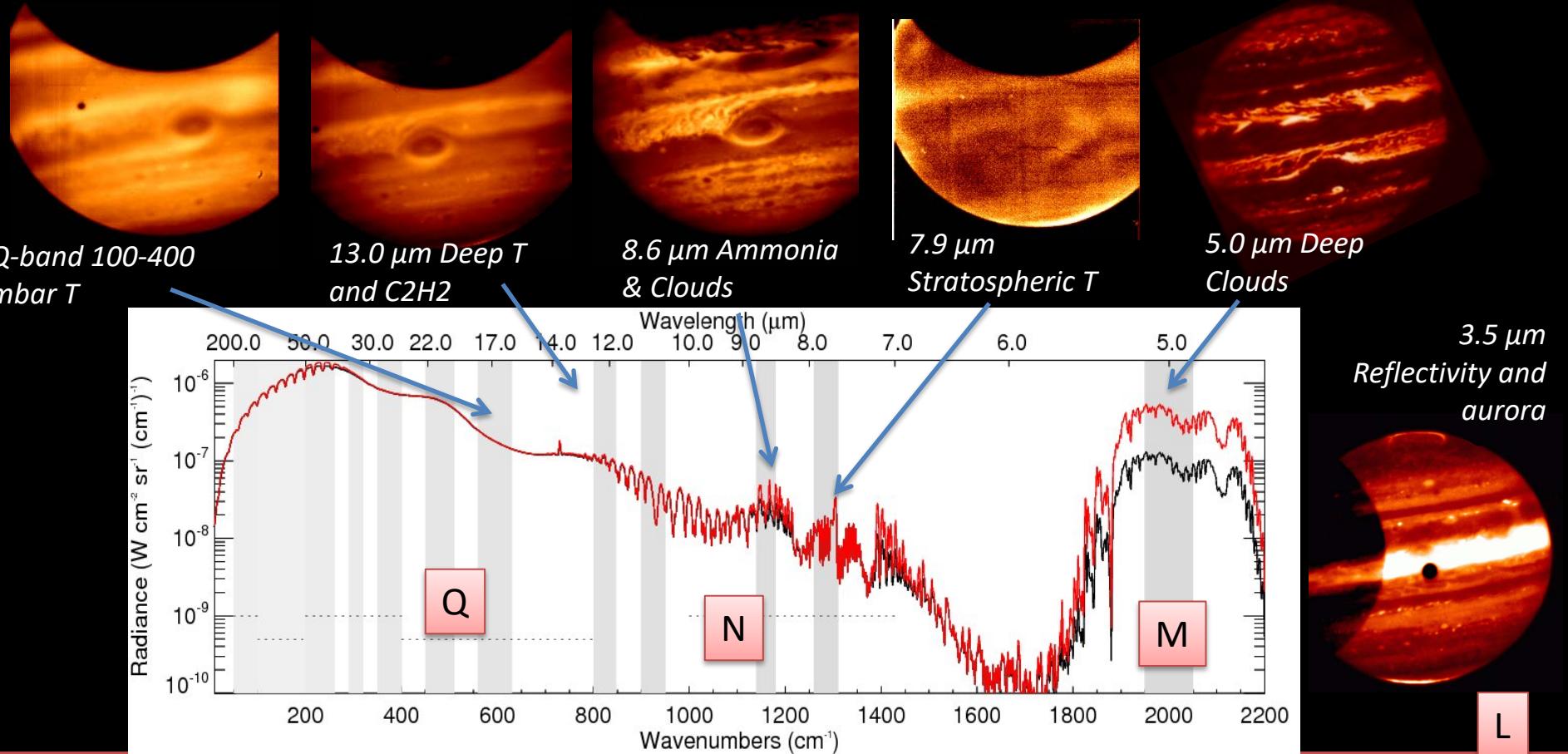
# Future Giant Planet Opportunities

- **Mid-IR** will be well-covered by JWST 5-30  $\mu\text{m}$  at R $\sim$ 3000, and imaging from 8-m facilities, BUT:
  - Jupiter saturation issues on Webb.
  - Lower spectral resolution than (T)EXES.
  - Limited prospect for temporal variability studies with Webb.
  - Webb cross-calibration with (T)EXES?
  - Desire for simultaneous spectro/spatial imaging (e.g., IFU-like).
- **Far-IR**  $> 25 \mu\text{m}$  remains challenging:
  - Complete carefully-calibrated FORCAST survey of all four giants for T/para-H<sub>2</sub>/He.
  - Adaptation of GREAT to sample HD and recover lost HIRMES science.

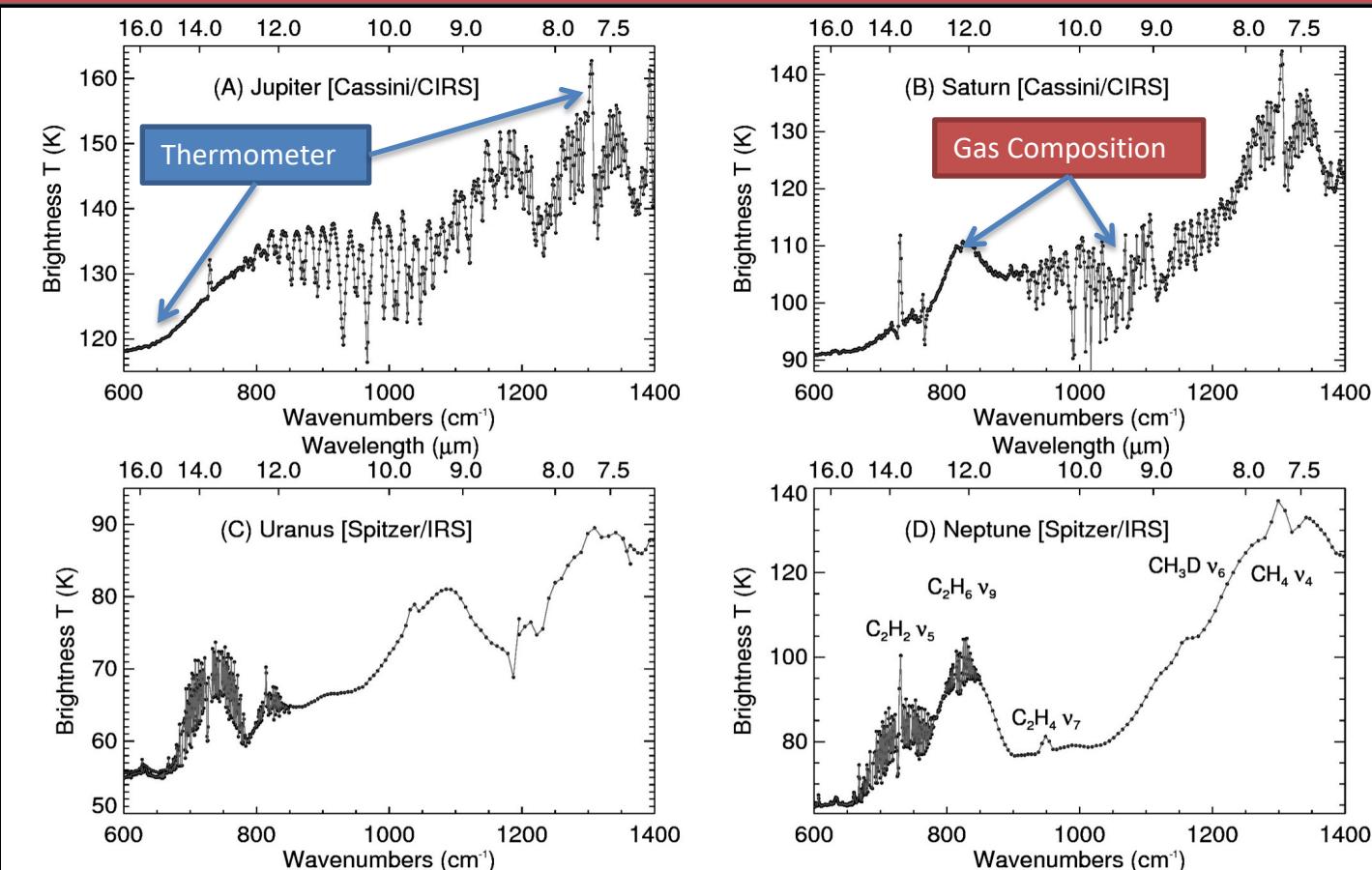


# Backup Slides

# Vertical Sounding of Jovian Atmosphere

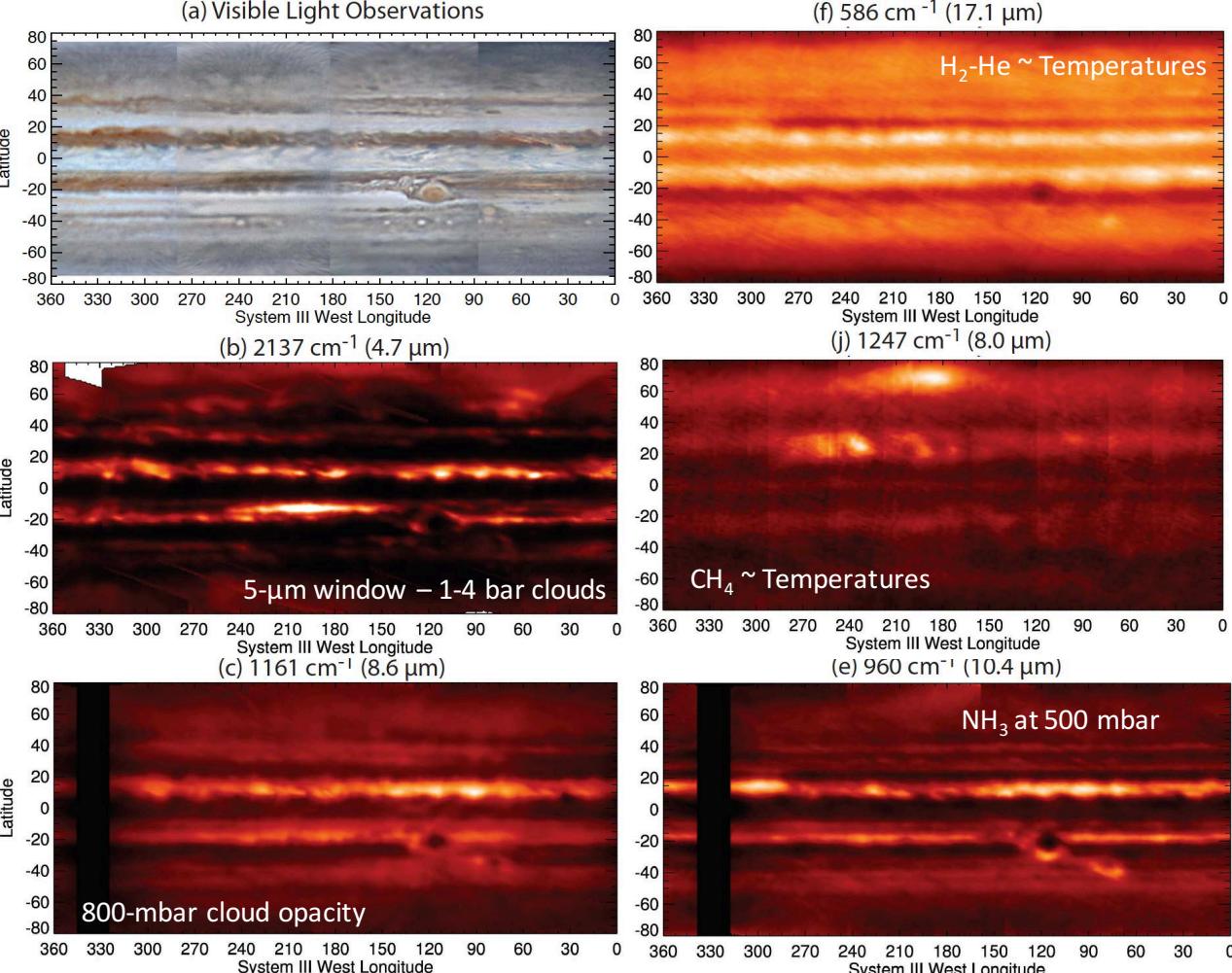


# Mid-IR 7-16 $\mu$ m Observations



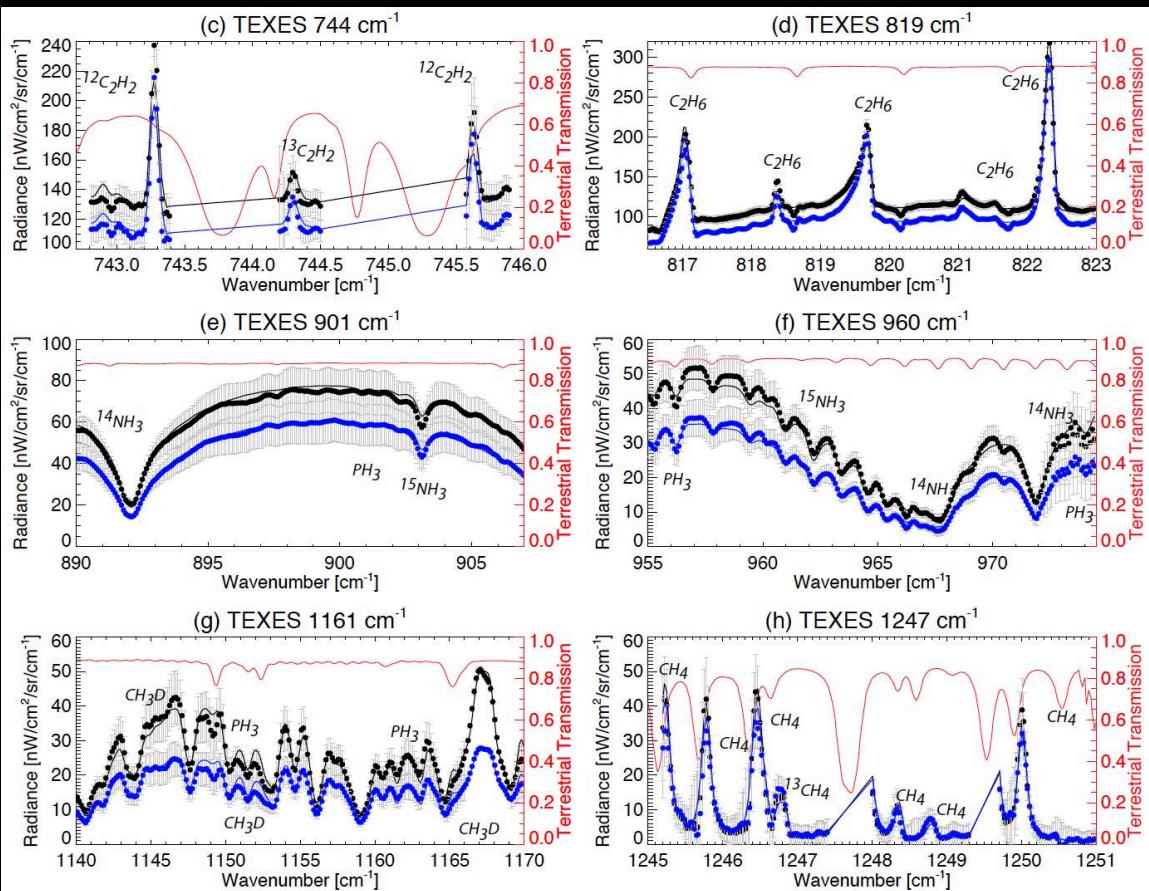
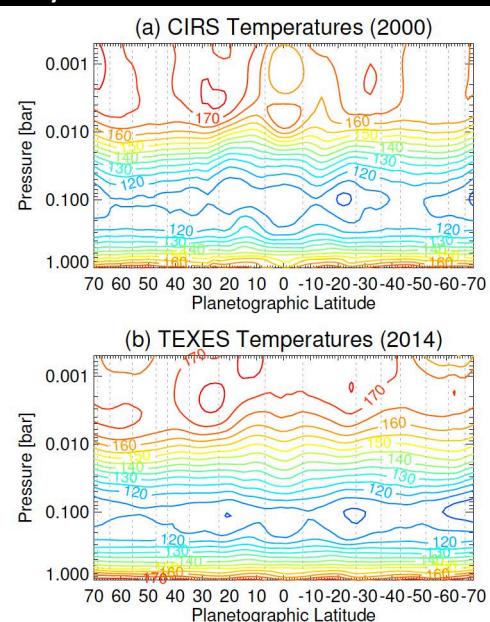
# IRTF Mapping

- Shorter wavelengths than FORCAST 5-20  $\mu\text{m}$ .
  - Programme to track jovian climate over full year.
  - Global spectroscopic mapping for 1<sup>st</sup> time with TEXES.
  - Only possible with  $\sim$ 10 hours of good conditions, challenge for EXES.

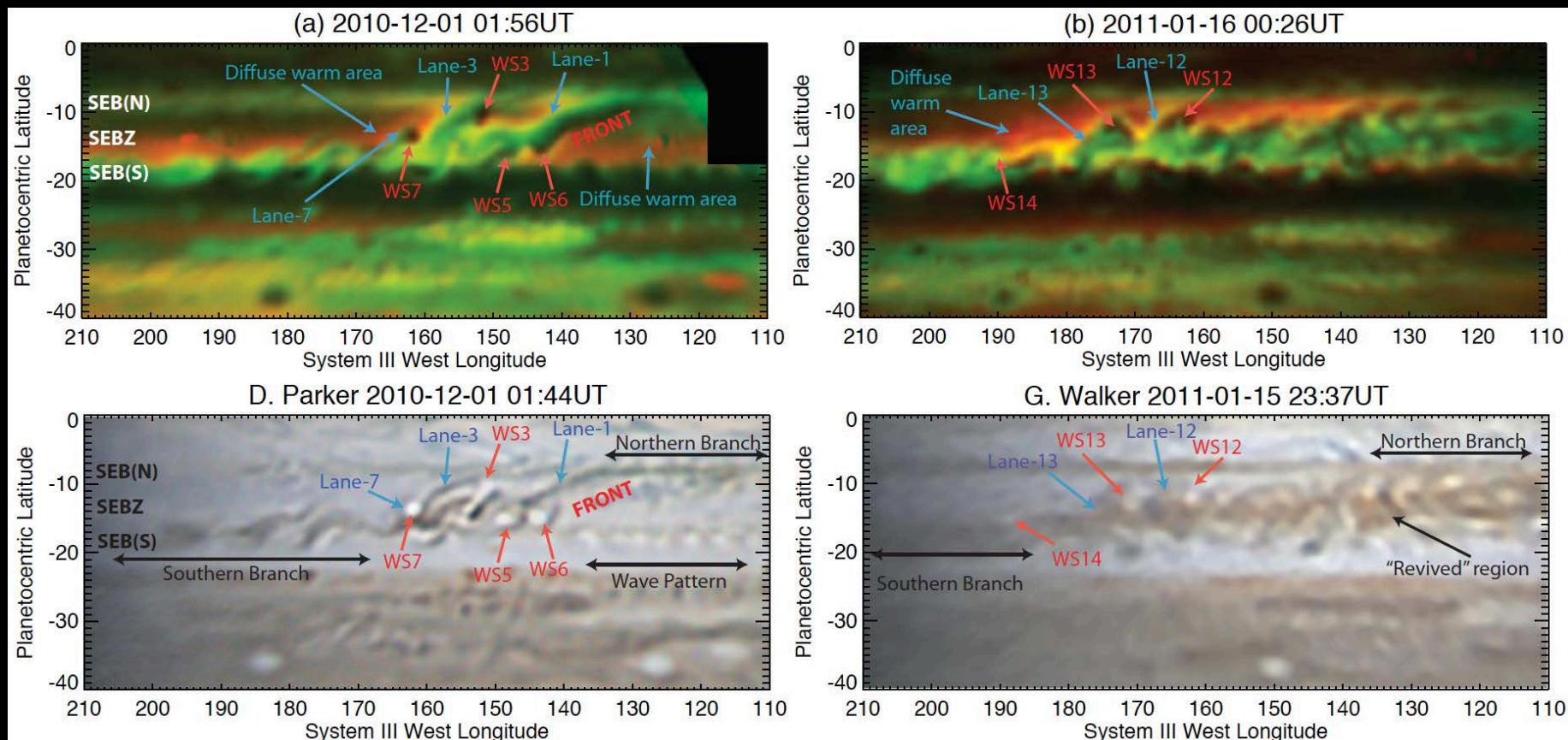


# TEXES Spectroscopy

- Spectra in multiple channels inverted simultaneously.
- NEMESIS optimal estimation retrieval code (Irwin et al., 2008).
- Map 3D temperature structure and windshears, NH<sub>3</sub>, PH<sub>3</sub>, aerosol opacity, stratospheric hydrocarbons.



# SEB Revival and Plume Evolution



# 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.

