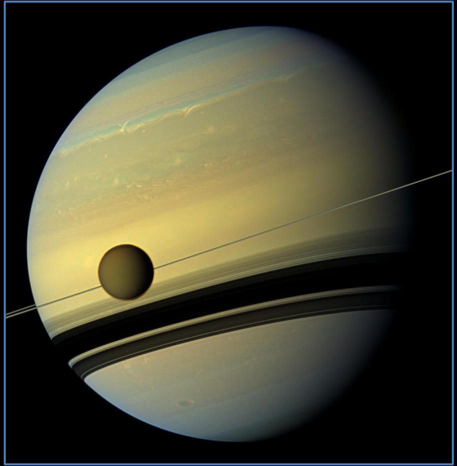
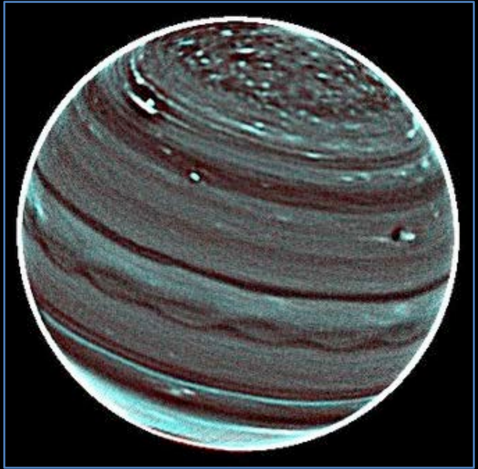
Giant Planet Science Opportunities with SOFIA

Building the SOFIA 2020-2025 Instrument Roadmap





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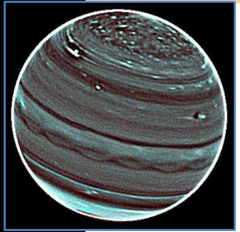
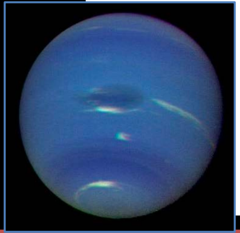
Glenn Orton, Thomas Greathouse, James Sinclair

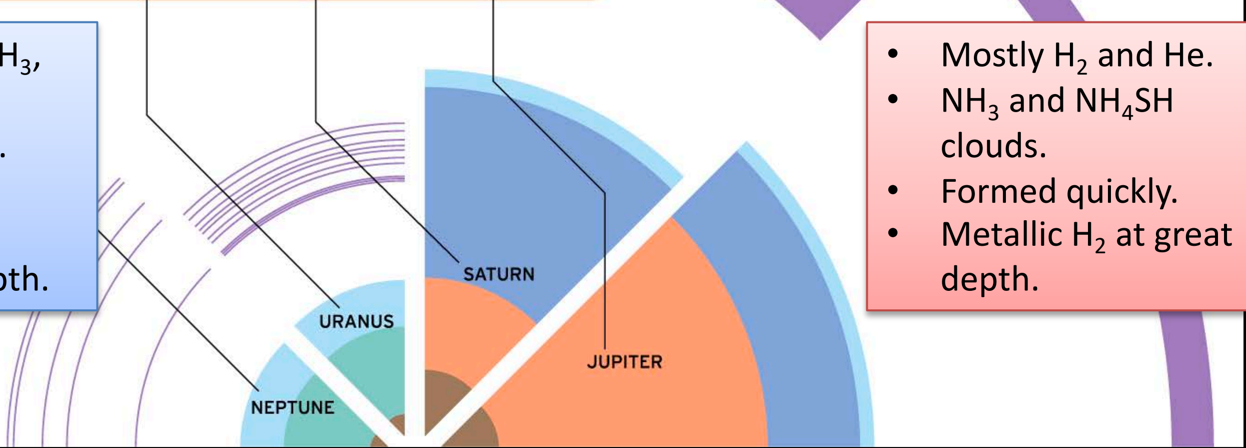
Comparative Planetology

	EARTH	NEPTUNE	URANUS	SATURN	JUPITER
Mass	1	17.1	14.5	95.2	317.8
Diameter	1	3.88	4.01	9.45	11.21
Density	1	0.297	0.230	0.125	0.240
Day length	1	0.671	0.718	0.444	0.414
Distance from Sun	1	30.05	19.20	9.58	5.20
Orbital period	1	164.8	84.0	29.4	11.9
Regular satellites	1	7	18	24	8
Irregular satellites	0	7	9	38	71



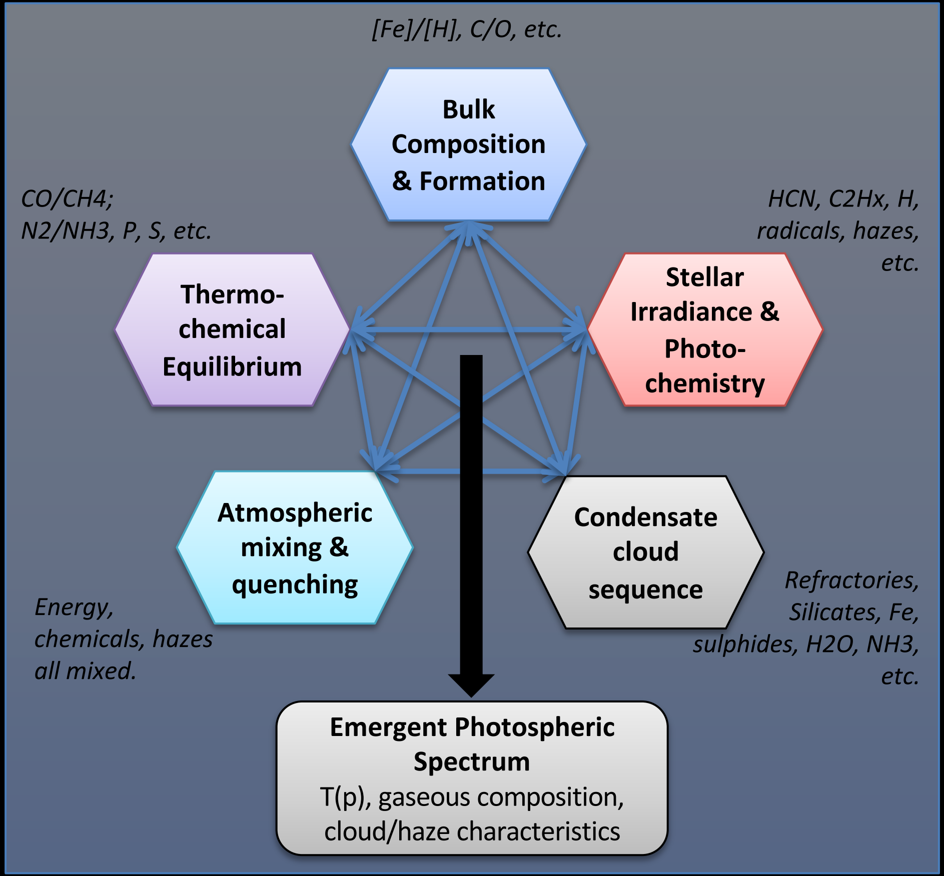


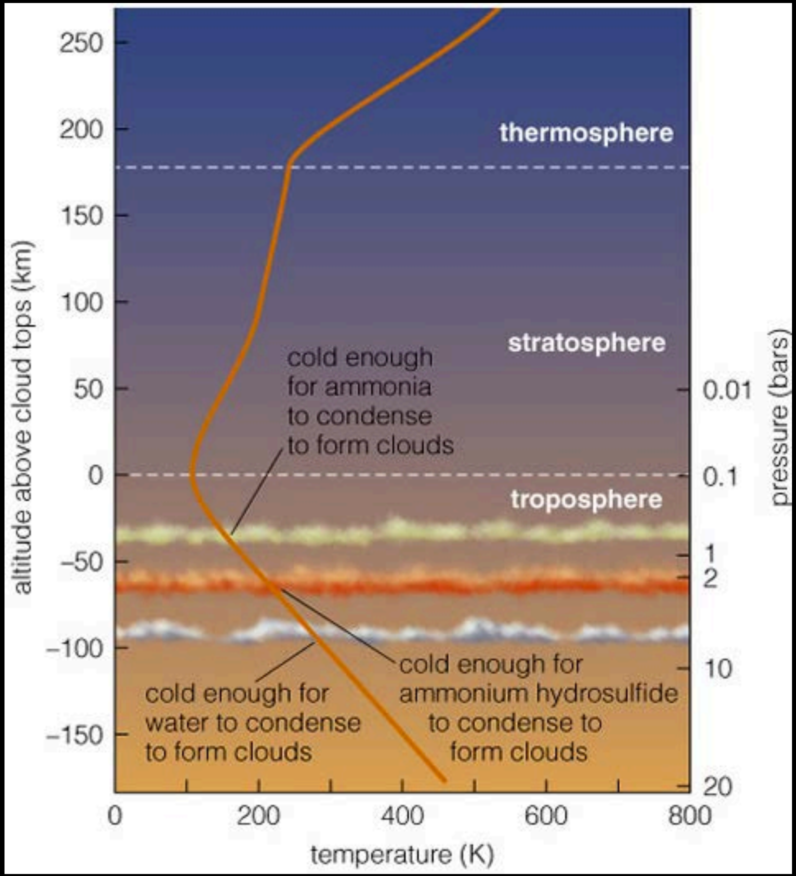
- Mostly CH_4, H_2O, NH_3, H_2S + rocks
- CH_4 and H_2S clouds.
- Formed slowly.
- Superionic H_2O ice mantle at great depth.



- Mostly H_2 and He.
- NH_3 and NH_4SH clouds.
- Formed quickly.
- Metallic H_2 at great depth.

Orientation: Infrared Sounding of Giant Planet Atmospheres



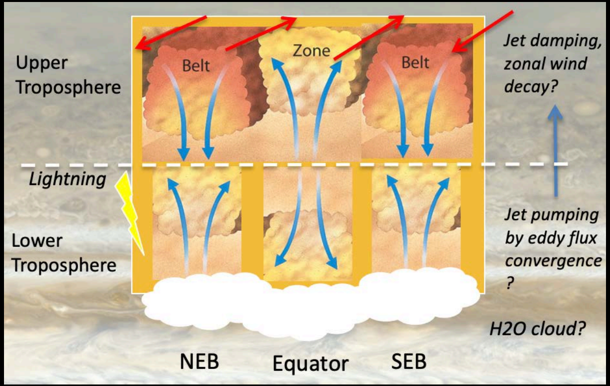


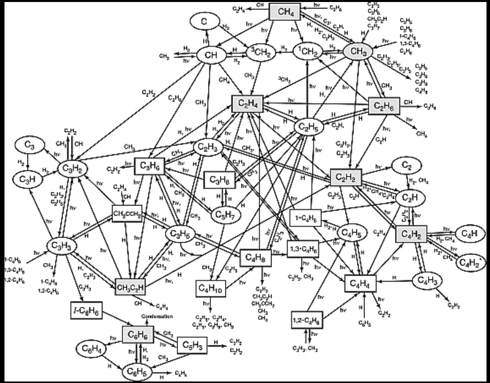
Key Questions for SOFIA

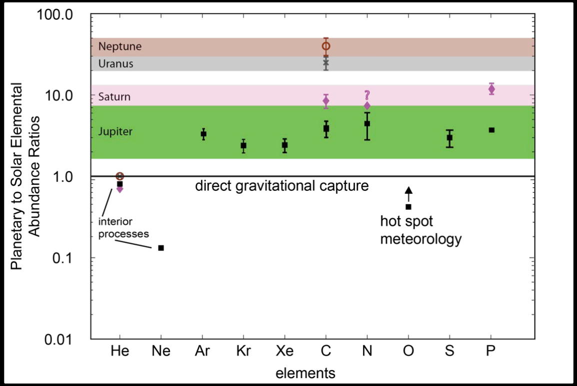
DYNAMICS:
How does planetary circulation differ from gas to ice giants?

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?

Spatially-resolved low-R thermal-IR spectra/images of H2-He continuum (>16 µm) to measure spatial contrasts in temperature & composition.

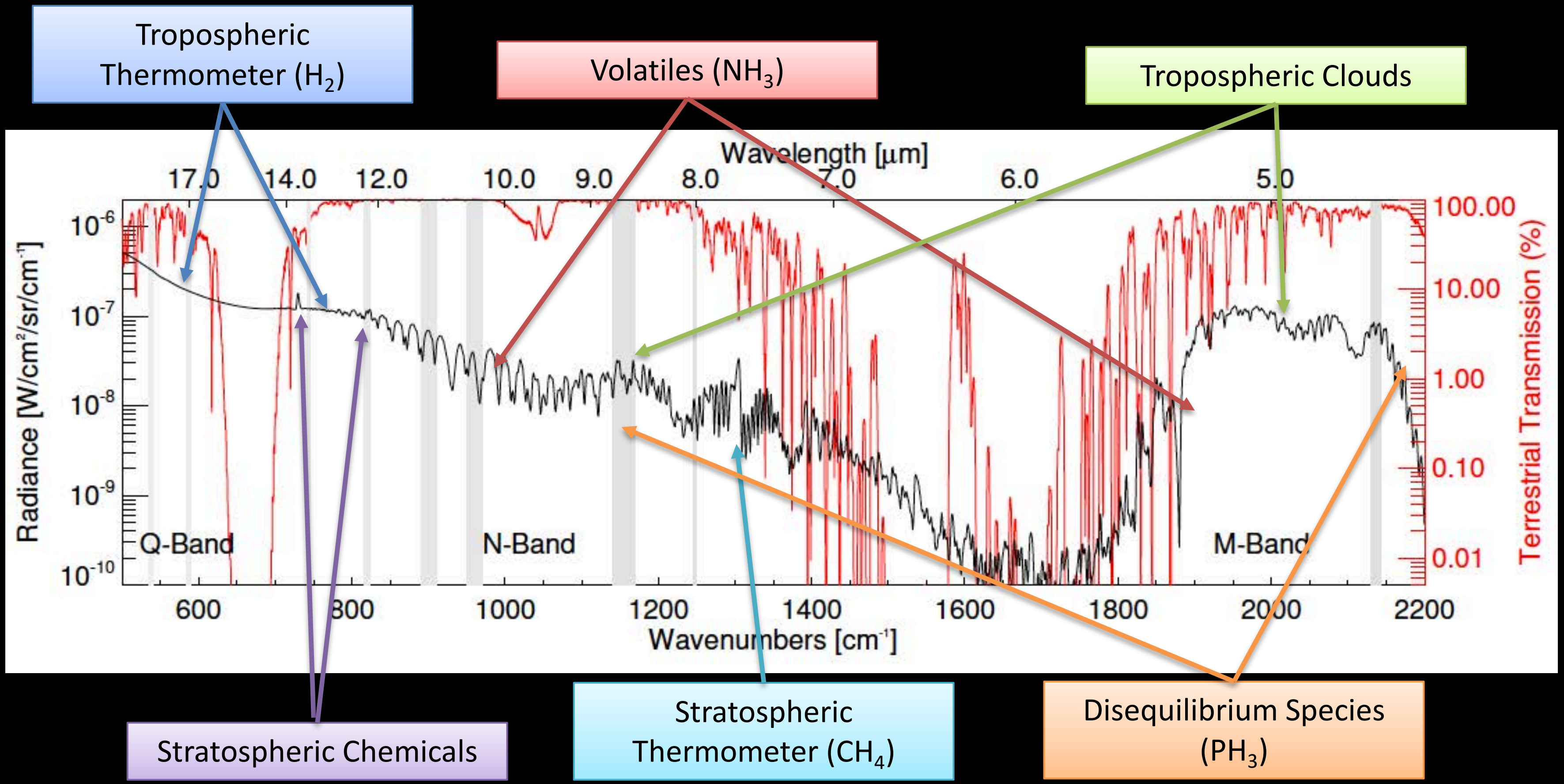
CHEMISTRY:
How do photochemistry, aurora, and exogenic material shape planetary stratospheres?

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

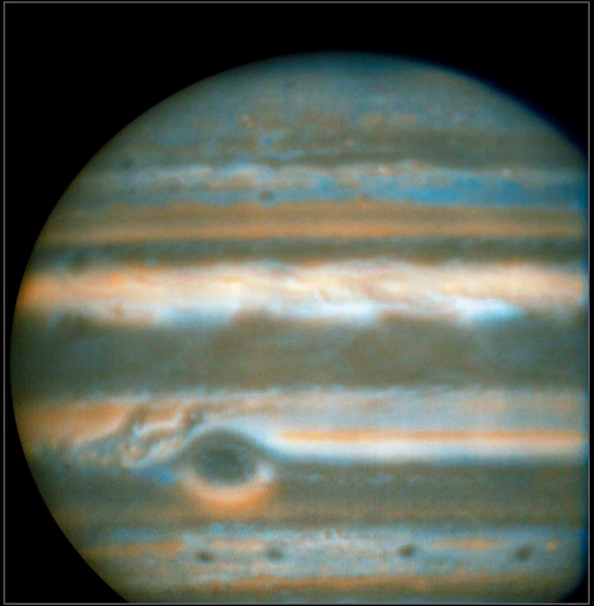
ORIGINS:
What does the bulk composition reveal about planetary origins?

Disc-integrated high-R far-IR spectra of HD, CH4, CO, H2O features inaccessible from the ground.

Mid-Infrared Observations



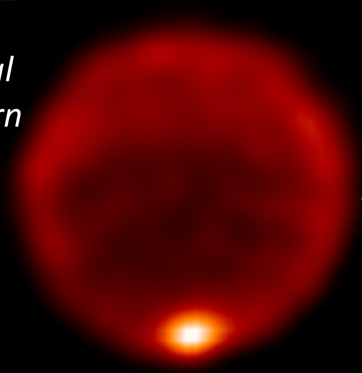
Mid-IR Highlights from VLT/VISIR



Natural cycles in jovian belts and zones at 8.6 and 10.8 µm – temporal variability (Fletcher et al., 2017).

Giant storms and seasonal change at 18 µm on Saturn (Fletcher et al., 2011).

Stratospheric circulation at 13 µm (acetylene) on Uranus (Roman et al., 2020).

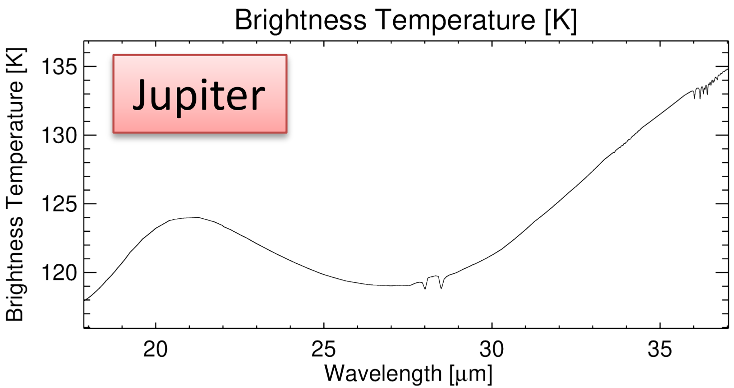


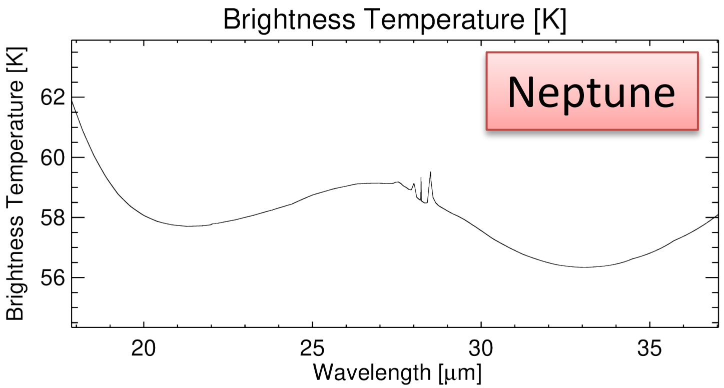
Polar vortex and stratospheric bands at 7.9 µm (methane) on Neptune (Sinclair et al., 2020)

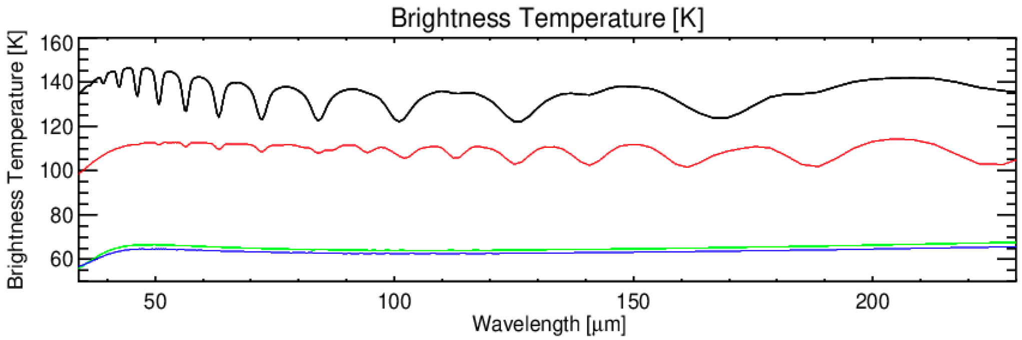
Giant Planets observed from 8-m facilities in telluric windows.

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

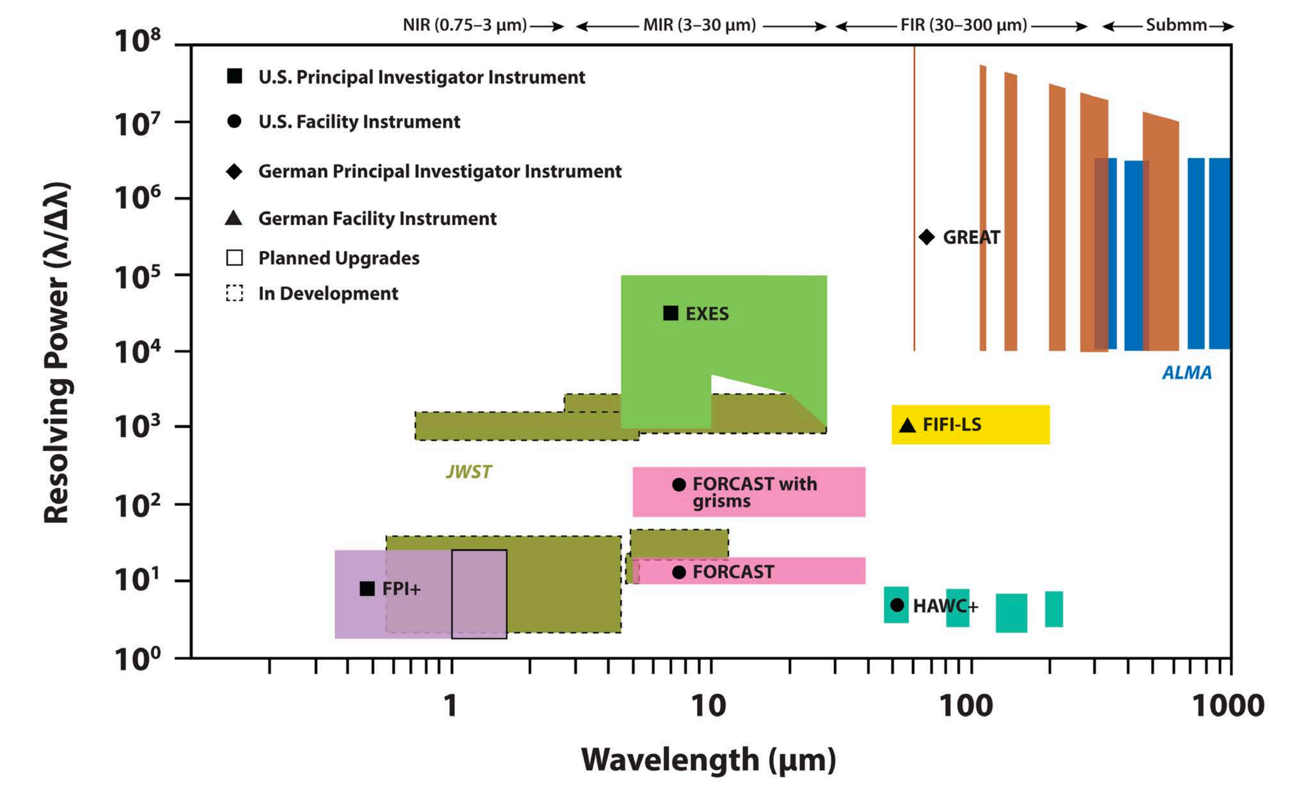






- Synthetic calculations of brightness temperature (low-R).
- H2-H2 and H2-He collision-induced absorption (plus dimers) reveal tropospheric T(p) and para-H2 (e.g., **circulation**).
- Rotational features of PH3 and NH3 (e.g., **clouds/chemistry).**
- Rotational features of HD and CH4 for D/H and C/H measurements (e.g., **origins**).

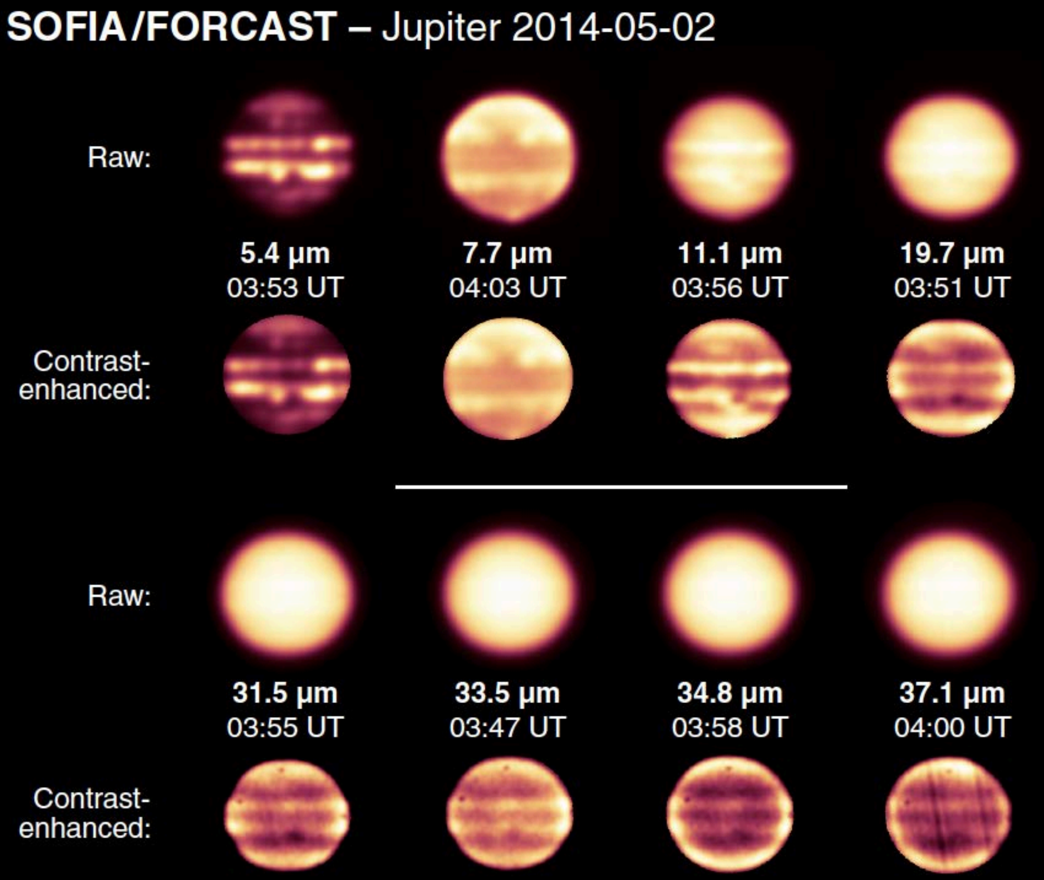
Assessing SOFIA's Current Instruments



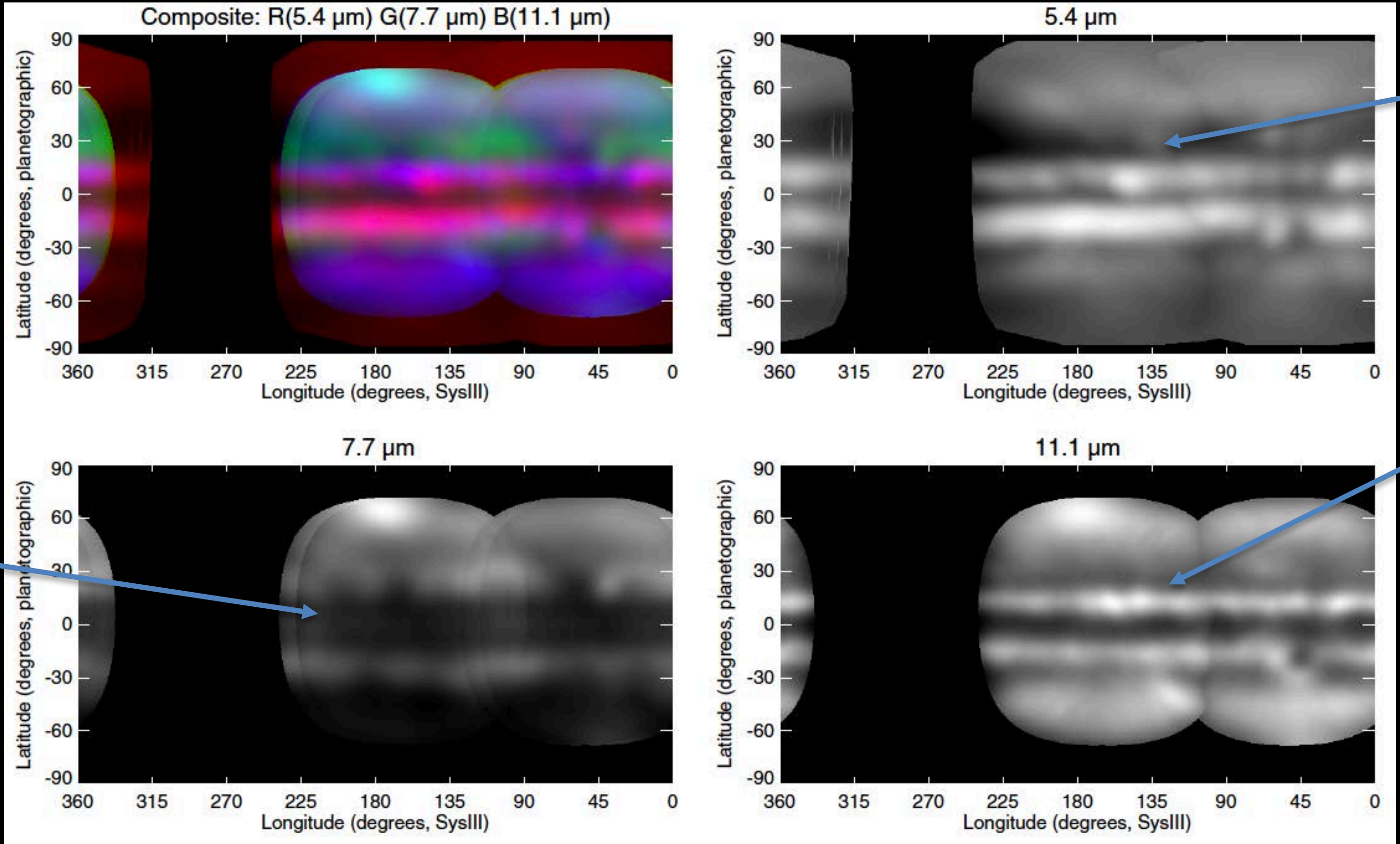
- **Dynamics**: FORCAST H2-He observations in MIR/FIR.
- **Chemistry**: EXES observations of stratospheric emission.
- **Origins**: GREAT observations of narrow features?
- FIFI, FPI+, HAWC+ don't contribute.

FORCAST Observations of Jupiter - Dynamics

- 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

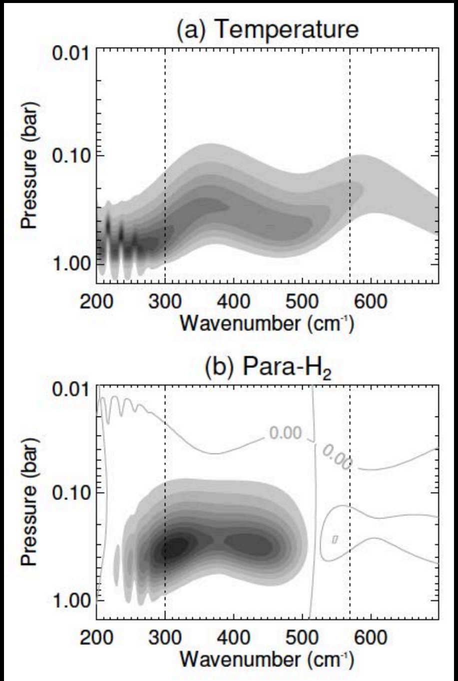


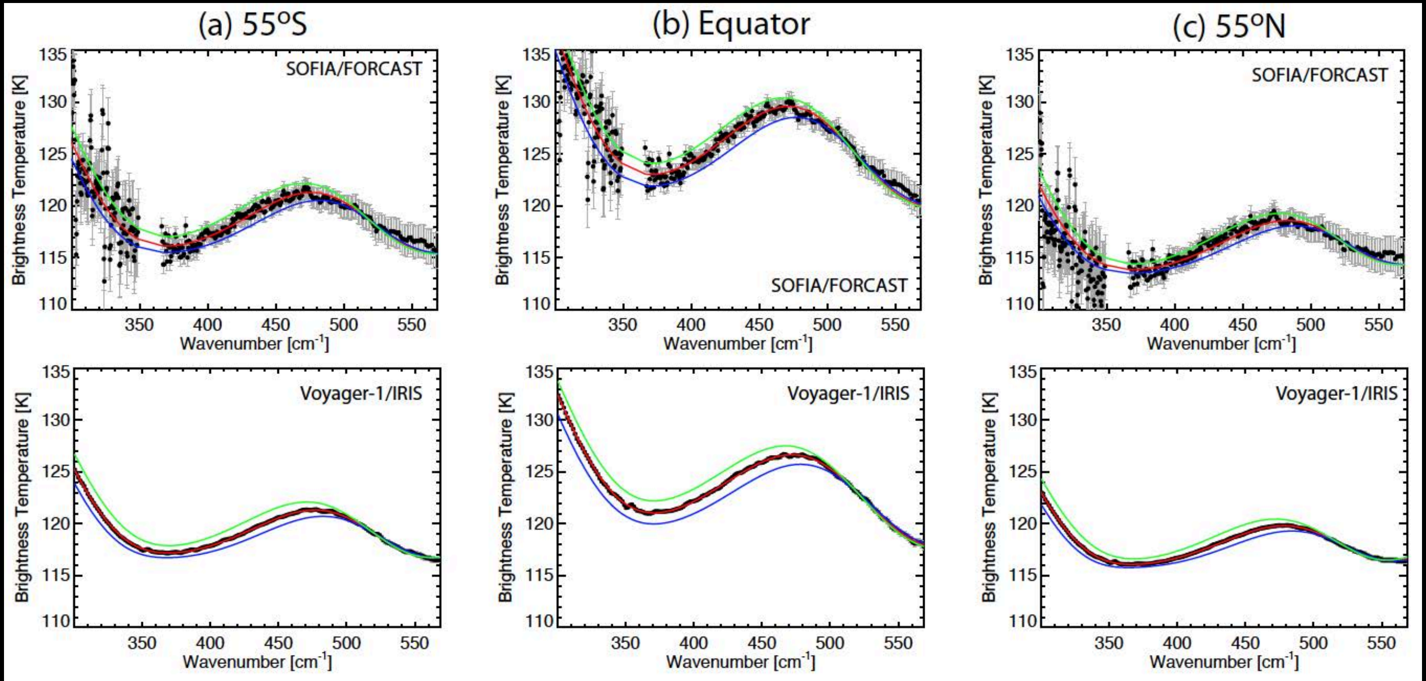
Thermal radiance from gaps in deep clouds.

Stratospheric temperatures, including auroral heating

Tropospheric temperatures and NH3 above clouds.

FORCAST Spectroscopy: Jovian Para-Hydrogen





- Comparing FORCAST and Voyager/IRIS (1979) spectra: both constrain temperature and para-H2 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-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)

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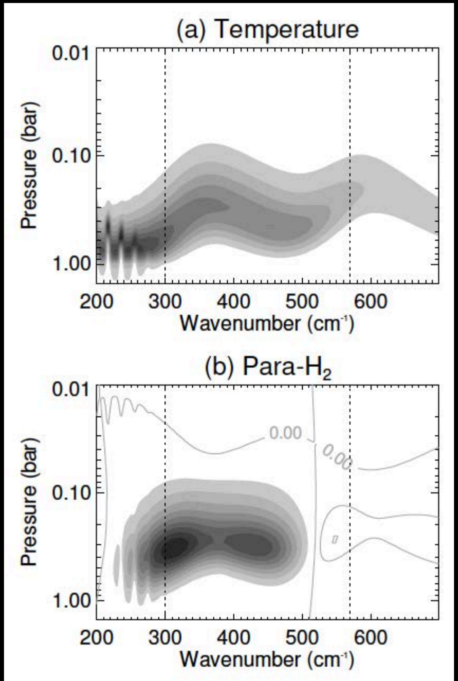

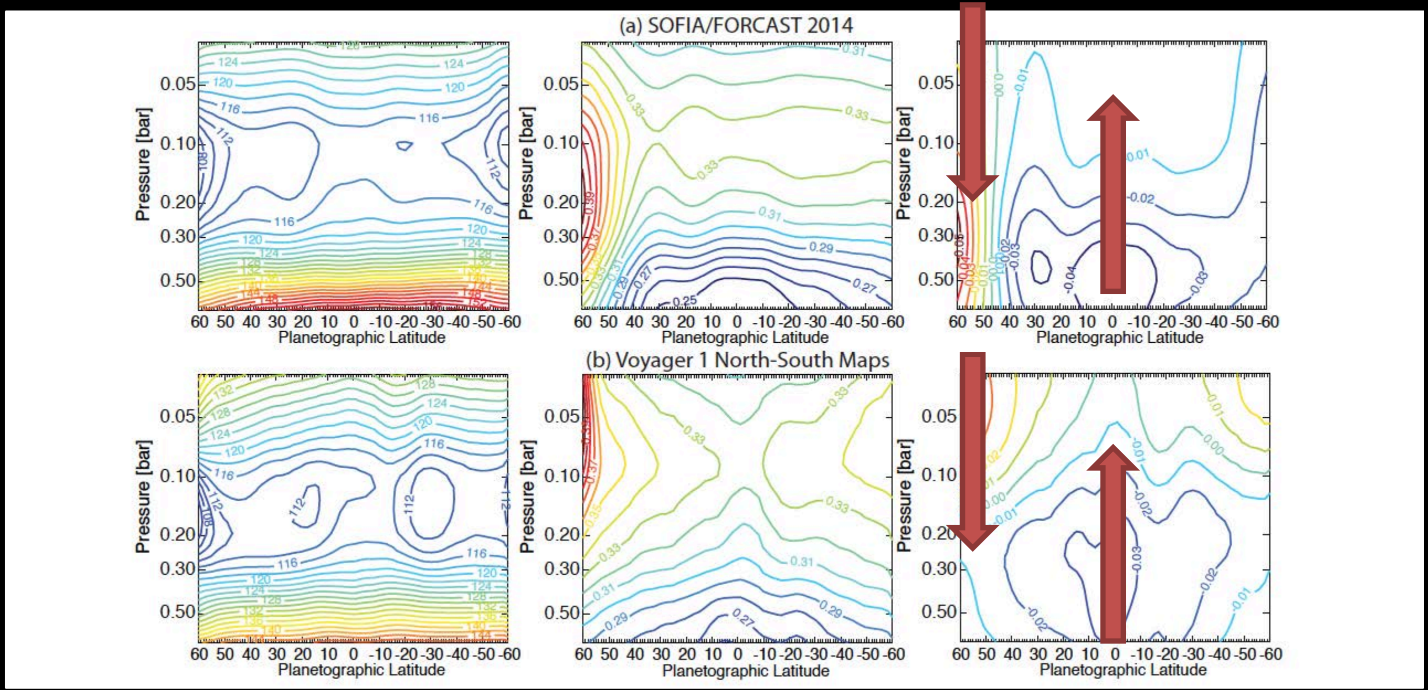

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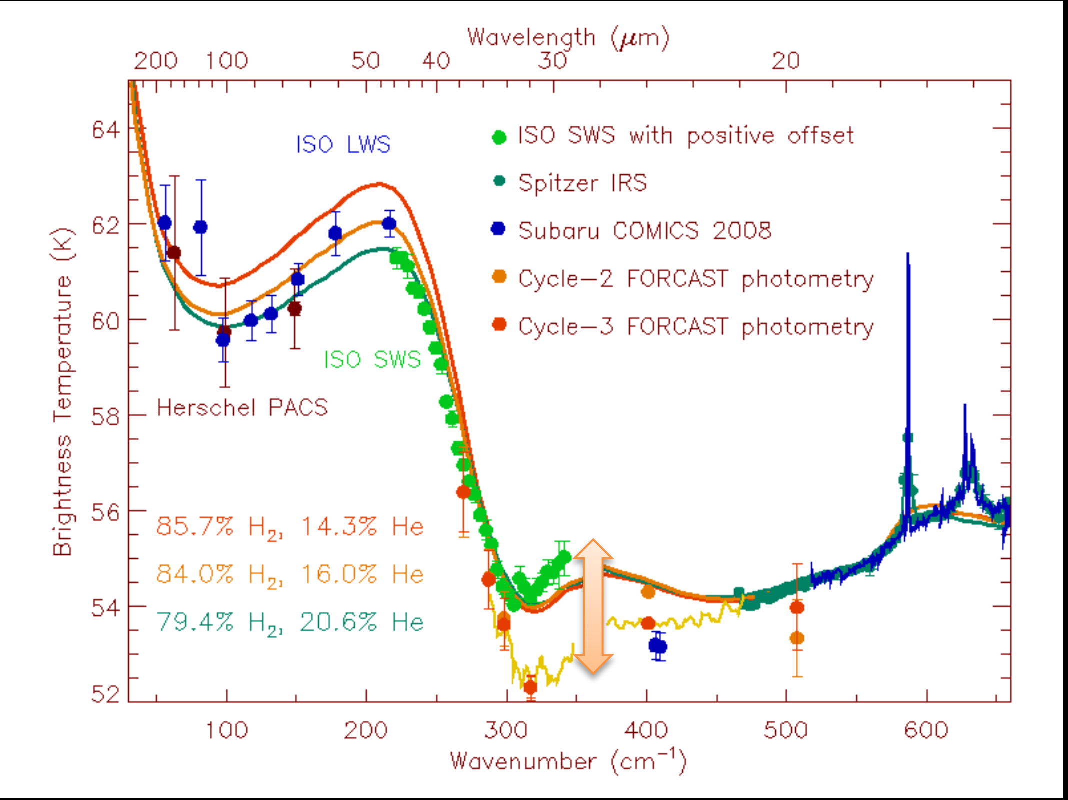
FORCAST Uranus – Ice Giant Origins

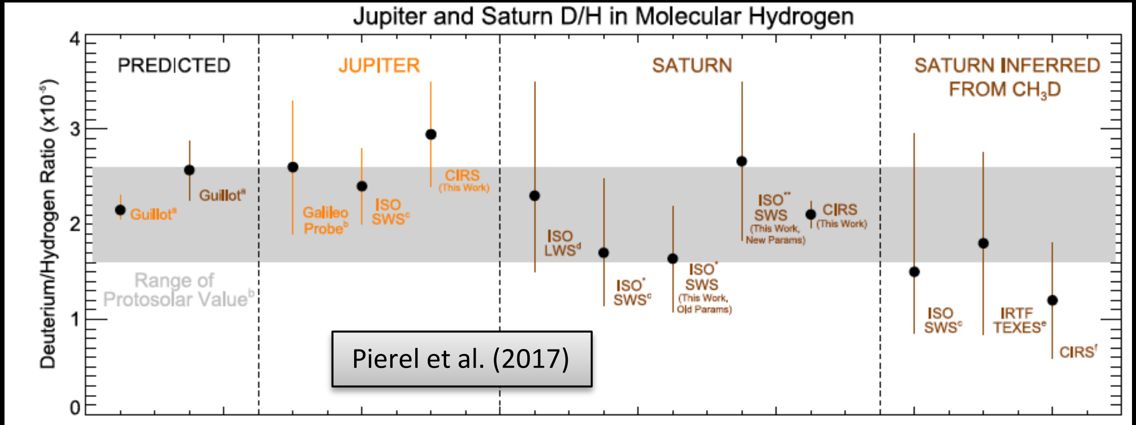
- Attempt to cross-calibrate Spitzer/IRS, SOFIA, Subaru, and ISO/SWS observations.
  - Much deeper than expected near 300 cm^{-1}.
- Fitting constraints on para-H_2 and He/H_2 ratio (poorly known for Ice Giants)
  - Key to achieving a unified physical model for structure, chemistry and their spatial variability.
- ***Careful new FORCAST measurements/calibration required to pin this down.***
- ***Maybe attempt to improve observational efficiency for more time on-sky?***



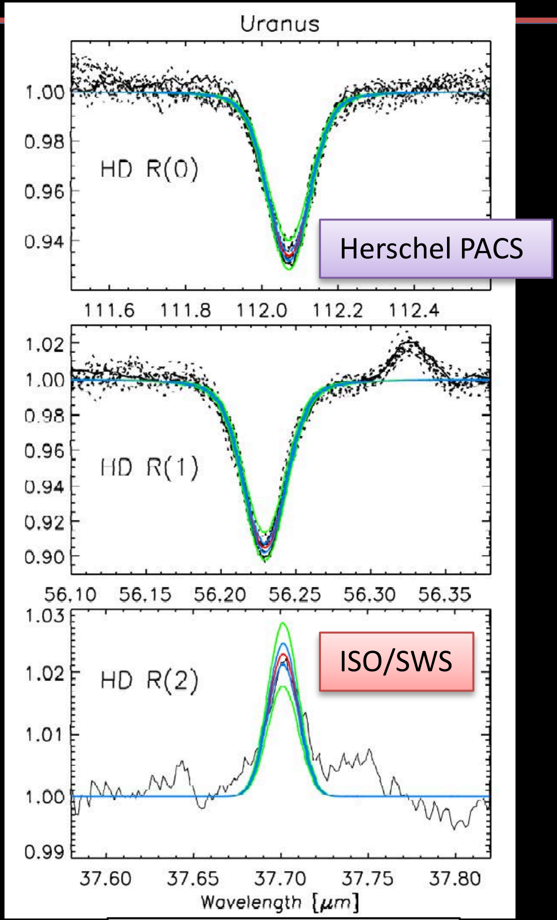
Credit: Orton et al.

GREAT – Planetary Origins

- Possible new mode of GREAT (not implemented): D/H on all 4 outer planets.
- HD R(0) line at 112.07 µm = 2.676 THz.
  - Currently 4GREAT 2.54THz works only 2.49 to 2.59 THz, missing HD.
  - Independent constraint on stratospheric T would come from CH_4 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).

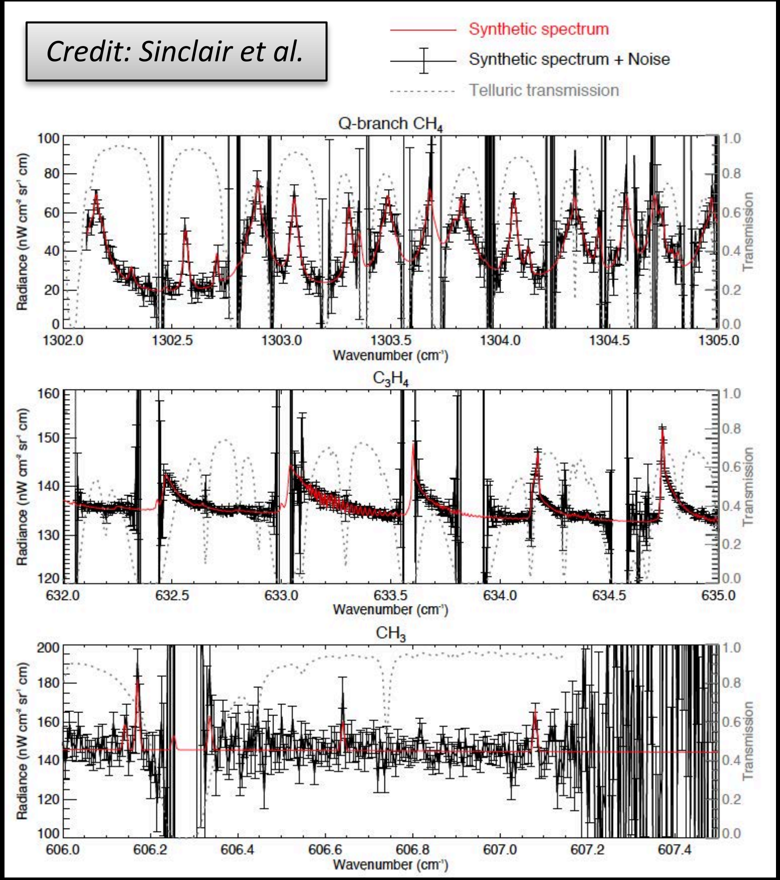


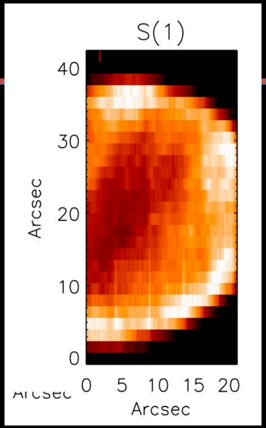
Pierel et al. (2017)

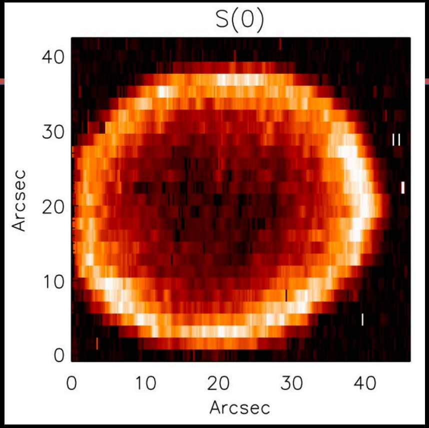


Feuchtgruber et al. (2013)

EXES Jupiter - Gas Giant Chemistry







- EXES Provides access to spectral regions inaccessible from the ground.
  - 2014 EXES spectral maps of H_2 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).

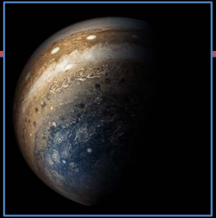
- ***A comprehensive EXES spectral survey would provide new insights into atmospheric chemistry.***
- ***Improve stabilization of instrument/aircraft for better spatial resolution.***

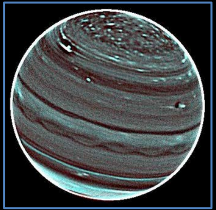
Returning to the Key Questions

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_2. Adaptation of GREAT to allow comparative planetology for HD.*

Existing instruments nicely bridge the gap between ALMA and JWST.
Identified upgrades to FIFI-LS, FPI+, HAWC+ will not necessarily assist the Giant Planet community.
Improved observational efficiency = more time on-sky (esp. spectra) would be a great improvement.
Increased stabilization for better spatial resolution = big help for Jupiter/Saturn.

Future Giant Planet Opportunities

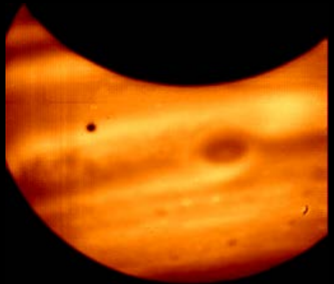


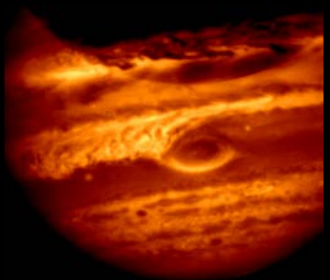


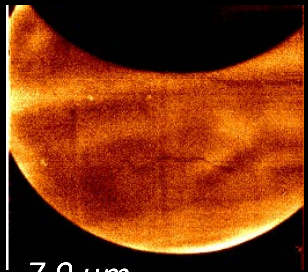
- **Mid-IR** will be well-covered by JWST 5-30 µm at R~3000, and imaging from 8-m facilities, BUT:
  - – Jupiter saturation issues on Webb.
    - Lower spectral resolution than (T)EXES.
    - Limited prospect for temporal variability studies with Webb.
    - Webb cross-calibration with (T)EXES?
  - – Desire for simultaneous spectro/spatial imaging (e.g., IFU-like).
- **Far-IR** > 25 µm remains challenging:
  - – Complete carefully-calibrated FORCAST survey of all four giants for T/para-H_2/He
    - *Use current instruments in a more productive way?*
  - – Adaptation of GREAT to sample HD and recover lost HIRMES science.

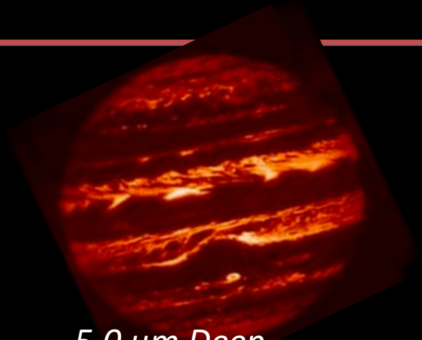
Backup Slides

Vertical Sounding of Jovian Atmosphere









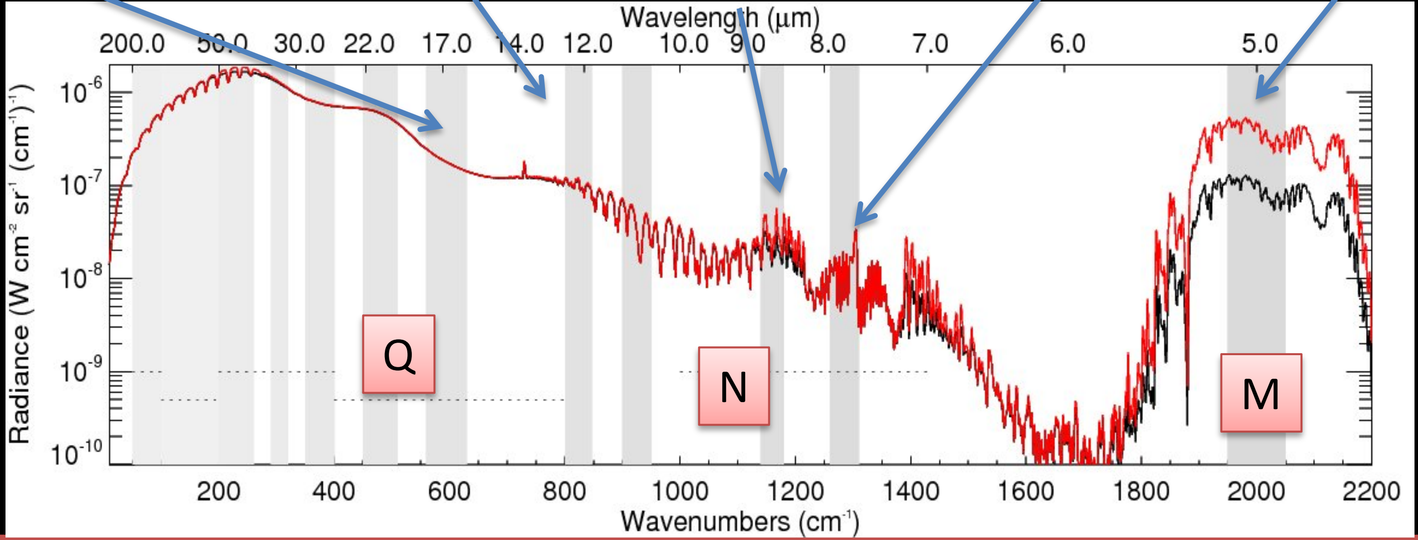
Q-band 100-400 mbar T

13.0 μm Deep T and C2H2

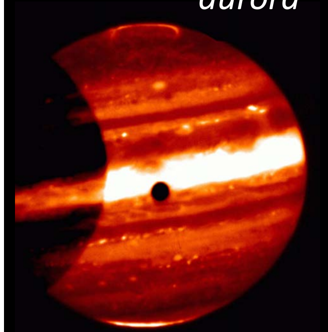
8.6 μm Ammonia & Clouds

7.9 μm Stratospheric T

5.0 μm Deep Clouds



3.5 μm Reflectivity and aurora



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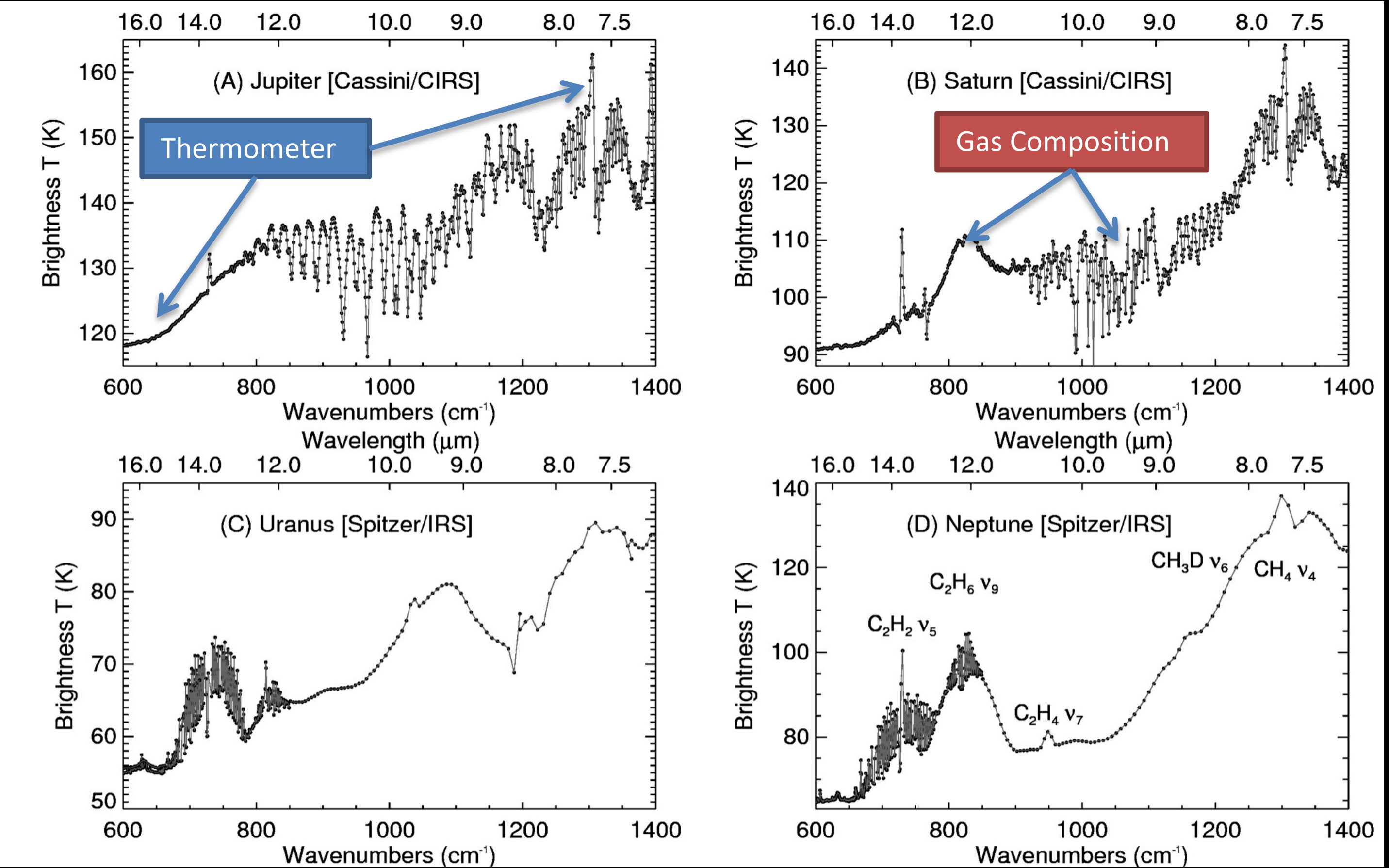
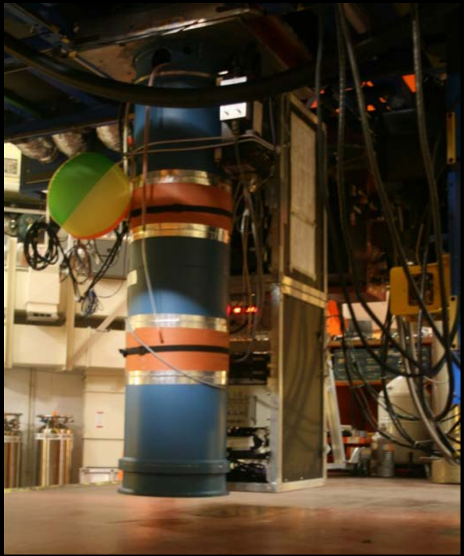
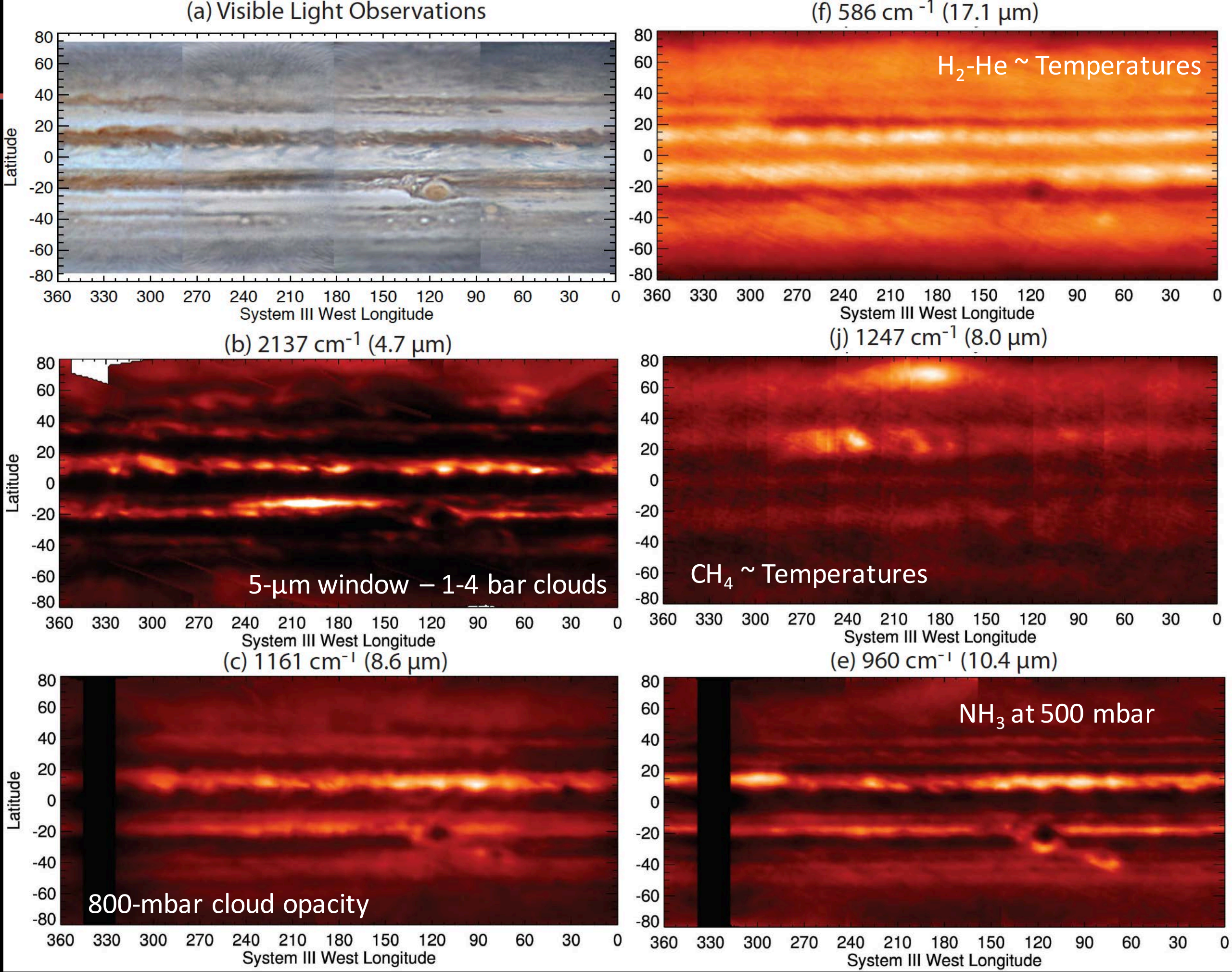
Mid-IR 7-16 µm Observations



IRTF Mapping

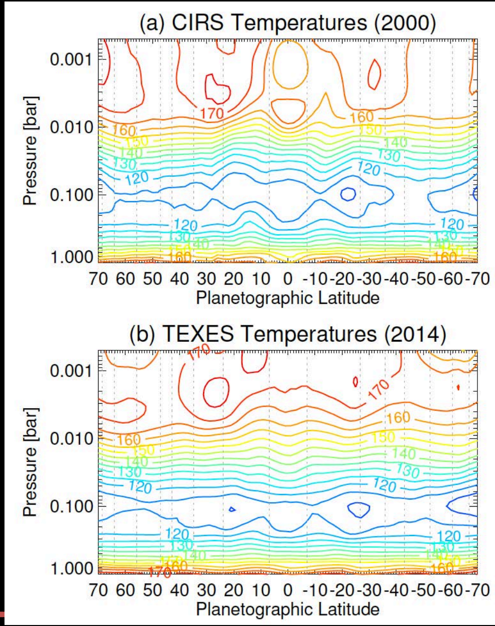
- Shorter wavelengths than FORCAST 5-20 μm.
- Programme to track jovian climate over full year.
- Global spectroscopic mapping for 1st time with TEXES.
- Only possible with ~10 hours of good conditions, challenge for EXES.

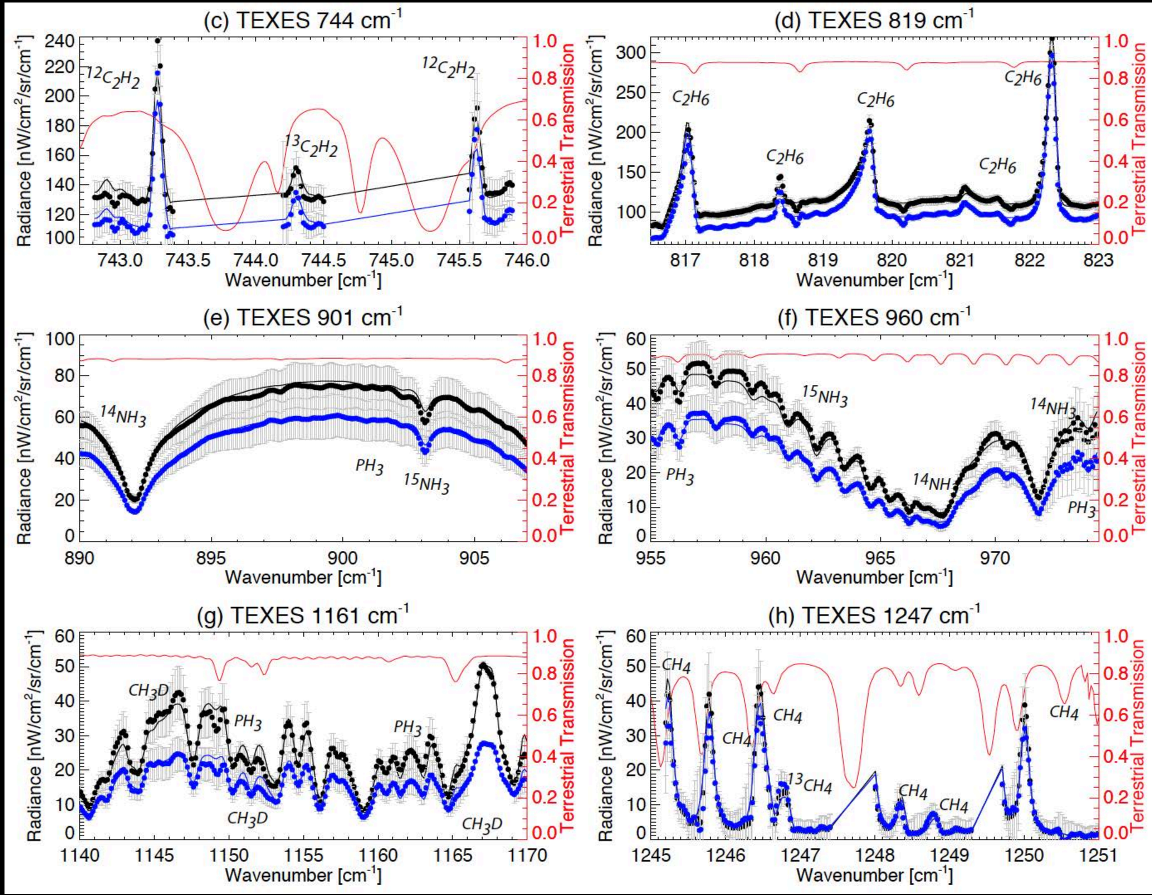




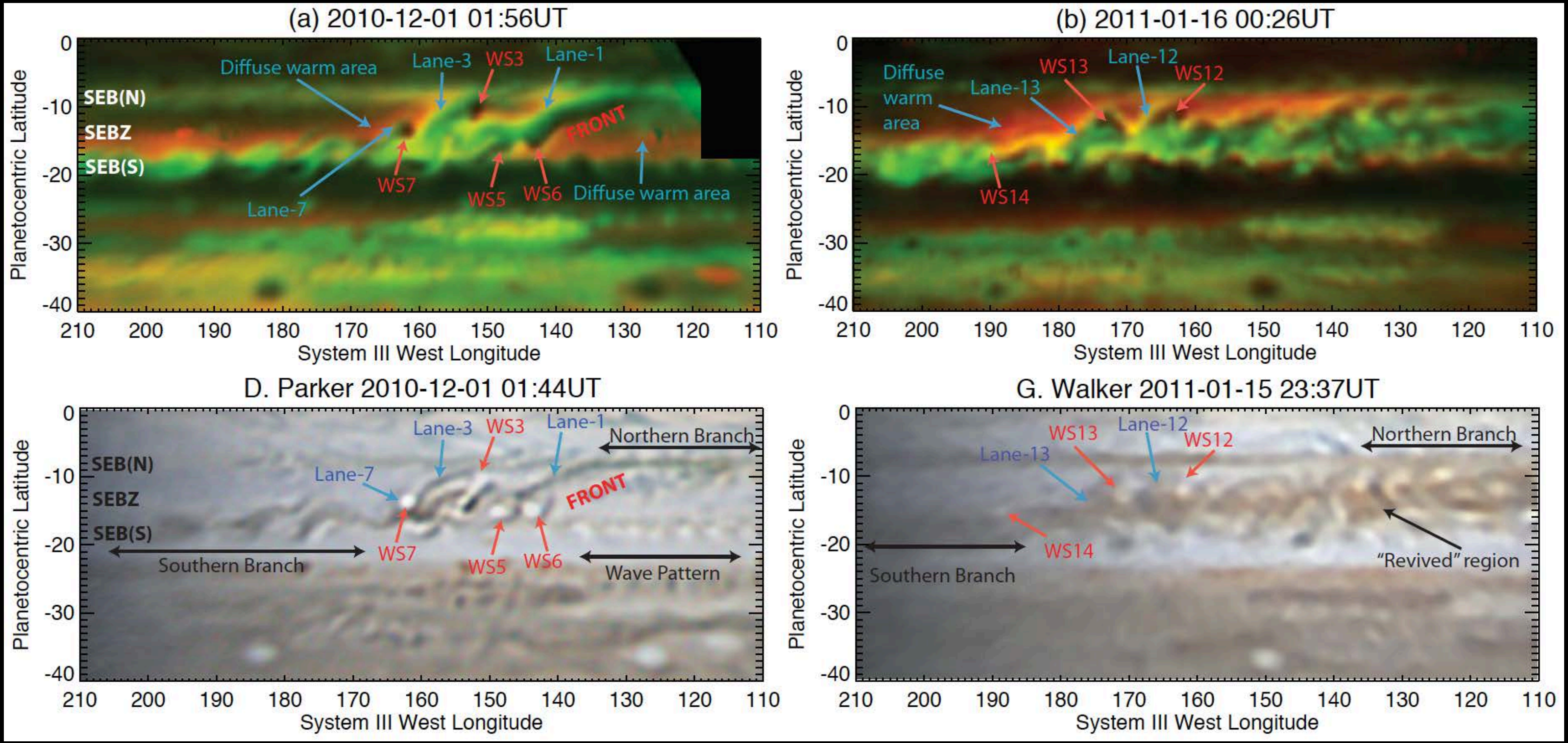
TEXES Spectroscopy

- 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.





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.