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

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Beyond the Clouds...

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...to 3D atmospheric sounding
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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?
Challenge of Outer Solar System Exploration

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

- Voyager 1 124 AU
- Voyager 2 102 AU
- Galileo @ Jupiter
- Cassini @ Saturn
- 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.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral Capabilities</th>
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<tbody>
<tr>
<td>MWR</td>
<td>radiometry in channels centered at 1.3, 3.125, 6.25, 12.5, 25, and 50 cm wavelength</td>
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<tr>
<td>JIRAM</td>
<td>imaging in filters at 3.4 and 5.0 µm; 9-nm resolution spectroscopy at 2.0-5.0 µm</td>
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<tr>
<td>JunoCam</td>
<td>broad-band red, green, blue filters; medium-band filter centered on the 890-nm CH₄ absorption feature</td>
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<tr>
<td>UVS</td>
<td>0.6-1.1 nm resolution spectroscopy at 70-205 nm</td>
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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.
Grim Spectroscopy

Grism Spectroscopy

(a) SOFIA/FORCAST
(b) Voyager 1

Wavenumber [cm⁻¹]

600.0 500.0 400.0 350.0 300.0 270.0

Brightness Temperature [K]

140 135 130 125 120 115 110

Wavelength [μm]

20 30 35

Grism | Wavelength range | R = λ/(Δλ) | 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

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- 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 $T = \text{rising}$, adiabatic expansion, cooling.
- High $T = \text{falling}$, adiabatic compression, heating.

**Para-H2:**
- Low $f_p$ (sub-equilibrium) = rising.
- High $f_p$ (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!

**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

- 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!

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

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

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

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

(a) MIRSI 8.70 μm 2010-11-04 23:19UT

(b) VISIR 8.59 μm 2010-11-11 23:56UT

A. Lasala 2010-11-05 18:52UT

C. Go 2010-11-12 1:03UT
SEB Revival and Plume Evolution

(a) 2010-12-01 01:56UT

(b) 2011-01-16 00:26UT

D. Parker 2010-12-01 01:44UT

G. Walker 2011-01-15 23:37UT

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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.