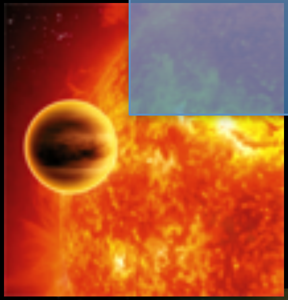
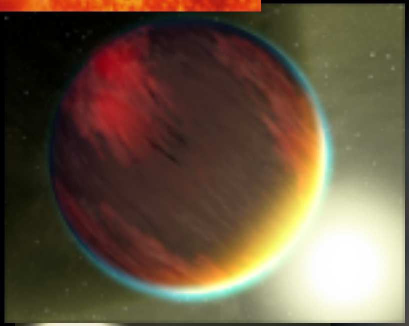
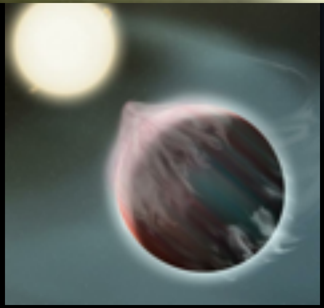
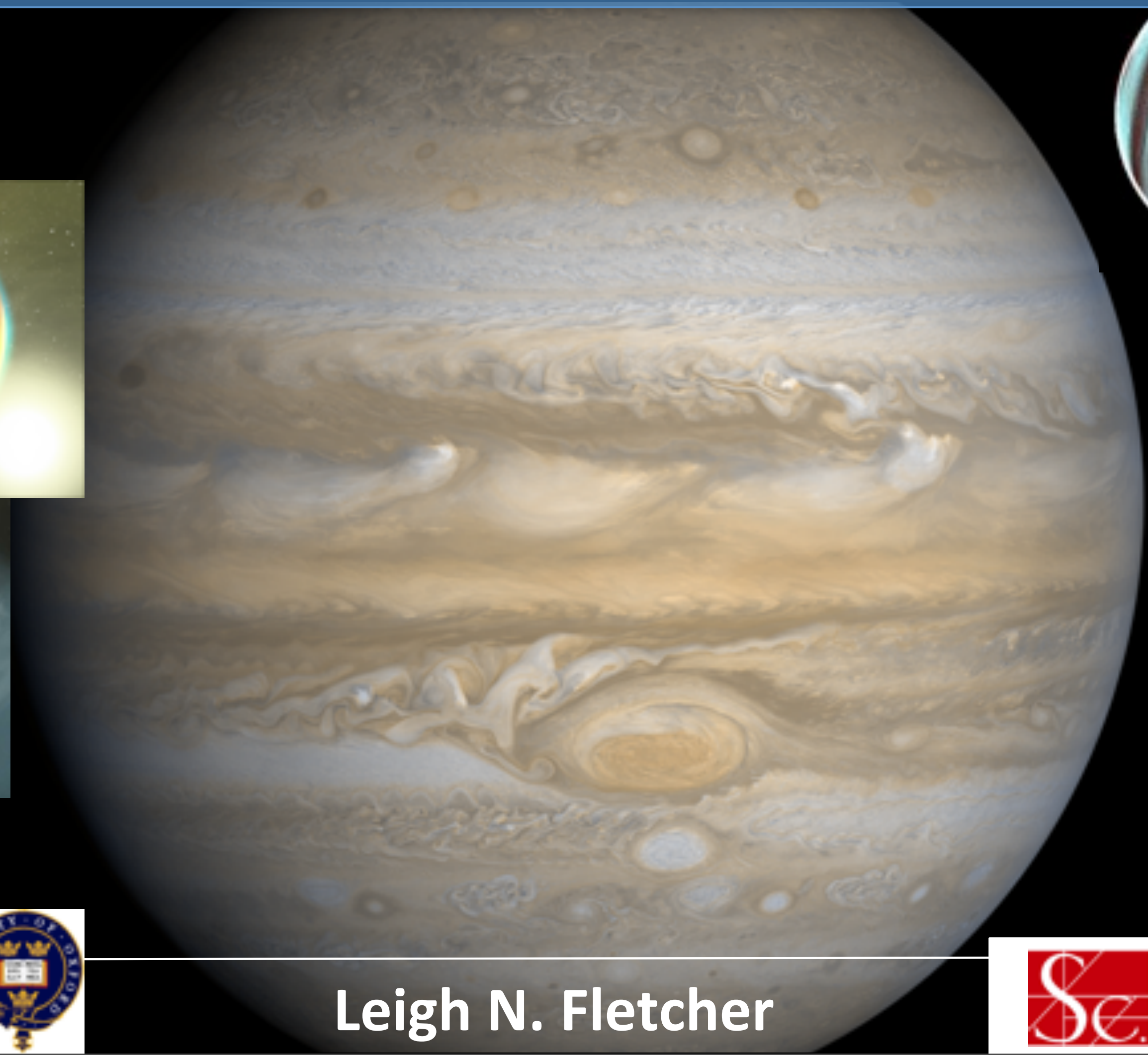
# The Diversity of Giant Planets:

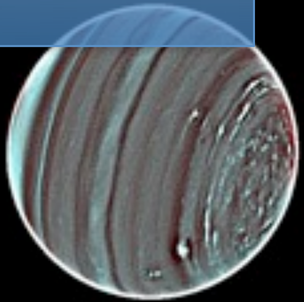
## Infrared Observation and Data Analysis

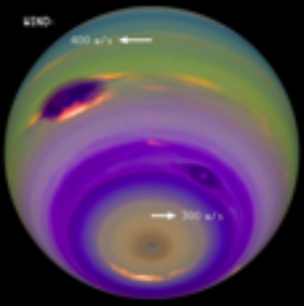












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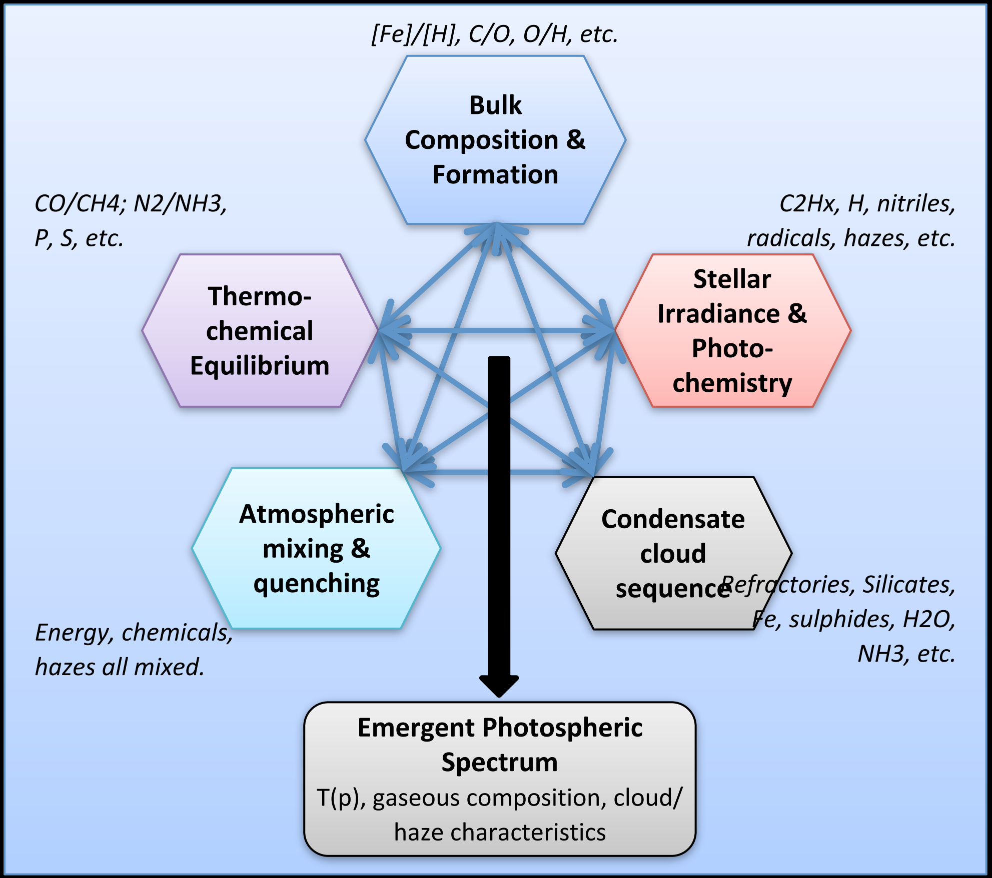
THE ROYAL SOCIETY

Leigh N. Fletcher

# Continuum of Jupiter-Class Planets

- **890+ exoplanets confirmed to date** is opening a new era for comparative planetology:
  - Not including Kepler candidates, high abundance of Neptune class.
- Cool (100 K) and hot (2500 K) **jovians exist on a continuum.**
  - **Our giants as a template for a common astrophysical object.**
- **Comparative planetology**:
  - Processes: How do physical/chemical processes interact to shape giant planet structure?
  - Origins: How do giant planets form, implications for habitable planetary systems?
  - Time domain science: What drives the spatial & temporal variability of planetary atmospheres?



# Overview: Challenges for Giant Planet Science

**OBSERVATION REQUIREMENTS**

1. Beyond imaging – high-resolution spectro-spatial mapping.
2. Broad simultaneous spectral coverage to connect environmental and visible changes.
3. Long baseline observations for time-domain science.
4. In situ exploration.

**SPECTRAL MODELING**

Inversion of spectra to deduce atmospheric properties.

**INTERPRETATION**

1. Condensation chemistry and planetary taxonomy.
2. Three-dimensional troposphere/stratosphere models: circulation, turbulence, waves, etc.
3. Bulk composition and formation of giant planets.
4. Sources of temporal variability.

*Challenges for future observation; new techniques; continuous 'real-time' records*

*Statistical approaches – what can we reliably extract from noisy, sparse data? What are the limitations?*

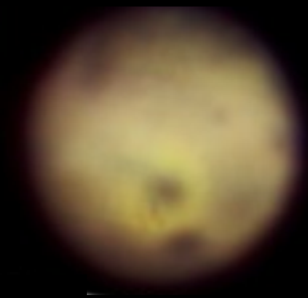
*A selection of four key objectives; hypothesis testing; comparative phenomenology; closer link between models and data.*

# Why the Infrared?

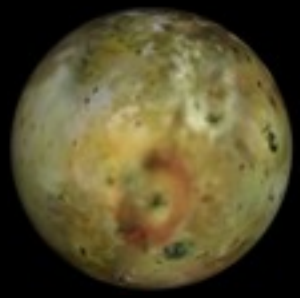
- **Crucial for T(p) and compositional measurement** - thermometers
- Amateur observers already providing a high-quality **record of visible albedo variability**.
  - Nightly records through online collaborations (e.g., PVOL).
  - Saturn storm watch
- IR challenging:
  - Telluric contamination
  - Diffraction-limited seeing requires larger facilities (e.g., long wavelengths often disc averaged).

Jupiter in 2010, Credit: Damian Peach

Credit: Darryl Milika and Patricia Nicholas



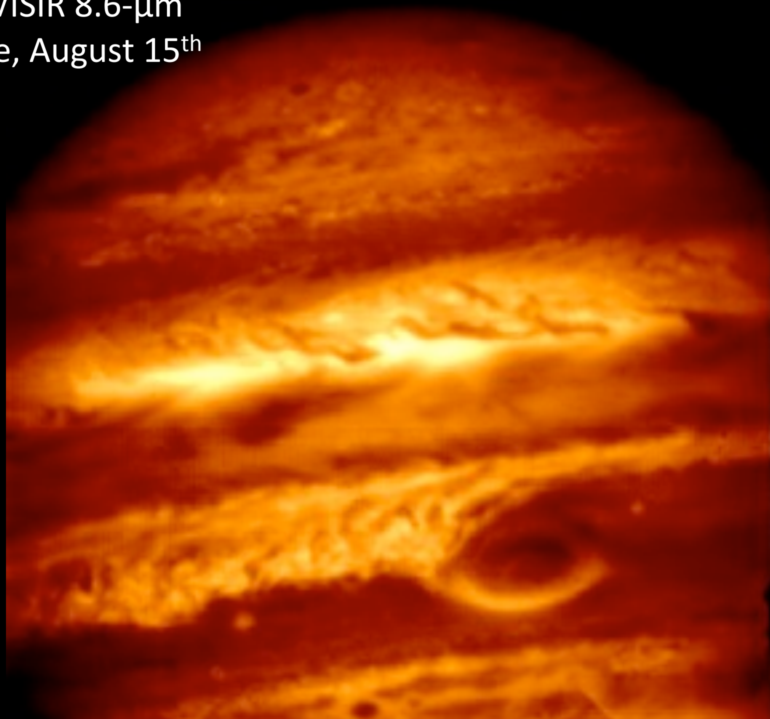
*Io from Palomar/ SWIFT (Dec 2012)*



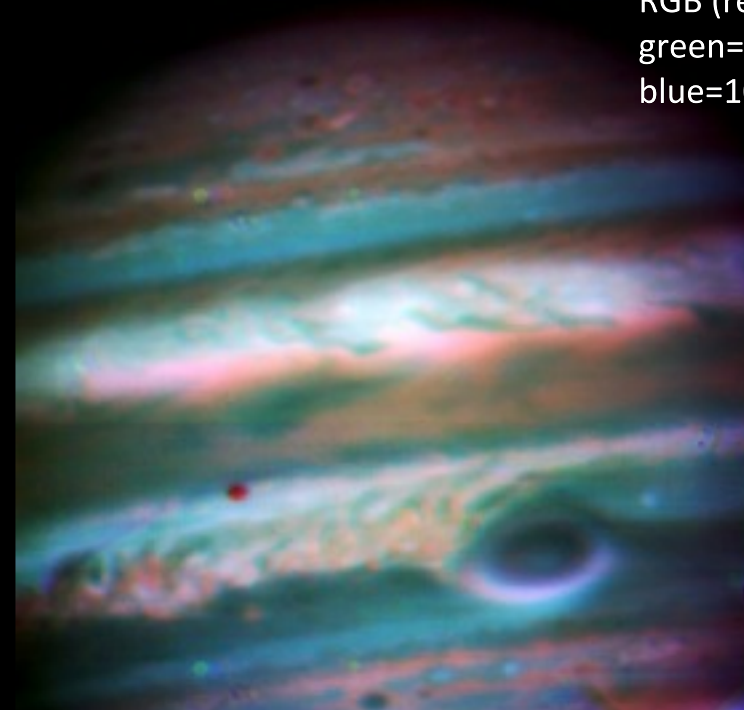
*Io from Galileo*

# Req 1: Beyond Imaging: Spectral Mapping

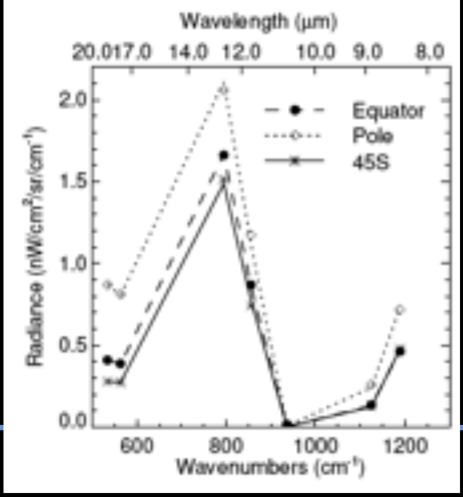
VLT/VISIR 8.6-μm image, August 15th 2007



RGB (red=8.6 μm, green=13 μm, blue=10.7 μm)

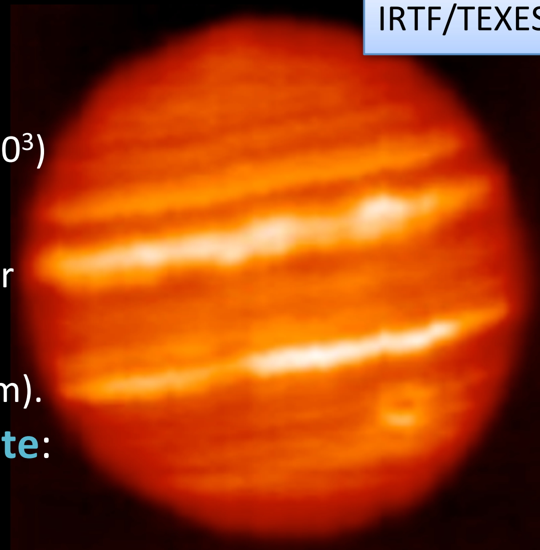


- IR Studies typically fall into two categories:
  - Narrow-band photometric imaging in selected bands.
  - Point spectroscopy of features of interest.
- Images are excellent for global context, poor on information content.
- Need a combination: full spectra for each of these pixels, e.g., Cassini/CIRS and Cassini/VIMS spectra of Saturn (image cubes).

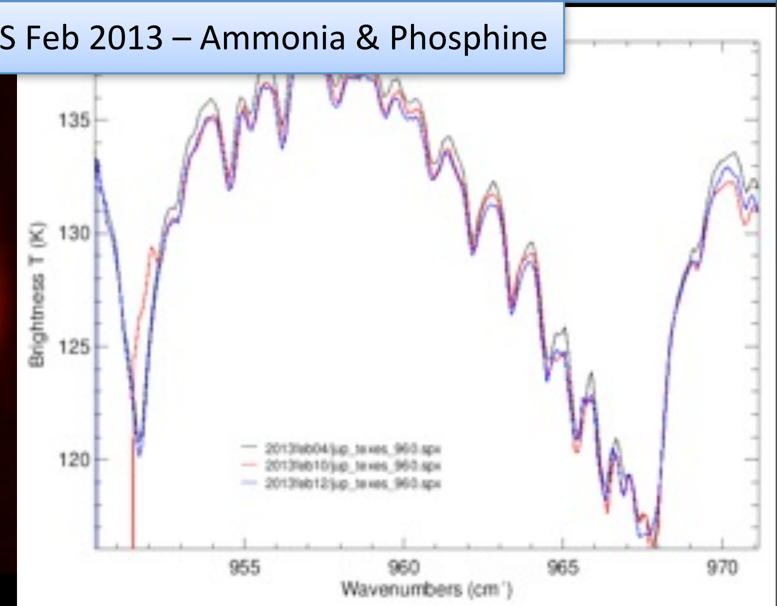


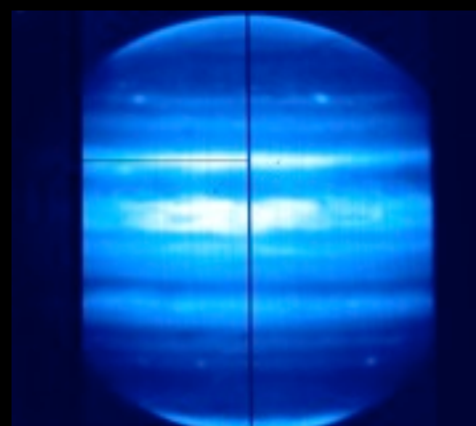
# Req 1: Beyond Imaging: Spectral Mapping

- Spectroscopy required to break degeneracies
  - Moderate resolution (R~$10^3$) for p-broadened tropospheric lines.
  - High (R~$10^6$) resolution for Doppler-broadened stratospheric lines, (e.g., Herschel and JUICE submm).
- **Two techniques used to date**:
  - Spectral scanning
  - Planetary rotation
- Future: integral field spectrographs and 2D interferometers, large class observatories?
- Planetary poles and seasonal asymmetries **still require visiting spacecraft**.



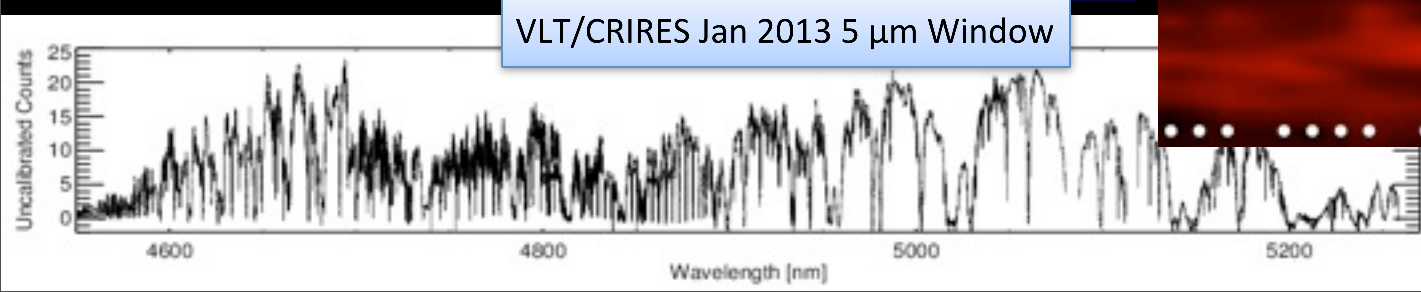
IRTF/TEXES Feb 2013 – Ammonia & Phosphine



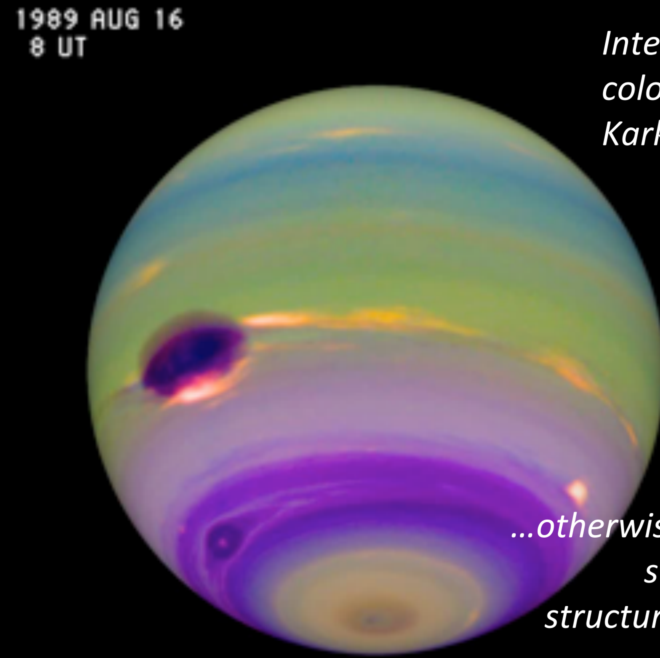
Gemini/TReCS 2010, Great Red Spot

VLT/CRIRES Jan 2013 5 µm Window



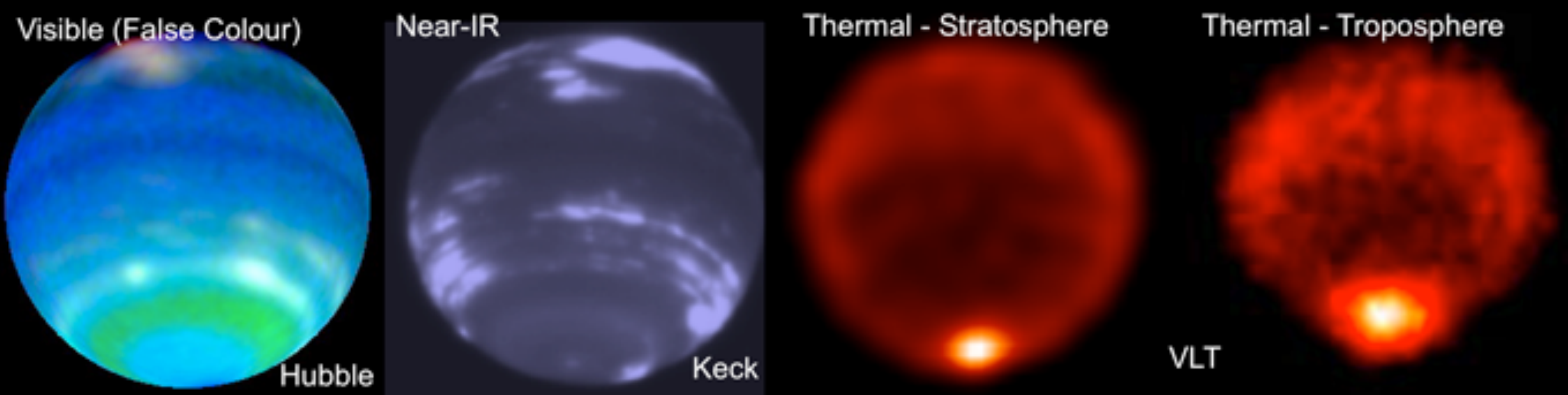
# Req 2: Broad, Simultaneous Coverage

- Aim to **connect visible changes** (clouds, colours, winds) to **environmental changes** (temperatures, composition, windshear).
- Requires reflected sunlight and thermal imaging at the same time.
  - E.g., Neptune stratospheric variability connected to convective activity at mid-latitudes?




*Interpolated images, false colour, from Voyager 2 (1989); Karkoschka (2011)*

*…otherwise we see changes in reflected sunlight with no idea of the 3D structure, temperatures, composition of the clouds…*



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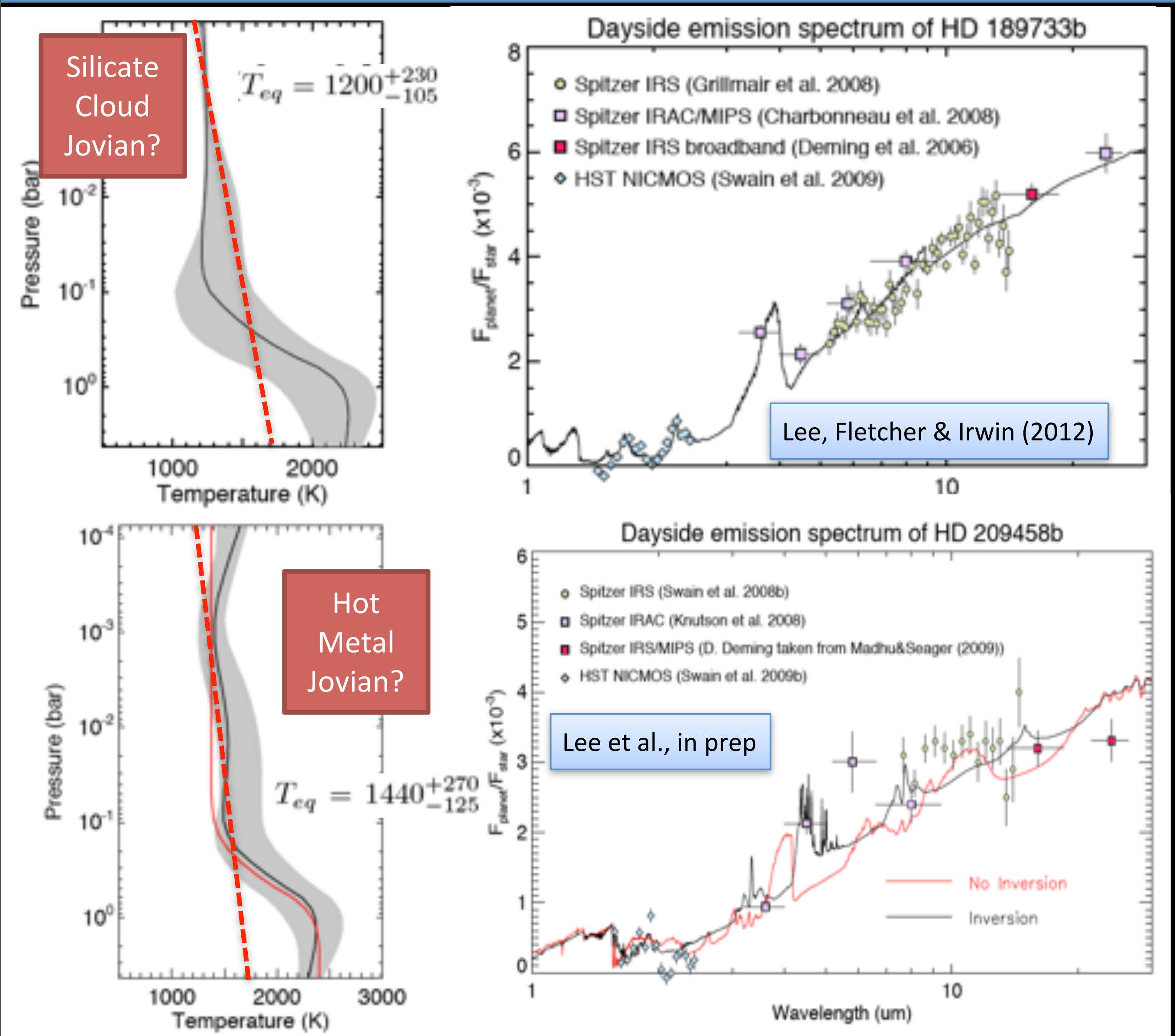



- Solar system science not alone - Broad spectral coverage extremely important for transit spectroscopy of exo-Jupiters.
- Solutions fitting broad-band filters wildly degenerate!
- Future missions (EChO) could provide 0.4-16 µm simultaneously.

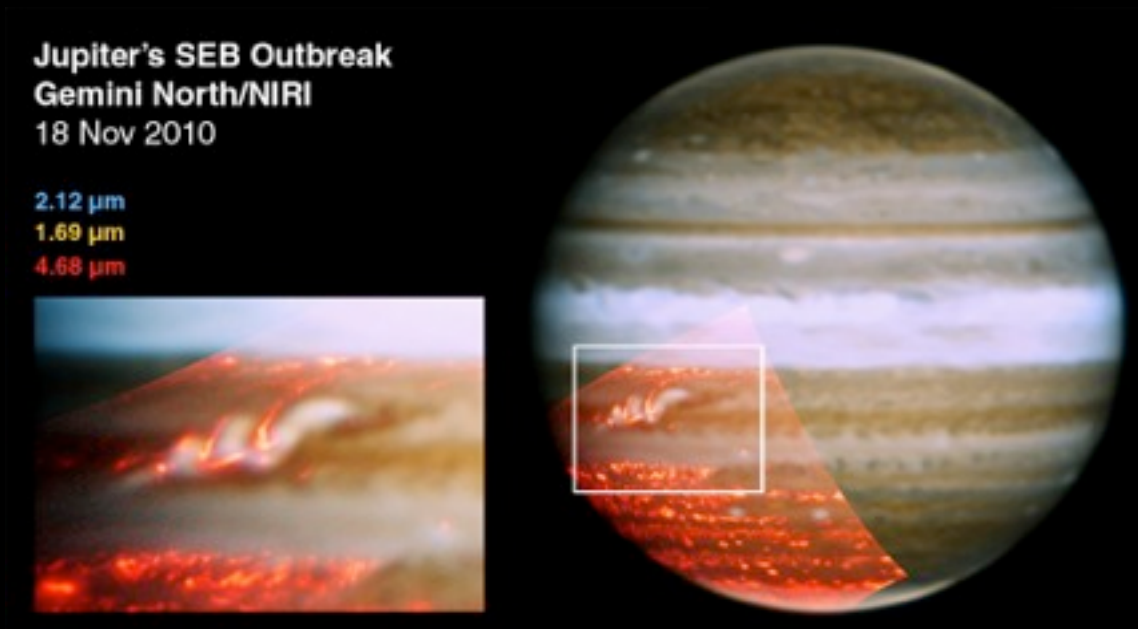
HD 189733b appears hazy but Na visible, no metals, no thermal inversion; HCN/C2H2 maybe important…

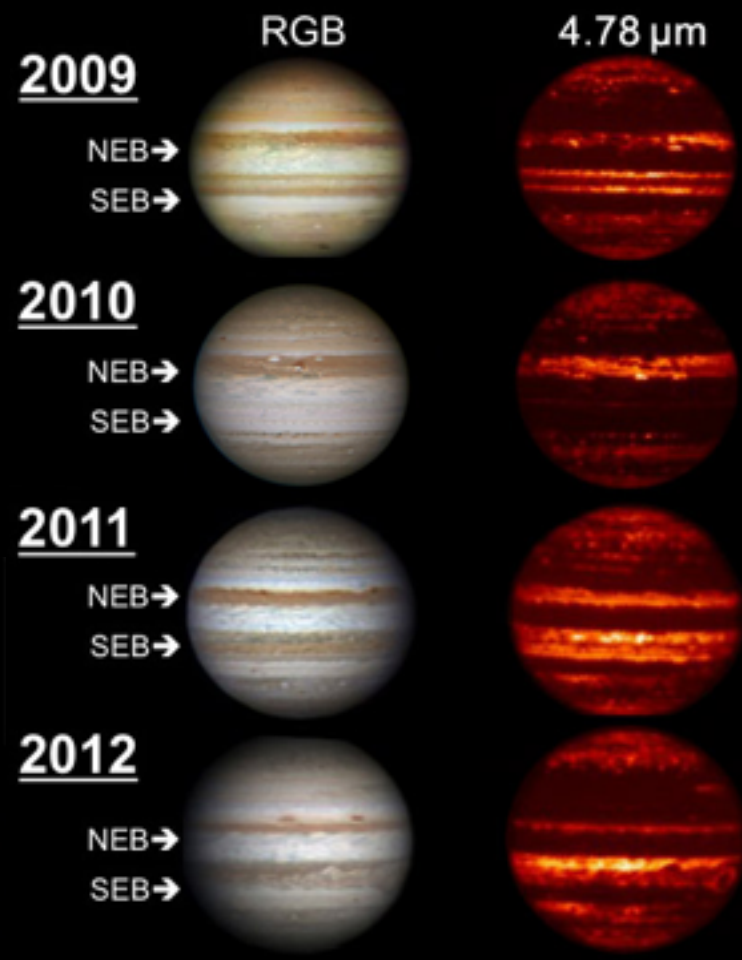
HD 209733b appears cloud-free, strong Na/K, metal oxides *could* cause thermal inversion…

*Are these representative of a transition in the Jupiter class?*

# Req 3: Long Baseline Observations

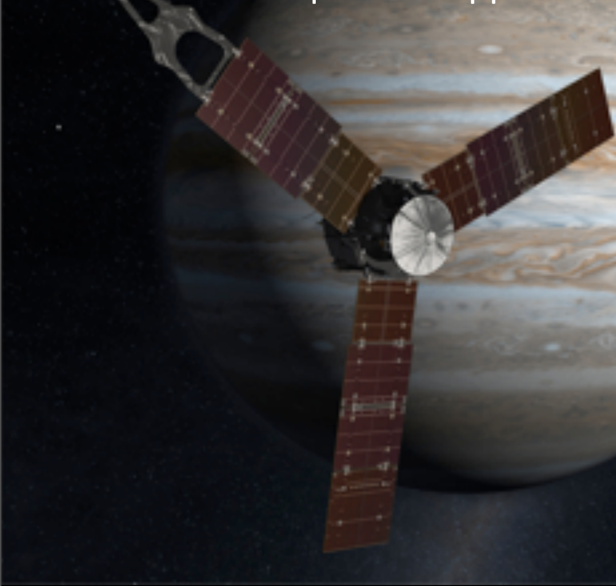
- Majority of observations are **snapshots at single epochs.**
- Reactive to rapid-change (e.g., impacts, plumes, storms).
- **Time-domain atmospheric science** for evolution of atmospheric processes on multiple timescales:
  - Hours-Days (storms, plumes, impacts)
  - Weeks-Months (belt/zone variability; storm evolution; waves).
  - Years-Decades (seasonal variability; response to solar cycle).

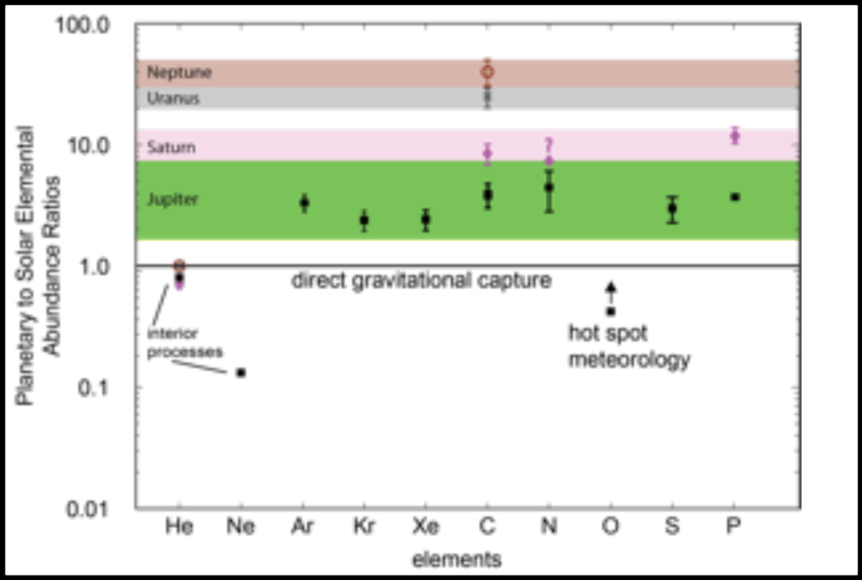


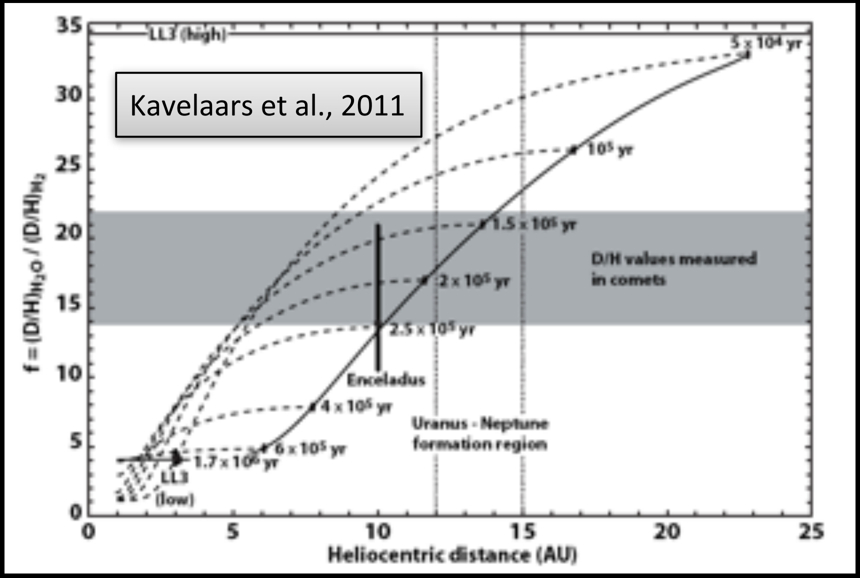



# Req 4: Beneath the Clouds

- Measurements of bulk composition and self luminosity **constrain planetary evolution**
- Remote sensing limited:
  - Condensation removes species from ‘photosphere’
  - Degeneracies with T(p) and aerosols.
- **In situ measurement**:
  - Single point observation (e.g., Galileo’s Sahara)
  - Shallow entry (may not reach well-mixed H2O).
- Juno MWR for deep O/H on Jupiter, but need comparison on all four giants.
- Future entry probe missions for Saturn and ice giants (e.g., Mousis et al., 2013). Buoyant, long-lived multi probes supported by orbiters?





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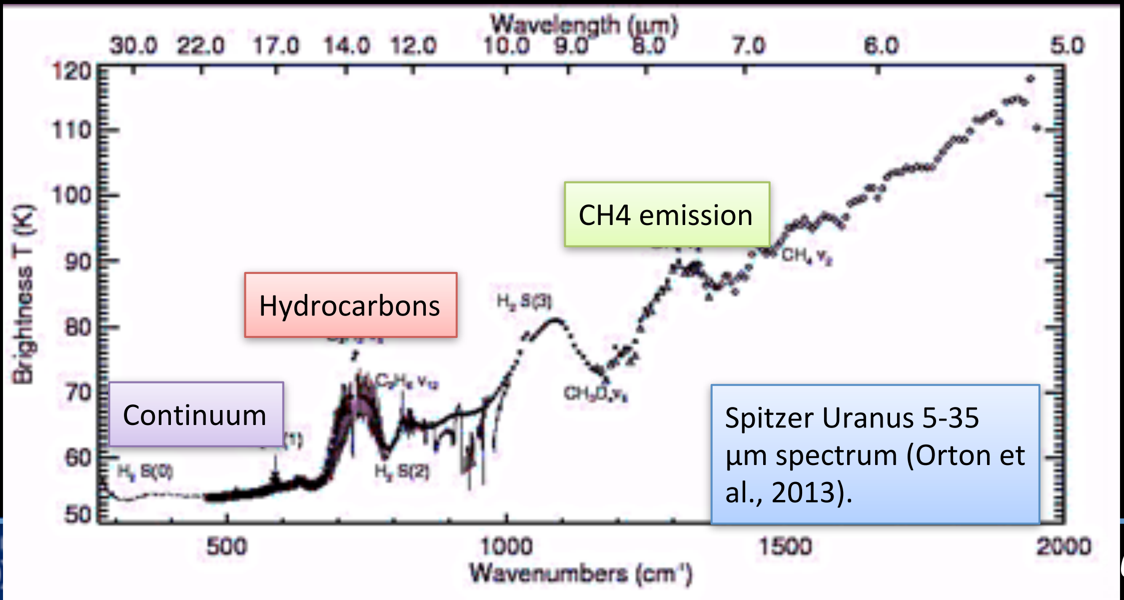
# Perils & Promise of Spectral Retrievals

- Once this long-baseline, hyperspectral imaging is obtained, what next?
- **Atmospheric structure determination requires inversion of spectra**.
  - Spectral retrieval: identify family of statistically-plausible solutions consistent with the data, independent of physical/chemical models.
  - Then reduce family of solutions using Occams' razor and physical constraints.
- Different treatments of measurement uncertainty and a priori bias can lead to different solutions.
  - Accurate error propagation essential, understand degeneracies in system.




Complete prior?

Line data at cold/hot T?

Data uncertainty & systematics?

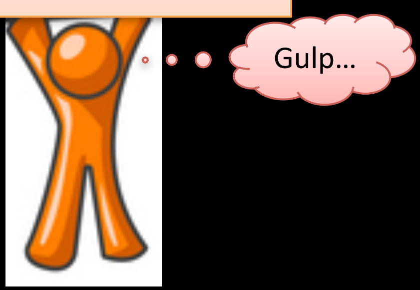
Type of Inversion (optimal estimation, MCMC?)

Spectral properties of gases & condensates?

Scattering?

Degeneracies with clouds/hazes?

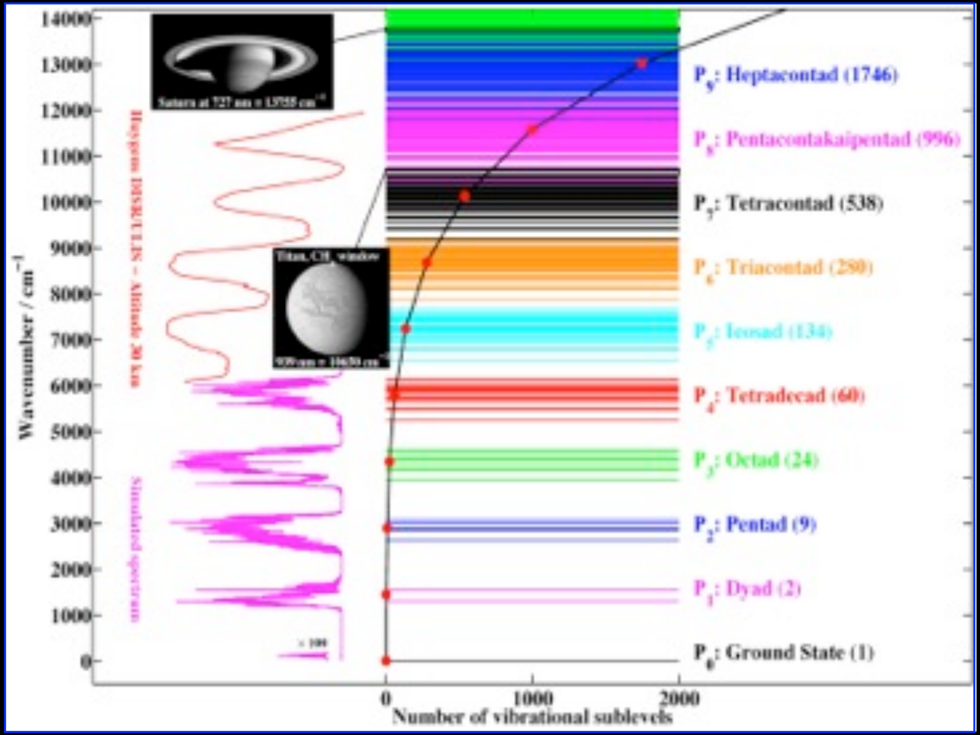
More model parameters than data points?

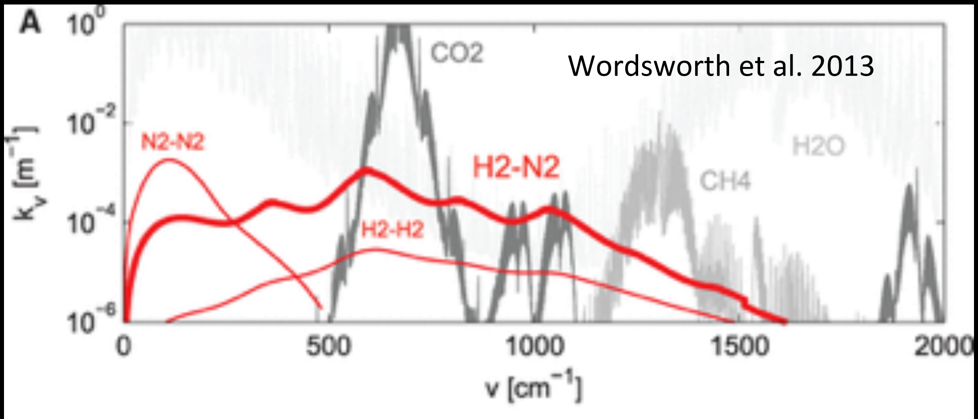



*Retrievals bracket reality*

# Retrievals Are Only as Good as their Radiative Transfer

- Detail of radiative transfer models evolve continuously, **sources of uncertainty:**
  - Measurements of intensity, wave number assignment, partition functions.
  - Collision broadening assumptions in H2-He environments, line widths and temperature dependencies.
  - Validity at high and low temperatures, e.g., high temperature lists for hot Jupiters.
  - Refractive indices of suspected aerosols; mixed and rimmed ices.
  - Ab initio models of collision induced absorptions.
- Vertical profiles of gaseous species (e.g., parameterised distributions).
- Well-mixed assumption may be invalid (e.g., methane on ice giants).
- **Observers duty to be specific, careful and verbose in describing assumptions**



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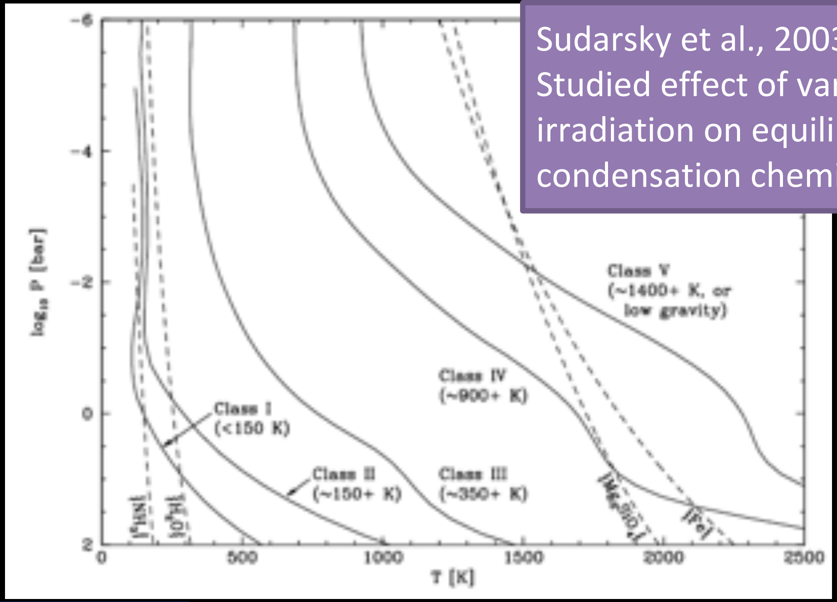
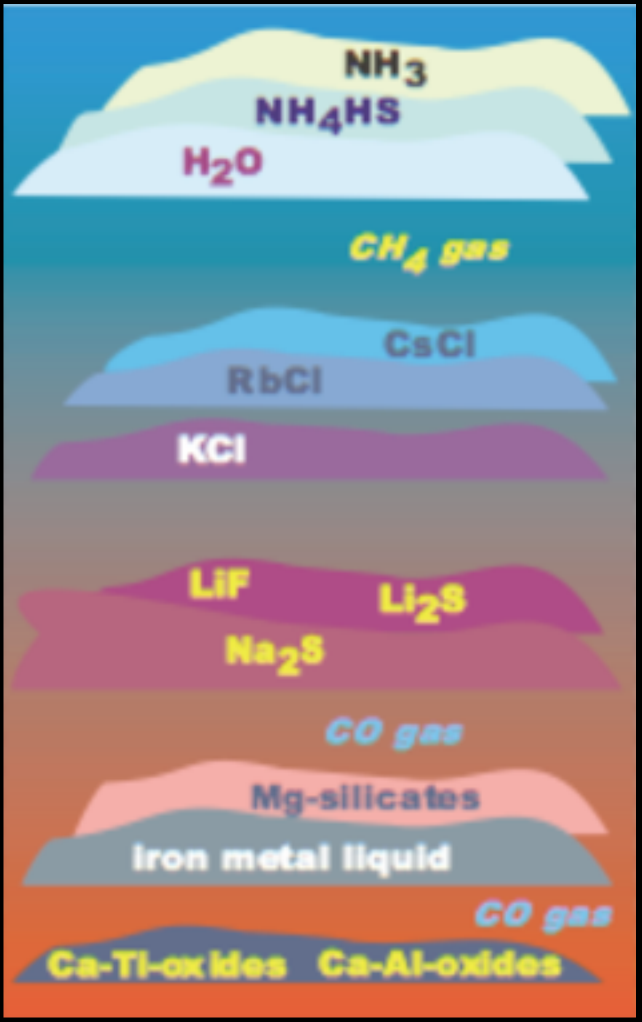
# Q1: Condensation & Classification?

- Influence of clouds dominates IR spectrum, but **broad condensate features difficult to identify unambiguously**.
- Condensate formation radically alters the balance of species available for chemistry.
- **Planetary taxonomy** schemes (e.g., Fortney et al., 2008) based on formation of condensates.
- 
- *….but we still have no model capable of accurately reproducing cloud altitudes, colours, abundances and composition in our own Solar System!*



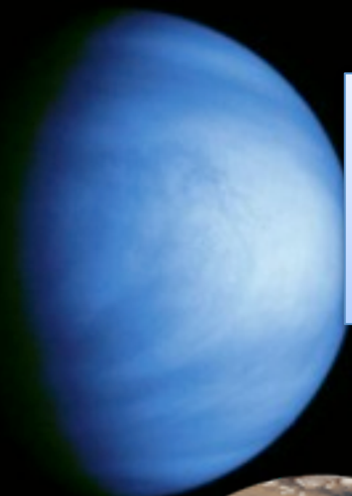

Sudarsky et al., 2003 Studied effect of variable irradiation on equilibrium condensation chemistry.

Increasing Temperature

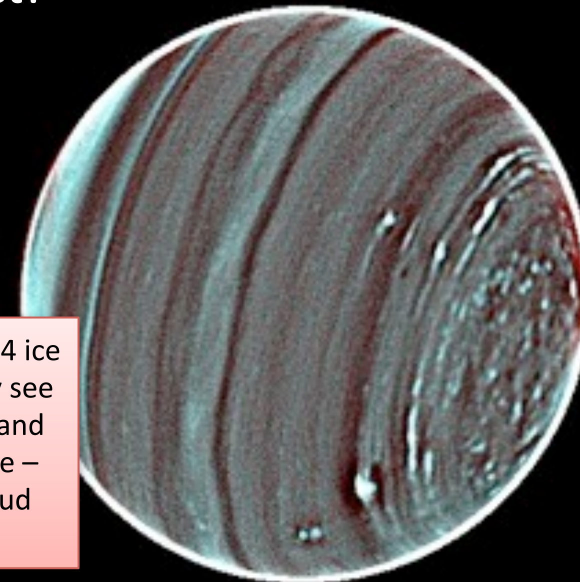


# Q1: Condensation & Classification?

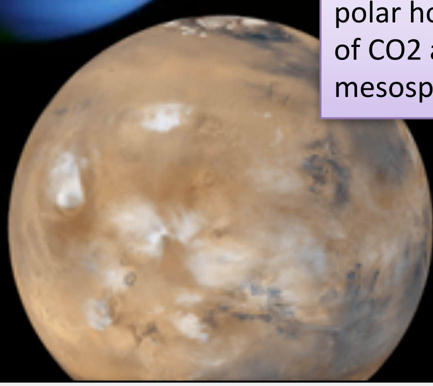
- Photochemical hazes can produce CCNs, coat condensates (rimming) or mix with condensates; clouds rarely occur where we expect!
  - Contamination masks spectral signatures.



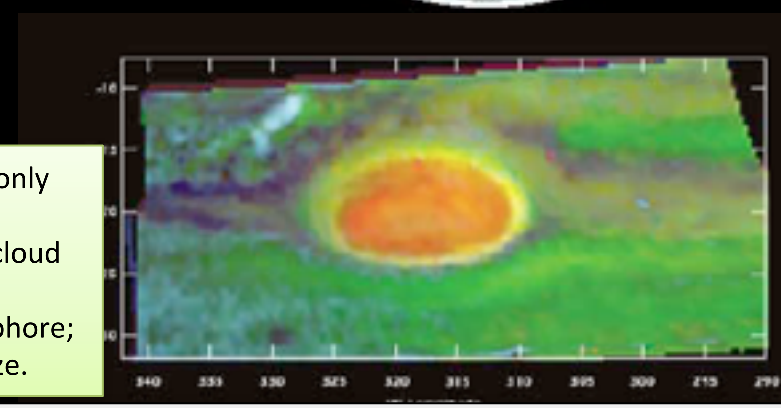
VENUS:
No condensate, thick photochemical $H_2SO_4$ clouds. Vertically extended haze.



URANUS: Expect $CH_4$ ice at 1 bar, but actually see thick cloud 2-3 bars and isolated clouds above – inhibition of $CH_4$ cloud formation?



MARS: Transient clouds; polar hood condensation of $CO_2$ and $H_2O$; mesospheric $CO_2$ clouds.

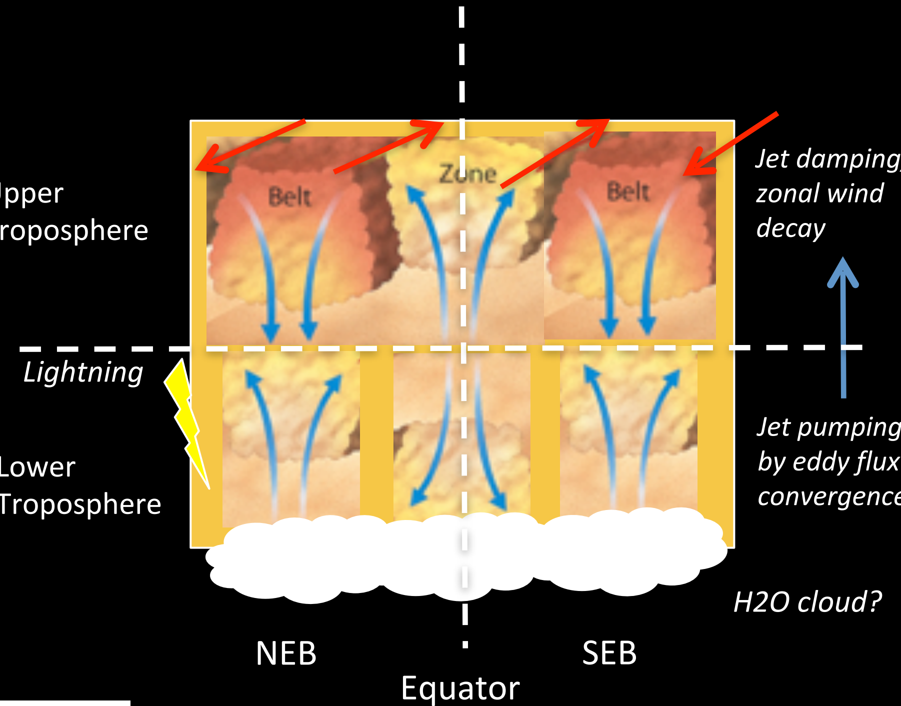


JUPITER: $NH_3$ ice only seen in strong convection; main cloud at wrong altitude; unknown chromophore; photochemical haze.

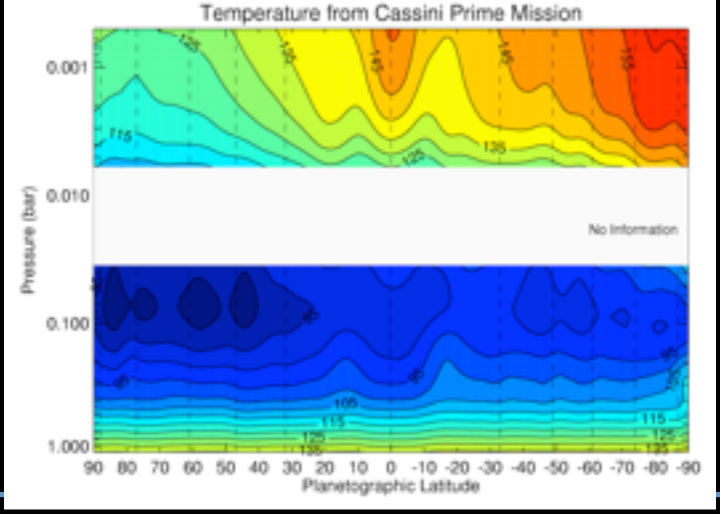
*We need to understand cloud properties on our giants as a function of environmental conditions; develop condensation, photochemical and spectral models to reproduce observations before applying to EGPs.*

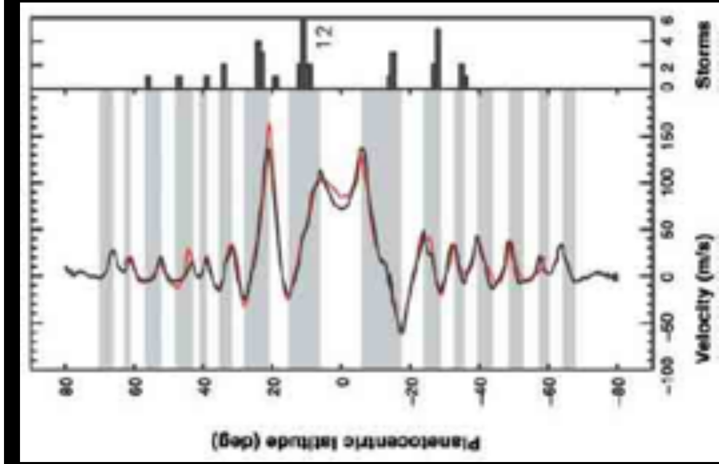
# Q2: General Giant Planet Circulation?

- Conventional idea of giant planet circulation challenged:
  - Cool temperatures, elevated $PH_3$, $NH_3$, aerosols suggest air rising in zones.
  - BUT! Eddy momentum flux causes **jet pumping**; suggests air rises in belts, descends in zones (e.g., del Genio et al., 2012). Lightning storms prevalent in belts.
  - Transition to **jet damping** and switched circulation in upper troposphere? Where??
  - How high do the jets penetrate the stratosphere? How deep below the clouds decks?
- **Need to think of these planets in three dimensions.**



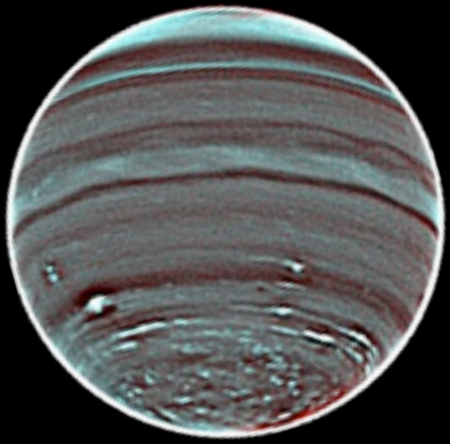

*Need simultaneous measurement of dynamic tracers, and a model to explain ALL observables, more than just PV.*

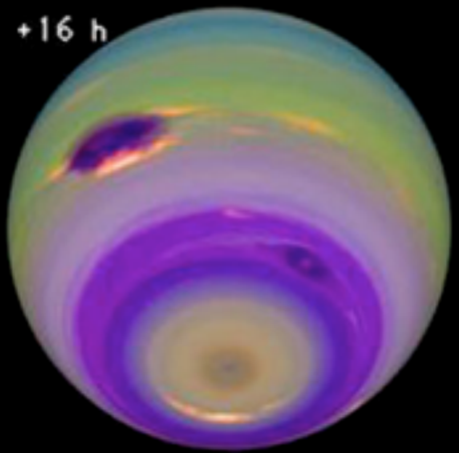


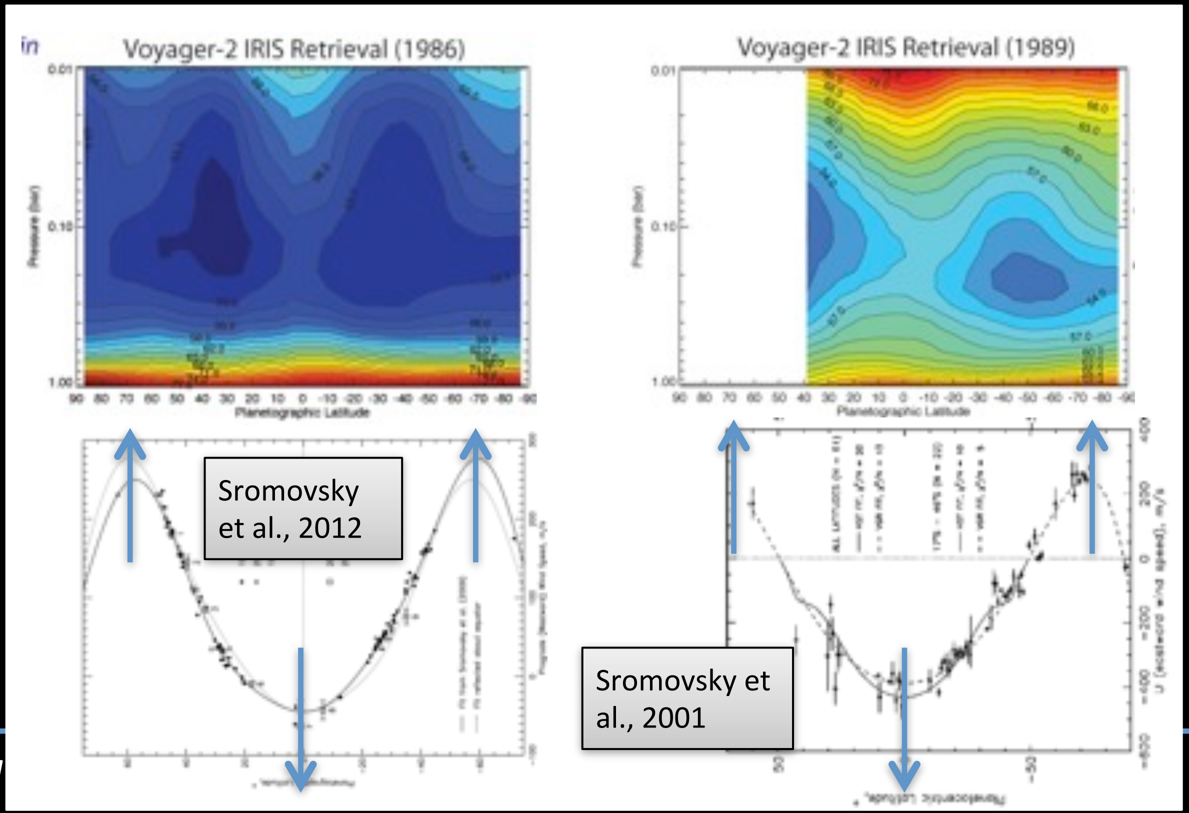



# Q2: General Giant Planet Circulation?

- ***Does tropospheric overturning work the same on the gas and ice giants?***
  - Similar banding, but little correspondence with temperature/ wind field.
- **Need ice giant exploration** (temperatures, winds, dynamic tracers, jet pumping/damping regimes).
- **Need ice giant modeling** to explain why they appear so different.

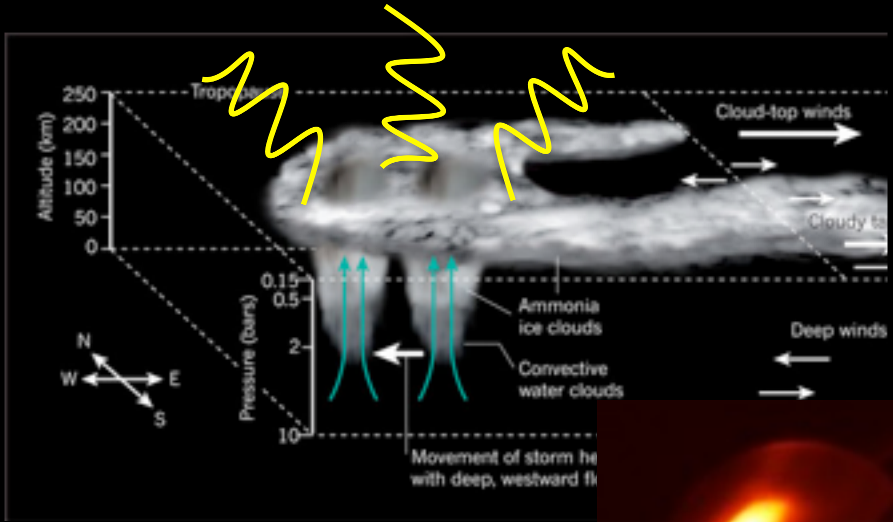


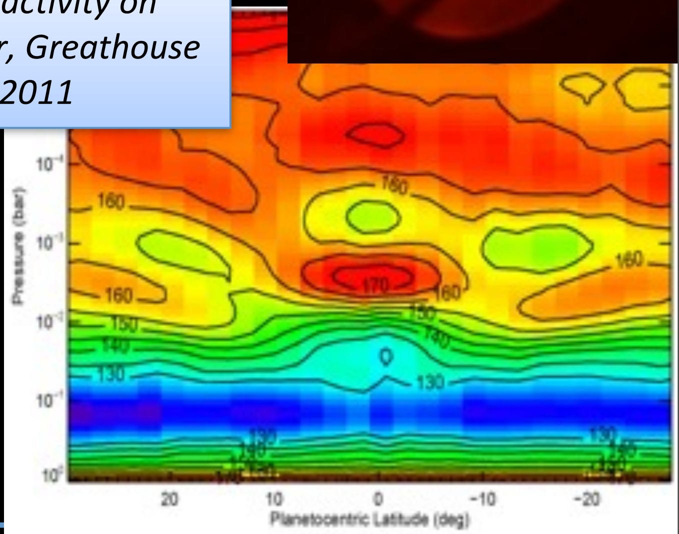


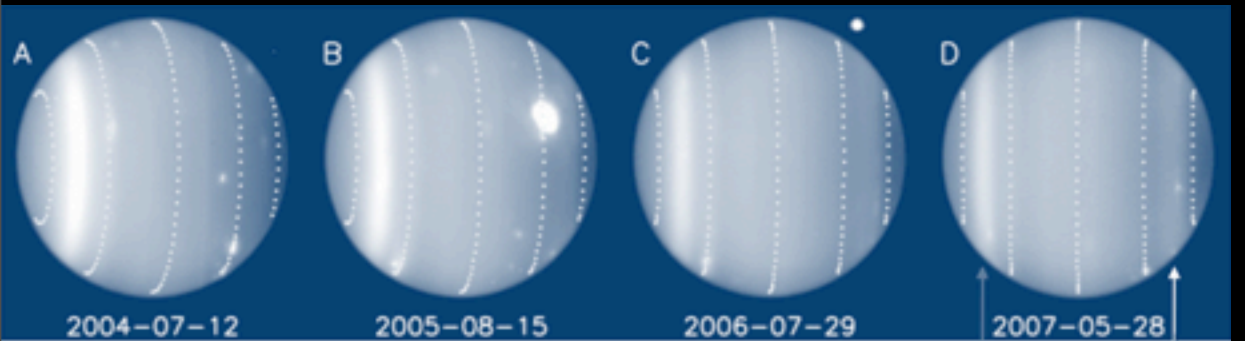
# Q3: Sources of Variability?

- Variability occur due to storms, plumes, waves, instabilities, belt/zone life cycles and seasonal evolution.
- What controls the timescales for **onset of polar vortices and development of new bands**?
- What is the energy source for **eruption of storms and plumes** (e.g., Saturn's GWS, jovian upheavals), and what controls their periodicity?
  – Role of CAPE, deep meridional circulation enhancing instability, past a trigger point?
- What is the **importance of waves in giant planet atmospheres;** how to waves and vortices interact?
  – Waves diagnostic of deeper atmosphere.



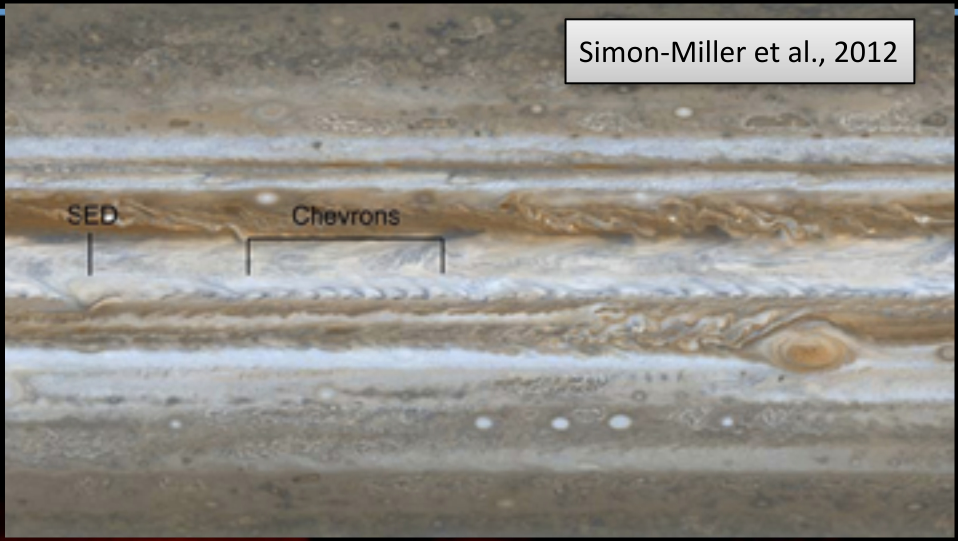

*Wave activity on Jupiter, Greathouse et al., 2011*

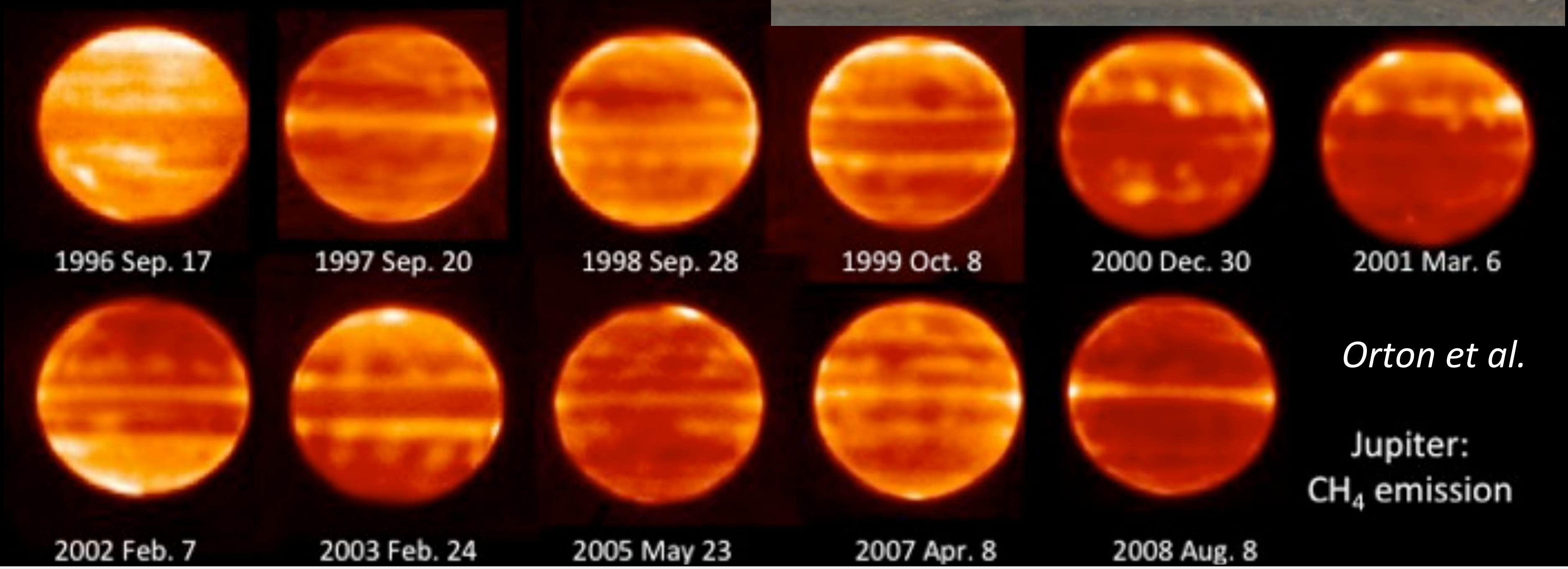



*Uranus from Keck, de Pater, Sromovsky et al.*

# Q3:  Sources of Variability?

- Need a model capable of coupling weather layer to middle and upper atmosphere; diagnose causes of large-scale variability.
- Example:  Appearance of **Jupiter's stratospheric emission** has changed substantially over a jovian year.
  - What is controlling the ephemeral nature of planetary waves?  Relation to troposphere?
  - How does auroral activity affect the temperature and composition of the polar atmosphere?

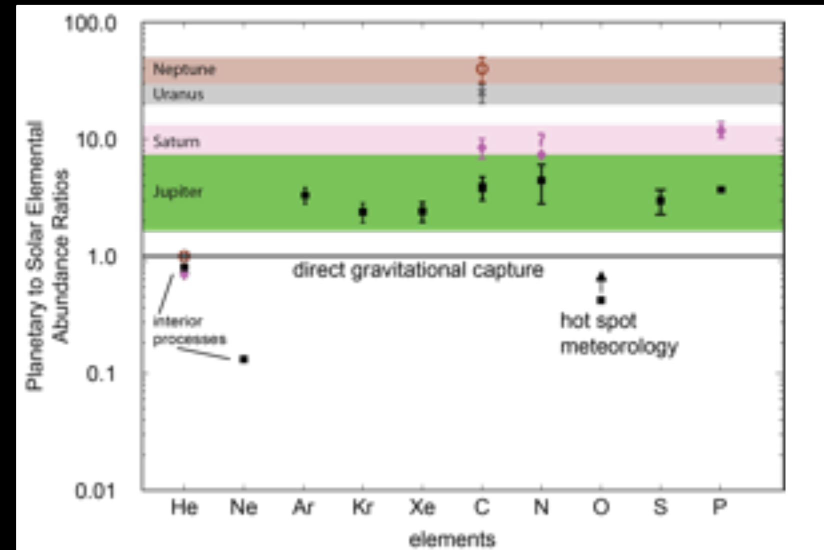


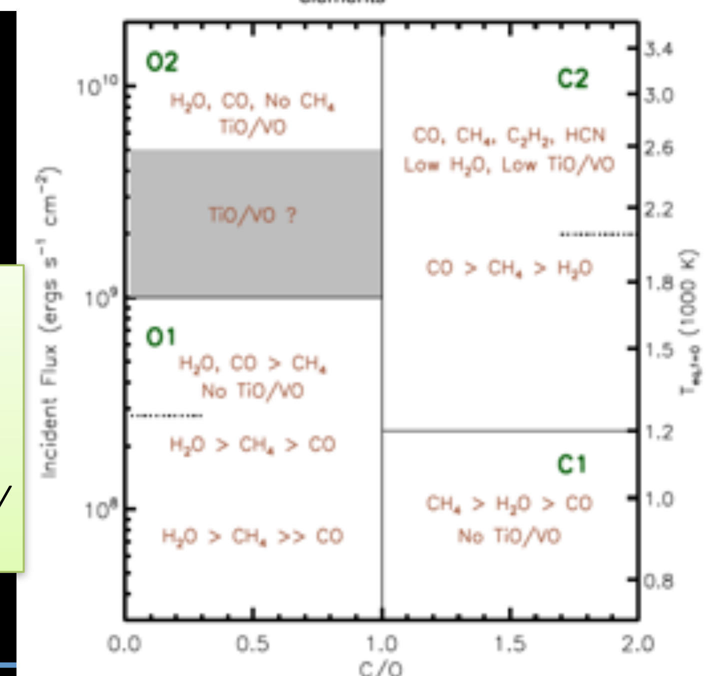




*Time domain atmospheric science over short and long timescales; importance of waves in controlling visible phenomena in planetary atmospheres.*

# Q4: Origin of the Giants?

- Crucial role of the giants.
- **Different formation modes imprint different bulk compositions.**
- Ratio of refractory to volatiles depends on **phys/chem conditions in accretion disc**:
  - Host star composition/metallicity & availability of planetary building blocks, migration
  - Radial T/p gradients and turbulent mixing in accretion disc, condensation ‘snow lines’ (H2O most important)
- Essential to have **comparable measurements on all four giants.**
- Can remote sensing reveal origin and evolution?
  - Does the atmospheric circulation and composition really reflect the interior?
  - Can we explain/predict giant planet abundances with a consistent formation framework?




*Madhusudhan (2012) based on modeling Spitzer data of hot Jupiters with variable temperatures and C/O ratio*

# Summary: Giant Planet Studies

## OBSERVING REQUIREMENTS

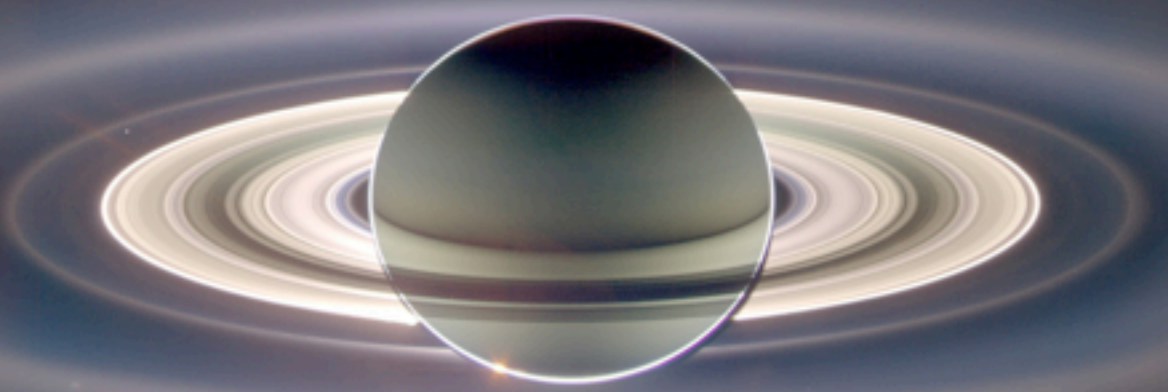
- Comparative studies of our four giants now requires:
  - **Long-term** self-consistent datasets over multiple years;
  - **Spatially resolved spectroscopy** rather than filtered imaging;
  - Near-**simultaneous coverage** in reflected sunlight and thermal-IR;
  - Careful comparisons of retrieved properties from sparse data;
  - **In situ exploration** to provide ground-truth for remote sensing.
- Space-based observations from a dedicated planetary science observatory would remove complicating terrestrial atmosphere.
- Move beyond the era of snapshots with very different instruments.

## INTERPRETATION REQUIREMENTS

- Interpretation requires a new generation of models addressing all observables:
  - Accurate reproduction of **observed cloud properties**/altitudes/composition.
  - Consistent **circulation models** from deep troposphere to middle/upper atmosphere; from equator to pole; explain jet pumping/damping; vertical range of belts/zones.
  - **Formation**/migration/evolution models to explain bulk composition; interior models to understand vertical mixing.
  - **Seasonal radiative models** combined with weather-layer dynamics to reproduce variability in plumes, waves, instabilities, etc.
- *Some of these models already exist, but we need to talk the same language – observers need hypotheses to test.*

# More Importantly: Why Study the Giants?

- What's the big picture?
  - [Or, how can we convince cosmologists that we're tackling fundamental science?]



Natural planetary-scale laboratories for processes at work in atmospheres/oceans.

Closest examples of an astrophysical object that appears commonplace in our universe.

Formation of the giants may have played a crucial role in the development of our habitable solar system.

Provide the extremes of temperature to test our understanding of physical/ chemical processes.

Miniature solar systems in their own right (rings, satellites, magnetospheres)