The Diversity of Giant Planets: Infrared Observation and Data Analysis
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?

**Diagram:**
- **Bulk Composition & Formation**
  - [Fe]/[H], C/O, O/H, etc.
  - CO/CH4; N2/NH3, P, S, etc.
  - C2Hx, H, nitriles, radicals, hazes, etc.
- **Thermo-chemical Equilibrium**
- **Stellar Irradiance & Photo-chemistry**
- **Atmospheric mixing & quenching**
- **Condensate cloud sequence**
  - Refractories, Silicates, Fe, sulphides, H2O, NH3, etc.
- **Emergent Photospheric Spectrum**
  - T(p), gaseous composition, cloud/haze characteristics

**Notes:**
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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.
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).

Credit: Darryl Milika and Patricia Nicholas

Jupiter in 2010, Credit: Damian Peach

Io from Palomar/SWIFT (Dec 2012)

Io from Galileo
Req 1: Beyond Imaging: Spectral Mapping

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 ($R \sim 10^3$) for $p$-broadened tropospheric lines.
  - High ($R \sim 10^6$) 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.**
**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...*
Req 2: Broad, Simultaneous Coverage

- 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?

Kavelaars et al., 2011
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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.

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--- 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**

Wordsworth et al. 2013
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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.
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 H2SO4 clouds. Vertically extended haze.

JUPITER: NH3 ice only seen in strong convection; main cloud at wrong altitude; unknown chromophore; photochemical haze.

URANUS: Expect CH4 ice at 1 bar, but actually see thick cloud 2-3 bars and isolated clouds above – inhibition of CH4 cloud formation?

MARS: Transient clouds; polar hood condensation of CO2 and H2O; mesospheric CO2 clouds.

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 PH3, NH3, 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.**

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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.

Sromovsky et al., 2012

Sromovsky et al., 2001
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.

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

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