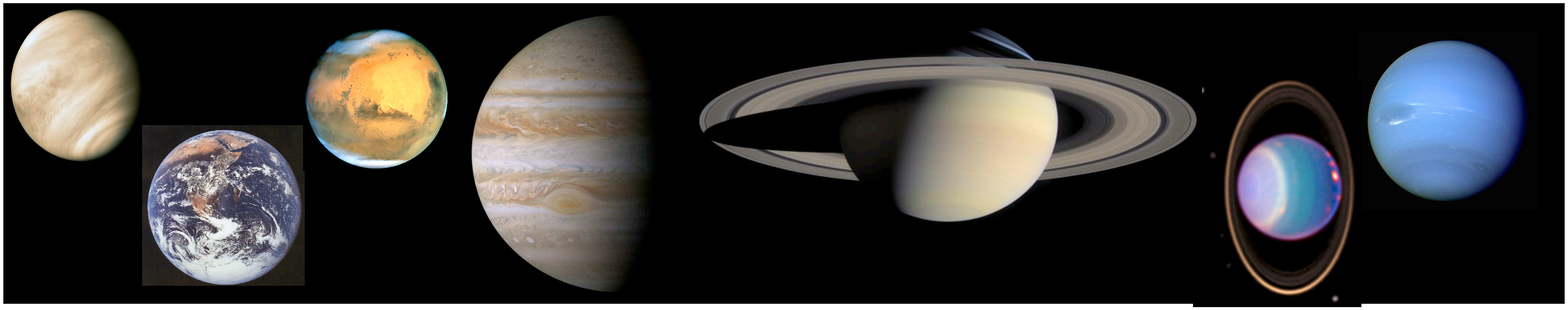
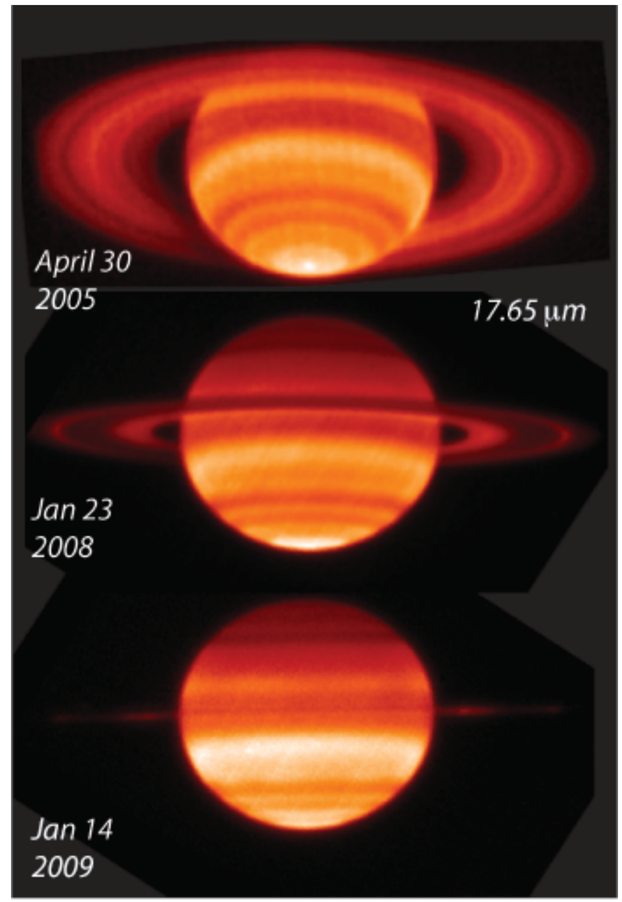


Solar System Planetary Atmospheres: Lessons Learned

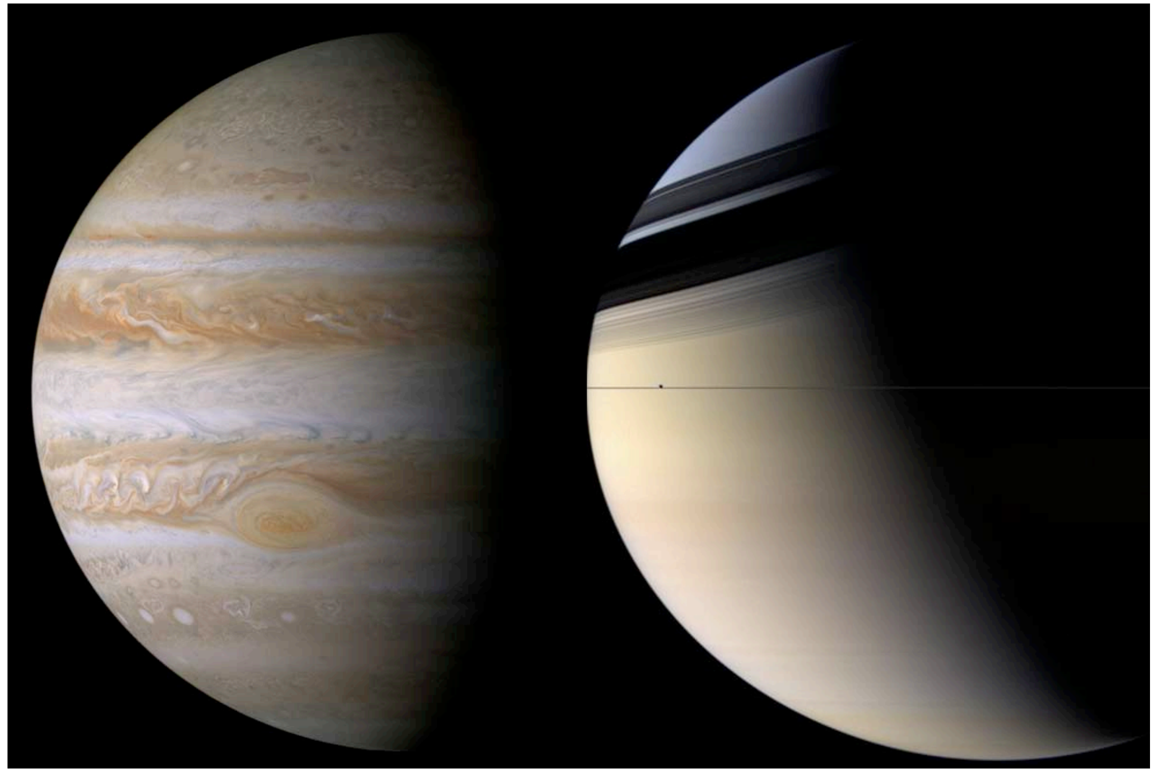


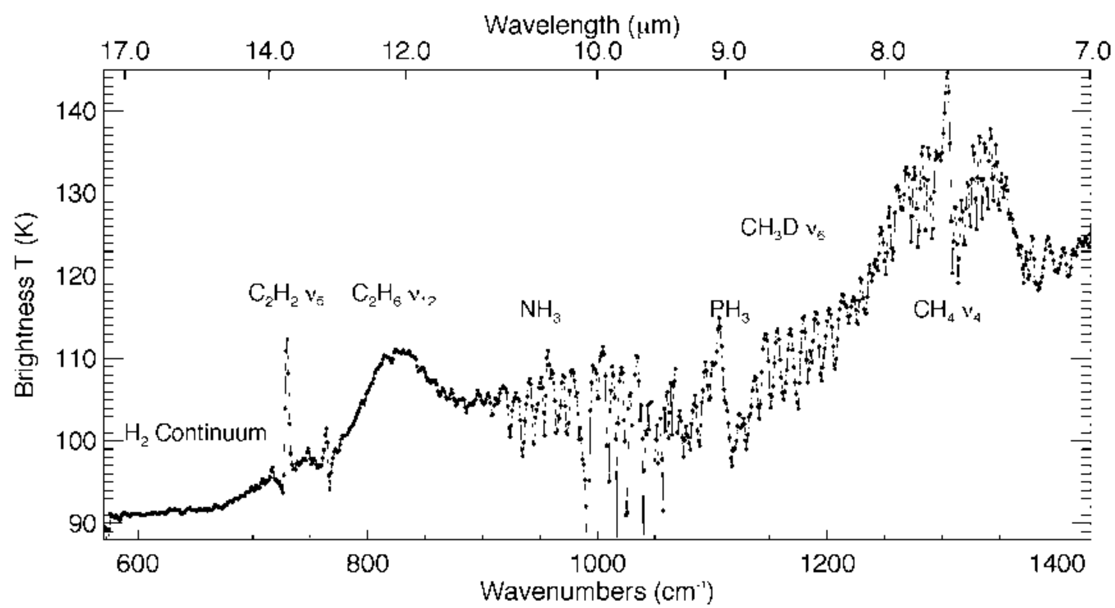
Sagan Exoplanet Workshop July 2009

Leigh N. Fletcher (JPL/California Institute of Technology, Leigh.N.Fletcher@jpl.nasa.gov)

Introduction

- Every object is different, a function of its history.
  - Determine common principals from a variety of unique environments.
  - Extrapolate lessons to new era of exoplanet remote sensing.
- Bias towards infrared:
  - Exoplanet characterisations is in its infancy: day/night contrasts, temperature inversions, composition.
- Start with the seven take-home messages…





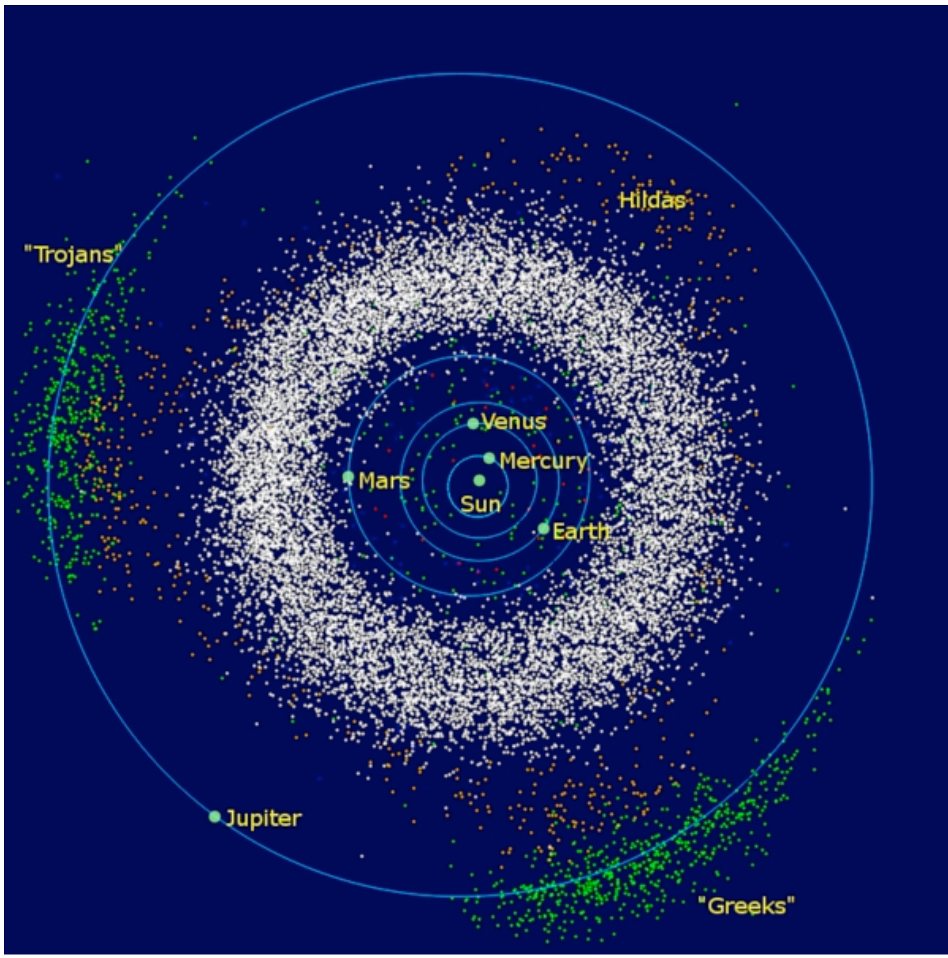
The Seven Lessons

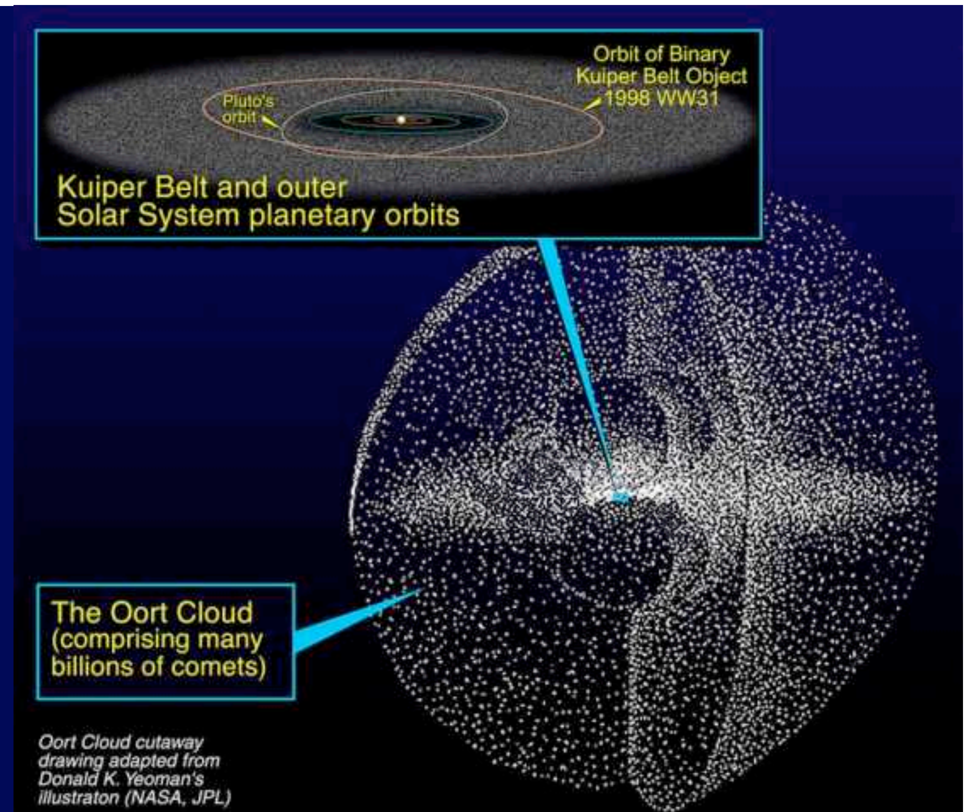
1. Atmospheric Structure is governed by the balance of energy.
2. More than Imaging: the need for spectroscopy.
3. More than Spectra: the need for contextual information.
4. Atmospheres contain fossilised signatures of planetary formation mechanisms.
5. Divergent Evolution: Small changes lead to large differences.
6. Goldilocks and the Misleading Concept of a Habitable 'Zone'.
7. Uniqueness: The huge manifold of remote sensing solutions.

…and there are likely to be many more

Top Lesson: Our Solar System is *Complex*

- …and we shouldn't expect anything less from exoplanetary systems!
- Terrestrial planets, gas planets, ice giants, icy moons, interplanetary dust, asteroids, comets, meteors, Kuiper belt, Oort cloud, solar wind, magnetic fields, etc.…





1. Energy Balance and Atmospheric Structure

- Hydrostatic equilibrium and fluid physics determine bulk properties of atmospheric structure:
  - Pressure decrease ~exponentially with height.
  - Scale height H: Massive planet with denser atmosphere has atmosphere more concentrated near the surface.
  - Scale heights 10-14 km on Mars/ Venus; 20-40 km on Jupiter/Saturn
- Determines the path through the atmosphere for remote sensing.
- Detailed temperature structure determined by energy transfer…

Hydrostatic equation:

$$dP = -\rho g dz$$

Ideal Gas Law:

$$\rho = \mu P / RT$$

Atmospheric Scale Height:

$$H = RT/\mu g$$

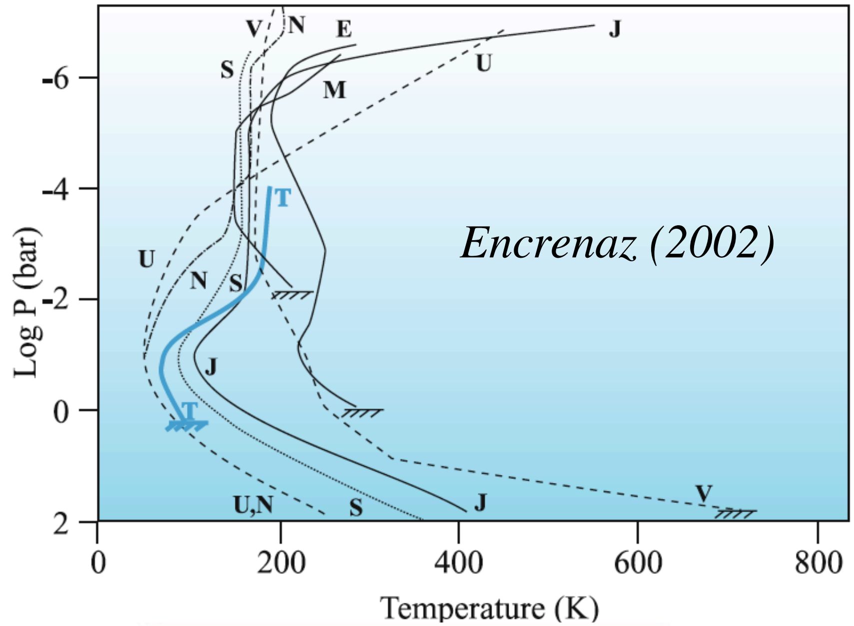
Variation of pressure with height:

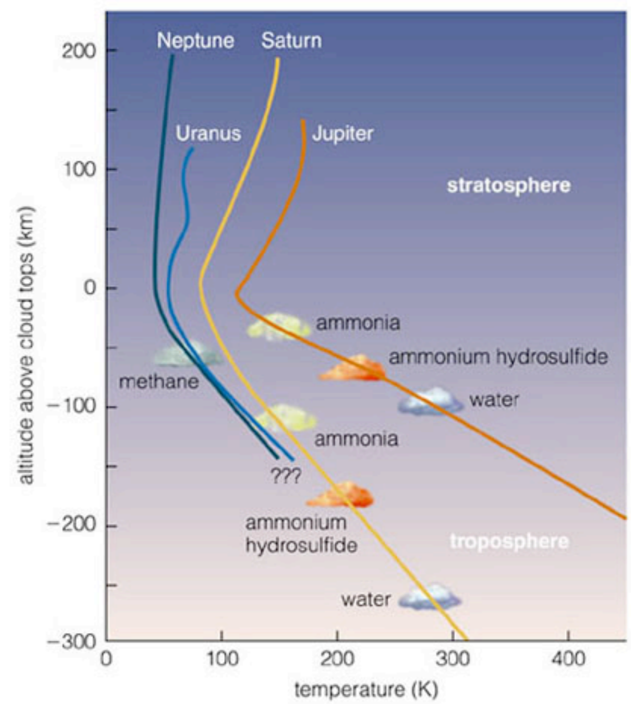
$$dP/P = dz/H$$

All symbols have their usual meanings: Andrews (2000).

Cooling via Convection or Radiation?

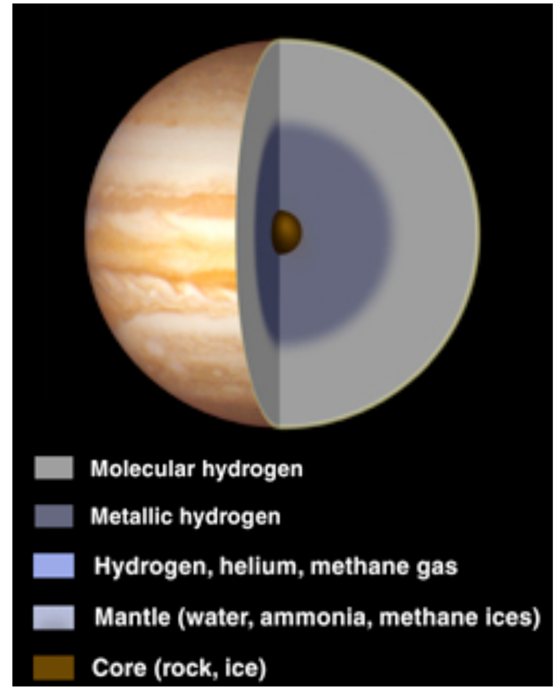
- Troposphere:
  - Convection cools faster than radiative processes, atmosphere follows adiabatic lapse rate.
  - Deviations from dry lapse rate if latent heat release from condensing volatiles (clouds) - moist adiabat.
- Temperature Inversion:
  - **Strong UV-visible-near-IR absorber** warms the atmosphere above tropopause (O_3 on Earth, CH_4 on giant planets).
  - Stably stratified region, radiative cooling dominates.
- Earth and Giant planets have stratospheres, Venus and Mars (lacking strong stratospheric heating) are relatively isothermal up to the mesosphere.
- Temperature **does not simply vary with heliocentric distance**, but depends on internal heat sources.





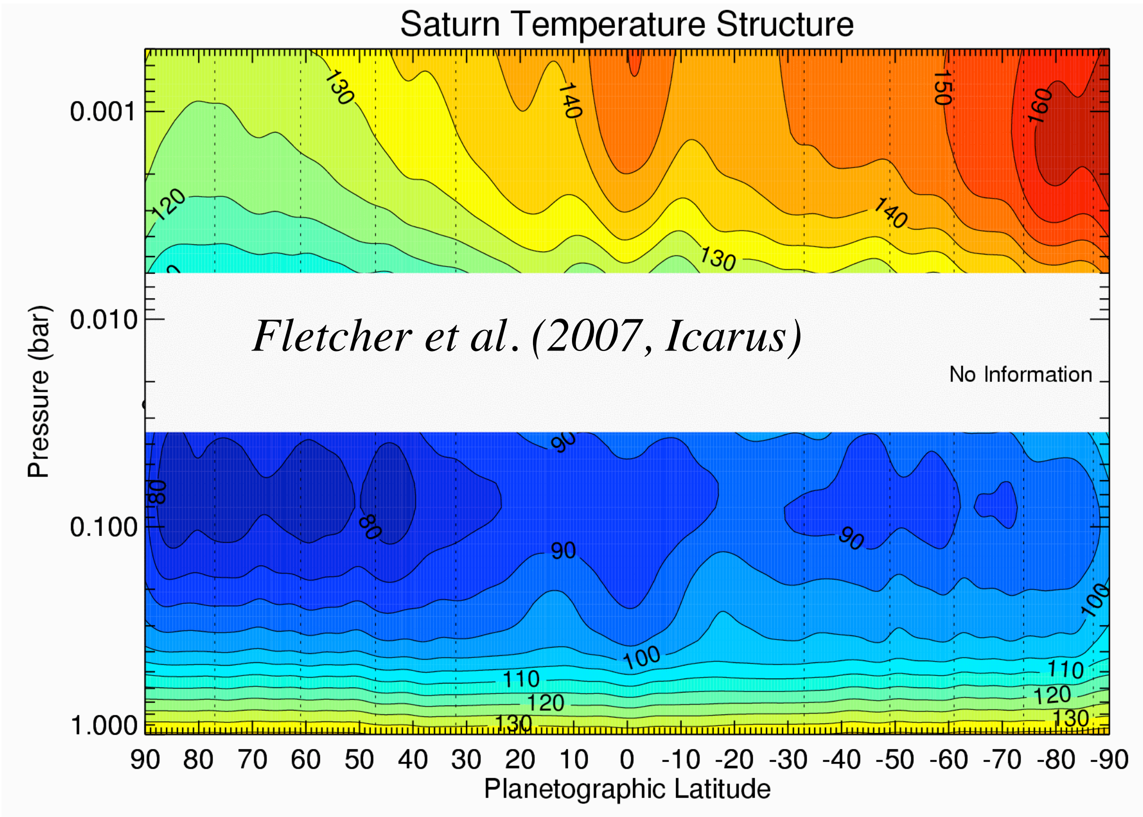
What are the Sources of Energy?

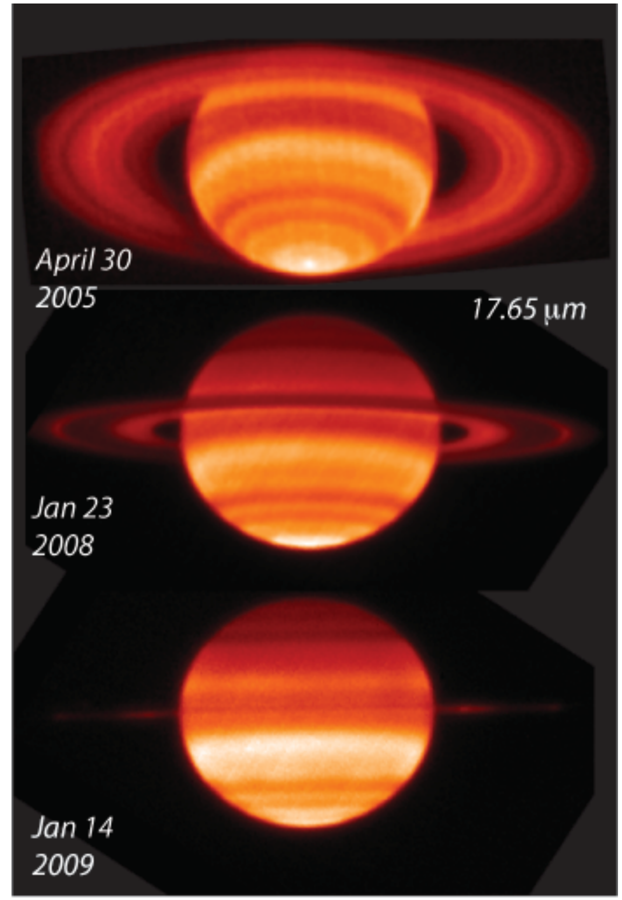
- Balance between energy sources is the origin of the thermal structure:
  - Solar energy deposition important in the weather-layers.
  - Internal energy: residual heat from the formation of the giant planets, slowly shrinking.
  - Release of gravitational potential energy as heavier elements settle and rain out.
  - Phase separation of hydrogen and helium as hydrogen becomes ‘metallic’ at high pressures in Jupiter/Saturn.
  - Dissipation of tidal energy as planetary orbits circularize.
  - Mechanical heating of the stratosphere and upper atmosphere from propagating vertical waves.
  - Upper atmosphere heating from UV dissociation and solar wind excitation.
- Giant planets are self-luminous, radiate away more energy than they receive from the Sun!



	Emitted/ Absorbed	Bolometric Temperature
Jupiter	1.67	124 K
Saturn	1.78	95 K
Uranus	1.06	59 K
Neptune	2.52	59 K

These Energy Sources may be inhomogeneous!





- Example: Cassini Composite Infrared Spectrometer derivations of Saturn's temperature structure shows that seasonal effects are very important, leading to large asymmetries in the temperature field.

#1: Similarities between vertical T(p) on all the planets, governed by a balance between internal energy and solar energy deposition

2. More than Imaging: The Need for Spectroscopy

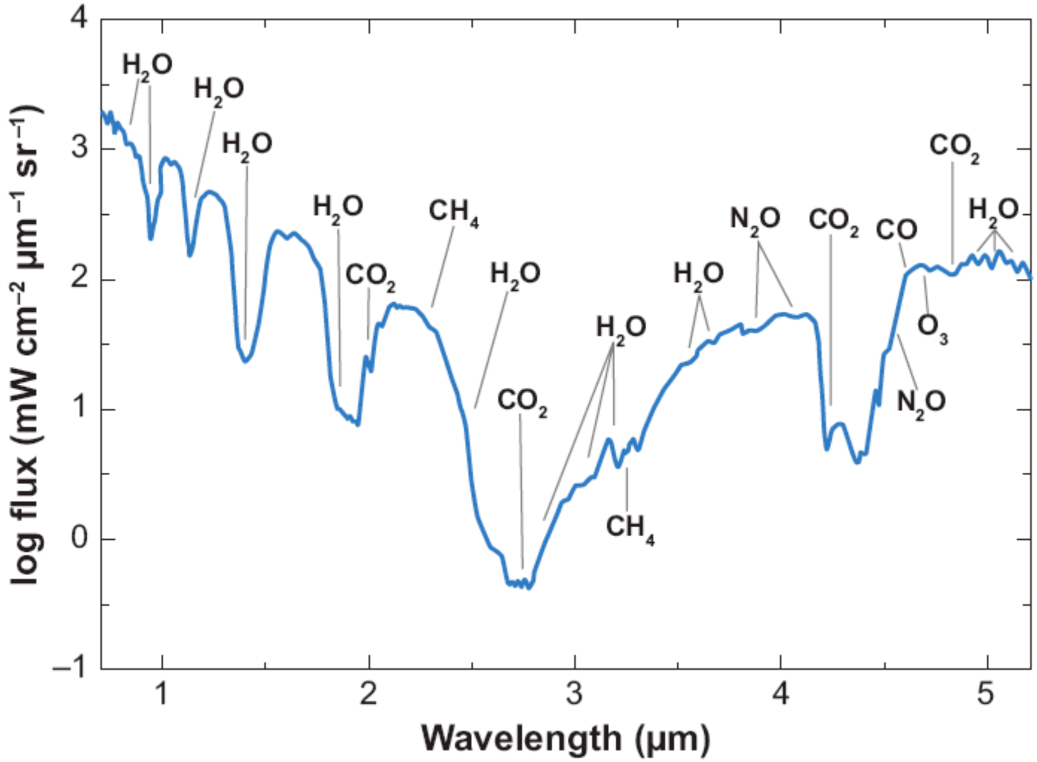
- Imaging is required for studies of atmospheric morphology, dynamics, temporal evolution; BUT:
- Spectra are vital for characterisation of composition and chemistry. Two components of all planetary spectra:

Short-λ: UV, visible, near-IR 3-5 μm *Long-λ: Mid-IR, millimeter, radio*

REFLECTED:	THERMAL:
Mimic blackbody spectrum of Sun (peak at 0.5 microns), bears the stamp of overlying absorption features.	Peak emission depends on effective temperature of the atmosphere.
Rayleigh scattering λ^{-4}	Interpretation **requires** knowledge of T(p), molecular bands in emission and absorption.
Use: cloud properties, column densities, tracking dynamics, fluorescence.	Use: Temperature, composition, vertical structure, indirect dynamical tracing.

Reflection Spectra (Short-λ)

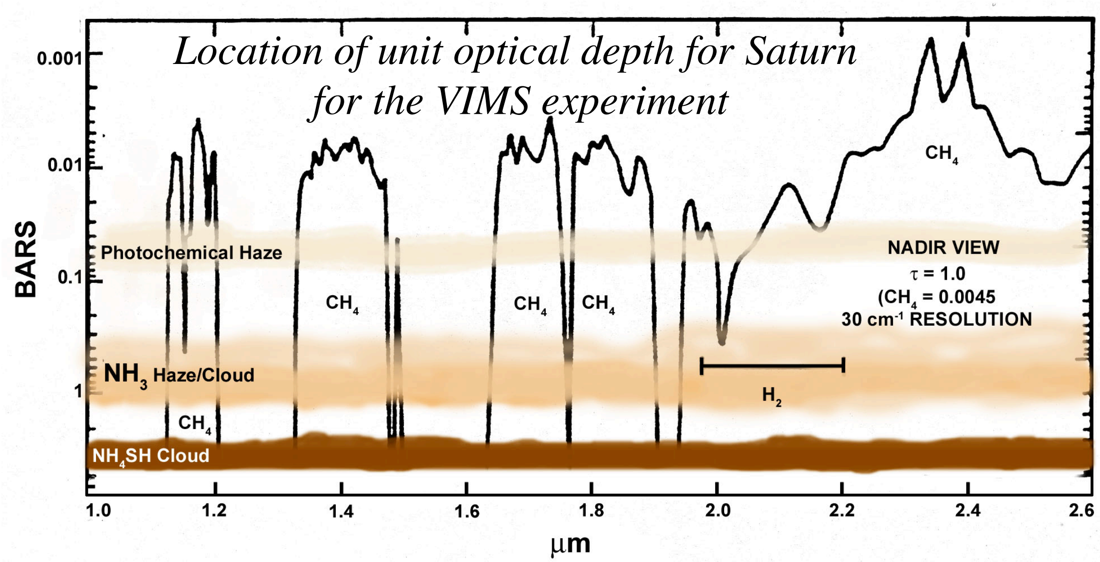
- Visible/near-IR: Depth of absorption bands used to determine column densities. High spectral resolutions permit T/p derivations from line broadening.
- Terrestrial spectra:
  - Dominated by CO_2 between 2-3 μm.
  - H_2O signatures absent from Venus, clear on Earth and small on Mars.
- Relative size of reflected spectrum versus thermal spectrum determined by albedo (typically 0.3 for solar system planets).

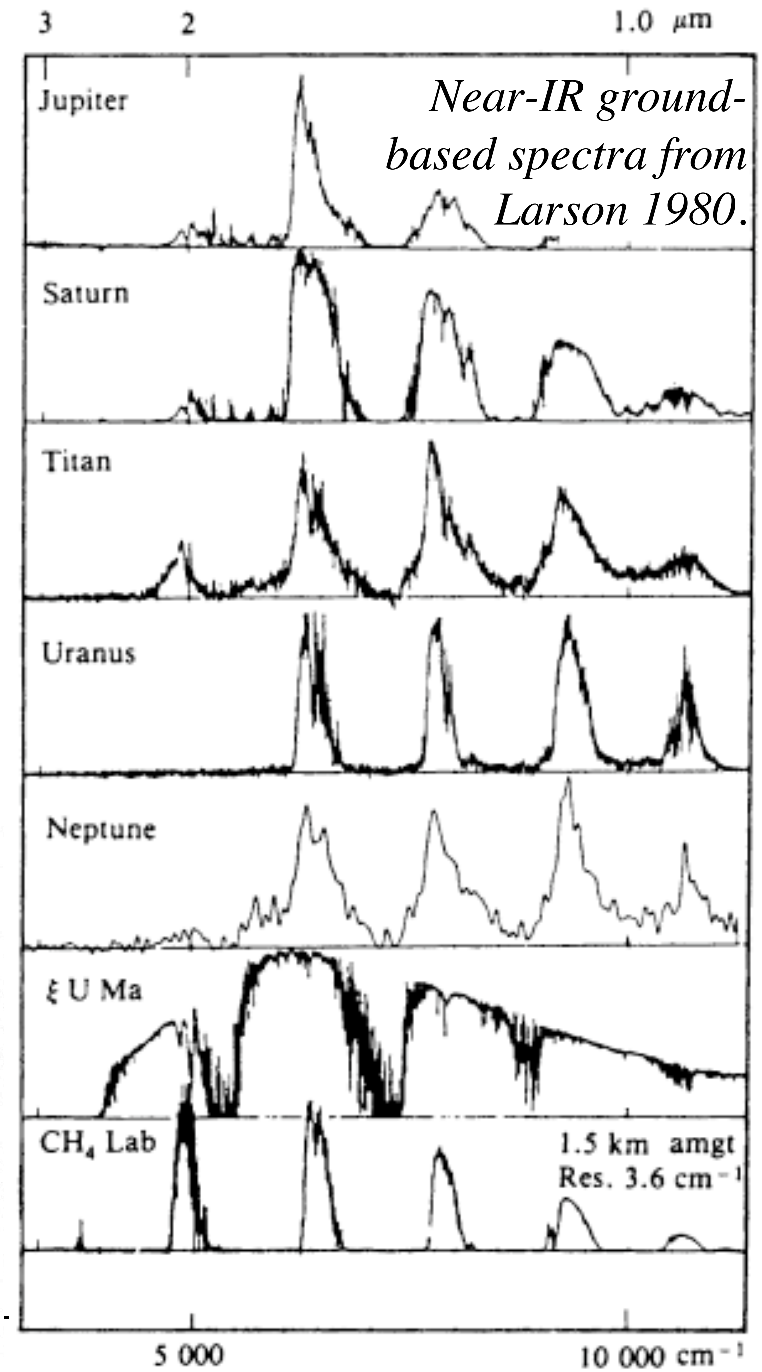


Galileo/NIMS near-IR Earth Spectrum (December 1990), from Drossart et al. (1993)

Giant Planet Near-IR spectra

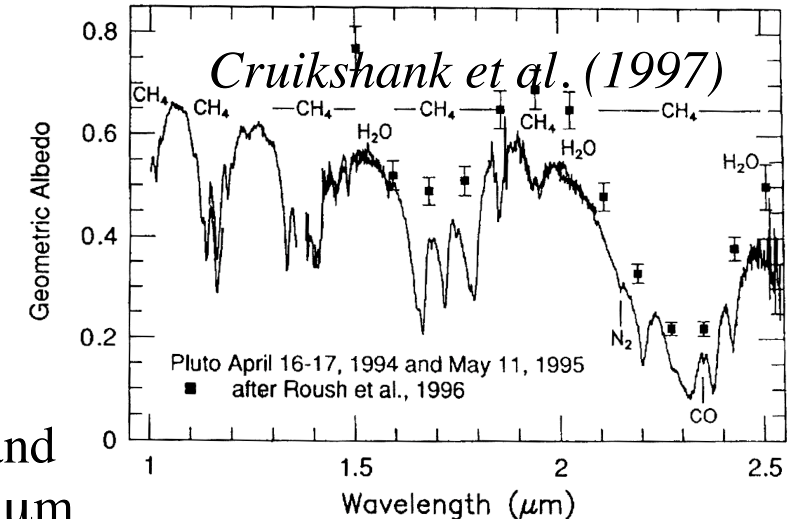
- Dominated by CH_4, with small contributions from molecular H_2, NH_3 on Jupiter, PH_3 on Saturn and CH_3D on Uranus and Neptune.
- Depth of CH_4 bands increase with heliocentric distance…
- Used to study clouds, aerosols, hazes, which increase scattering and suppress absorption features.

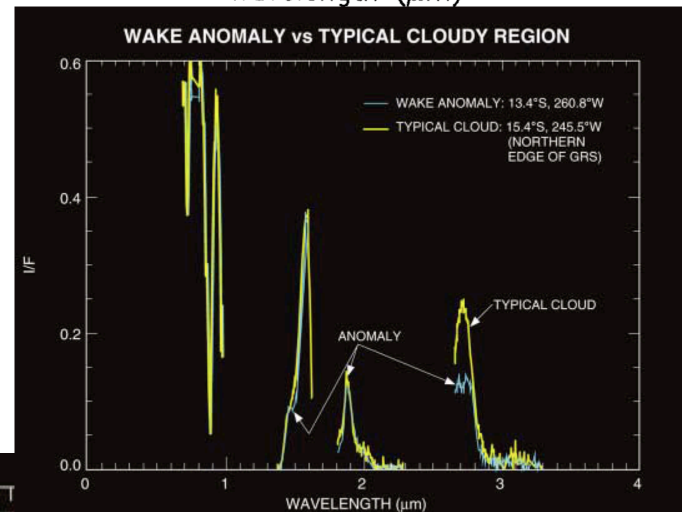


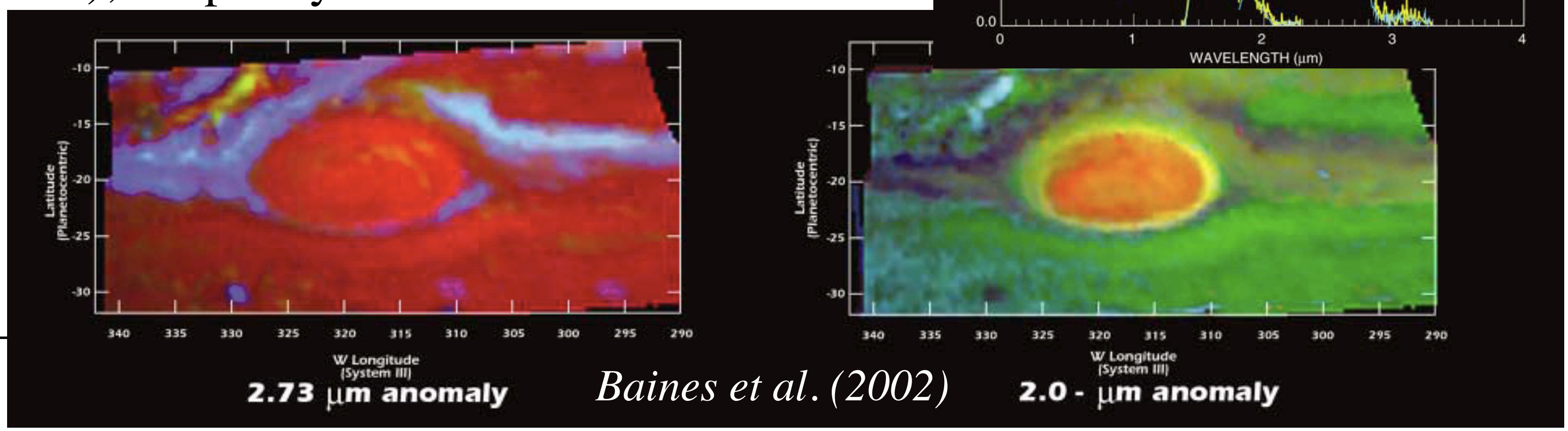


The Trouble with Condensates!

- Near-IR probes ices and condensates responsible for cloud colouration:
  - But features are often broad and hard to identify.
  - Example: broad CH_4 ice features on Pluto and Triton, water ice features at 1.5, 2.0 and 3.1 µm on outer planet satellites and rings.
  - We still do not know the composition of the blue-absorber responsible for the red colour of Jupiter's Great Red Spot!
  - Composition of Titan's smoggy atmosphere thought to consist of nitriles and hydrocarbons (tholins), but poorly understood.





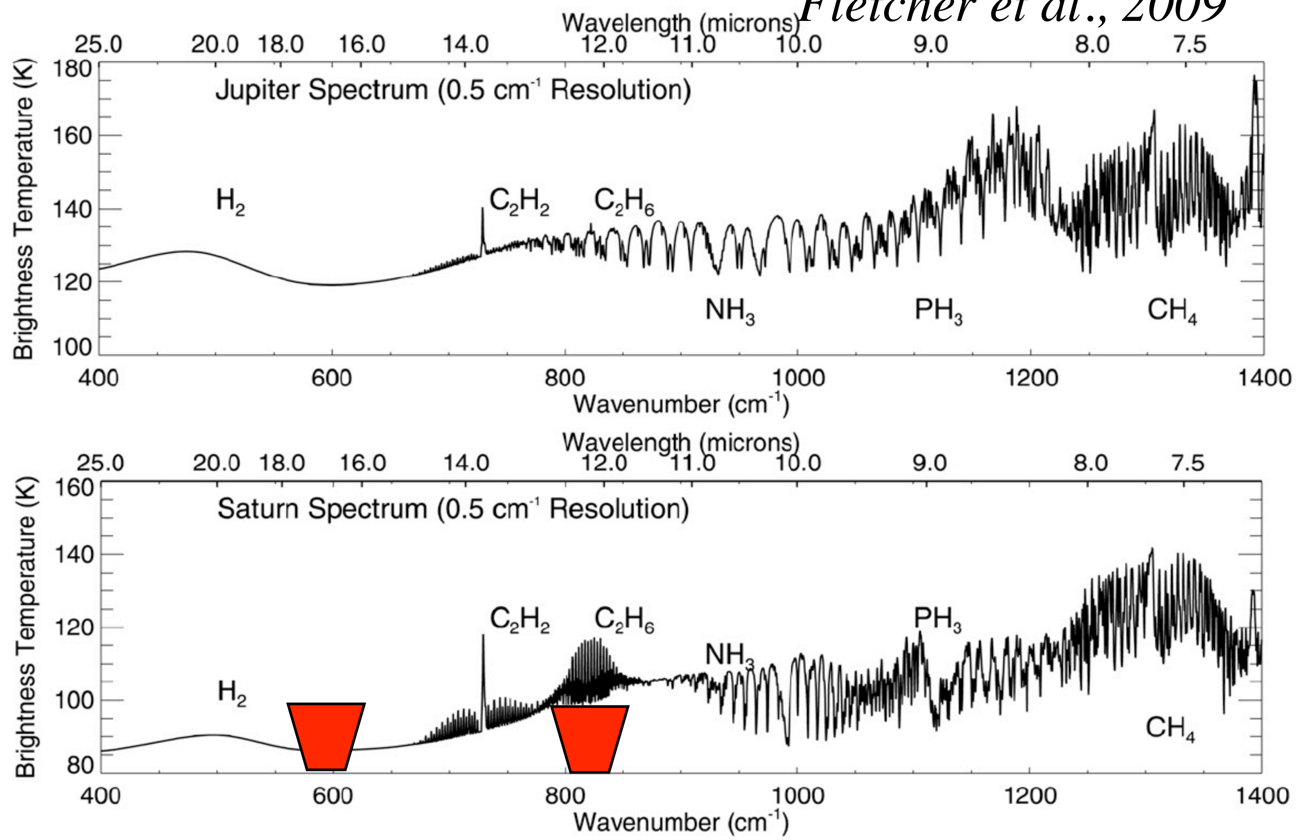


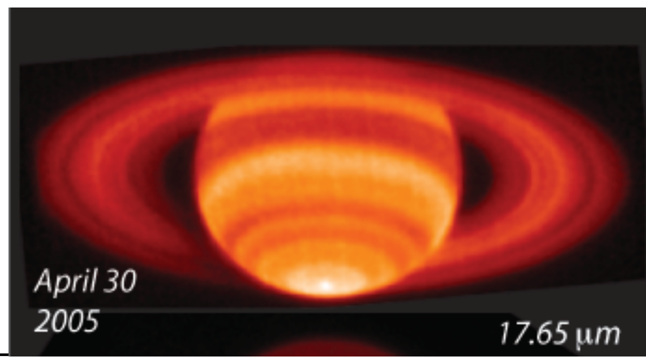
Baines et al. (2002)

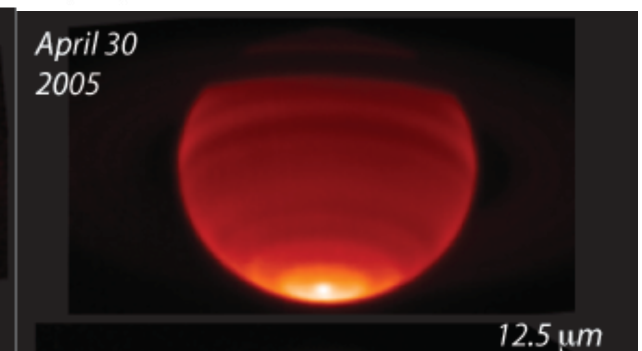
Thermal Infrared Spectra: choose a thermometer!

- Mid-IR spectra rich in absorption (positive lapse rate) and emission features (negative lapse rate).
  - Knowledge of the T(p) is vital for interpretation.
- Thermometers:
  - Tropospheric T from H_2 and He collision induced opacity.
  - Stratospheric T from CH_4 and hydrocarbon emission.

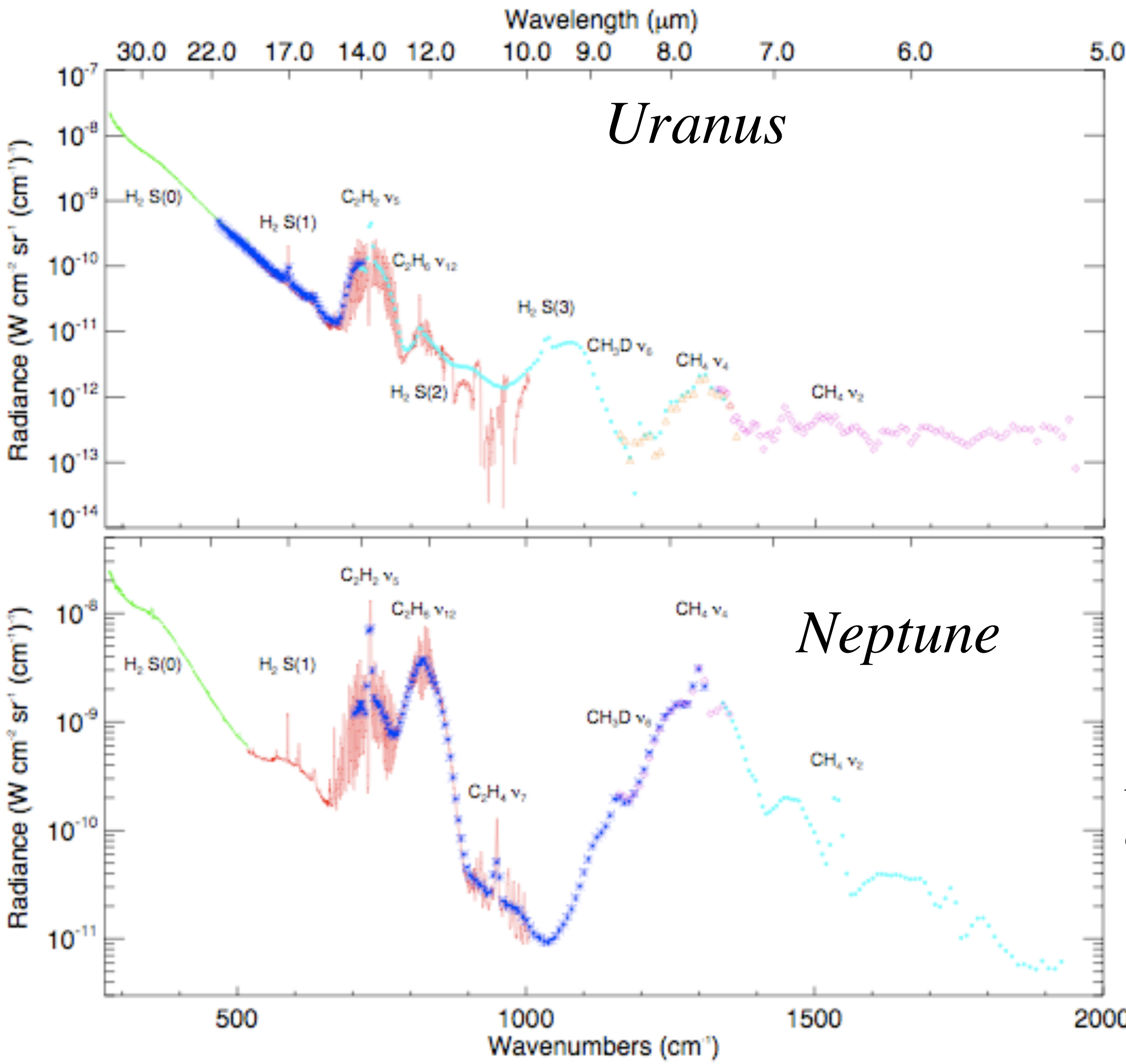
Fletcher et al., 2009







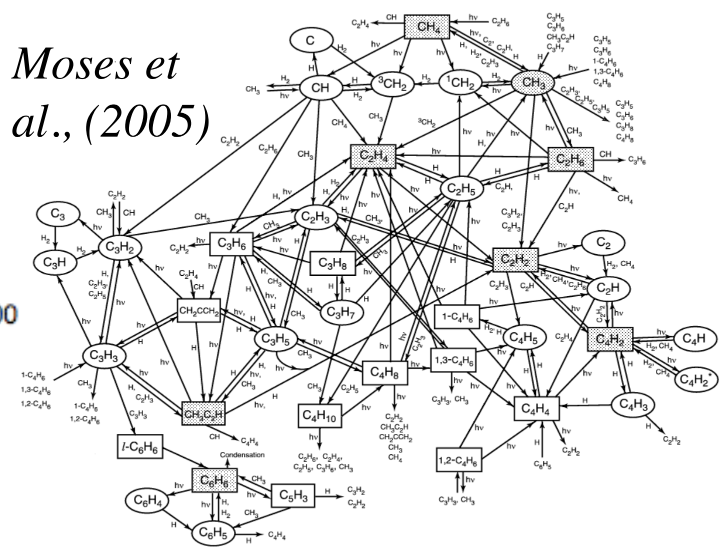
Giant Planet Spectra Reveal Chemistry



Spitzer data, Orton et al.

- Plethora of emission features on the gas giants:
  - Products of CH_4 photolysis: ethane, acetylene, ethylene and higher order hydrocarbons.
- Also see stratospheric CO, CO_2, H_2O and HCN.

Moses et al., (2005)



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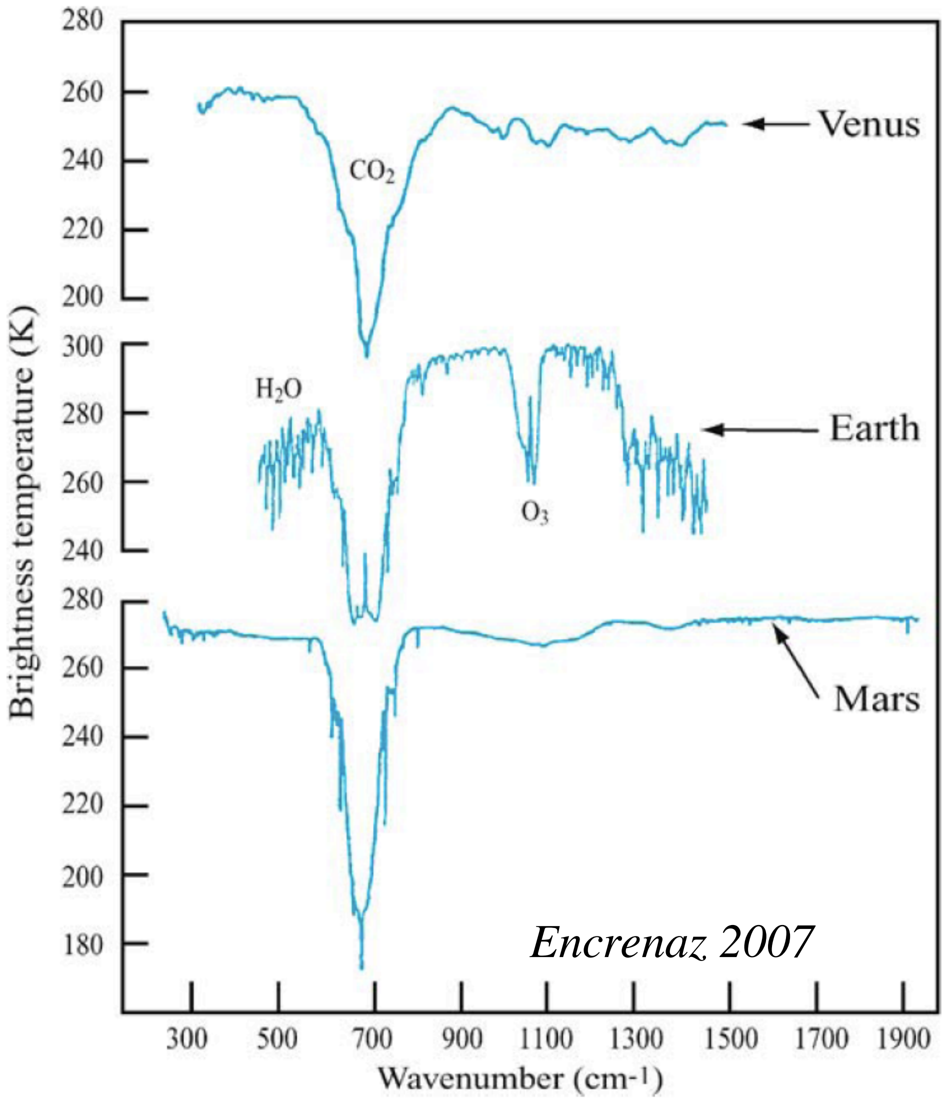
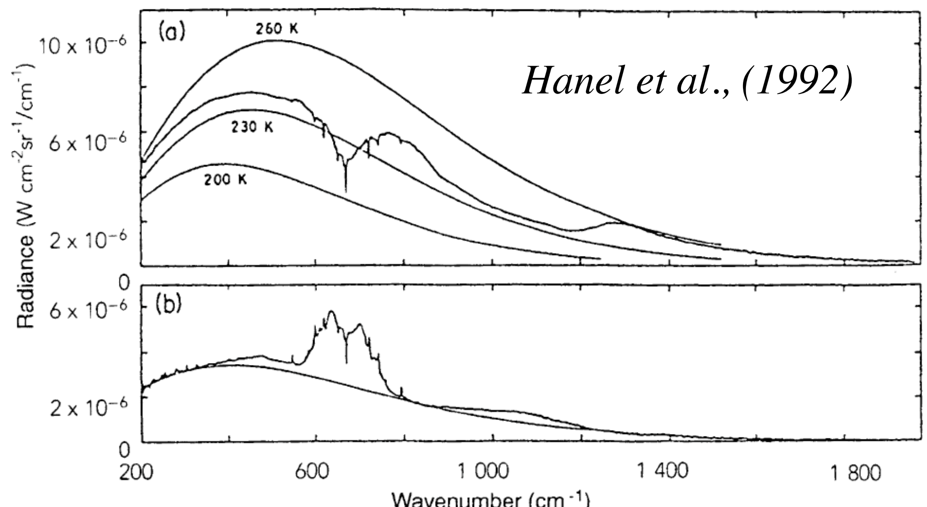
Terrestrial Thermal Spectra

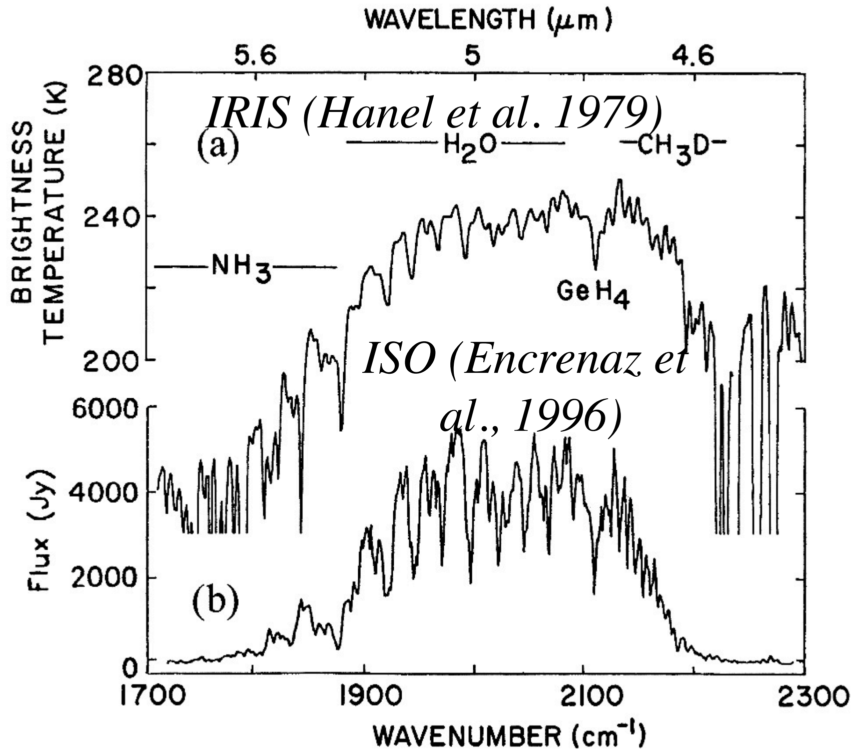
- Mid-IR spectra from Venera 15 (Venus), Nimbus 4 (Earth), Mariner 9 (Mars).
- CO_2 dominates at 15 μm, used to derive T(p).
- Water present at 6.2 μm on Earth, absent elsewhere.
- O_3 easily detectable at 9.7 μm in the Earth's spectrum, a possible biomarker.
- CO_2 on Mars can be in emission or absorption depending on the presence of an inversion.

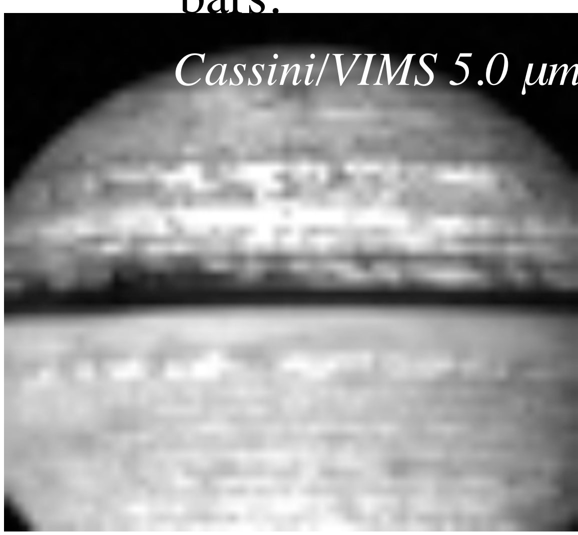


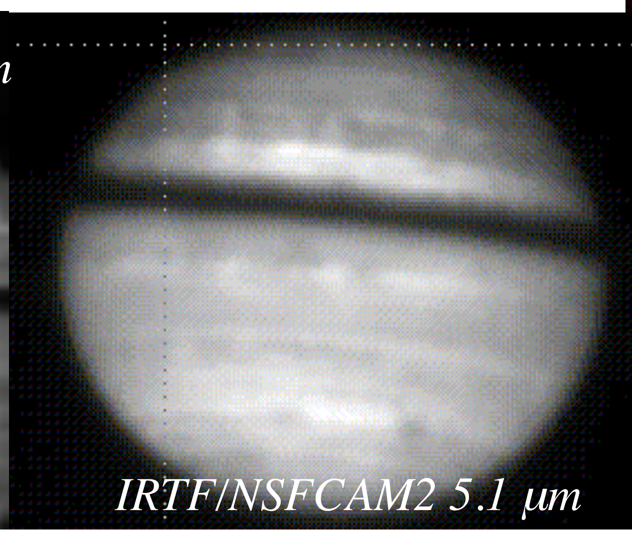


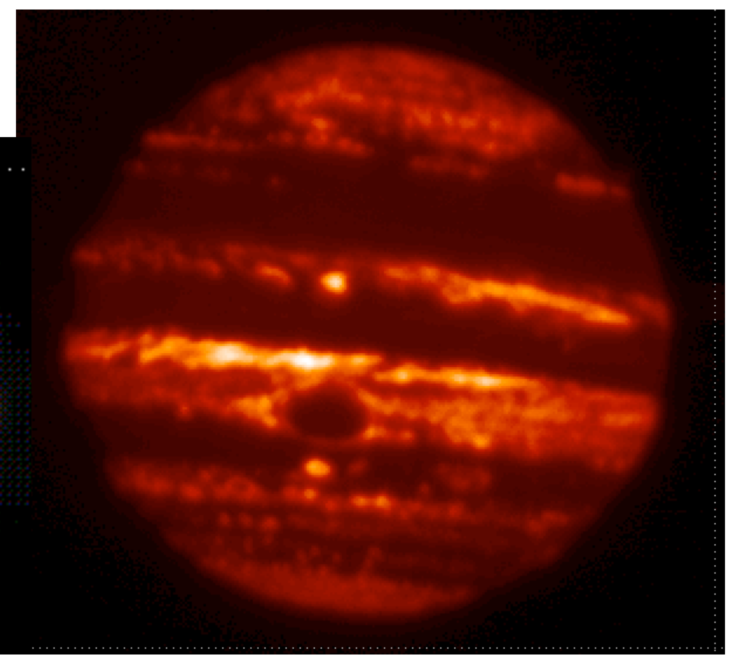
The 5 Micron Window

- Transition region between reflected and thermal components:
  - Dearth of opacity sources on giant planets, see thermal emission from deep within the planet.
  - High opacity clouds silhouetted against bright thermal emission.
  - Detect trace species: NH_3, PH_3, CH_3D, CO, GeH_4, H_2O, AsH_3.
  - Cassini/VIMS probing a new dynamical regime on Saturn at 2-5 bars.



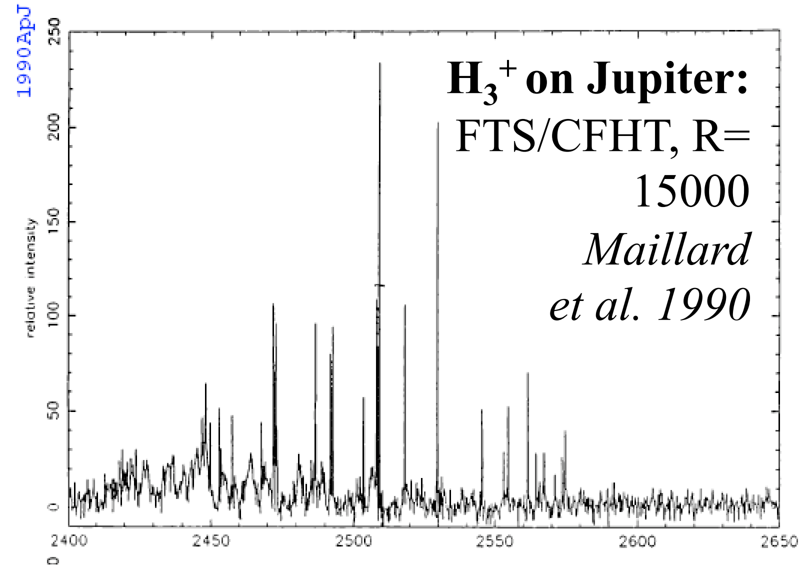


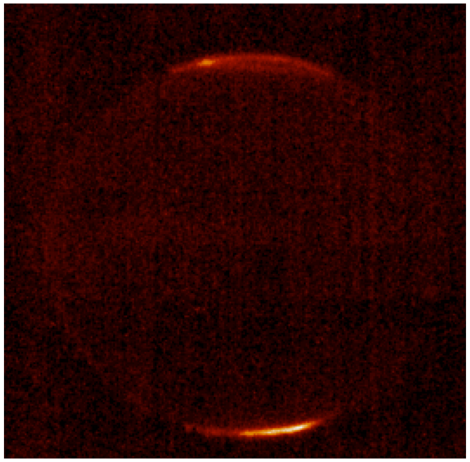




Fluorescence

- Fluorescent emission observed in all giant planet spectra and Titan:
  - Resonant fluorescence of CO at 2.4 and 4.7 µm (Mars, Venus, Uranus, Neptune); CO_2 at 2.0 and 4.25 µm; O_2 at 1.27 µm and CH_4 at 3.3 µm.
- H_3^+ is the only ion detected spectroscopically
  - Jupiter, Saturn and Uranus using band at 2 and 4 µm (Drossart et al., 1989). Could be fluorescence or thermal emission.



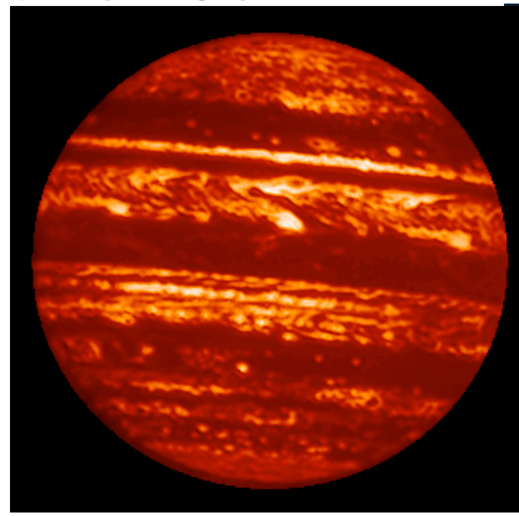


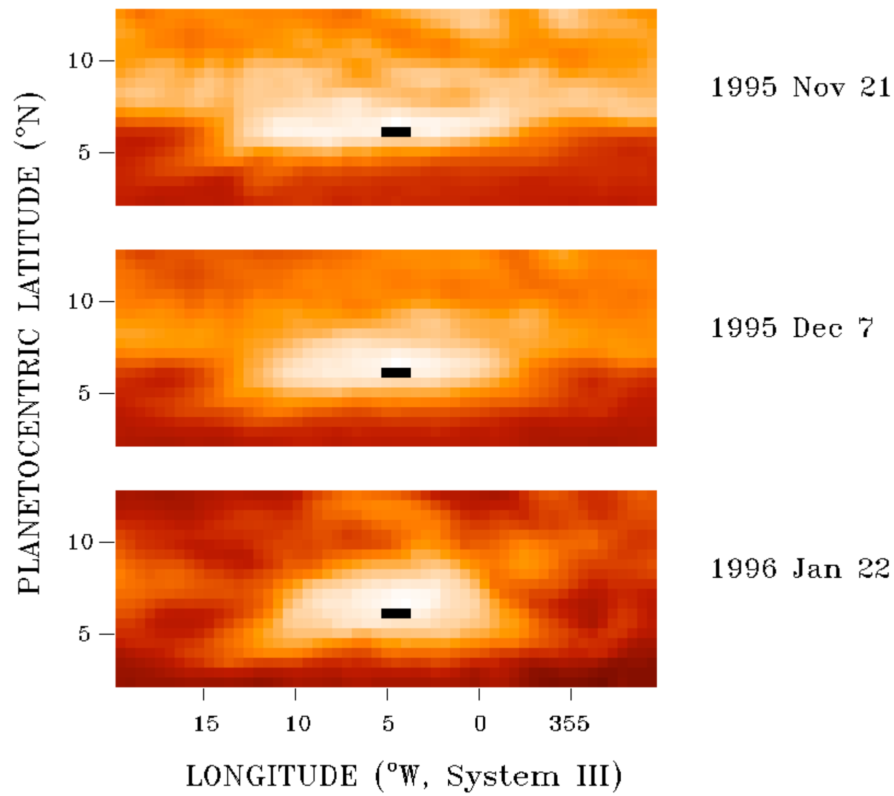
IRTF/NSFCAM2 3.43 µm H_3^+ Emission from auroral regions of Jupiter.

#2: Spectra of planetary atmospheres contain a wealth of compositional information which cannot be obtained via photometric imaging alone.

3. More than Spectra: The Need for Contextual Images

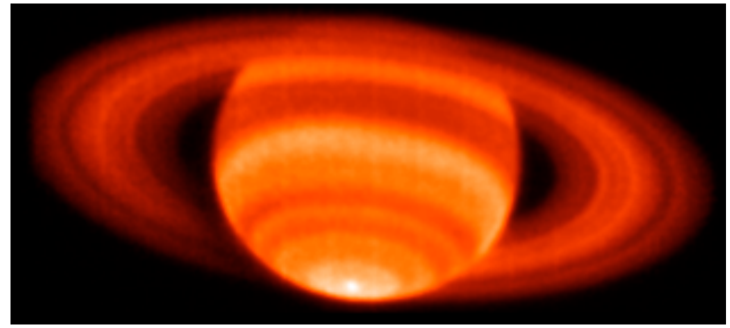
- Even in our Solar System, much of the high-resolution spectroscopy is disc-averaged. But there are pitfalls to interpretation of the composition from these measurements.
- Example: Galileo Probe (1995)
  - Discovered atmosphere unexpectedly depleted in volatiles.
  - O/H abundance much lower than expected.
  - Orton et al. (1998): Probe entered a 5-µm hotspot, depleted in volatiles.
  - Roos-Serote et al. (2004): Bright 5-µm hotspots depleted in H_2O but come to dominate the disc-average.
  - Not representative of global conditions.





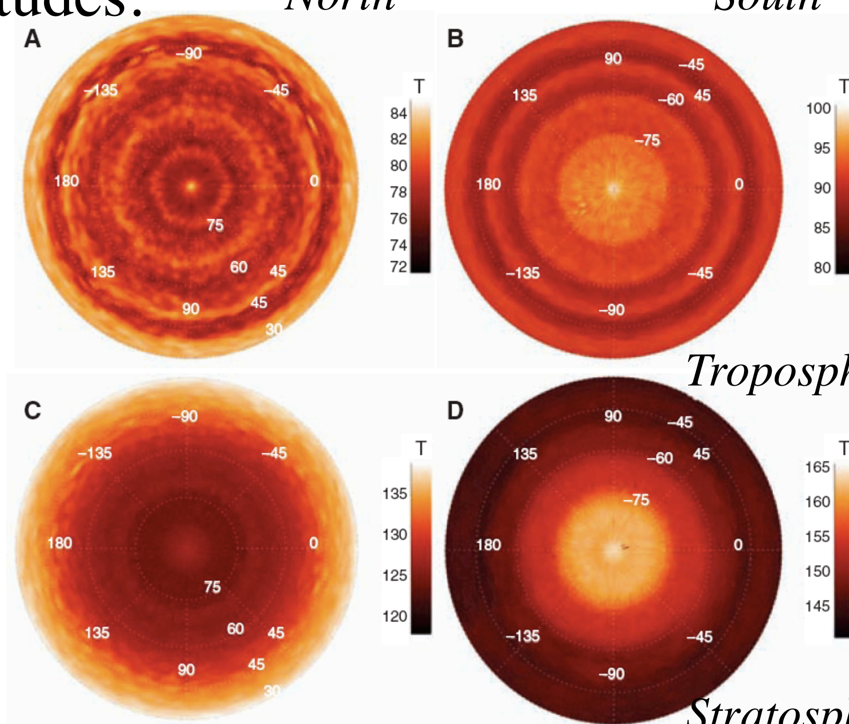
Hot Polar Vortices Dominate Thermal Emission

- Saturn and Neptune both exhibit hot polar vortices, brighter than other regions of the planet.
- Enhanced in hydrocarbons, unusual auroral chemistry, disc-average dominated by anomalous polar region.
- Limb brightening also weights stratospheric emission to high altitudes.



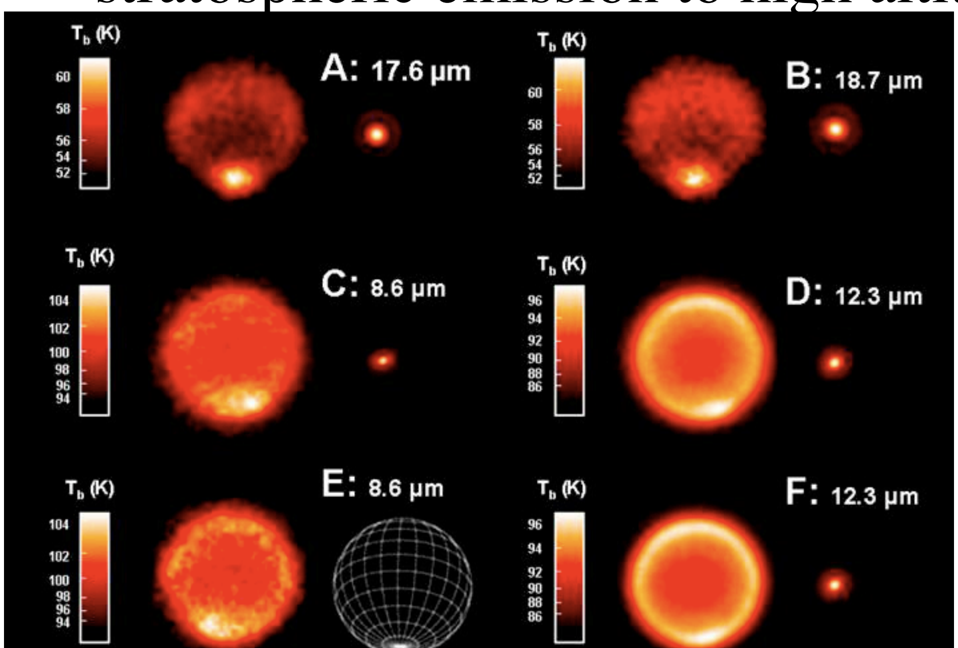
Saturn, Fletcher et al., 2008

North *South*



Troposphere

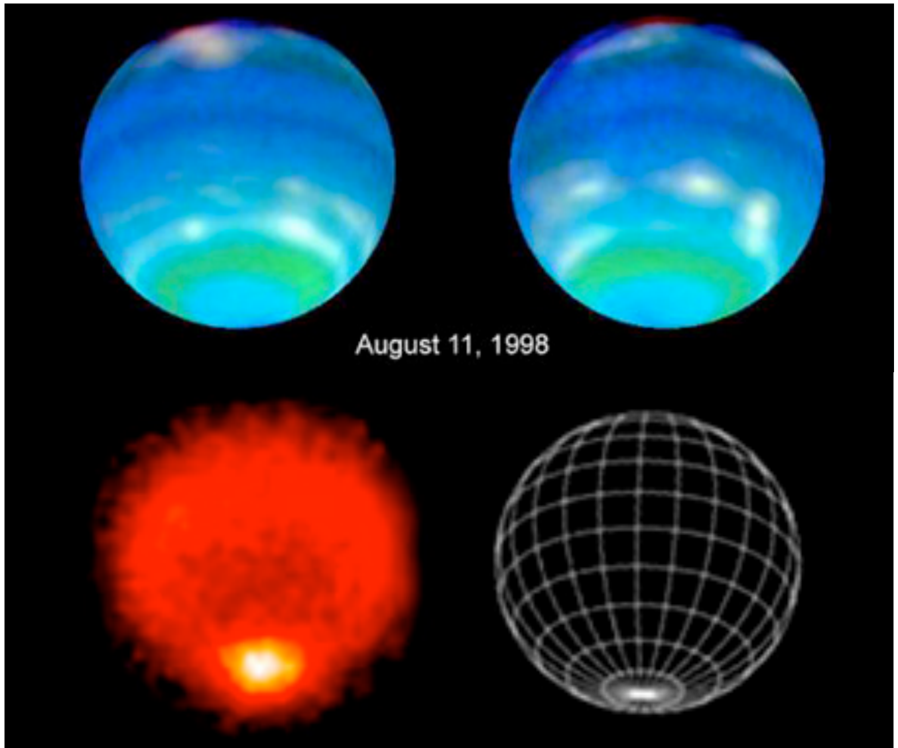
Stratosphere

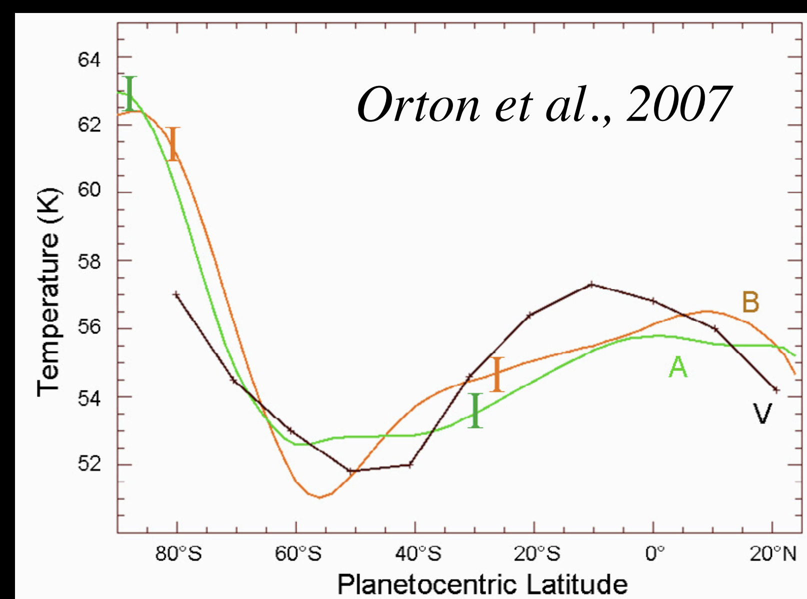


Neptune, Orton et al., 2007

Cold Trap for CH_4 on Ice Giants

- Example: Neptune's stratospheric CH_4
  - Tropopause should act as a cold-trap, but CH_4 detected in stratosphere from disc-averages.
  - Convective overshooting of CH_4-ice laden air invoked as an explanation.
  - But observations of warm southern pole permits 'leakage' of tropospheric CH_4 into the stratosphere without overshooting.
  - **Without imaging, the disc-averages proved difficult to interpret.**





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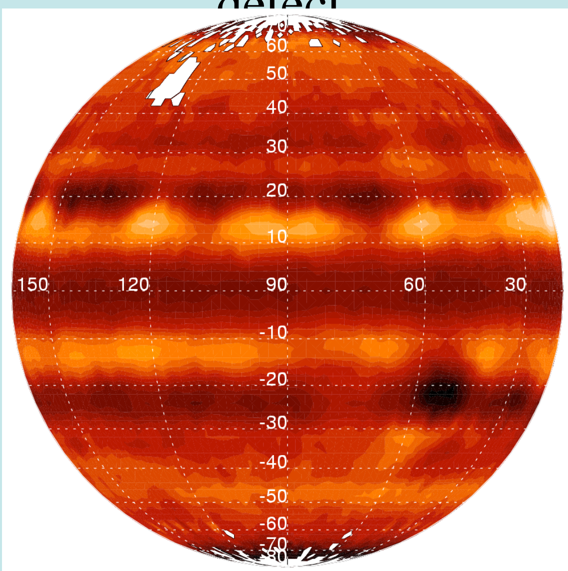
How to Detect Spatial Variations?

LATITUDINAL

Equatorial currents, belt/zone contrasts and jet streams, seasonal asymmetries, polar vortices.

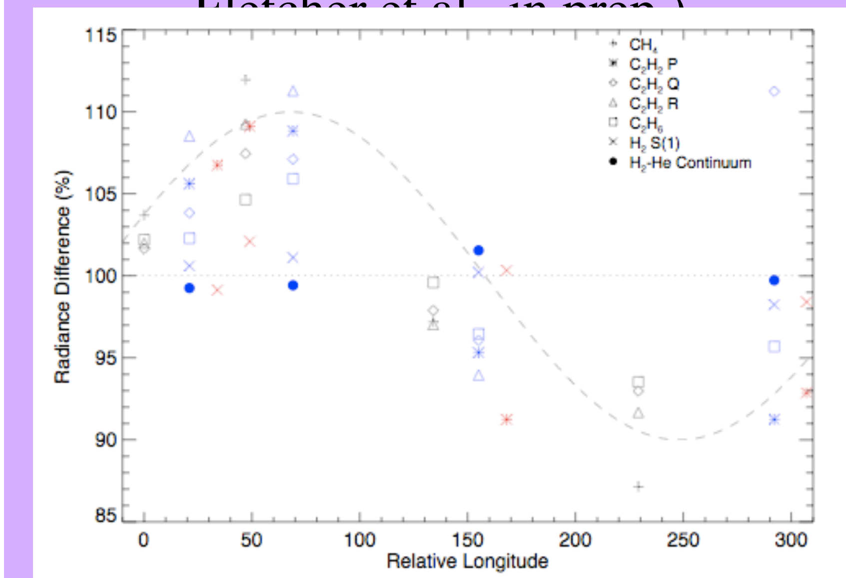
No variation with rotation, so hard to detect.



LONGITUDINAL

Large storms, zonal waves.

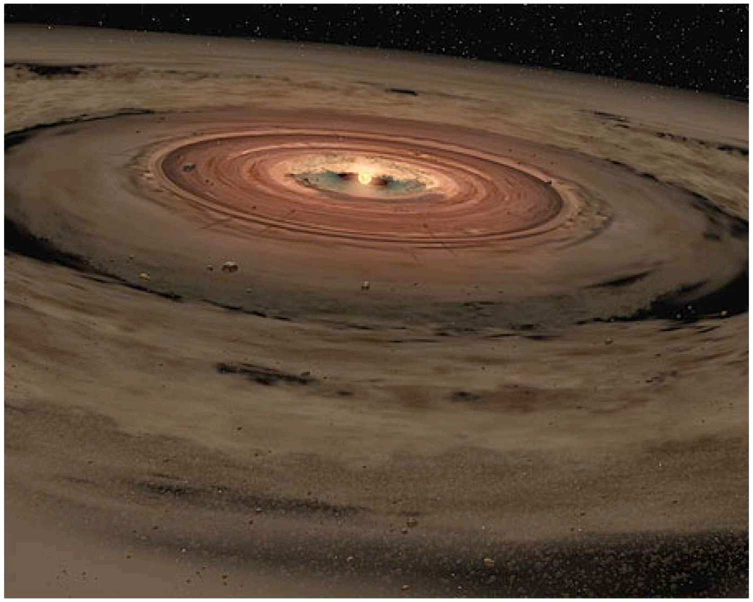
Variation in disc-averaged flux as the planet rotates (e.g. Spitzer observations of Uranus' stratospheric emission, Fletcher et al., in prep.)



#3: Atmospheric dynamics and chemistry modulate the reflected and thermal components of spectra, so contextual information (images, models) may be required to interpret disc-averaged results.

4. Fossils from the Early Solar System

- Composition of planetary atmospheres bear signatures of their formation:
  - Elemental abundances and isotope ratios representative of the primordial solar nebula.
  - Extrapolate weather-layer composition to 'bulk' composition of the planets.
- Refractories condensed close to the Sun (small amount of material for dense, rocky worlds), lighter elements at greater distances (large amount of material for low density giants).
- Water condenses to ice at highest nebula T, forming a 'snow-line'.
  - H_2O expected to play a crucial role as the dominant ice. Should be the primary constituent of planets beyond the snow-line.



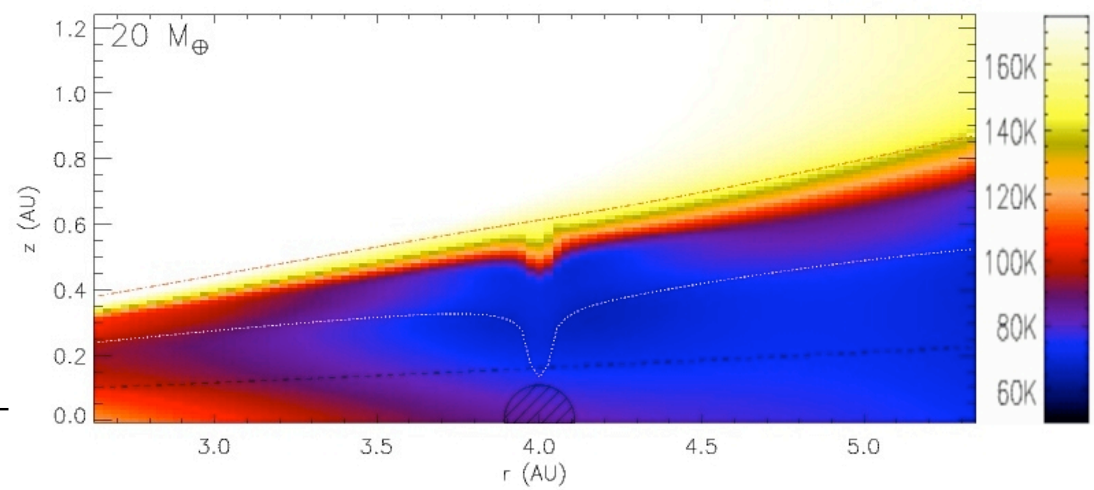
- Giant planet cores 10-15 M_{earth}, gravitational collapse of H_2-He, heavy elements homogenized with light gases.
- More H_2/He available to Jupiter and Saturn; Uranus and Neptune expected to have more than 50% of their mass from protoplanetary cores.

Thermochemistry explains the Broad Trends

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2$$

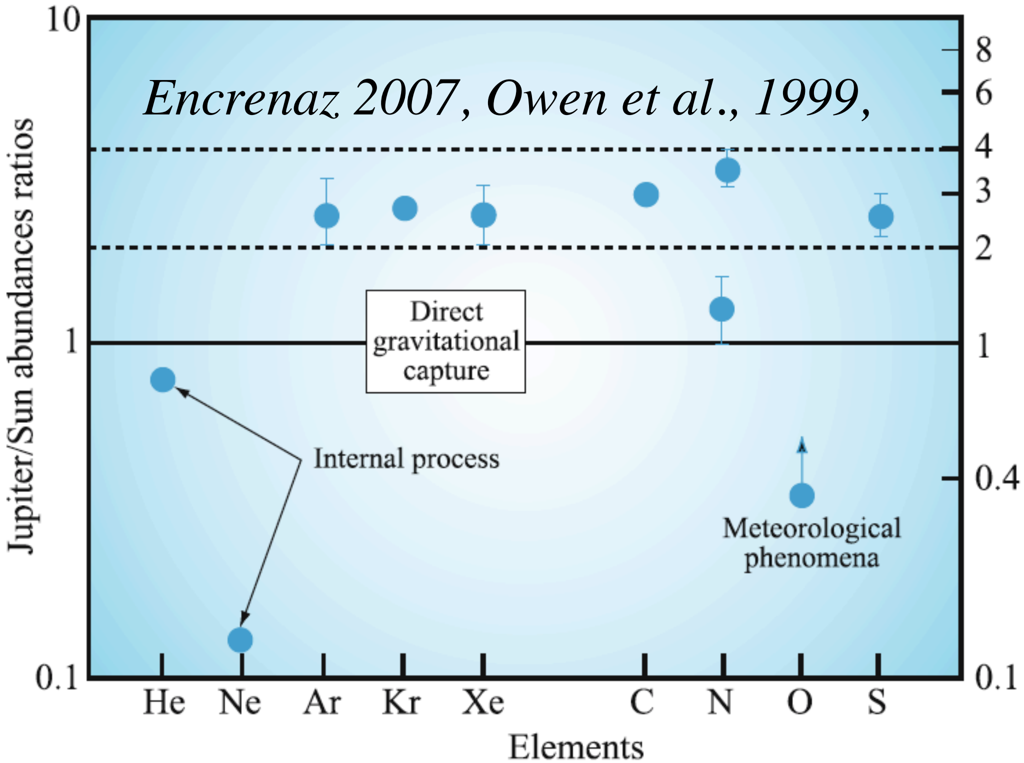
$$2NH_3 \longleftrightarrow N_2 + 3H_2$$

- Reactions evolve to the right for high T and low p, providing terrestrial planets with atmospheres dominated by N_2 and CO_2.
- CH_4 and NH_3 were likely available in the cold sub-nebulae of the giant planets.
- Explains the dominant species in terrestrial and giant planet spectra to first-order.
- Thermochemical arguments will be a vital constraint on the interpretation of exoplanetary spectra.



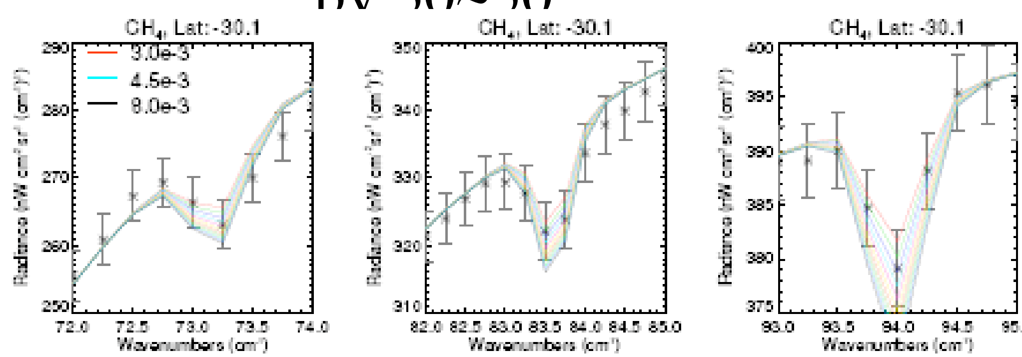
Temperature of a protoplanetary disc, Jang-Condell 2008.

Comparative Planetology: Enrichments in Giants



- Nucleation theory (Mizuno, 1980): Core-to-envelope ratio increases with heliocentric distance, so outer planets more enriched with heavy elements.
- Jupiter uniformly enriched by ~4, Saturn by ~10, Uranus and Neptune by 30~50

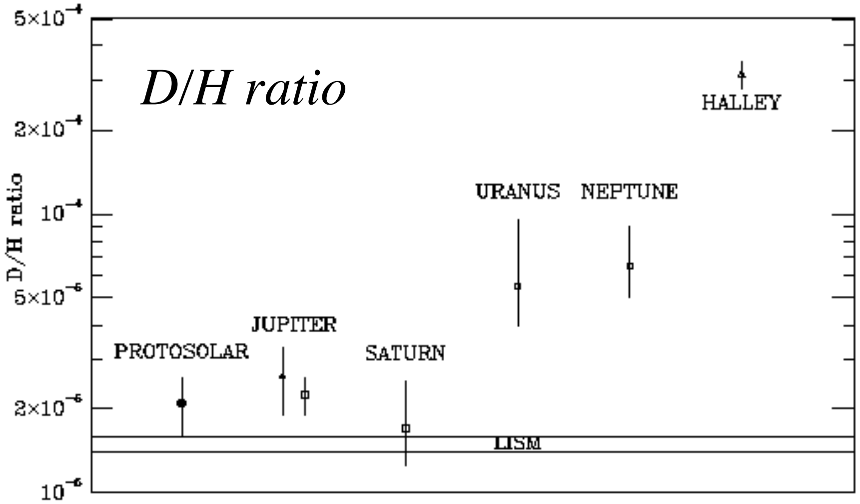
C/H Measured on all Giant Planets:
Saturn C/H enrichment from Cassini far-IR CH_4 lines:
Mole Fraction = 4.7 ± 0.2 x 10-3
Enrichment = 10.9 ± 0.5



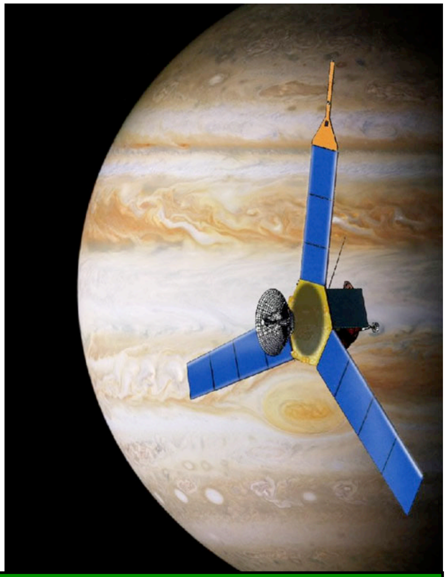
Fletcher et al. (2009)

Elemental and Isotopic Measurements

- Important measurement objectives:
  - Deuterium enrichment in H_2 and CH_4 increases with heliocentric distance, suggestive of a cold-temperature origin.
  - $^{13}C/^{12}C$ is the same on all planets measured to date: a shared reservoir for carbon incorporated into the planets.
  - $^{15}N/^{14}N$ on Jupiter smaller than terrestrial value, unique reservoir for Earth's primordial nitrogen (Fouchet et al, 2004)?



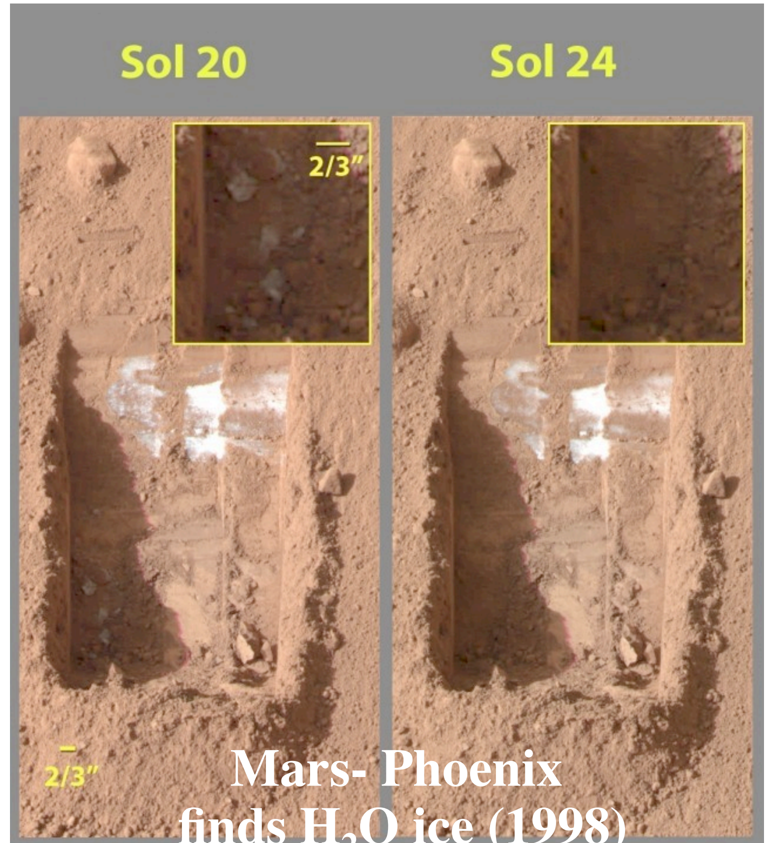
- O/H is a key parameter not yet constrained: JUNO microwave radiometer should measure deep H_2O on Jupiter in 2016, and we need comparative measurements on all the gas giants.



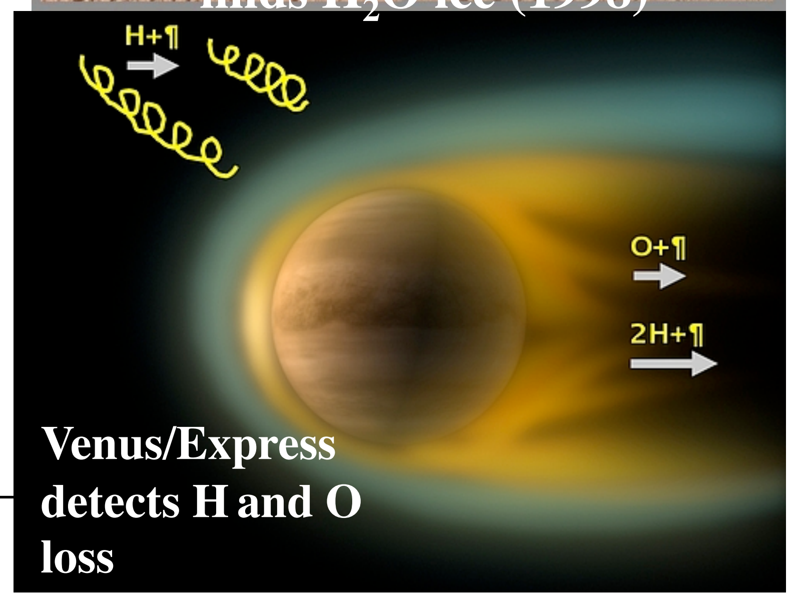
#4: Bulk composition derived from atmospheric spectra supports the nucleation model of planet formation, comparisons of elemental and isotope ratios provides an understanding of their origins.

5. Divergent Evolutionary Paths

- Small changes in physiochemical conditions dramatically affected subsequent evolution to produce the end-states we see today.
- Divergent evolution of Venus, Earth, Mars from similar starting conditions: N_2, CO_2 and H_2O.
  - Differences in heliocentric distance meant H_2O was a vapour on Venus (730 K), liquid on Earth (288 K) and solid on Mars (150-300 K).
  - Absence of magnetic field on Venus and Mars, solar wind could dissociate H_2O, H_2 could escape, leading to high D/H ratios of 120x and 5x terrestrial on Venus (de Bergh, 1991) and Mars (Owen et al., 1988) respectively.
  - Low Martian T allowed H_2O to be locked away as ice beneath the ground.

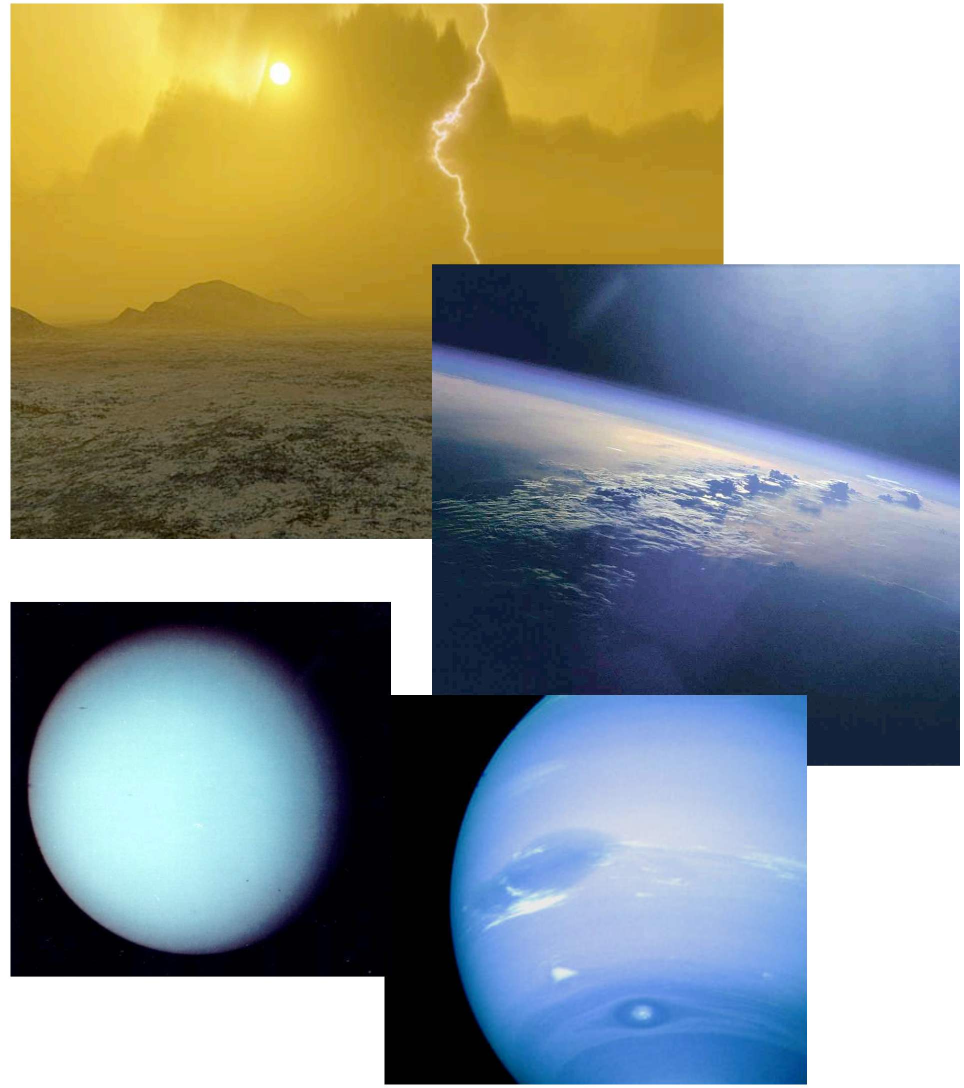


Mars- Phoenix finds H_2O ice (1998)



Venus/Express detects H and O loss

Planetary Science continues to seek answers…

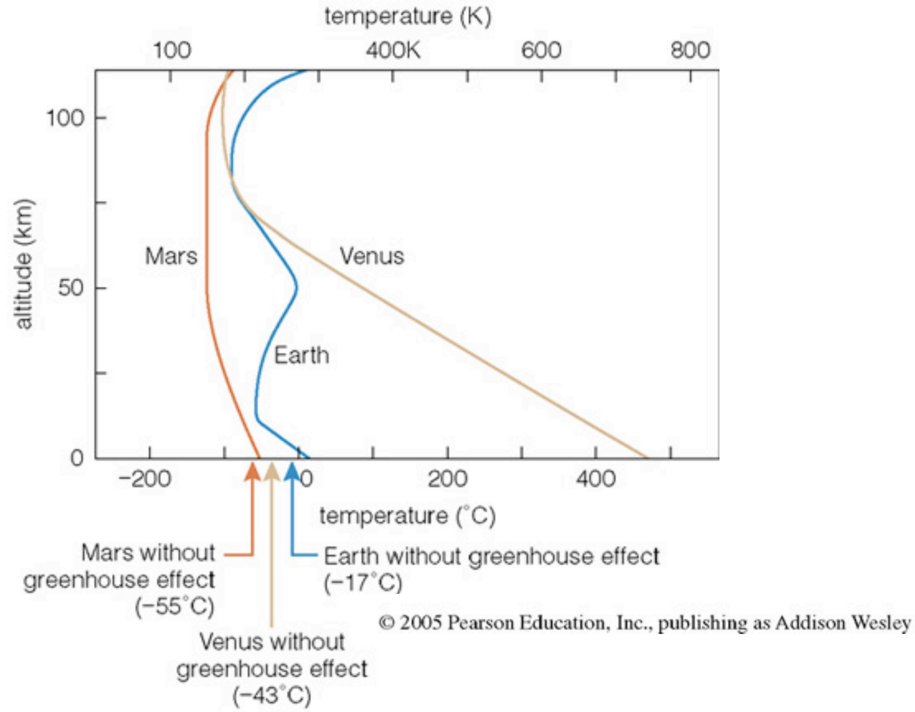


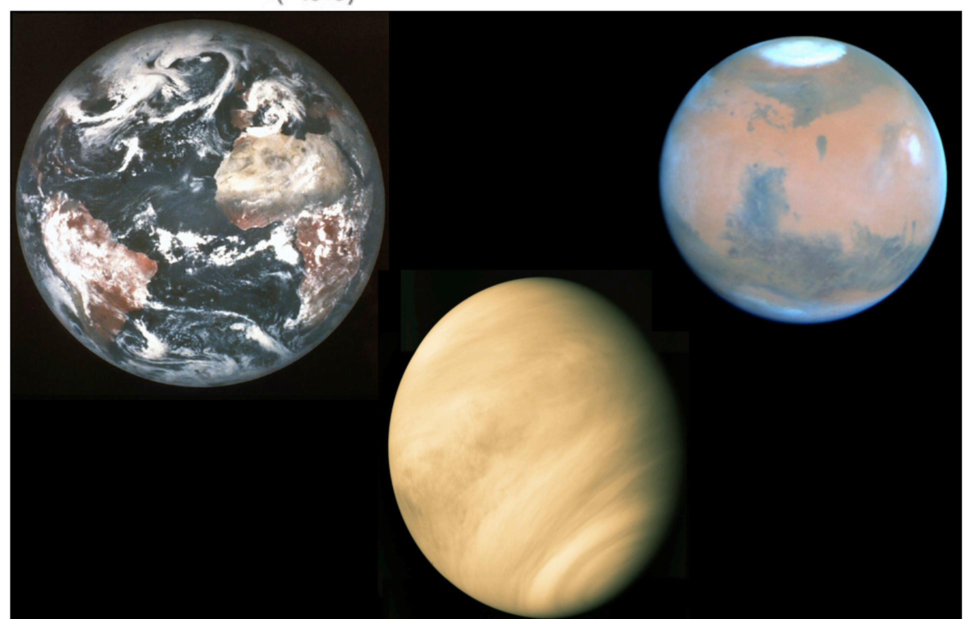
- Many mysteries remain unresolved:
  - What made Earth perfect for life to evolve? Because it retained liquid water and locked away CO_2 as $CaCO_3$ in the oceans, this prevented the runaway greenhouse effect that occurred Venus, but that’s only part of the story….
  - Why is Uranus sluggish, knocked on its side with a negligible internal heat, but Neptune is highly active with a strong internal source?
  - Is the presence of giant outer planets important to prevent catastropic impacts on inner planets?

#5: Small differences in initial conditions created the myriad of atmospheric conditions observed in our Solar System, some of which remain poorly understood.

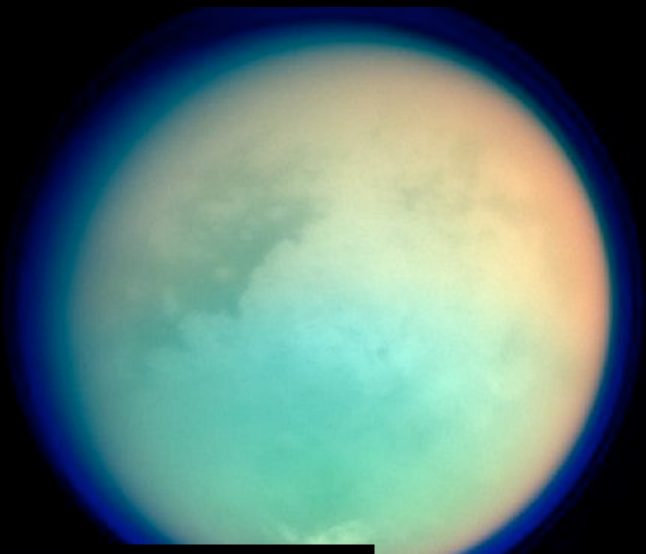
6. The Goldilocks Idea

- *Not too hot, not too cold, but* ***just right****…*
- Water in liquid form (acting as an excellent solvent) is thought to be a prerequisite for the development of life.
- Concept of Earth as having formed in the Solar System's **habitable zone**, but this may be misleading or too restrictive.
  - Liquid water in Mars' past?
  - Oceans beneath the surfaces of icy outer planet satellites?
- Extremophiles on Earth demonstrate that life perseveres in the most unexpected of environments.



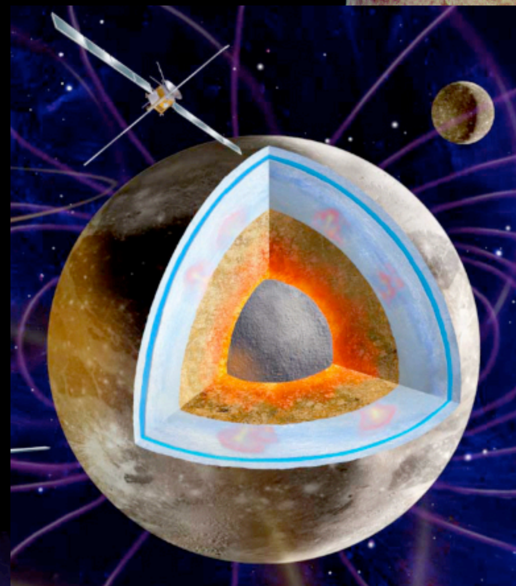


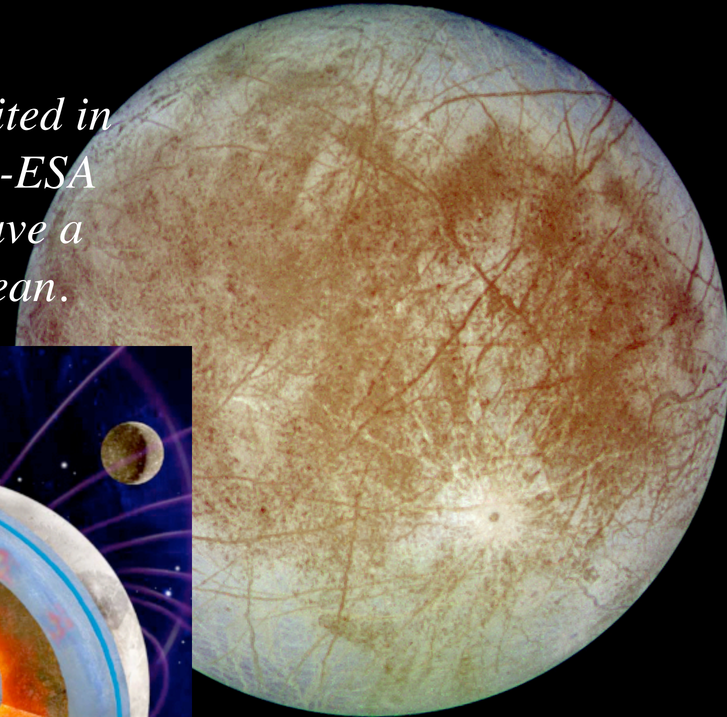
New Habitable Environments?

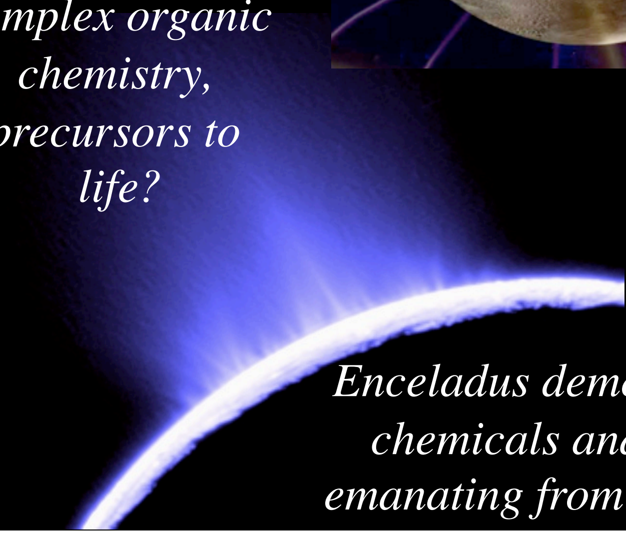


Titan, being studied by Cassini, harbours complex organic chemistry, precursors to life?

Europa, to be visited in 2025 by a NASA-ESA mission, may have a subsurface ocean.

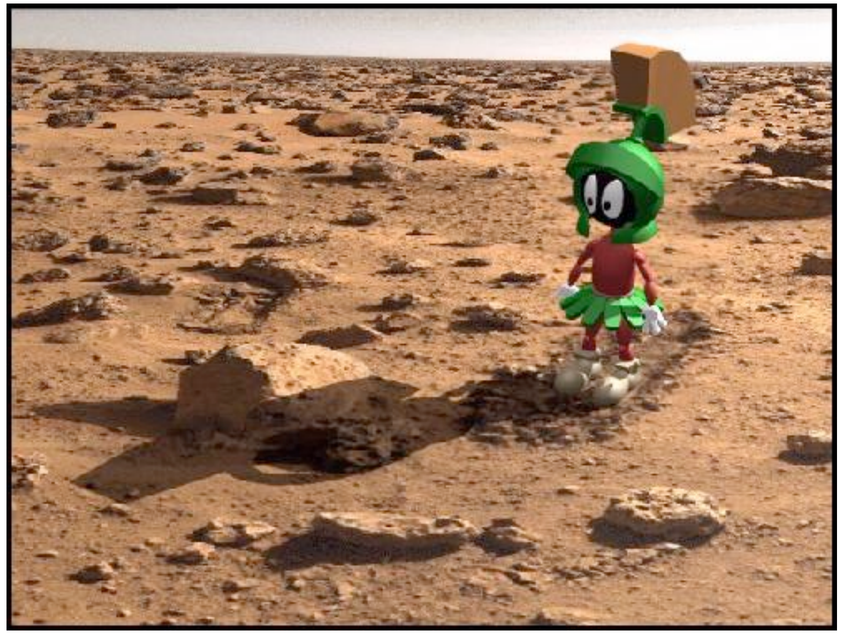






Enceladus demonstrates water, chemicals and intense heat emanating from it’s tiger stripes.

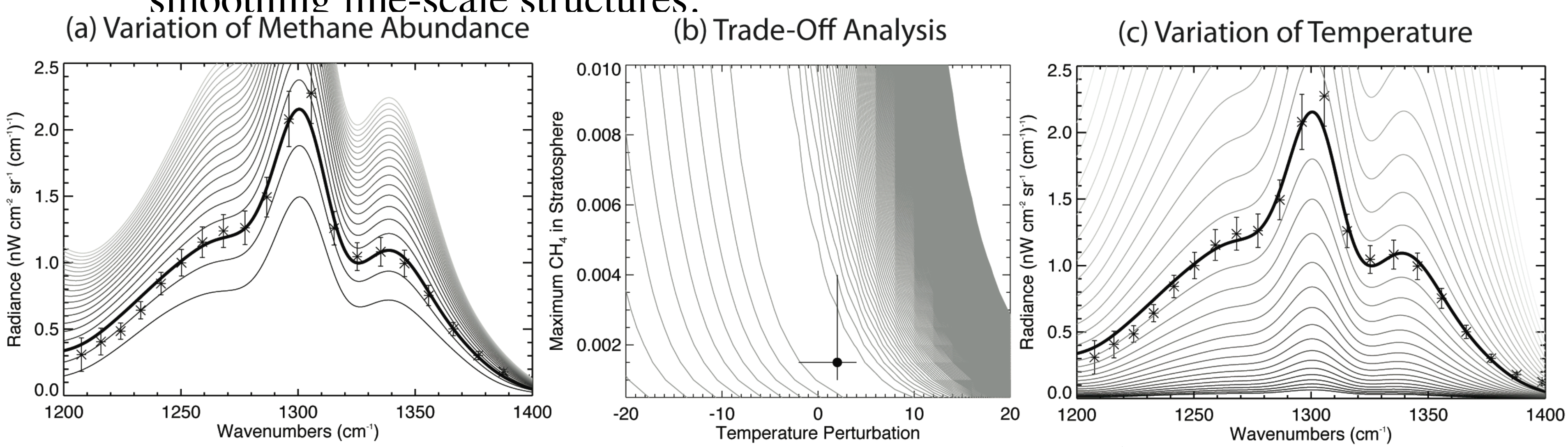
- What if an icy moon orbited a giant planet close to the parent star?
- What if a runaway greenhouse effect heats up a distant (otherwise cold) planet to Earth-like temperatures?
- What if gravitational tides heated a moon to survivable temperatures?
- … life, but not as we know it…



#6: Solar system science teaches us not to be too restrictive about our concepts of "zones of habitability" in the solar system, as there are sources of energy other than the Sun…

7. A Myriad of Solutions

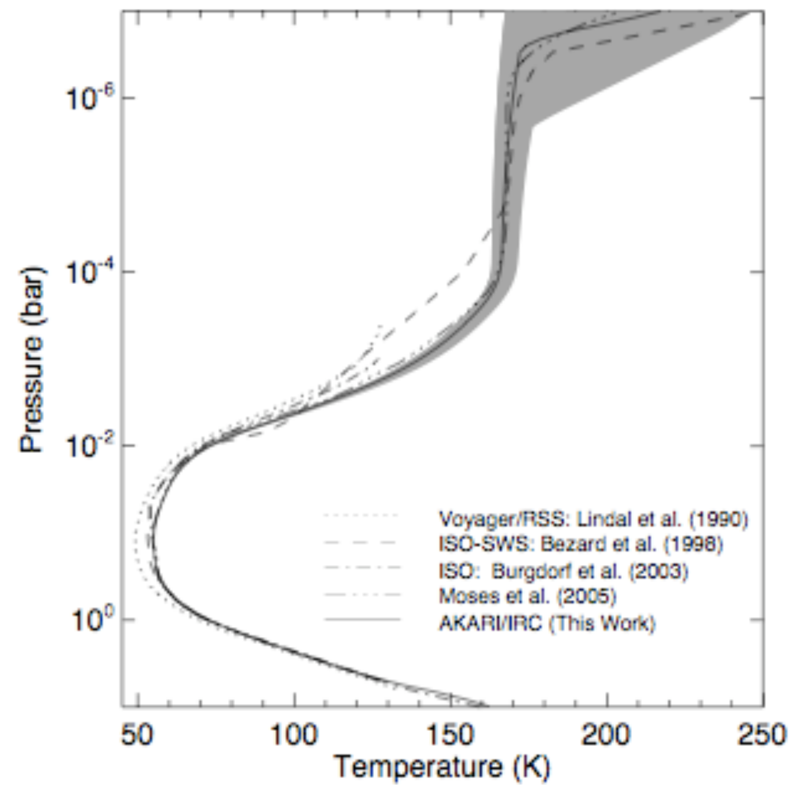
- Non-uniqueness in remote sensing solutions plagues solar system atmospheres:
  - Fundamental degeneracy in deriving temperature profiles from a well-mixed constituent (CO_2 on terrestrial planets; H_2/He and CH_4 on giant planets).
  - Atmospheric retrievals rely on probabilistic techniques (inverse problem, retrieval) to determine composition based on statistical likelihood.
  - T(p) errors propagate to compositional uncertainties.
  - Nadir remote sensing has a vertical resolution equivalent to one scale height, smoothing fine-scale structures.



Fletcher et al., 2009, in prep. AKARI Spectra of Neptune, tradeoff between CH_4 and T(p) in the stratosphere.

Spectral Modelling Maturing all the time…

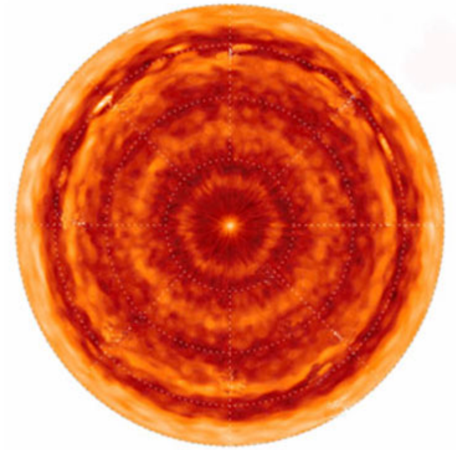
- Radiative transfer uncertainties, cont.
  - Disc-averages can be misleading.
  - Cold-T and long-path laboratory spectra of gases improving all the time, high-T linelists less mature.
  - Models may have incomplete approximations to the physics, or be missing broad-band continuum absorbers like aerosols/condensates which lead to T(p) uncertainties.
- Interpretation via chemical, dynamical and radiative modelling also improves in sophistication…

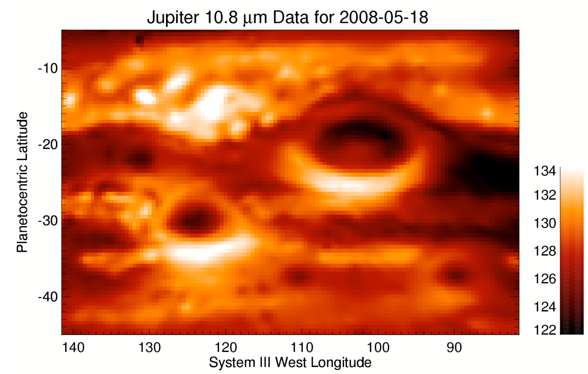


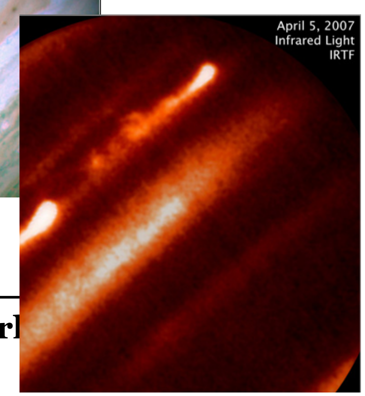
#7: Remote sensing relies on statistical techniques to determine atmospheric composition from a large manifold of potential solutions. There can be more than one 'right' answer!

Conclusions

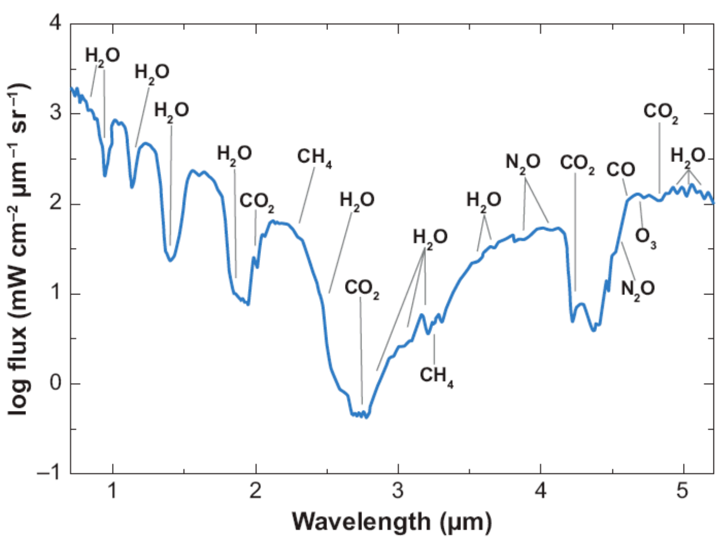
- **Atmospheric structure and energy balance:**
  - Fluids in hydrostatic equilibrium.
  - Balance between energy deposition from the Sun and internal energy from the planet.
- **Spectroscopy is a vital tool:**
  - **Required** to constrain the composition of atmospheres, though disc-averaged spectra are weighted towards brighter regions (dynamic features, limb brightening, polar phenomena) that need contextual imaging to understand.
- **Solar system spectra consist of reflection and thermal emission components:**
  - These are well separated for solar system bodies.
  - Different spectral regions sensitive to different altitudes and used for different studies (cloud tracking, compositional measurements).
- **Temperature determinations are a vital prerequisite for interpretation of thermal emission spectra:**
  - But these can be highly correlated with assumptions about composition, leading to a myriad of possible 'right-answers' for models of atmospheric structure.







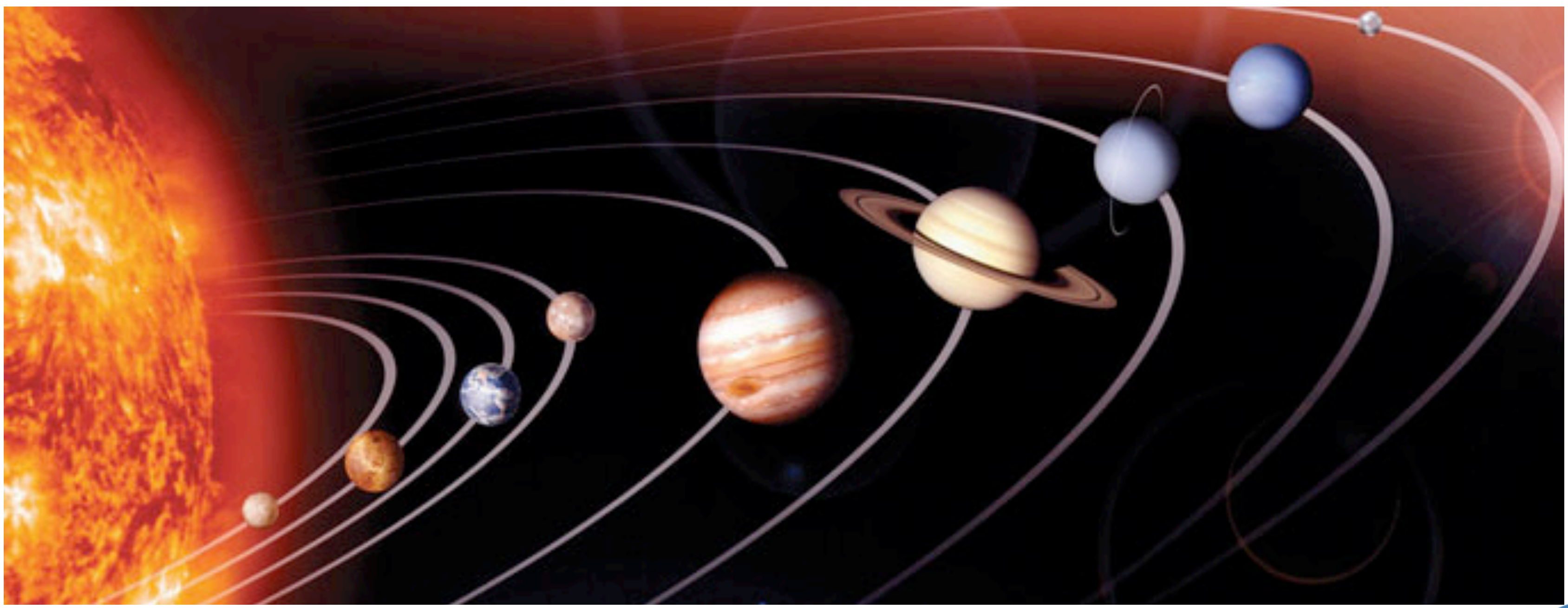
Conclusions, cont.



- **Spatial Variations:**
  - Latitudinal inhomogeneities may be difficult to detect.
  - Longitudinal variations could be monitored via rotational variability.
- **Comparative planetology:**
  - Elemental abundances and isotope ratios contain fingerprints for the mechanisms of planetary formation and the subsequent evolution.
- **Thermochemical arguments provide a first-order understanding of the composition of our solar system**
  - Water is expected to play a key role in formation.
- Small differences in initial conditions (temperature, mass, availability of material) can lead to divergent evolutionary paths for different planets.
- **The concept of a habitable zone may be misleading**
  - Continued exploration of our solar system reveals many surprising potential sites for the development of life.

Complexity: myriad of diverse of planetary environments in our solar system, we should expect nothing less from exoplanetary systems.

Learning about planets in distant star systems may help us discover answers about the origins of our own Solar System



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