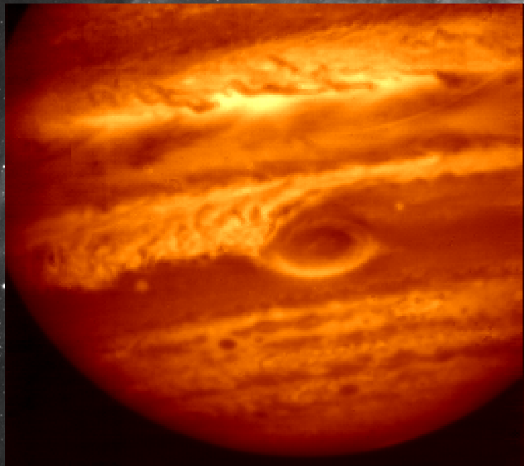
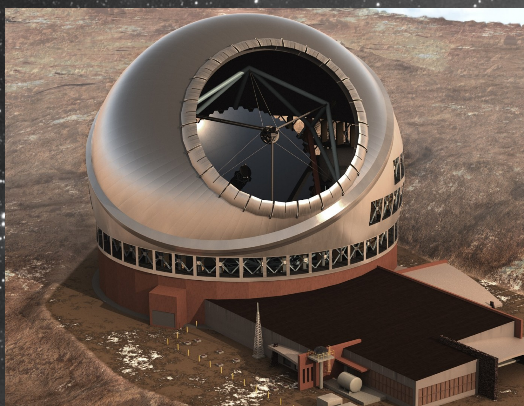
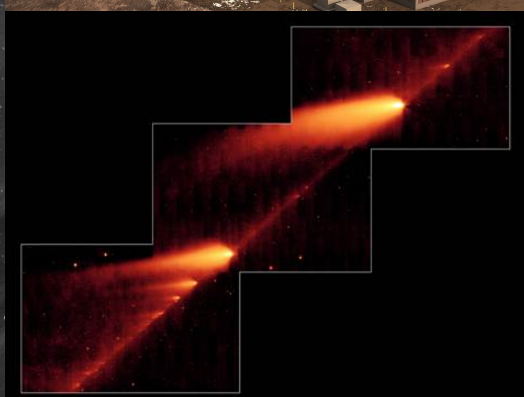


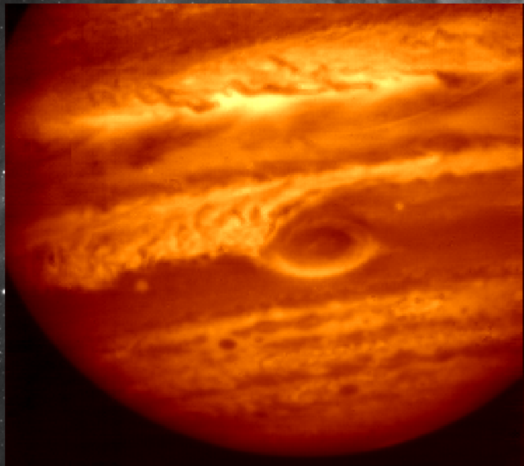


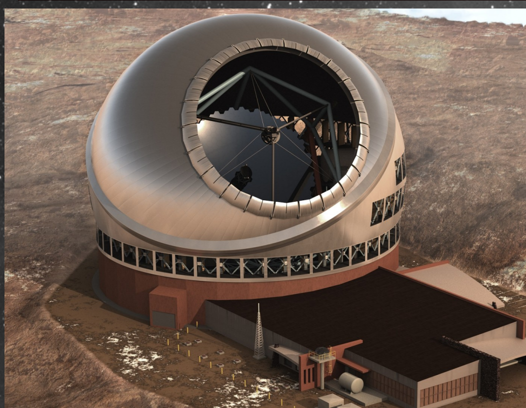


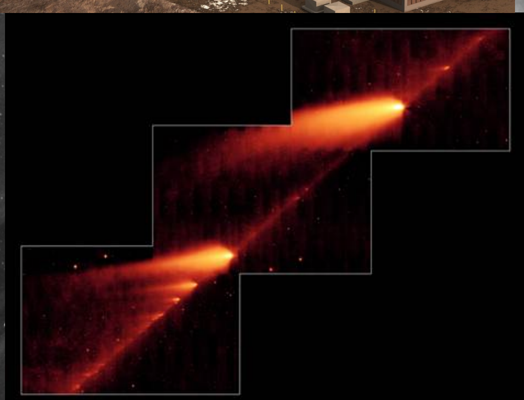
Solar System Science with the TMT

Glenn Orton
Jet Propulsion Laboratory
California Institute of Technology

Thanks To Leigh Fletcher,
as well as Athena Coustenis, Therese Encrenaz, with additional input from N. Bowles, T. Greathouse, R. Giles, C. Howett, P. Irwin, R. de Kok, H. Melin, I. de Pater, T. Stallard, C. Tsang, N. Teanby, C. Wilson







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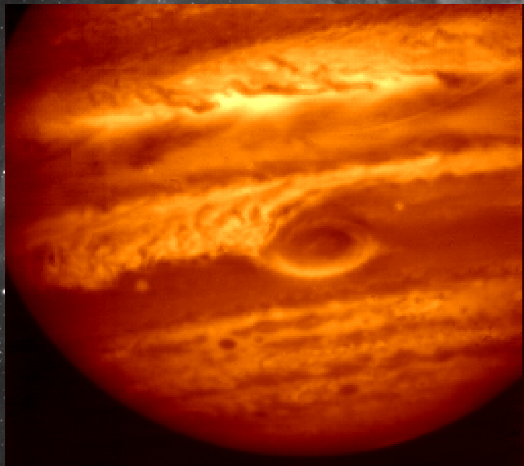

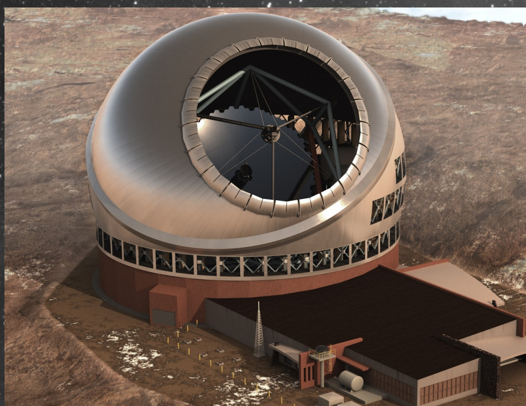

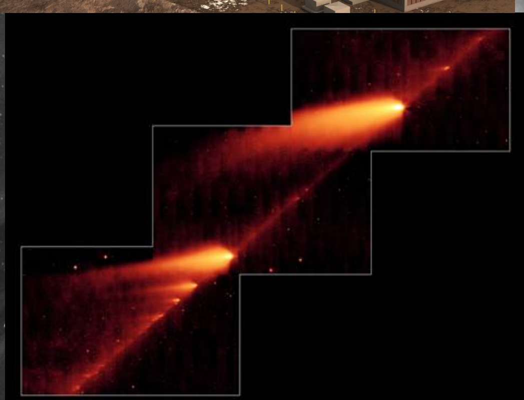

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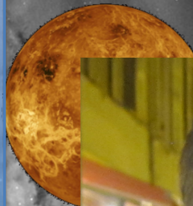

2016 recipient of AAS/DPS Urey Prize for outstanding accomplishments in planetary research by an early-career scientist

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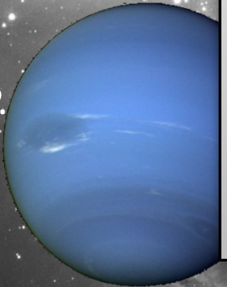
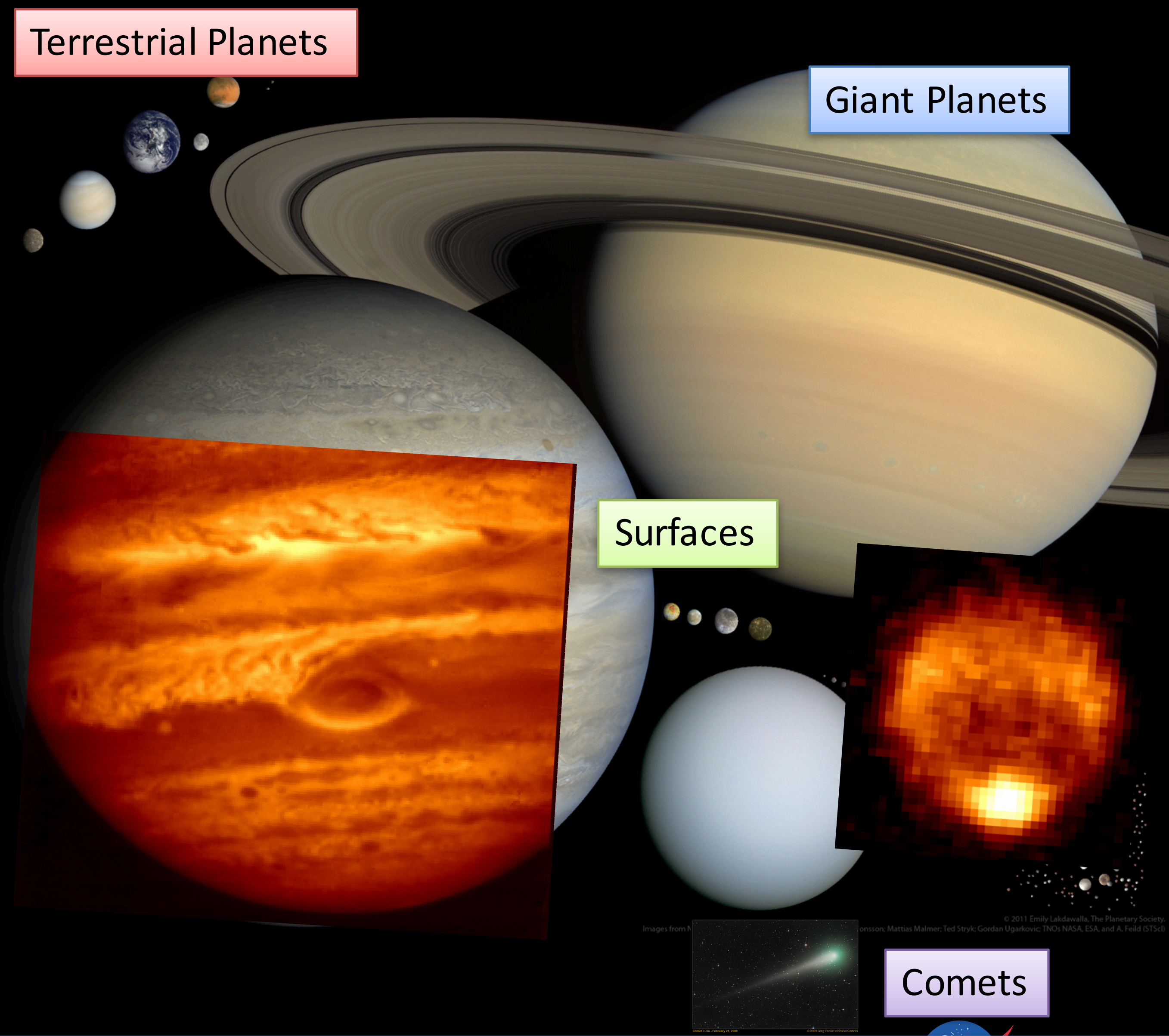


TMT: New Opportunity for Planetary Science

- Spatially-resolved imaging and spectroscopy is a crucial diagnostic of environmental conditions within our solar system.
- Understand diversity of planetary climates and processes to place our own world in broader context.
- Combination of exquisite spectral/spatial resolution enables new opportunities for planetary science.



Intro: Spectral range?

Origins

Chemistry

Fluid dynamics

Astrobiology

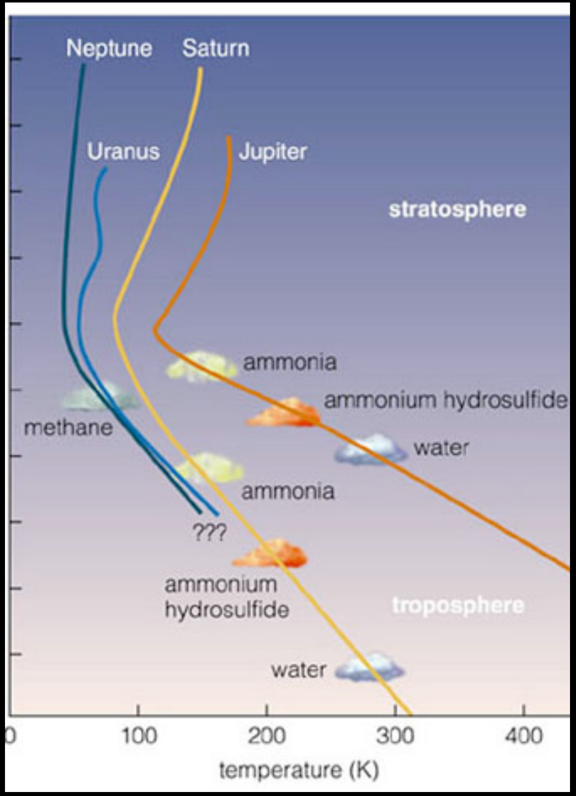
Geophysics

Meteorology

Composition

Climate

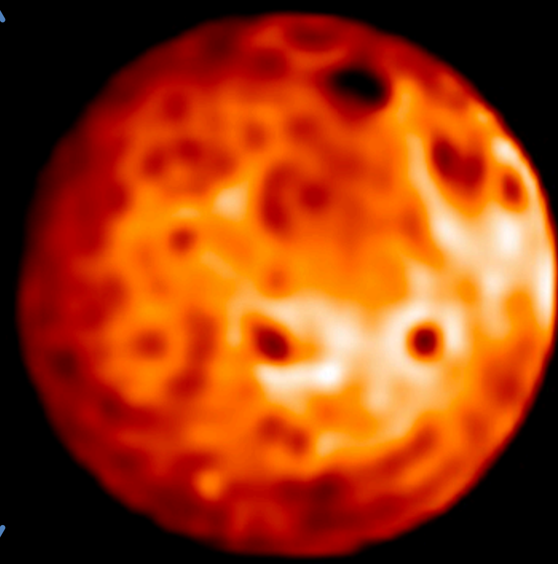
- TMT instrumentation should cover both reflected sunlight (<5 μm) and thermal emission (>5 μm) in the IR.
  - Relate **climate/environmental conditions** to surface/atmosphere albedo characteristics.
- For atmospheres, IR provides:
  - **third dimension** (vertical) to otherwise 2D images.
  - IR signatures of traces gases used to understand **planetary chemistry and circulation**.
- IR allows study of **energy exchange processes** (aurora, ionospheres).
- IR provides access to elemental and isotopic composition of primitive material to test **planetary origins**.
- Thermal infrared has been overlooked over the past decades in favor of reflectance spectroscopy.
  - Thermal-IR (> 5 μm) absent from future outer solar system missions.
  - **Infrared spatial resolution and spectral coverage primitive** compared to 'optical/near-IR' wavelengths.
  - TMT will help change that!



IR sounding allows us to probe atmospheres from the thermosphere to the cloud-forming troposphere.

Intro: High Spatial Resolution

- TMT diffraction-limited seeing factor of 6 improvement over JWST, provided good AO correction.
- Issues for largest targets:
  - Small FOV need mosaics?
  - Chopping off disc?
  - AO guide star availability and angular separation?
  - Brightness and saturation?



Io in L-band, Keck/NIRC2, Mignant and Marchis, 2002.

Diffraction-Limited Resolution

Telescope	**JWST**	**VLT**	**TMT**
Wavelengh (μm)	**6.5**	**8**	**39**
3	0.116	0.094	0.019
4	0.155	0.126	0.026
5	0.194	0.157	0.032
8	0.310	0.252	0.052
14	0.542	0.440	0.090

Size of Planetary Targets

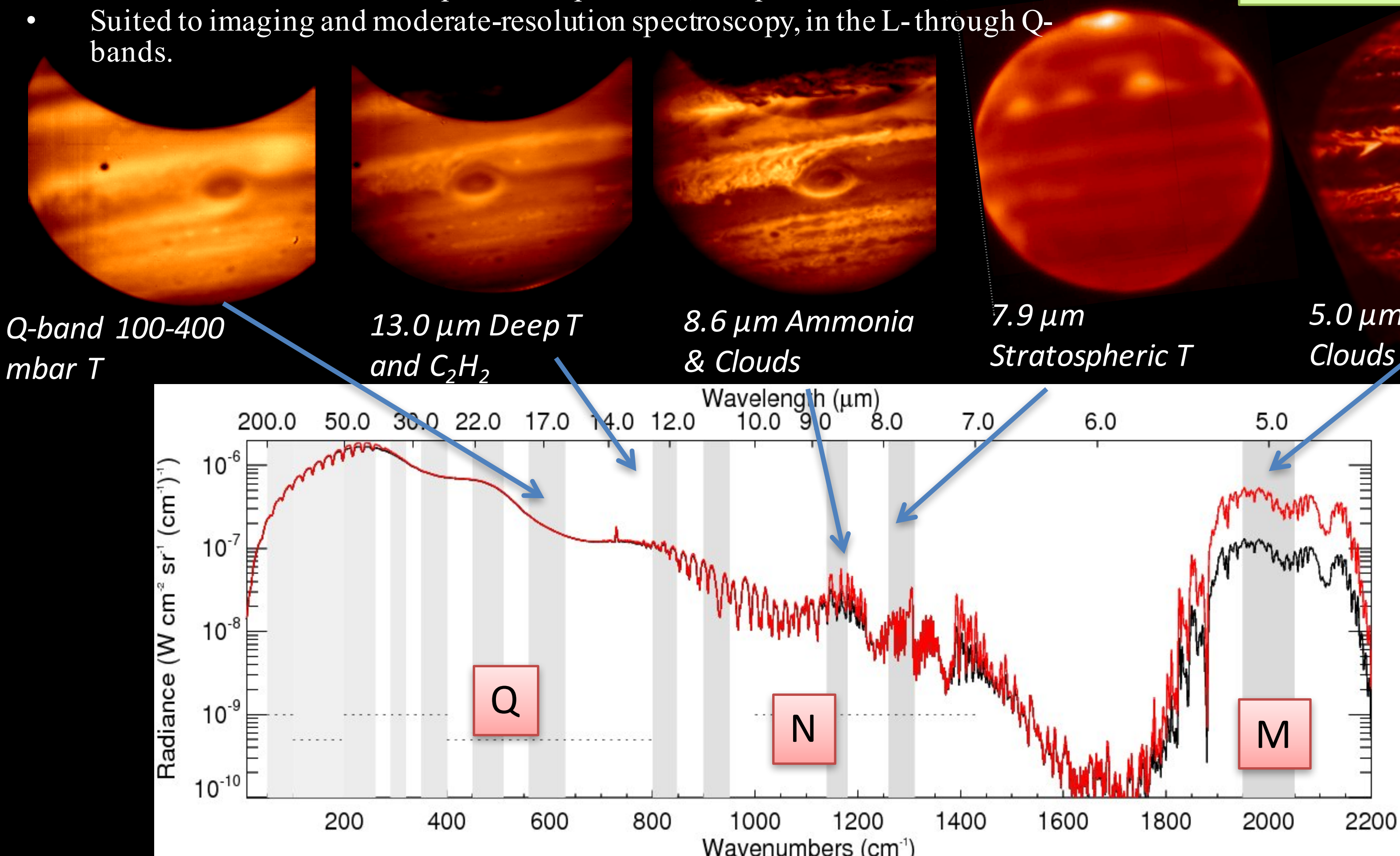
Target	**Diameter**	**Target**	**Diameter**
Venus	66”	Neptune	2.4”
Mars	25.1”	KBO/Pluto	0.11”
Ceres	0.84”	Io	1.2”
Vesta	0.64”	Ganymede	1.8”
Jupiter	50.1”	Titan	0.8”
Saturn	20.1”	Triton	0.13”
Uranus	4.1”		

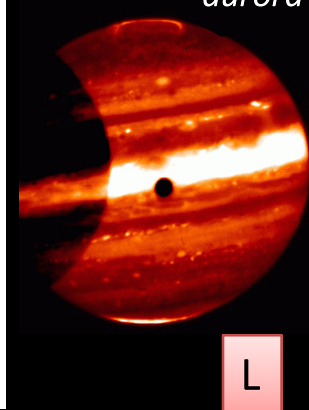
Giant Planet I: Climate & Circulation

Variation of climates

How does atmospheric circulation vary between planets?

- What is the 3d circulation of giant planet atmospheres and the factors shaping variability?
- Aim to **connect visible changes** (clouds, colors, winds) to **environmental changes** (temperatures, composition, wind shear).
- 3D Reconstruction of atmospheric temperatures, composition, winds, clouds, etc.
- Suited to imaging and moderate-resolution spectroscopy, in the L- through Q-bands.





Giant Planet II: Temporal Changes

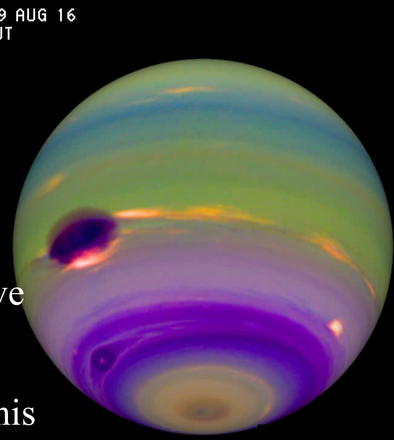
Variation of climates

- Giant planet atmospheres evolve on timescales from:
  - Minutes (impacts)
  - Days (Plumes, storms)
  - Weeks (Belt/zone life cycles)
  - Years (seasonal evolution)

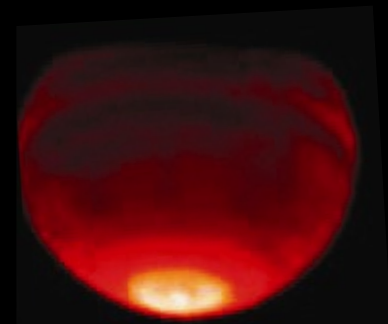
- The TMT would provide the same understanding of ice giants as we have for Jupiter/Saturn.

- Environmental changes underlying this variability.
  - Would benefit from simultaneous measurement of reflected sunlight and thermal imaging

- TMT diffraction-limited resolution provides good altitude coverage for temperatures, gaseous abundances and clouds
  - Temperatures from N- and Q-band H_2 absorption and CH_4 emission imaging and spectroscopy
  - Gaseous abundances from N-band thermal emission, primarily from hydrocarbons
  - Cloud properties from <5 µm reflection spectroscopy, K-, M-, N- and Q-band center-to-limb behavior

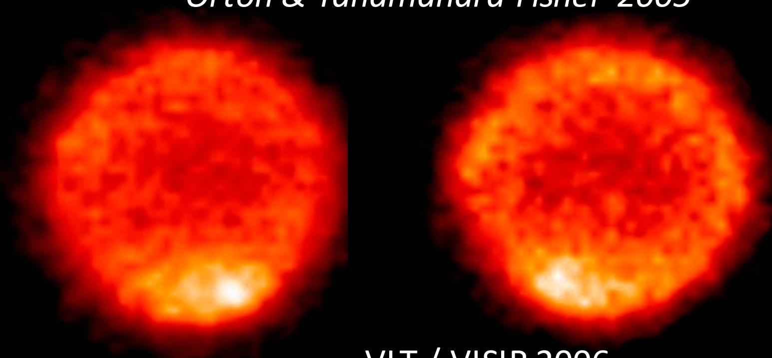


7.8 µm Keck LWS



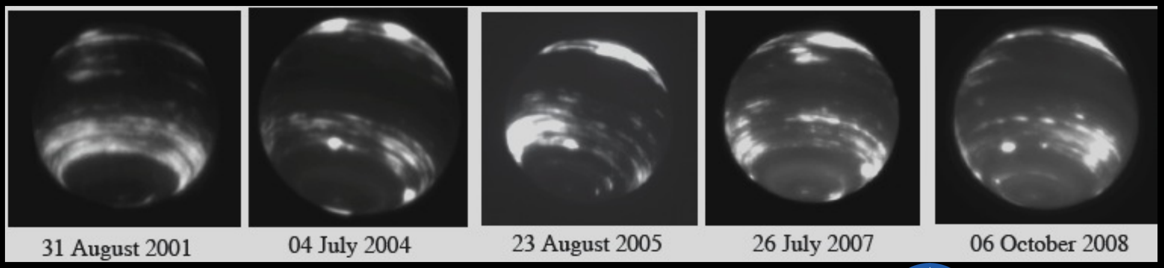
What drives atmospheric variability?

Saturn's thermal emission
Orton & Yanamandra-Fisher 2005



VLT / VISIR 2006

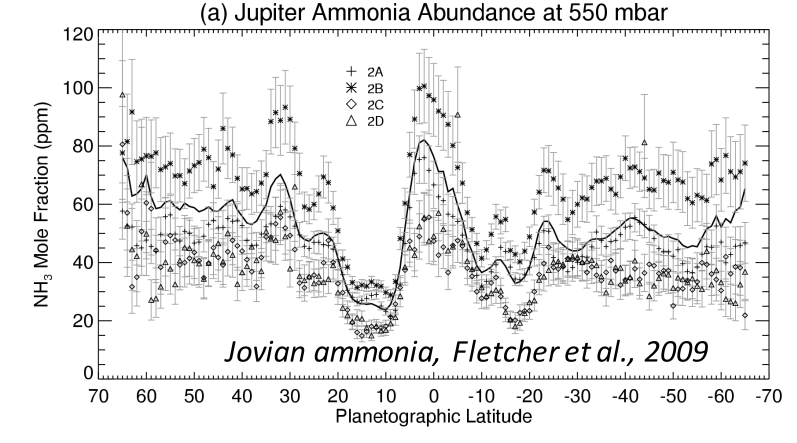
Neptune's thermal emission, Orton et al., 2007

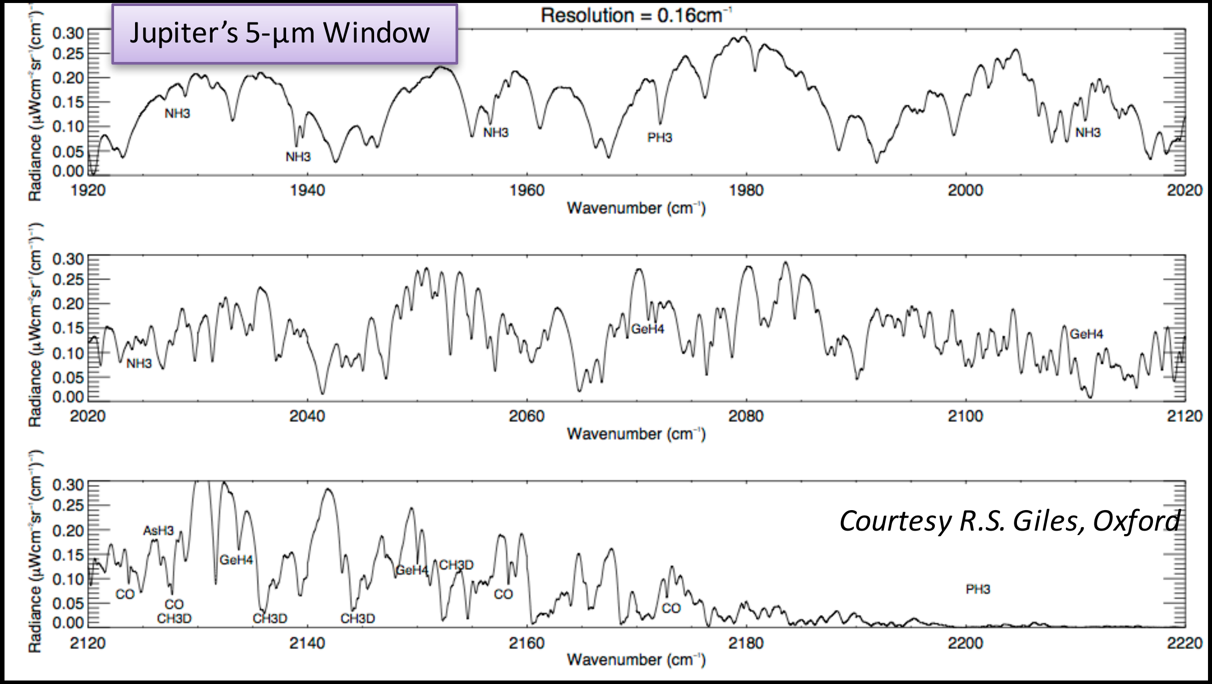


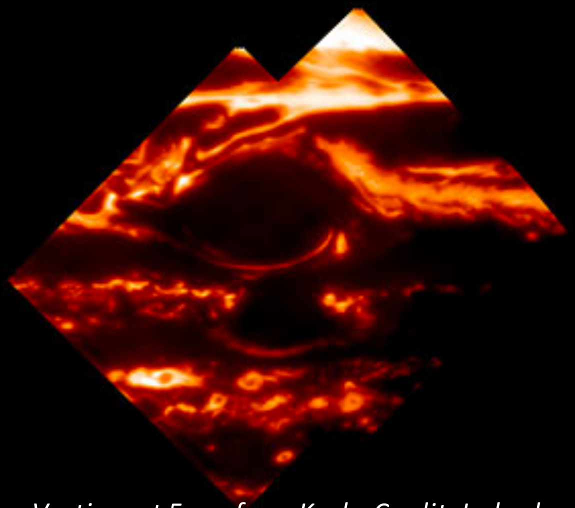
Giant Planet III: Deep into the Clouds

Fundamental Processes

- M-band provides a unique window – minimal reflected sunlight, minimum H_2 and CH_4 opacities allow deep sounding.
- Giant-planet cloud condensation region.
- M-band spectroscopy allows separation of gaseous species.
  - NH_3 for cloud-condensation
  - PH_3, AsH_3, GeH_4 for deep atmospheric circulation
  - CO for external influx of O-species.
  - CH_3D for cloud sounding, D/H ratio for origins.
  - High-temperature H_3^+ emission
- Never exploited for the ice giants before!







Vortices at 5 µm from Keck. Credit: Imke de Pater, Michael Wong (UC Berkeley); Al Conrad (Keck), and Chris Go (Cebu, Philippines)

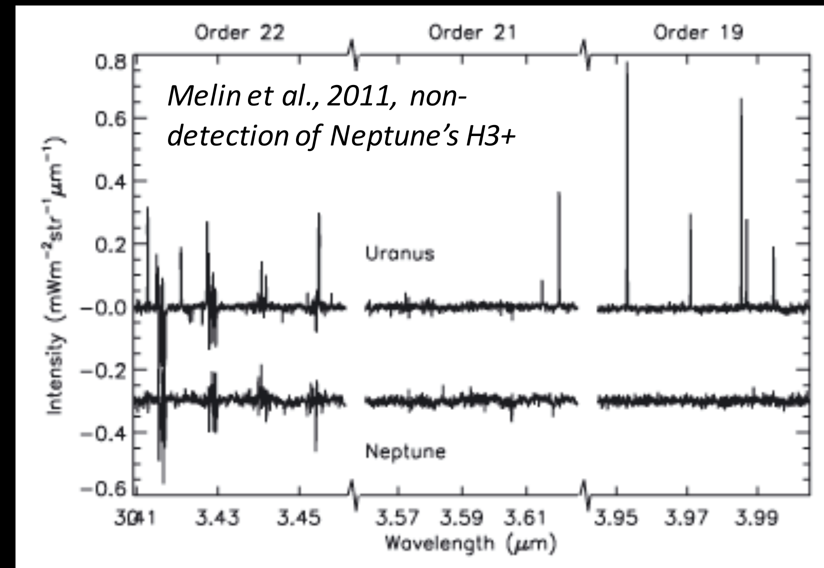
Giant Planet IV: Planetary Aurora

Energy exchanges

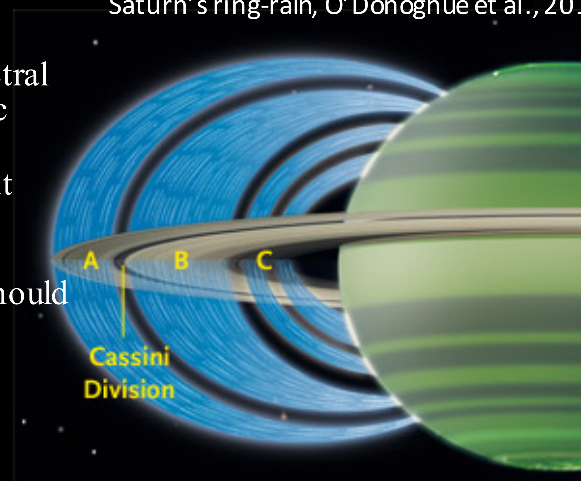
How does solar wind control planetary aurorae and heating?

- H_3^+ auroral emission allows mapping of giant planet ionospheres (temperature/density) by tracing heat flow within upper atmospheres.
  - Ionospheric flows coupled to magnetic field, connects planet to external environment.
  - Focus on auroral variability; but….
  - Non-auroral regions are driven by complex dynamics that comes from multiple sources, including low-latitude precipitation, upper atmosphere dynamics and upwelling heat
  - How does upper atmospheric temperature change with altitude/latitude – a key question for planetary aeronomy!

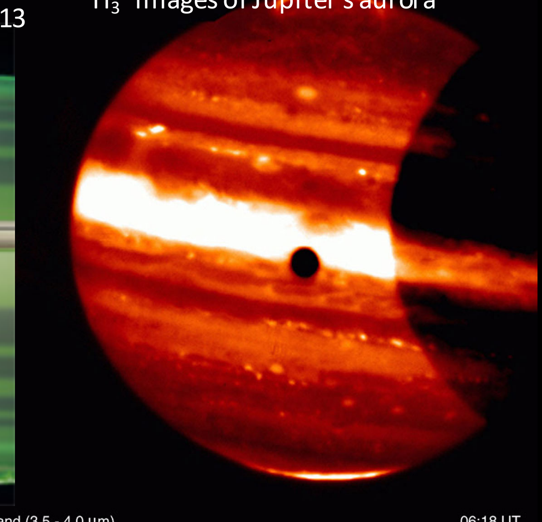
- Cassini can image Saturn's aurorae, but low spectral resolution prevents measurements of ionospheric properties
- Uranus H_3^+ hard to detect (first seen in 1992), but long-term upper atmospheric temperatures have decreased over time.
- Neptune H_3^+ still undetected, models predict it should be there!
- L-band measurements are required.



Saturn's ring-rain, O'Donoghue et al., 2013



H_3^+ images of Jupiter's aurora



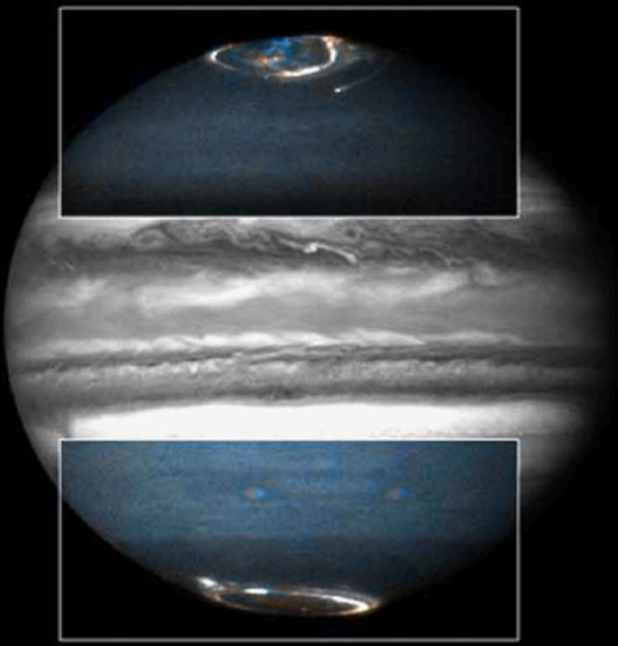
Giant Planet V: Planet-Satellite Interaction

Energy exchanges

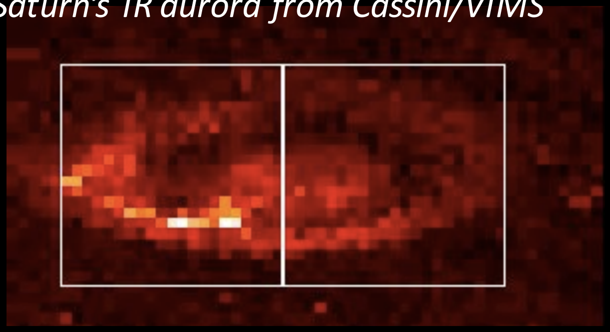
How are planetary ionospheres coupled to their satellite systems?

- Plasma sources within the magnetosphere (e.g. Io) cause auroral UV footprints, but also IR heating.
  - How far does heating extend, vertically & latitudinally?
  - How is the energy dissipated with time?
  - Does Enceladus produce a similar spot at Saturn?
  - Do auroral spots vary with volcanic (Io) or water plume (Europa, Enceladus) activity?
- Insights into energy flow between ionosphere, magnetosphere and satellites.
- Requires the high (i) sensitivity, (ii) spectral resolution and (iii) spatial resolution.

Hubble UV imaging of auroral footprints.



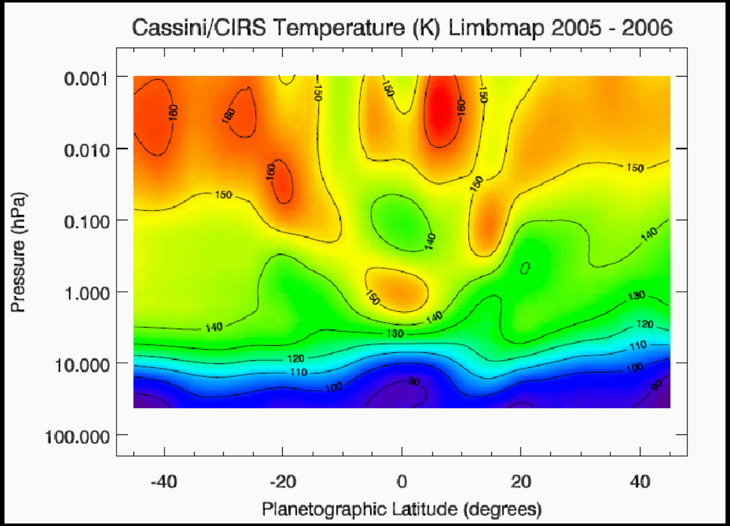
Saturn's IR aurora from Cassini/VIMS



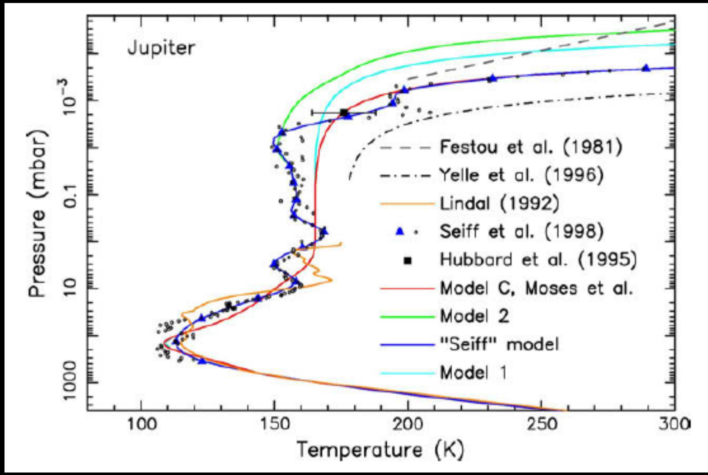
Giant Planet VI: Middle Atmosphere

Fundamental Processes

- Wave activity may dominate energy transport and material distribution in planetary stratospheres.
- Investigate via:
  - (i) High-resolution sounding of Doppler broadened CH_4, C_2H_6 lines (3, 7, 12 μm)
  - (ii) Stellar occultations to probe atmospheric T/density structure (e.g., using Io hotspots as point source)



Saturn's SAO from Fouchet et al., 2008



Jupiter occultation study, Greathouse et al., 2010

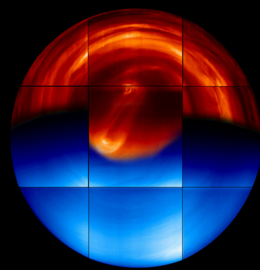
Terrestrial I: Trace Species (Venus)

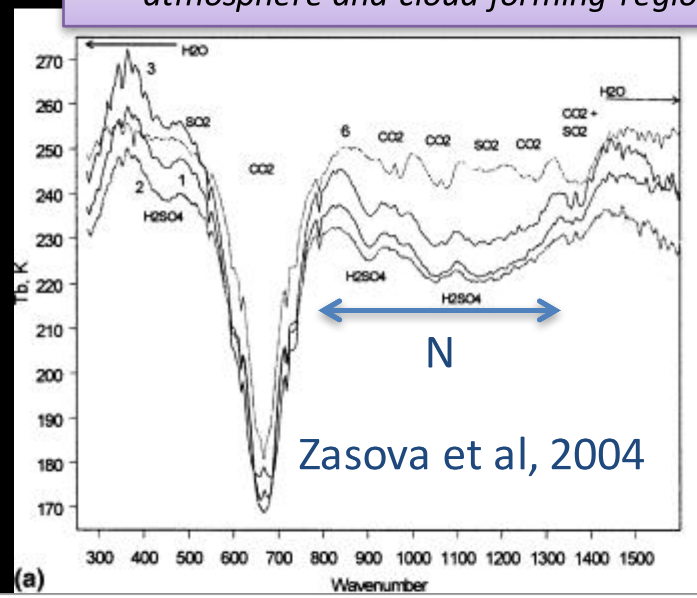
Variation of climates

What drives the dynamics of Venus' upper atmosphere and cloud-forming region?

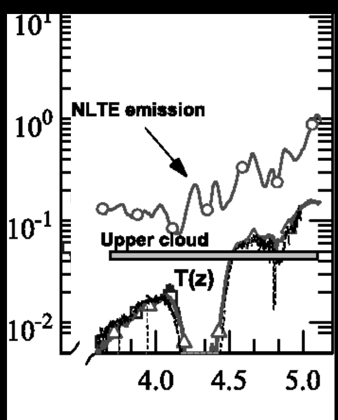
- What causes the dramatic variability of gaseous species on Venus? We want to work towards a comprehensive climatology:
  - N-band shows CO_2, SO_2, H_2SO_4 features.
  - SO_2 shows dramatic variations.
- M-band non-LTE emission from CO (4.7 µm), CO_2 (4.3 µm) can be used to measure spatial variability in the mesosphere.
  - Sensitivity to gravity wave propagation/breaking
- But is Venus too bright for TMT?

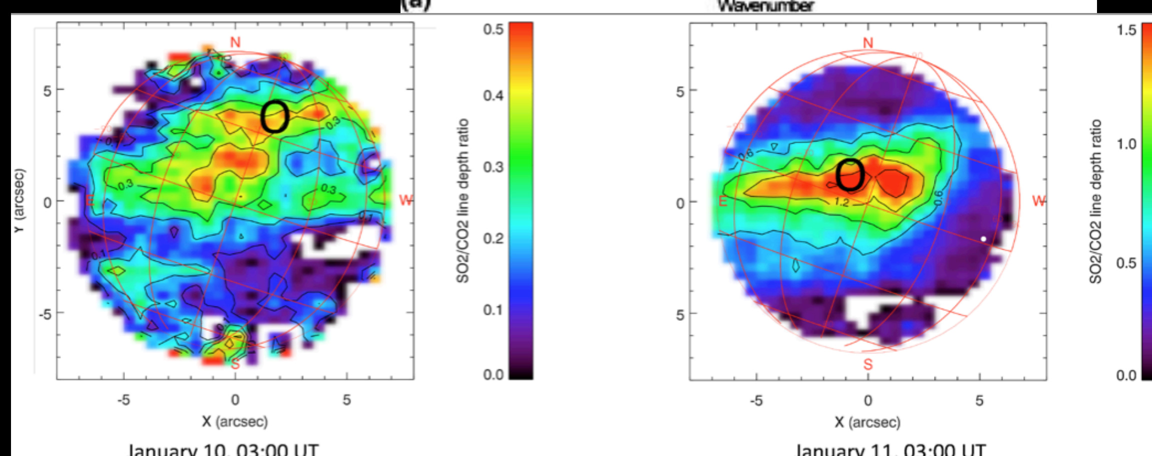
Nightside thermal emission 3-5 µm from Venus Express





VIRTIS observations, Arnold et al., 2012



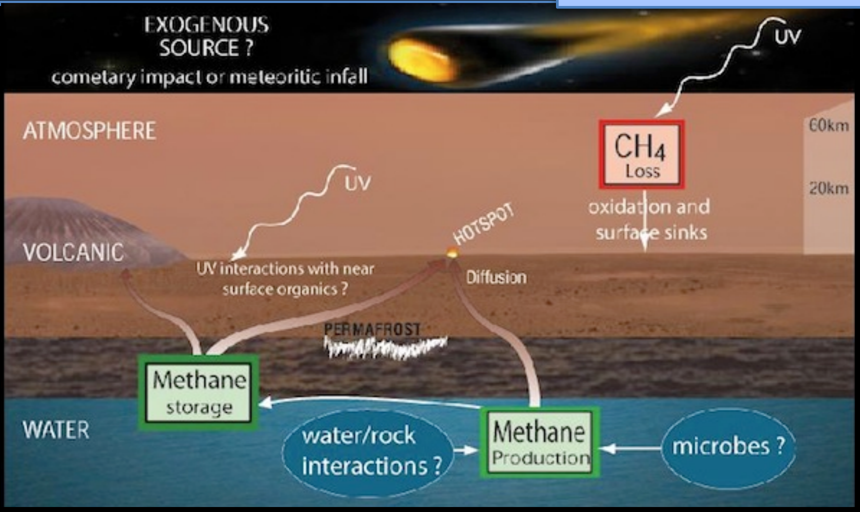


Variability of SO_2 mapped using ratios of SO_2/CO_2 lines at 7 µm, Encrenaz et al., 2013

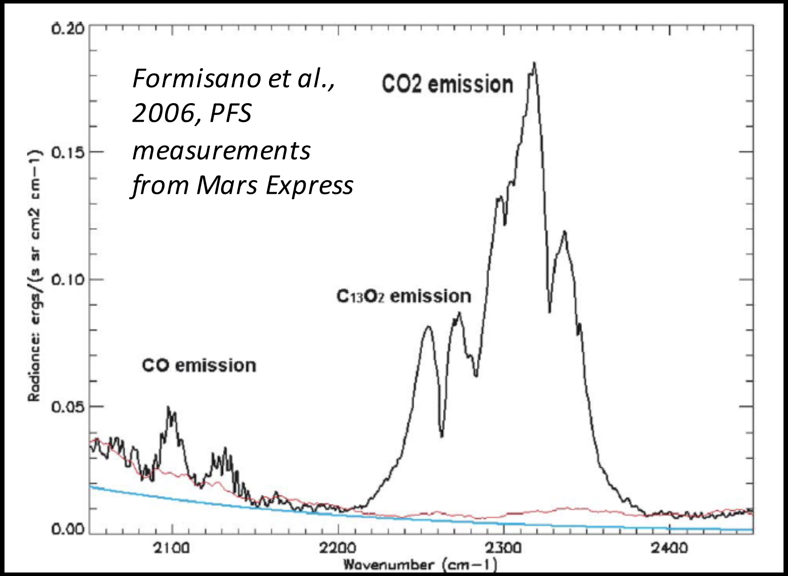
Terrestrial II: Trace Species (Mars)

Fundamental Processes

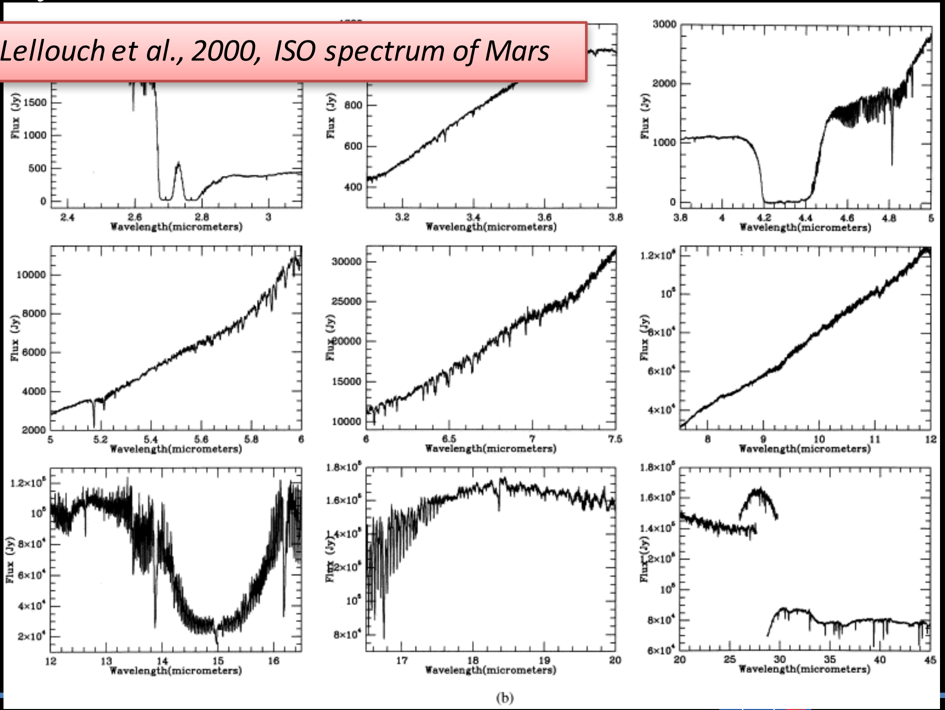
What are the sources and sinks of trace species in the Martian atmosphere?



- Sensitive search for trace species on Mars (e.g., controversial Martian methane).
  - CH_4 at 3.3, 7.8 µm
  - HDO at 3.7 µm, unsuccessful searches by ISO.
- Non-LTE emission from CO and CO_2 first detected by ISO (Lellouch et al., 2000).
  - Probing upper atmospheric circulation, as on Venus.
- Carbonate signatures in the M and N bands tentatively identified by Lellouch et al. (2000).



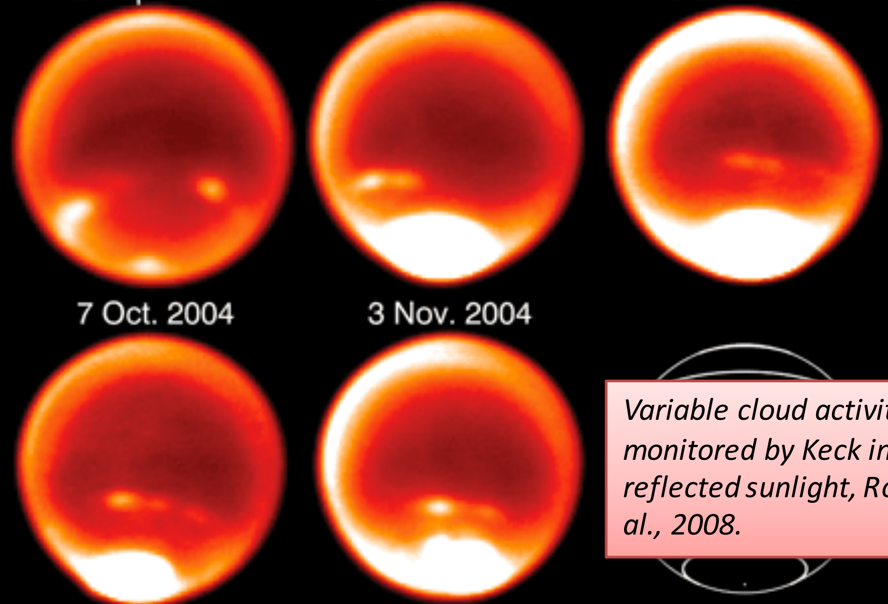
Lellouch et al., 2000, ISO spectrum of Mars



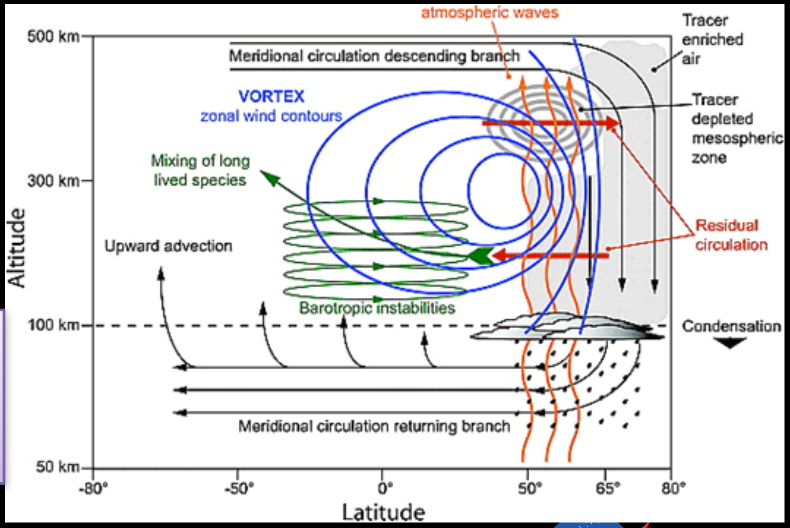
Terrestrial III: Titan Beyond Cassini

Variation of climates

- Titan's rich atmospheric composition considered as an example of a prebiotic atmosphere.
- Extensive studies by Cassini/VIMS and Cassini/CIRS will come to an end in 2017.
  - TMT could continue these over a full Saturnian year.
- High-resolution imaging (reflectivity and thermal) and N-band spectra to understand:
  - Methane cycle and variable cloud activity (K- and L-band)
  - Seasonal evolution of circulation through temperatures, trace gases and cloud activity (N-band)



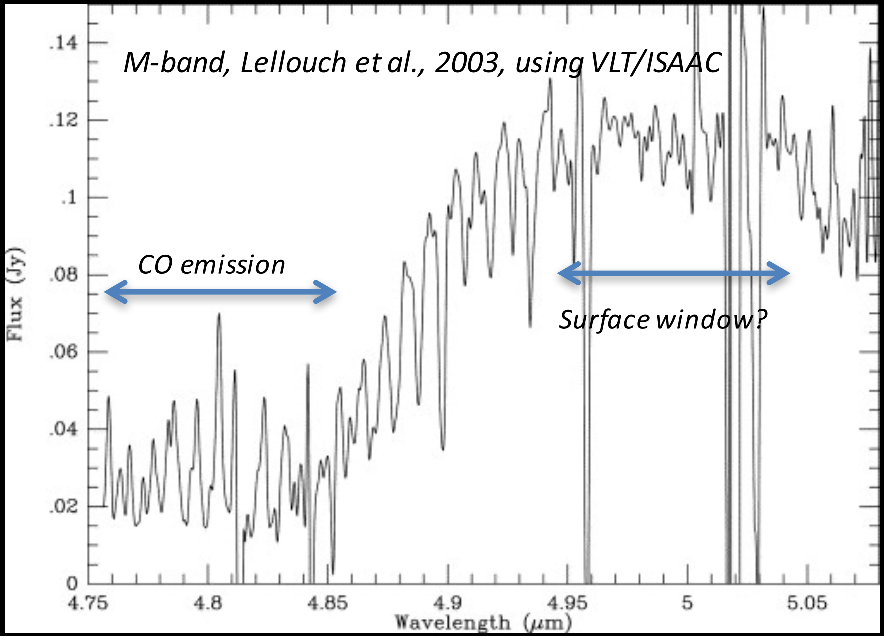
Variable cloud activity monitored by Keck in reflected sunlight, Roe et al., 2008.

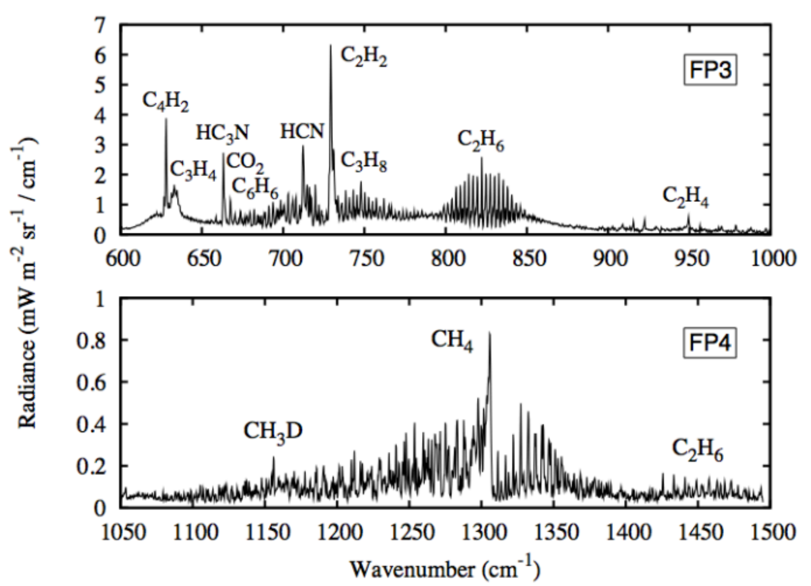


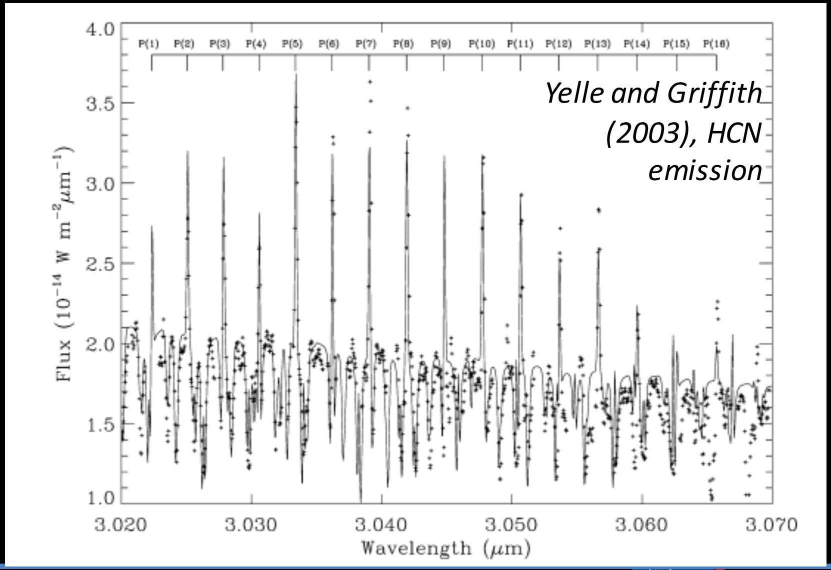
Titan's atmospheric circulation during northern winter, Teanby et al., 2008

'Terrestrial' IV: Titan Surface to Upper Atmosphere

- Surface variability from M-band: Using high-resolution infrared windows (e.g., M-band where CH_4 opacity at a minimum).
- Upper atmospheric studies from:
  - CO fluorescence near 4.7 μm allow measurement of external oxygen influx.
  - HCN fluorescence near 3 μm to understand upper atmospheric circulation.

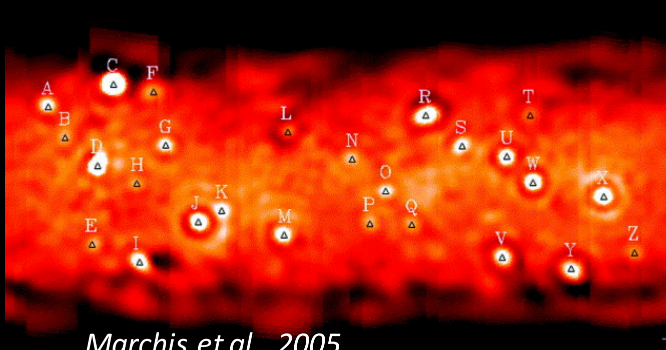




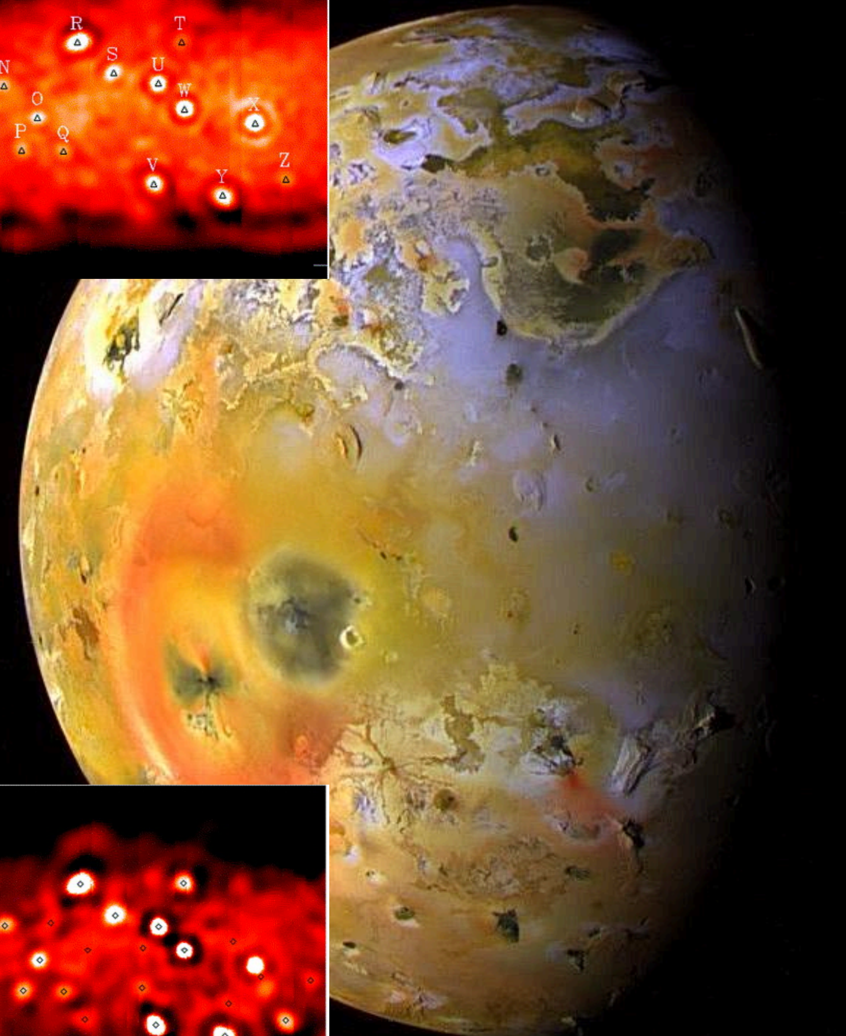


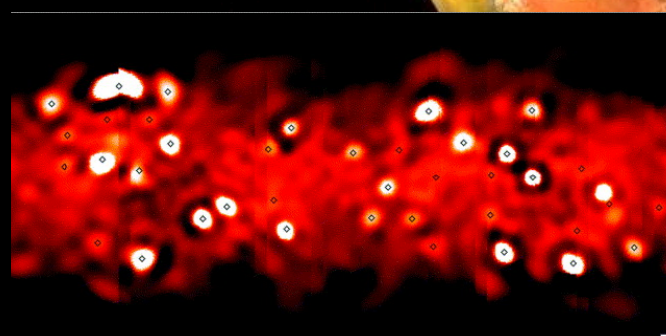
Surfaces I: Volcanic Io

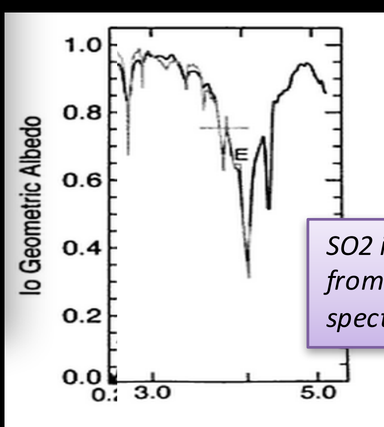
- Unprecedented resolution will allow us to monitor volcanism on a distant world.
- Io thermal output – finding the missing power
  - Currently miss smaller volcanoes/lava flows, missing maybe half heat output.
  - Cooler flows will show up at longer N-band and Q-band wavelengths.
- Surface atmosphere interaction – SO_2 frost:
  - SO_2 atmospheric collapse in eclipse should strengthen surface ice bands 1.9-4.2 μm, but never seen, K-, L- & M-band spectroscopy.



Marchis et al., 2005 using Keck L and M band imaging





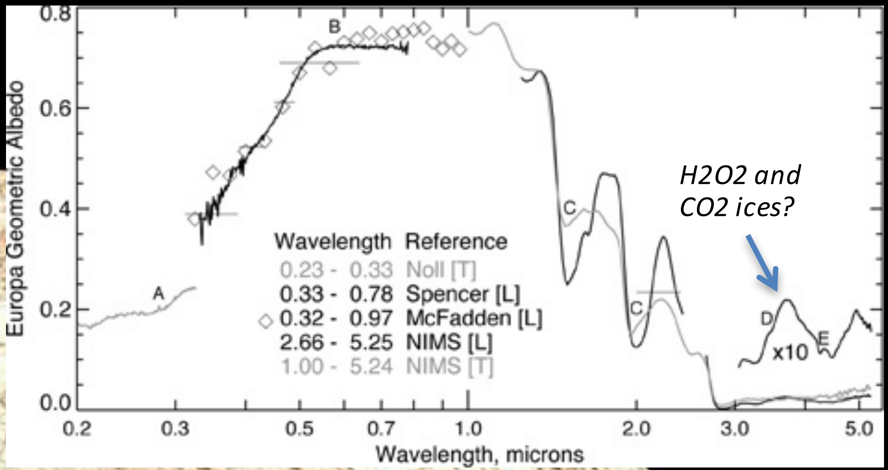


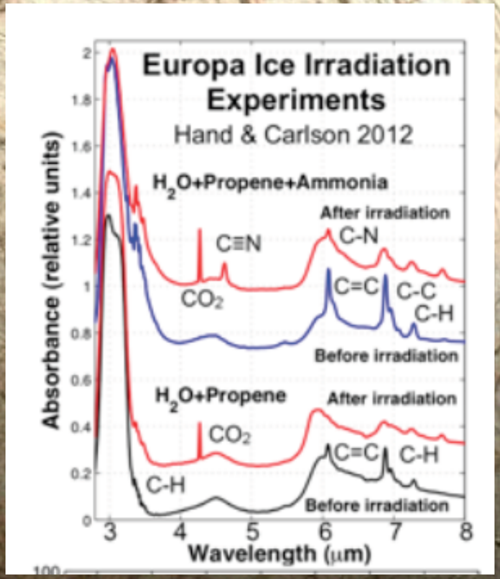
SO2 ice bands from NIMS spectra

Surfaces II: Europa

Can icy surfaces reveal insights into their watery interiors and plasma interactions?

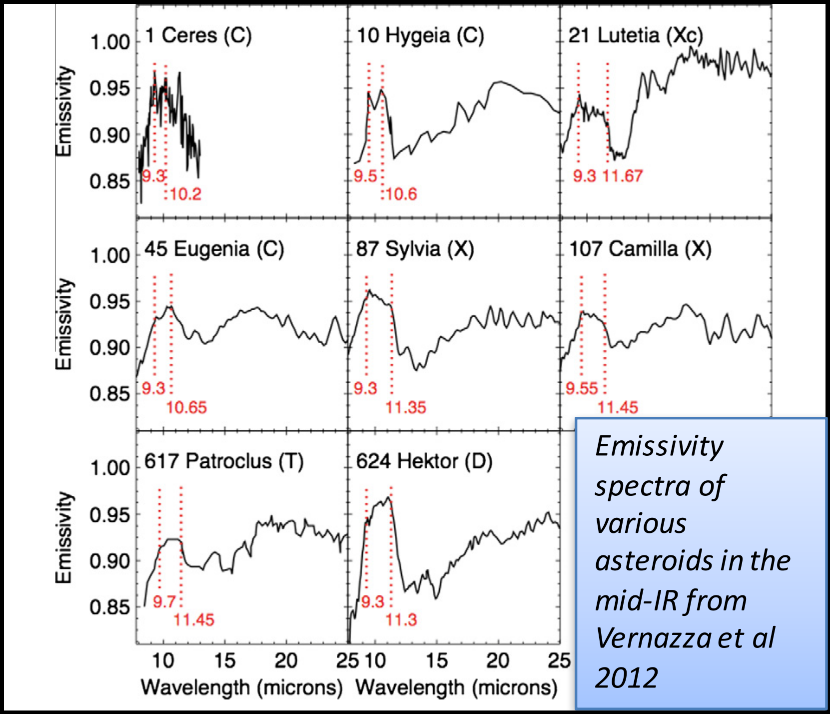
- Reading surface geology and composition reveals (i) connection to potentially-habitable subsurface ocean; and (ii) effects of interaction of surface materials with plasma environment.
- Search for evidence of endogenic emission associated with plume/geologic activity (as on Enceladus).
  - Location of plume sources?
- Requires broad-band imaging and low-resolution spectroscopy.
  - Reflectance spectroscopy may sense broad bands of nitrates, hydroxides, water and organics, (e.g., species containing C-H, C=N, C=S bonds and CO_2)





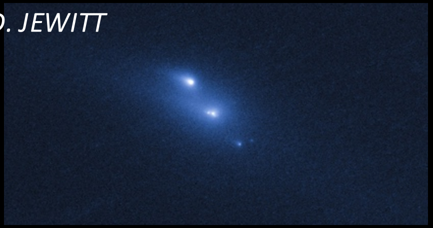
Surfaces III: Asteroids

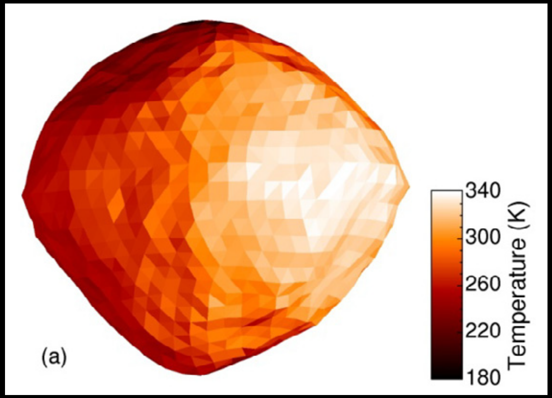
- Detect and map **diagnostic features of many asteroid types**
  - Christiansen emissivity maximum diagnoses silicate polymerization
  - Slope at shorter wavelengths gives surface porosity.
  - Comparisons to lab spectra (e.g., carbonaceous chondrites) could reveal parent reservoirs for meteorites.
- Spatially-resolved thermal emission (e.g., NEOs) can reveal variations in thermal inertia, surface properties. Photon pressures causes by emission variation influences **orbital history** of these objects.
- Requires imaging and low-resolution spectroscopy.
- Could emission from volatiles also be detected at higher spectral resolution? (e.g., volatile rich main-belt comets)



Emissivity spectra of various asteroids in the mid-IR from Vernazza et al 2012

P/2013 R3 asteroid breaking up into ten pieces, taken by the Hubble Space Telescope and distributed by the European Space Agency. Photograph: D. JEWITT (UCLA)/AFP/Getty Images

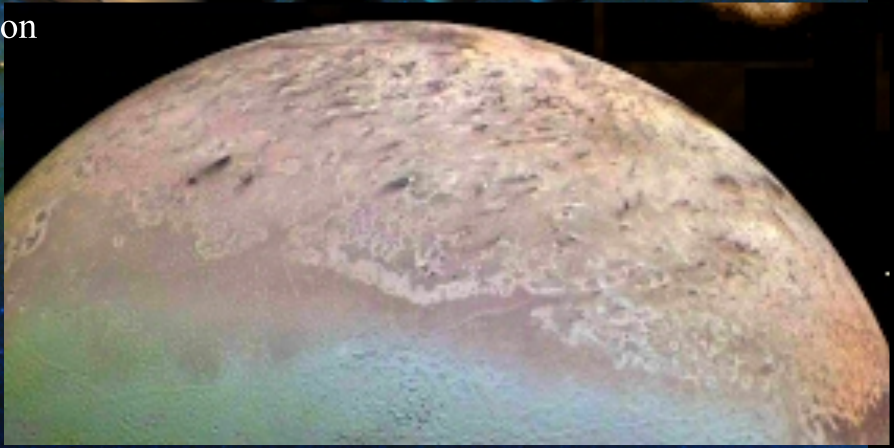




Thermal model of near Earth asteroid Bennu, target of the OSIRIS-REX mission. Shape model derived from radar data. Taken from Emery et al. 2014

Surfaces IV: Distant Icy Bodies

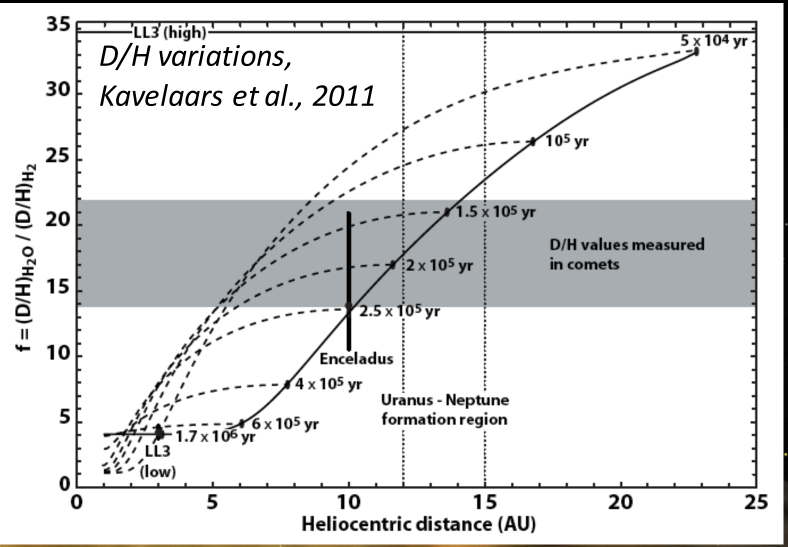
- Pluto
  - Follow-up observations from New Horizons, e.g. documenting atmospheric collapse with increasing distance from the sun: CO, CH_4,
  - Search for C_2H_2, C_2H_6
  - Direct spectroscopy or occultation signatures.
- TNOs
  - Searches for atmospheres in other TNOs
- Icy satellites
  - Spatial variability of thermal emission
  - Variable atmosphere of Triton
- Rings and ring arcs of icy giants
- L- through Q-band imaging and moderate- to high-resolution spectroscopy,



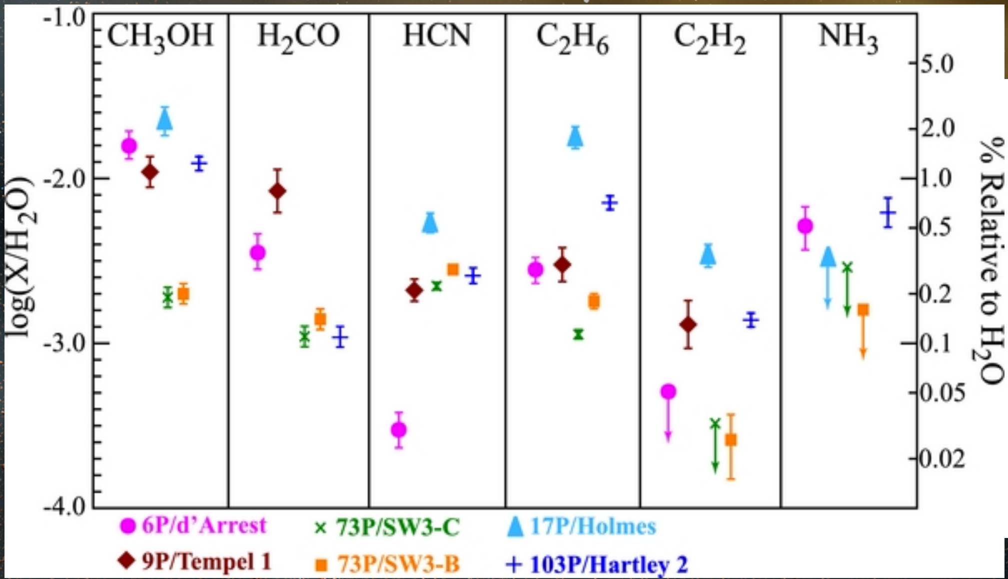
Comets I: Remnants of Formation

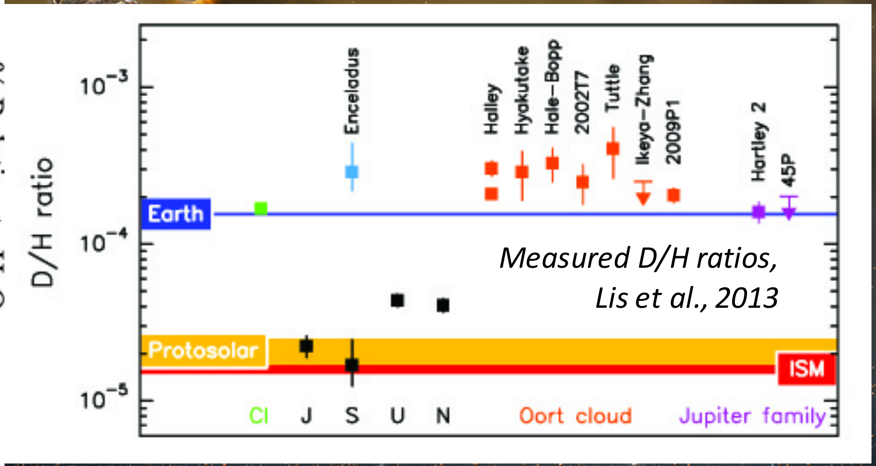
Origins of the Solar System

- Comets are the icy remnants of planet formation, compositional signatures of primitive materials reveals conditions in the protoplanetary disc
- Origin, migration and reprocessing history.
  - D/H in cometary volatiles related to terrestrial water, $^{15}N/^{14}N$ and $^{13}C/^{12}C$.
  - Water, CO, NH_3, CH4, C_2H_2, C_2H_6, CH_3OH, HCN can all be measured at 3-5 μm.



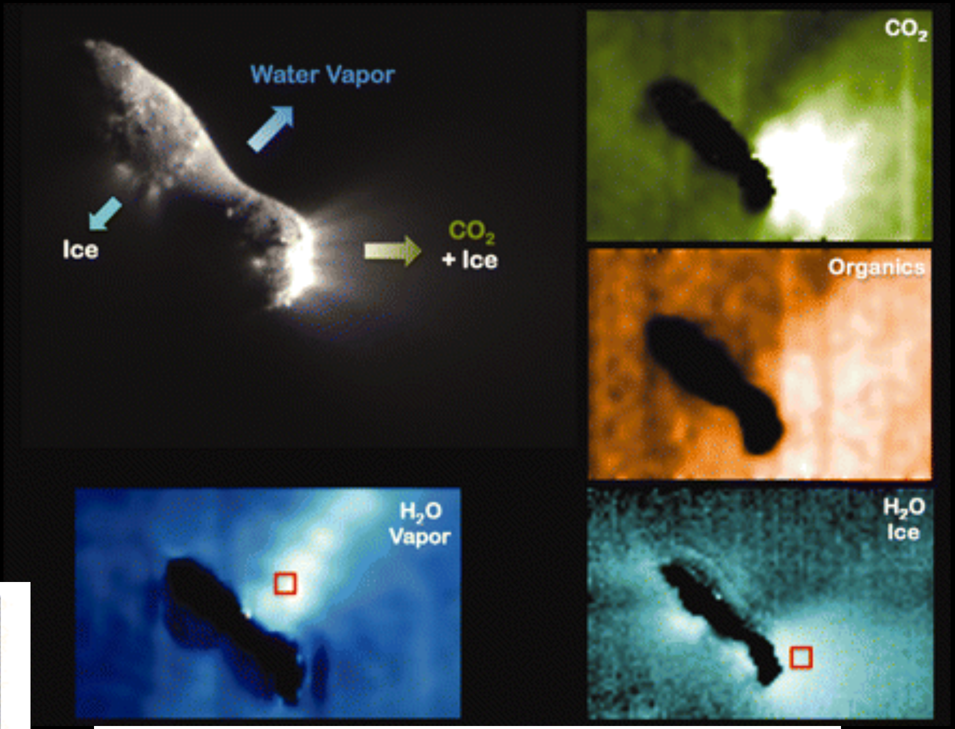
Compositional comparison of Jupiter-family comets, Della Russo et al., 2011.

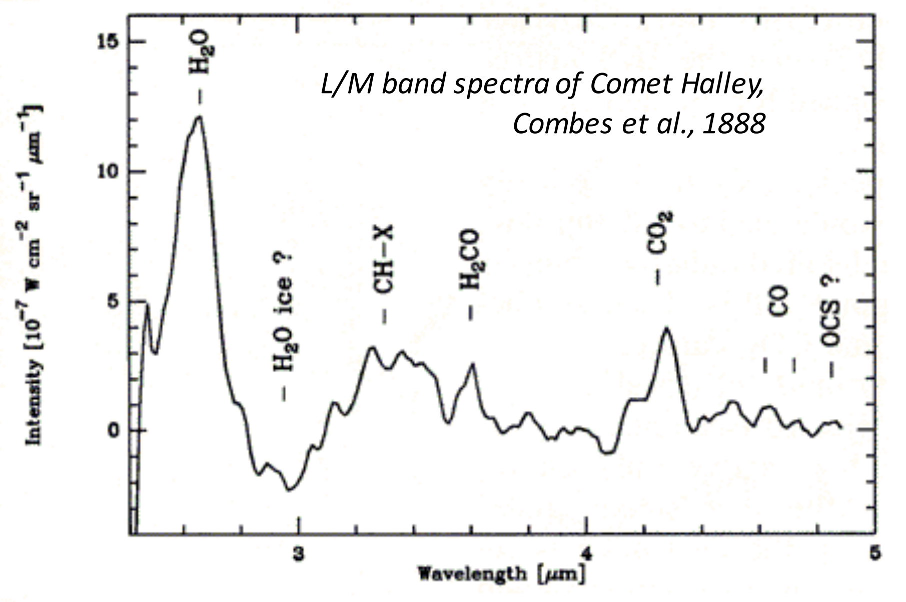


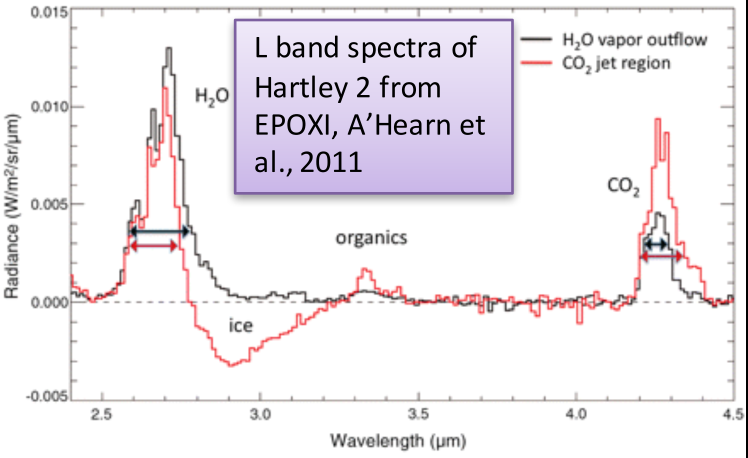


Comets II: Rich L/M Spectra

- Comets important for volatile transport throughout forming solar system; understand source reservoir for our own planet.
- L- & M-bands:
  - Non-LTE emissions from gases, organics, some scattered sunlight.
  - Unique identification of hydrocarbons & organics.
  - Spatial mapping of source regions in cometary nucleus/coma







Summary: Understanding the 'Near Universe'

How does our solar system work?

Fundamental Processes	Variation of climates	Origins of the Solar System	Surface environments	Energy exchanges

High-resolution spectroscopy: Non-LTE emissions from atmospheres and comets; reflectance spectra for clouds; thermal emission windows on deep atmospheres and surfaces; middle-atmospheric sounding

Imaging & Low-Resolution Spectroscopy: 3D sounding of planetary climate; reflectance spectra of rock/ice surfaces; thermal contrasts on satellites/asteroids; comet / asteroidal silicates.

End

Although we're not on the road we thought we'd be on at this point, and there may be a rough ride ahead…

End

Although we're not on the road we thought we'd be on at this point, and there may be a rough ride ahead…

Let's just buckle up tightly!

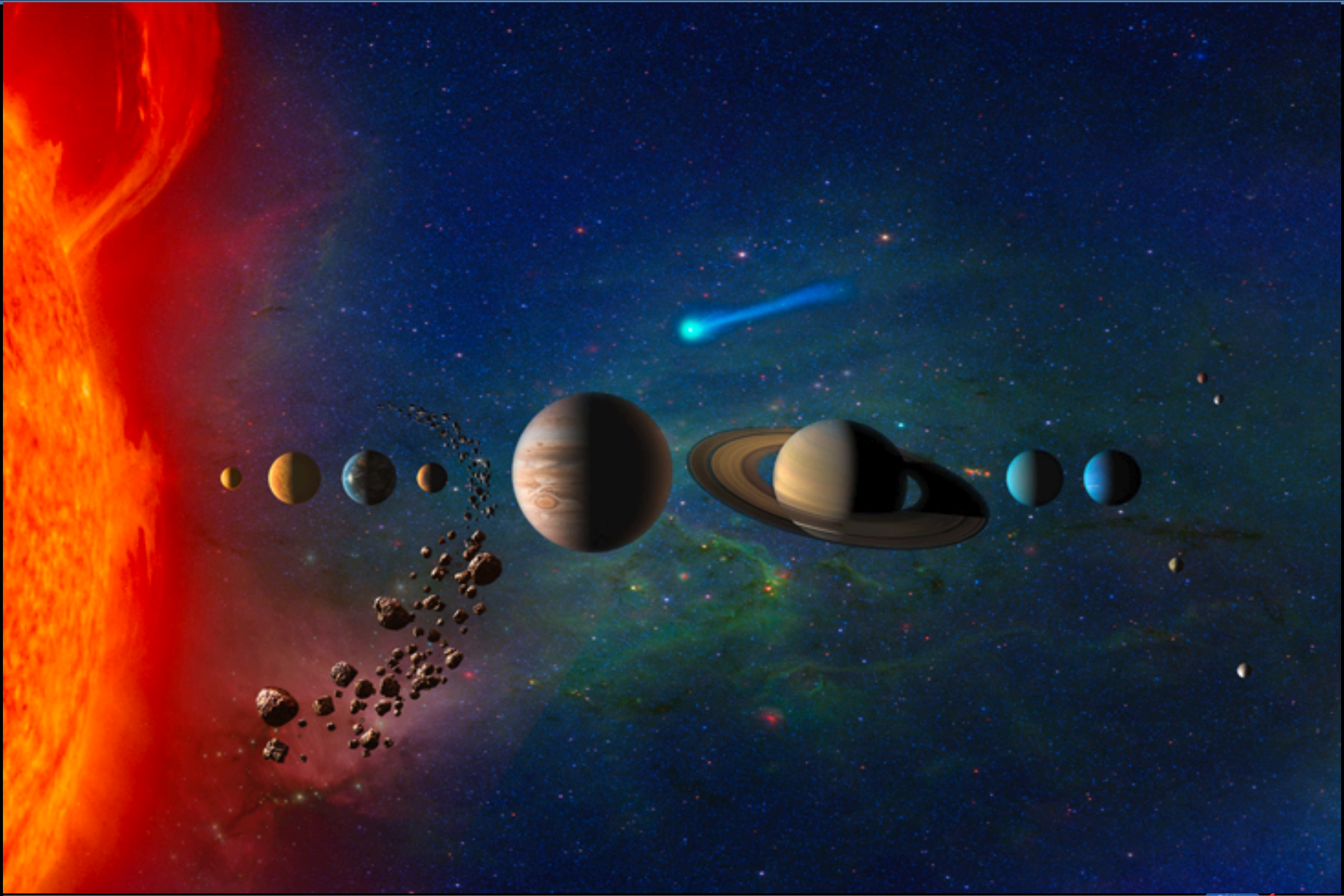
End

Although we're not on the road we thought we'd be on at this point, and there may be a rough ride ahead…

Let's just buckle up tightly!

Because there are going to be great rewards at the finish!

Supplemental Information

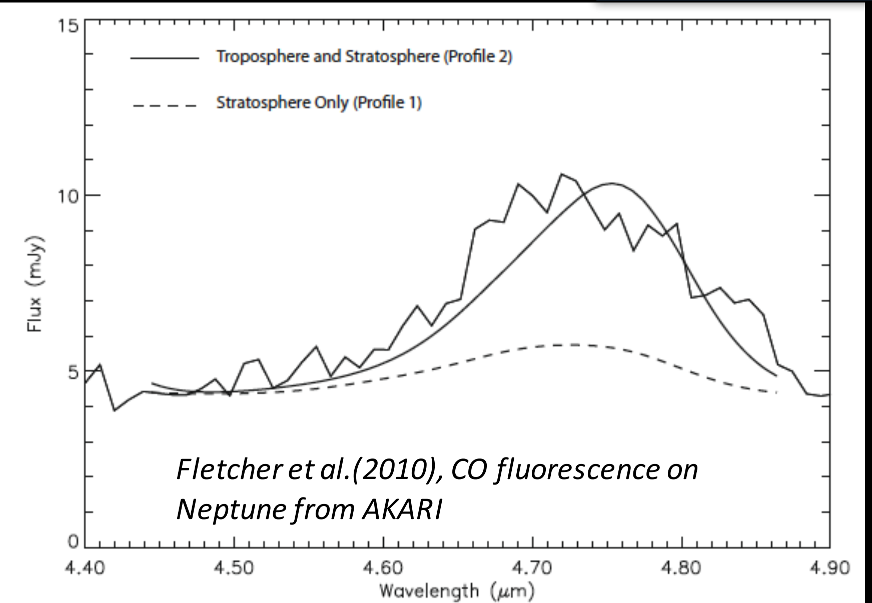


Giant Planet IV: External Oxygen

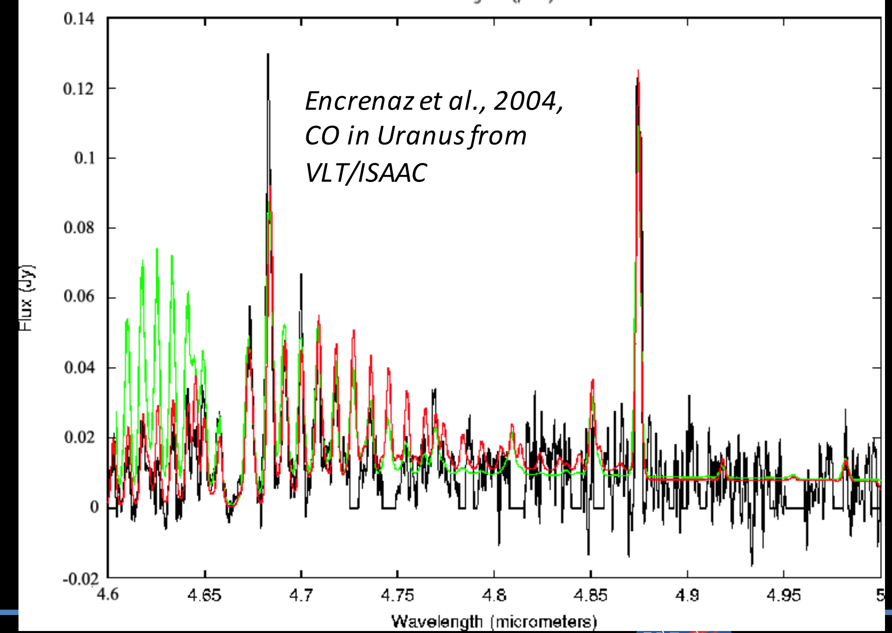
Fundamental Processes

How are planetary atmospheres coupled to their external environments?

- CO non-LTE emission in M-band detected on ice giants.
- External source from cometary impacts, interplanetary dust, etc.
- Spatially-resolved CO fluorescence requires high sensitivity and spatial resolution
  - Sources and sinks of giant-planet stratospheric oxygen.



Fletcher et al.(2010), CO fluorescence on Neptune from AKARI

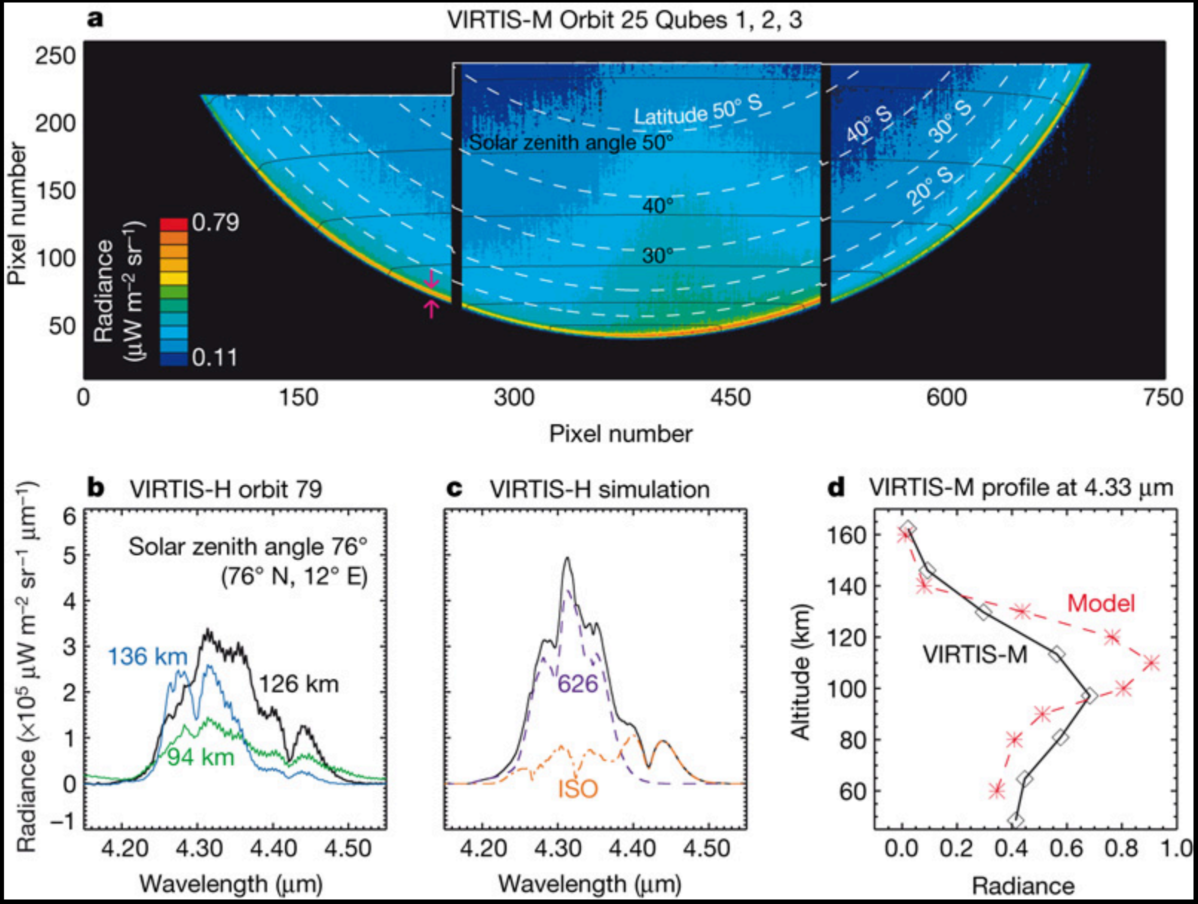


Encrenaz et al., 2004, CO in Uranus from VLT/ISAAC

Terrestrial I: Trace Species (Venus)

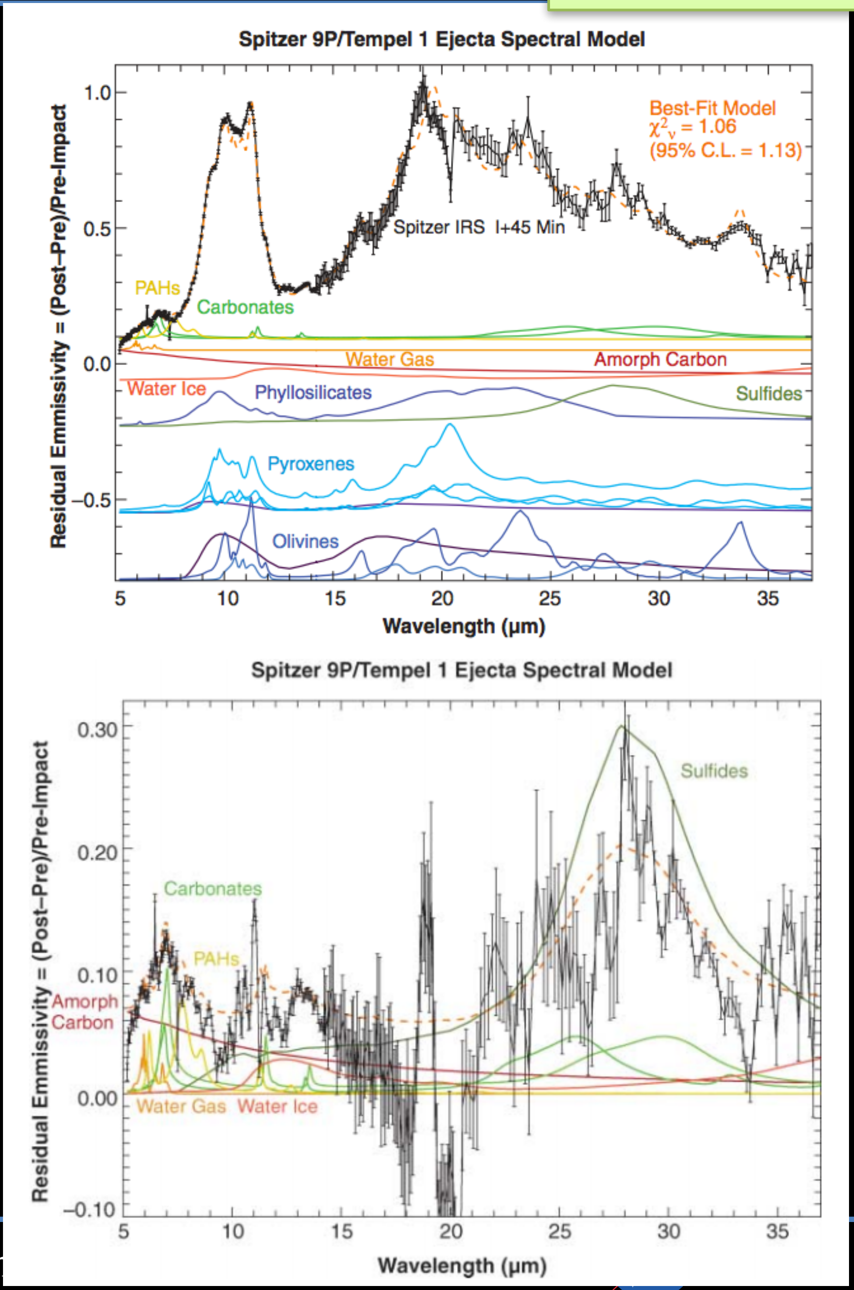
Variation of climates

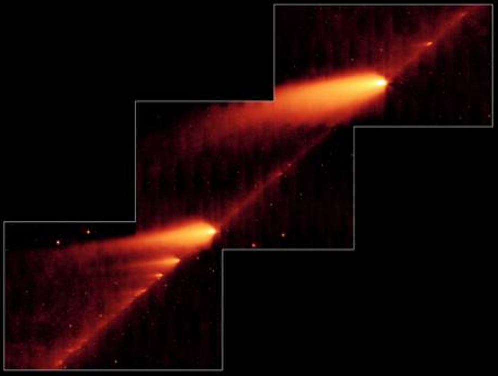
- Drossart et al., 2007; CO_2 mapping at 4.3 μm shows a dynamic upper atmosphere



Comets III: N-band Silicate Emission

- Measuring the rock/ice composition of the building blocks of our solar system.
- Emissivity of Comet Tempel 1 before and after Deep Impact (Lisse et al., 2006) allows identification of silicate types
  - Diagnostic of cometary origins and thermal evolution.
- Bottom panel have silicate emissions removed, reveals carbonates, PAHs, amorphous carbon, ices.
- Requires N-band imaging and low-resolution spectroscopy.





Comet 73P/Schwassman-Wachmann 3 imaged by Spitzer in the Q-band