Les Houches
Lessons to learn from Solar System studies for exoplanets

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Plan : Lessons to learn from Solar System

1. Transits and occultations in the Solar System
2. Complexities in radiative transfer of planets : inhomogeneities, aeronomy of upper atmospheres
3. Difficulties and errors in planetary spectroscopy
4. An unusual journey in the Solar System

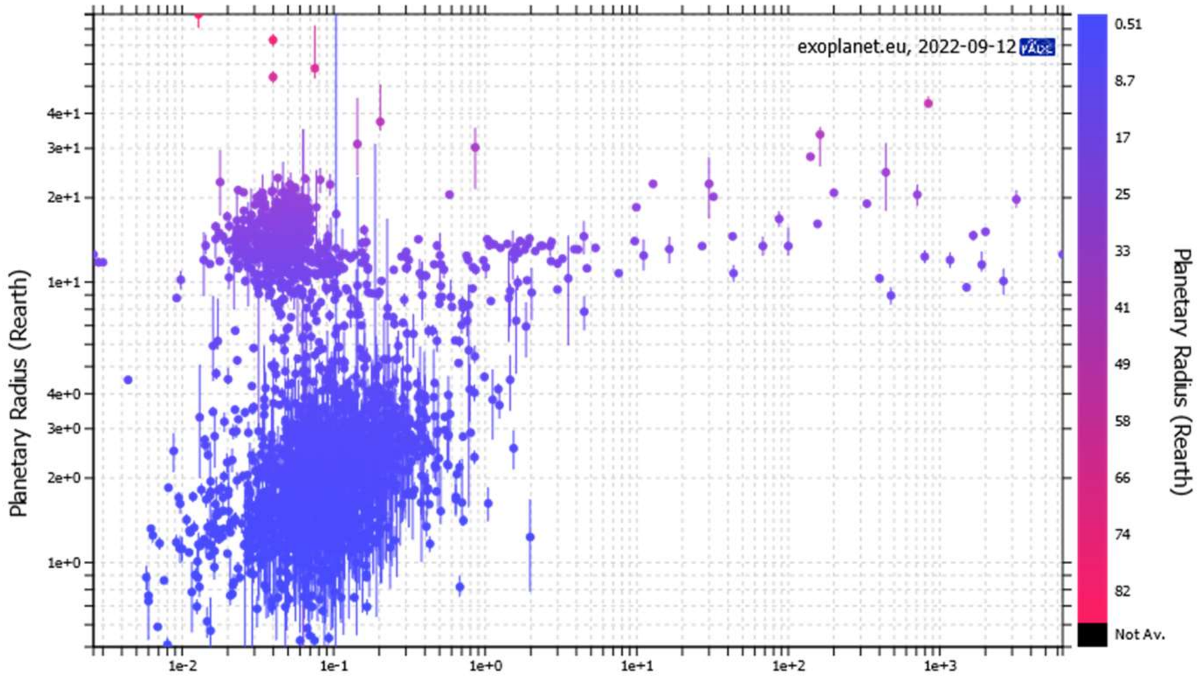
Objectives of the course

After decades of space exploration, the Solar System objects are today known with high accuracy, to the point that Earth sciences are dominent in the study of planets, more than astronomy !

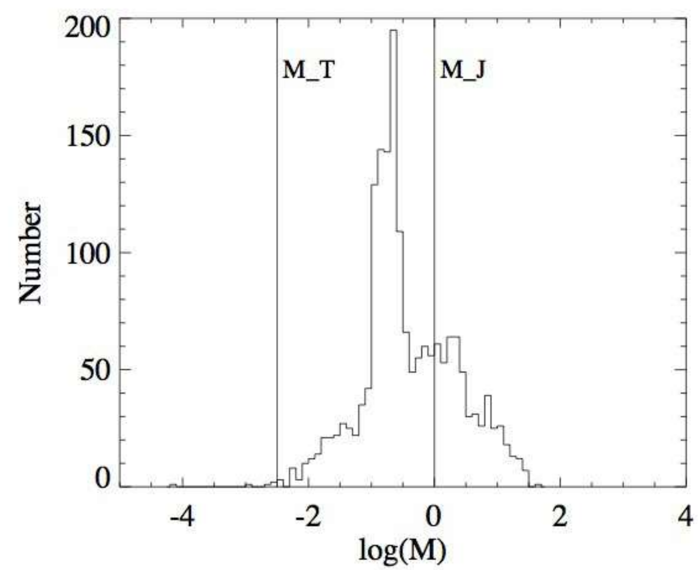
This knowledge can be translated to exoplanets only if we extrapolate from the physical mechanisms, even if average parameters of exoplanets are NOT similar to our planets !

The main objective of the course will also to remember all the errors made in planetology during decades, to try not to repeat them in exoplanets study

Exoplanet demography : current status



Histogram of exoplanets mass

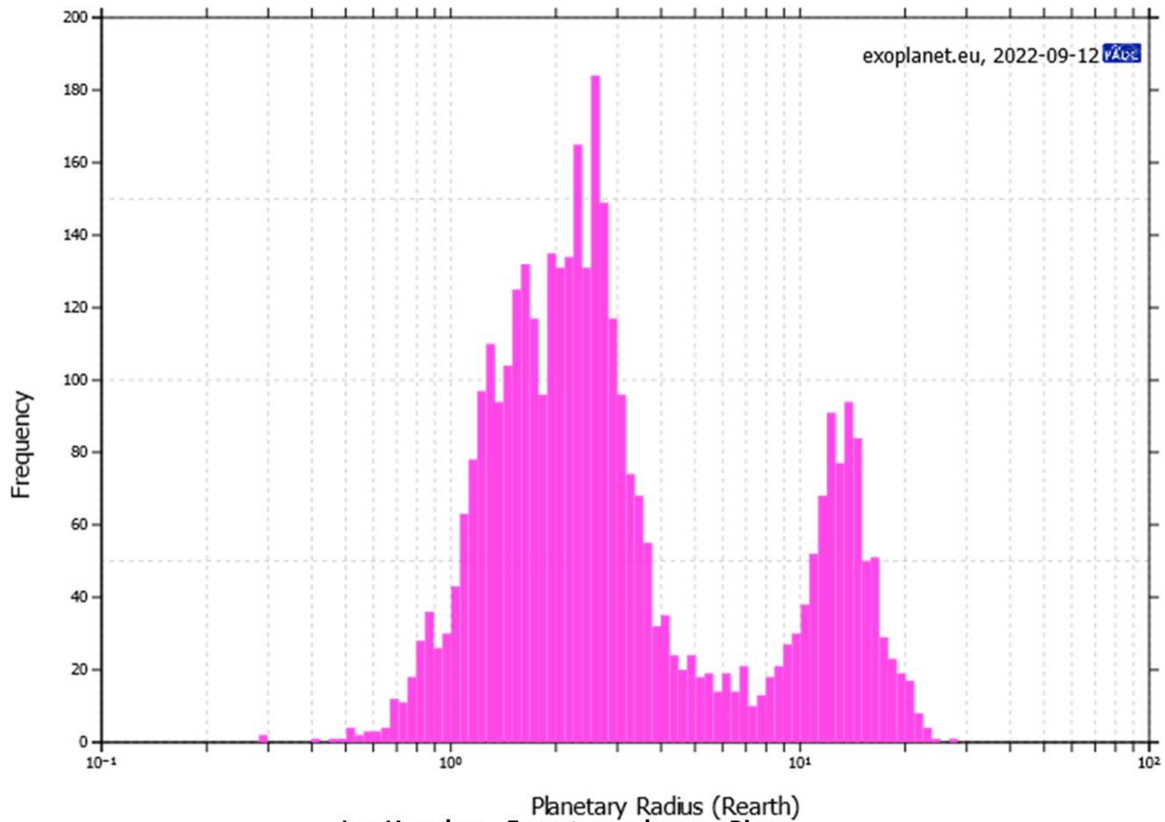


Exoplanets.eu – 09/12/2022 planets 5168 (2207 represented)

G. Tinetti, priv. comm.

Today, known planets plotted as a function of distance to the star (up to 20 au) and planetary radii (in Earth masses). Temperature of the host stars is given through the color grid

Histogram of planetary radii



SUPER-EARTHS OR MINI-NEPTUNES ?

Philosophical context

1) The Earth is **not** at the center of the (planetary) universe

Paradigm : Earth-like planets around Sun-like stars are not the most common planets…

2) The Solar System planets are **not** the representative templates for exoplanets study : superEarths/subNeptunes are the most common (and we don't know much about them) !

3) Why do we need to study Solar System planets ? Not as templates, but for the physical mechanisms which are universal

The name of Ariel mission – correcting major misunderstanding

Ariel holds for Atmospheric Remote-sensing Infrared Exoplanet Large-survey

- Ariel is not only a washing powder !
- Ariel is not only a Disney mermaid !
- Ariel is not only a satellite of Uranus !
- An acceptable symbol could be the spirit Ariel

 in The Tempest of William Shakespeare

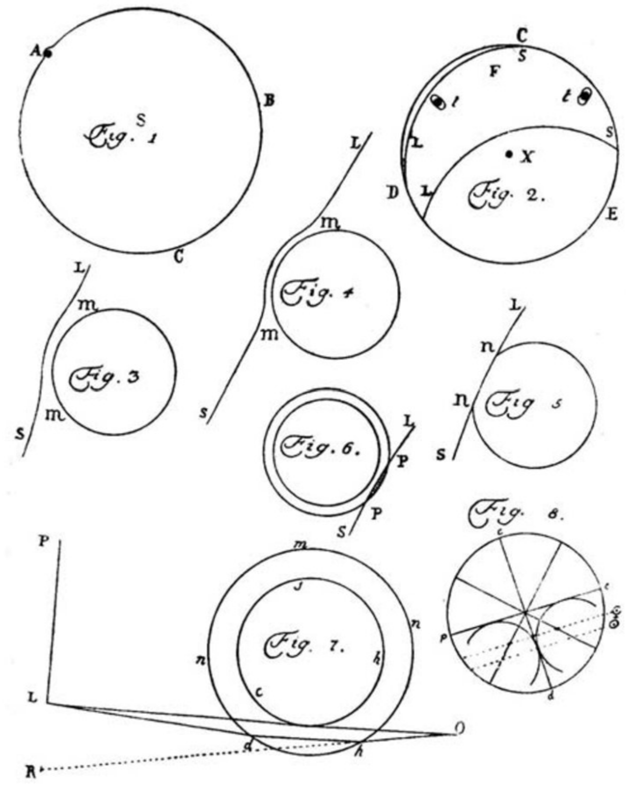
By the way, the calibration facility built for Ariel/AIRS Spectrometer will be named Caliban

Transits and eclipses in the Solar System

- Transit observable from Earth only for inner planets ! Mercury & Venus transits

Lomonosov discovery of the atmosphere of Venus (1761)

Lomonosov's drawing of
Venus transit across the
Sun's disc



1. Entering the solar disk in B
2. Colors caused by refraction
3. & 4. Bulge as Venus leaves the Sun

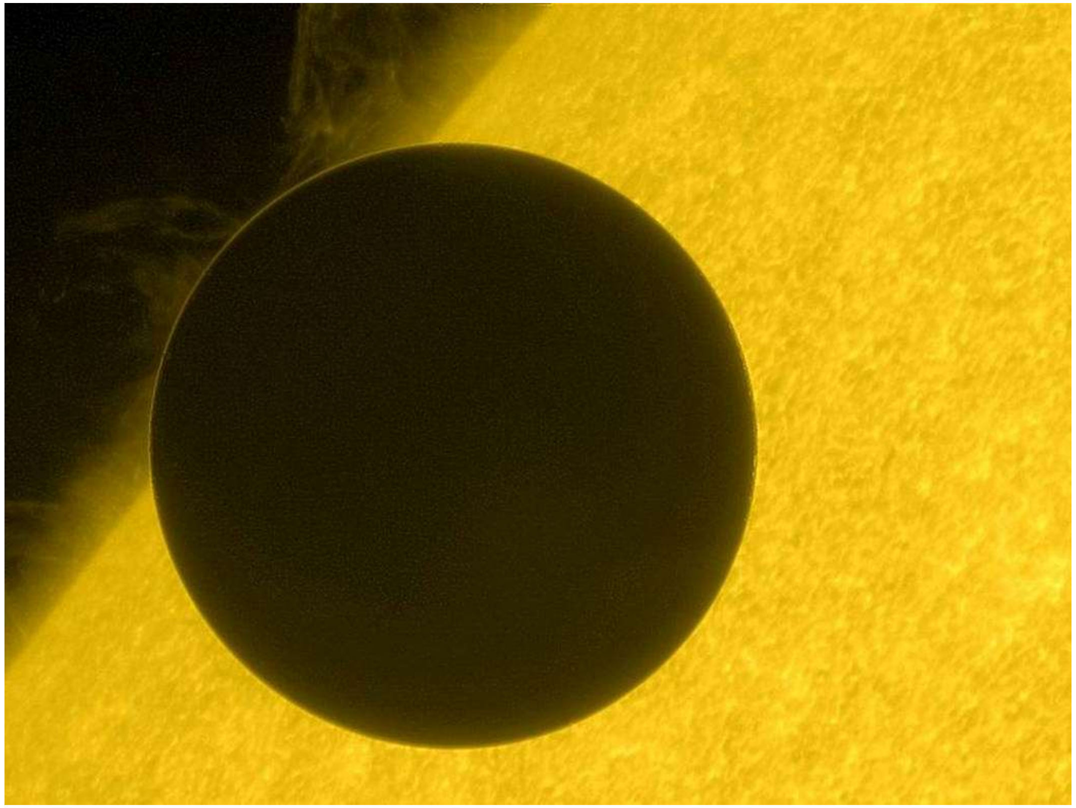
Marov, 2004, IAU proceedings

Transit of Venus in 2012 observed by Hinode

Observation of Venus
Transit in 2012

Satellite Hinode (JAXA)

Credit: JAXA/NASA/Hinode



Transits and eclipses in the Solar System

- Transit observable from Earth only for inner planets ! Mercury & Venus transits

- For any planets (and small bodies…), a powerful tool for investigation is the star occultation

An interesting example: the Jupiter spectral occultation in 1999 by HIP9369

Solar occultation by space missions

Many observations available :

Titan, Saturn – VIMS/Cassini

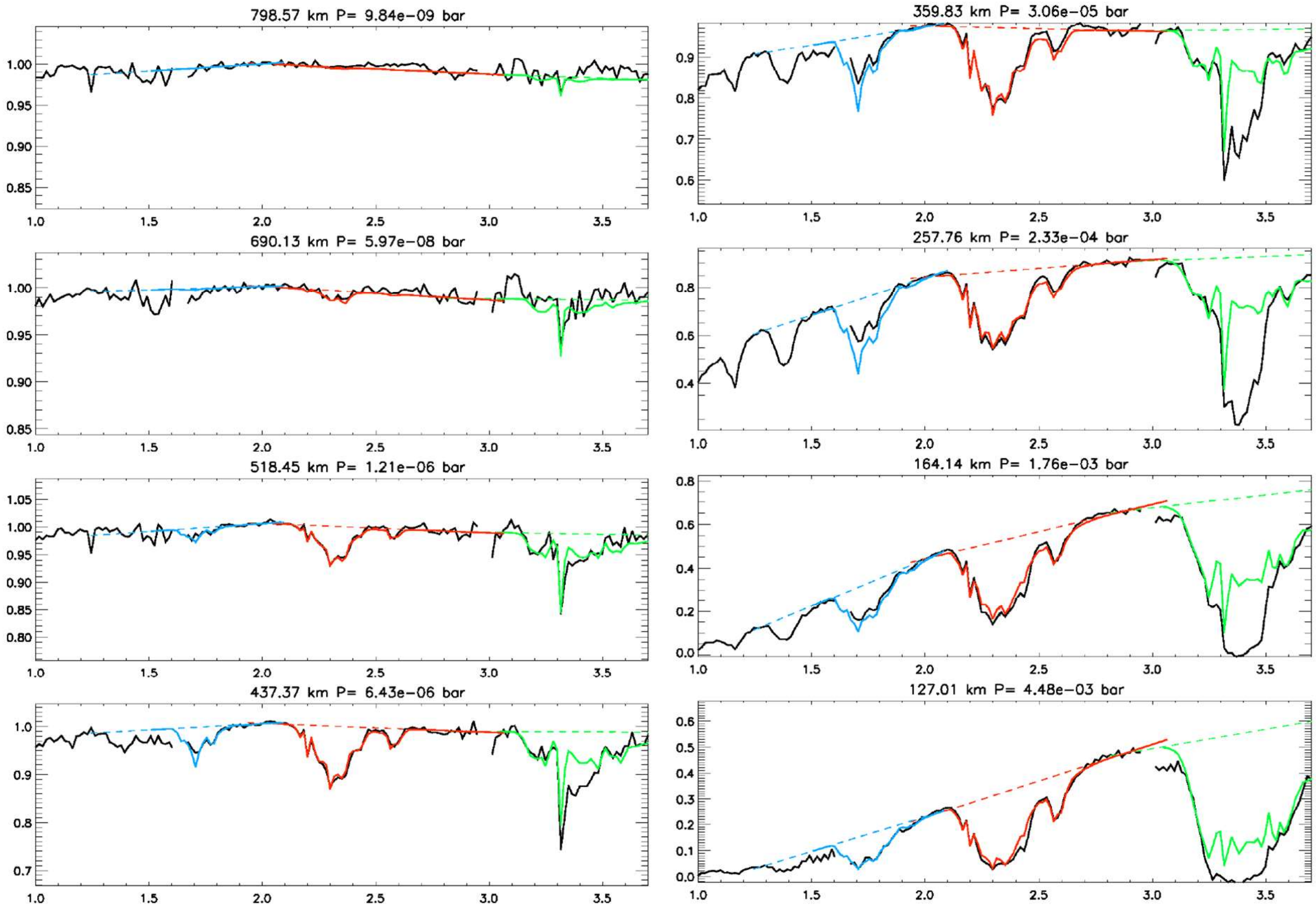
Mars : Auguste/Phobos 2 – SPICAM/Mars Express

Venus : SPICAV/SOIR Venus Express

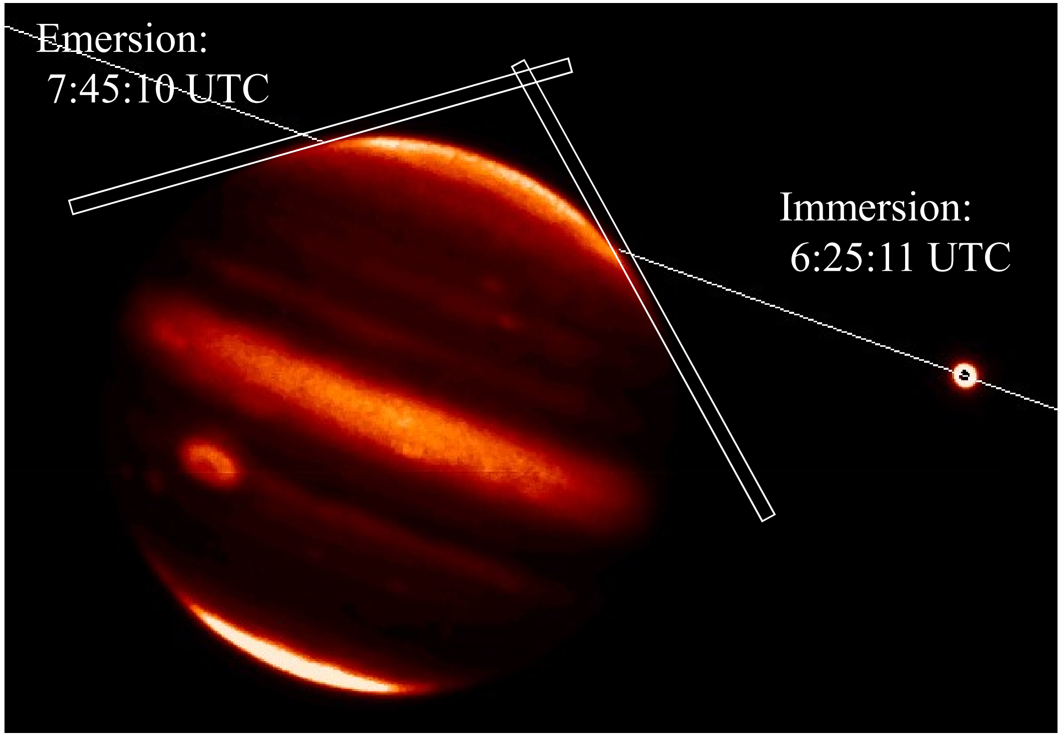
VIMS Titan occultation observations

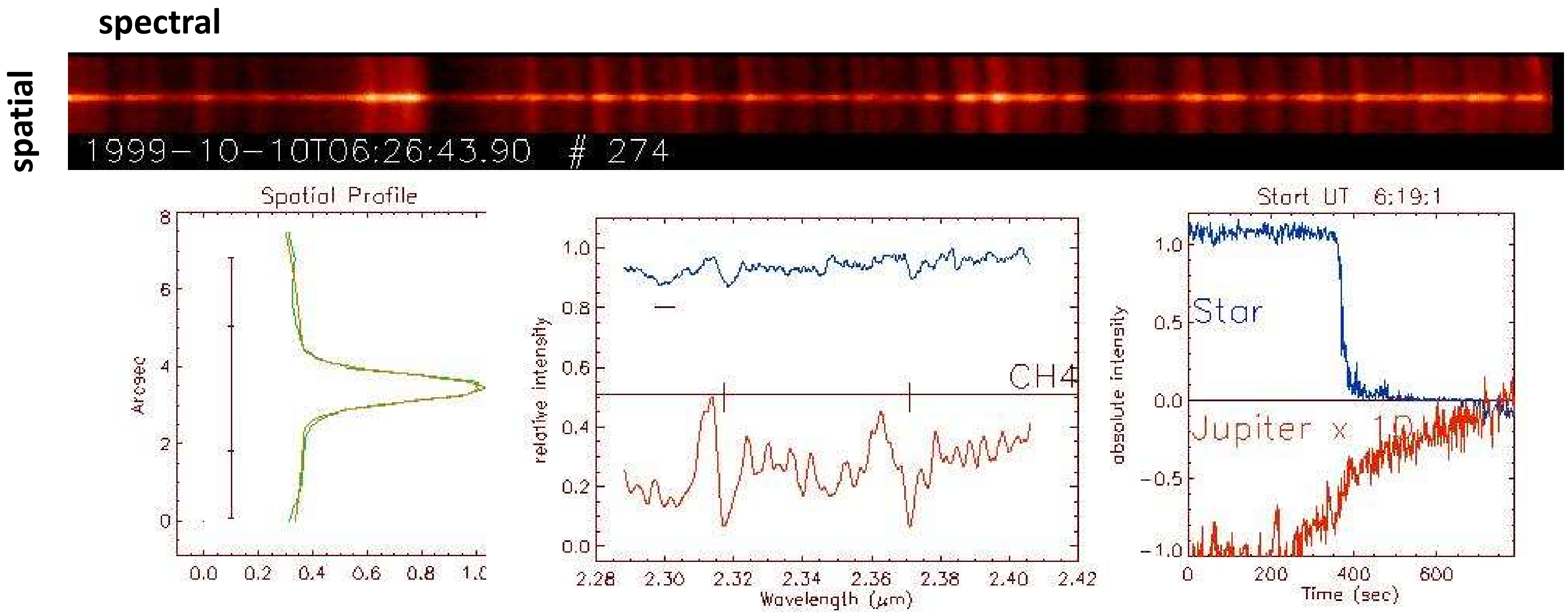
Series of spectra during Titan solar occultation (15 January 2006)

Bellucci et al., Icarus, 2009



Occultation of Star HIP9369 by Jupiter
10 October 1999

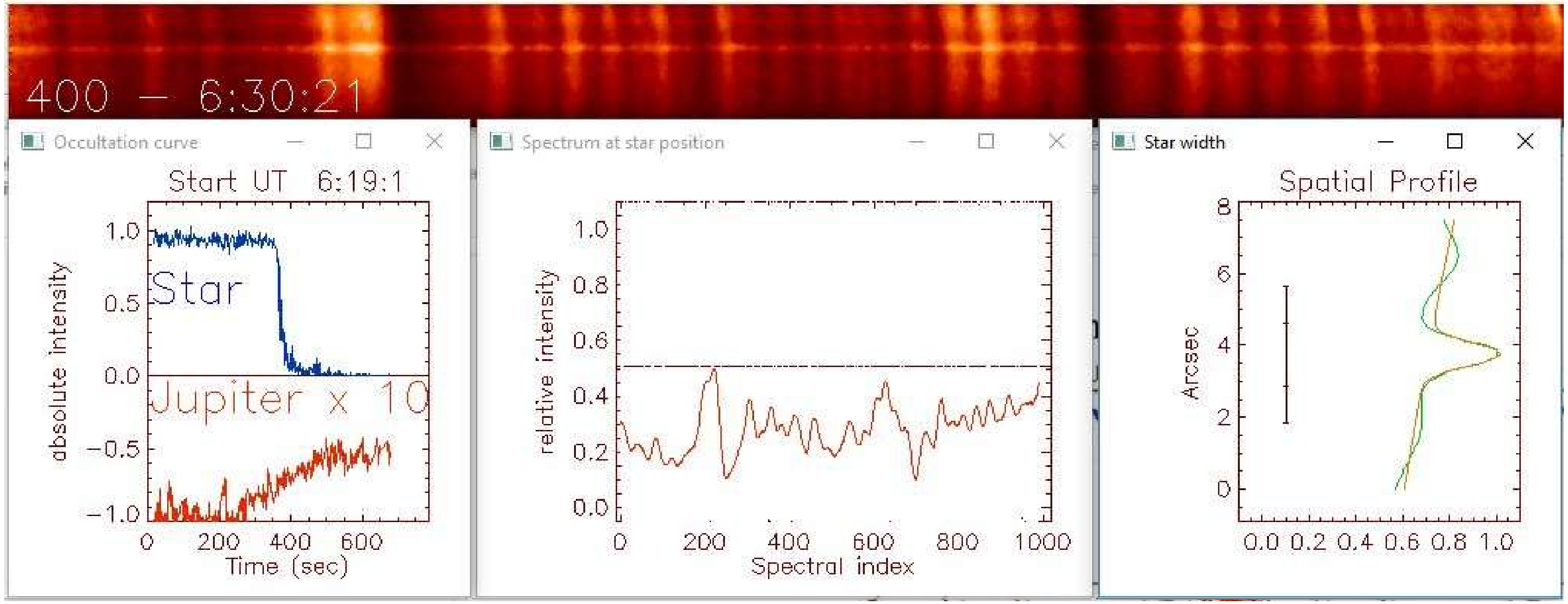




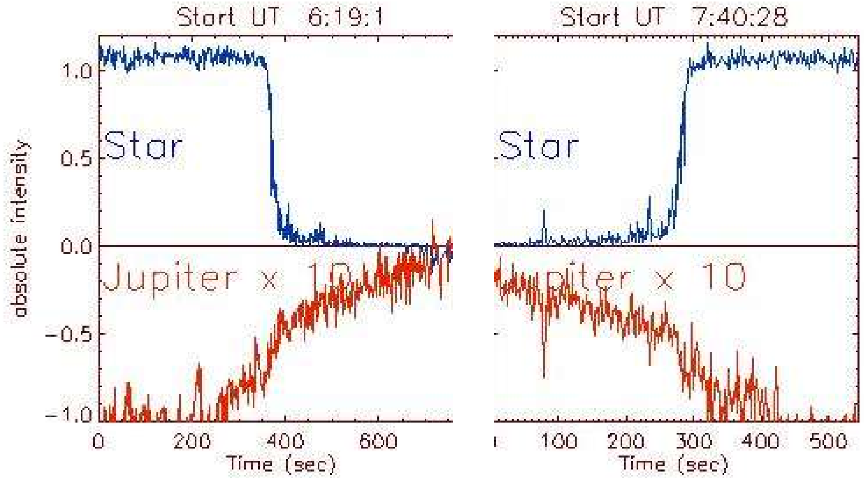
Raynaud, Drossart et al, Icarus 2003

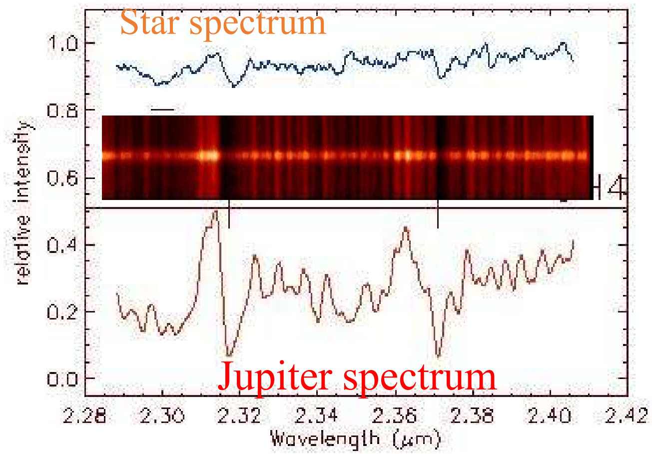
Observations and data reduction :

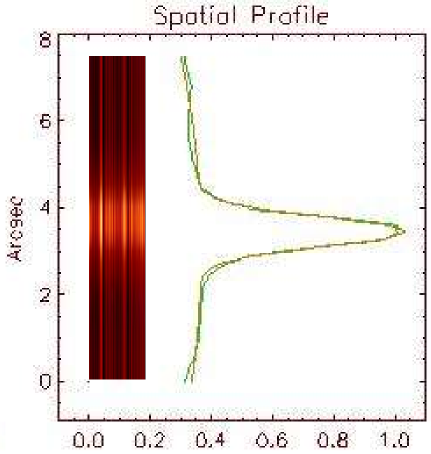
Disentangling star and planetary spectra

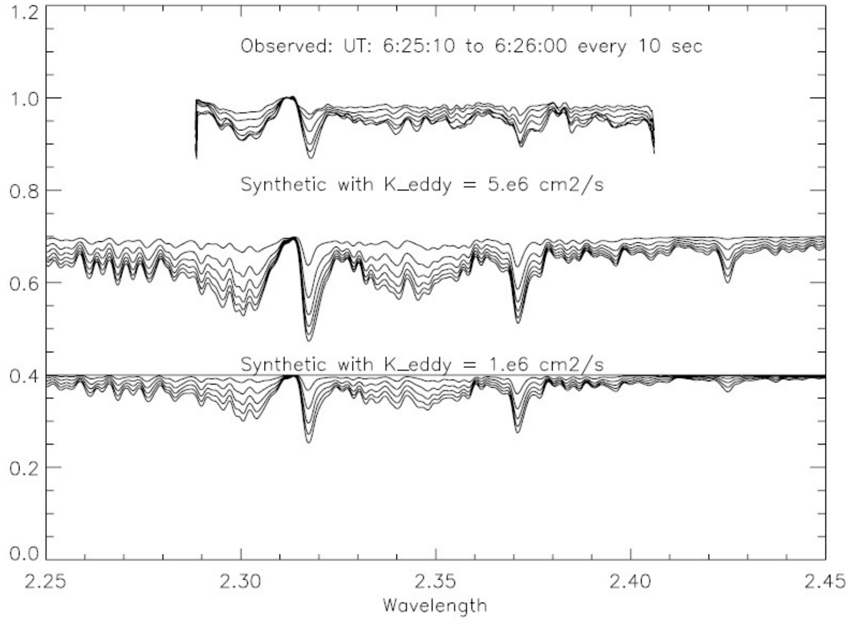


Immersion | emersion

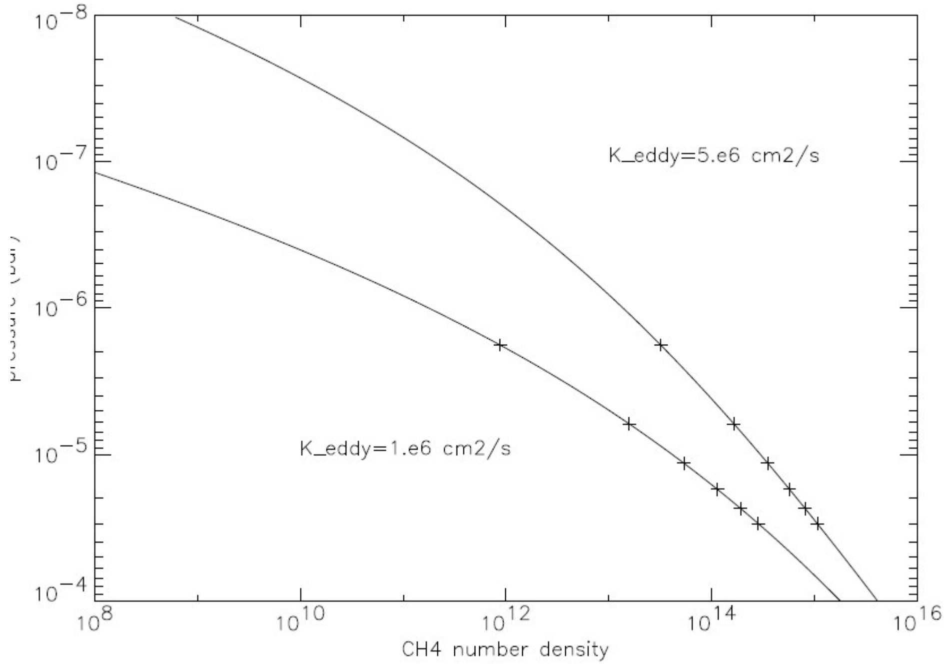








CH_4 vertical profiles vs K_{eddy}



CH_4 observations and simulations for different CH_4 profiles

Equation of diffusion in an atmosphere

Mass conservation equation for the flux of a i^{th} consitutent in the atmosphere:

$d\varphi/dz = 0$

(in the absence of chemical/photochemical sources & loss, see O. Venot course)

Lower atmosphere : turbulent mixing => one scale height $H_a = RT/M_a g$

Molecular diffusion : one scale height per constituent $H_i = RT/M_i g$

General Equation of diffusion

$$\phi_i = n_i \left[-D_i \left(\frac{1}{n_i} \frac{dn_i}{dz} + \frac{1}{H_i} + \frac{1}{T} \frac{dT}{dz} \right) - K \left(\frac{1}{n_i} \frac{dn_i}{dz} + \frac{1}{H_a} + \frac{1}{T} \frac{dT}{dz} \right) \right]$$

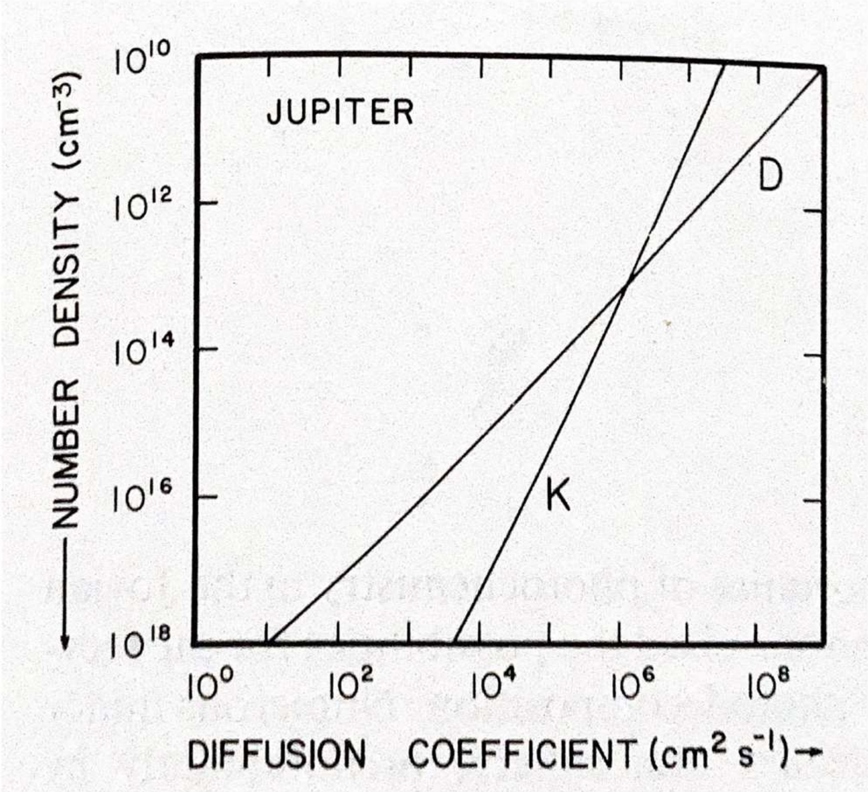
$$n_i(z) = n_i(z_0)(T_0/T) \exp\left(-\int_{z_0}^{z} dz/H_i \right)$$

Variation of number density in molecular regime $D_i \gg K$

$$n_i(z) = n_i(z_0)(T_0/T) \exp\left(-\int_{z_0}^{z} dz/H_a \right)$$

Variation of number density in turbulent regime $D_i \ll K$

Molecular diffusion coefficient



From the kinetic gas theory we have :

- $D_i = A\ T^s / n$
- $K \sim n^{-0.5}$

Thererefore the D coefficient will dominate at high altitude

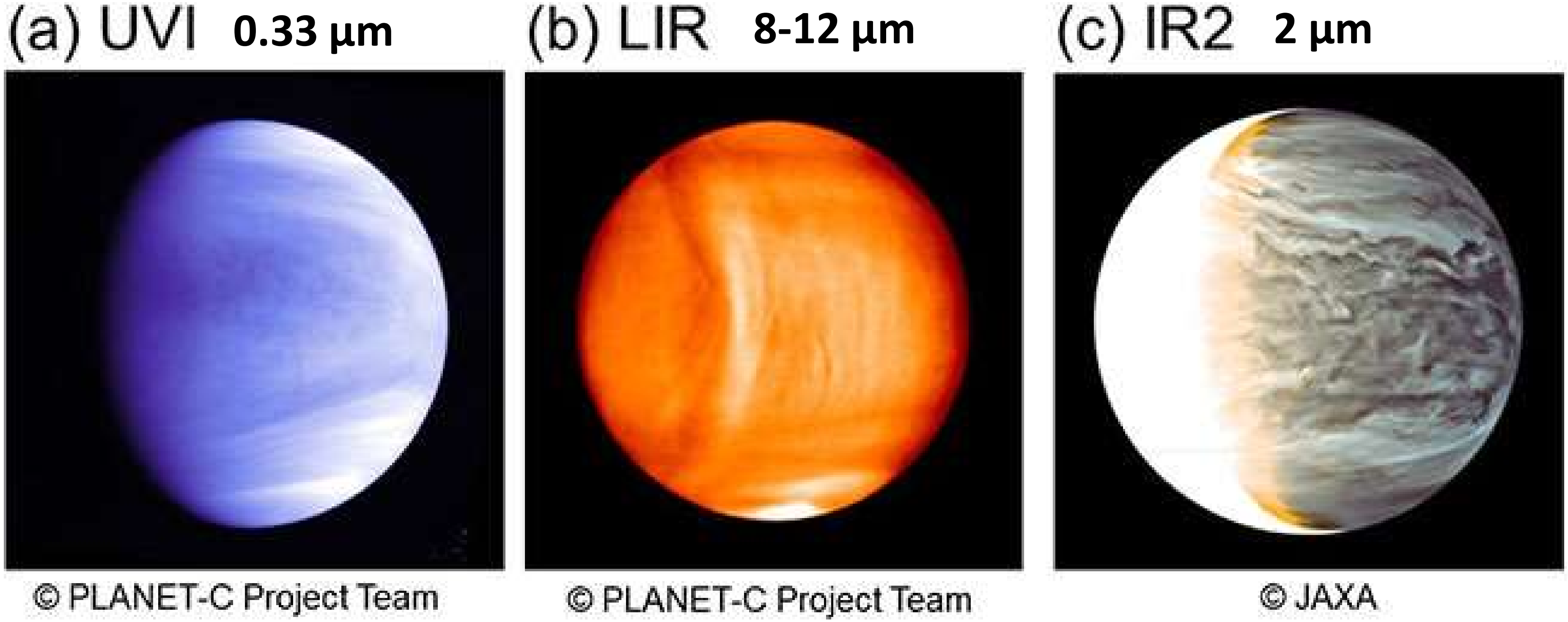
$K = D_i$ defines the homopause

Plan : Lessons to learn from Solar System

1. Transits and occultations in the Solar System
2. Complexities in radiative transfer of planets : inhomogeneities, auroral effects and non-LTE phenomena in the upper atmospheres of giant planets

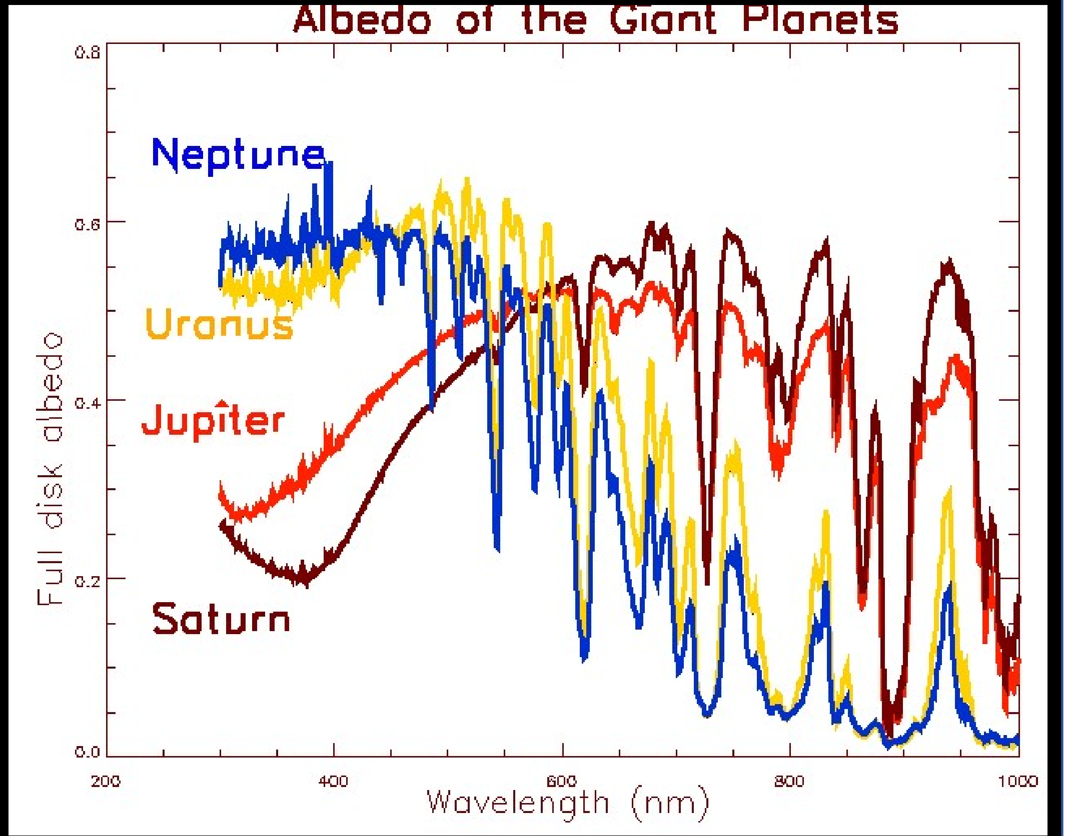
Inhomogeneities in planetary atmospheres

- **Spatial inhomogeneities : horizontal or vertical**



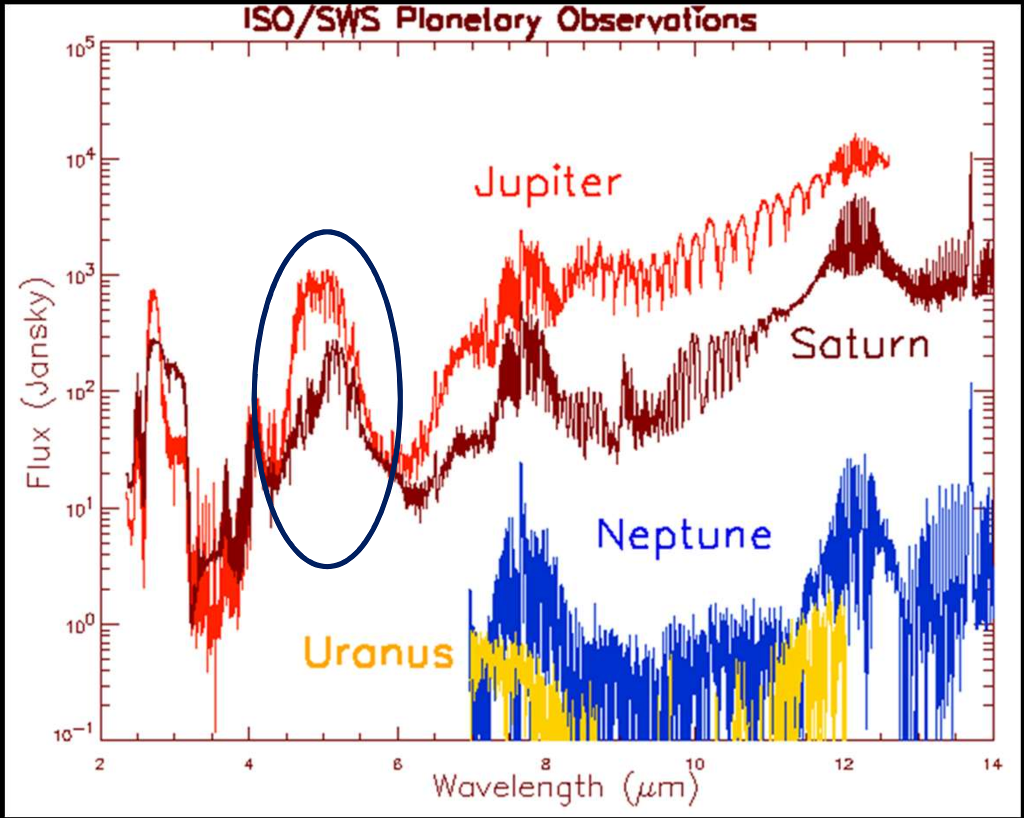
Jupiter

A. Simon (Goddard Space Flight Center), M. H. Wong (University of California, Berkeley) and the OPAL team. HST, 25 August 2020. Credit NASA, ESA

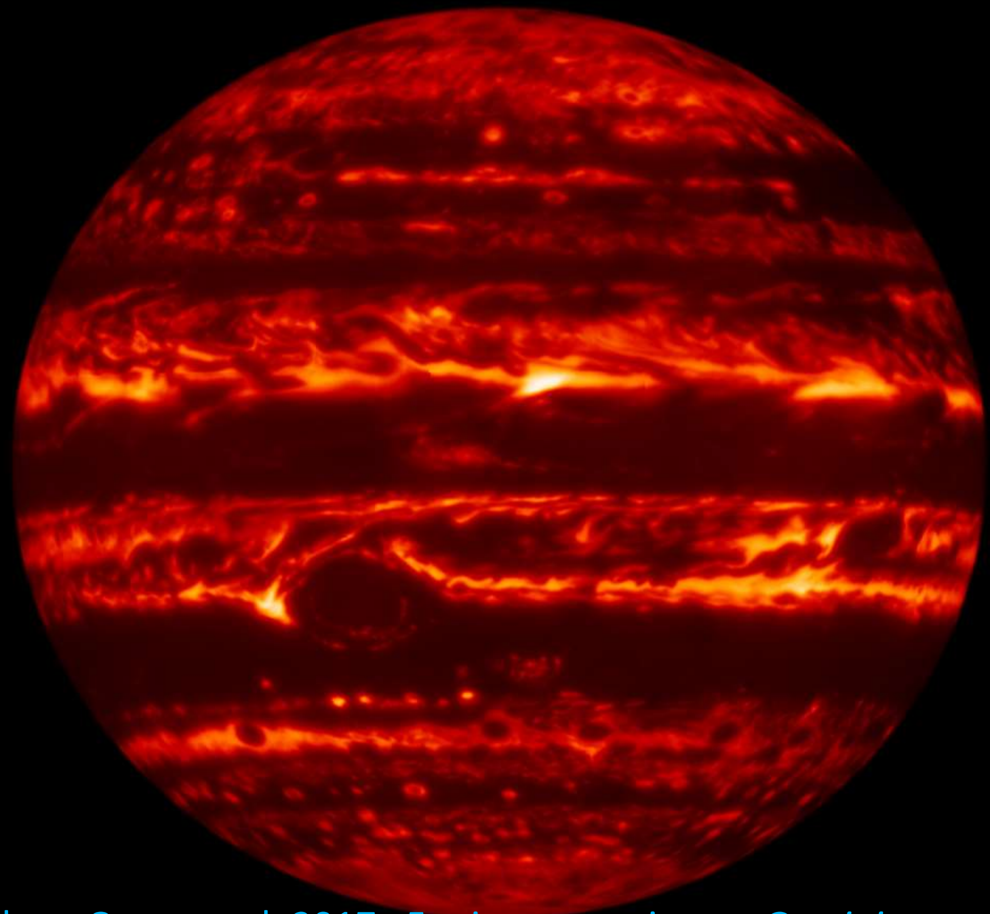


Karkoshka, Icarus, 1996

Jupiter in the infrared



ISO/SWS



Glenn Orton et al, 2017 . 5 micrometer image *Gemini Observatory/ AURA/NSF/UC Berkeley*

Auroral phenomena in giant planets

Importance of particle precipitations in a H_2/He atmosphere

H and H_2 UV emission :

- Lyman & Werner band for H2,
- Lyman alpha for H

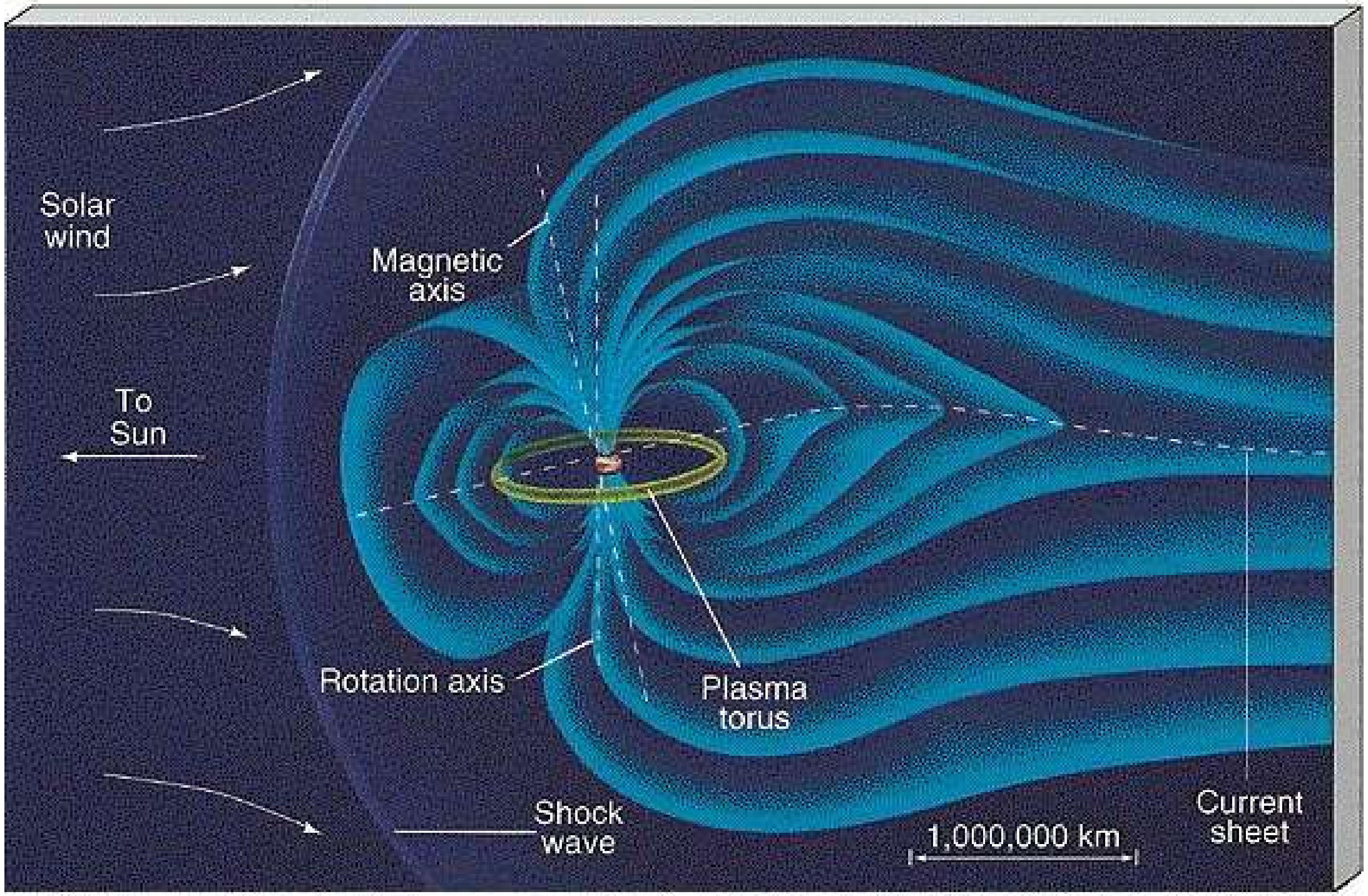
Infrared emissions :

- H_3^+ emission in the ionosphere
- Infrared emissions : hydrocarbon emissions (CH_4 , C_2H_2 , …)

Dynamic phenomena

Heating of the thermosphere

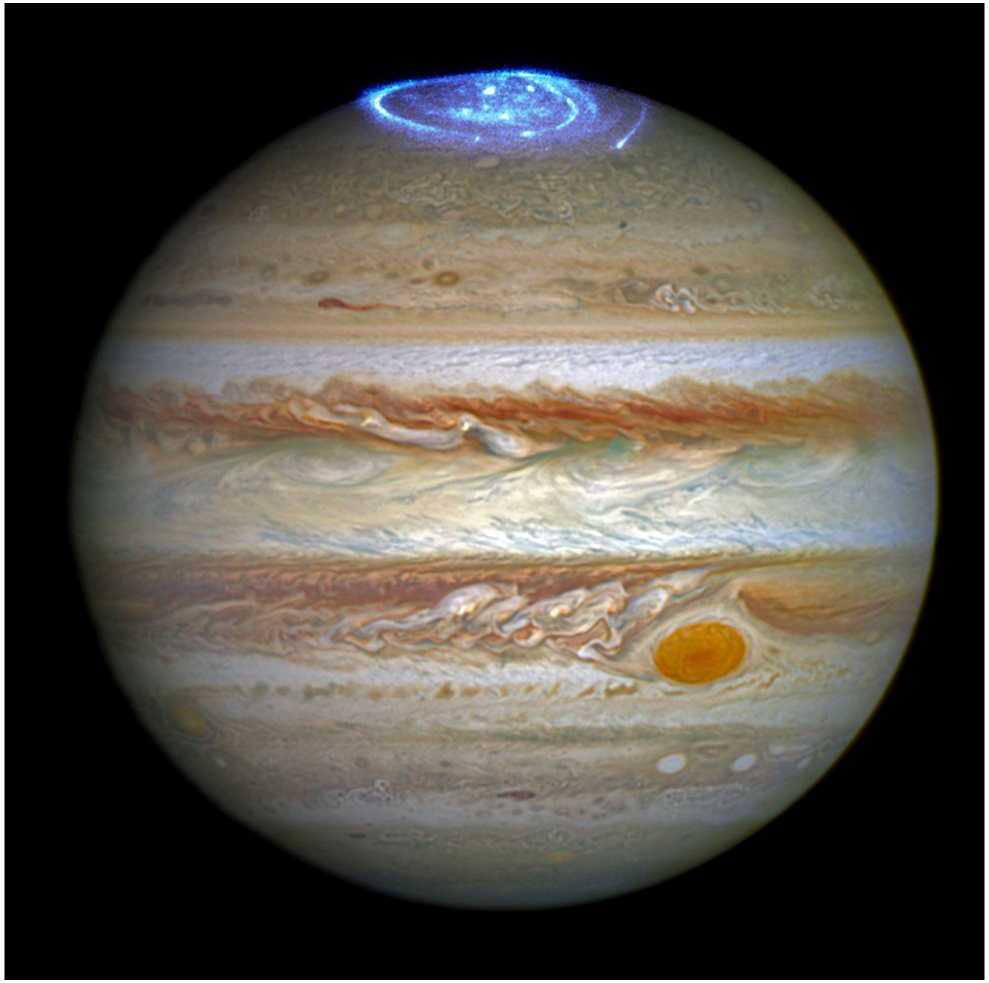
The magnetosphere of Jupiter



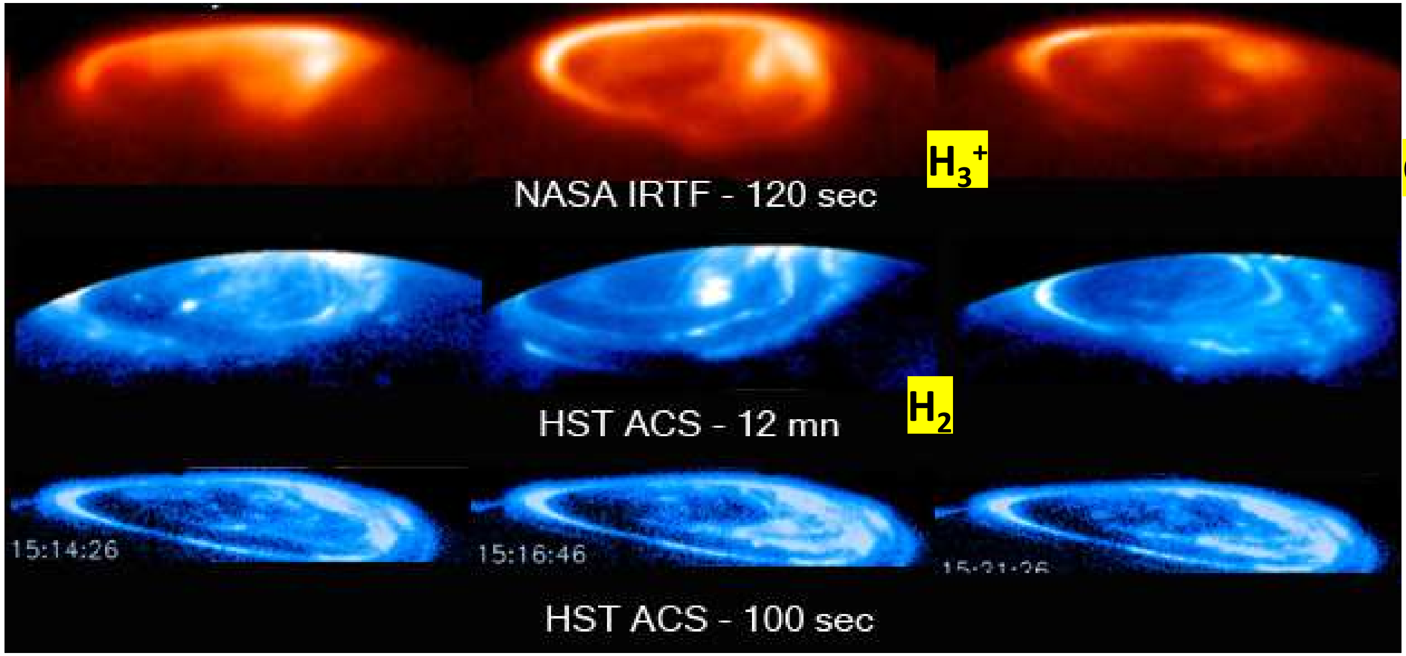
Auroral emissions

Precipitation of particles from the magnetosphere :

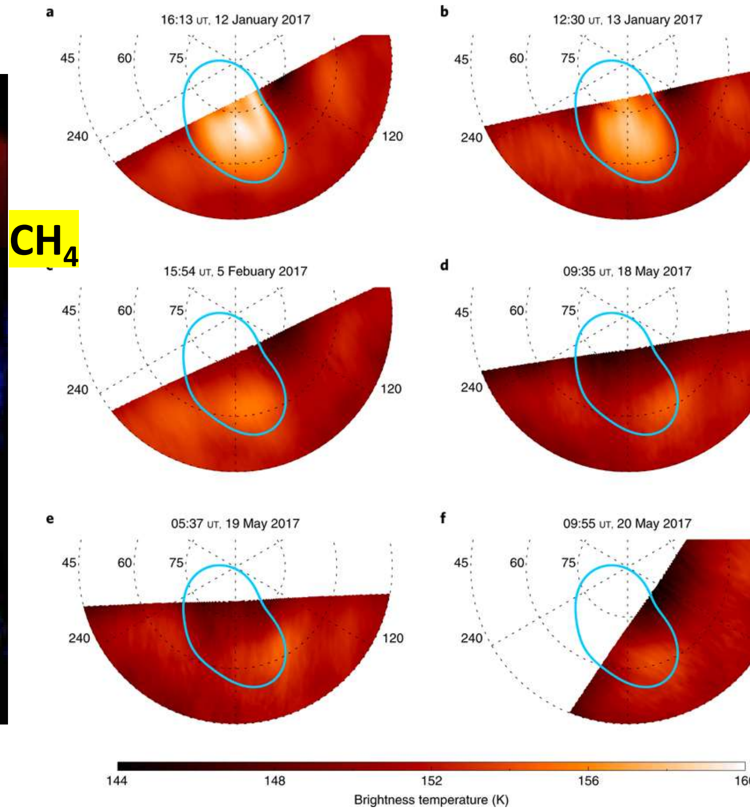
- Primary or secondary emissions : H Ly_{α} & H_2 Lyman and Werner bands
- Chemical modifications
- Thermal heating of the upper stratosphere
- Dynamical effects



Auroral emissions on Jupiter



adapted from *Stallard et al., 2016*



- ***Similar morphology on the global scale***
- Blurring of ground-based H_3^+ images by atmospheric "seeing" ***local features*** associated to magnetospheric precipitating beams structure ***undiscernable.*** Instrumental effect.
- ***Short-term variability (min) only visible in UV***, direct excitation by particle precipitation. IR emission, indirectly excited, depend on intermediate processes (lifetime, thermalisation, ..). Physical effect.

Sinclair et al 2019
A brightening of Jupiter's auroral 7.8-µm CH 4 emission during a solar-wind compression

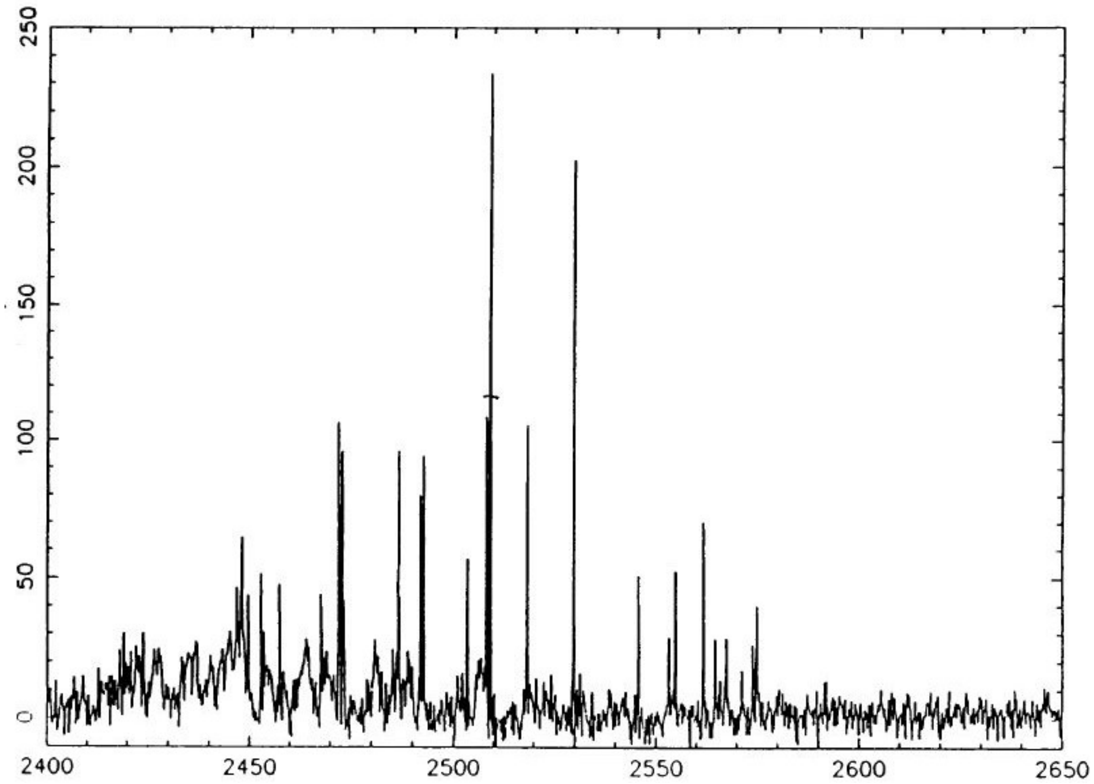
Rotational temperature retrieval

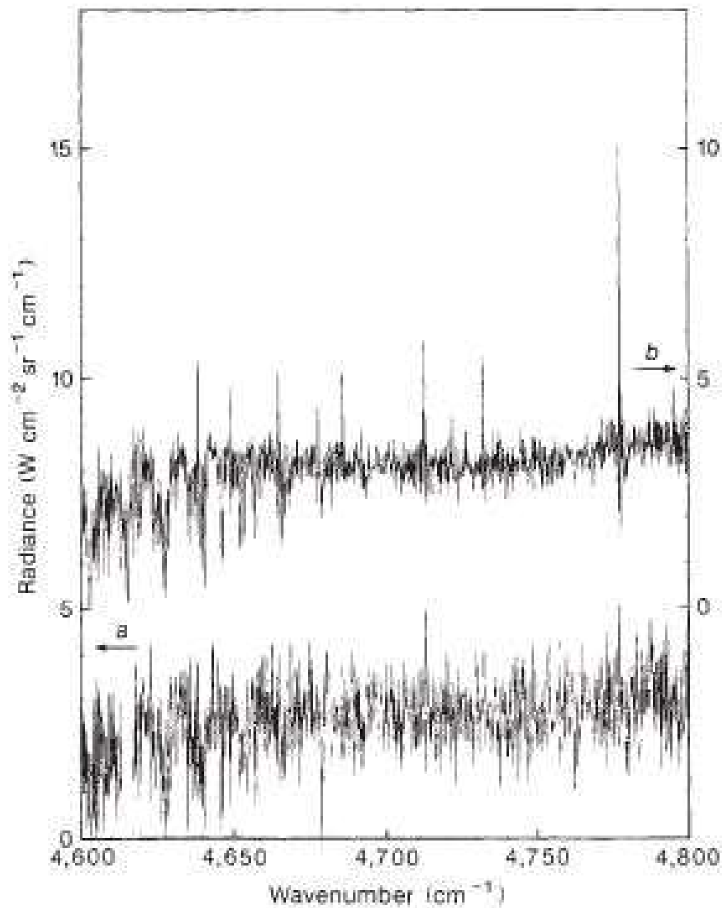
$2\nu_2$ band of H_3^+ (1st detection) – 2 µm (K band)

ν_2 band 4 µm

L band

FTS spectra of Jupiter – R ~ 20,000
Maillard et al, 1990



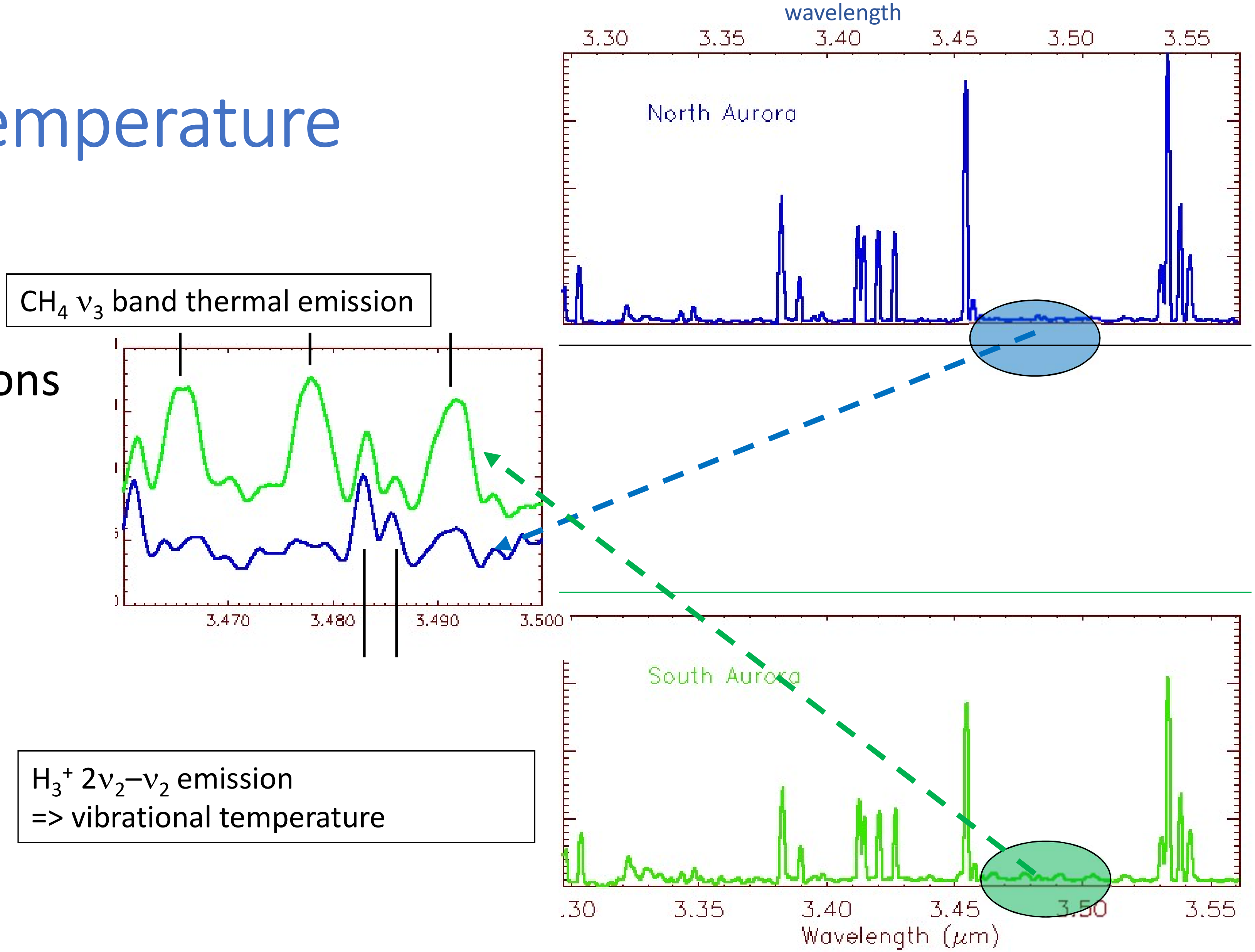


FTS spectra of Jupiter – R ~20,000
Drossart et al, 1989

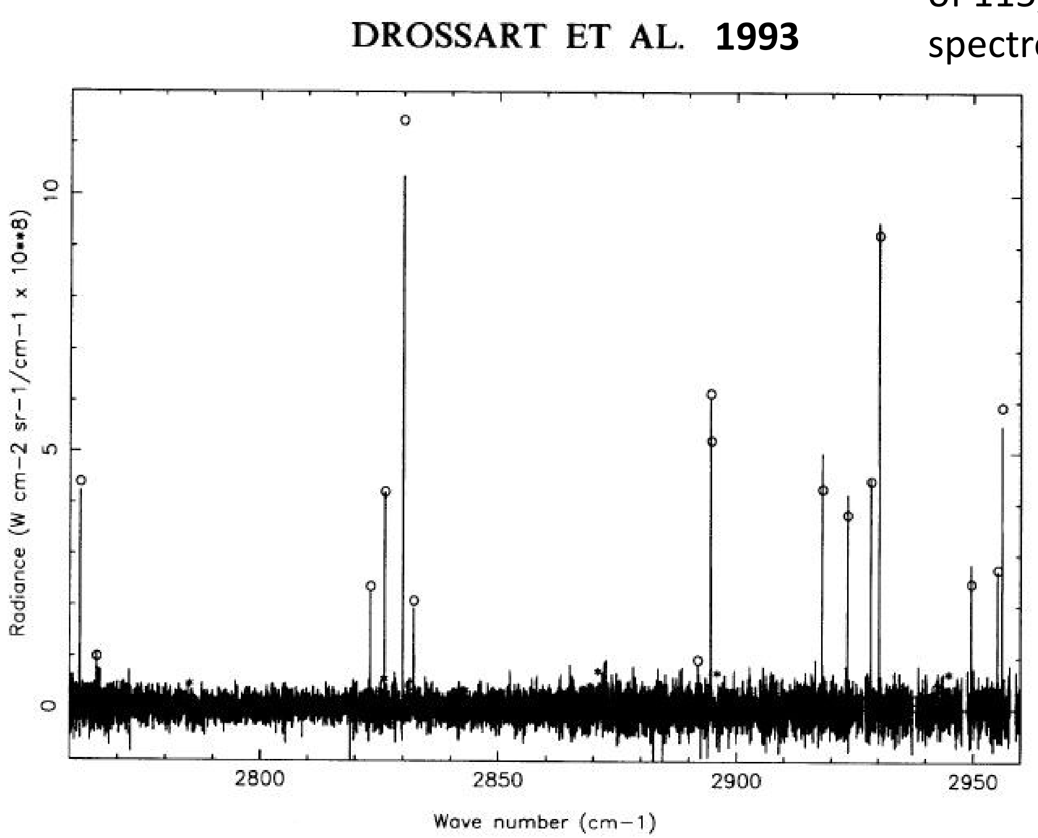
Vibrational temperature retrieval

VLT/ISAAC observations

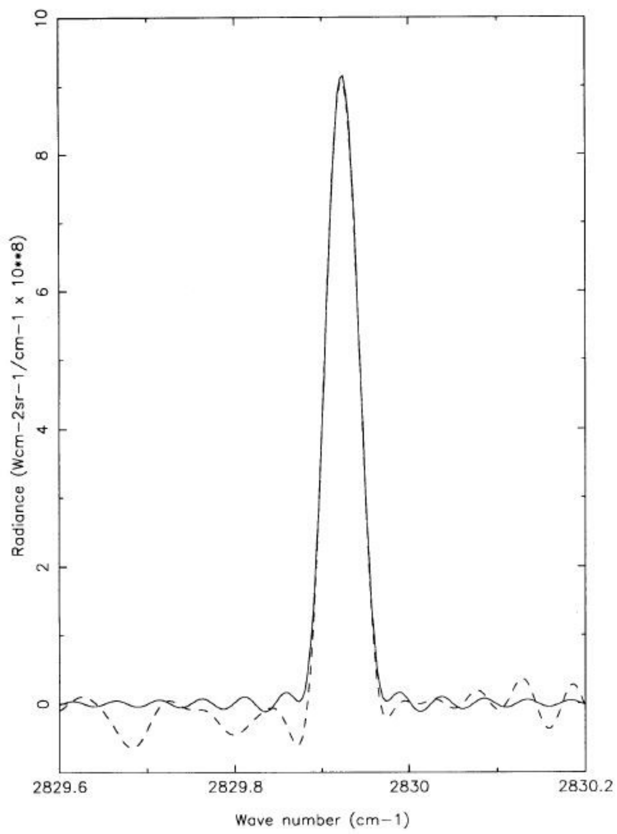
(12/14/2000)



Kinetic temperature retrieval



CFHT/FTS spectral resolution of 115,000 – line resolved spectroscopy



Least square fit
Tk = 1150 K
Trot = 1250 K

Drossart et al., APJ Lett. 1993
Giles et al., A&A, 2016

Non-LTE effects

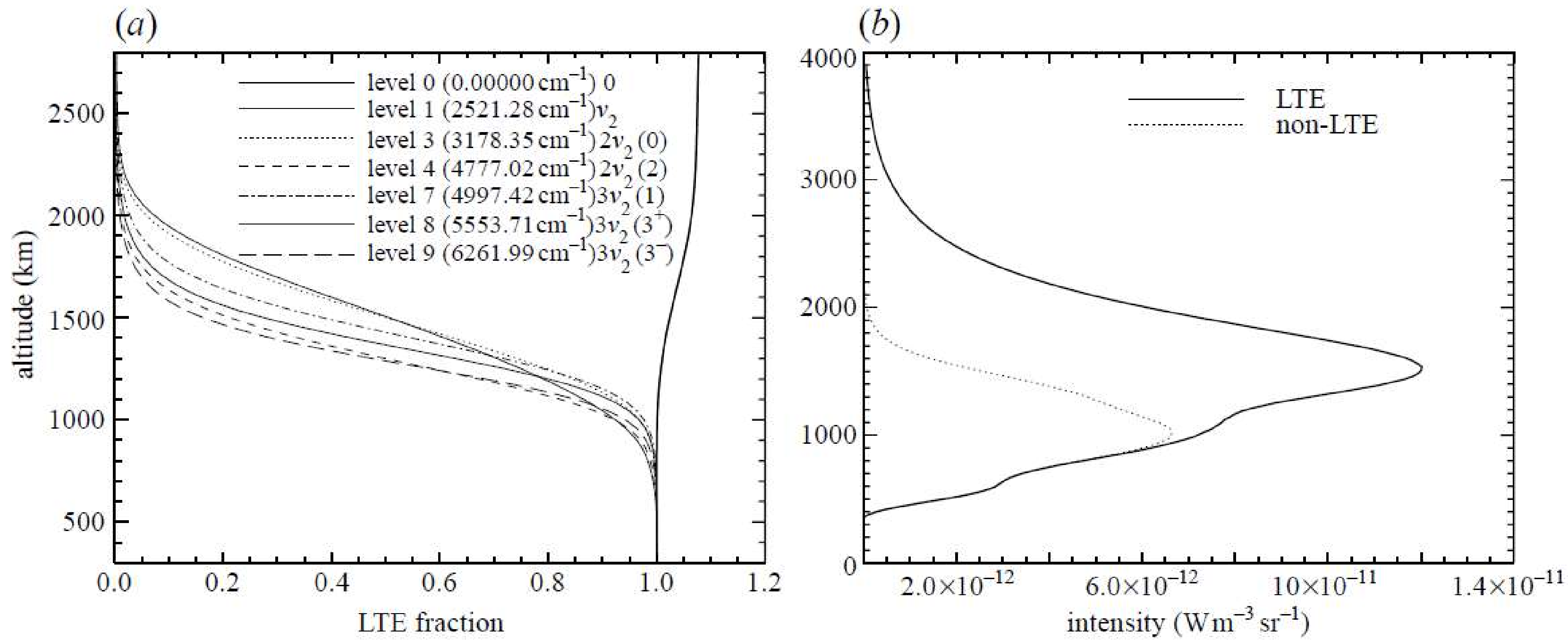


Figure 6. (*a*) Departure from thermal population of the nv_2 levels. (*b*) Emission from $2v_2^2R(6,6)$ line as a function of altitude for LTE and non-LTE models. From Melin *et al.* (2005).

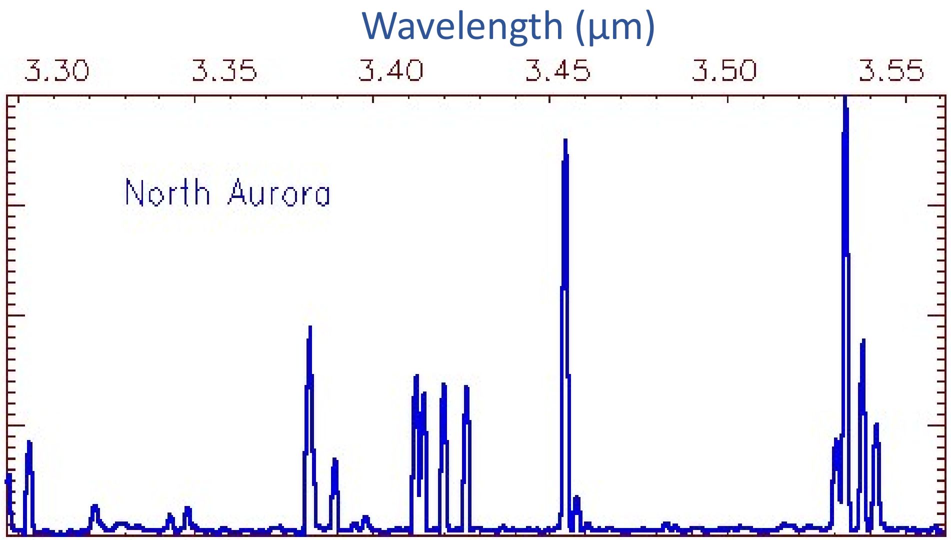
Beyond simple isothermal LTE or QLTE models…

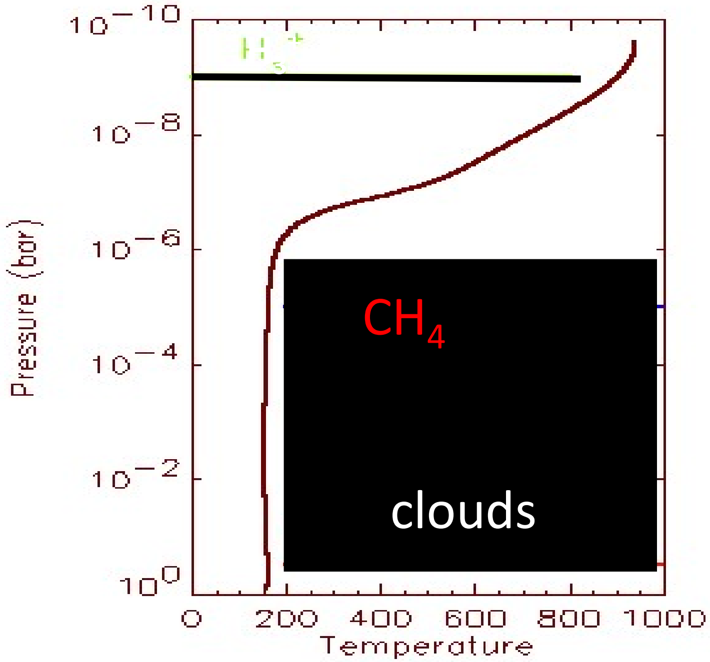
From spectrum to planetary physics

Measurable parameters :

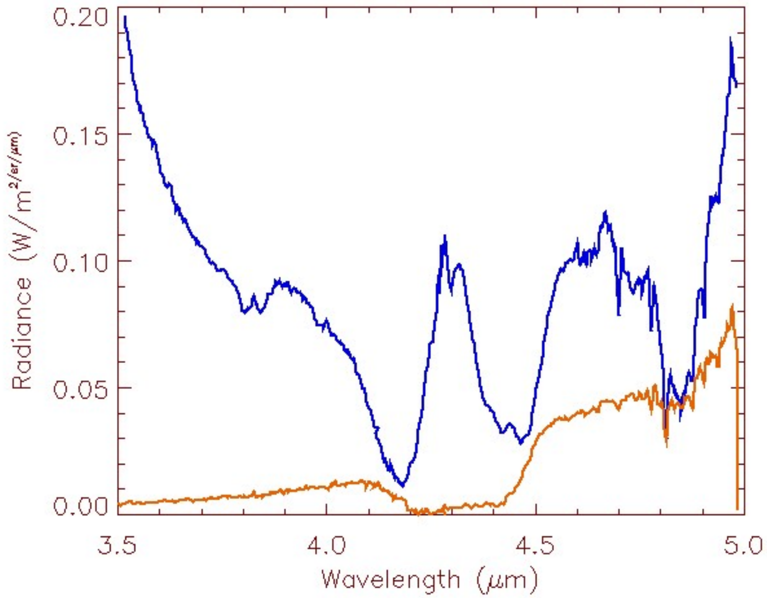
- **Temperature** of the ionosphere
- H_3^+ **column density**
- **H_3^+ as a wind tracer (from Doppler shift)**
- Spatial / temporal **variability**
- **Altitude** of emission from limb observations
- **Multiwavelength** : X-ray, UV, IR, radio

=> correlations with other processes (magnetosphere, solar wind, internal dynamics)





Non-LTE mechanisms in planetary atmospheres



Venus, VIRTIS/Venus Express, 2006
Observation of CO_2 fluorescence at 4.3 μm

Radiative transfer equation in LTE conditions

Formal radiative transfer equation $dL_\nu(P,s) = - e_\nu \, n_a \, [\, L\nu(P,s) - J\nu(P,s\,]\, ds$

L = radiance ; e : extinction coeff. ; n : density of absorber ; J = source term

The complexity is hidden in the source term…

True thermal equilibrium :

$J_\nu = B_\nu$ **and** $L_\nu = B_\nu$ **: blackbody condition => 1 temperature T**

Local Thermal Equilibrium => $J_\nu = B_\nu$ **but** $L\nu \neq B\nu$

Observed when thermal collision ensures that all form of energy equilibrate the temperatures (vibrational, rotational, kinetic). Partial LTE possible (rotational vs vibrational, etc.)

Limitations of LTE sounding in infrared emission for dynamical purposes:

- **dependence in limited number of atmospheric parameter (temperature profile T(z))**
- **vertical resolution = weighting function in the RT equation**
- **optical depth** $\tau \sim 1$ **sounding => limitation to stratospheric levels**

Radiative transfer non-LTE scheme

Non-LTE regime:

$J\nu \neq B\nu$

Thermal collision time > radiative time

Collisional, chemical processes to be taken into account to calculate the source function

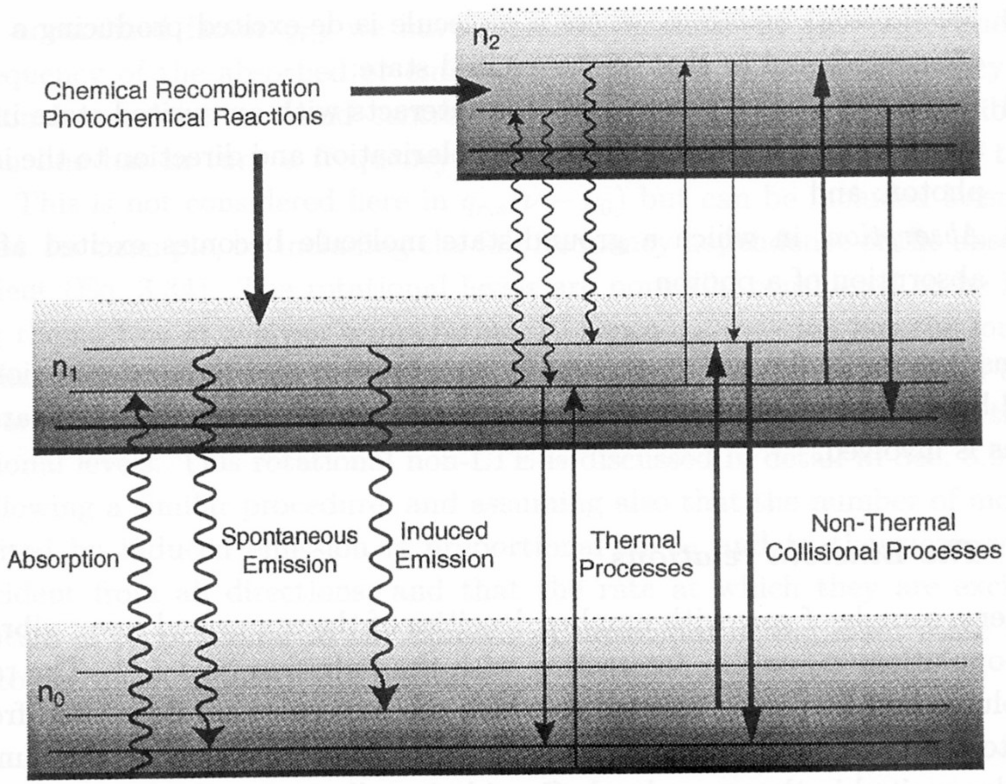


Fig. 3.3 Processes affecting the populations of vibrational levels.

Some non-thermal processes

1. **Vibrational-vibrational energy transfer.**

   Example : CO_2 molecule ; exchange with N_2

2. **Electronic to vibrational energy transfer.**

   Example: O(^{1}D) state excitating the N_2 vibrational modes

3. **Chemical recombination or chemiluminescence Example: ozone bands at 10 μm**

4. **Photochemical reactions**

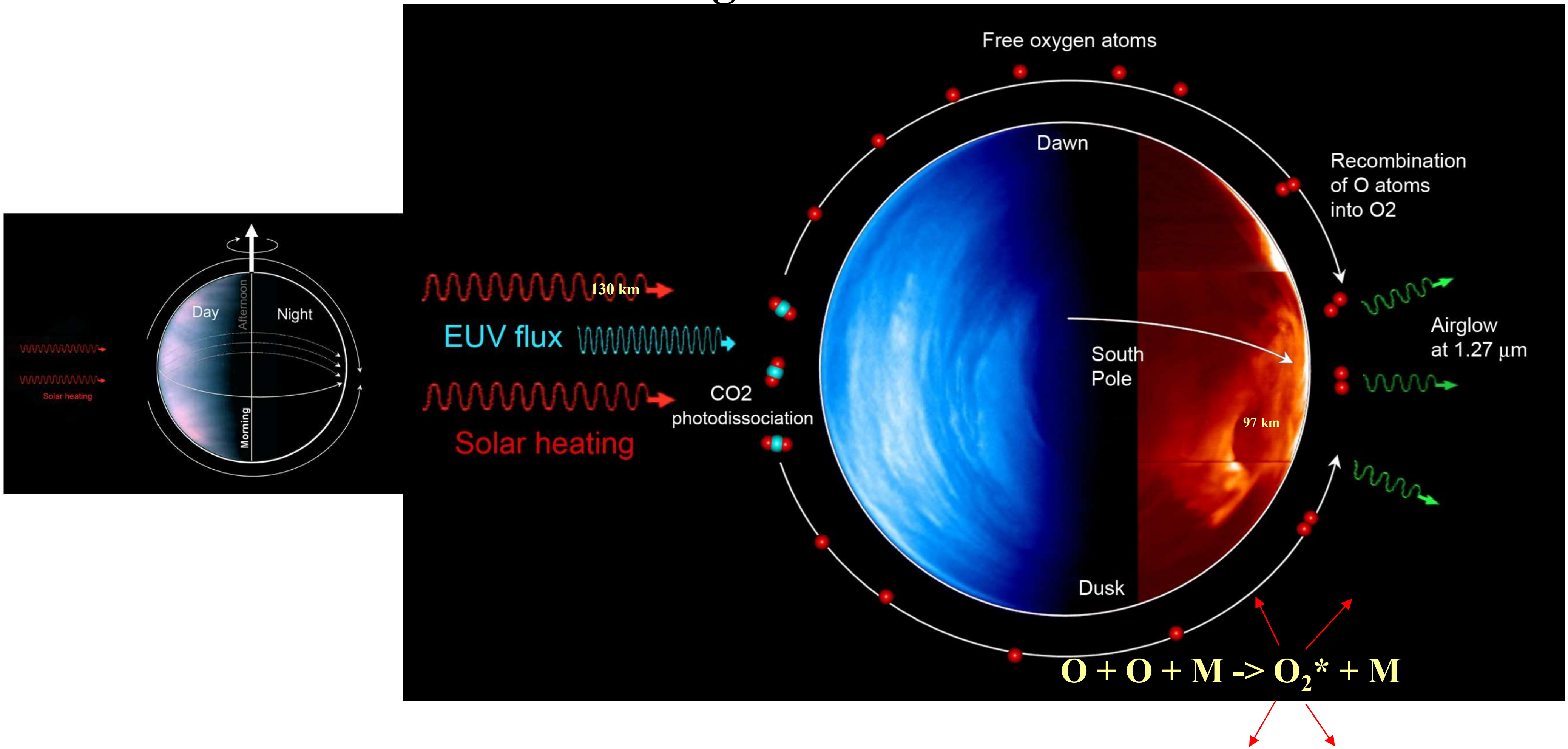
   Example : O_2 emissions at 1.27 μm

5. **Dissociative recombination (O_2^+ + e- $\rightarrow$O* + O)**

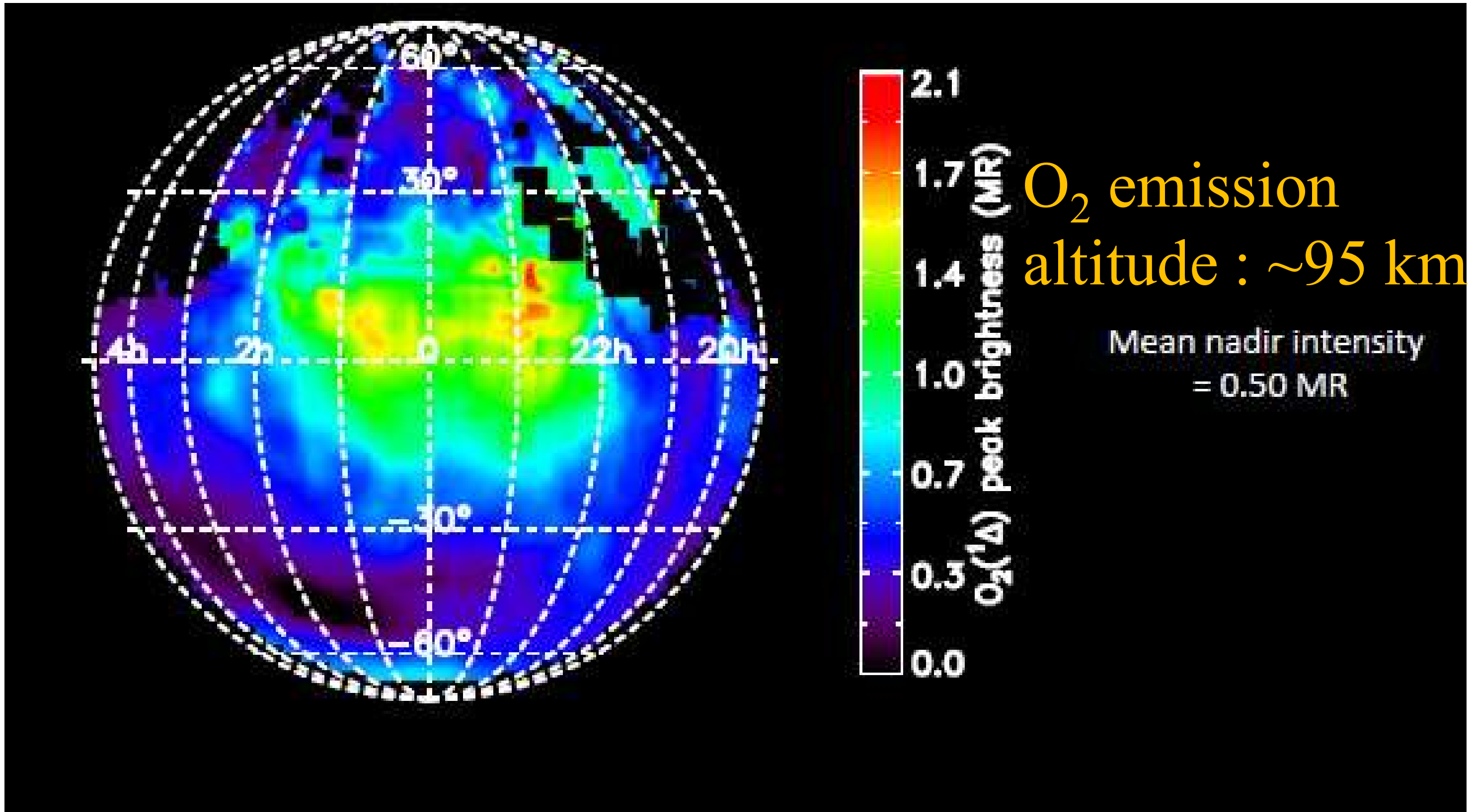
6. **Collisions with charged particles (auroral processes)**

Moreels et al, Experimental Astronomy, 2008
Observations from Observatoire de Haute Provence (1998)

A conceptual picture of O_2 (Δ) production and airglow on Venus



O_2 average emission

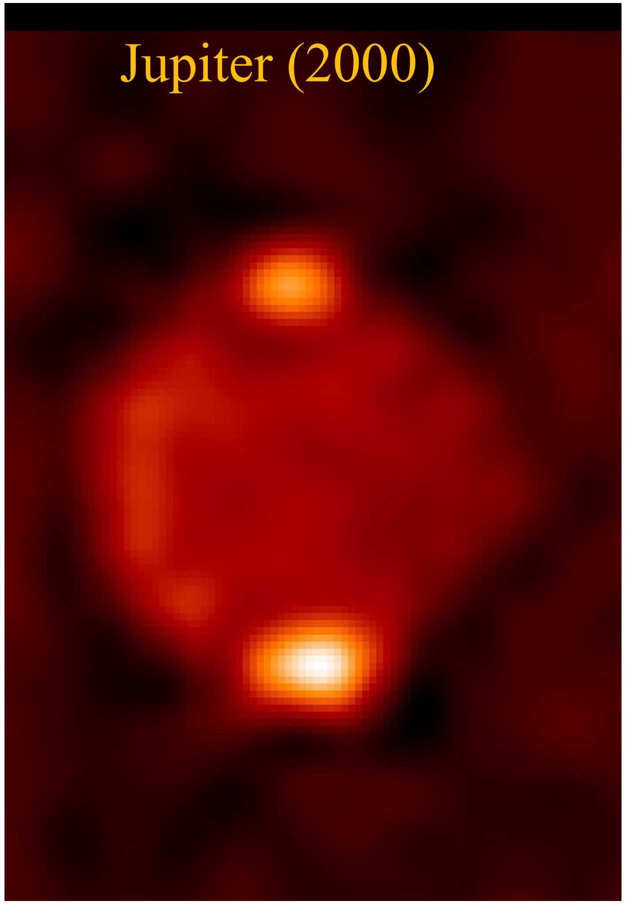


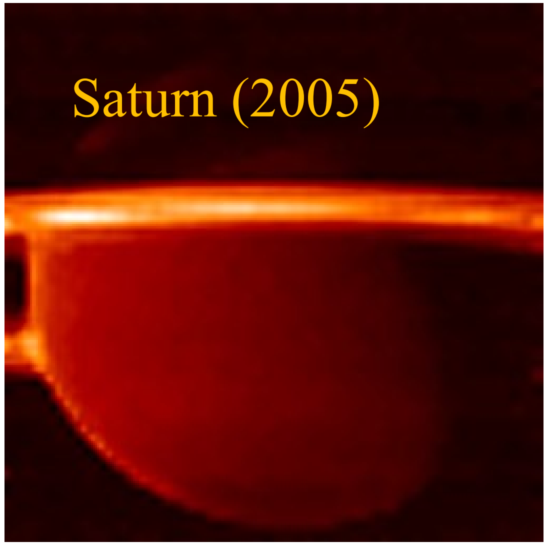
Latitudinal – local time distribution of the O_2 infrared atmospheric band in the Venus lower thermosphere - Soret et al. (2012)

Soret, Lauriane; et al. The OH Venus nightglow spectrum: Intensity and vibrational composition from VIRTIS—Venus Express observations Planetary and Space Science,. 2012

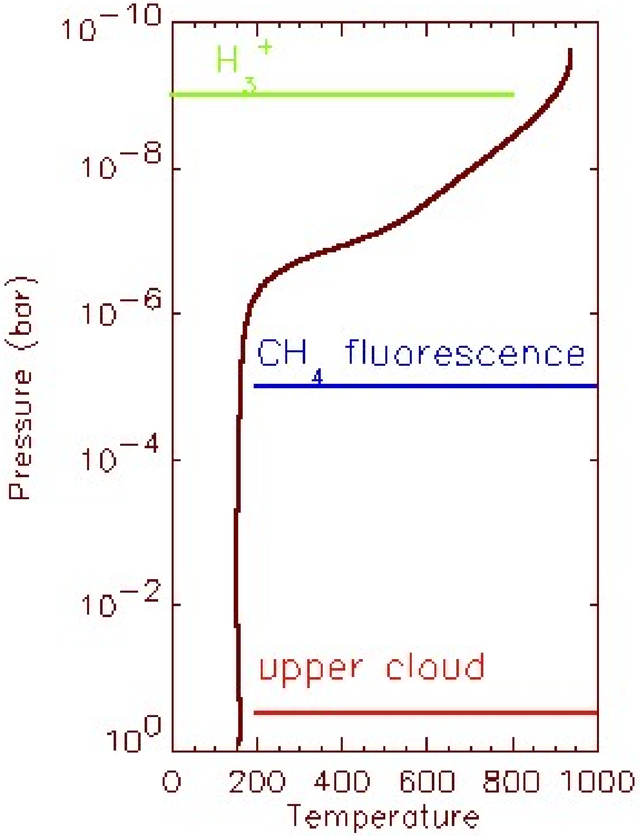
Giant Planets :

Cassini/VIMS CH_4 emissions at 3.3 μm

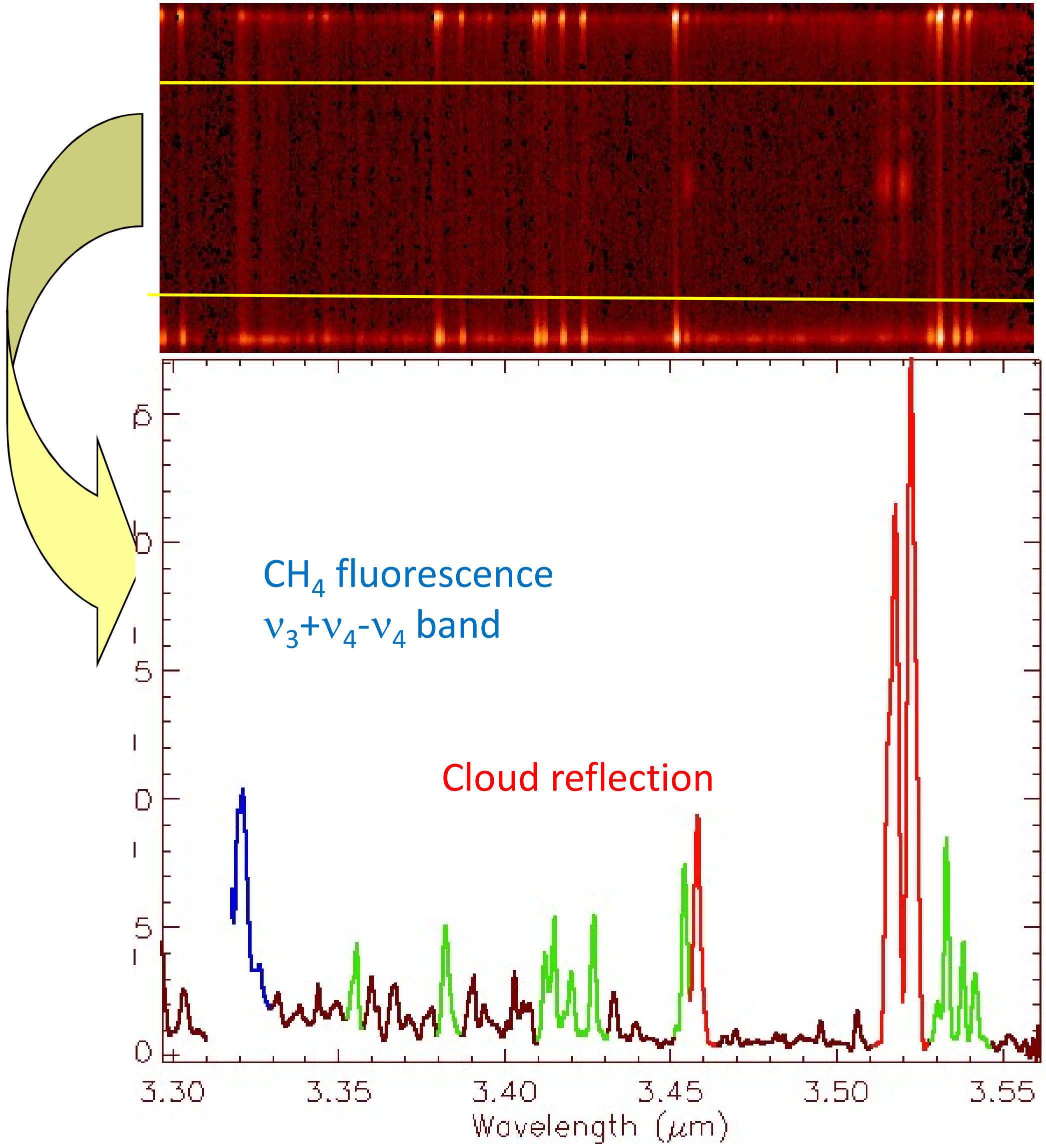


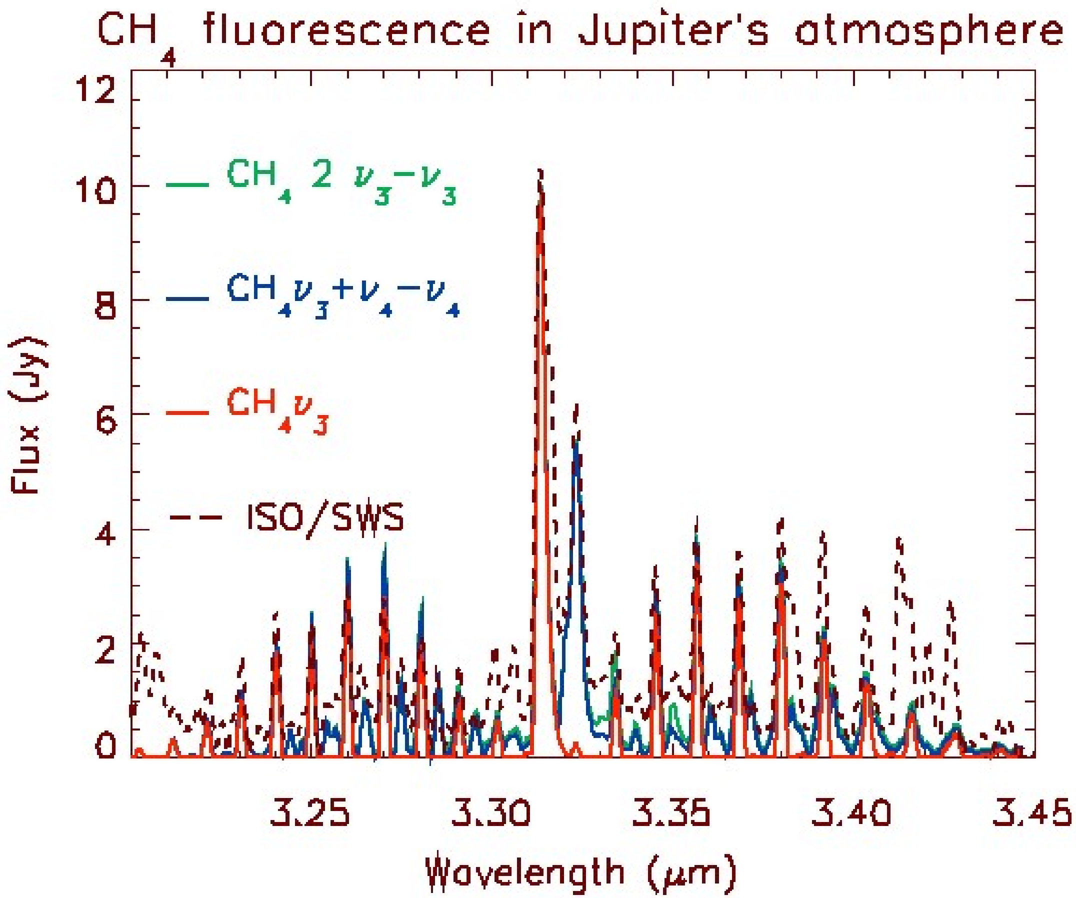


Mid-latitude spectra



Jupiter thermal profile

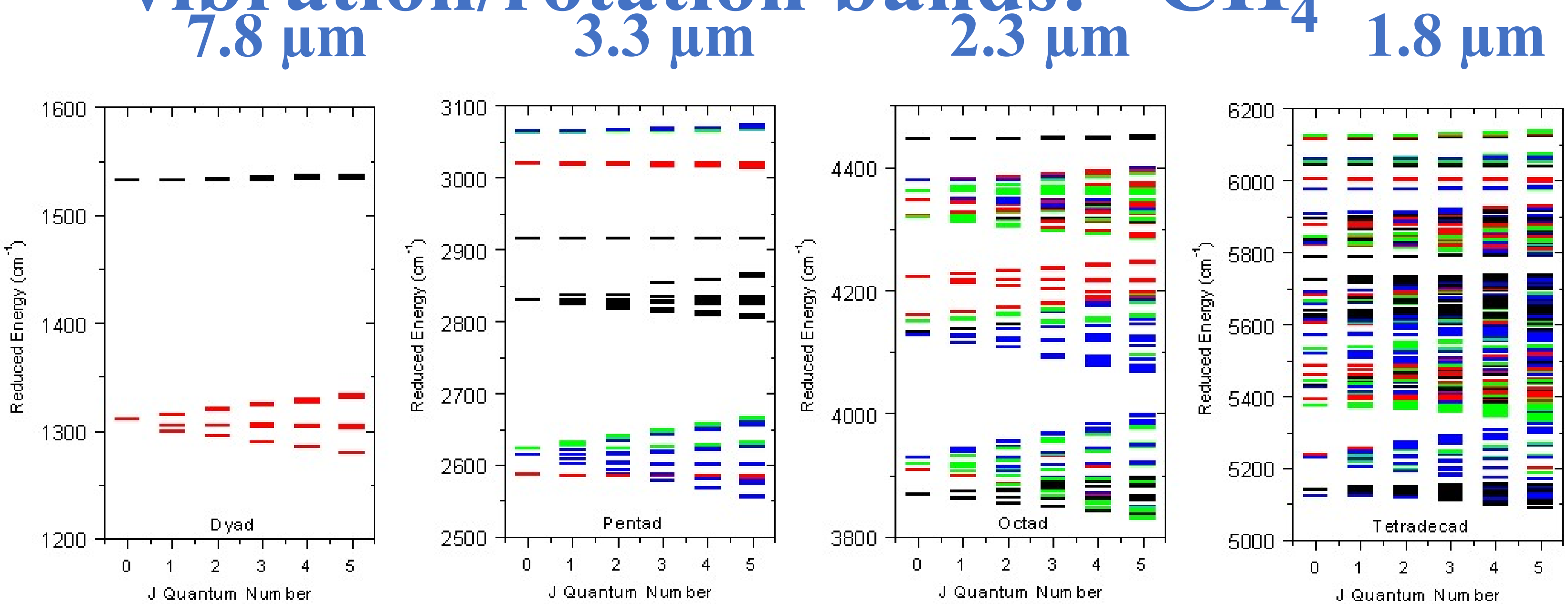




Drossart et al, ESA-SP 427, 1999

Comparison of synthetic spectra with ISO/SWS observations

vibration/rotation bands: CH_4



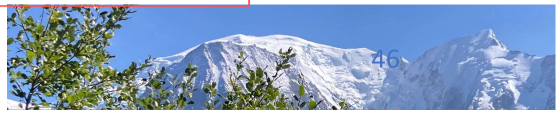
Dyad
2 vibrational states
2 sublevels

Pentad
5 vibrational states
9 sublevels

Octad
8 vibrational states
20 sublevels

Tetradecad
14 vibrational states
60 sublevels

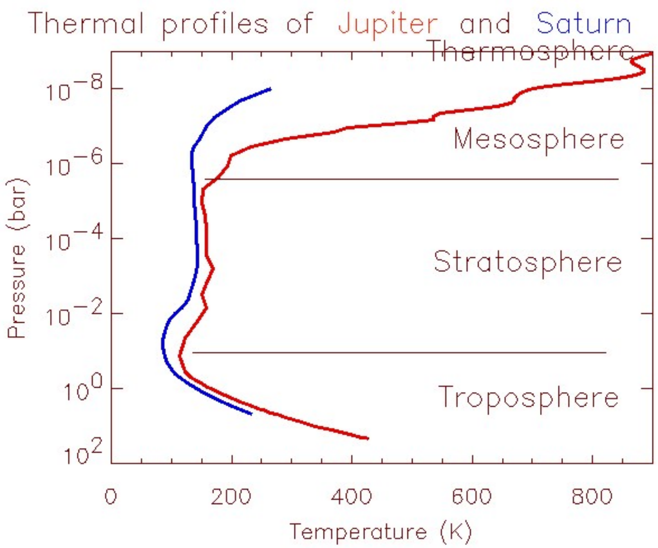
Wenger and Champion, JQSRT, 1998

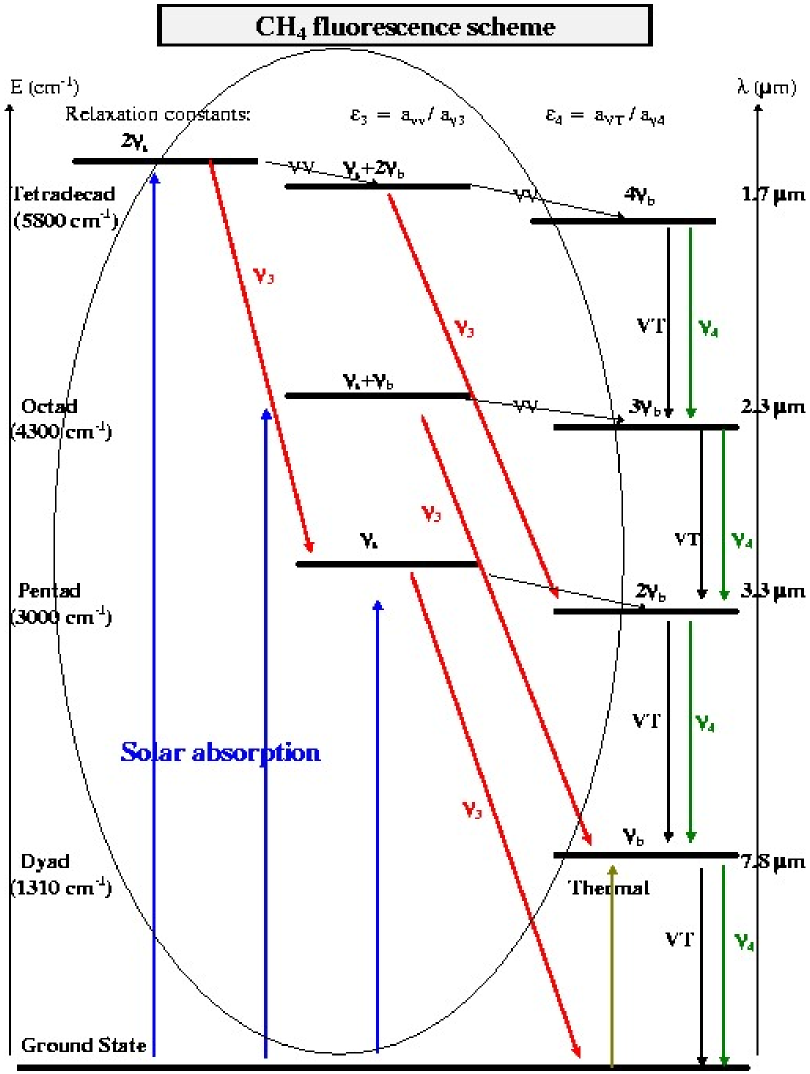


Simplified scheme of fluorescence in CH_4 in planetary atmospheres

- grouping stretching/ bending levels of CH_4
- CH_4 radiative transitions:
- ν_4 (7.8µm) ν_3 (3.3µm)

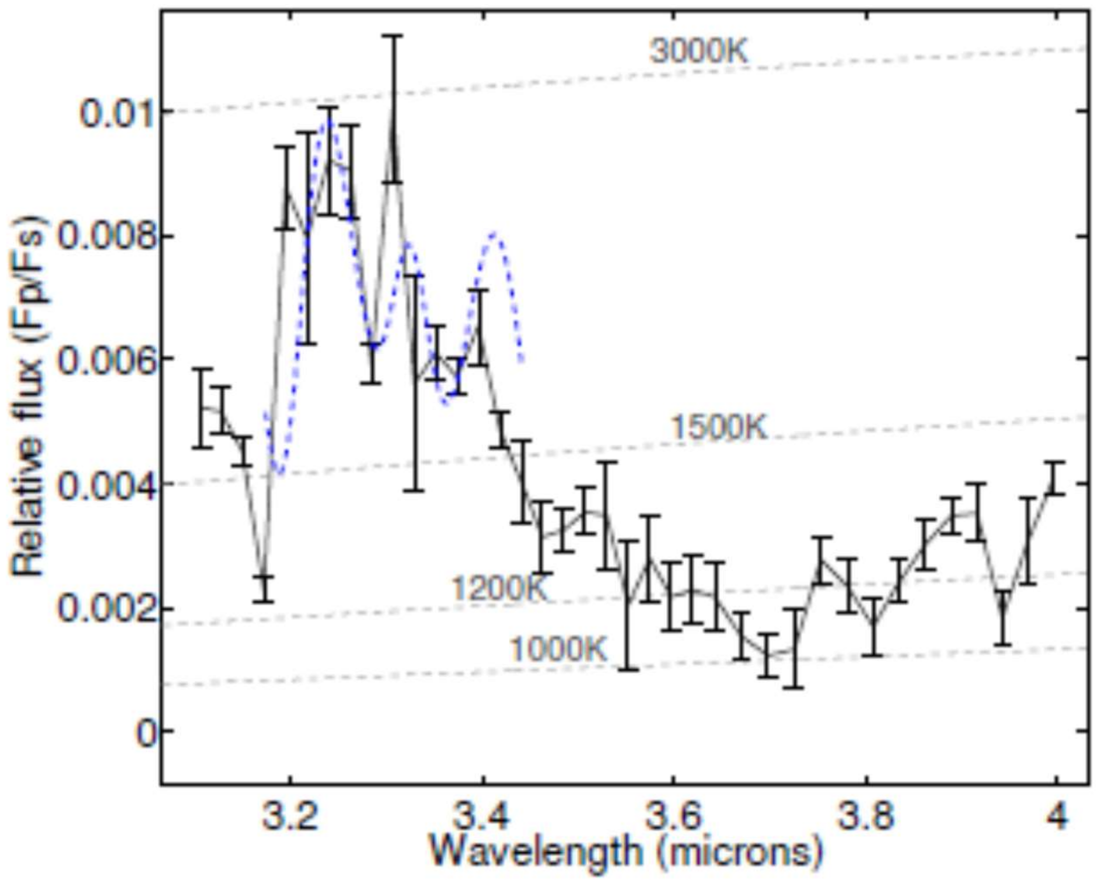
$\nu_3 + \nu_4$ (2.3µm) $\nu_3 + 2\,\nu_4$ (1.7µm)





Fit of HD 189733b in L band

Waldmann et al., ApJ, 2012



Fluorescence scheme

CH_4 vibrational modes : stretching (ν_1 , ν_3) / **bending** (ν_2 , ν_4) **modes with s ~ 2 b**

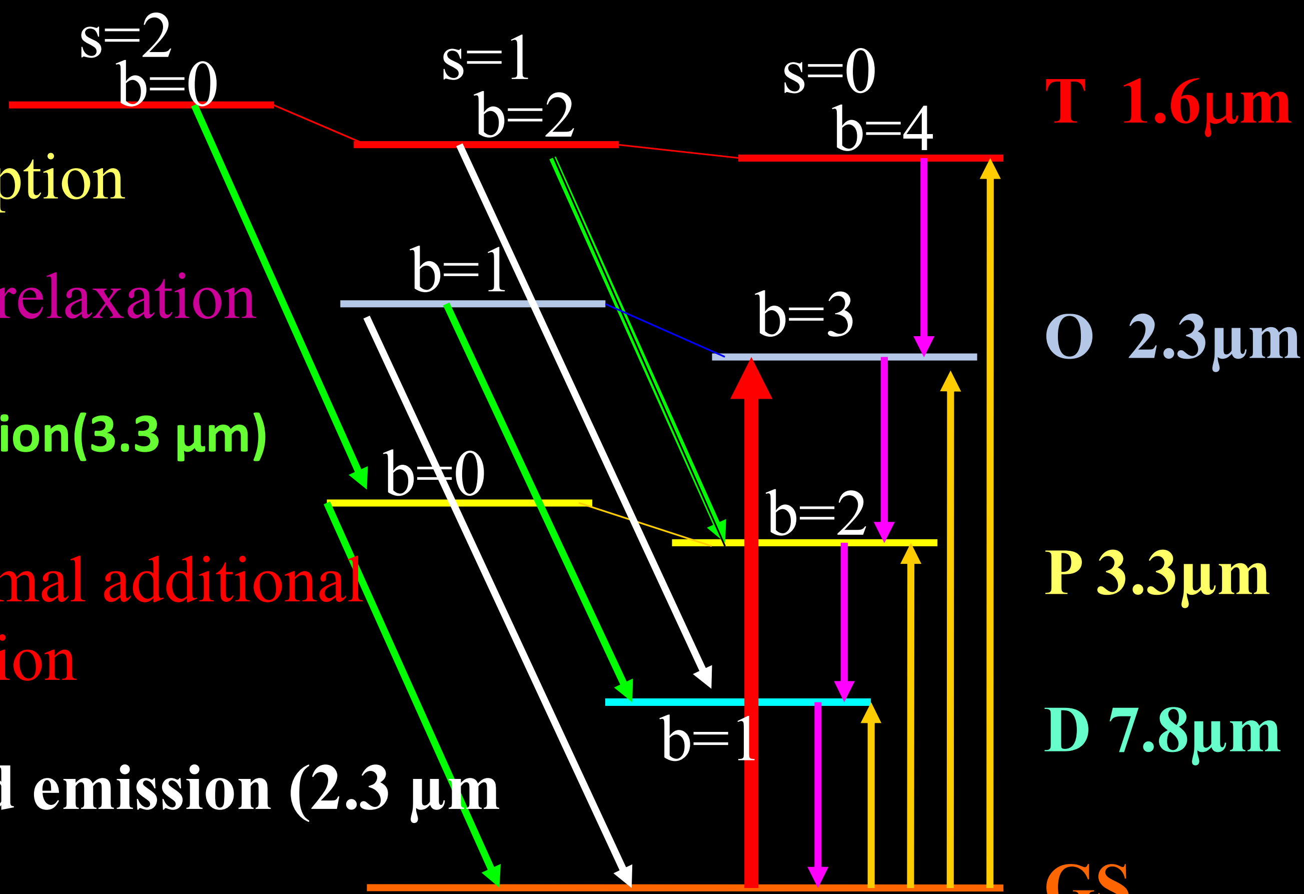
Stellar absorption

Vibrational relaxation

L band emission(3.3 µm)

Suprathermal additional population

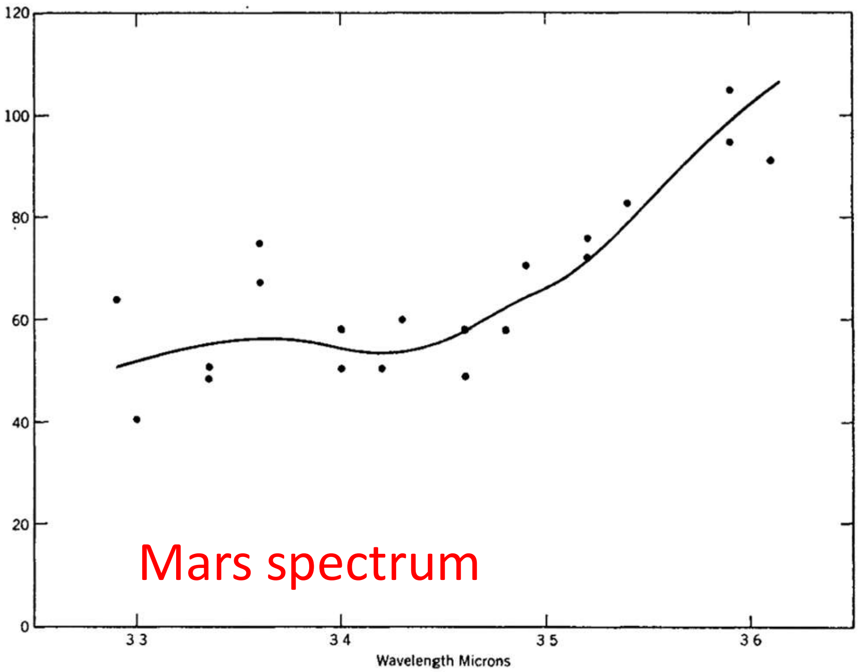
K band emission (2.3 µm

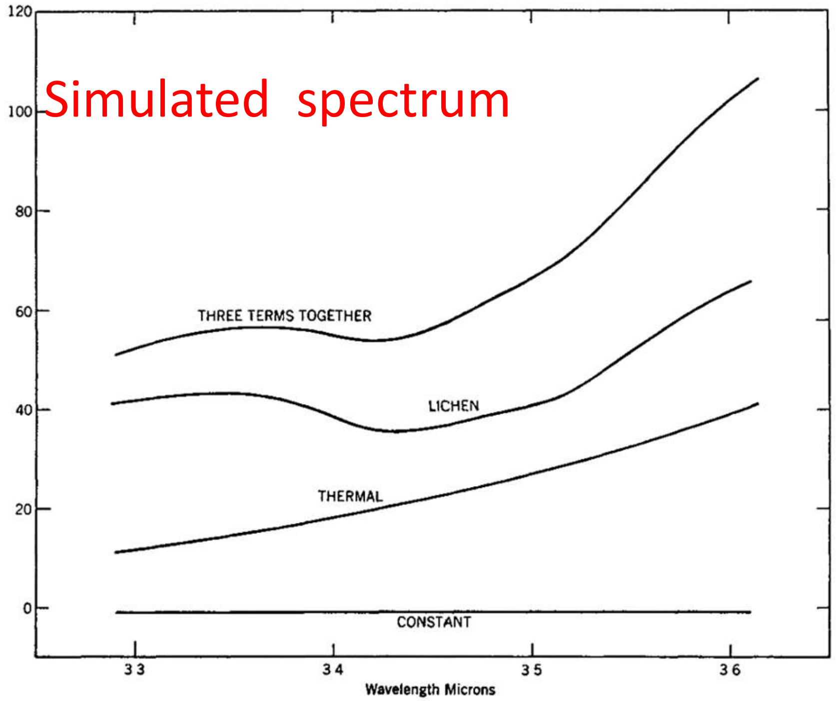


3. A summary of historical errors or difficulties in the navigation through planetary data

A summary of historical errors or difficulties

- Spectroscopic evidence for vegetation on Mars (Sinton, ApJ, 1957)



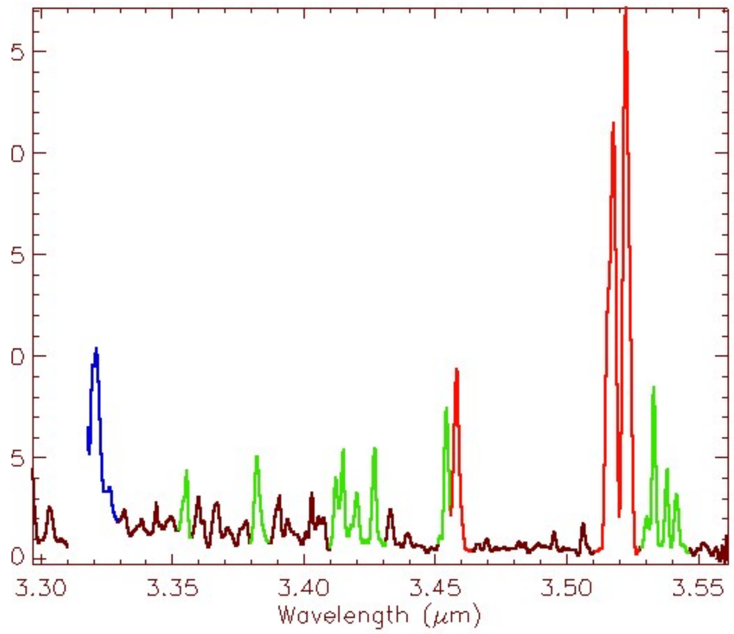


A summary of historical errors or difficulties

- Detection of chlorophylle on Mars (Sinton, 1957)
- Spectral confusion absorption/emission – « doublet » 3.52 micron

Ballester et al. 1994 claiming for unknown emission features

Re interpretation Drossart et al. 1995 as CH_4 features and cloud deck reflection between absorption



A summary of historical errors or difficulties

- Detection of chlorophylle on Mars (Sinton, 1957)
- Spectral confusion absorption/emission – doublet 3.52 micron (Ballester et al. 1994 / interpretation Drossart et al. 1995)
- Methane on Mars : where is the CH_4 ?

A story of CH_4 detections on Mars

- Mars Express/PFS Formisano et al, ground based observations – intermittent detection from orbit 0-30 ppbv

Formisano, Vittorio; Atreya, Sushil; Encrenaz, Thérèse; Ignatiev, Nikolai; Giuranna, Marco Detection of Methane in the Atmosphere of Mars 2004Sci...306.1758F

- Curiosity Chemcam : sporadic detection 5 to 21 ppbv local on Gale crater
- Exomars TGO and ACS : CH_4 less than 0.06 ppbv

Knutsen, Elise W.; Villanueva, Geronimo L.; Liuzzi, Giuliano et al. Comprehensive investigation of Mars methane and organics with ExoMars/NOMAD 2021Icar..35714266

A summary of historical errors or difficulties

- Detection of chlorophylle on Mars (Sinton, 1957)
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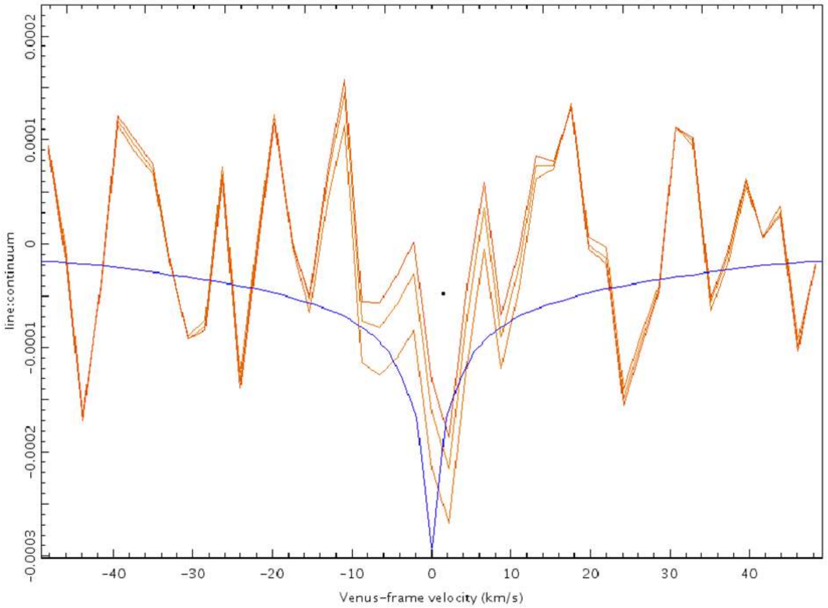
- Methane on Mars : where is the CH_4 ?
- Phosphine on Venus : where is the PH_3 ?

A story of PH_3 detections on Venus

- Greaves, Jane S.; Richards, Anita M. S.; Bains, William et al. Phosphine gas in the cloud decks of Venus 2021NatAs...5..655G
- Trompet, L.; Robert, S.; Mahieux, A. et al. Phosphine in Venus' atmosphere: Detection attempts and upper limits above the cloud top assessed from the SOIR/VE: spectra 2021A&A...645L...4T
- Snellen, I. A. G.; Guzman-Ramirez, L.; Hogerheijde, M. R. et al. Re-analysis of the 267 GHz ALMA observation: of Venus. No statistically significant detection of phosphine
- Encrenaz, T.; Greathouse, T. K.; Marcq, E. et al. A stringent upper limit of the PH3 abundance at the cloud top of Venus 2020A&A...643L...5E



A summary of historical errors or difficulties

- Detection of chlorophylle on Mars (Sinton, 1957)
- Spectral confusion absorption/emission – doublet 3.52 micron (Ballester et al. 1994 / interpretation Drossart et al. 1995)
- Methane on Mars : where is the CH_4 ?
- Phosphine on Venus : where is the PH_3 ?
- Sodium in HD209458 : where is Na ?

A story of Na detection on HD209458b

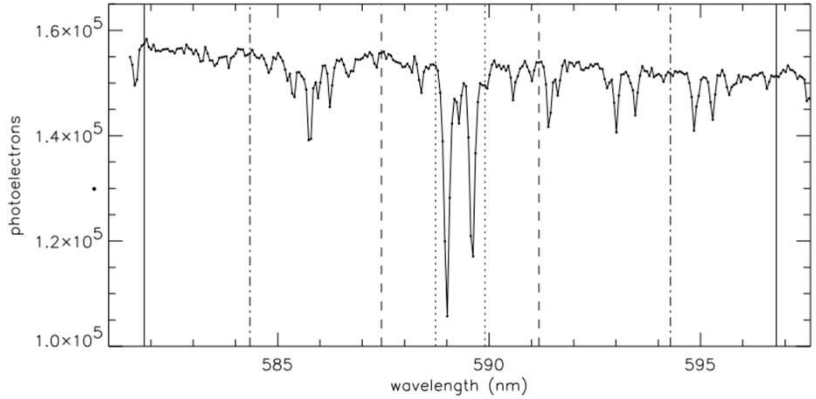


FIG. 1.—Portion of an STIS spectrum of HD 209458, centered on the Na D lines. The vertical axis is the number of detected photoelectrons per

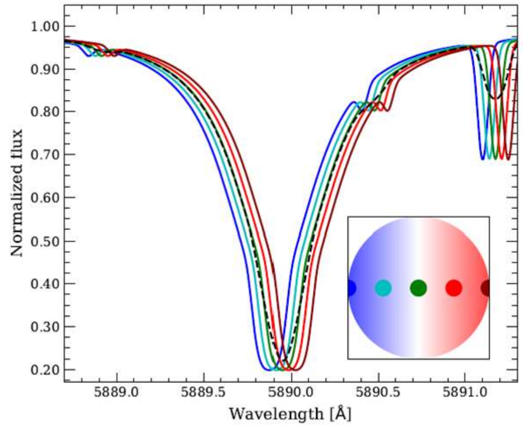


Fig. 3. Modelled stellar spectra around the Na I D2 line of HD 209458 system, containing only the RM effect. The black dashed line shows

- Charbonneau, David; Brown, Timothy M.; Noyes, Robert W.; Gilliland,

Ronald L. *Detection of an Extrasolar Planet Atmosphere* 2002ApJ...568..377C

- Casasayas-Barris, N.; Pallé, E.; Yan, F. et al. *Is there Na I in the atmosphere of HD 209458b?. Effect of the centre-to-limb variation and Rossiter-McLaughlin effect in transmission spectroscopy studies* 2020A&A...635A.206C
- Morello, G.; Casasayas-Barris, N.; Orell-Miquel, J.; Pallé, E.; Cracchiolo, G.; Micela, G. *The strange case of Na I in the atmosphere of HD 209458 b. Reconciling low- and high-resolution spectroscopic observations.* 2022A&A...657A..97M

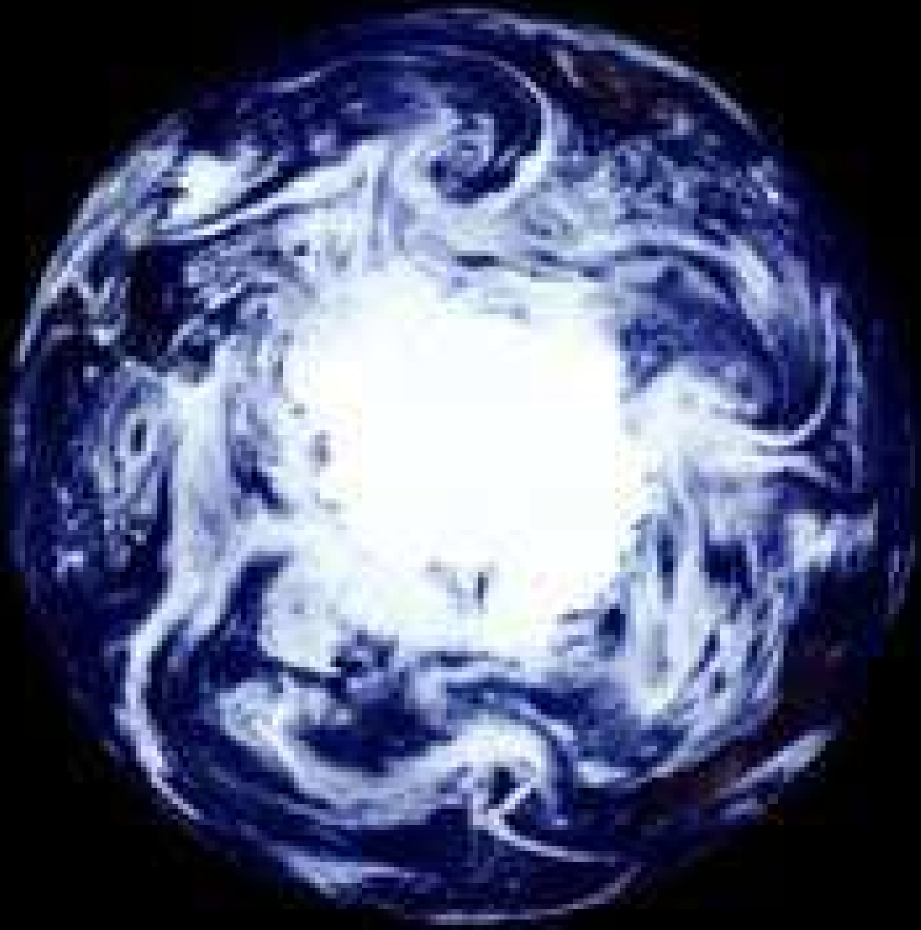
Concluding remark

Thou shouldst be careful before announcing any molecular detection on a planet. Especially if the molecule is of biological interest.

An unusual journey in the Solar System

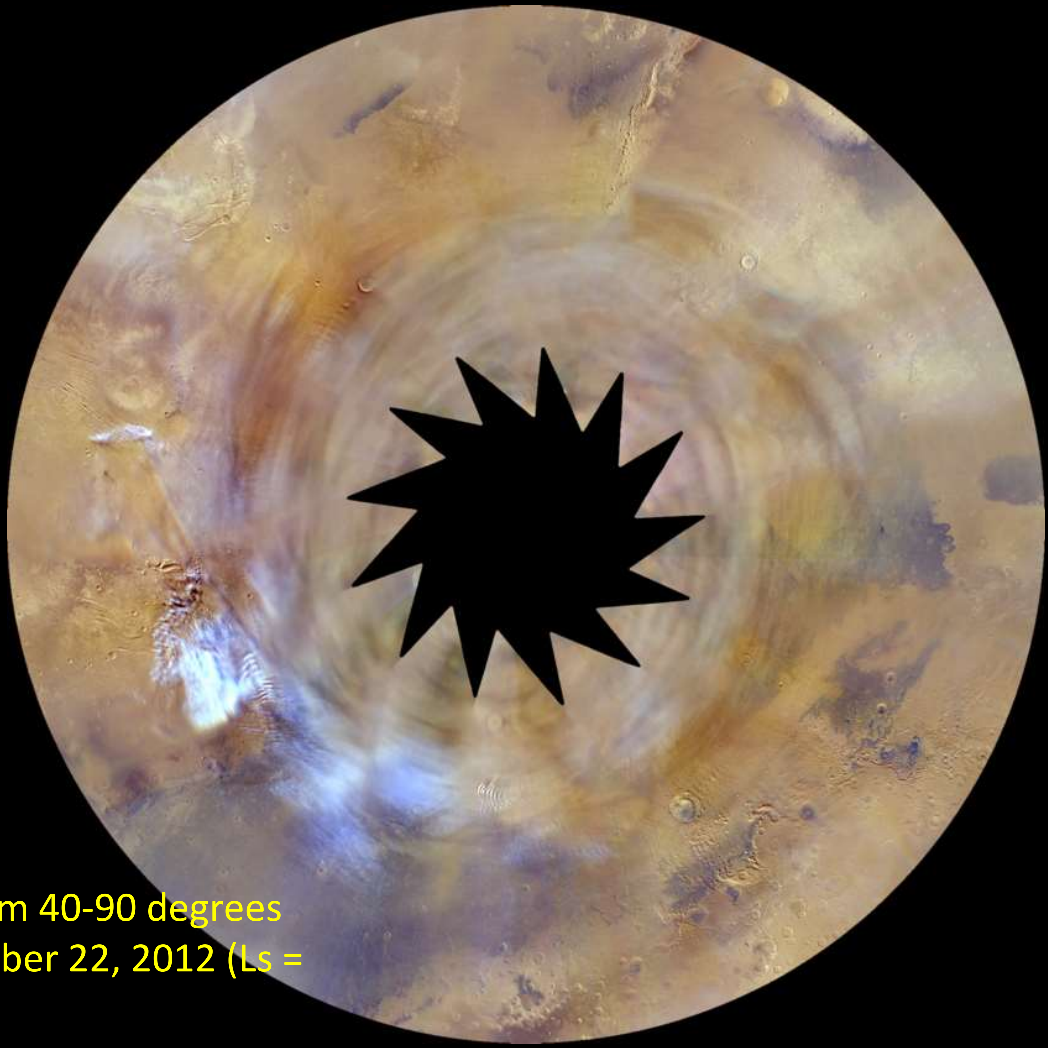
Polar view is difficult to access from Earth telescopes for Solar System planets – not even talking about exoplanets

Polar views were obtained by various missions of exploration and have revealed key parameters in the atmospheric structure and dynamics, of importance not only locally, but even for the global redistribution of energy



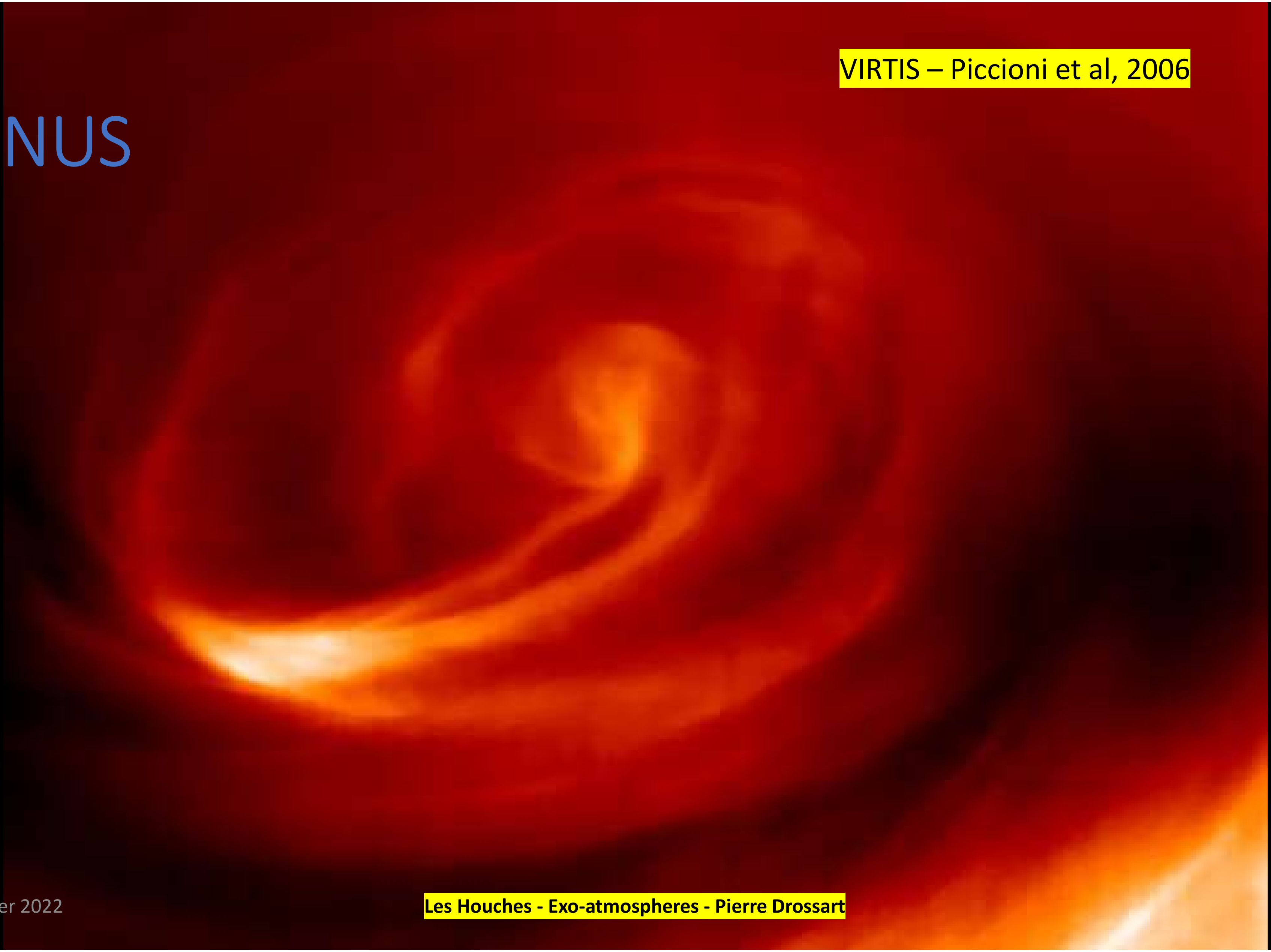
Galileo/SSI – Earth observations 1990

Mars north polar regions



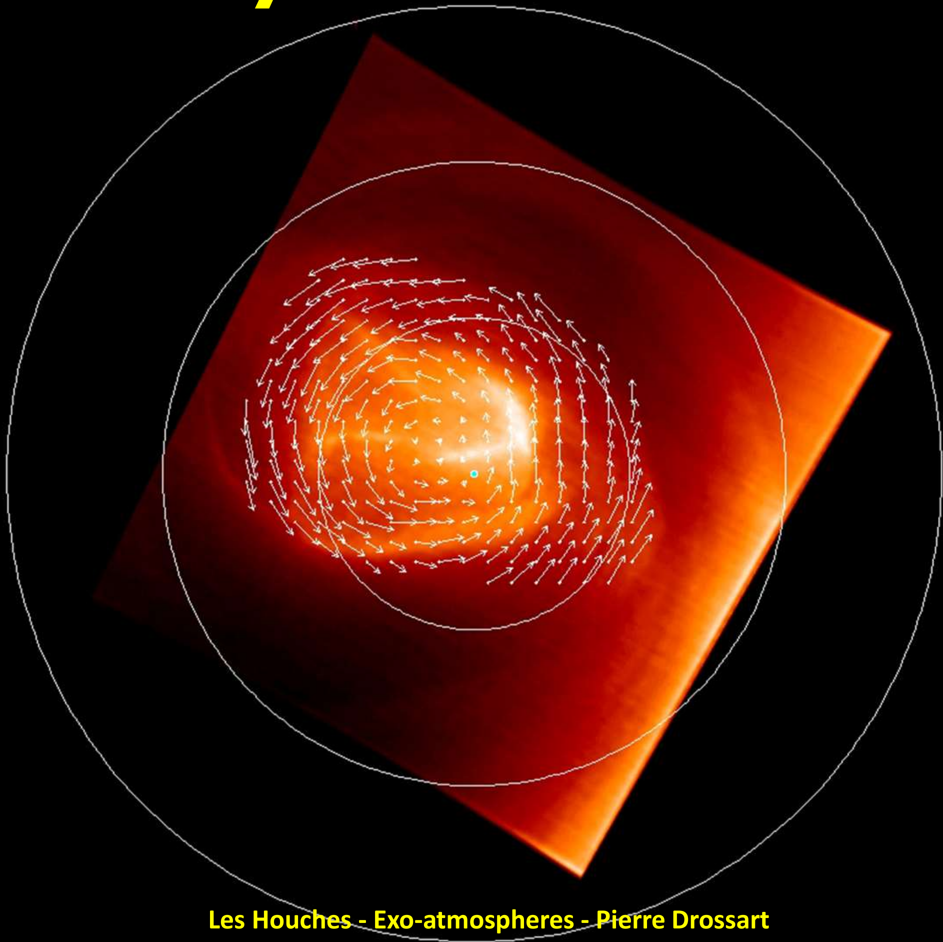
MARCI/MRO color mosaic of the north polar region of Mars from 40-90 degrees North, 0-360 degrees West, generated from data taken on October 22, 2012 (Ls = 192.8), early-autumn in the northern hemisphere.

VENUS

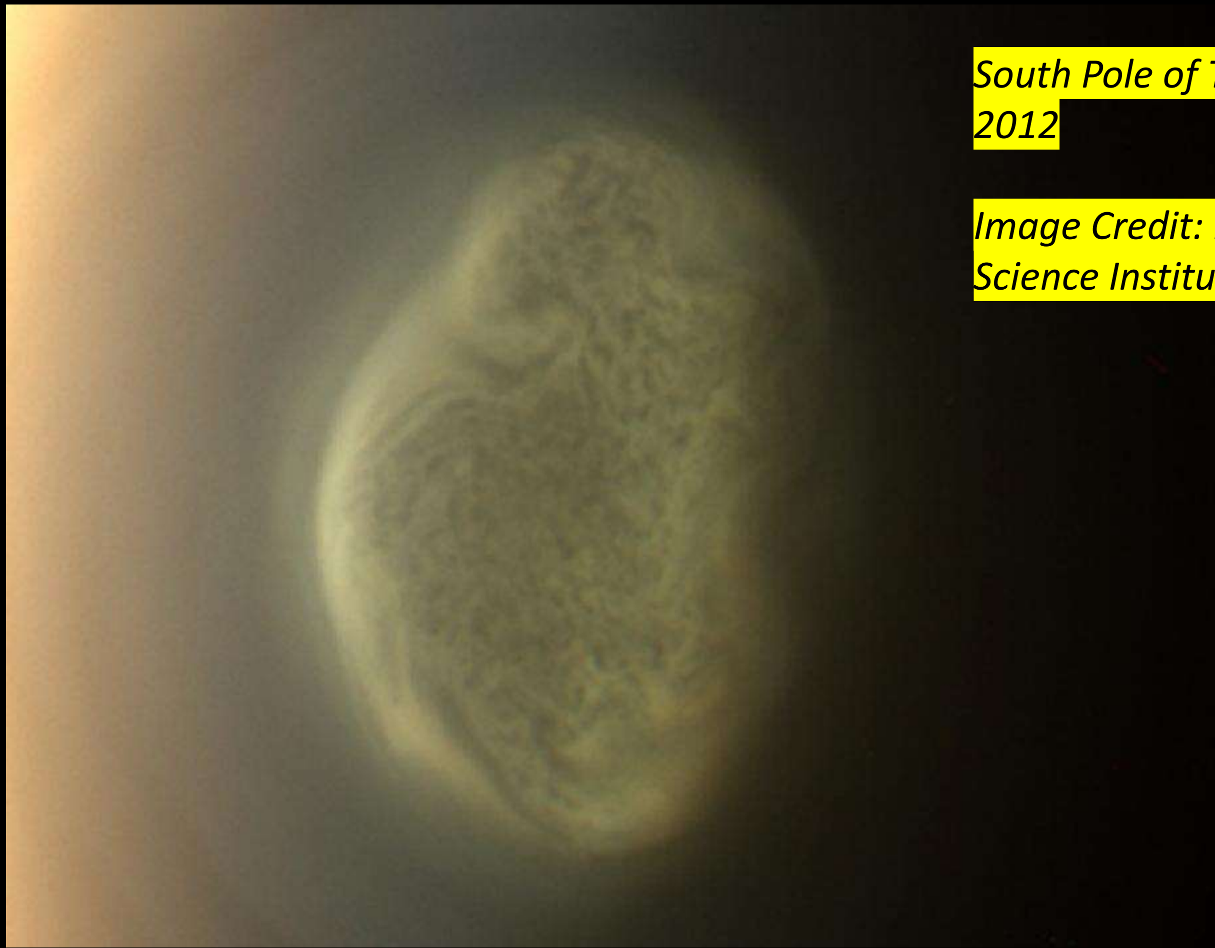


VIRTIS – Piccioni et al, 2006

The rotation of the Venus polar vortex as observed by Venus



A polar vortex on Titan



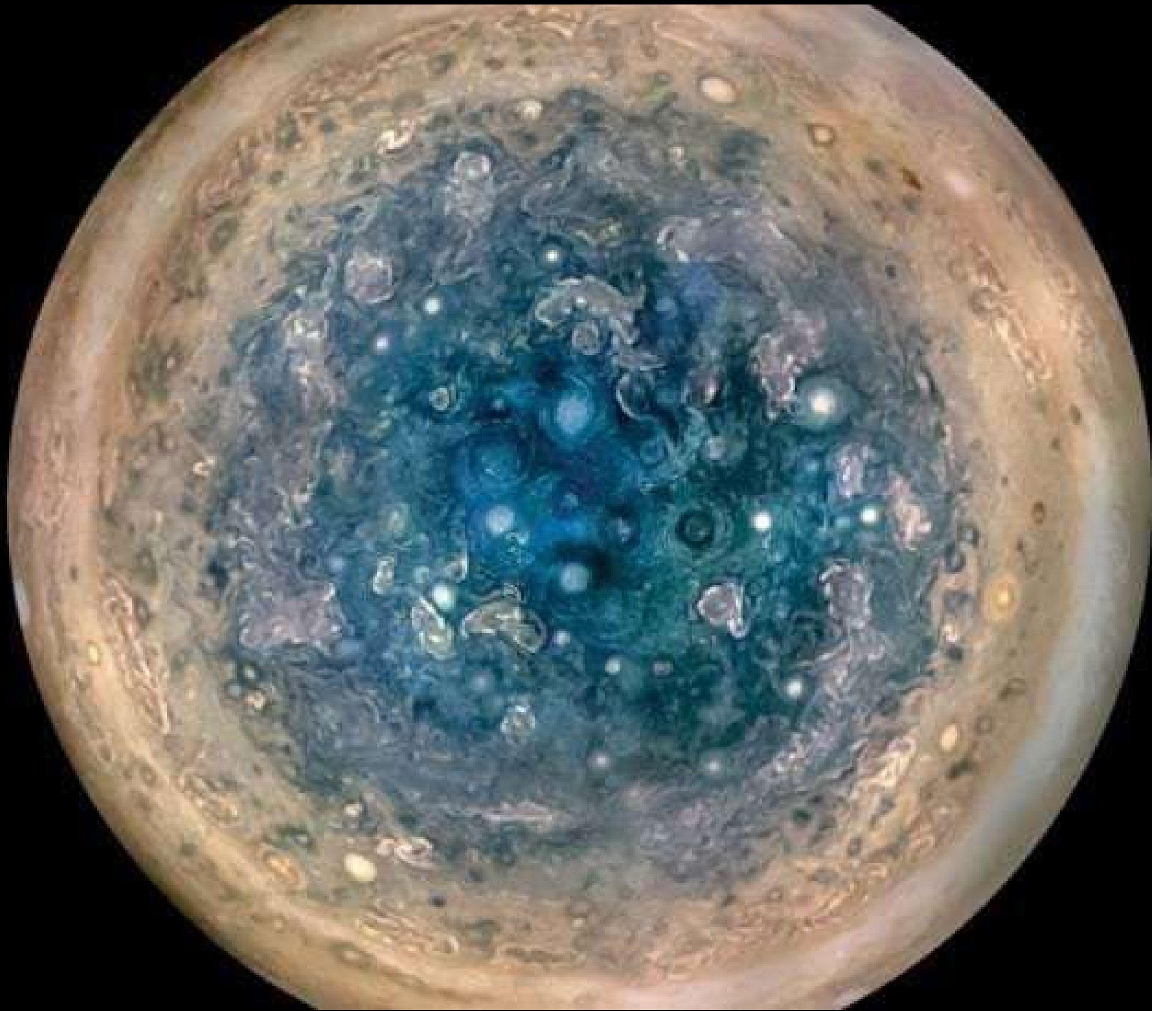
South Pole of Titan, observed by Cassini in 2012

Image Credit: NASA/JPL-Caltech/Space Science Institute

Jupiter

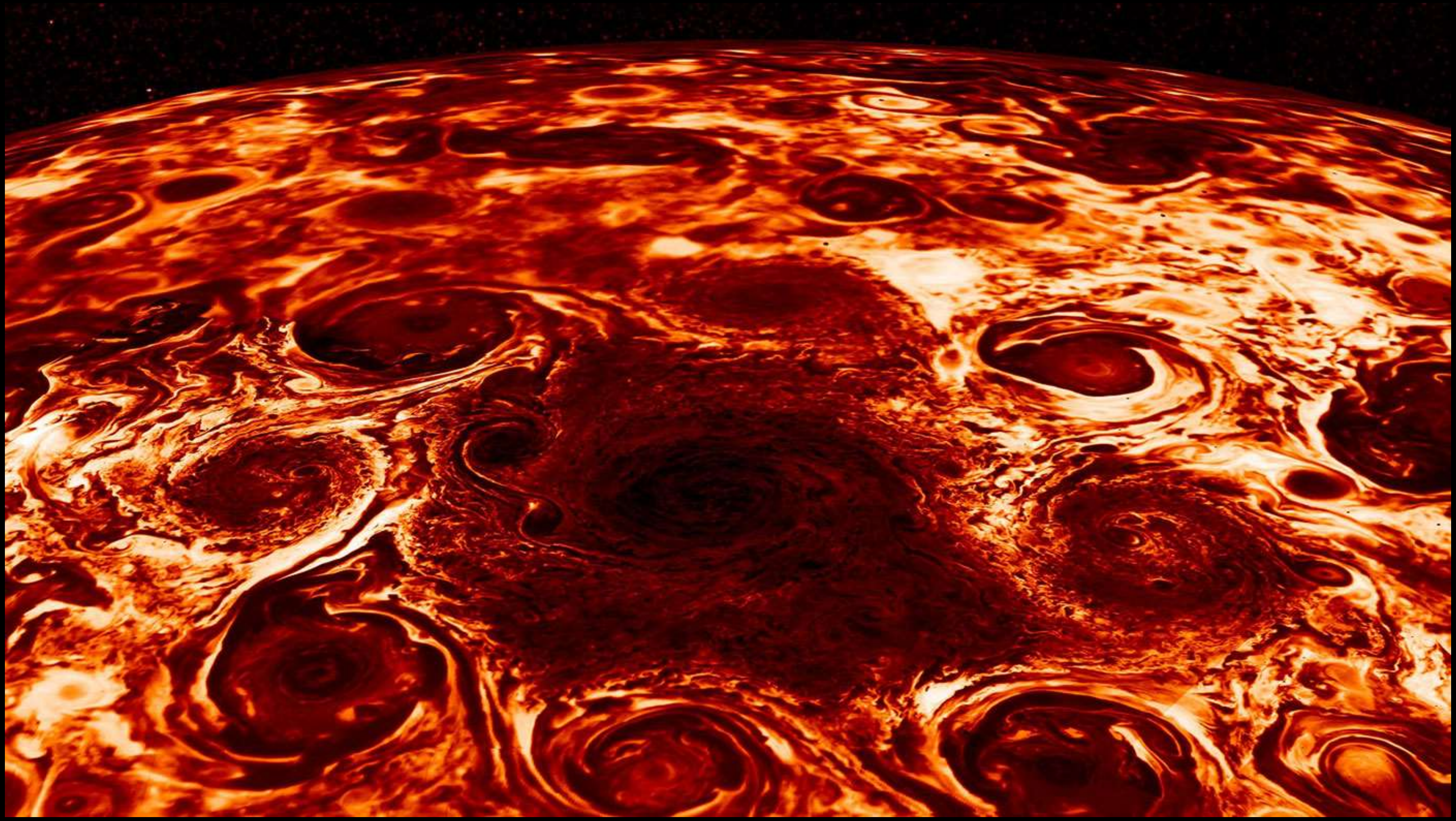
JUNO

NASA/JPL-
Caltech/SwRI/MSSS



JunoCam NASA/ASI - 2017

Jupiter North pole @ 5 micron



Juno/JIRAMNASA/ASI - 2017

This composite image, derived from data collected by the Jovian Infrared Auroral Mapper (JIRAM) instrument aboard NASA's Juno mission to Jupiter, shows the central cyclone at the planet's north pole and the eight cyclones that encircle it.
Credits: NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM

Saturne south pole

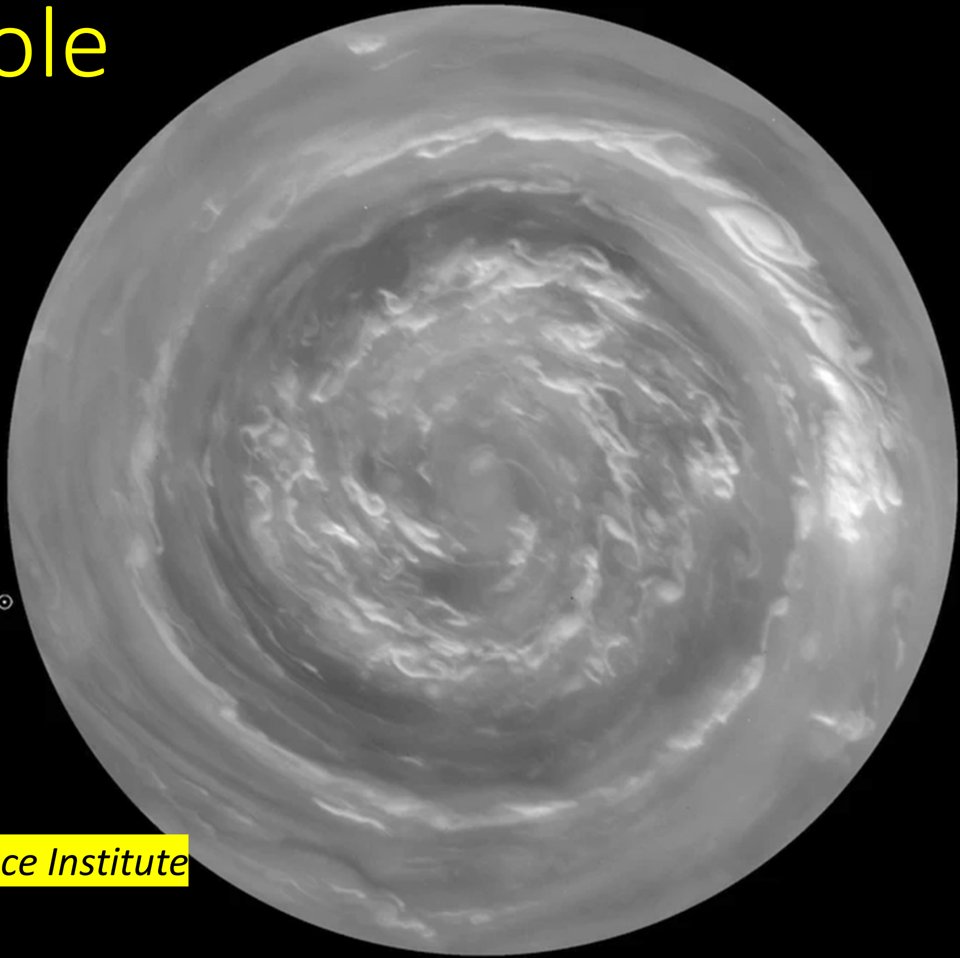
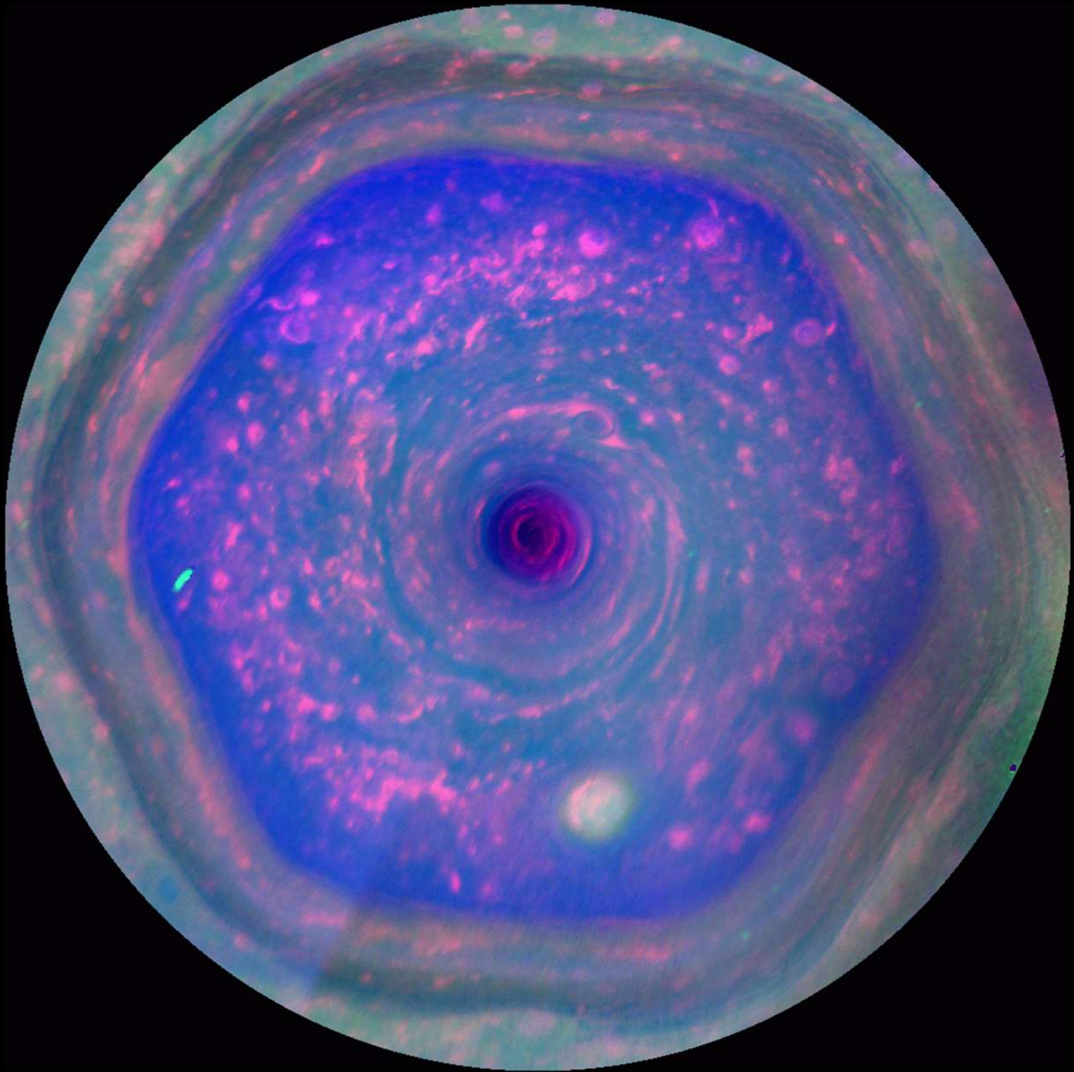


Image Credit: NASA/JPL-Caltech/Space Science Institute

Saturn North pole



Composite image of Saturn North Pole – combination of filters in the visible from SSI camera.

Image Credit: NASA/JPL-Caltech/Space Science Institute

And exoplanets ?

… knowing the polar processes in the Solar System may help to better address the exoplanets simulations