Biarritz S3 : Relations between Solar System and exoplanets

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Plan

1. An itinerary in the Solar System
2. Disequilibrium chemistry
3. Escape phenomena
4. Magnetospheric effects
5. Non-LTE phenomena

Objectives of the course

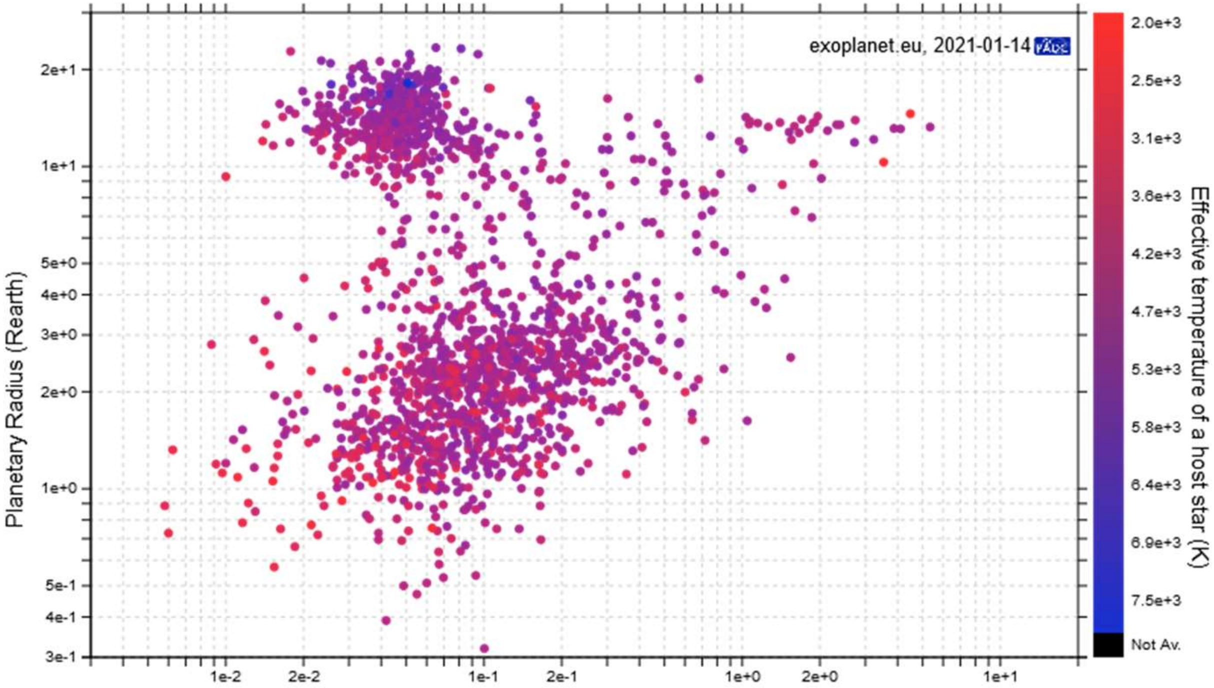
After decades of space exploration, the Solar System objects are today known with high accuracy, to the point that Earth sciences are dominent in the study of planets, more than astronomy !

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

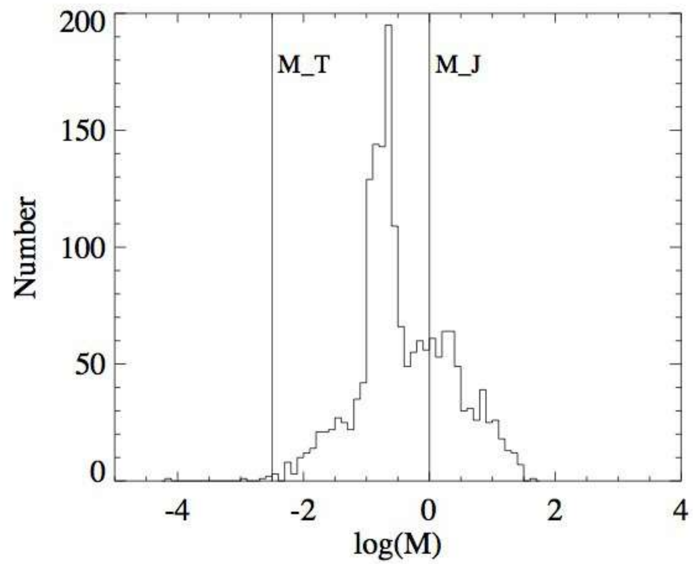
The main objective of the course will also to remember all the errors made in planetology during decades, to try not to repeat them in exoplanets study

Exoplanet demography : current status

Currently 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



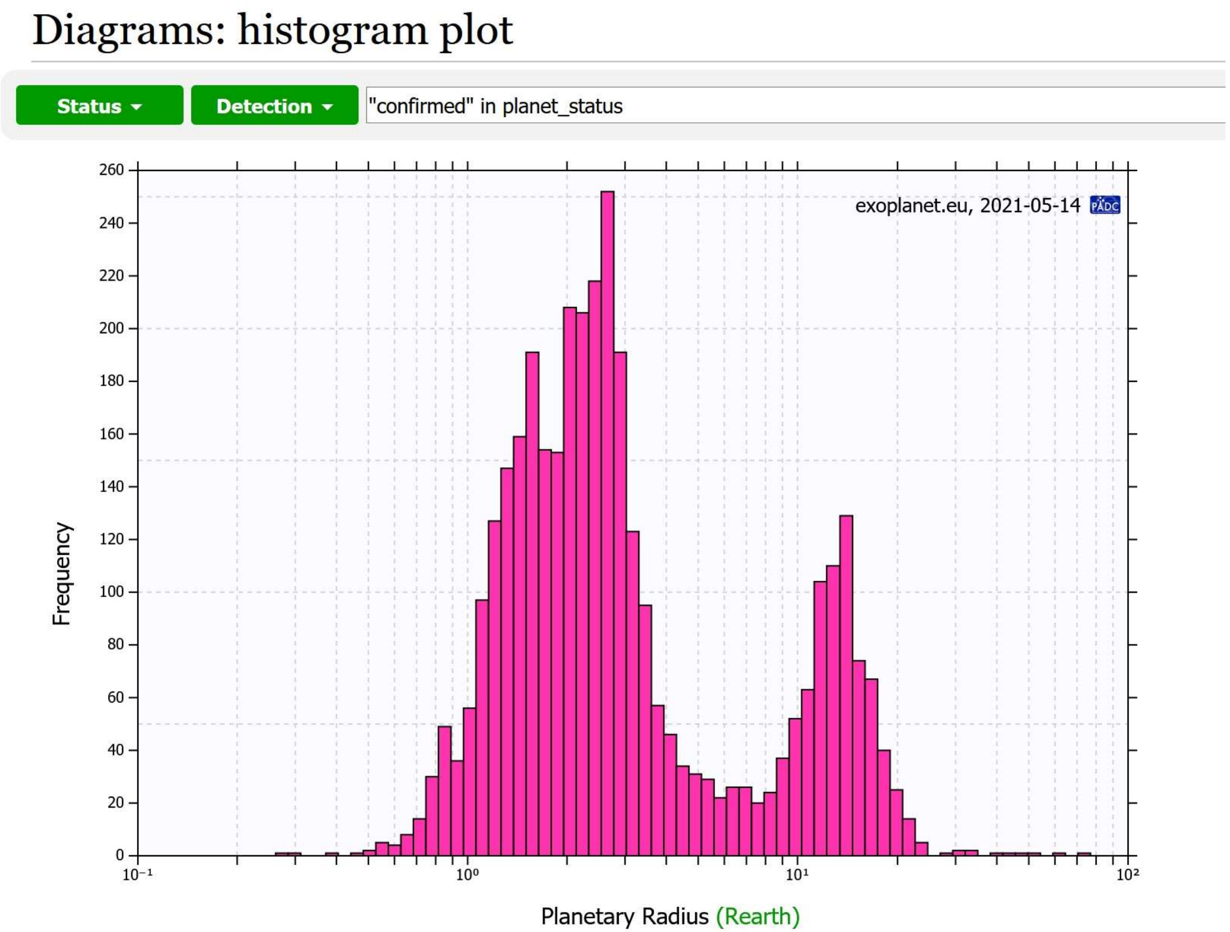
Histogram of exoplanets mass



Exoplanets.eu – 14/1/2021
4404 planets

G. Tinetti, priv. comm.

Histogram of planetary radii



SUPER-EARTHS OR MINI-NEPTUNES ?

Philosophical context

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

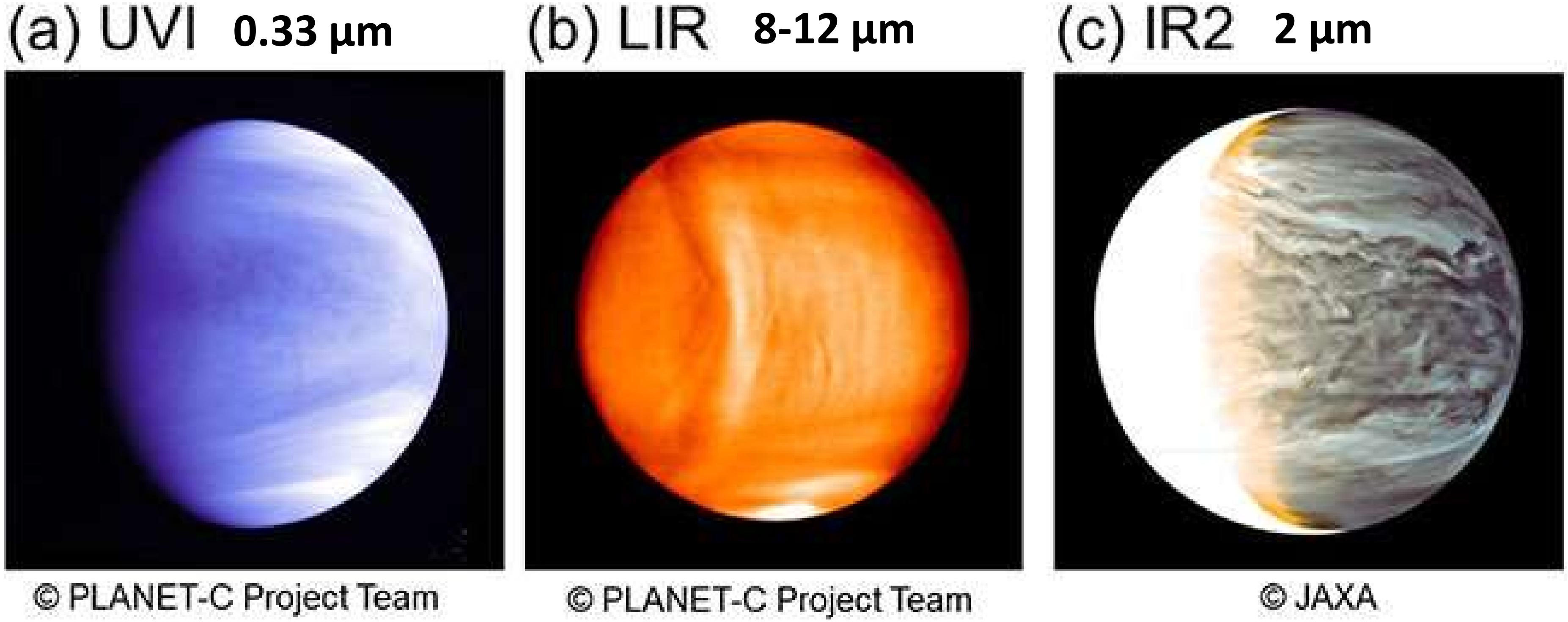
Paradigm : Earth-like planets around Sun-like stars are not the most common planets…

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

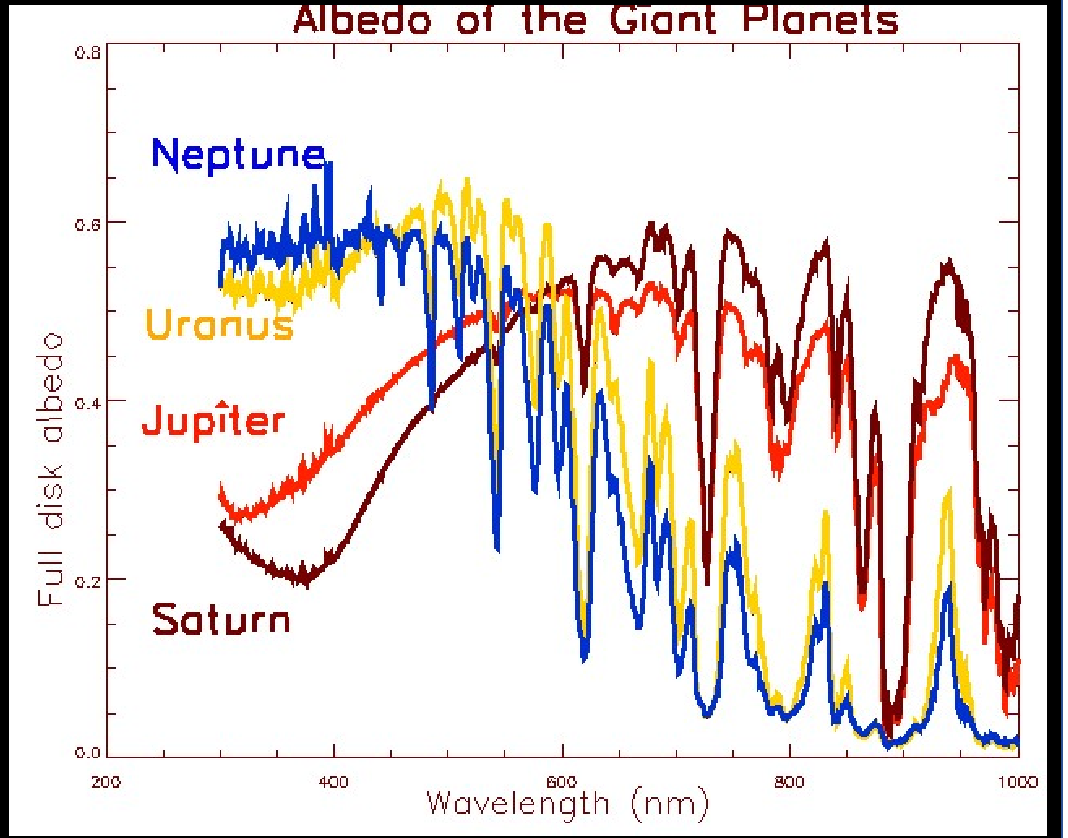
1. Radiative transfer in planetary atmospheres

- Inhomogeneities in surface radiance can produce spatial variations in abundance retrievals
- Homogeneities are observed horizontally (cloud coverage) and vertically (convective effects)



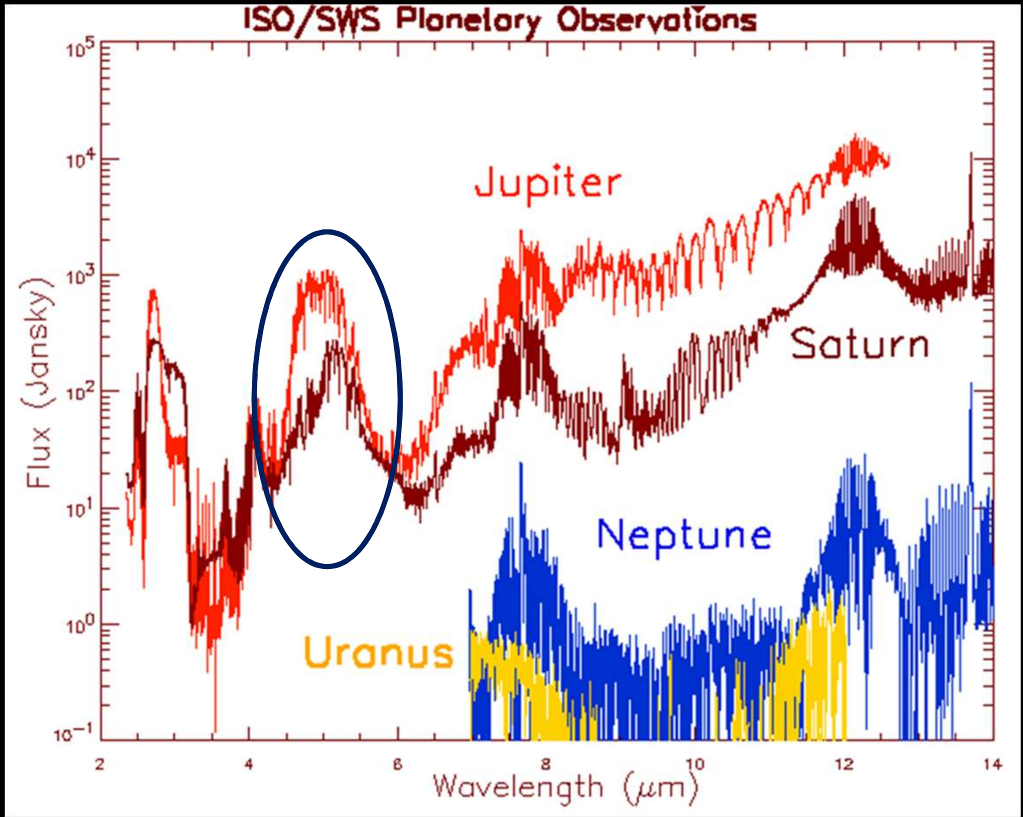
Jupiter

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

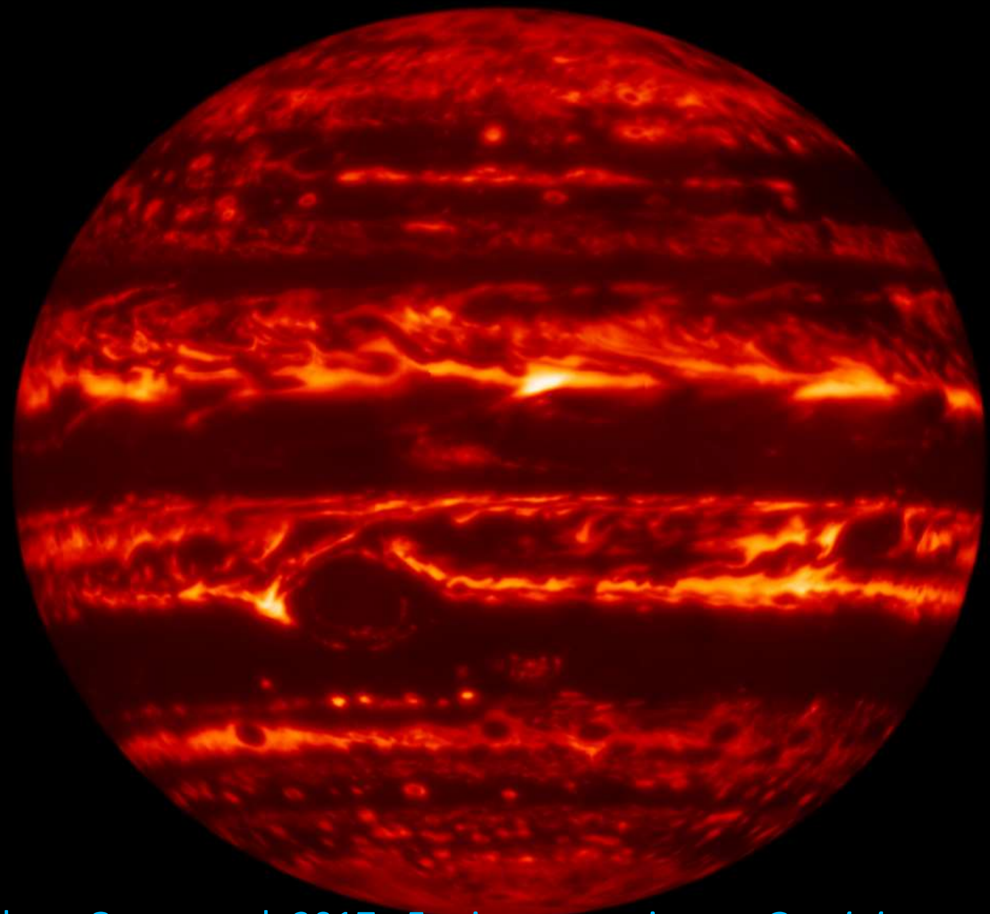


Karkoshka, Icarus, 1996

Jupiter in the infrared



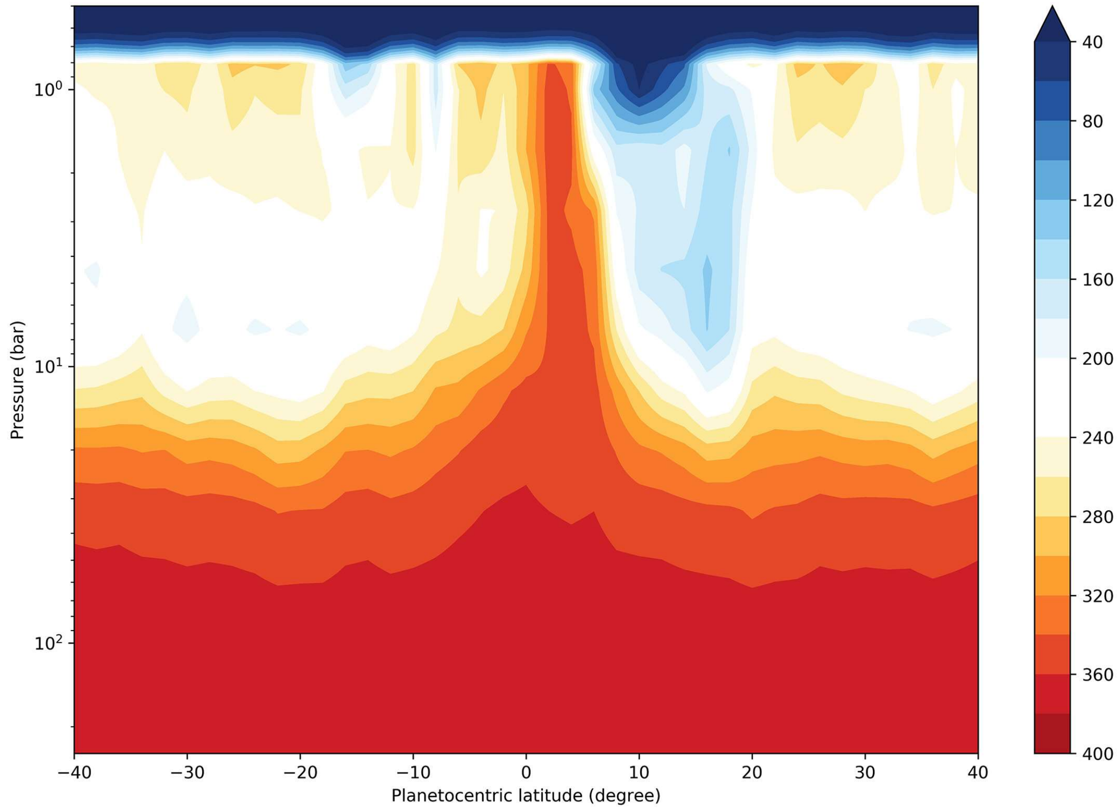
ISO/SWS



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

Storms & ammonia on Jupiter from NASA/Juno

The colored contours show the ammonia concentration in parts per million inverted from nadir brightness temperatures during PJ1 flyby assuming the the deep water abundance is 0.06%. The deep ammonia abundance is 373 ppm and the reference temperature is 132.1 K at 0.5 bar.

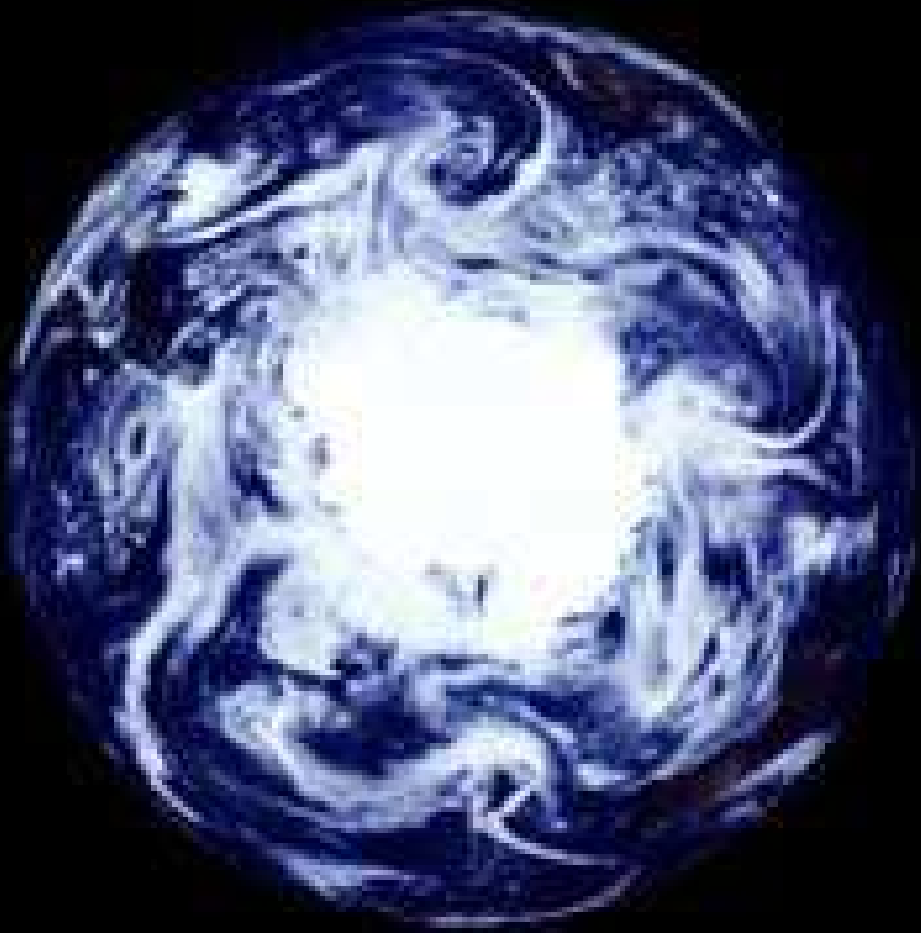


- Cheng Li et al. *The distribution of ammonia on Jupiter from a preliminary inversion of Juno microwave radiometer GRL 2017*

A review of the planets in polar views

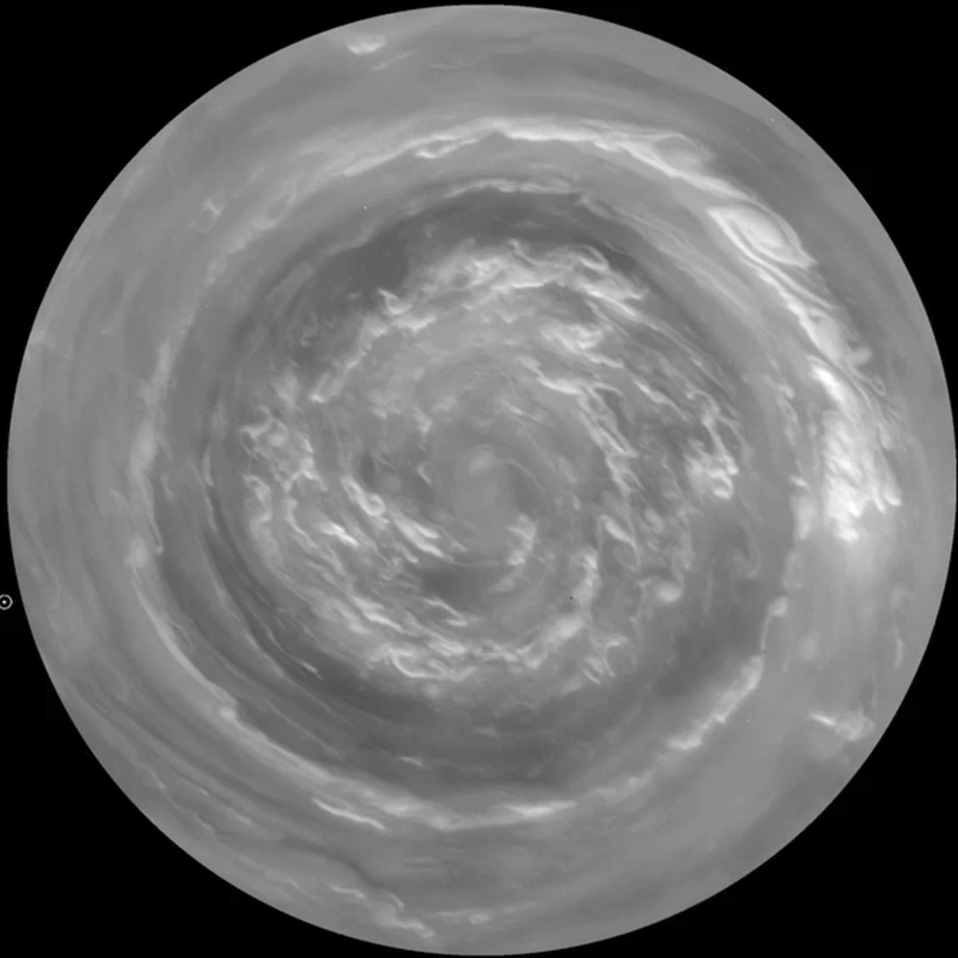
Polar view is difficult to access from Earth telescopes for Solar System planets – not even talking about exoplanets

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

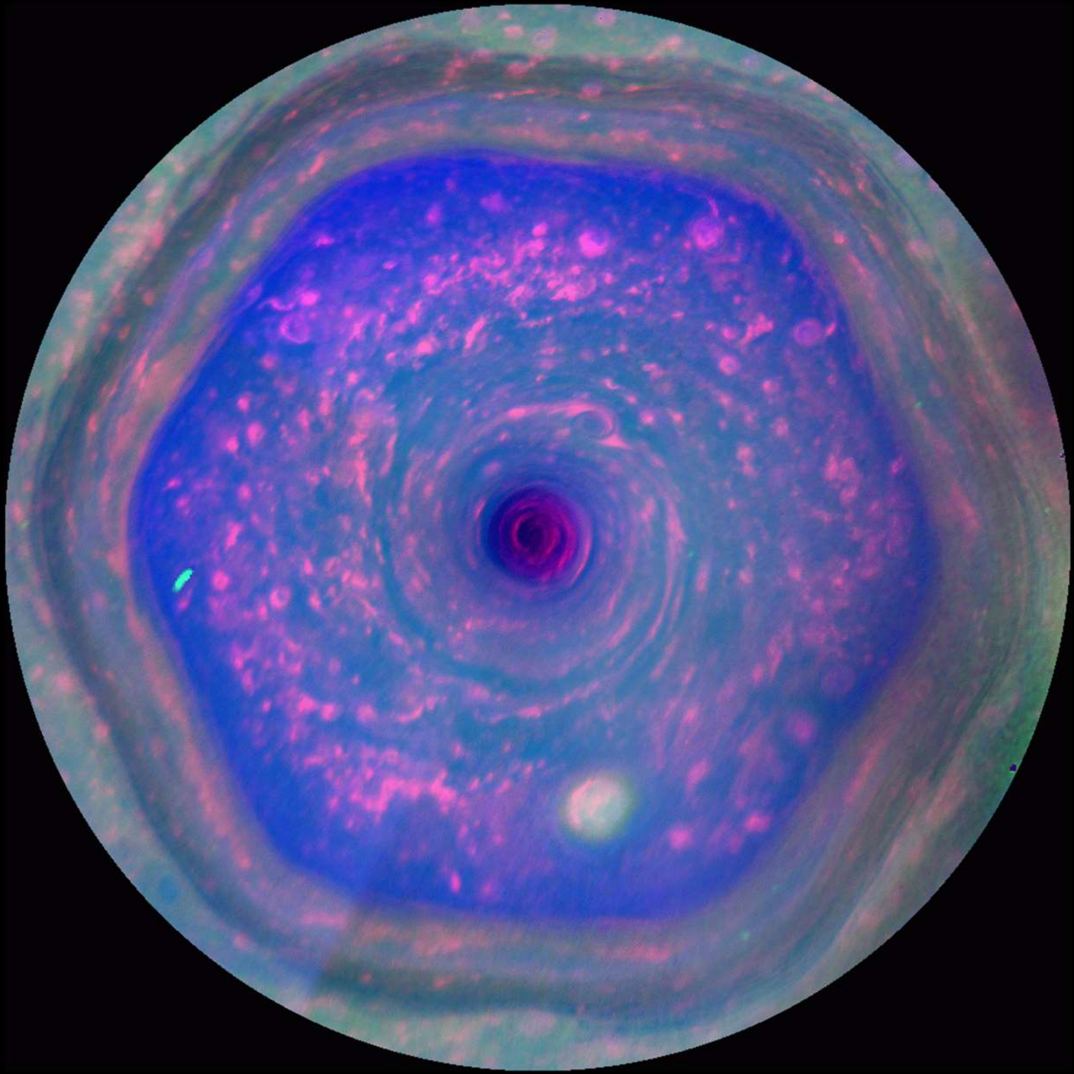


Galileo/SSI – Earth observations 1990

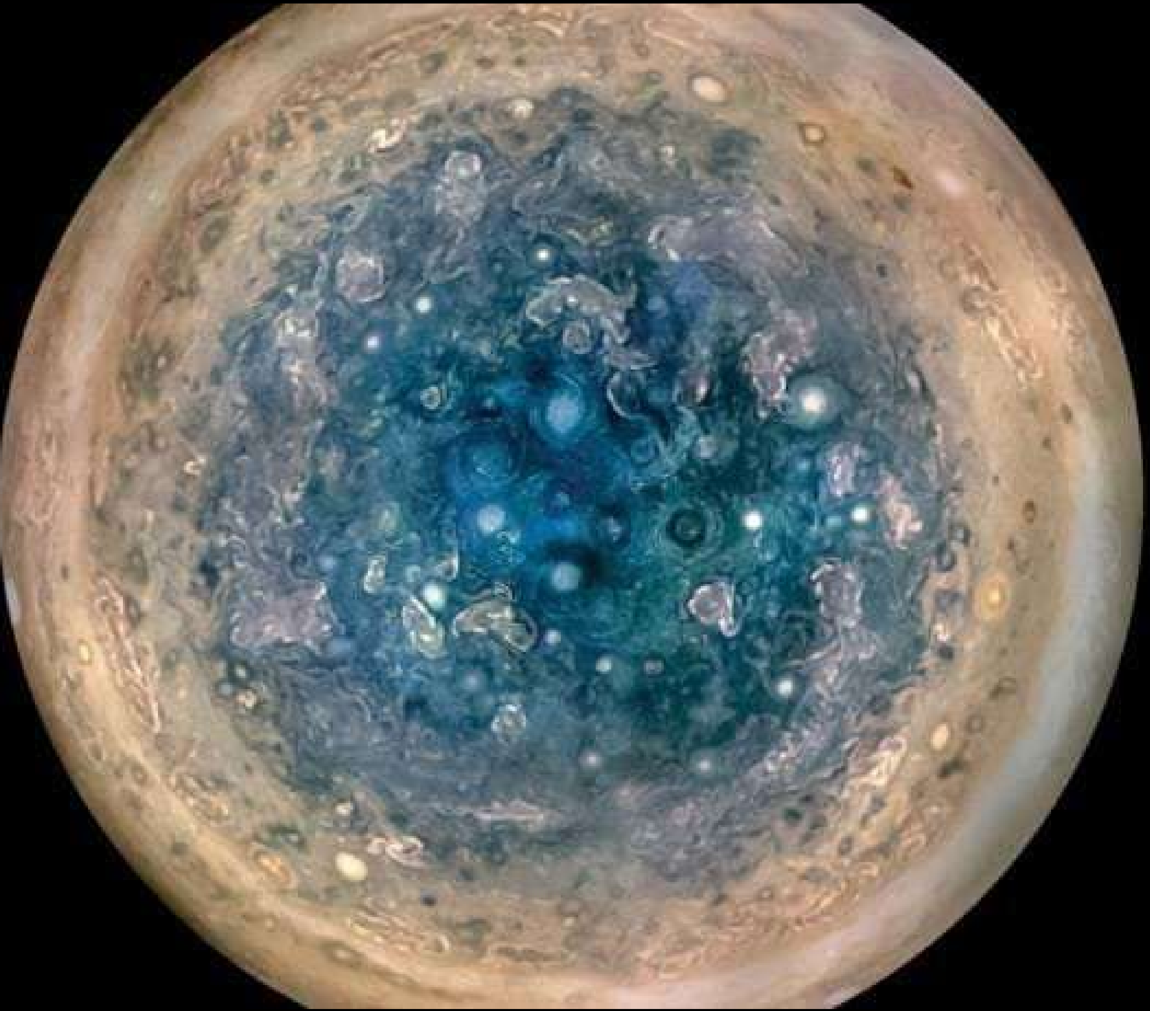
Saturne south pole



Saturn North pole

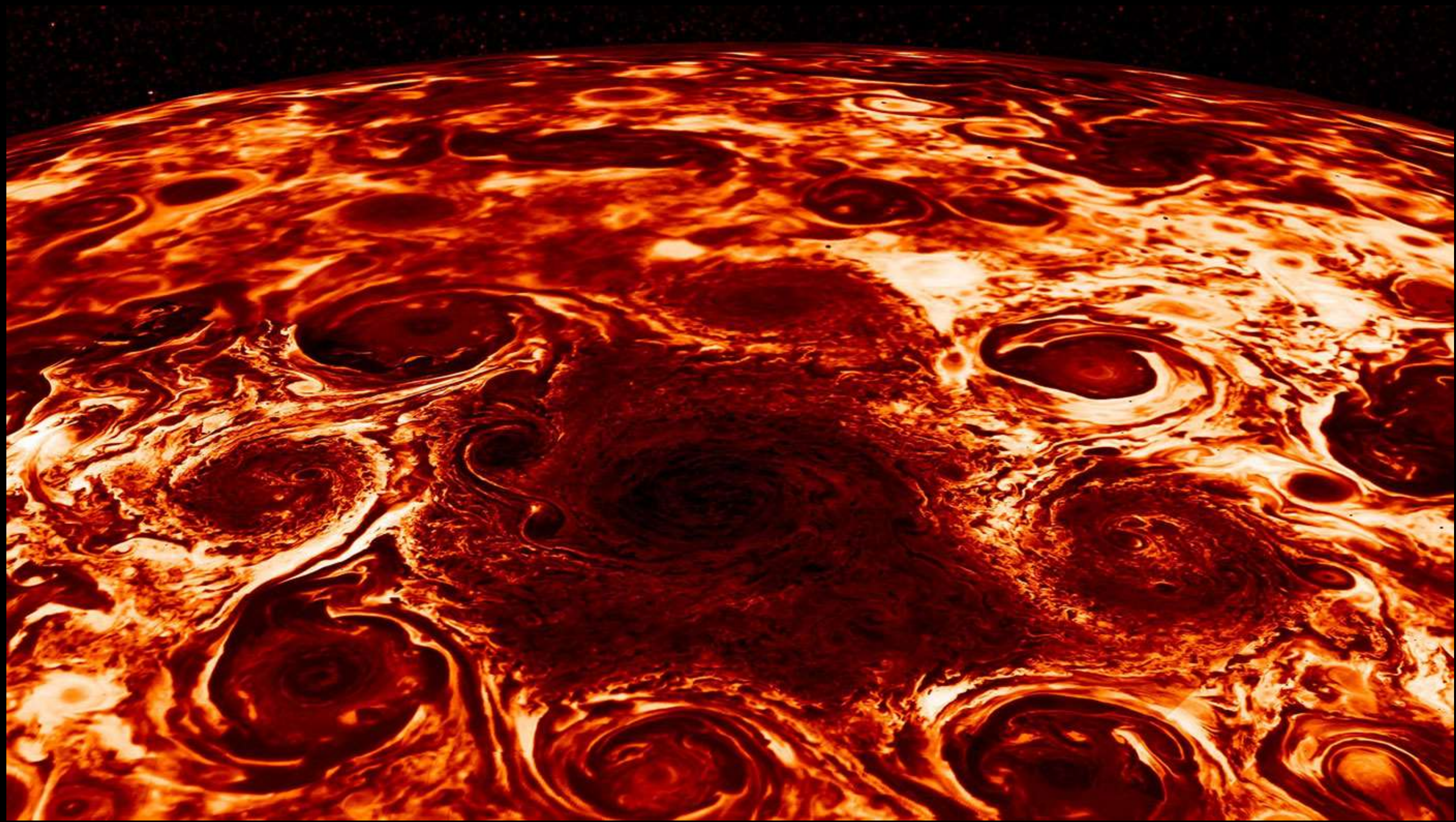


Jupiter



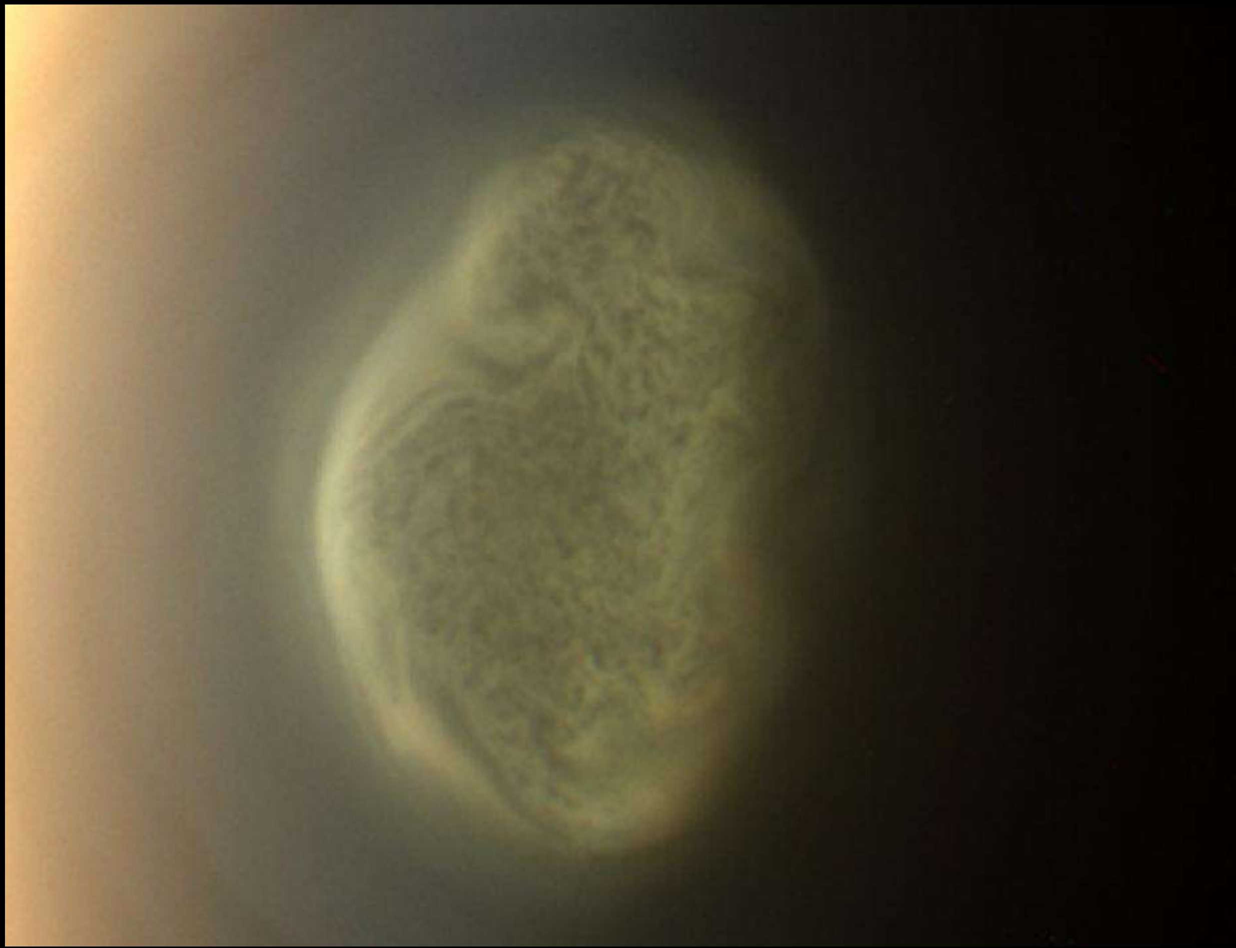
JunoCam NASA/ASI - 2017

Jupiter North pole @ 5 micron

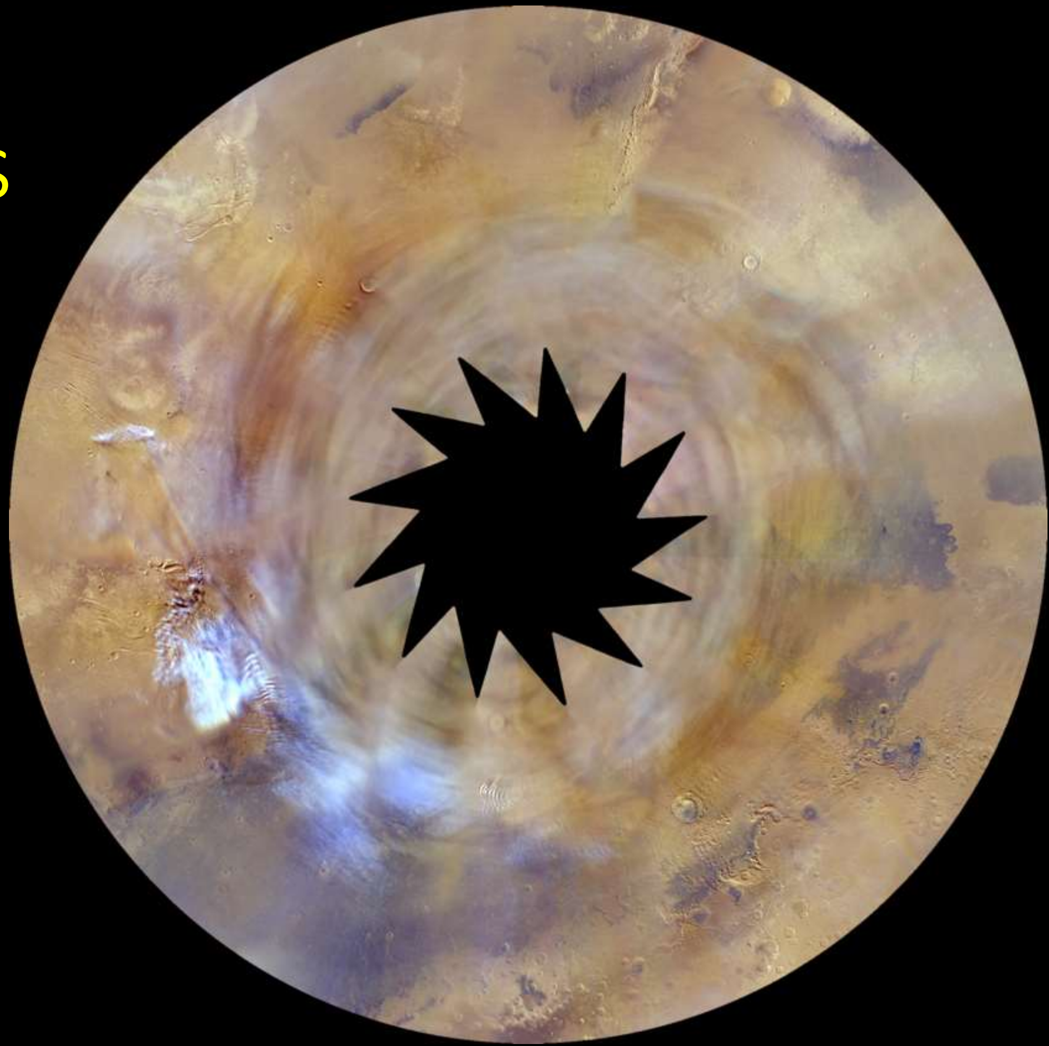


Juno/JIRAMNASA/ASI - 2017

A polar vortex on Titan

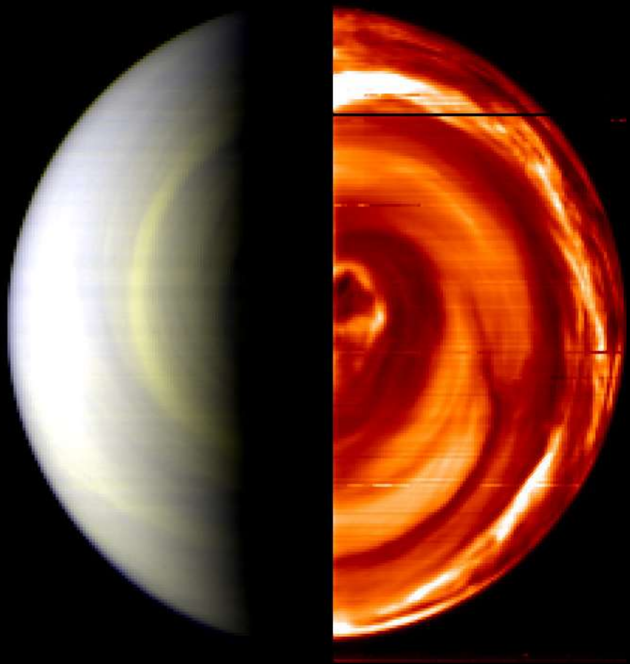


Mars north polar regions

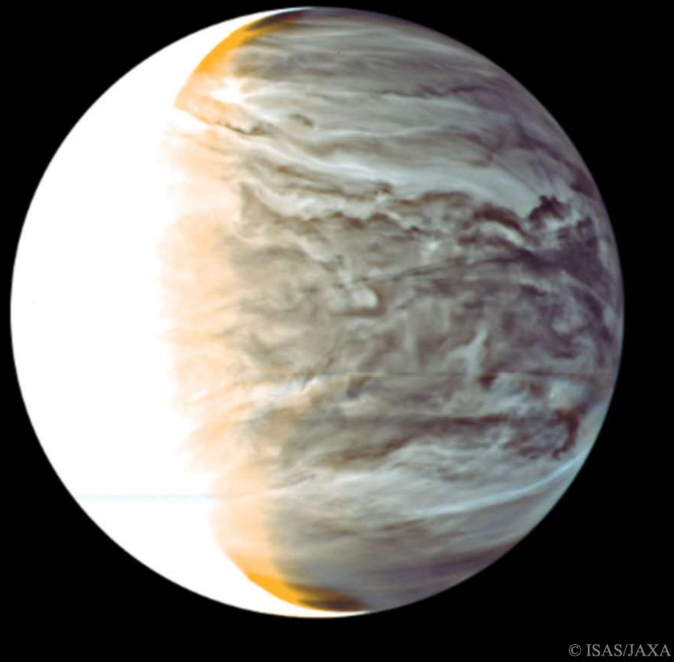


MARCI/MRO color mosaic of the north polar region of Mars from 40-90 degrees North, 0-360 degrees West, generated from data taken on October 22, 2012 (Ls = 192.8), early-autumn in the northern hemisphere.

Venus missions : Venus Express (ESA, 2005), Akasuki (JAXA, 2010)

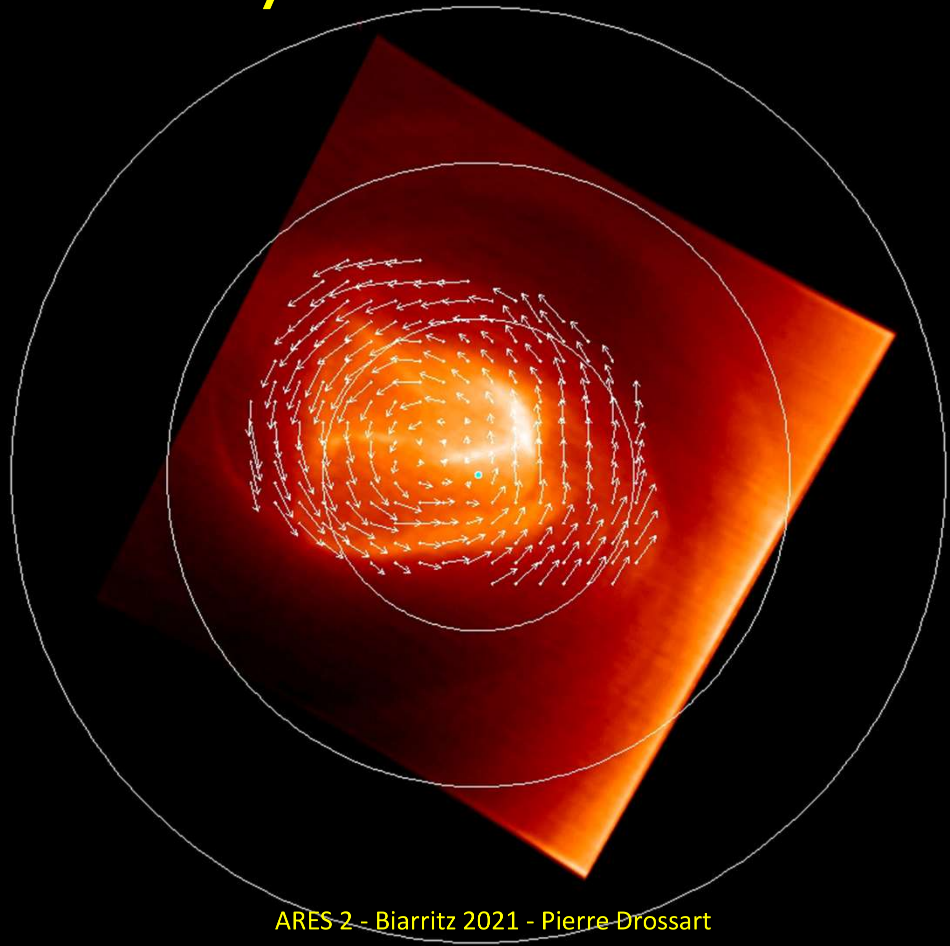


Venus Express/VIRTIS 2.3 micron / visible



Akatsuki, IR2 camera 2.3 micron

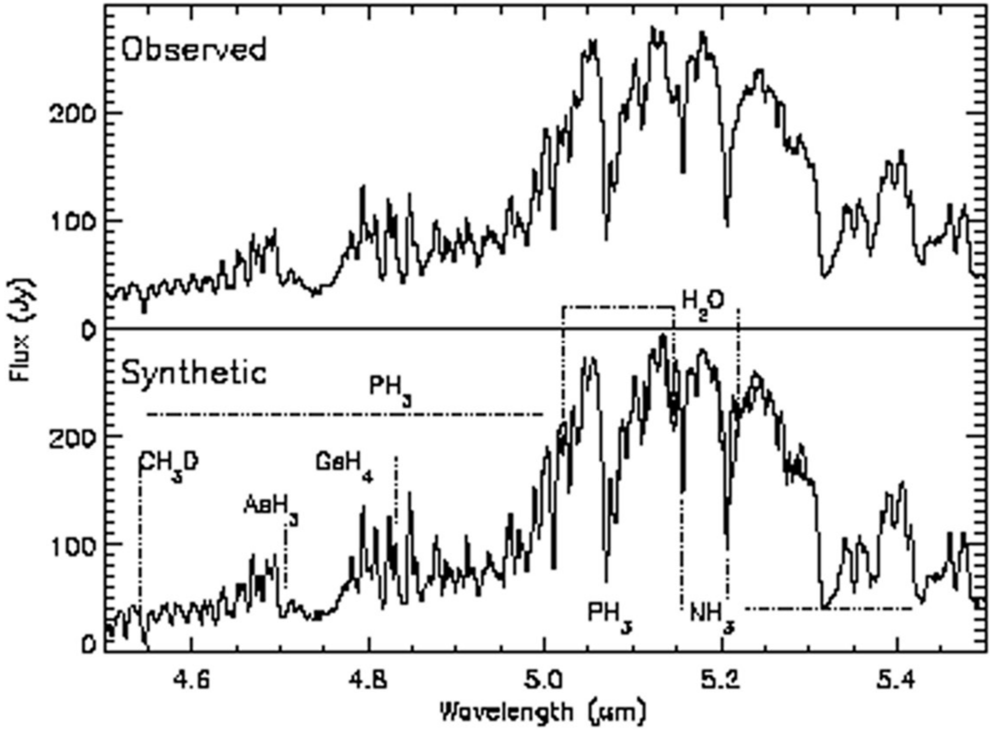
The rotation of the Venus polar vortex as observed by Venus



2) Disequilibrium chemistry

- * Out of equilibrium chemistry is observed on giant planets
- Molecules in the troposphere : CO, PH_3, GeH_4, AsH_3 : not expected from thermochemical equilibrium
- Abundances related to quenching temperatures chemical modelization
- Cf Thesis Rohini Giles, 2016

- Well known example is CO/CH_4 equilibrium reaction

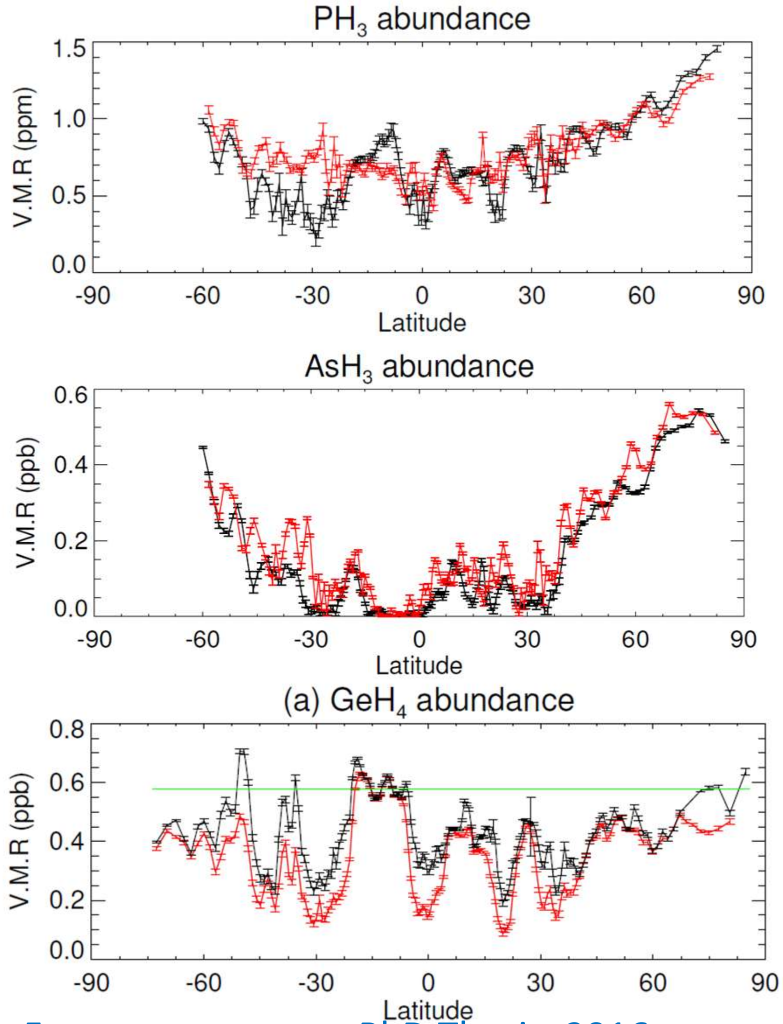


Encrenaz et al., First results of ISO/SWS on Jupiter, A&A 1996

Latitudinal variation of disequilibrium species on Jupiter

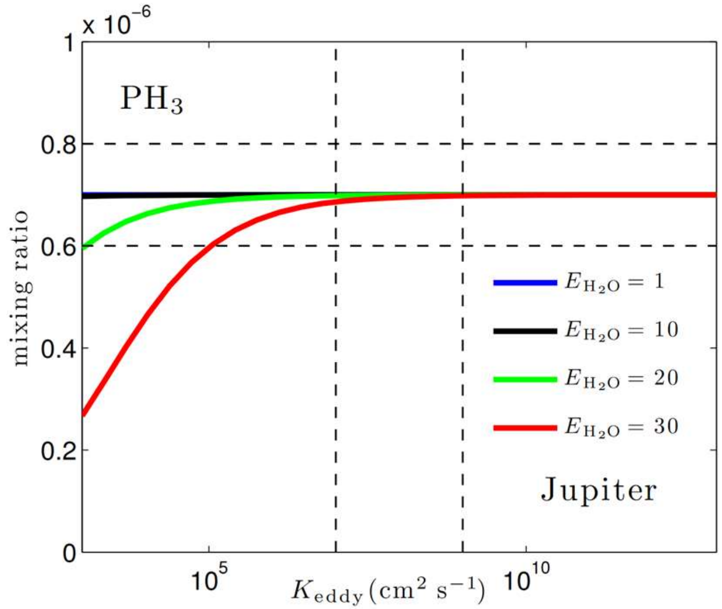
5 µm spectroscopy of Jupiter

1. PH_3 abundance vs latitude (observations at 12/11/2012 and 1/1/2013 CRIRES/VLT)
2. AsH_3 abundance vs latitude (observations of 12/11/2012 and 1/1/2013 CRIRES/VLT)
3. GeH_4 abundance vs latitude (observations of 12/11/2012 and 1/1/2013 CRIRES/VLT)



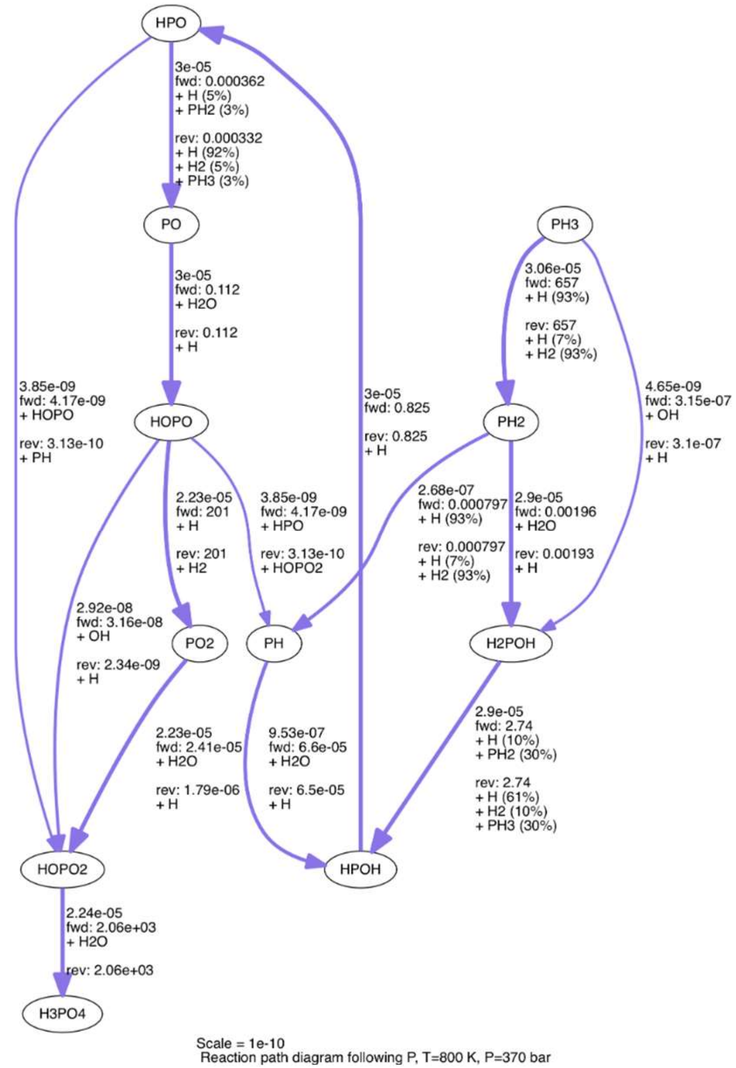
R. Giles, Jupiter's tropospheric composition and cloud structure from 5-µm spectroscopy PhD Thesis, 2016

H/P/O reaction path diagram and formation of PH_3



Variation of PH_3 mixing ratio as a function of vertical eddy diffusion coefficient K_{eddy} in Jupiter's atmosphere

Reaction path diagram for phosphorus : H/P/O network of (main) reactions



Wang et al., *Modeling the disequilibrium species for Jupiter and Saturn: Implications for Juno and Saturn entry probe* Icarus, 2018

3) Escape phenomena in planetary atmospheres

High interest for atmospheric escape to define the stability of planetary atmospheres and estimate the evolution of their composition.

Examples:

- stability of a H_2/He primary atmosphere for telluric planets after their formation
- Atmospheric escape of secondary atmospheres like on Venus (loss of H_2O proved by the D/H ratio) or Mars

=> Strong need for parametric modeling for long term evolution

Problem : even for Solar System planets, the escape phenomena are still not fully understood !

« 2010 crisis » : discrepancy between observations and models for Titan atmosphere

Physical parameters in escape models

Simplest physical model for a one component, spherically symmetric and 1D modeling, with energy deposition at a level R_0 below the simulation region: models show a dependance in only two parameters :

Jeans number :

$$\lambda(r) = \frac{v_{esc}^{\ 2}}{U(r)^2} = \frac{G\,M\,m}{r\,k\,T(r)} = \frac{r}{H(r)} = \frac{\text{gravitational PE}}{\text{random thermal KE}}$$

With $v_{esc} = \sqrt{2GM / r}$

With $v_{th} = \sqrt{2kT / m}$

Knudsen number :

$$Kn(r) = \frac{l(r)}{H(r)} = \frac{\text{molecular mean free path}}{\text{atmospheric scale height}}$$

Small values of λ (comets) : hydrodynamical outflow / Large values of λ (giant or terrestrial planets) : Jeans escape

Kn << 1 corresponds to hydrodynamical escape; Kn >~1 : molecule-by-molecule escape (or Jeans escape)

Definition of exobase Kn ~ 1 : for Pluto at the exobase λ ~ 8.5 for CH_4 (moderately gravitationally bound atmosphere)

Pluto temperature : 68K / rp=1190km / Rexobase= 2900 km

Strobel, Pluto Atmospheric Escape, University of Arizona Press, Pluto book 2019

Kinetic theory of gases applied to escape

Boltzmann equation

$$\frac{\partial f_s}{\partial t} + \overleftrightarrow{v_s} \cdot \nabla f_s + \overleftrightarrow{g} \cdot \nabla_{v_s} f = \left(\frac{\delta f_s}{\delta t}\right)$$

Here $f_s = f_s(\overleftrightarrow{r}, \overleftrightarrow{v_s}, t)$ is the distribution function of species s,

$\overleftrightarrow{v_s}$ $\left(\frac{\delta f_s}{\delta t}\right)$, the Boltzmann collision integral.

Boltzmann equation is unfortunately difficult to apply, but can be handled with MC simulation

Strobel, Pluto Atmospheric Escape, University of Arizona Press, Pluto book 2019

Kinetic theory of gases applied to escape

Hydrodynamical escape valid for Kn < 0.2 and l <1 (derivation of Navier-Stokes and thermal conduction equations from Boltzmann equation)

Thermal heating equation is reduced to a Bernoulli equation

$$\frac{1}{2}v^2 + c_p T + \Phi_g \approx c_p T_0 + \Phi_{g0}$$

Strobel, Pluto Atmospheric Escape, University of Arizona Press, Pluto book 2019

Kinetic theory of gases applied to escape

Jeans escape takes place when $\lambda > 3$ at the exobase (located at Kn ~ 1)

f_{exo} = distribution function at the exobase (truncated Maxwellian) ; μ = cosine of v with radial direction

integration over the velocity volume. Escape flux is usually calculated at the exobase ($r=r_{exo}$)

$$\Phi(r \to \infty) = \iiint v \mu f_{exo} d^3 v = n_{exo}(r_0) \frac{n v_{th}}{4} (1 + \lambda_0) e^{-\lambda_0}$$

Strobel, Pluto Atmospheric Escape, University of Arizona Press, Pluto book 2019

Jeans escape : kinetic escape

Exact calculation of the distribution function possible, with some assumptions:

- No collision above exosphere
- Distribution function = truncated maxwellian
- Consequence : column density above the exobase ~ $n0 \times H$
- Escape flux calculation

Intermediate escape model

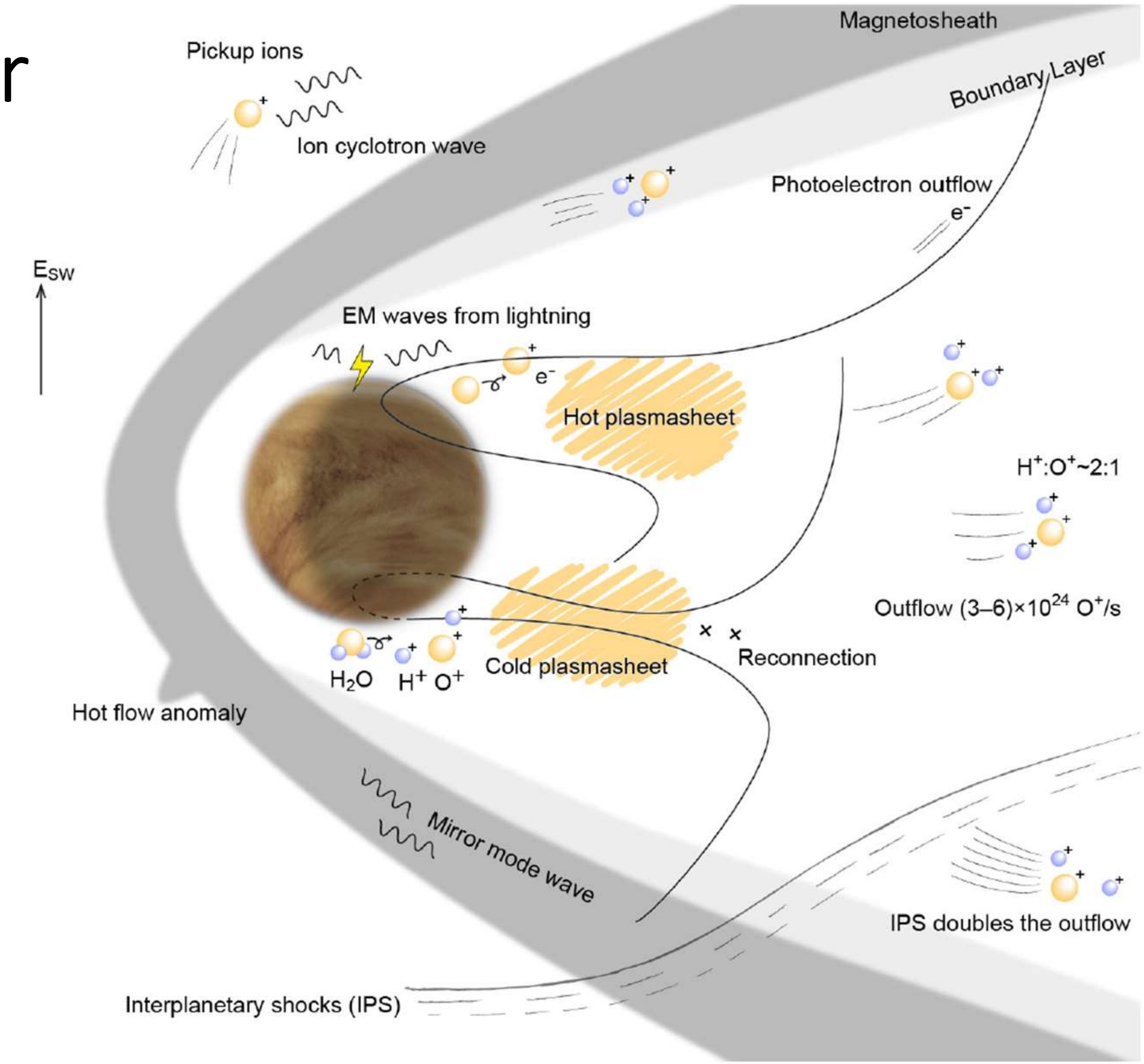
- Direct Simulation with Monte-Carlo (DSMC) models have revisited the intermediate case
- With boundary condition at R_0 (exobase) : maxwellian distribution and no energy deposition above R_0
- For collisional flow, transition parameter λ~ 2 between molecule-by-molecule escape (Jeans) to organized outflow (hydrodynamical)

Strobel, 2019 (PSS, Pluto special issue)
On the theoretical front the two papers by Volkov et al. (2011a, 2011b) have clarified the general problem of thermal escape from planetary atmospheres and the transition, as the gravitational binding energy relative to thermal energy increases, from organized supersonic outflow to random evaporation of individual atoms/molecules at the exobase known as Jeans escape. This transition is narrow and very abrupt. They also found that escape rates were enhanced over traditional Jeans escape rates by approximately a factor of 2 in thermal escape regime for moderately gravitationally bound atmospheres such as Pluto's.

Strobel, *Pluto Atmospheric Escape*, Planetary Space Science, Pluto Special Issue 2019
Volkov et al. a*, Kinetic simulations of thermal escape from a single component atmosphere*. Phys. Fluids, 2011
Volkov et al. b,*Thermally-driven atmospheric escape: Transition from hydrodynamic to Jeans escape*. ApJ Lett., 2011

Venus general scheme for interaction with space environment (Venus Express)

A variety of mechanisms have been studied with Venus Express Aspera, Mag and RSE instruments :
Interaction with solar wind
Wave activity
Outflows
Etc.



Futanaa et al., *Solar wind interaction and impact on the Venus atmosphere*. Space Sci. Rev. 2017

Auroral phenomena in giant planets

Particle precipitations in H2/He atmosphere =>

H and H2 UV emission : Lyman & Werner band for H2, Lyman alpha for H

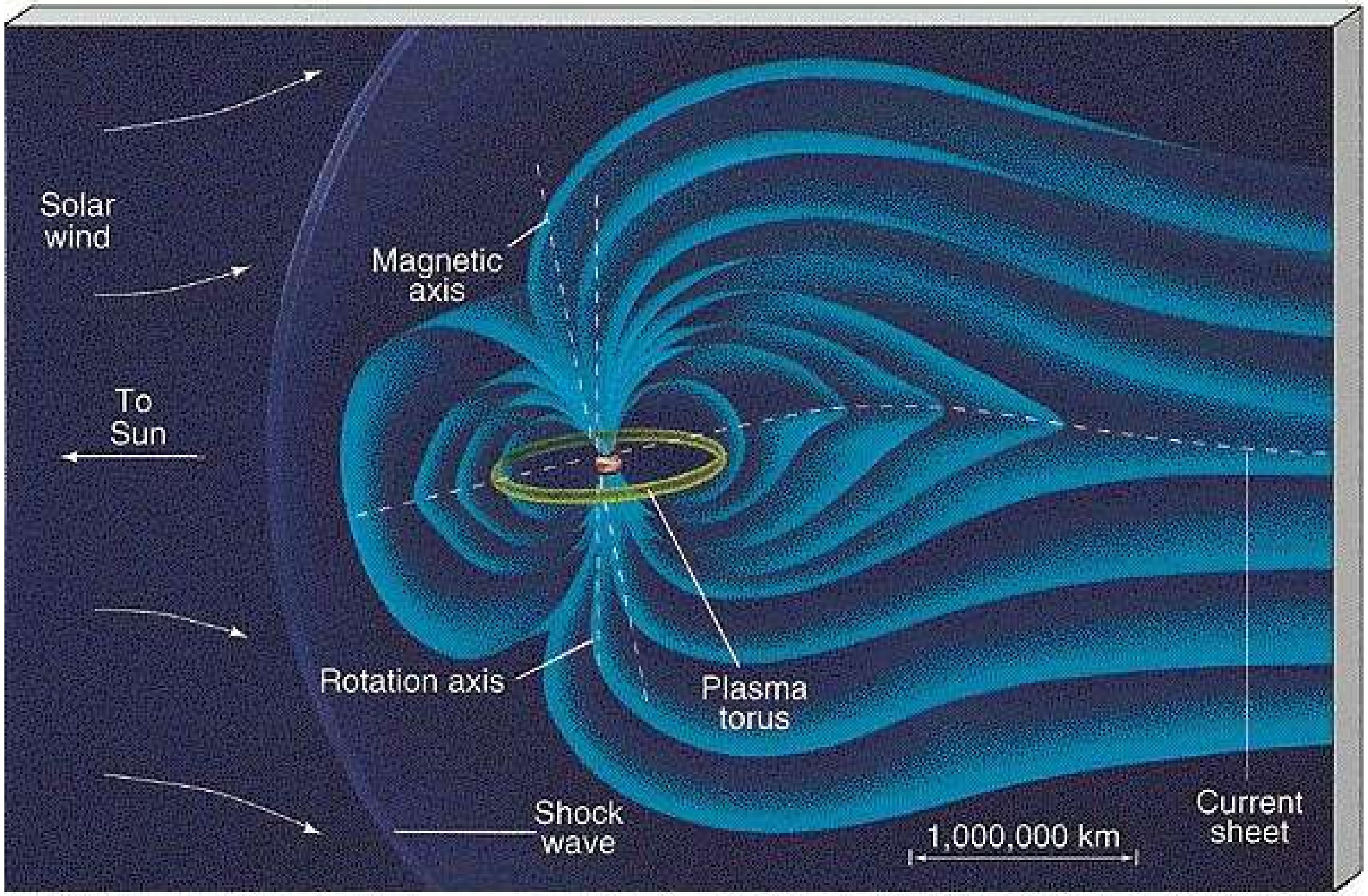
Infrared emissions : atmospheric heating => hydrocarbon emissions

H3+ emission

Dynamic phenomena

Heating of the thermosphere

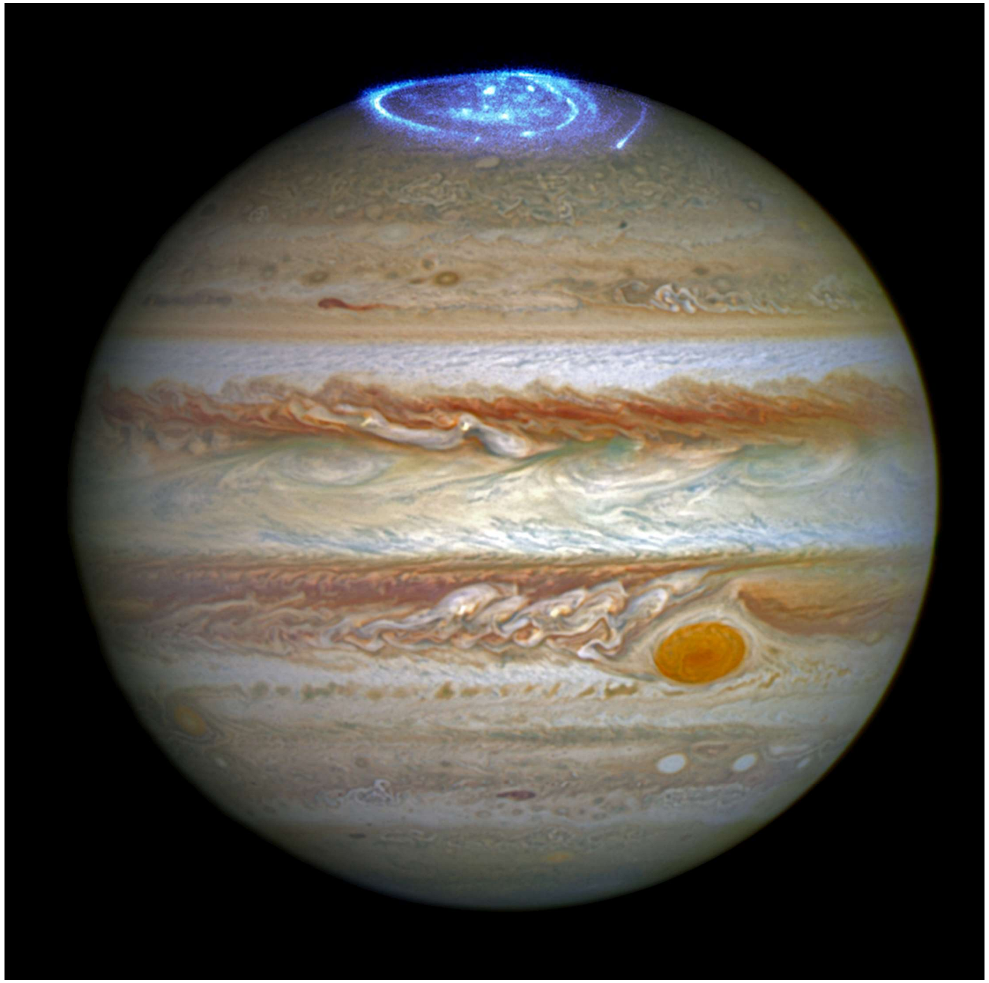
The magnetosphere of Jupiter

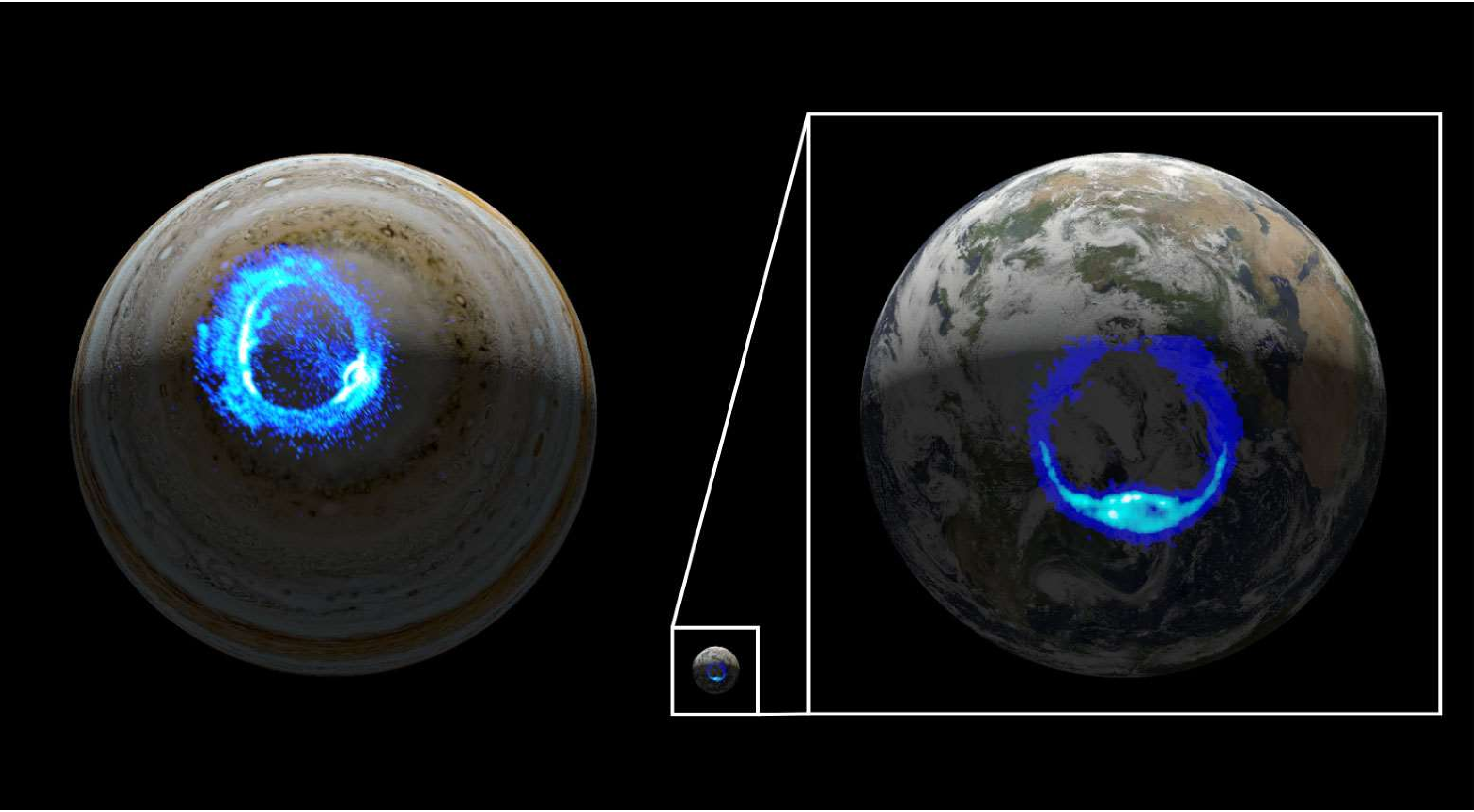


Auroral emissions

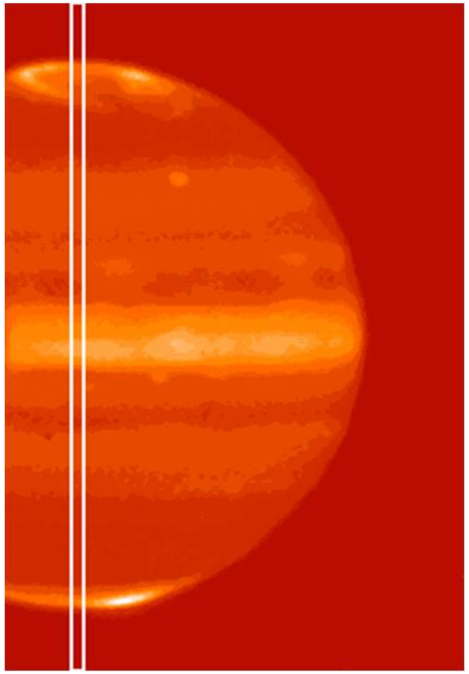
Precipitation of particles from the magnetosphere :

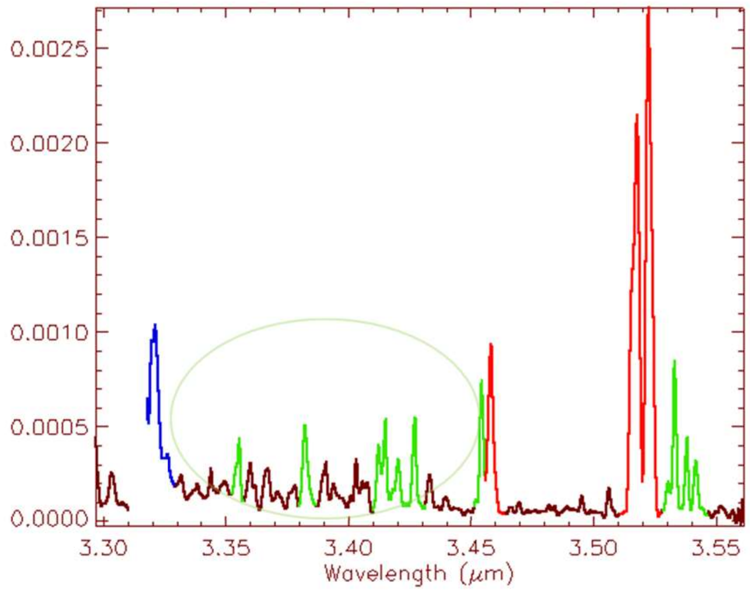
- Primary or secondary emissions : H Ly_α & H_2 Lyman and Werner bands
- Chemical modifications
- Thermal heating of the upper stratosphere
- Dynamical effects

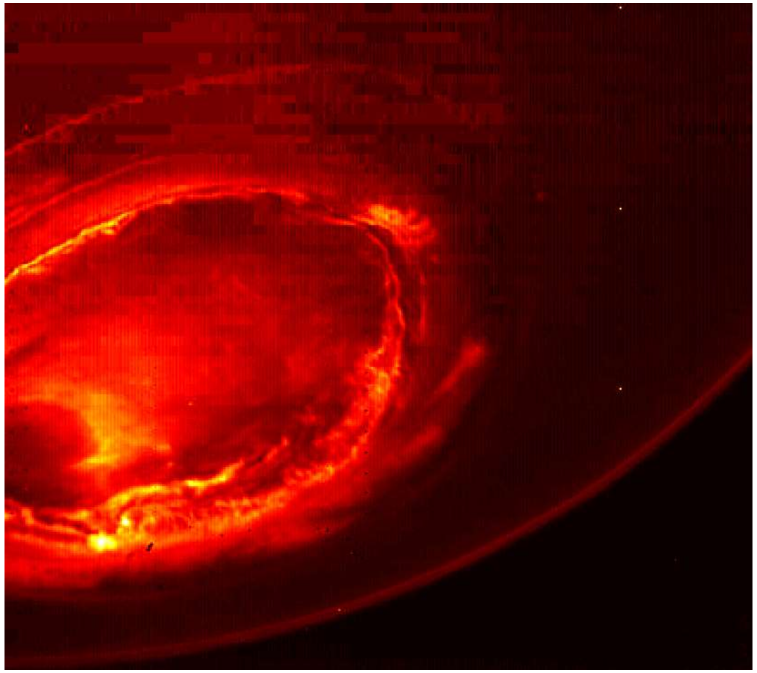




Infrared emission of H_3^+ in the Southern auroral oval



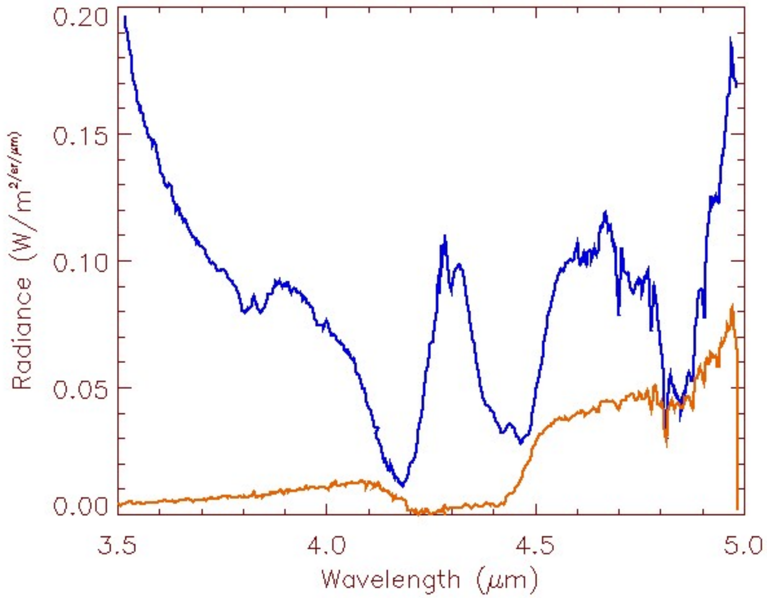




VLT/ISAAC - Drossart, 2019

JUNO/JIRAM Dinelli et al, 2019

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 τ ~ 1 sounding => limitation to stratospheric levels**

=> Limited dynamical examples : QBO on Earth, QQO on Jupiter/Saturn, expansion of the thermal wave in the SL9 collision with Jupiter

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

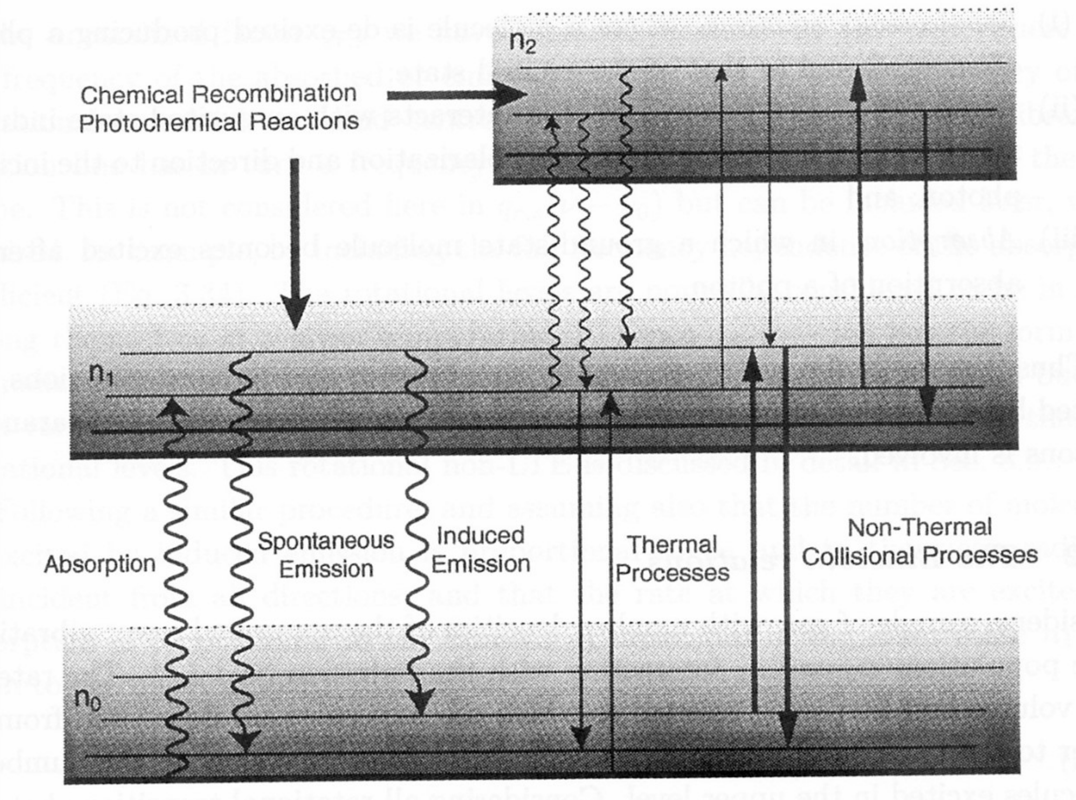


Fig. 3.3 Processes affecting the populations of vibrational levels.

Some non-thermal processes

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

   Example : CO_2 molecule ; exchange with N_2
2. **Electronic to vibrational energy transfer.**

   Example: $O(^1D)$ state excitating the N_2 vibrational modes
3. **Chemical recombination or chemiluminescence Example: ozone bands at 10 μm**
4. **Photochemical reactions**

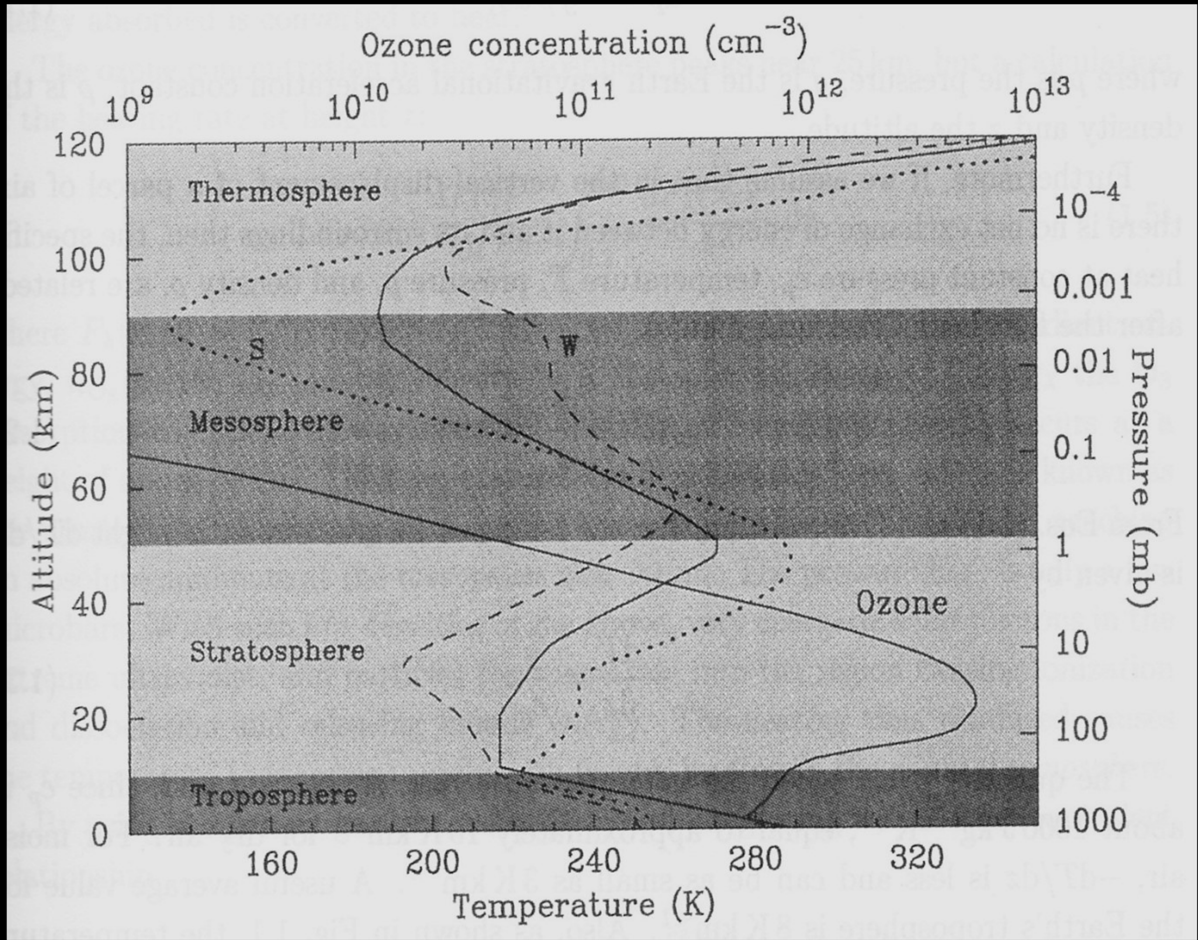
   Example : O_2 emissions at 1.27 μm
5. **Dissociative recombination (O_2^+ + e- $\rightarrow$ O* + O)**
6. **Collisions with charged particles (auroral processes)**

- Moreels et al, Experimental Astronomy, 2008

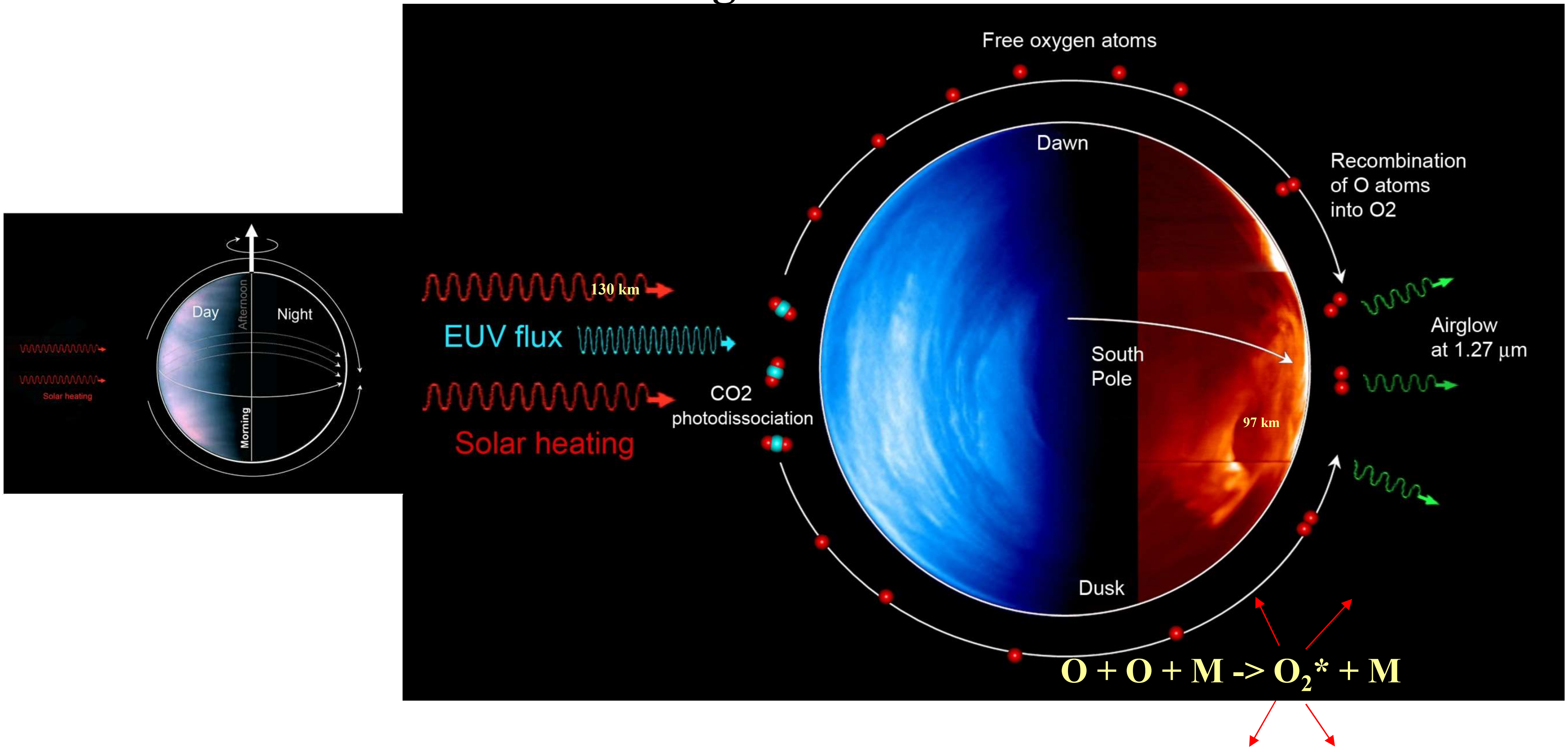
Observations from Observatoire de Haute Provence (1998)

Context of comparative aeronomy of planets

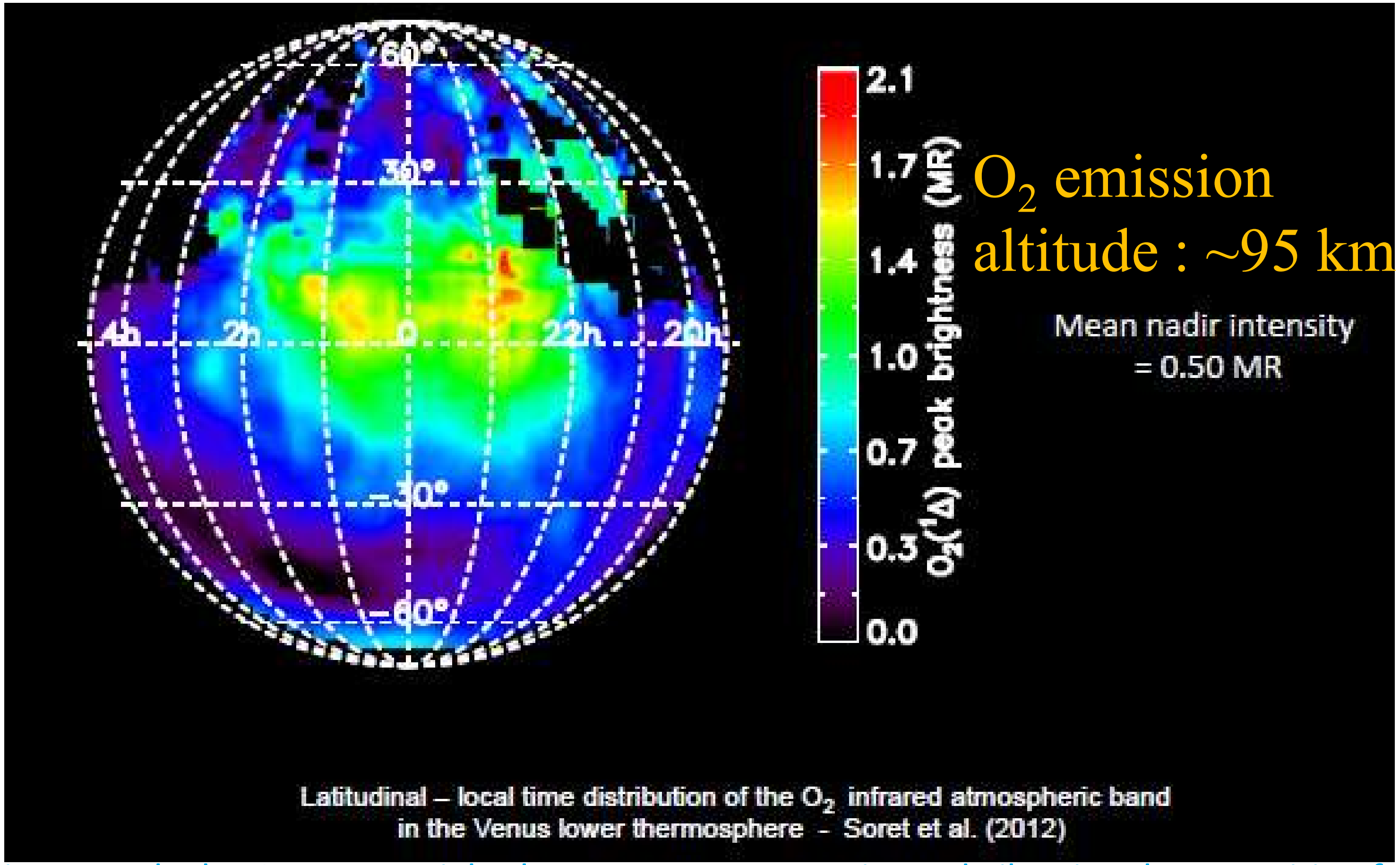
Mesosphere = between stratosphere and thermosphere



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



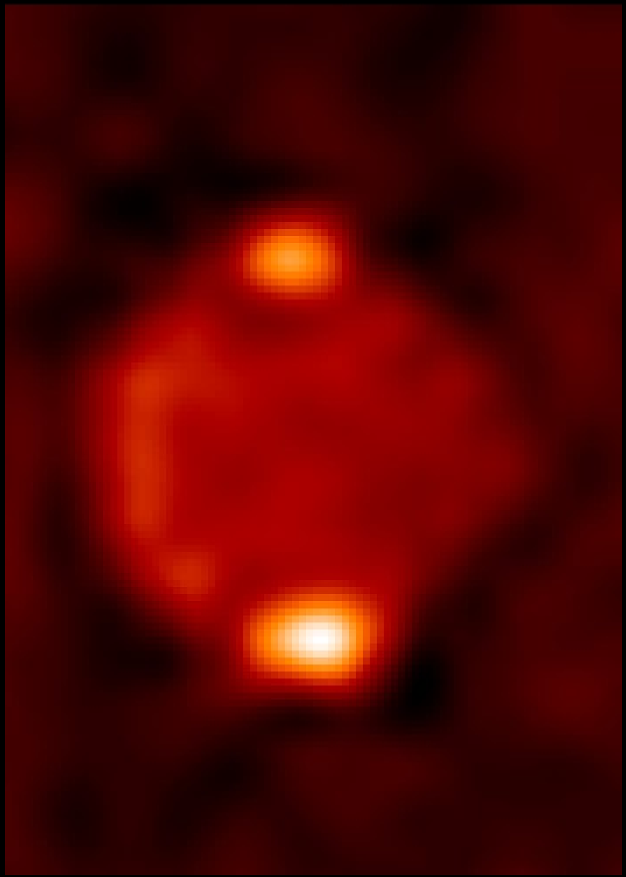
O_2 average emission



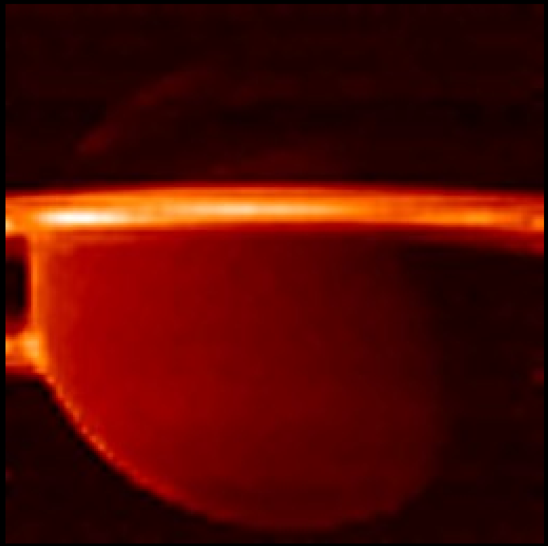
Soret, Lauriane; et al. The OH Venus nightglow spectrum: Intensity and vibrational composition from VIRTIS—Venus Express observations Planetary and Space Science,. 2012

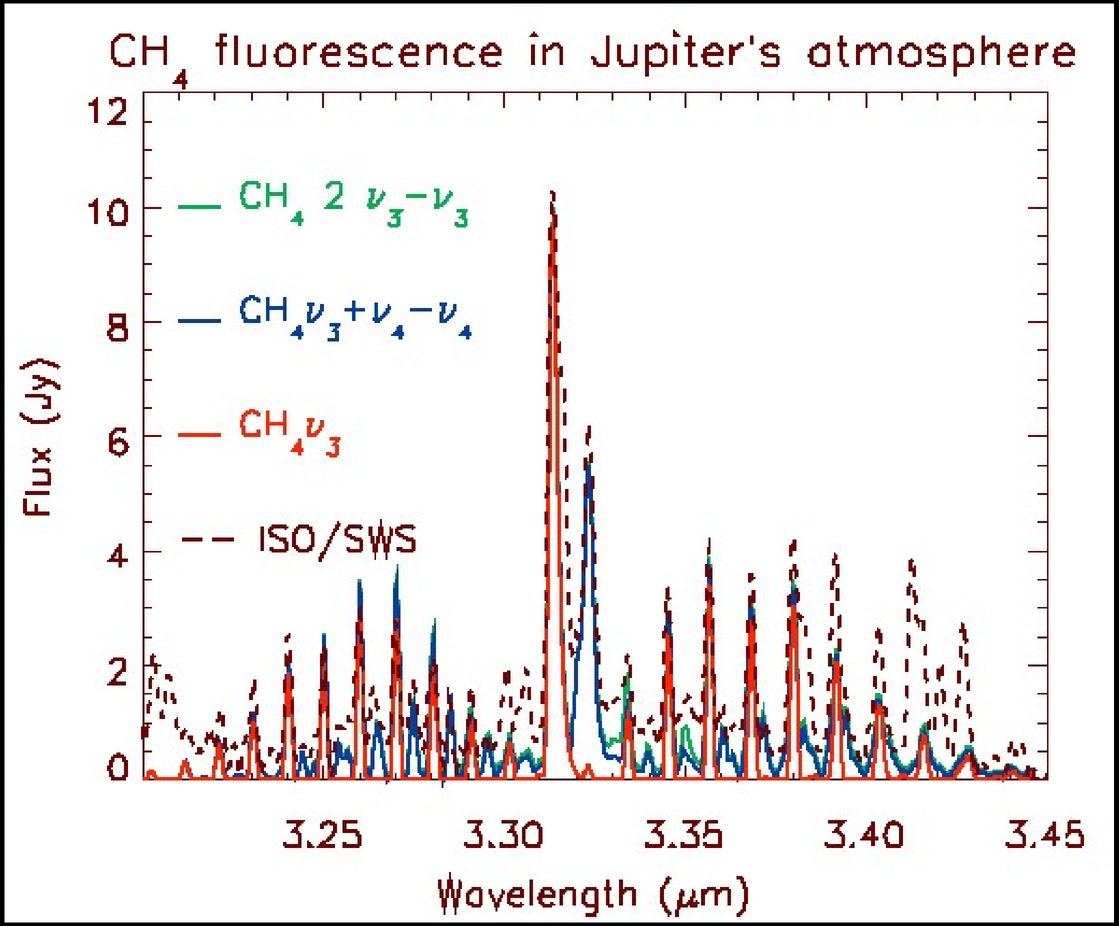
Giant Planets :

Jupiter (2000)



Saturn (2005)

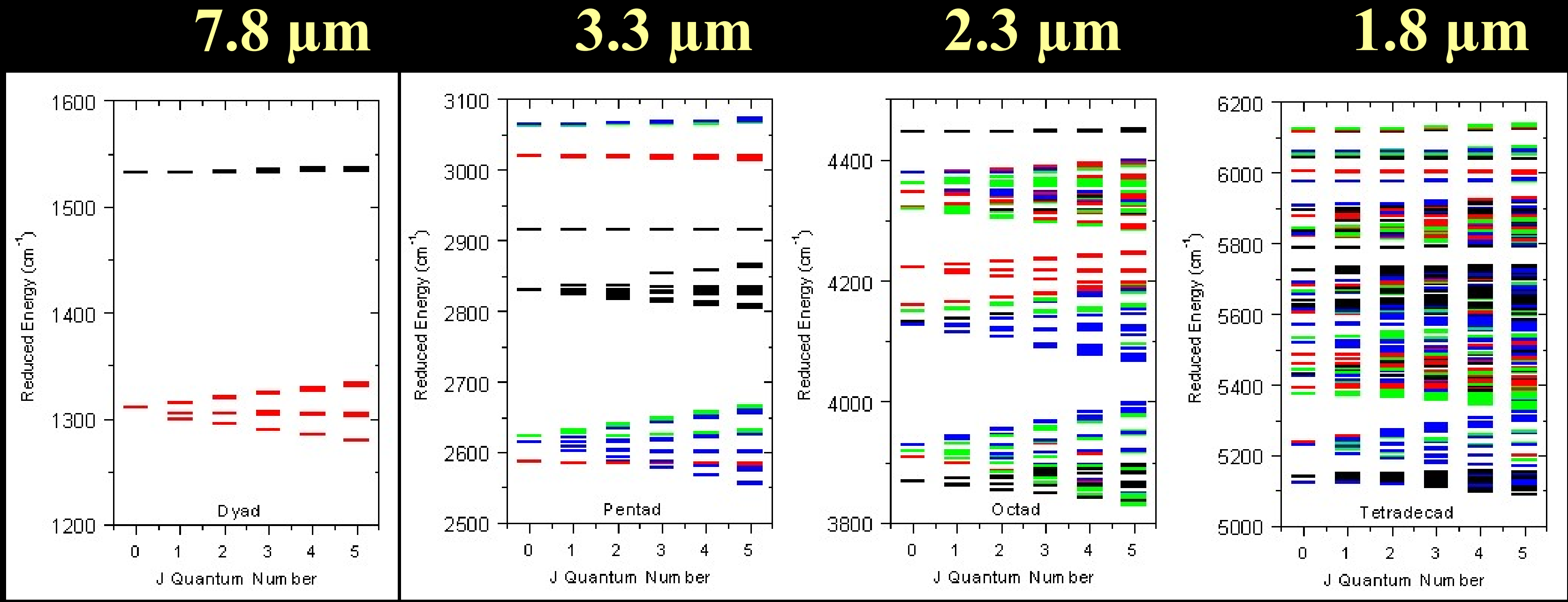




Drossart et al, ESA-SP 427, 1999

Comparison of synthetic spectra with ISO/SWS observations

vibration/rotation bands: CH_4



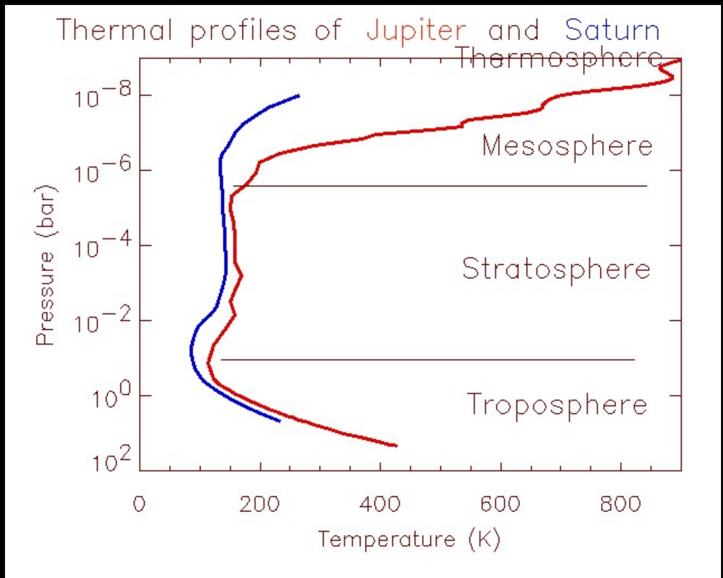
Dyad	Pentad	Octad	Tetradecad
2 vibrational states	5 vibrational states	8 vibrational states	14 vibrational states
2 sublevels	9 sublevels	20 sublevels	60 sublevels

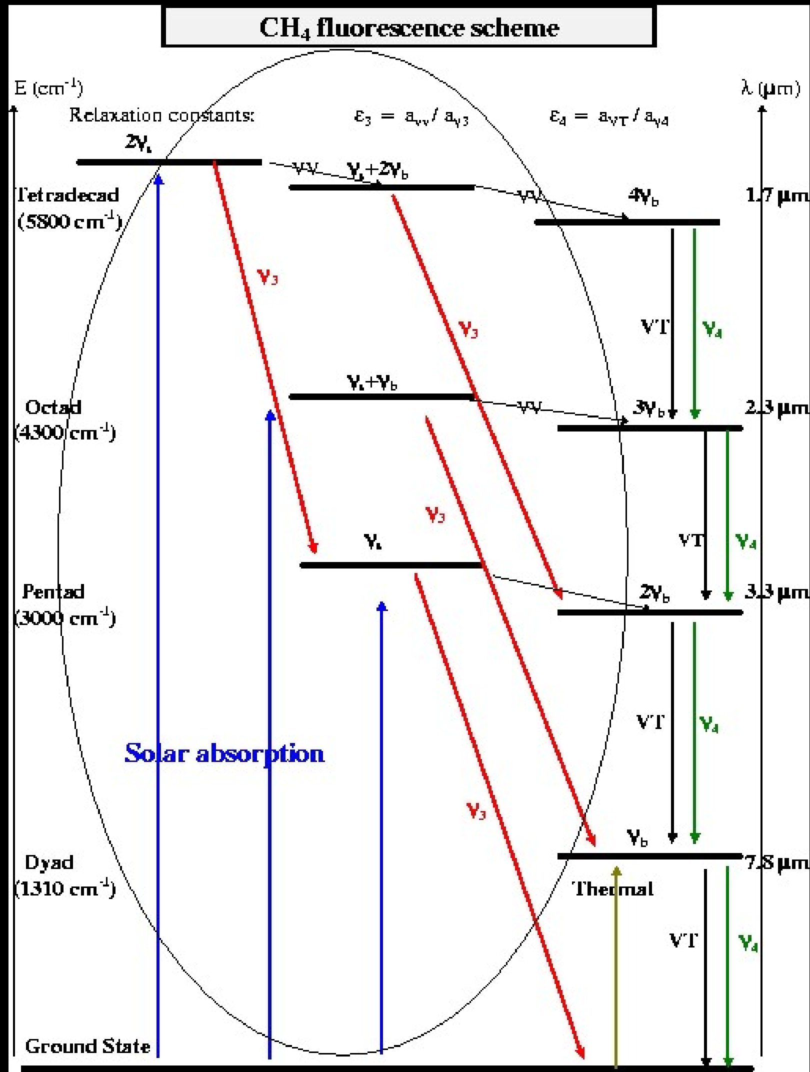
Wenger and Champion, JQSRT, 1998

Simplified scheme of fluorescence in CH_4 in planetary atmospheres

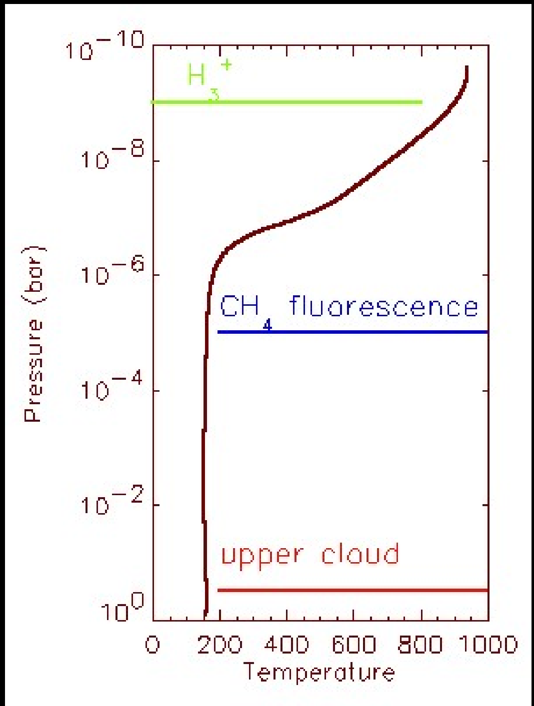
- grouping stretching/ bending levels of CH_4
- CH_4 radiative transitions
- ν_4 (7.8µm) ν_3 (3.3µm)

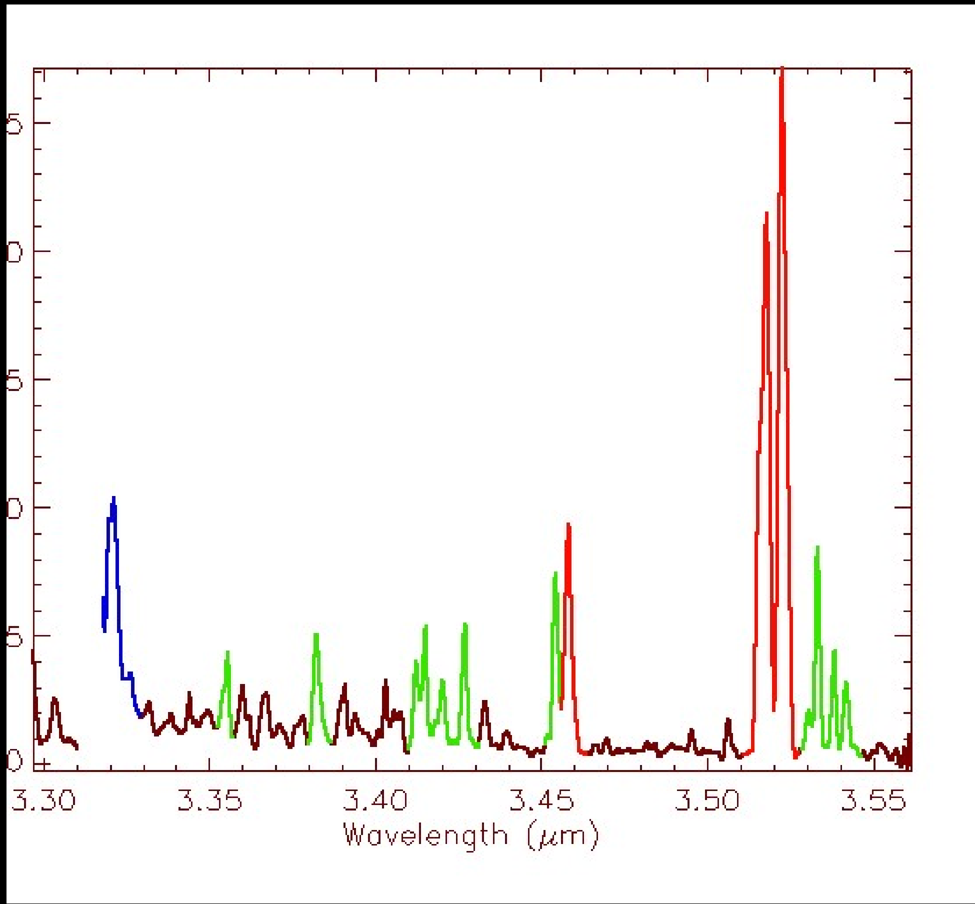
$\nu_3 + \nu_4$ (2.3µm) $\nu_3 + 2\,\nu_4$ (1.7µm)





Jupiter infrared observations (VLT/ISAAC)

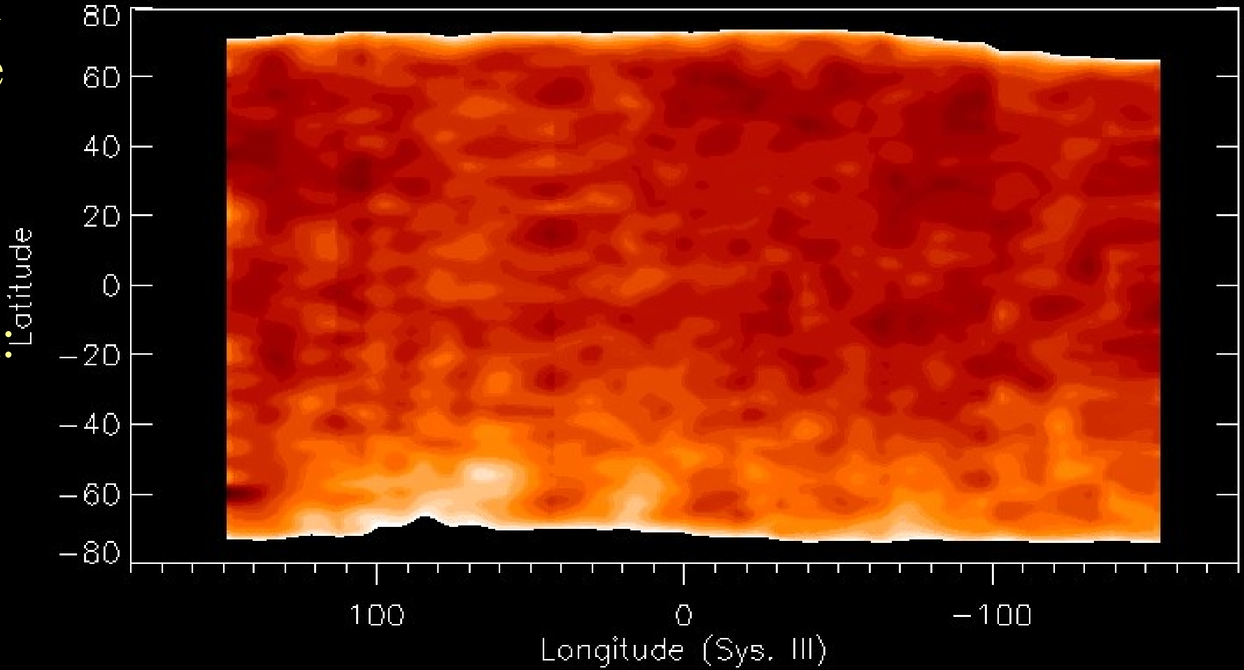




Jupiter : CH_4 fluorescence map

H_3^+ contamination in the auroral zone => measurements limited to l< 60°

CH_4 flux variation: variation ≈ noise $\Delta CH_4 < 20\%$

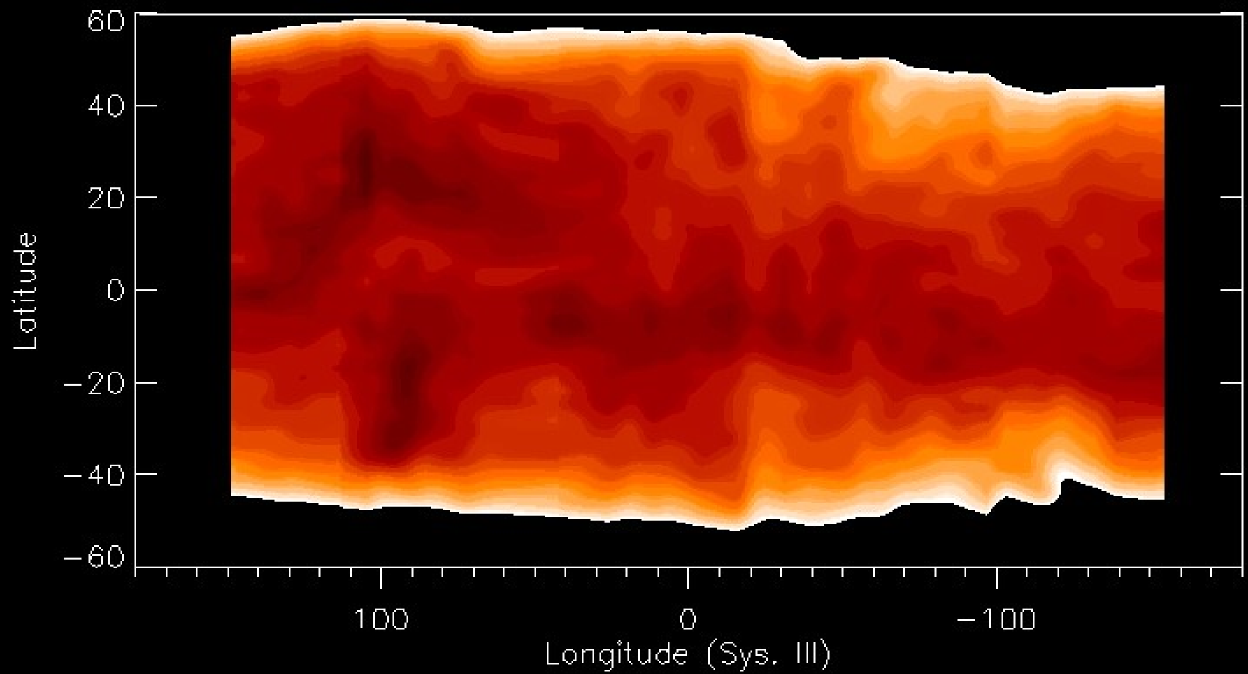


Jupiter : H_3^+ map at mid latitudes

H_3^+ variations detected at ±10% level <=> $\Delta T = \pm 30K$

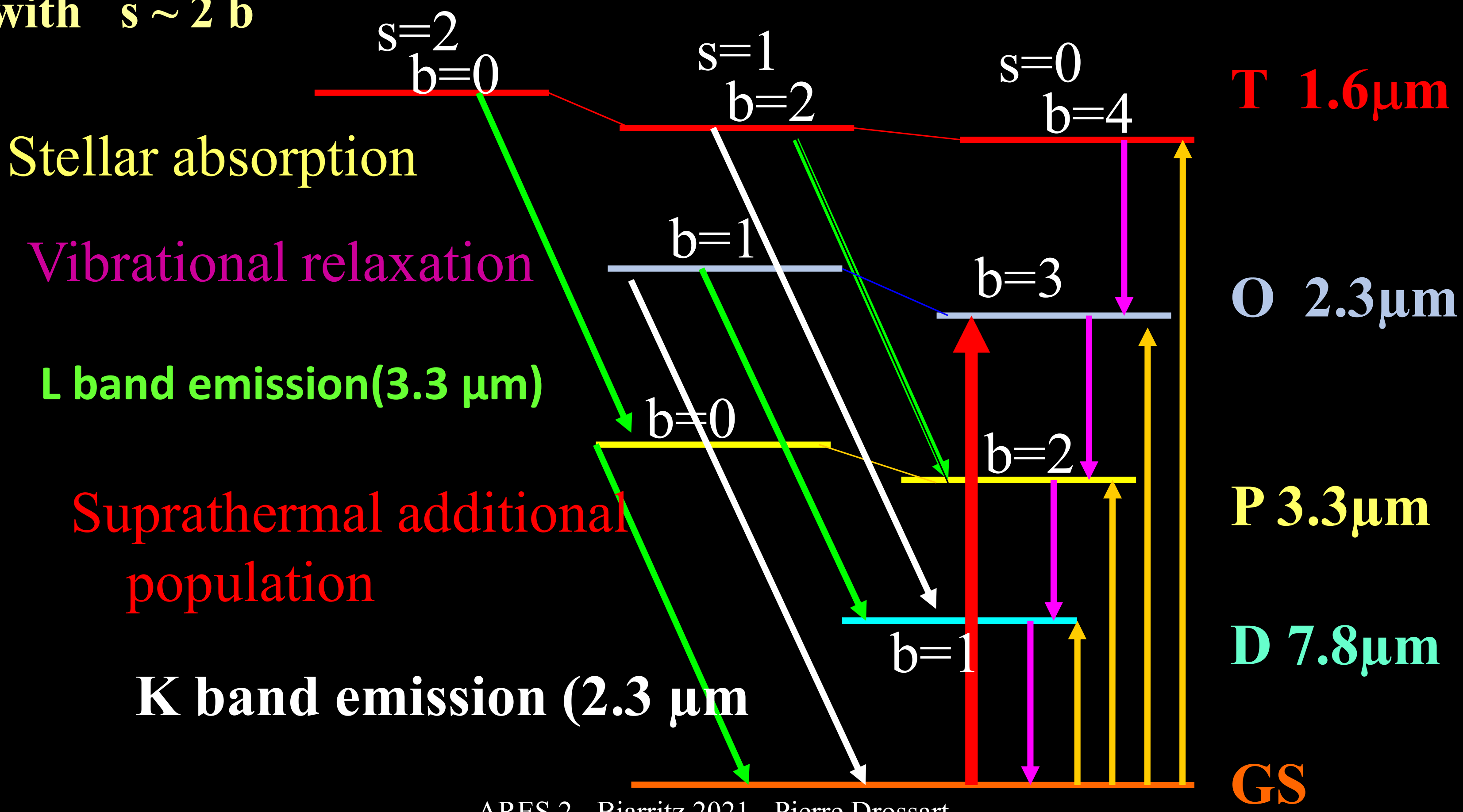
•large scale: hemispheric asymmetry

•small scale: Wave activity?



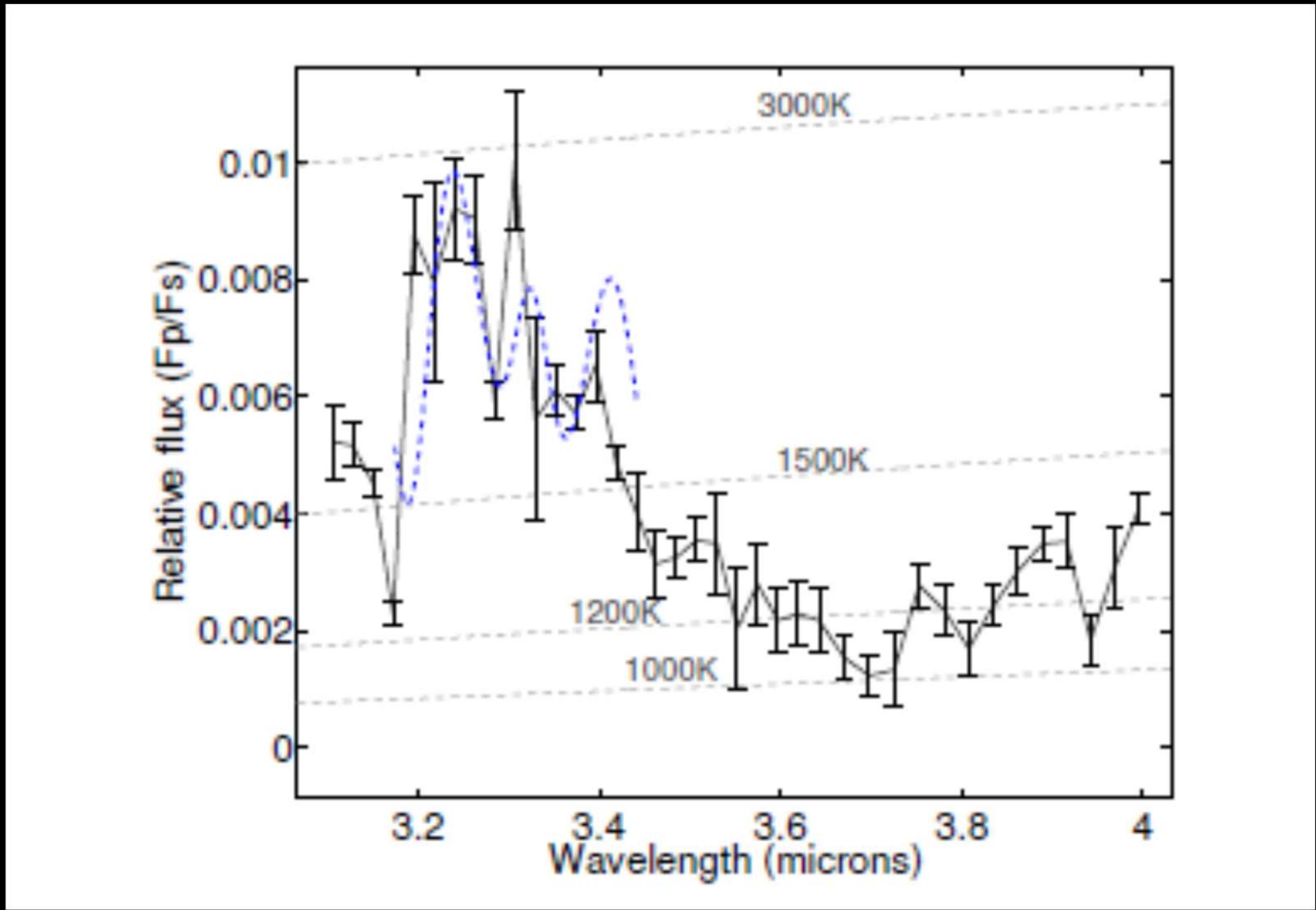
Fluorescence scheme

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



Fit of HD 189733b in L band

Waldmann et al., ApJ, 2012



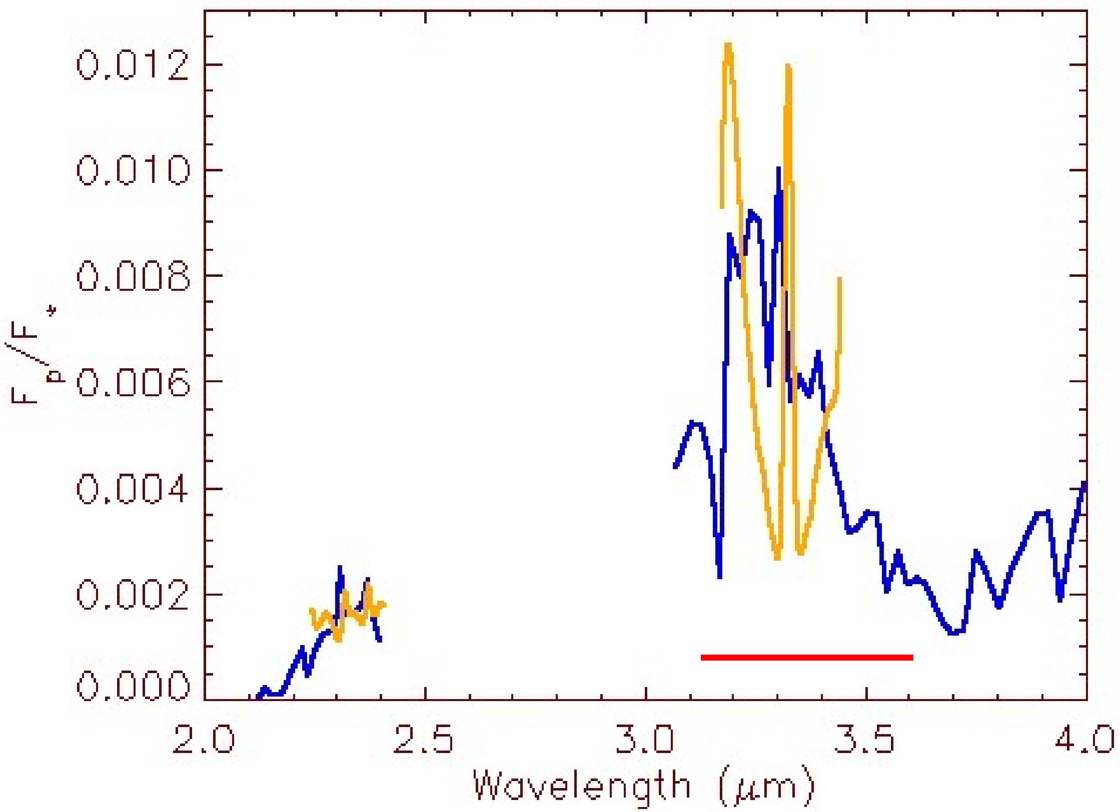
HD 189733b K+L bands

- Observations

(Waldmann et al, ApJ 2012)

- Non-LTE model joint K+L band

- Thermal emission only



References

List of papers will be provided in a separate document for the school