Atmospheric evolution and the search for species of astrobiological interest in the Solar System

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EPSC Granada 2022

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1 – Institute of Astrophysics and Space Sciences (IA), Lisbon

2- Faculty of Sciences, University of Lisbon

Summary

1.

Background. Atmospheric composition and evolution

2.

Methods. The Planetary Spectrum Generator and NEMESIS

3.

Positive detection of methane on Mars and non-detection of Phosphine on Venus

3.

Determination of the sulphur dioxide abundance on Venus

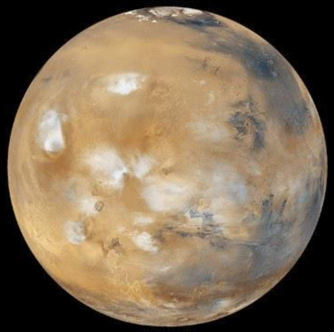
4.

Determination of the deuterium to hydrogen ration on Mars and the search for methane

5.

Ongoing work: Effect of vulcanic plumes (SO2+H2O) on the spectra of Venus and determination of the D/H ratio on Jupiter

Open Questions



1. What are the sources and sinks of SO_2? Variability and possible connection with volcanism (Encrenaz2022)

2. Is there phosphine on Venus? (Encrenaz2022) Connection with Astrobiology (Sousa-Silva+2019)

3. Evolution of water abundance on Mars. Loss of water through time (Villanueva+2021, Jakosky2021)

4. Study methane detection and abundance variability. What is the source of methane? (Korablev+2019, Giuranna+2019, Webster+2021)

Methods – The Planetary Spectrum Generator

Villanueva+2018

Methods – NEMESIS

nemesiscode.github.io

- **NEMESIS** (**N**on-linear Optimal **E**stimator for **M**ultivariat**E** Spectral Analy**SIS**) is a general purpose radiative transfer and retrieval tool designed for analysing visible/infrared observations of any planetary atmosphere (Irwin+2008)
- Originally developed for solar system studies (Cassini/CIRS observations of Jupiter, Saturn and Titan), but extended for primary transit, secondary eclipse and direct imaging of exoplanets/brown dwarfs.
- Designed from start to be generally applicable to any planetary atmosphere and originally designed for use with a correlated-k forward model.
- Handles thermal emission and scattering
- Open Source

NEMESIS

Methane on Mars and Phosphine on Venus
3.3 µm, 10.5 µm

Positive Detection on Mars Express

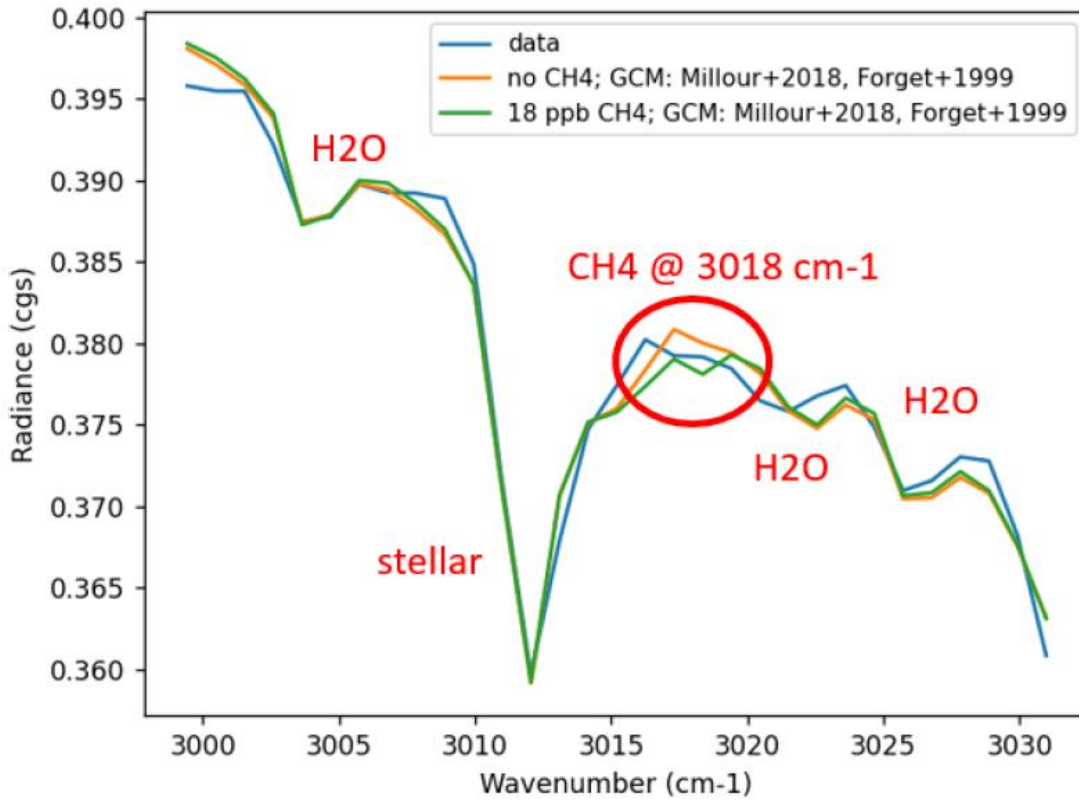


Fig.1- Data (blue) (Giuranna+2019) compared with a model with no CH4 (orange) and other with 18 ppb of CH4 (green)

Non-Detection of Phosphine – IRFT (Mauna Kea)

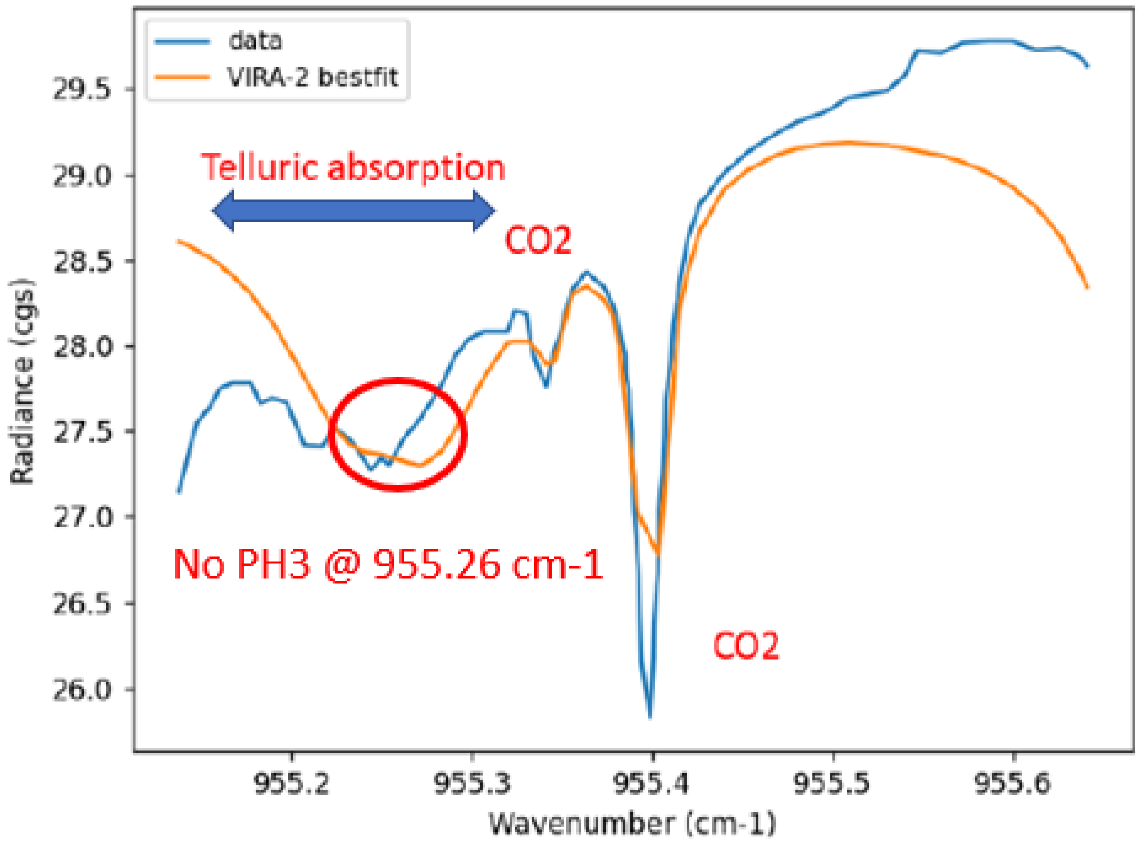


Fig.2. Best-fit model (VIRA) as compared with TEXES observations (Encrenaz+2020)

Dias+2022, Atmosphere 13(3), 461

Sulphur Dioxide on Venus
7.4 µm

vmr (SO2) ~ 120 ppb

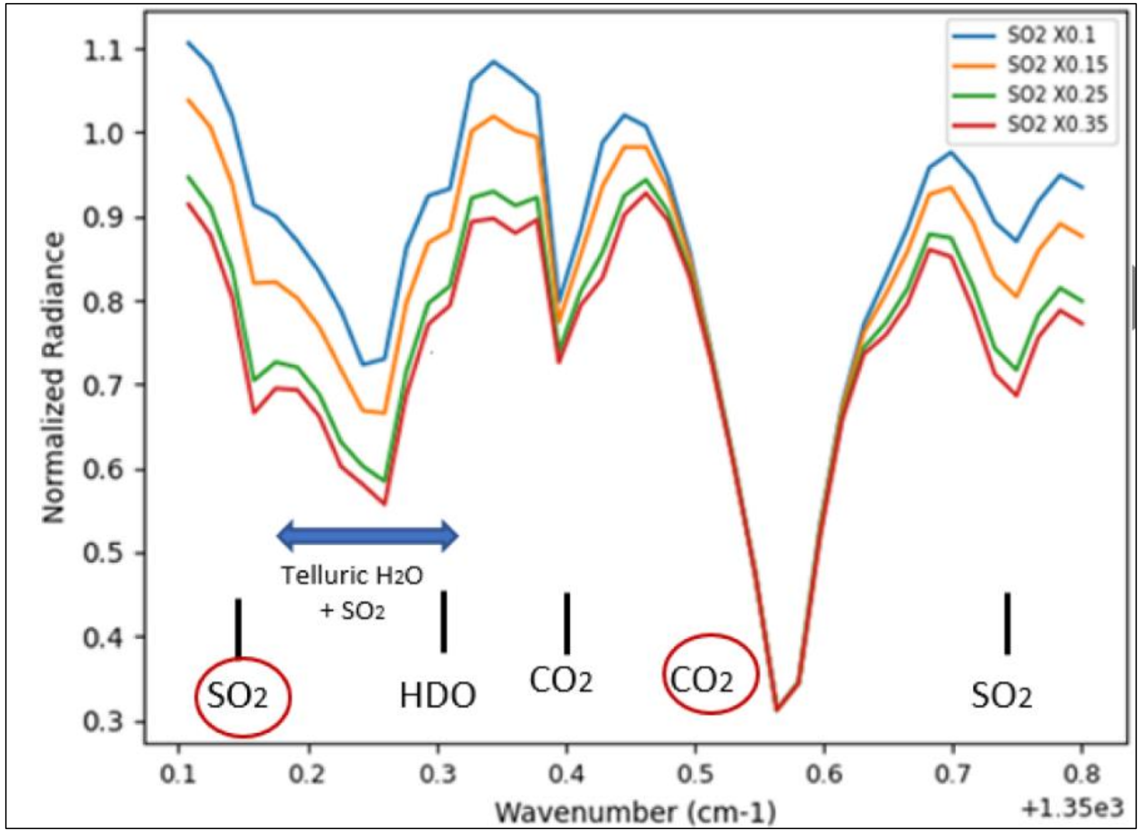


Fig.3. Method of the line depth ratio. Ldr=d(SO2)/d(CO2). Model input: VIRA (Zasova+2006)

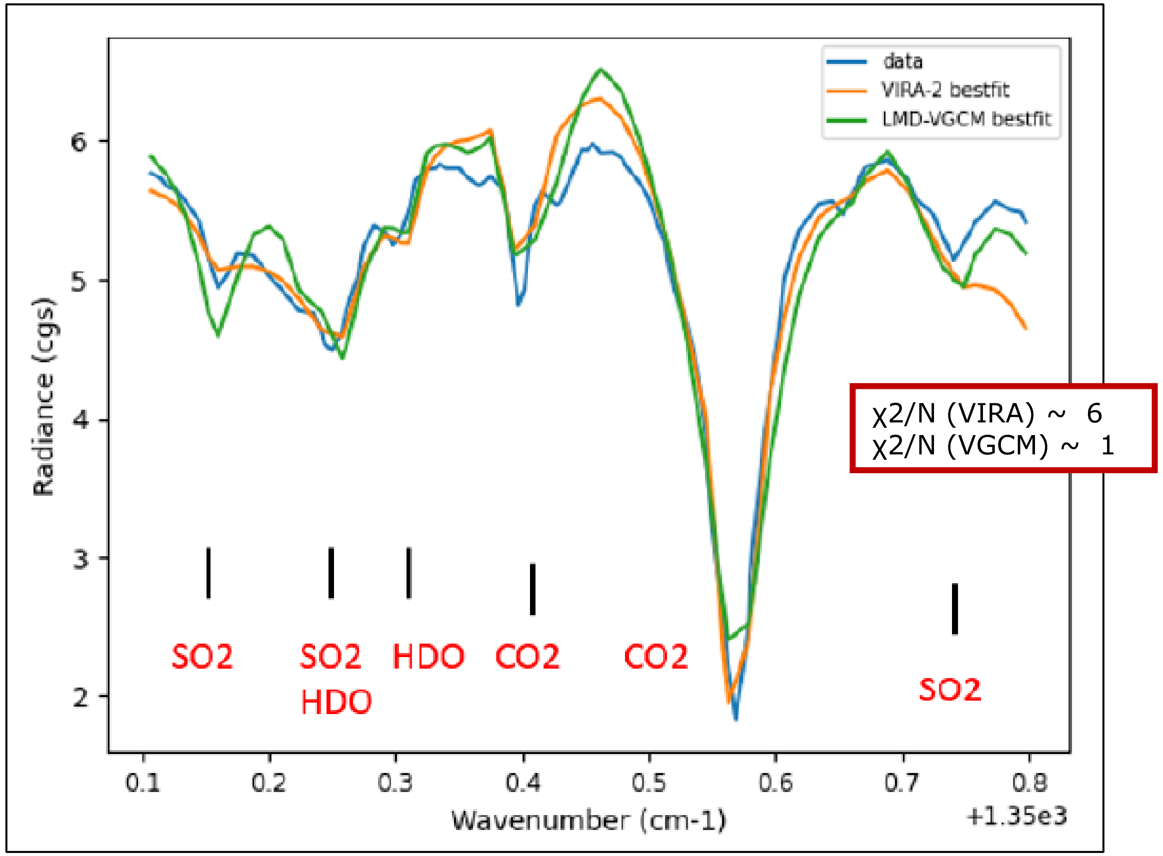


Fig.4. Best-fits obtained for TEXES observations (Encrenaz+2012).

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Determining the D/H ratio on Mars
7.2 µm

D/H ~ (5.3-6.5) D/H (Earth)

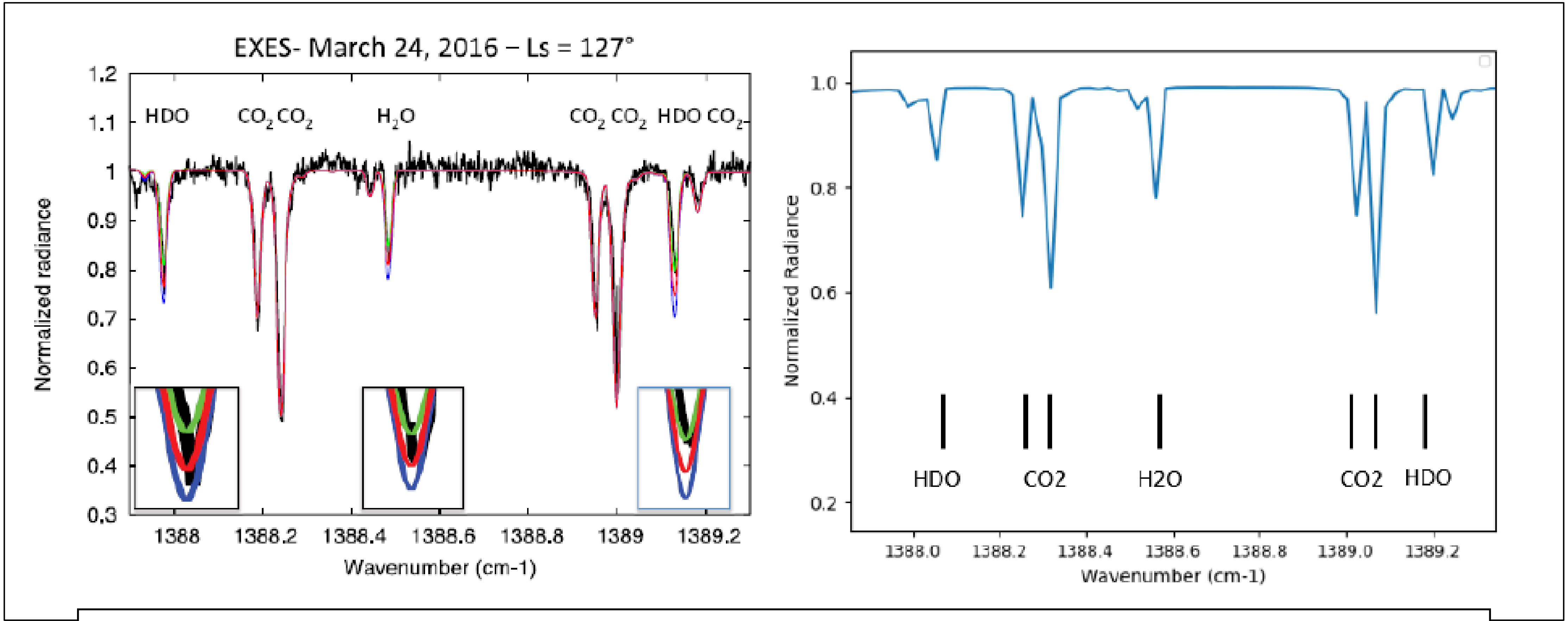

Fig.5. Comparison between EXES data (left) (Encrenaz+2019) and normalized radiance simulation (right), at 1388-1389.2 cm-1.

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Vulcanic plumes on Venus
Creating a model using VIRTIS-H nightside observations

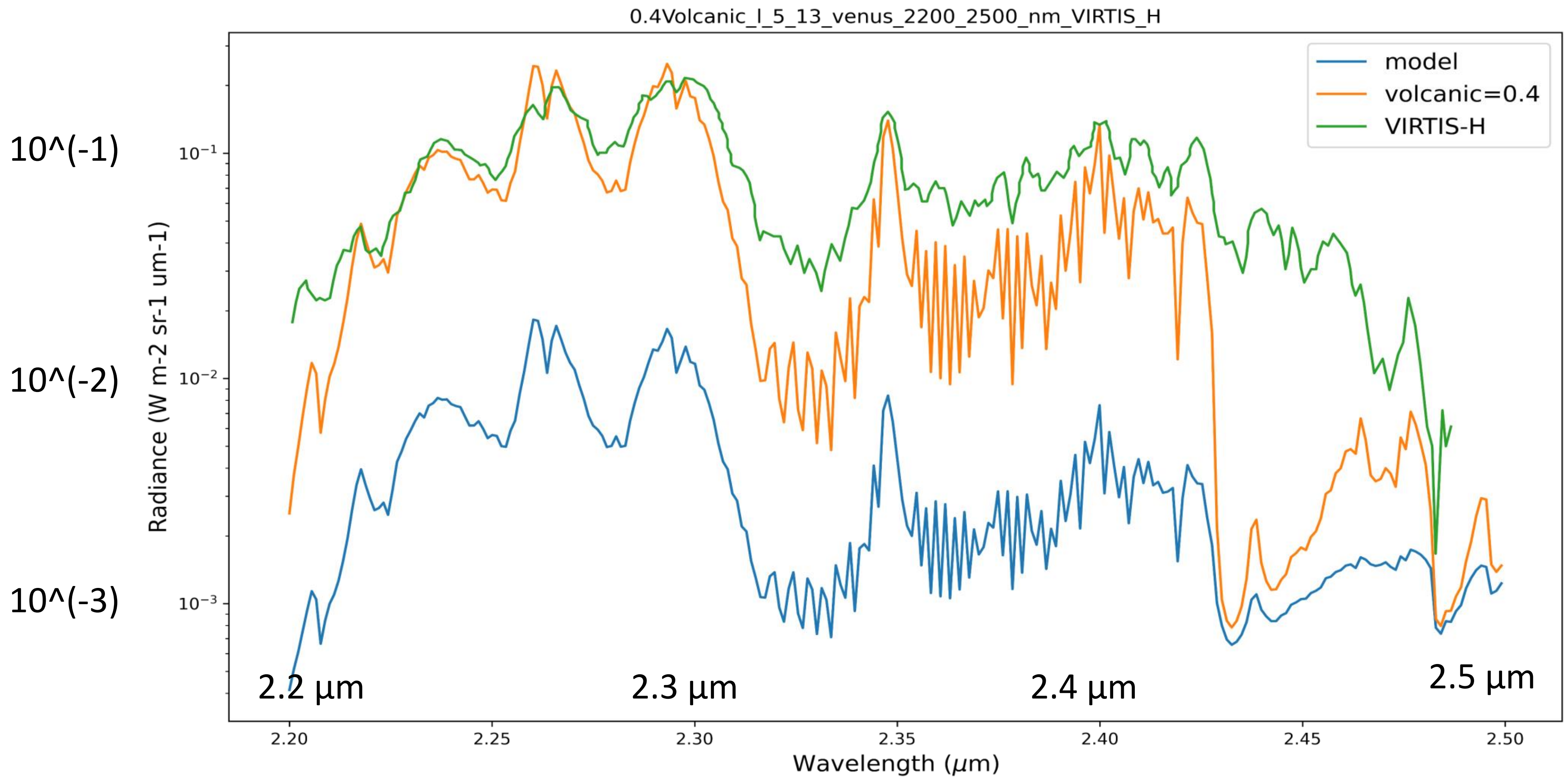
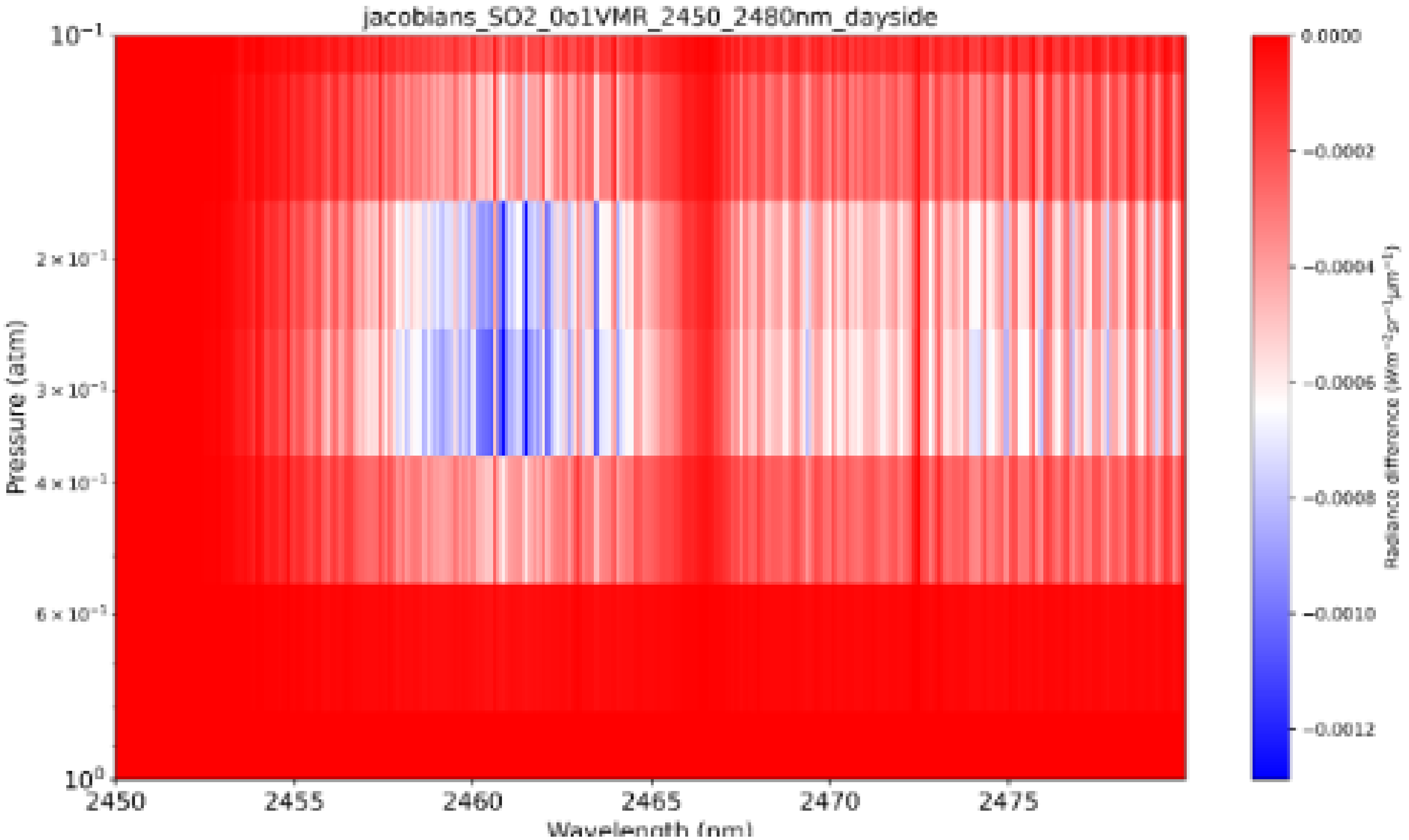


Fig.6. Comparison between VIRTIS-H data (green) (ref) and simulated spetra (blue – a priori model, Orange – first fit with scaled volcanic profile)

How to identify vulcanic plumes on Venus?

SO2 variations, 1-2.5 µm, Dayside

Radiance difference
(W m-2 sr-1 µm-1)



0

2e-4

4e-4

6e-4

8e-4

1e-3

Fig.7. Radiance variation in response to a 10 % variation of the SO2 abundance, for each pressure layer of the model atmosphere.

The D/H ratio on Jupiter
7-12 μm, ISO data

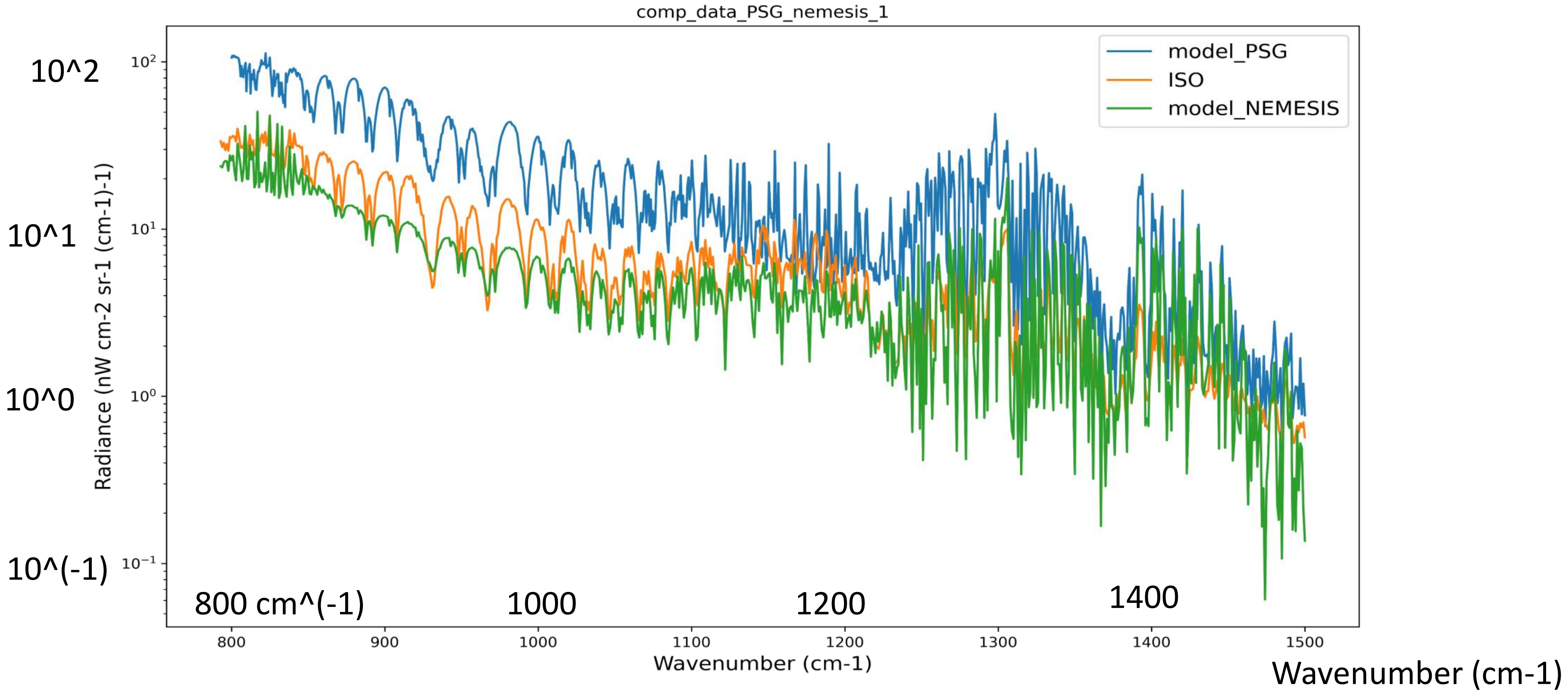
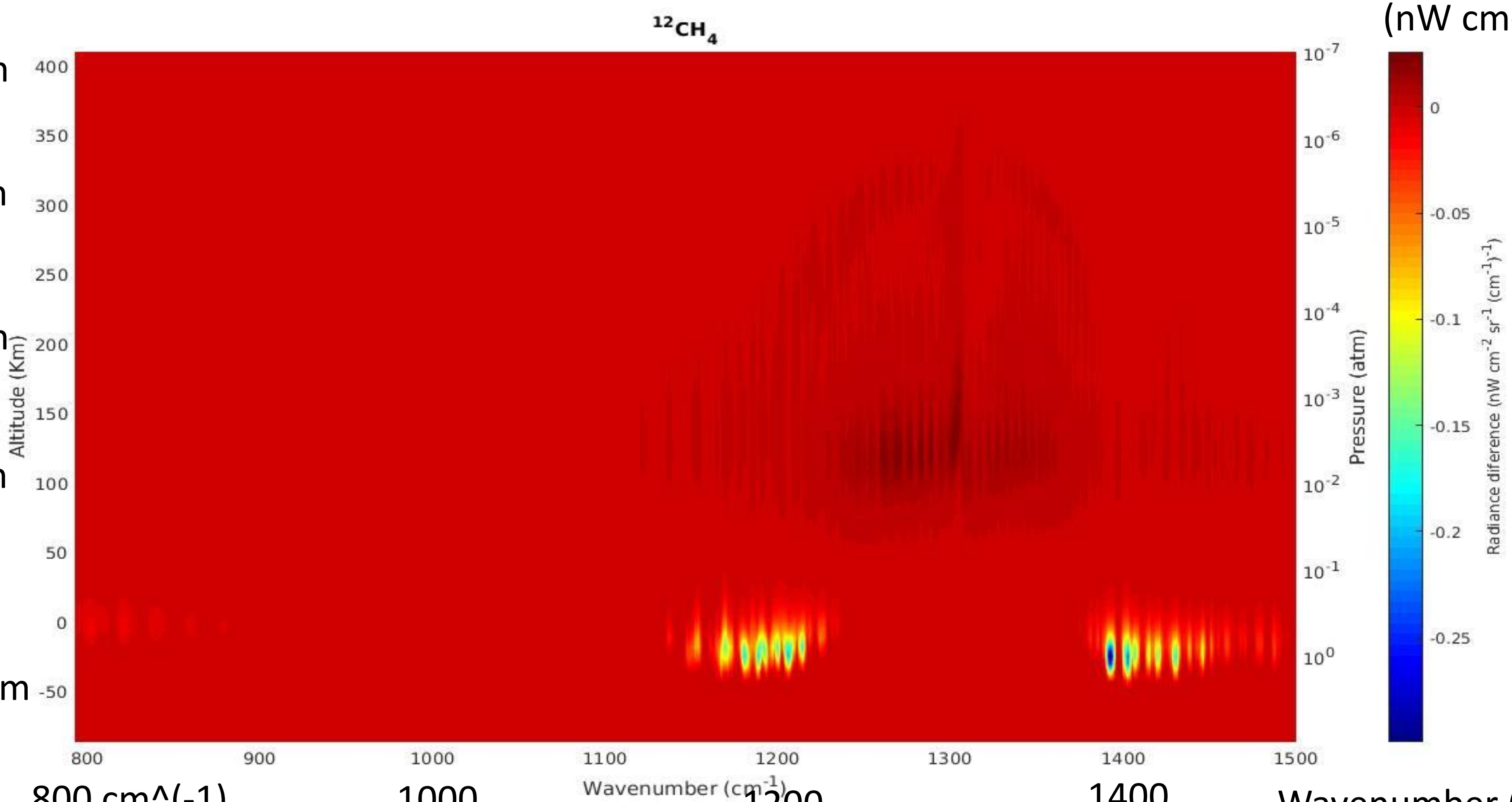


Fig.8. Comparison between ISO data (orange) and modelling. PSG model – blue, NEMESIS model - green

Constraining the methane abundance
800-1200 cm-1

Radiance difference
(nW cm-2 sr-1 (cm-1)-1)

400 Km
300 Km
200 Km
100 Km
-50 Km



0
-0.1
-0.2

800 cm^(-1) 1000 1200 1400 Wavenumber (cm-1)

Fig.9. Radiance variation in response to a 5 % variation of the CH4 abundance, for each pressure layer of the model atmosphere, using NEMESIS.

Fitting the T and the CH4 abundance
800-1200 cm-1

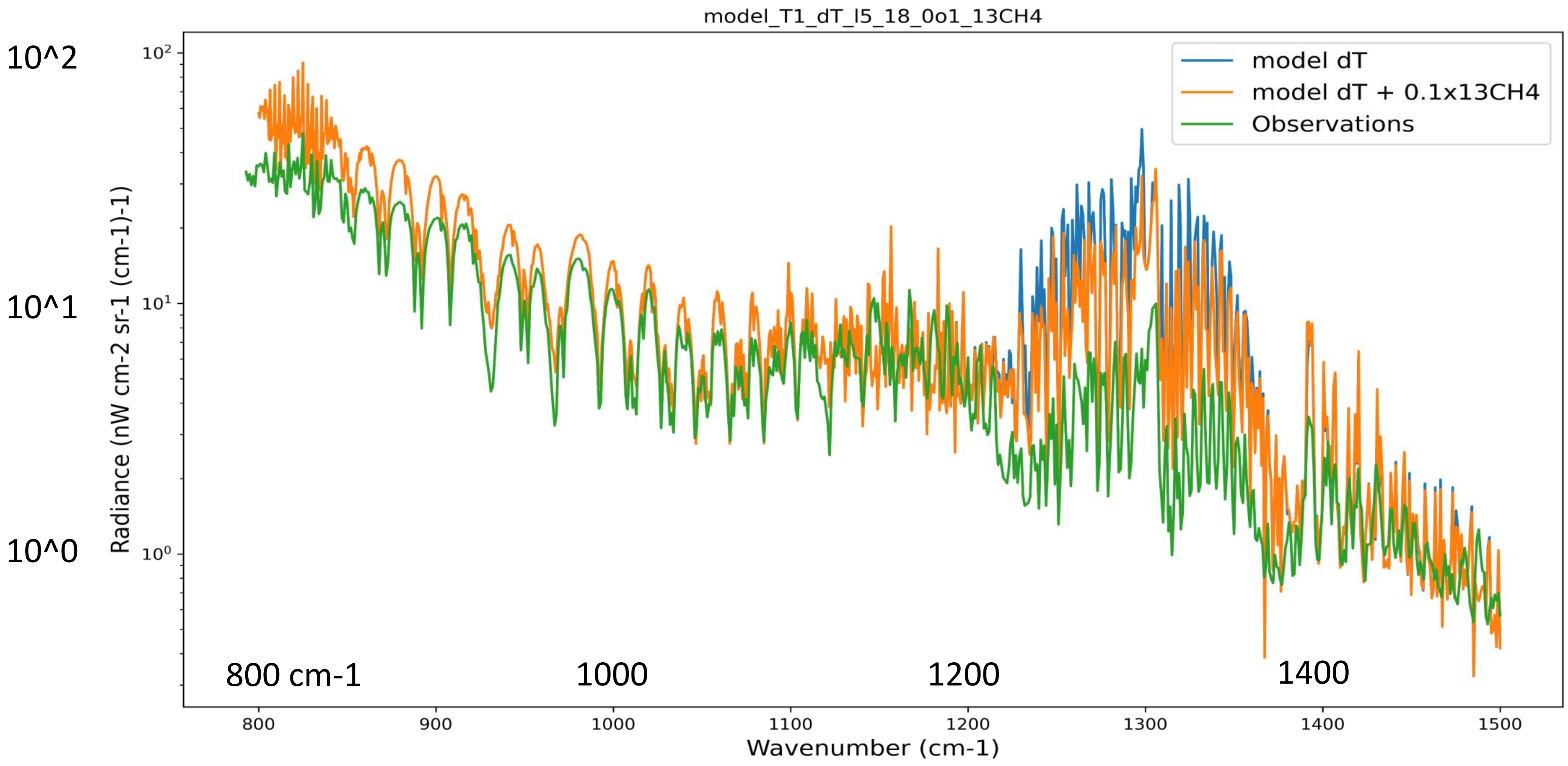


Fig.10. Comparison between ISO data (orange) and fitted models. ISO data – green, PSG best fit - orange

Conclusions and prospects

- Positive detection of SO_2 and estimated abundance in agreement with literature (Encrenaz+2012). Ongoing work on simulation of vulcanic plumes.
- The sensitivity of the PSG model to small variations of H_2O and SO_2 was explored to study the Effect of possible vulcanic plumes on the spectra of Venus (EnVision mission)
- The historic detection of methane by Mars Express was reproduced using PSG.
- Determination of D/H on Jupiter with PSG and NEMESIS is ongoing.
- Ongoing work in the context of the EnVision and Ariel space missions


Thank you!!

Acknowledgments

- We thank **Thérèse Encrenaz**, from LESIA, Observatoire de Paris, for all the support and fruitful discussion; **Geronimo Villanueva**, from NASA-Goddard Space Flight Center, for discussing issues regarding PSG; **Marco Giuranna**, PI of the PFS instrument of Mars Express (ESA), **Alejandro Cardesin**, from ESAC-ESA, **Ann Carine Vandaele**, PI of the NOMAD instrument of ExoMars (ESA) and **Severine Rober**t, from the ExoMars team, for all the support regarding Mars dedicated research; **Gabriella Gilli (IAA)**, for the collaboration regarding the LMD-VGCM model; **Patrick Irwin**, from the University of Oxford (UK), and my colleague **José Ribeiro**, for the collaboration under the NEMESIS radiative transfer code; **Asier Munguira**, from the University of the Basque Country, for his availability to discuss atmospheric research methods in the context of the present work; **Constança Freire** for the fruitful and ongoing collaboration regarding the study of possible vulcanic plumes on Venus, in the context of the EnVision mission.

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ia instituto de astrofísica e ciências do espaço

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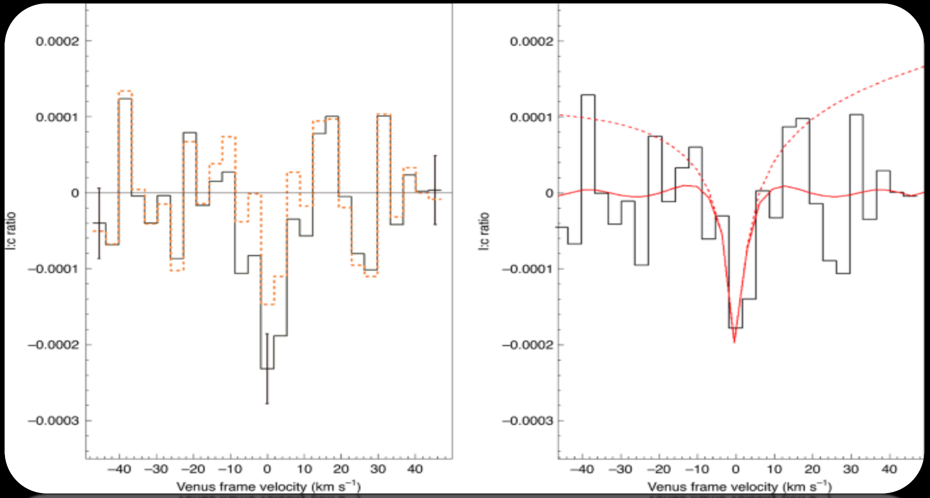
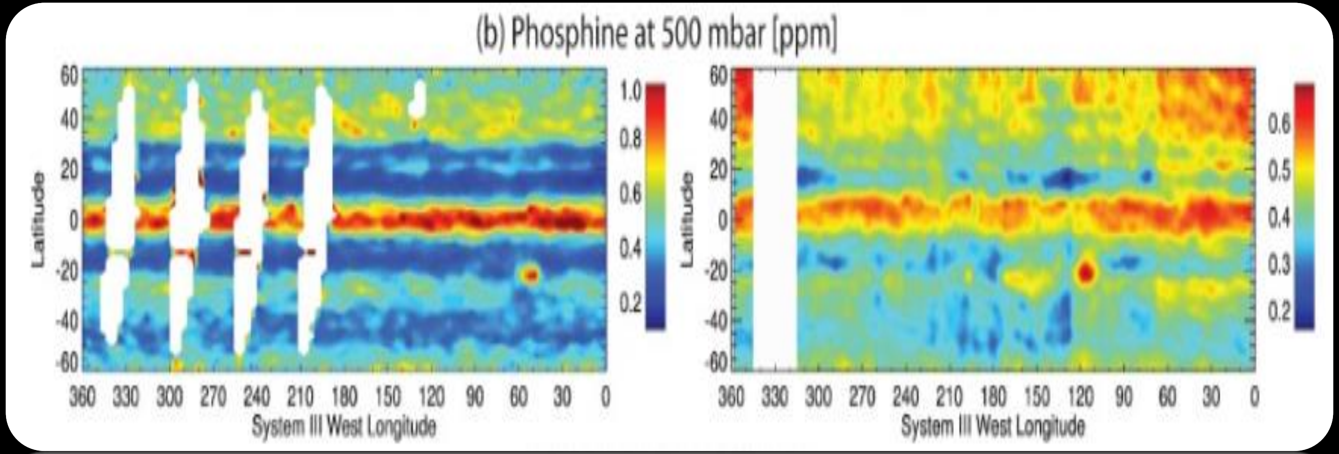
Extra slides
Observations

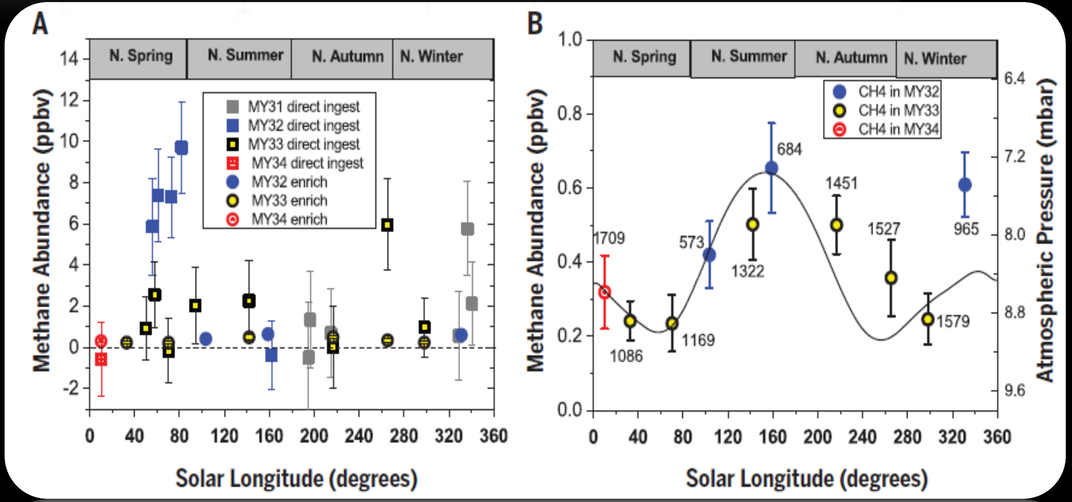
Phosphine and methane as (possible) Biosignatures



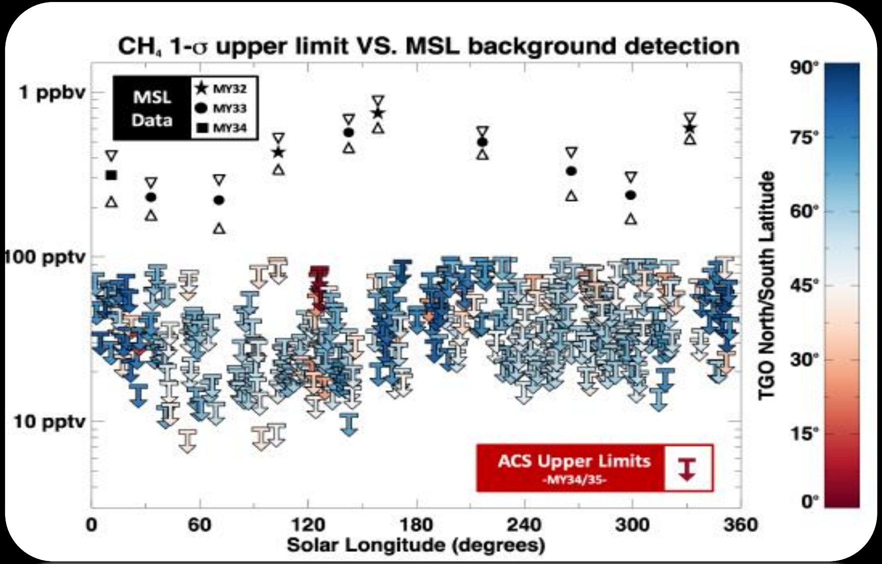
Greaves+2020



Fletcher+2016

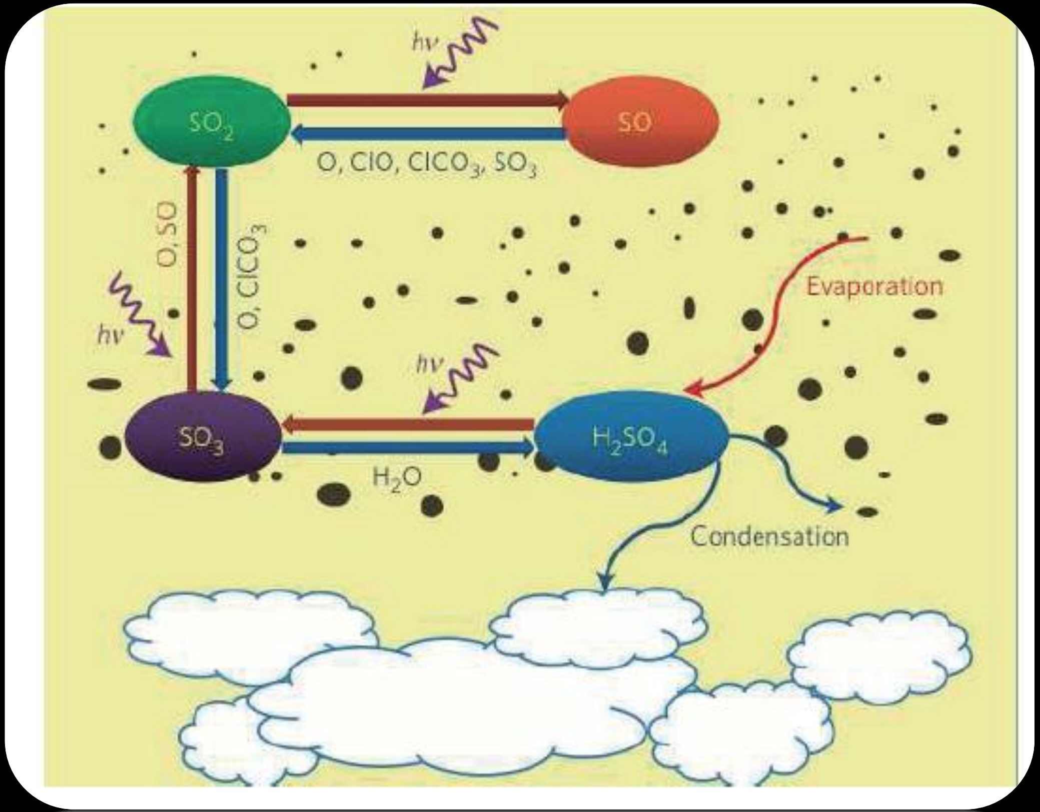


Webster+2021

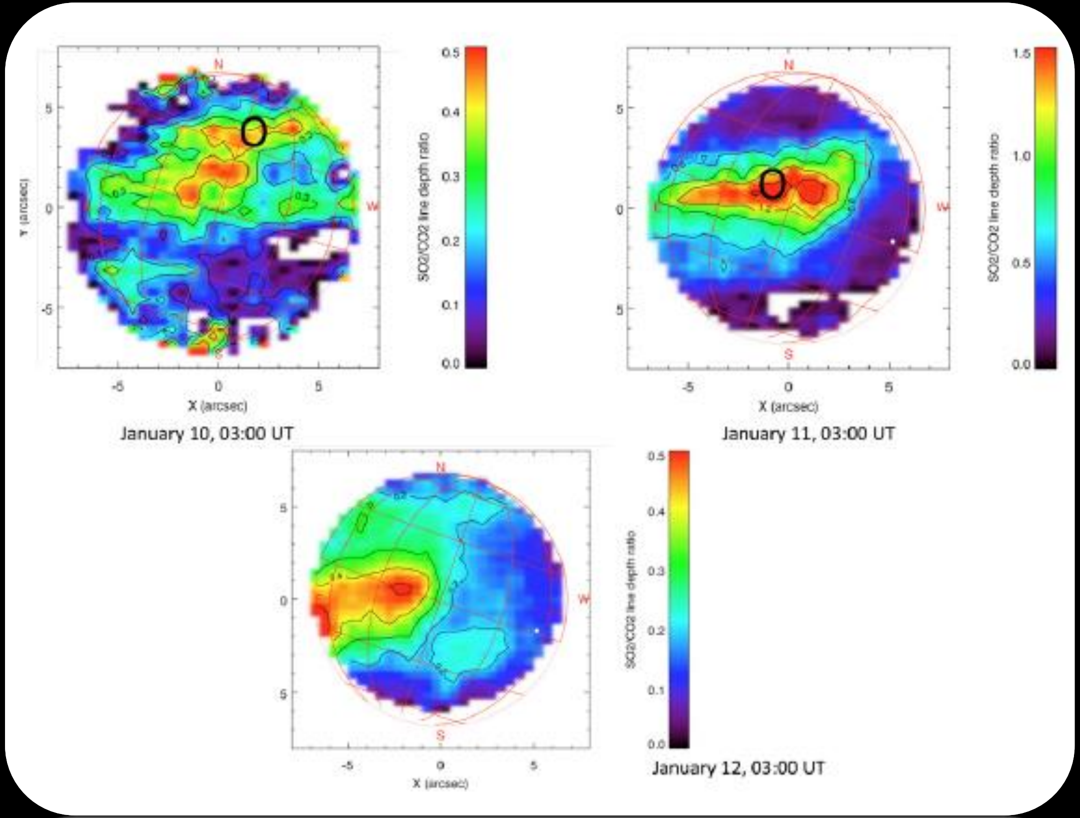


Korablev+2021

The Importance of Sulphur Dioxide



Zhang et al. 2012



Encrenaz et al. 2012

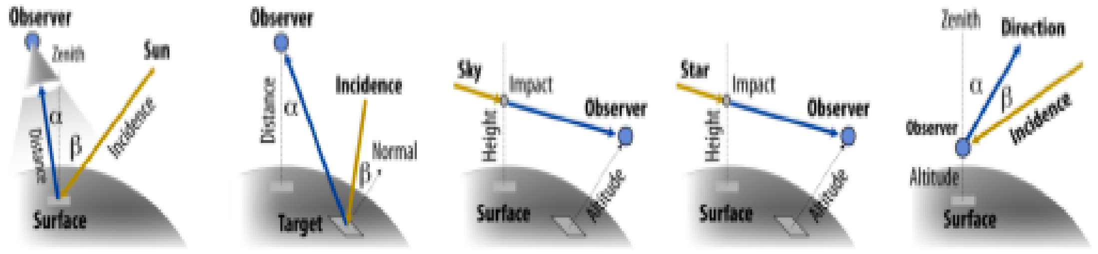
Atmospheric Composition

Composition of the Atmospheres of Earth, Venus, Mars, and Titan

Species	Earth	Venus	Mars	Titan
N_2	0.7808	0.035	0.027	0.98
O_2	0.2095	0–20 ppm	0.13 ppm	
CO_2	385 ppm (*var*)	0.965	0.953 (*cond*)	10 ppb
CH_4	3 ppm (*var*)		33 ppb (*var*)	0.016 (*cond*)
H_2O	<0.03 (*var*) (*cond*)	50 ppm	0–300 ppm (*cond*)	0.4 ppb
Ar	0.009	70 ppm	0.016	30 ppm (Ar^{40})
CO	0.2 ppm	50 ppm	700 ppm	10 ppm
O_3	10 ppm		0.01 ppm	

Species	Jupiter	Saturn
H_2	0.864	0.881
He	0.136	0.11-0.16
H_2O	$2-20\times10^{-9}$ (P<50 mbar)	1.7×10^{-7} (strat)
	6×10^{-4} (19 bar, cond)	
CH_4	2.1×10^{-3}	4.5×10^{-3}
NH_3	2.6×10^{-4} (cond)	5×10^{-4} (cond)
	8×10^{-4} (8 bar)	
H_2S	7.7×10^{-5} (16 bar) (reac)	(4×10^{-4}) (reac)
PH_3	6×10^{-7} (dis)	7×10^{-6} (dis)
C_2H_2	$3-20\times10^{-8}$ (phot)	2.1×10^{-8} (phot)
C_2H_6	$1-5\times10^{-6}$ (phot)	3×10^{-6}(phot)

Geometry of Observation



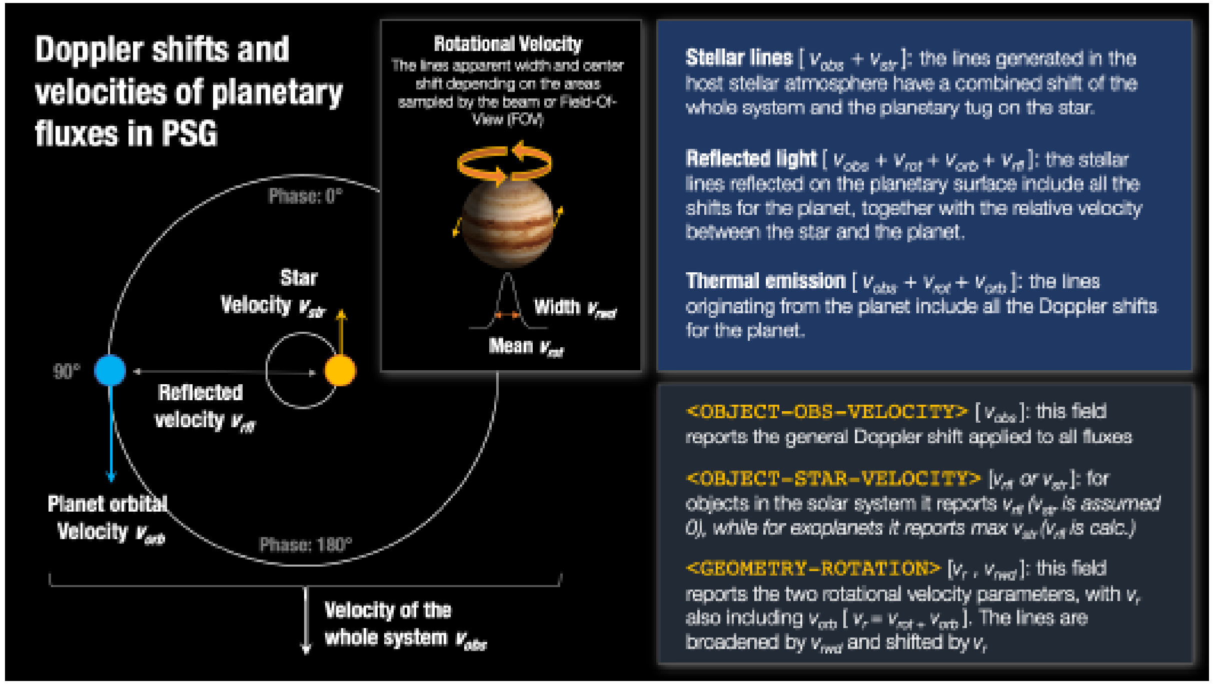
Observatory: in this configuration the observer is located above the sub-obs location, and lateral displacements (x/y) are entered as offsets.

Nadir: in this configuration the observer is located above the sub-obs location, and only the distance (z) and angle relative to this point are defined. Of relevance to orbiters.

Limb: in this configuration the observation is performed tangentially to the surface towards empty space. The sub obs point defines the shortest distance to the surface.

Solar/stellar occultation: in this configuration the observation is performed tangentially to the surface towards the sun or a star. The sub-obs point defines the shortest distance to the surface.

Looking up: in this configuration, the observer is located at a specific altitude and observes upwards. Of relevance for computing telluric radiances / transmittances.



Atmosphere – Composition and Thermal Sctructure

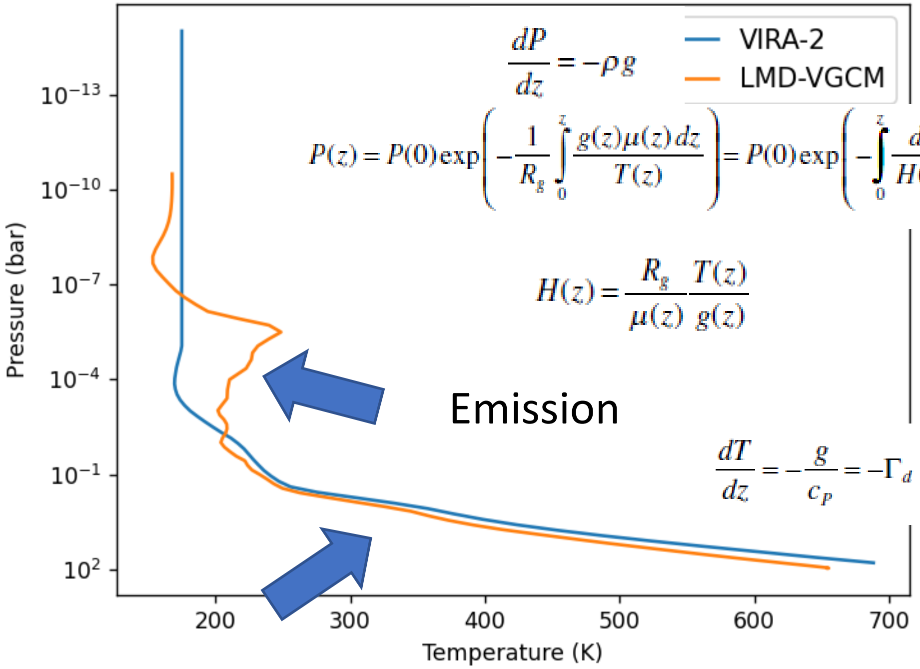
Hydrostatic Equilibrium

$$\frac{dP}{dz} = -\rho g$$

$$P(z) = P(0)\exp\left(-\frac{1}{R_g}\int_0^z \frac{g(z)\mu(z)\,dz}{T(z)}\right) = P(0)\exp\left(-\int_0^z \frac{dz}{H(z)}\right)$$

$$H(z) = \frac{R_g}{\mu(z)}\frac{T(z)}{g(z)}$$

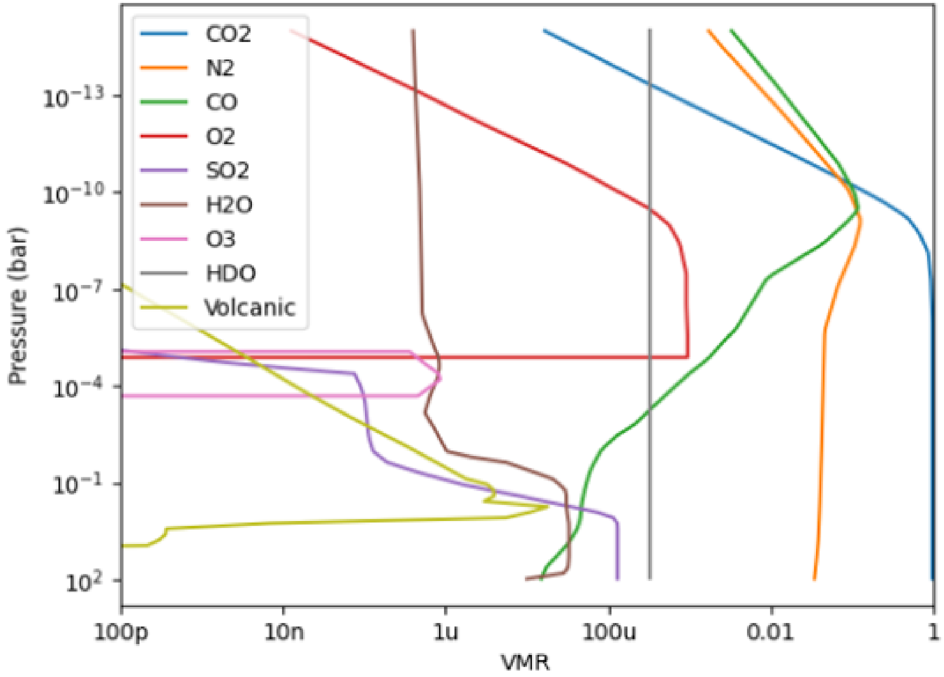
$$\frac{dT}{dz} = -\frac{g}{c_p} = -\Gamma_d$$



Emission

Absorption

Adiabatic lapse rate



Instrument Parameters