Mem. S.A.It. Suppl. Vol. 12, 66

Memorie della
Supplementi

A simple Radiative Transfer model for the atmosphere of Saturn from the Cassini/VIMS observations

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Abstract. A simple Radiative Transfer model has been developed for the Saturn's atmosphere and convalidated using the VIMS images data. VIMS (Visible Infrared Mapping Spectrometer) is one of the instruments on board the Cassini spacecraft, that has been in orbit around the ringed planet since July 2004, still sending its data to Earth. VIMS is an image spectrometer able simultaneously the scene and spectral information of the target under observation, covering the visible and near infrared part of the electromagnetic spectrum. In order to test the model, we simulated the radiance spectra inside a hot spot that, for its particular dynamical structure, is characterized by low optical depths. This means that the model can theoretically sound all the tropospheric layers, down below to the deeper levels as well, in contrast to the rest of the planet. All the simulated radiances have been realized using a line by line radiative transfer code, based on the spectroscopic archives HITRAN (HIgh TRANsmission molecular absorption database). The simulation covers the atmospheric emission in the spectral interval between 4.4 μm and 5.4 μm. The main gaseous constituents of the atmosphere have been taken into consideration in the chemical model, with varying mixing ratios. The simulations have demonstrated the potential to investigate the internal dynamic of the hot spots using phosphine (PH3) abundance as a tracer. Phosphine, formed at the deeper levels of the atmosphere of Saturn and then destroyed by photodissociation in the stratosphere, plays a very important role for our understanding of the upwelling forces generated in the regions of the planet too deep to sound directly. The model is able to reproduce well the observed spectra in almost the total range sounded, with the exception of the portion around 4.8 μm.

Key words. Saturn's atmosphere, RT model, *hot spot*, sinthetic spectra.

1. Introduction

The Cassini orbiter provides the opportunity to investigate the chemistry and dynamics of the atmosphere of Saturn through its Visible and Near-Infrared Mapping Spectrometer (VIMS), which takes images and spectra in the near-infrared. Here we describe development of a radiative transfer model that allow use of VIMS data to explore the dynamics and com-

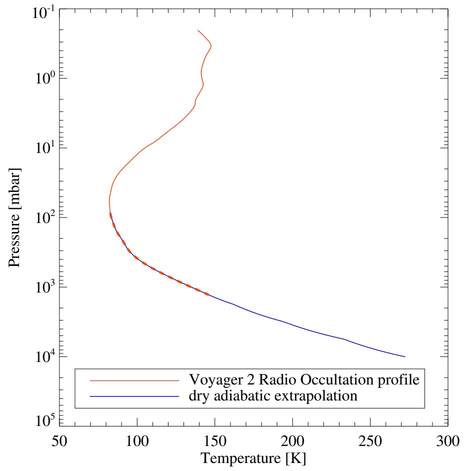

Fig. 1. Temperature, pressure and altitude profiles: the Voyager 2 , with bottom at 1.3 *bar* (red line) and the adiabatic extrapolation one (blu line), partially overlayed around 1 *bar* (red dots).

position within regions of excess thermal emission on Saturn, called "*hot spots*". We focus in particular on the phosphine abundance and its relationship to vertical motions in the hot spot regions.

2. The simulation

The model simulates the atmosphere of Saturn as a mixture of 9 different gases using ARS, a radiative transfer code developed by Ignatiev (2005) and based upon the spectroscopic database HITRAN 2004. In origin, the code was developed for the atmosphere of Mars to convalidate the PFS (Planetary Fourier Spectrometer) data, an instrument of the Mars Express's payload. Currently, it's used by the VIRTIS (Visible InfraRed Thermal Imaging Spectrometer) team, in the Venus Express mission.

The simulation of the atmospheric emission was performed in the spectral interval $4.2 \div 5.2$ μm where the atmospheric radiation comes from the inner regions of the planet. Every simulated radiance hence, is considered as the thermal emission of the planet, considered as a black body, modulated by the absorption of the involved costituents. The chemical model takes into account the main molecules which the atmospheres of giant planets are made of: H_2O, CH_4, NH_3, PH_3, $^{12}CH_4$, $^{13}CH_4$, CH_3D, CO and GeH_4. H_2 has been also considered to define the *continuum* level of IR emission. All these species are spectroscopically and optically active in the considered range.

For the simulations, we have chosen the temperature-pressure profiles taken from Voyager 2 Radio Occultation data (Lindal 1982). The profile, calculated with the radio occultation technique, is only able to reach the 1.3 *bar* as bottom level. According with the real *hot spot* condition, our model needed to get deeper in pressure values, hence a dry adiabatic profile has been extrapolated down to the 10 *bar* level. Fig.1 shows both of them.

The atmosphere has been split in 55 layers, with a constant layering step of 5 *Km*, assuming constant, inside every single layer, all the calculated physical parameters. The pressure covers the $80 \div 10^4$ *mbar* range and the temperature $82 \div 270$ *K* for a total altitude of 270 *Km*.

Fig.2 shows the mixing ratio versus pressure plot of the profiled gases, while the others are mantained constant along all the atmospheric layers and their values are shown in Table 1. The water vapor mixing ratio profile was taken from Atreya (1999), the phosphine and ammonia profiles from Fletcher (2007).

Next, we have synthesized a Line-By-Line (LBL) spectrum, using a 400.000 points grid with a resolution of 0.001 cm^{-1}, and we have calculated the absorption coefficient for every species in the mixture. A Voigt line shape function with truncated wings has been assumed. The cutoff has been chosed at 500 cm^{-1} from the line center.

Then the radiance, computed by ARS at high spectral resolution, has been convolved with the instrumental transfer function (gaussian with 19.0 *nm* of FWHM) gridded on the instrument's channel wavenumbers and then adapted to the wavelength units, in order to have the resulting spectrum in equally spaced wavelengths, as the comparison with VIMS requires. The parameters used for the simulation are listed in Table 2. All the instrumental data

Table 1. *a priori* mixing ratio values and references. Mixing ratio are given relative to H_2, only hydrogen value is referred to the total atmosphere.

[H2]	0.964	Conrath (1984)
[CH4]/[H2]	4.4 e-3	Encrenaz (2005)
[CH3D]/[H2]	3.2 e-7	Encrenaz (2005)
[GeH4]/[H2]	2.0 e-9	de Graauw (1997)
[CO]/[H2]	1.0 e-9	Encrenaz (2005)
[PH3]/[H2]	profiled	Fletcher (2007)
[NH3]/[H2]	profiled	Fletcher (2007)
[H2O]/[H2]	profiled	Atreya (1999)

Table 2. Main parameters used for the simulation.

Molecules	H_2O, CH_4, NH_3, PH_3, $^{12}CH_4$, $^{13}CH_4$, CH_3D, CO, GeH_4, H_2	-
Wavelength range	4400 ÷ 5400	[nm]
LBL wavenumber range	1850 ÷ 2250	[cm^{-1}]
LBL resolution	0.001	[cm^{-1}]
Wings cutoff	500.0	[cm^{-1}]
LBL grid points	400.000	-
VIMS channels	38	-
Gaussian FWHM	19.0	[nm]

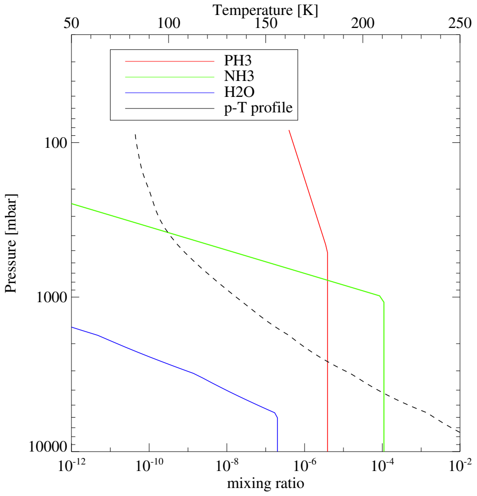

Fig. 2. Non constant value mixing ratio profiles of the molecules used in the simulation. Values and references are summarized in Table 1.

have been taken from the official ancillary data header file, linked to the observation.

Moreover, in order to evaluate the depth of the sounding for understanding the atmospheric levels where the maximum signal comes from, we have defined the transmittance and the Contribution Function for all of the species and for the total atmosphere as well. The calculation of Contribution Functions has been done using the monochromatic outputs of the code convolved on the instrumental grid in the same manner previously described. In Table 3 we report the results for the main significant wavelengths with the related maximum pressure levels sounded.

The code was never used before with the atmosphere of giant planets so, as first trial, we have set as radiative conditions for the calculations, the simplest ones. We consider only the planet emission with no solar contribution, any opacity source (clouds, aerosols,...) and only nadir looking geometry (view angle $< 30°$).

The VIMS data are two dimensional, high resolution multi-spectral images named 'qubes' due to their informatic architecture. Being the spacecraft still orbiting around Saturn, a huge amount of data are avaible for different scientific purposes.

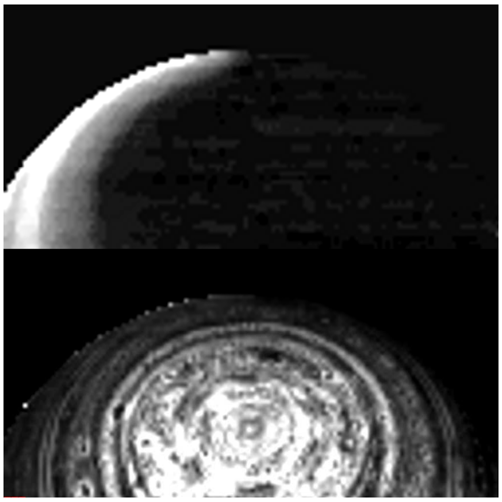

Fig. 3. Same image of Saturn north pole seen at two different wavelengths. At 2 μm (upper picture) and at 5 μm. The gray scale emphasizes the thermal emission (white colored) that comes from the inner regions of the planet.

Anyway, because our very simple model, the requests of no solar source, no clouds and nadir pointing have been a strong 'filters' for the choice of the right images. The image used is a mosaicking of two very close observations (V1549719317_1.QUB_IRCAL_1, V1549719808_1.QUB_IRCAL_1.) of the north pole of the planet, acquired the 9 february 2007 during the S27 orbit, when the spacecraft was at 1.6 MKm from the target. It's a night side observation and is shown in gray scale in Fig.3. We can see the cold and warm parts of the planet, *hot spots* are visible as well, localized along the middle latitude and polar zones.

In order to verify the code and the goodness of the choices of model we have calibrated the image in units of radiance[1], looking for the hottest regions. In Fig.4 the same image is in false color to emphasize the contrast between the relatively clear sky zones, where thermal emission comes out, and the clouds covered ones, where the opacity attenuates the signal. Moreover, the image shows (in a yellow box) a *hot spot* structure located around 70° N latitude and 100° E (III° system), extremely brigth.

[1] erg/[s cm^{2}str nm]

The reason of the choice of this image is now evident.

The clearness of atmosphere at 5 μm assures that the contribution of clouds to the signal is negligible and the night side condition of the observation, on the other hand, assures the exclusion of the solar contribution as well.

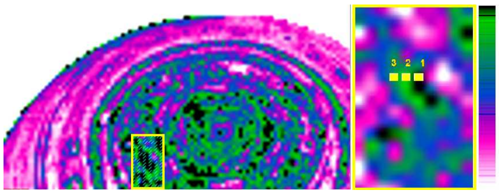

Fig. 4. Radiance calibrated image. On the left: image at 5 μm in false color with a yellow boxed region, zoomed in the right panel. Are visible the three pixels that cover the *hot spot* from the 'eye' to the external collars. The radiance color scale at right covers, from down to up, the $(2.56\ 10^{-2} \div 9.78\ 10^{-2})$ erg/(s cm^2 str nm) range.

Next, the spectra of three different pixels have been choosen, from the center of the *hot spot* structure towards the outside. As first order of approximation, we can consider negligible the effect of the opacity of the clouds, in the sourranding collars of the center, to the signal so that the change in level of the spectra of the three pixel, can be considered due only to the different mixing ratio species quantity.

The spectrum of Saturn in the considered range, has a very strong absorption feature centered around 4750 nm due to phospine. To understand if the three spectra were differents in terms of band depth, a comparison of the depth of the band at 4721 nm with the value of the spectrum at 5041 nm as reference, has been done for the considered spectra.

Finally, a synthetic spectra database has been created and used to find the best fit between the observed spectra and the synthetic ones. Notice that, the database is valid for a generic giant planet-like atmosphere in the sounded spectral interval and can be used for different simulations that can be completely independent by the actual VIMS data.

What we found is that our model has a good agreement with the observations until it

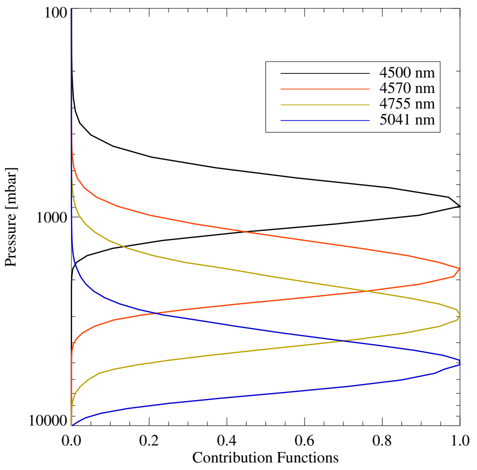

Fig. 5. Normalized Contribution Functions for different instrumental wavelengths. We report the pressure levels in Table 3.

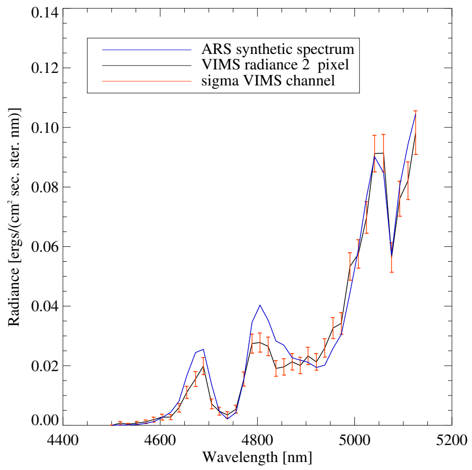

Fig. 7. Simulated spectrum of the collar near the centre. It's referred to the pixel # 2.

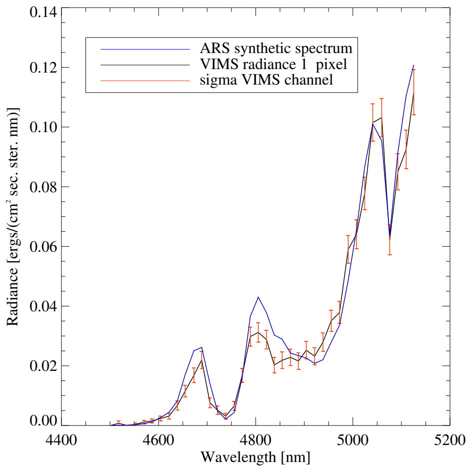

Fig. 6. Simulation of the centre of the *hot spot*. It's referred to the pixel # 1. The shape of all the simulated spectra in the next three pictures seems quite similar but the radiance level is different.

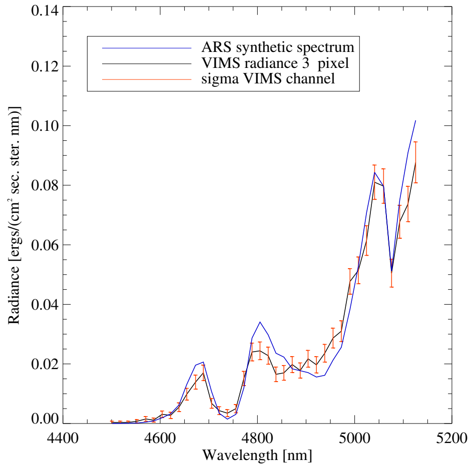

Fig. 8. Spectrum of the environment near the collar. It's referred to the pixel # 3.

reproduces the higher part of the atmosphere ($< 3\,bar$, $< 4750\,nm$), but when it tries to simulate the deeper part ($> 3\,bar$, $[4750 \div 5000]\,nm$), the p-T profile used isn't able to describe the real one. In Fig.6, Fig.7 and Fig.8 are shown the three real spectra with the relative synthetic ones.

3. Future development

A retrivial technique, based on functional derivatives and Jacobian matrix, is planned in

Table 3. Wavelengths and relative pressure levels sounded by the Contribution Function. Only the most significative wavelengths values are reported. The model can't sound pressures below ∼ 5 *bar*

VIMS channel [*nm*]	Pressure max [*mbar*]
4500	890
4570	1770
4755	2946
5041	5100

order to evaluate the change in radiance of the synthetic spectra with respect to all the other variables, in order to determine the best p-T profile for every observations. Temperature change in the layers sounded by the (4750 ÷ 5000) *nm* range should be able to reproduce much better the observed spectra in the same range. Moreover, the chemical model is still not complete. The introduction of the *continuum* due to the H_2−He interaction and the absorption features of arsine (AsH_3), active around 4700 *nm* will help us to reproduce in a better way the spectra.

The main goal of this work was the setting up of a simulation that could reproduce the atmospheric conditions within Saturnian hot spots, so that we may understand what is the VIMS sensitivity in tracing the various charateristics of the Saturnian atmosphere. This knowledge will be used to retrieve key properties of the Saturnian atmosphere by means of VIMS multispectral imaging observations.

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