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Retrieval of Venus' cloud parameters from VIRTIS nightside spectra in the latitude band 25°-55°N

Davide Magurno [a,*], Tiziano Maestri [a], Davide Grassi [b], Giuseppe Piccioni [b], Giuseppe Sindoni [b]

[a] Department of Physics and Astronomy, University of Bologna, Viale Carlo Berti Pichat 6/2, 40127, Bologna, Italy
[b] INAF-IAPS, Via del Fosso del Cavaliere 100, 00133, Roma, Italy

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ABSTRACT

Two years of data from the M-channel of the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS), on board the European Space Agency mission Venus Express operating around the planet Venus, are analysed. Nocturnal data from a nadir viewpoint in the latitude band 25°N-55°N are selected for their configuration advantages and maximisation of the scene homogeneity. A reference model, and radiance spectrum, is defined based on average accepted values of the Venus main atmospheric and cloud parameters found in the literature. Extensive radiative transfer simulations are performed to provide a synthetic database of more than 10 000 VIRTIS radiances representing the natural variability of the system parameters (atmospheric temperature profile, cloud H_2O—H_2SO_4 solution concentration and vertical distribution, particle size distribution density and modal radius). A simulated-observed fitting algorithm of spectral radiances in window channels, based on a weighting procedure accounting for the latitudinal observed radiance variations, is used to derive the best atmosphere-cloud configuration for each observation.

Results show that the reference Venus model does not adequately reproduce the observed VIRTIS spectra. In particular, the model accounting for a constant sulphuric acid concentration along the vertical extent of the clouds is never selected as a best fit. The 75%/96% and 84%/96% concentrations (the first values refer to the upper cloud layers and the second values to the lower ones) are the most commonly retrieved models representing more than 85% of the retrieved cases for any latitudinal band considered. It is shown that the assumption of stratified concentration of aqueous sulphuric acid allows to adequately fit the observed radiance, in particular the peak at 1.74 μm and around 4 μm.

The analysis of the results concerning the microphysics suggests larger radii for the upper cloud layers in conjunction with a large reduction of their number density with respect to the reference standard. Considerable variation of the particle concentration in the Venus' atmosphere is retrieved for altitudes between 60 and 70 km. The retrieved models also suggest that lower cloud layers have smaller particle radii and larger number density than expected from the reference model. Latitudinal variations of microphysical and chemical parameters are also analysed.

1. Introduction

The current knowledge of the nature and properties of the Venus' aerosols derives from a variety of sources, including ground based observations, satellite remote sensing and in situ measurements by entry probes and balloons. In particular, data from the Pioneer probe nephelometer were fundamental to depict the overall scenario that is still considered valid today (Knollenberg and Hunten, 1980). From space to surface, we first meet a population of sub-micron haze, detected yet at about 100 km. A second micron-size component shows up below 70 km. This is the main constituent, in terms of mass, of the upper clouds of Venus and has a large impact on what is typically observed from space at visible and infrared (IR) wavelengths. A local minimum in cloud opacity at about 57 km marks the transition to what is considered the middle/lower cloud deck, where larger particles are found. The altitude of 48 km shows a sharp decrease in aerosol opacity, and below only optically thinner diffuse haze and spotted clouds of uncertain nature can be found (e.g. Grieger et al., 2003). In situ analysis (Hoffman et al., 1980), as well

* Corresponding author. Present address: Department of Physics, University of Roma Tor Vergata, Via Della Ricerca Scientifica 1, 00133, Roma, Italy.
E-mail addresses: davide.magurno@roma2.infn.it (D. Magurno), tiziano.maestri@unibo.it (T. Maestri), davide.grassi@iaps.inaf.it (D. Grassi), giuseppe.piccioni@iaps.inaf.it (G. Piccioni), giuseppe.sindoni@iaps.inaf.it (G. Sindoni).

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as remote IR (Zasova et al., 2007) and polarimetric measurements (Hansen and Hovenier, 1974) have allowed to identify a liquid mixture of sulphuric acid and water as the main constituent of haze and upper clouds. Consistently, the clearing observed at the altitude of 48 km is met where Venus' environmental temperature allows the sulphuric acid to evaporate Krasnopolsky and Pollack (1994). Other components fill the atmosphere as well: UV observations show high contrasting details, demonstrating the existence of a still unidentified UV absorber, strongly variable in space and time (e.g. Markiewicz et al., 2007); the VEGA balloon instruments clearly suggest the presence of Chlorine, Phosphorus and Iron in unknown components of the deeper clouds (Andreichikov et al., 1987).

The long observing campaign of Venus Express from 2006 to 2014 represents a milestone in the exploration of the Venus' atmosphere. The large suite of instruments operating from thermal IR (5 μm) to UV enables a series of studies, mostly focused on upper clouds and hazes. Several efforts have been performed and some are resumed in what follows. The studies of latitudinal trends in upper cloud heights and scale heights by Ignatiev et al. (2009), Lee et al. (2012) and Haus et al. (2014) from VIRTIS nadir data demonstrated that both parameters decrease poleward from about 50° in latitude. The sun occultation measurements by SPICAV/SOIR (Wilquet et al., 2012) demonstrated that haze presents occasionally detached layers (also found by SPICAV/IR, Luginin et al., 2014) and that also haze is characterized by a bi-modal size distribution, making therefore weaker the distinction between haze and upper clouds. A recent study of phase functions derived from VMC nadir observations by Shalygina et al. (2015) shows that sub-micron particles are preferentially found on the morning hemisphere and highlighted an increase of refractive index in the region between 40°S and 60°S, as well as a slight increase of the size for the so-called "mode 2" population toward the poles (a conclusion also found by Wilson et al., 2008).

The main objective of the present study is to provide a statistical retrieval of the Venus' cloud chemical and microphysical properties by exploiting VIRTIS data in the nadir viewing geometry. Some previous studies on cloud analysis based on VIRTIS data focused on the Venus' southern hemisphere (e.g. Barstow et al., 2012; Haus et al., 2014); however, the pixel footprint of the instrument is smaller over the northern hemisphere, so that it is expected that the atmospheric variability within a single pixel is also smaller and a more detailed analysis can be performed. Nighttime data are necessary to avoid the solar scattering, that would completely mask the deep cloud spectral features. VIRTIS data are then compared with a large synthetic dataset of spectral radiances computed with DISORT on the modelled atmosphere and clouds. The new approach on the clouds modelling is to consider them as vertically non-uniform in sulphuric acid concentration instead of a homogeneous layer as usually done (e.g. Zasova et al., 2007; Bézard et al., 2011).

A short overview of the instrument is given in Section 2. In Section 3 we explore the data archive and data selection. Section 4 defines the initial model for the Venus' atmosphere. Some sensitivity analysis is performed in Section 5. In Sections 6 and 7 we define the parameters for the creation of a synthetic dataset and the fitting of observed data with the synthetic ones. The dataset analysis is performed in Section 8. Finally, the conclusions are presented in Section 9.

2. VIRTIS on Venus Express

The Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) is a diffraction spectrometer on-board Venus Express (VEx), a mission of the European Space Agency (ESA) operating around the planet Venus from 2006 until the end of 2014. The orbit was highly elliptical, near-polar, 24 h, with the pericentre located between 80°N and 90°N at about 250 km altitude and the apocentre located approximately 66 000 km above the surface. The Venus Express mission is based on the opportunity to re-fly a spare model of the Mars Express spacecraft and some related payload. In addition, a spare model of the precursor VIRTIS instrument devoted to study the comet 67P/Churyumov-Gerasimenko, has been adapted ad hoc for the Venus environment and then included in the core payloads of VEx. VIRTIS operated in the spectral range from UV to thermal IR in two separated optics, named VIRTIS-M and VIRTIS-H (Piccioni et al., 2007a,b; Erard, 2012). VIRTIS-M had high resolution imaging capability at moderate spectral resolution in the range between 0.25 μm and 5.2 μm. It was in turn divided into two channels, M-VIS from 0.25 μm to 1 μm and M-IR from 1 μm to 5.2 μm. VIRTIS-H had high spectral resolution in the range between 2 μm and 5 μm but without imaging capability. This work focuses on data collected by VIRTIS-M IR. One of the main parameters affecting observations is the exposure time, that can change from 0.02 s to 18 s. The majority of nocturnal observations has an exposure time of 3.3 s for long-lasting observations or 0.36 s for the briefest ones. The advantage in long-lasting records is the high SNR, the disadvantage is the loss of information for wavelengths longer than about 4 μm since the detector is saturated by the thermal background (Piccioni et al., 2007a,b).

3. Data archive selection

The archive of VIRTIS-M IR data consists of a set of measurements collected in 517 orbits performed from 11/04/2006 to 27/10/2008 (after this date the M-channel of the instrument turned off). Each orbit is divided into sub-sections, called *cubes*, characterized by uniform observing conditions, such as the same exposure time and pointing mode. The total number of available cubes is 4537 all over the planet, each of them storing from less than 10 to more than 100 000 individual spectra. Only part of the whole dataset is selected in accordance with the following specific observing conditions: a) Observations above the northern hemisphere, where the orbit is closer to the surface, have a relatively small pixel footprint at nadir. The spatial resolution is about 190 m at 45°N, given that the observation altitude is at around 760 km. Therefore, the observed pixel area is expected to be more homogeneous than in the southern hemisphere; b) Nocturnal observations give more information about the whole vertical extent of the clouds, because the atmospheric radiance is not masked by the solar reflected component; c) Nadir-looking of the instrument is accounted for, limiting the pointing angle to values between 0° and 1 degree off-nadir. In others words, we assume that the upper limit for nadir viewing is 1°. These conditions reduce the dataset to only 90 cubes, on 90 different days, spanning the whole mission lifetime. The useful observations are strongly reduced with respect to the initial database since the majority of nadir observations were taken in the southern hemisphere. To carry out a statistical analysis of the nadir dataset an additional selection is performed, excluding the data outside the latitude band between 25°N and 55°N. This choice allows to maintain a small pixel footprint and to avoid possible interactions with peculiar atmospheric phenomena, such as the cold collar (60–80°N) and the hot dipole (75–85°N) (Zasova et al., 2007; Piccioni et al., 2007a,b). The final selection accounts for a total number of 65 cubes.

As a consequence of the near polar orbit, all the cubes have a similar structure for nadir observations: a very narrow scan in longitude (the maximum width is about 0.8°) but extended in latitude from the north pole to the equator (Fig. 1, left panel). Therefore, atmospheric changes are mainly visible as meridional variations, looking as horizontally homogeneous radiance stripes in the images. Observations are then grouped in 0.2° × 0.2° grid of latitude × longitude (about 21 km × 16 km footprint at 40°N). For each bin, it is assumed that the measured radiance is representative of an homogeneous scene. The choice of the bin size has been made after testing the latitudinal/longitudinal variation of radiance from one pixel to another. Fig. 2 shows an example of radiance variation versus latitude. The latitudinal difference between the two groups of data is about 0.7°. A sensible radiance difference is noticed between the two groups, whereas only small changes are observed along the longitude (as also noticed from the left panel of Fig. 1). Radiance measured at specific wavelengths shows, in some cases, evident outliers mainly due to cosmic