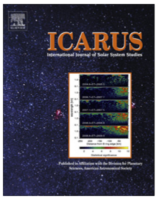
Icarus 226 (2013) 428–436

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Venus nitric oxide nightglow mapping from SPICAV nadir observations

A. Stiepen [a,*], J.-C. Gérard [a], M. Dumont [a], C. Cox [a], J.-L. Bertaux [b]

[a] *Laboratoire de Physique Atmosphérique et Planétaire Université de Liège, Allée du 6 Août, 17, B5c, 4000 Liège, Belgium*

[b] *Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS), Université de Versailles Saint-Quentin, Boulevard d'Alembert, 78280 Guyancourt, France*

ARTICLE INFO

Article history:
Received 6 March 2013
Revised 6 May 2013
Accepted 17 May 2013
Available online 2 June 2013

Keywords:
Ultraviolet observations
Venus
Venus, atmosphere
Atmospheres, Dynamics
Atmospheres, Structure

ABSTRACT

Nitric oxide δ (190–240 nm) and γ (255–270 nm) bands have been observed on the Venus nightside with Venus Express SPICAV instrument operated in the nadir mode. These ultraviolet emissions arise from the de-excitation of NO molecules created by radiative recombination of $O(^3P)$ and $N(^4S)$ atoms. These atoms are produced on the dayside of the planet through photodissociation of CO_2 and N_2 molecules and are transported to the nightside by the global subsolar to antisolar circulation. We analyze a wide dataset of nadir observations obtained since 2006 to determine the statistical distribution of the NO nightglow and its variability. Individual observations show a great deal of variability and may exhibit multiple maxima along latitudinal cuts. We construct and compare a global NO map with the results obtained during the Pioneer-Venus mission and with the recently observed $O_2(a^1\Delta_g)$ nightglow distribution. The NO airglow distribution shows a statistical bright region extending from 01:00 to 03:30 local time and 25°S to 10°N, very similar to the Pioneer results obtained 35 years earlier during maximum solar activity conditions. The shift from the antisolar point and the difference with the O_2 airglow indicate that superrotating zonal winds are statistically weak near 97 km, but play an important role near 115 km. We compare these results with other evidence for superrotation in the thermosphere and point out possible sources of momentum transfer.

1. Introduction

Observations of planetary airglow emissions are a useful tool to remotely probe the characteristics of upper atmospheres. Indeed, the study of airglow morphology, its temporal or geographical variations and its brightness provide valuable information concerning the composition, temperature and dynamics of an atmosphere. In the case of Venus, the presence of the γ (225–270 nm) and δ (190–240 nm) bands of nitric oxide in the nightglow was detected and identified by Feldman et al. (1979) using the ultraviolet spectrograph on board the International Ultraviolet Explorer (IUE) satellite. It was also observed by Stewart and Barth (1979) with the ultraviolet spectrometer on board the Pioneer Venus Orbiter (PV-OUVS). This emission is produced by radiative recombination through inverse predissociation of nitrogen (^4S) and oxygen (^3P) ground-state atoms. These atoms recombine producing NO molecules in the ($C^2\Pi$) state that can relax following the scheme:

$$O(^3P) + N(^4S) \rightarrow NO(C^2\Pi) \tag{1}$$

$$NO(C^2\Pi) \rightarrow NO(X^2\Pi) + \delta\,\mathit{bands} \tag{2}$$

$$NO(C^2\Pi) \rightarrow NO(A^2\Sigma, v' = 0) + 1.22\ \mu m \tag{3}$$

$$NO(A^2\Sigma, v' = 0) \rightarrow NO(X^2\Pi) + \gamma\,\mathit{bands} \tag{4}$$

The widely accepted global picture is that the N and O atoms are mainly created by dissociation of N_2, CO_2 and, to a minor extent, CO molecules on the dayside of Venus by extreme ultraviolet (EUV) photons and photoelectrons. $N(^4S)$ and $O(^3P)$ atoms are then carried to the nightside by the overall global wind circulation. Downward transport takes place on the nightside, followed by radiative recombination providing excited NO ($C^2\Pi$) molecules in the lower thermosphere.

Stewart et al. (1980) analyzed images of the Venus nightside $\delta(0,1)$ band at 198 nm obtained every 24 h with PV-OUVS during a solar maximum period and showed that the emission is highly variable in brightness and morphology over consecutive observations. The location of bright spots in successive global images ranged from 2130 to 0300 LT and 39°S to 60°N, as was confirmed by Bougher et al. (1990). They constructed a global map of the NO UV nightglow showing that the emission is statistically concentrated in a bright spot located near 0200 LT, 10–20° south of the equator. After revisions by Bougher et al. (1990), the estimated vertical emission rate of this bright spot emission was ~1.9 kiloRayleighs (kR) for the $\delta(0,1)$ band, whereas the average hemispheric nightside intensity was 0.45 kR for this emission band (see Table 1). These observations confirmed the general picture of the Venusian N and O global circulation. This concept was numerically validated by a three-dimensional model using the Venus Thermospheric General Circulation Model (VTGCM) (Bougher et al., 1990). The statistical location of the bright spot was well predicted by this

---

[*] Corresponding author.
E-mail address: arnaud.stiepen@ulg.ac.be (A. Stiepen).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.05.031

three-dimensional model and implied retrograde zonal winds of $\sim$50–75 ms^{-1} in the 115–150 km altitude region. The observed shift toward dawn of the statistical location of the airglow maximum was also well reproduced by the VTGCM and interpreted as a persistence of the atmospheric zonal superrotation into the thermosphere. The presence of a helium bulge (Niemann et al., 1980) near the morning terminator appeared consistent with the persistence of a dawnward zonal component into the thermosphere. Niemann et al. (1980) Figure 13 sketched a possible flow pattern in the nightside thermosphere. They proposed that the Coriolis force may divert the flow vectors of the superrotation to a stagnation point at low latitudes close to the morning terminator. Brecht et al. (2011) updated the original VTGCM and decreased the altitude level of the lower boundary to model both the NO and the $O_2(a^1\Delta)$ emissions. They summarized the existence of two different dominating circulation patterns in the Venus upper atmosphere (Dickinson and Ridley, 1977; Schubert et al., 1980, 2007; Bougher et al., 1997, 2006; Lellouch et al., 1997). For an altitude range from the surface to $\sim$70 km, the retrograde superrotating zonal (RSZ) flow dominates. This wind flows in the direction of the planetary spin and is faster than Venus' rotation. Above $\sim$120 km, the SSAS flow pattern is dominant. In the intermediate altitude region, these two flows are thought to be superimposed with relative contributions varying in time and space.

Limb observations of the NO γ and δ emission bands performed by SPICAV have been reported and analyzed by Gérard et al. (2008) and Stiepen et al. (2012). The mean altitude of the emission layer was found at 115 km, with large variations, in agreement with Gérard et al. (1981) who found a peak altitude of 115 ± 2 km from the analysis of PV-OUVS limb scans. The limb brightness depends on latitude and local time and is highly variable with a mean value of 60 kR. Stiepen et al. (2012) used SPICAV grazing limb observations to determine the volume emission rate (VER – in photons cm^{-3} s^{-1}) of NO through the Abel inversion technique. They analyzed the distribution of the deconvolved peak intensity and altitude of the NO UV nightglow and VER, as well as its dependence on latitude, local time, etc. They found that the highest VER values are observed around 0200 LT. Unfortunately, as a consequence of orbital characteristics, limb scans are limited to the northern hemisphere. The highest VER values are located close to the equator in the northern hemisphere. They defined an angle from the statistical brightest spot (ABS) centered on 0200 local time and 10–20°S latitude and found a decreasing trend of the VER intensities with increasing ABS values, thus confirming the presence of the statistical brightest spot previously observed by Stewart et al. (1980). Altitude and brightness information have also been retrieved by Royer et al. (2010) by analyzing the additional atmospheric signal observed during slitless stellar occultation measurements made with the SPICAV instrument. They also used a forward model to derive a peak altitude of 113.5 ± 6 km, a topside scale height of 3.4 ± 1 km and a brightness ranging from 19 to 540 kR for the vertical distribution of the NO UV emissions, in full agreement with the direct spectral observations.

Soret et al. (2010) constructed a global map of the $O_2(a^1\Delta)$ emission around 96.5 km altitude by assembling nadir images taken by the VIRTIS-M-IR instrument (Drossart et al., 2007; Piccioni et al., 2009) on board Venus Express. They also extracted emission profiles of the 1.27 μm emission from limb images obtained by VIRTIS. They derived the equivalent vertical intensity from these profiles by vertical integration of the local emission rate derived from the Abel inversion of the limb profiles. They combined nadir profiles in the southern hemisphere with limb observations in the northern hemisphere to produce a statistical global map of the $O_2(a^1\Delta)$ emission. They found that the region of enhanced emission is located around the antisolar point (Soret et al., 2010, Fig. 1), with a maximum brightness of 1.6 MR and dropping with decreasing solar zenith angle. The mean hemispheric brightness at the nadir of the $O_2(a^1\Delta)$ nightglow was found to be 0.5 MR. The position of the brightest region was previously observed by ground observations (Crisp et al., 1996; Ohtsuki et al., 2005, 2008). This result is counter-intuitive and contradicts the 3-D models (e.g. Bougher et al., 1990) results predicting that superrotation of the atmosphere vanishes in the lower thermosphere. It indicates that the superrotating zonal flow is statistically quite weak near 96 km, but picks up strength again at higher altitude.

In this study, we analyze SPICAV ultraviolet observations collected in the nadir direction in order to construct a global map of the NO emission and analyze its spatial distribution. Our main purpose is to compare the morphology of the nightside NO airglow observed with Venus Express during the low to medium solar activity period 2006–2011 with that observed with PV-OUVS over 30 years ago at high activity. In particular the question arises whether the statistical location of the bright spot was still shifted dawnward from the antisolar point. We first describe the geometry of the observations, signal processing and construction of the airglow map. We then compare these results with those of Pioneer Venus and the recent Venus Express observations of the O_2 Infrared Atmospheric band at 1.27 μm. Finally, we draw some conclusions about the variability of the atmospheric dynamics in the mesosphere-thermosphere transition region.

2. Nadir observations

The Venus Express (VEx) spacecraft (Svedhem et al., 2007)) of the European Space Agency has been orbiting Venus along a quasi-polar eccentric trajectory with a period of 24 h since April 2006. The apocenter is located at 66,000 km, while the altitude of the pericenter varies between 250 km and 185 km. The orbit is fixed in the inertial space and therefore precesses at the rate of 1.6° per day. As a consequence of the precession of the orbital plane with regard to the direction of the Sun, a very large variety of configurations exists on both the day and night sides of the planet. The Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus (SPICAV) ultraviolet spectrometer has been extensively described by Bertaux et al. (2007). SPICAV-UV covers a spectral range extending from 118 nm to 320 nm, entirely including the NO γ (225–270 nm) and δ (190–240 nm)) bands. The detector is a 288 × 407 pixel CCD and the angular field of view of one pixel is 0.7 × 0.7 arcmin. For reasons of telemetry limitations and because of the time needed to read all the lines of the CCD, five adjacent zones of the CCD detector are usually read out. Several observation modes may be selected, namely nadir observations, star pointing for stellar occultations by the Venus atmosphere, fixed point tracking and limb observations, all described by Titov et al. (2006). These data are available from ESA's planetary science archives (http://www.rssd.esa.int/index.php_project=PSA&page=home).

In the nadir observation mode, the width of each spatial bin of SPICAV-UV is 32 pixel lines, corresponding to a field of view of 1.7°. These lines are seen through the large slit (500 μm), providing a spectral resolution of $\sim$15 nm. The planetary area intercepted by the field of view depends on the location of the spacecraft on its orbits and it must be calculated for each individual spectrum. The non-uniform dark current and offset values are carefully subtracted from each individual spectrum, using similar observations performed with a null amplification of the UV image intensifier (see Appendix A). The absolute calibration obtained by observing well-known hot stars spectra is then applied to obtain emission rates of the total gamma and delta NO emission expressed in kilo-Rayleighs (kR). Other intermediate steps are necessary before building up a global statistical airglow map.