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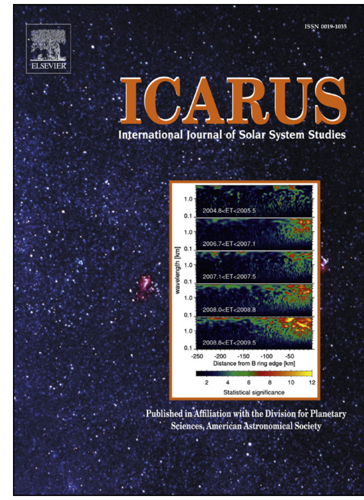

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Lauriane Soret, Jean-Claude Gérard

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Is the $O_2(a^1\Delta_g)$ Venus nightglow emission controlled by solar activity ?

Lauriane Soret[1*]

Jean-Claude Gérard[1]

[1] LPAP, Université de Liège, Liège, Belgium

* Lauriane.Soret@ulg.ac.be

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Abstract

Several past studies showed that the $O_2(a^1\Delta_g)$ Venus nightglow emission at 1.27 μm is highly variable on a timescale of hours. We examine whether the intensity of this emission shows a more global trend linked to solar activity.

1. Introduction

The Venus nightglow has been extensively studied is order to properly understand the upper mesosphere dynamics. It is now assumed that the transition region between 90 and 120 km is mostly governed by the subsolar to antisolar (SS-A) circulation that carries toward the nightside atoms created on the dayside by N_2 and CO_2 EUV photodissociation. There, they recombine to form excited molecules that will produce an observable emission due to radiative deexcitation. The NO ultraviolet and the O_2 infrared nightglow emissions are the most important nightside emissions on Venus. Barth et al. (1967) first detected the NO ultraviolet emission with Mariner 5 observations. Stewart et al. (1980) more systematically studied this emission using Pioneer Venus Orbital UltraViolet Spectrometer (PV-OUVS) observations acquired between May 20, 1979 (orbit 167) and July 2nd, 1979 (orbit 210). They generated an average statistical map of the Venus nightside based on all the available NO nightglow observations. A bright patch reaching 7.5 kR (1 Rayleigh = 10^6 photons cm^{-2} s^{-1} in 4π sr) was observed at ~10°S and 0200 LT. They observed a large variability of the emission from day to day though, both in intensity and morphology but no periodicity was noted. They also investigated the possibility that the intensity variability may be related to the F10.7 cm solar flux index but found no evidence confirming this hypothesis. Actually, the correlation coefficient between the emission intensity and the solar flux was found to be only 5%. At this time, data were obtained during a high solar activity period.

Nearly three decades after Pioneer Venus orbiter, the Venus Express (VEx) spacecraft was launched by the European Space Agency (ESA) on November 2005. Until the end of 2014, the SPICAV (Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus) instrument extensively studied the NO nightglow emission during a low solar activity period. Unfortunately, this spectrometer has no imaging capabilities. Therefore, it is not possible to determine if the brightest patch is actually being observed during a spectral acquisition. Making a similar daily correlation study of the NO brightness with the solar activity was thus not feasible. Here, we study the possible correlation between the solar flux and the O_2 infrared emission using VIRTIS-VEx (Visible and Infrared Thermal Imaging Spectrometer) image observations at 1.27 µm. This question has only been addressed before in the model calculations by Bougher and Borucki (1994). They used the VTGCM (Venus Thermospheric General Circulation Model) for conditions of minimum (SMIN: F10.7=70), medium (SMED: F10.7=150) and maximum (SMAX: F10.7≥200) solar flux. From SMAX to SMED, they showed that the dayside temperature decreases by 25 K in the exosphere and 13 K at 150 km. Instead, temperatures on the nightside of Venus do not change. No significant change of the horizontal wind speeds with respect to the F10.7 variations was predicted either with the VTGCM. Only minor changes have been calculated in dayside and nightside for the atomic oxygen density at ~110 km over the solar cycle. The calculated $O_2(a^1\Delta_g)$ peak intensity reaches 0.49, 0.54 and 0.70 MR for SMIN, SMED and SMAX, respectively. A correlation of the O_2 nightglow with the solar activity is thus predicted to exist, but effects appear to be minor. However, it is important to note that the daily variability observed in the data (not reproducible by the VTGCM) can be much more important than this long-term variability, suggesting a highly variable wind system in the upper atmosphere. Similarly, simulations of the NO nightglow intensity by Bougher et al. (1990) predict a brightness increase by a factor of 3 from solar minimum to maximum activity.

The present work is based on actual observations obtained during a period of low solar activity (2006-2008). The VIRTIS imaging spectrometer will first be briefly presented in Section 2, together with the data acquired at 1.27 μm. The solar EUV radiance during this period will be presented in Section 3. The correlation between the two data sets will be studied in Section 4 and results will be discussed in Section 5.

2. VIRTIS $O_2(a^1\Delta_g)$ nightglow observations

The VIRTIS instrument is an imaging spectrometer (Drossart el al., 2007 ; Piccioni et al. 2009) onboard Venus Express (Titov et al., 2006), which has been orbiting around Venus in a 24-h polar elliptical orbit from April 2006 to December 2014. The pericenter of Venus Express was located near 250 km and the apocenter at 66 000 km. The 1.27 μm emission was observed with the VIRTIS-M-IR instrument, which is a medium-spectral resolution imaging spectrometer from 1 to 5 μm by steps of 10 nm. VIRTIS-M-IR was operational from May 2006 to October 2008, with the breaking off of its cryocooler. Nadir acquisitions, preferentially made in the Southern hemisphere due to the quasi-polar elliptical orbit of VEx, are very useful to observe the $O_2(a^1\Delta_g)$ emission bright patch over the Venus nightside and its variations. However, because of its 64 mrad field of view, VIRTIS-M-IR could not cover more than 25% of the Venus nightside during one observation, even from apocenter. Gérard et al. (2008) and Piccioni et al. (2009) corrected VIRTIS-M-IR nadir observations from geometrical effects and thermal emission and found that the emission peak is statistically located around the antisolar point, with an averaged maximum value of respectively 3 MR and 1.2 MR and a mean intensity for the Venus nightside of 1.3 MR and 0.52 MR, respectively. Averaging nadir and limb data from the entire VIRTIS-M-IR database, Soret et al. (2012 ; 2014) produced a detailed statistical map of the 1.27 μm nightglow emission showing an enhanced emission around the antisolar point, with a maximum brightness of 2.1 MR and a hemispheric mean vertical brightness on the Venus nightside of 0.50 MR, in agreement with the predicted intensity by the VTGCM for SMIN conditions (0.49 MR). However, they insisted that the bright patch around the antisolar point was only the result of the statistical accumulation of more than 3000 nadir measurements. Using the entire VIRTIS-M-IR nadir database, they showed that statistical maps generated with 500 observations at a time could be highly different from the very global map (see Figure 2 from Soret et al., 2014) and that the brightest emission was not necessarily located at the antisolar point. They suggest that it reflects the high variability of the circulation in the transition region over time. They made their point by analyzing individual nadir data and following bright emission patches over time. Most of the time, they noticed changes both in their intensity and shape in observations acquired 30 minutes apart.

In the present work, we use data from the seven statistical maps of the $O_2(a^1\Delta_g)$ intensity shown in Figure 2 of Soret et al. (2014), based on the full VIRTIS-M-IR nadir database. We first look at the average brightness of each map and study its evolution over time. To avoid any bias caused by a different spatial coverage, we only consider intensities in an area that is common to all of the seven maps. We find average intensities of 0.35 MR, 0.44 MR, 0.41 MR, 0.47 MR, 0.34 MR, 0.40 MR and 0.48 MR. These average intensities have been multiplied by 10 and plotted over time in Figure 1 with blue squares. We can observe variability in the brightness global increase over time. Overall, the intensity changed by 37% from mid-2006 to end-2008. We then determine the maximum intensity of each map: 2.7 MR, 3.3 MR, 2.6 MR, 2.6 MR, 2.7 MR, 2.3 MR and 2.3 MR. These maximum intensities have been plotted as a function of time in Figure 1 with green triangles. A very slight decrease can be observed overall. At this point, it is very difficult to see a global trend in the $O_2(a^1\Delta_g)$ nightglow emission brightness over two years of data since results based on maxima and averages differ, without much variations over time.

3. SEM solar flux

We now focus on solar flux variations in the time of VIRTIS observations (between May 2006 and October 2008). We use the SOHO-CELIAS/SEM (Judge et al., 1998) EUV daily average full solar disk fluxes available from the Space Sciences Center of the University of Southern California. In this work, we do not use the F10.7 index since Chen et al. (2011) showed that this proxy does not correctly describe the variations of solar extreme ultraviolet (EUV) irradiances during the deep solar minimum of 2007-2009. They suggest to directly use the EUV solar flux at 1 AU between 0.1 and 50 nm instead. Figure 1-a of Chen et al. (2011) shows that during a solar cycle, the F10.7 index can vary from ~250 to 50 while the SOHO/SEM EUV flux varies from ~7 to 2 (in units of 10^{14} photons m^{-2} s^{-1}) between solar maximum and solar minimum, respectively. $EUV_{0.1\text{-}50}$ daily average fluxes used for this work decrease from ~2.6 in May 2006 to ~1.9 in October 2008. VIRTIS data have thus been collected during a deep solar minimum period. Also, the change of the $EUV_{0.1\text{-}50}$ during this period only represents a modulation of 14% relatively to an absolute variation of 5 (from 2 to 7) for a complete solar cycle. The $EUV_{0.1\text{-}50}$ values are for the Earth though. They have thus been converted for Venus by taking into account the distance from the Sun to the planet, but also the shift in date, considering the difference in solar longitude $\Delta_{longitude}$ of the two planets. We apply a time shift of ΔT=27×$\Delta_{longitude}$/360 days. The $EUV_{0.1\text{-}50}$ daily average fluxes calculated for Venus have been plotted as a black solid line in Figure 1. Values vary from 4.4 to 3.4, which corresponds to a decrease of 10.4% of the solar flux at Venus compared to a complete solar cycle (ranging from 13.5 to 3.9).

4. Comparison of VIRTIS and SEM datasets

The time evolution of the $O_2(a^1\Delta_g)$ brightness and the EUV solar flux are plotted on Figure 1 to observe a potential correlation. In order to make the comparison easier, the $EUV_{0.1\text{-}50}$ index has been averaged over the same ranges of time as the seven $O_2(a^1\Delta_g)$ intensities. Mean $EUV_{0.1\text{-}50}$ fluxes have been plotted with red diamonds. The correlation coefficient between the solar flux (red diamonds) and the intensity peak (green triangles) is found to be 0.62, which expresses the global decreasing trend for both quantities. This coefficient is not higher because internal variations of the two studied variables do not occur simultaneously. More significantly, the correlation coefficient between the solar flux (red diamonds) and the averaged intensities (blue squares) is found to be -0.35, meaning that no relationship exists between the $O_2(a^1\Delta_g)$ brightness and the solar activity.

We have also compared the results of the average nightside intensity with those calculated by the VTGCM. The VTGCM predicts a variation from 0.70 to 0.49 MR from solar maximum to solar minimum. For the period considered in this work, we observe a variation of 10.4% of the solar flux (see Section 3). Thus, the variation in the average nightside intensity according to the VTGCM for the same period is expected to decrease by (700-490) x 0.104=22 kR. Instead, we found an increase of 130 kR.

5. Discussion and conclusions

This study was made to determine whether a correlation between the $O_2(a^1\Delta_g)$ brightness and the solar flux exists, as expected by the VTGCM (Bougher and Borucki, 1994). We do not observe any correlation of the solar activity with the average nightside brightness. However, VIRTIS data were acquired during a deep solar minimum (from 2006 to 2008) and, more importantly, during a relatively stable phase of the solar activity.

A high level of variability of the $O_2(a^1\Delta_g)$ emission has been detected in the same dataset from day to day though (Hueso et al, 2008 ; Soret et al., 2014). It thus seem that the variability is more due to internal than to external conditions: transport appears to play a major role in the nightglow emissions than the solar activity eventually does. This conclusion is at least valid for solar minimum conditions. We could wonder whether the situation would be identical for high solar activity. It could be worth considering that a solar flux threshold exists above which solar activity becomes dominant over atmospheric dynamics. This hypothesis is somehow unlikely, since the NO emission maximum intensity was found to be 2±0.5 kR during the 1980s solar maximum (Stewart et al., 1980; Bougher et al., 1990) and that the same value (1.9 kR) was found with Venus Express during solar minimum (Stiepen et al., 2013). Thus, solar activity do not appear to control the NO nightglow emission, in contrast to the VTGCM predictions. The NO PV-OUVS and the Venus Express VIRTIS observations thus both lead to the conclusion that internal factors play a major role that masks out the effect of changing solar EUV flux on the production of N and O atoms on the dayside. Such sources of variability have been investigated with global circulation models of the Venus upper atmosphere. In a 23-day simulation, Hoshino et al. (2012) showed that the presence of Kelvin waves produces temperature and zonal wind perturbations together with time variations of the equatorial $O_2(a^1\Delta_g)$ airglow intensity with an amplitude up to 10%. They also calculated a shift of the local time of the peak airglow intensity reaching at most 20 minutes. These fluctuations have a characteristic period of ~4 days. Neither the calculated amplitude nor the periodicity are in agreement with the observed observations of the NO and oxygen airglow. Another possible source of variability is linked to breaking gravity waves that are believed to slow down the day-to-night circulation of the upper atmosphere (Alexander, 1992). An attempt to substitute the effect of gravity wave braking to Rayleigh friction by Zalucha et al. (2013) was unsuccessful. The modeled vertically propagating waves launched from the cloud top are reflected before they break or break in strong shear zones, so that they do not efficiently slow down the atmospheric flow. At this point, neither solar activity nor internal sources have been able to model the time variations observed in the NO and O_2 airglow.

Finally, a space mission with imaging capabilities and dedicated to the observation of both the NO and the O_2 nightglow emissions over an entire solar cycle would definitely allow determining whether or not these emissions are linked to solar activity.

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http://www.sciops.esa.int/index.php?project=PSA&page=vex.

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Figure

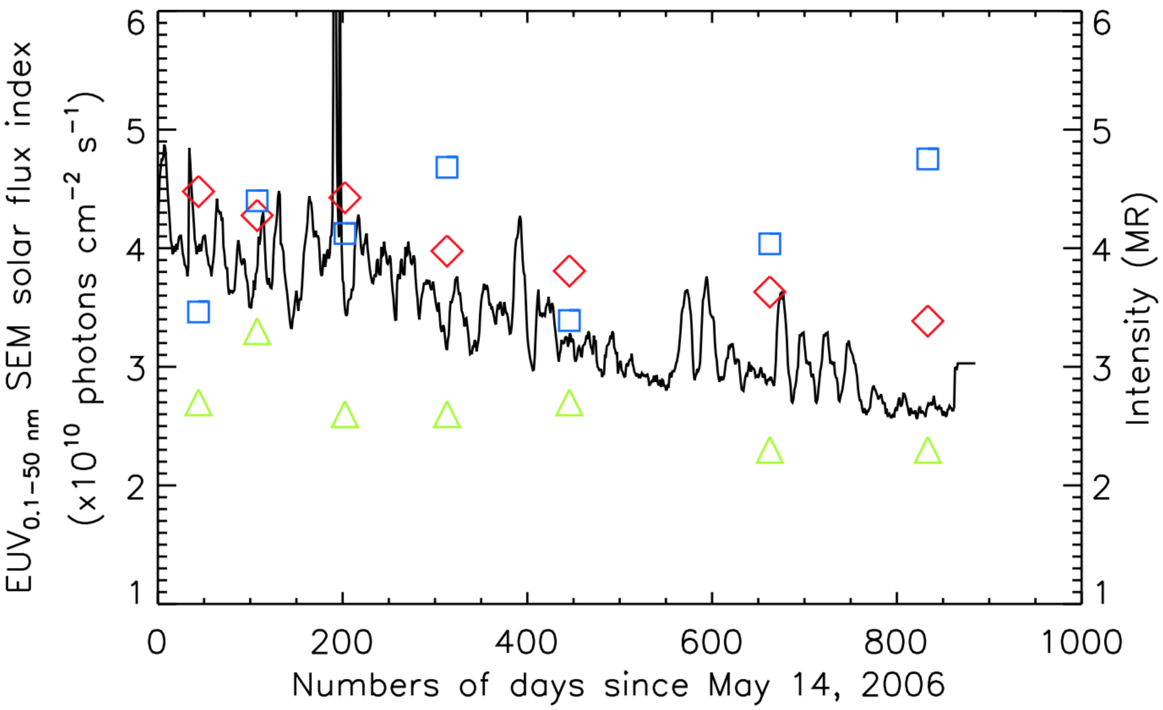

Figure 1: The $EUV_{0.1\text{-}50}$ daily average fluxes at Venus from May 14, 2006 to October 15, 2008 (black solid line) have been averaged (red diamonds) between May 14, 2006 - August 9, 2006; August 9, 2006 - September 16, 2006; September 16, 2006 - February 13, 2007; February 13, 2007 - April 26, 2007; April 26, 2007 - November 6, 2007; November 6, 2007 - July 1st, 2008 and July 5, 2008 - October 15, 2008. The $O_2(a^1\Delta_g)$ maximum brightness at these same periods are represented with green triangles. The average emission intensities have been multiplied by 10 and are shown with blue squares.

Highlights

- Variations of the $O_2(a^1\Delta_g)$ Venus emission brightness have been studied.
- Those variations have been compared to the solar activity.
- No evidence of a correlation between those two variables could have been shown.
- This is in agreement with NO emission observations by PV-OUVS and Venus Express.