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The distributions of the OH Meinel and $O_2(a^1\Delta–X^3\Sigma)$ nightglow emissions in the Venus mesosphere based on VIRTIS observations

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Abstract

$O_2(a^1\Delta)$ and recently discovered OH Meinel nightglow emissions have been observed at the limb with the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS-M) instrument on board the Venus Express satellite. Hydroxyl bands belonging to $\Delta v = 1$ sequence between 2.60 and 3.14 μm and to $\Delta v = 2$ sequence at 1.40–1.46 μm have been unambiguously identified. In this study, we analyze the statistical distribution of the $\Delta v = 1$ OH Meinel band sequence and the $a^1\Delta_g - X^3\Sigma$ (0–0) band of the O_2 Infrared Atmospheric bands at 1.27 μm. We also present an analysis of the correlation between the two emissions. From a statistical point of view, we find that the limb intensity of both emissions reach their maximum value near the antisolar point, while they are significantly dimmer in the vicinity of the terminator. The average altitude of the limb emissions peaks are 95.3 ± 3 km and 96 ± 2.7 km, respectively for the OH $\Delta v = 1$ sequence and $O_2(a^1\Delta)$ emissions. The average intensities are 0.41 ± 0.37 MR and 28 ± 22 MR, respectively, corresponding to a mean ratio of about 70. The altitude of the OH nightglow layer is closely related to that of the $O_2(a^1\Delta)$ emission and some level of co-variation of the maximum intensity along the line of sight is observed. It is suggested that the global subsolar to antisolar circulation plays a key in the control of both airglows by carrying oxygen atoms from the day to the night side of the planet. The O atoms recombine to produce $O_2(a^1\Delta)$ molecules and they also act as precursors of ozone whose reaction with H produces excited hydroxyl.

Keywords: Venus; Airglow; OH; O_2; Infrared emission; Atmosphere dynamics

1. Introduction

The presence of the OH (2–0), (1–0), (2–1) and possibly (3–2) Meinel bands has been recently identified by Piccioni et al. (2008) in the Venus atmosphere using infrared limb observations made with the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on board Venus Express. It was found that the limb intensities are 880 ± 90 kiloRayleighs (kR) for the (1–0) band and 100 ± 40 kR for the OH (2–0) band. The emission layer peaks at an altitude of 96 ± 2 km near midnight, in the case of the orbit used for the analysis. Taking these characteristics into account and assuming a conversion factor of 55.4 between limb and the vertical observations, the associated vertical emission rates were estimated to be 16 kR and 1.8 kR, respectively. These emission rates are 55 ± 5 and 480 ± 200 times weaker than the $O_2(a^1\Delta)$ (0–0) band intensity at 1.27 μm (Piccioni et al., 2008). For a total of 10 orbits examined, these ratios vary from orbit to orbit by ±50%, but the peak altitude appeared to remain constant within the vertical resolution of the measurements. The OH (1–0) P1(4.5) and (2–1) Q1(1.5) OH airglow lines were recently detected by Krasnopolsky (2010) using a ground-based

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telescope. The total hydroxyl emission rate f derived from these observations is consistent with the value obtained by Piccioni et al. (2009).

The O_2 $a^1\Delta$–$X^3\Sigma$ (0–0) band emission at 1.27 μm has been described in considerably more detail. It was first observed on Venus more than 30 years ago (Connes et al., 1979) using Fourier transform spectroscopy from the ground. Spatially resolved ground-based observations (Allen et al., 1992; Crisp et al., 1996; Lellouch et al., 1997; Ohtsuki et al., 2008; Bailey et al., 2008a,b) have demonstrated that the spatial distribution of the $O_2(a^1\Delta)$ infrared airglow is quite variable in space and time. The O_2 (a–X) airglow shows regions of enhanced emission which are usually 1000–2000 km wide. Nightside images indicate that these rapidly changing bright areas occur most frequently at low latitudes between midnight and 03:00 local time. During the Venus flyby by Galileo, Drossart et al. (1993) observed with the Near-Infrared Mapping Spectrometer (NIMS) a large enhancement of the 1.27 μm emission near 40°S, over a spatial area ~100 km wide. The apparent motion of gas masses transported by horizontal winds has been analyzed by Hueso et al. (2008) using the O_2 (a–X) airglow. This study showed that the details of the distribution changed over 30 min, but indicated that large structures usually survive for several hours. Gérard et al. (2008) presented a statistical map of the average $O_2(a^1\Delta)$ infrared nightglow in the southern hemisphere observed with VIRTIS over an 11-month period of low solar activity. They found that the distribution is characterized by an enhanced brightness region located near the midnight meridian at low latitude. The location of the bright airglow region was further studied by Piccioni et al. (2009) who confirmed that it is centered on the antisolar point. They also analyzed the statistical distribution of the $O_2(a^1\Delta)$ infrared airglow using both nadir and limb viewing geometries. Drossart et al. (2007a) determined that the $O_2(a^1\Delta)$ peak emission is located near 96 km, which is consistent with excitation by three-body recombination of oxygen atoms proposed by Connes et al. (1979):

$$O + O + CO_2 \rightarrow O_2^* + CO_2 \quad (1)$$

which gives rise to radiative deexcitation of the $O_2(a^1\Delta)$ molecules and collisional quenching:

$$O_2^* + CO_2 \rightarrow O_2 + CO_2 \quad (2)$$

Gérard et al. (2008) found that limb profiles observed at northern mid-latitudes exhibit large intensity variations over short time periods. They compared the limb profiles to those obtained with a one-dimensional chemical-diffusive model. The altitude of the peak and its intensity were well reproduced by the model, but the width of the airglow layer was narrower than in the numerical simulation. Piccioni et al. (2009) illustrated the variability and the complexity of the observed airglow limb profiles. They showed that the altitude, the brightness and the width of the emission peak sometimes vary systematically with latitude. They also argued that a secondary peak, possibly generated by upward propagating gravity waves, may be present above 100 km. The O_2(a–X) airglow emission has been used to infer the oxygen density distribution at different locations using the Abel inversion (Gérard et al., 2009).

Two chemical reactions have been proposed so far (Piccioni et al., 2008) as possible sources of excited hydroxyl molecules. The first one is the Bates-Nicolet mechanism (Bates and Nicolet, 1950) occurring in the terrestrial atmosphere:

$$H + O_3 \rightarrow OH^* + O_2 \quad (3)$$

where OH* denotes a hydroxyl molecule in a vibrationally excited level of the X $^2\Pi$ state.

The second one involves hydrogen peroxide and atomic oxygen:

$$HO_2 + O \rightarrow OH^* + O_2 \quad (4)$$

On Earth, the first process leads to the formation of vibrationally excited OH near the mesopause. It preferentially populates the $v = 6$–9 vibrational levels. In the Mars and Venus atmospheres, subsequent radiation and collisional quenching by CO_2 are thought to populate the lower v levels. Reaction (4) does not play a major role in the terrestrial mesosphere (Dodd et al., 1994; Meriwether, 1989), but could be a source of vibrationally excited OH in the Venus mesosphere, where the ozone abundance is smaller. Piccioni et al. (2008) suggested that these reactions contribute to the observed OH emissions on the Venus nightside. They argued that the observed intensity variability may be related to the dependence on temperature of both the efficiency of the production reactions and collisional quenching. In addition, variability in the HO_2, H, O, and O_3 densities can also be important. Similar sensitivity of OH and O_3 to temperature variations has been reported in model calculations for Mars (Zhu and Yee, 2007). Profiles of OH airglow emission calculated from a model (Pernice et al., 2004) show reasonable agreement with the observations both in brightness and vertical distribution, with some deviations.

In this study, we determine the statistical properties of the $\Delta v = 1$ Meinel OH nightside emission and their relationships to the $O_2(a^1\Delta)$ Venus night airglow at 1.27 μm observed during the same time period. This analysis is based on limb profiles obtained with the VIRTIS spectral imager on board Venus Express. We compare the vertical and latitudinal distributions of the OH airglow with those obtained for the $O_2(a^1\Delta)$ emission.

2. Observations

VIRTIS is an imaging spectrometer on board the Venus Express satellite orbiting Venus on a highly elliptical polar orbit with a period of 24 h, an initial pericenter of 250 km from the planet surface at 80°N, and an apocenter at 66,000 km. The orbital configuration and different science missions have been described elsewhere (Svedhem et al., 2007; Titov et al., 2006; Drossart et al., 2007b). The