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Oxygen nightglow emissions of Venus: Vertical distribution and collisional quenching

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ABSTRACT

We compare the altitude of three O_2 night airglow emissions observed at the limb of Venus by the VIRTIS spectral imager with those values predicted by a model accounting for the different radiative lifetimes and collisional deactivation of the upper O_2 states. The O and CO_2 density profiles are based on remote sensing observations from the Venus Express spacecraft. Effective production efficiencies of the involved O_2 metastable states and quenching coefficients by oxygen and carbon dioxide are adjusted to provide the best match with the measured emission limb profiles. We find values in general good agreement with earlier studies for the $c^1\Sigma_u^-$ state which gives rise to the Herzberg II bands. In particular, we confirm the low net yield of the c state production and the importance of its deactivation by CO_2, for which we derive a quenching coefficient of $3 \times 10^{-16}\,cm^{-3}\,s^{-1}$. The ~4.5 km higher altitude of the Chamberlain band emission also recently detected by VIRTIS and the ratio of the Herzberg II/Chamberlain bands observed with Venera are well reproduced. To reach agreement, we use a 12% yield for the $A'^3\Delta_u$ production following O atom association and quenching coefficients by O and CO_2 of $1.3 \times 10^{-11}\,cm^{-3}\,s^{-1}$ and $4.5 \times 10^{-13}\,cm^{-3}\,s^{-1}$ respectively. We conclude that the different peak altitudes of the IR Atmospheric, Herzberg II and the Chamberlain bands reflect the relative importance of radiative relaxation and collisional quenching by O and CO_2.

1. Introduction

The oxygen nightglow has been used as a tool to probe the Venus global dynamics and composition of the night side of the planet. Through its comparison with the airglow of the Earth and Mars, it has also been a valuable source of information on the production and collisional deactivation of the O_2 metastable states when two oxygen atoms recombine in a three-body reaction. Interestingly, in spite of considerable efforts devoted for decades to quantify the recombination products and their subsequent fate in terrestrial planetary atmospheres, uncertainties remain to get a consistent quantitative picture of the processes involved. The set of observations collected with the VIRTIS instrument on board Venus Express has recently provided information on both the intensity and the vertical distribution of several O_2 nightglow emissions with unprecedented accuracy. In this study, we take advantage of new observations of the Venus O_2 visible nightglow reported in a companion paper (Migliorini et al., 2013) to compare the characteristics of three O_2 emissions with the modeled distributions expected from the atomic oxygen and the CO_2 vertical density distributions derived from remote sensing observations performed from Venus Express.

The source of the O_2 nightglow is the recombination process with a third body M (mainly CO_2, CO or O):

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

whose excess energy is 5.12 eV if the O_2 molecule is formed in the ground state $X(v = 0)$ level. Consequently, the oxygen molecule may be produced in several electronic excited state denoted here O_2^*. As the molecule relaxes radiatively, photons are emitted in several band systems. Some of these have been observed in the Earth, Mars and Venus nightside airglow. The main transitions associated to these states are the $A^3\Sigma \rightarrow X^3\Sigma$ Herzberg I bands, the $A'^3\Delta \rightarrow a^1\Delta$ Chamberlain bands, the $a^1\Delta \rightarrow X^3\Sigma$ Atmospheric IR bands, the $c^1\Sigma \rightarrow X^3\Sigma$ Herzberg II bands, the $b^1\Sigma \rightarrow X^3\Sigma$ Atmospheric bands, and the $b^1\Sigma \rightarrow a^1\Delta$ Noxon bands. The relative intensity of these emissions in the atmospheres of the three terrestrial planets has been discussed in several studies (Slanger et al., 2006; García-Muñoz et al., 2009; Krasnopolsky, 2011). The relative concentrations of CO_2, N_2 and O in the upper mesosphere of Venus and the Earth control the relative intensity of the nightglow emissions arising from the various O_2 metastable states (Slanger and Copeland, 2003; Krasnopolsky, 2011).

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The O_2 $a^1\Delta–X^3\Sigma$ (0–0) Infrared Atmospheric band emission at 1.27 μm (IR Atm) has been extensively studied during the recent years. Following its detection by Connes et al. (1979), spatially resolved ground-based observations (Allen et al., 1992; Crisp et al., 1996; Lellouch et al., 1997; Ohtsuki et al., 2008; Bailey et al., 2008) have shown that the spatial distribution of the O_2 atmospheric infrared airglow exhibits spatial and time variations on time scales of about one Earth day. Images indicate that these rapidly changing bright areas are observed most frequently at low latitudes between midnight and 03:00 local time. Drossart et al. (2007) reported the first limb observation of the 1.27 μm emission on Venus and showed that the $O_2(a^1\Delta)$ peak at the limb is located near 96 km, a value consistent with excitation by three-body recombination of oxygen atoms. Gérard et al. (2008) analyzed the statistical distribution of the $O_2(a^1\Delta)$ airglow using both nadir and limb viewing geometries. They found that limb profiles observed at northern mid-latitudes exhibit large intensity variations over short time periods. They also showed that the limb profiles compare favorably with those obtained with a one-dimensional chemical-diffusive model. Piccioni et al. (2009) and Gérard et al. (2009a) illustrated the variability and the complexity of the observed airglow limb profiles. The altitude, the brightness and the width of the emission peak vary with latitude. The altitude of maximum emission at the limb varies between 90 and 103 km, with a mean value of 96 ± 2 km and the mean peak intensity along the line of sight is 28 ± 23 MR (Gérard et al., 2010). As was shown by Gérard et al. (2009a), the O_2(a–X) airglow distribution may be used to infer the oxygen density distribution at different locations using the Abel inversion. They also found that the altitude of the airglow emission exhibits altitude variations as large as 10 km over short latitudinal distances. Additionally, Gérard et al. (2009b) demonstrated that the ultraviolet nitric oxide emitted near 115 km and the O_2 IR Atmospheric bands near 96 km emissions are spatially uncorrelated. Soret et al. (2012) analyzed the full set of VIRTIS-M limb profiles at 1.27 μm to derive the three-dimensional distribution of O atoms in the mesosphere–thermosphere transition region. They found that the peak altitude of the $O_2(a^1\Delta)$ emission statistically increases from 94 km at the antisolar point to 99 km near the terminator, with a mean limb intensity over the northern nightside hemisphere of 27.5 MR at 96.2 km and a global mean nadir brightness of 500 kR. Following deconvolution and Abel inversion of each limb profile, the mean altitude of maximum volume emission rate was found at 99 km.

The Herzberg II (HzII) system was first observed with the spectrometers on board Veneras 9 and 10 spacecraft by Krasnopolsky (1983). They found that the vertical intensity of the Herzberg II bands varied from 2 to 3 kR, with the highest values located near 00:00–01:00 LT. Observations with the spacecraft star tracker on board the Pioneer Venus confirmed the presence of the O_2 Herzberg II emission (Bougher and Borucki, 1994). The highest intensities were observed at low latitudes (3.6 kR vertical brightness) and only weak local time variations were seen both in the Venera 9–10 and the Pioneer Venus nightglow. The presence of several bands of the weaker (0–v'') progression of the $A'^3\Delta \rightarrow a^1\Delta$ Chamberlain (Ch) system was also identified in the Venera spectra by Slanger and Black (1978).

The Venus Express spacecraft was inserted into an elliptical 24-h period orbit around Venus on April 11, 2006. It carried a suite of seven experiments designed to study Venus' atmosphere and plasma environment. One of them, the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) allows to acquire simultaneous spectra in the visible (0.28–1.1 μm) and infrared spectral ranges (1–5 μm) (Piccioni et al., 2009). It can be operated both in nadir and limb observing modes, depending on the spacecraft position along its orbit. Among other objectives, nadir observations are used to investigate the distribution with latitude and longitude of selected airglow emissions, while the limb observations are best suited to study the altitude distribution of the emissions. García-Muñoz et al. (2009) carried out a first detailed study of the O_2 nightglow in the visible range using VIRTIS limb observations. They identified the (0–v'') Herzberg II bands with v'' = 6–11, exhibiting on the average a maximum emission at 95 ± 1 km and a total c → X system intensity of 128 kR. They also suggested the presence of the Chamberlain bands, but no quantitative analysis was conducted. They compared these observations with a one-dimensional calculation where the c state is quenched by CO_2 and O and concluded that the net production of the c(0) state is on the order of 1–2%.

A recent campaign of VIRTIS observations in the limb-tracking mode allowed a new detection of the O_2 nightglow emissions in the visible spectral range (Migliorini et al., 2013). About 8700 spectra, acquired in the period from March 4, 2007 to July 18, 2011, were averaged in order to obtain a mean spectrum in the altitude region 90–120 km. The spectrum is dominated by the presence of the Herzberg II $c^1\Sigma \rightarrow X^3\Sigma$ system, from which they were able to clearly identify eight bands, ranging from (0–6) to (0–13) bands. The authors discussed the statistical behavior of the sum of the most intense bands including the (0–7) to the (0–11) bands. However, they indicate that the full (0–v'') progression was not always observable in the dataset. This fact does not affect the peak altitude as it was previously verified that, as expected, each single band peaks at close altitudes. However, this affects the intensity, which is underestimated in those cases when some of the bands are not observed. Migliorini et al. (2013) only reported the intensity of (0–v'') progression for those data when the set of v'' = 7–11 bands was detected. The intensity of the sum of the 0–7 to 0–11 bands was found to vary from 84 to 116 kR at the airglow peak. The average altitude of the maximum of all analyzed limb profiles was 95.5 ± 1.6 km, in close agreement with the value of 95 ± 1 km determined by García-Muñoz et al. (2009) from their average VIRTIS limb spectrum.

Three bands belonging the (0–v'') progression of the Chamberlain $A'^3\Delta \rightarrow a^1\Delta$ system were also occasionally observed at the limb (Migliorini et al., 2013). They are centered at 560 nm, 605 nm, and 657 nm, corresponding to the (0–6), (0–7), and (0–8) bands respectively. However, due to a lower efficiency above 650 nm of the VIRTIS grating, it was only possible to investigate the intensity and the peak altitude of the (0–6) and (0–7) bands. The two bands peak at about 100 km, that is ~5 km higher than the Herzberg II bands. The measured relative intensity of these two bands is variable, a consequence of the difficulty to separate the Chamberlain bands from the adjacent Herzberg emission and the underlying noise. However, the (0–7)/(0–6) ratio was found to be 1.05 in one case and 1.27 in another case. These ratios are in satisfactory agreement with the theoretical value of 1.28 based on transition probabilities, considering the signal to noise limitations.

2. VIRTIS observations of the O_2 nightglow emissions

In brief, our methodology is as follows. We first summarize the peak altitude and the intensity ratio observations and determine the average characteristics of the O_2 airglow layers that will be modeled in the next section. For comparison with the airglow characteristics expected from a one-dimensional model, we then present the expression used to calculate the volume emission rate of the three band systems. We review the values initially adopted for the effective production efficiency of the excited states, the radiative lifetimes and the quenching coefficients by CO_2 and O atoms. The values of these coefficients are based on recent studies synthetizing the characteristics of the O_2 airglow on the three