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Latitudinal structure of the Venus O_2 infrared airglow: A signature of small-scale dynamical processes in the upper atmosphere

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ABSTRACT

Images of the nightside limb of Venus have been obtained in the northern hemisphere with the VIRTIS multispectral infrared imager on board Venus Express between April 2006 and October 2008. We analyze the latitudinal distribution of the $O_2(a^1\Delta)$ airglow limb profiles at 1.27 μm to characterize its distribution and variability. We show that the instantaneous structure of the emission is very different from the statistical global view of an enhanced emission near the equator, decreasing in brightness and slightly increasing in altitude toward the poles. The peak intensity of the limb profiles varies by a factor up to 50 between the brightest spots and the darkest regions. The bright airglow spots correspond to regions of enhanced downward flow of oxygen atoms originating from the dayside. Considerable variations in brightness and morphology are observed in the altitude–latitudinal distribution over a 24-h period. Analysis of the limb profiles indicates that secondary airglow peaks located at altitudes higher than the mean value of 96 km are observed on about 30% of the latitudinal cuts, but they are concentrated in narrow latitude areas extending over a few hundred kilometers. Most of them occur in transition regions between two altitude regimes in the 50° to 60°N region, possibly associated with the drop of the cloud top altitude observed equatorward of the "cold collar". We interpret these results as an indication that the strength of vertical transport in this mesosphere–thermosphere transition region is very variable both in location and time. This variability, also observed in nadir airglow images and wind measurements, is a key characteristic of the mesosphere–thermosphere transition region. It may be caused by fluctuations of the global day-to-night circulation generated by gravity waves. We show with a one-dimensional model that local enhancements of eddy transport is a possibility. This variability is currently not accounted for by global circulation models that predict a single stable region of enhanced airglow in the vicinity of the antisolar point.

1. Introduction

Connes et al. (1979) first observed the presence of the O_2 infrared airglow at 1.27 μm on both day and night sides of Venus with nearly equal intensity. They proposed that the observed emission corresponds to radiative relaxation of the $O_2(a^1\Delta)$ metastable molecules to the ground-state following three-body recombination of oxygen atoms. They suggested that the atoms are produced on the Venus dayside by photodissociation and electron impact dissociation of CO_2 and CO and transported to the nightside by the subsolar to antisolar circulation (SSAS). This global SSAS circulation transports the O and N atoms from the lower thermosphere near the subsolar point to higher altitudes where the recombination rates between atoms are much lower. The downward flow near the antisolar point then carries atomic oxygen back to the upper mesosphere where the O and CO_2 densities increase, the atoms recombine and emit photons. The reaction scheme may be written:

$$2O + CO_2 \xrightarrow{k} O_2^* + CO_2 \quad (1)$$

$$O_2^* \xrightarrow{A_{1\Delta}} O_2 + h\nu \quad (2)$$

$$O_2^* + CO_2 \xrightarrow{C_q} O_2 + CO_2 \quad (3)$$

where O_2^* represents excited oxygen molecules; k is the reaction rate coefficient of reaction (1) taken to be 3.1×10^{-32} cm^6 s^{-1} and

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obtained by multiplying the experimental value with N_2 as a background gas at 187 K (Huestis et al., 2008) by a factor 2.5 (Nair et al., 1994). This temperature is the mean result of several studies implying different methods summarized in Table 3 of Bailey et al. (2008) and Krasnopolsky (2010); $A_{1_\Delta} = 2.19 \times 10^{-4}\ s^{-1}$ is the Einstein coefficient of the 1.27 μm transition; C_q is the quenching coefficient, for which only an upper limit of $2 \times 10^{-20}\ cm^{-3}\ s^{-1}$ has been set (Sander et al., 2003).

Other weaker O_2 airglow emissions resulting from processes (1)–(3) have also been observed on the Venus nightside (Migliorini et al., 2013 and ref. therein).

The global circulation of the Venus upper atmosphere is generally described as a combination of two components: a superrotating zonal flow below the cloud top (about 70 km) altitude and the previously described subsolar-to-antisolar flow in the lower thermosphere above 120 km (Dickinson and Ridley, 1977; Bougher and Borucki, 1994; Lellouch et al., 2008; Clancy et al., 2012a). The transition region between the two regimes is still poorly known, although substantial progress has been made during the last few years both theoretically and observationally. In situ or remote measurements of the distribution of constituents have indicated the accumulation of atoms or molecules in regions of the nightside thermosphere (Niemann et al., 1980; Schubert et al., 2007; Clancy et al., 2012b). Series of airglow measurements made with instruments on board Venus Express have confirmed and complemented earlier measurements made during the Pioneer Venus era (Stewart et al., 1980). Observations of the ultraviolet nitric oxide nightglow indicated an accumulation of nitrogen atoms carried on the nightside by the SSAS global circulation, but shifted 2–3 h dawnward by the presence of a statistical retrograde zonal wind. Whether this thermospheric zonal wind is an upward extension of the zonal circulation observed near the cloud top or a different regime disconnected from that prevailing at lower altitude is still an open question. Alexander (1992) suggested that gravity waves generated in the clouds region are able to force the zonal flow much above the cloud top and account for the presence of zonal winds in the thermosphere.

Three-dimensional thermospheric general circulation models coupling transport and chemistry models have been developed to validate and understand the concept of global circulation in the Venus upper atmosphere. Early three-dimensional model studies suggested that the circulation above about 90 km is dominated by a subsolar to antisolar flow, with upwelling over the subsolar point, rapid flow across the terminator and subsidence near the antisolar point (Dickinson and Ridley, 1977; Bougher et al., 1988). Considerable success was obtained with more recent versions of the Venus Thermospheric General Circulation Model (VTGCM) (Bougher et al., 1990; Brecht et al., 2011, 2012) which included a zonal wind component. They were able to reproduce the observed day–night thermal contrast, the average intensity of the NO and O_2 nightglow emissions and their horizontal and vertical distribution. However, the flow across the terminators is decelerated using a Rayleigh friction scheme which has no clear physical interpretation.

When all nadir observations at 1.27 μm made with the Visible and InfRared Thermal Imaging Spectrometer (VIRTIS) instrument on board Venus Express are co-added to provide a global view of the airglow distribution on the Venus nightside, a statistical picture emerges. The airglow is statistically characterized by a region of enhanced intensity centered on the antisolar point. This bright statistical region is about four times brighter than the average nadir intensity of about 0.5 MR (Piccioni et al., 2009; Soret et al., 2012). By contrast, Hueso et al. (2008) and Piccioni et al. (2009) showed that, in individual nadir observations, the O_2 airglow structure is complex and shows significant deviations from its globally averaged distribution on the nightside. Soret et al. (in press) analyzed in detail individual VIRTIS nadir images and showed that bright zones are observed at nearly any nightside location and move at speeds up to 100 ms^{-1}, while changing brightness and shape. However, individual spots are generally more intense in the vicinity of the anti-solar point than closer to the terminator. These spotty regions of enhanced O_2 intensity are believed to correspond to zones of maximum supply of atomic oxygen into the recombination region (Allen et al., 1992; Crisp et al., 1996; Ohtsuki et al., 2008; Soret et al., in press). Inhomogeneous structures in the distribution of the OH Meinel $\Delta v = 1$ airglow around 3 μm highly correlate in brightness (Soret et al., 2010) and morphology (Gérard et al., 2012) with those of the O_2 IR airglow. A large daily variability was also observed in the morphology of the nitric oxide airglow observed with the ultraviolet spectrometer on board Pioneer Venus (Stewart et al., 1980) and the SPICAV instrument on board Venus Express (Gérard et al., 2008; Stiepen et al., 2013). The peak of the NO limb profiles is statistically located near 115 km, that is 15–20 km higher than the O_2 infrared airglow. Comparisons between model and data suggested a highly variable Venus wind system in the lower thermosphere, with intermittently strong variations in nightside eddy diffusion. These two emissions may be viewed as tracers of the global circulation in the Venus upper mesosphere and lower thermosphere in two different regimes. The NO ultraviolet nightglow is mostly controlled by the SSAS transport of O and N atoms from the dayside along streamlines above 140 km on the dayside, and down to 115 km on the nightside (Bougher and Borucki, 1994). Similarly, the O_2 emissions are produced by recombination of O atoms created above 110 km on the dayside, which travel across the terminator and recombine near 96 km on the nightside (Drossart et al., 2007a; Gérard et al., 2009a, 2010; Piccioni et al., 2009). At a given time, the two emissions generally show no spatial correlation as was shown by comparing simultaneous SPICAV and VIRTIS nadir observations (Gérard et al., 2009b).

The observed airglow inhomogeneity suggests that the thermospheric global circulation may be considerably more complex than a simple SSAS Hadley-type cell. Alexander (1992) suggested that the observed variability may be associated with gravity wave-induced turbulence which modifies the local supply of O atoms over periods of a few hours. Bougher and Borucki (1994) argued that the upward propagating gravity waves can modulate the dayside supply of mesospheric O atoms and the intensity of the flow across the terminator. This mechanism could produce temporal variations in the eddy diffusion coefficient in the lower thermosphere by modifying the altitude at which the waves break.

Following a description of the VIRTIS-M observations used in this study (Section 2), we provide additional evidence and constraints for the importance of the inhomogeneity and variability of the transport of constituents from the day to the night side and/or local nightside inhomogeneous vertical transport. We also show that the vertical distribution of the O_2 airglow may change dramatically over relatively limited latitudinal distances. The sensitivity of emission limb profiles to local turbulent transport, parameterized by eddy diffusion in one-dimensional models, is discussed in Section 3. We also show how transitions between altitude regimes may coincide with limb profiles with double peaks and their relationship to the presence of upward propagating gravity waves.

2. VIRTIS observations

The limb images analyzed in this study were obtained with the VIRTIS-M spectral imager on board the Venus Express satellite. The Venus Express spacecraft has been orbiting Venus since April 2006 on an elliptical orbit with a period of 24 h, an apocenter at