Icarus 300 (2018) 386–391

Contents lists available at ScienceDirect

Icarus

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

Temperature estimation from hydroxyl airglow emission in the Venus night side mesosphere

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ARTICLE INFO

Article history:
Received 24 May 2017
Revised 11 September 2017
Accepted 21 September 2017
Available online 22 September 2017

Keywords:
Venus, atmosphere
Atmospheres, structure
Spectroscopy
Infrared observations

ABSTRACT

The temperature of the night side of Venus at about 95 km has been determined by using spectral features of the hydroxyl airglow emission around 3 μm, recorded from July 2006 to July 2008 by VIRTIS on-board Venus Express. The retrieved temperatures vary from 145.5 to about 198.1 K with an average value of 176.3 ± 14.3 K and are in good agreement with previous ground-based and space observations. The variability with respect to latitude and local time has been studied, showing a minimum of temperature at equatorial latitudes, while temperature values increase toward mid latitudes with a local maximum at about 35°N. The present work provides an independent contribution to the temperature estimation in the transition region between the Venus upper mesosphere and the lower thermosphere, by using the OH emission as a thermometer, following the technique previously applied to the high-resolution $O_2(a^1\Delta_g)$ airglow emissions observed from ground.

1. Introduction

The study of Venus' atmosphere has progressed considerably in the last decade, thanks to the Venus Express space mission, which has been orbiting the planet from April 2006 to January 2015. Several experiments on board Venus Express have been used to derive the atmospheric temperature, by using either direct measurements (SOIR, VeRa, SPICAV), or through inversion methods (VIRTIS). Considering all the available datasets, the observed thermal profiles cover the altitude range from roughly 40 km to 150 km, the different datasets covering overlapping ranges. A comprehensive review of the available temperature measurements and airglow observations is provided in Limaye et al. (2017) and Gérard et al. (2017), respectively. Here, we summarize the basic observations concerning the thermal structure at 90–100 km, from space and ground-based measurements.

The atmospheric region between 90 and 100 km appears to be a permanent warm layer in the Venus Express/SPICAV measurements (Bertaux et al., 2007; Piccialli et al., 2015), with temperatures reaching values as high as 250 K at 90 km at the night side of Venus, with a variability with respect to latitude and local time on the order of 50 K within the altitude range. Although this observation is in agreement with the Venus Thermospheric General Circulation Model (VTGCM) simulations (Brecht et al., 2011), which explain this warm layer with an adiabatic compression due to air subsidence on the Venus night side, the observed temperatures at 90–100 km are about 30 K warmer, compared to models reported in Zasova et al. (2006, 2007). The observing geometry of Venus Express/SOIR (Mahieux et al., 2015) limits the observations of the mesosphere and lower thermosphere (70–150 km) to the morning and evening terminators. The temperature measured with this instrument on board Venus Express shows a maximum value of 204 ± 17 K at 0.01 mbar (about 102 km height), which is reproduced by the VTGCM model (Bougher et al., 2015). Radio science measurements, obtained with the Venus Express/VeRa experiment, report values around 170 K at 90 km at all latitudes on the Venus night side (Tellmann et al., 2009). The altitude region 90–100 km marks the transition between the two dynamic regimes acting in the Venus atmosphere; hence turbulence and wavy structures are expected (Bougher et al., 2015). To better constraint the Global Circulation models developed to understand the Venus atmosphere, more information about the temperature at the studied altitudes is required. The recent discovery of OH Meinel band emission in the Venus atmosphere by Venus Express allows one to investigate the photochemistry in the upper mesosphere of the planet (Piccioni et al., 2008). The (1–0), (2–1), (3–2) and (4–3) OH

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https://doi.org/10.1016/j.icarus.2017.09.026
0019-1035/

transitions around 3 μm, as well as the (2–0) band at 1.46 μm have been identified in the spectra acquired with the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) on board the spacecraft (Piccioni et al., 2008; Migliorini et al., 2011; Soret et al., 2012). These emissions occur at about 95 km height (Piccioni et al., 2008; Gérard et al., 2010) and have been observed so far only on the night side of the planet. The emission altitude is somewhat variable, for example with latitude or distance from the anti-solar point. However, it was pointed out that when $O_2(a^1\Delta_g)$ and OH emissions are observed simultaneously, the difference of their peak altitude is only about 0.5 km (Gérard et al., 2012). In the present study, we adopt an OH peak altitude emission along the line of sight of 95.3 ± 3 km (Gérard et al., 2010), in comparison with the mean O_2 nightglow emissions at about 95.0 ± 2.4 km height, observed along the line of sight (Piccioni et al., 2009). The dominant excitation process is believed to be the $O_3 + H \rightarrow OH(v) + O_2$ reaction yielding the hydroxyl molecule in a vibrationally excited state, followed by radiative and collisional relaxation.

The complex structure of the OH($\Delta\nu = 1$) band sequence at 2.8–3.2 μm can be used to derive the rotational temperature at these altitudes, under the assumption of an atmosphere in local thermodynamic equilibrium (LTE). A local thermodynamic equilibrium exists when all internal degrees of freedom of a molecule are in equilibrium with the kinetic energy. This equilibrium is generally maintained through collisional transfer of energy. However, at low densities, the collision frequency is too small to guarantee an efficient transfer from the excited electronic, vibrational and rotational states to the kinetic energy of the molecule. The rotational degree of freedom is expected to be in LTE (see Rodgers et al., 1992) and thus the intensity distribution of the rotational levels can be used to estimate the temperature. However, on the Earth, it was pointed out that there is a variation of up to 15 K of the rotational temperature in the $v = 3$ manifold with respect to the $v = 8$ manifold, while the temperature difference is at most 5 K for the vibrational levels $v = 3$, 4, 5, 6 (Noll et al., 2015; Cosby and Slanger, 2007). In our approach, by fitting the rotational manifolds for the vibrational levels $v = 1$, 2, 3 and 4, we consider an average rotational temperature of the 4 vibrational levels.

The present investigation uses the rotational structure of the OH emission spectra recorded by the VIRTIS spectrometer aboard Venus Express to determine the temperature at the airglow altitudes (90–100 km). Although the spectral resolution of the VIRTIS multispectral imager is not sufficient to resolve individual rotational lines, comparison of the observed spectra with synthetic spectra convolved with the line spread function provides reliable estimates of the ambient atmospheric temperature. In the following, we describe the method and the data used to determine the rotational temperature (Section 2); results are discussed in Section 3, while a summary is provided in Section 4.

2. VIRTIS-M data and method

For the proposed analysis, we selected VIRTIS data acquired in the limb mode, during the period from 2006-07-06 to 2008-07-05. A detailed description of the instrument and the observing geometry can be found in Piccioni et al. (2007). The advantage of observations in limb-mode is the long path length, which provides the intensity required for detecting the low intensity OH emission as well as a good vertical resolution (1–2 km for a slant distance of 7000 km). In addition, the full wavelength range is acquired simultaneously, as a consequence of the instrument design, and hence the measured radiance at the covered wavelengths is directly comparable. However, the necessity to use only limb observations limits the spatial coverage. The list of selected data is reported in Table 1.

Table 1
Details of the analyzed VIRTIS data. Geometric parameters are also provided.

Cube	Start time	Latitude	Local time
VI0076-18	2006-07-06T01:34:11.885	30.0–65.0°N	21.8–23.9
VI0317-06	2007-03-04T06:12:02.447	15.0–30.0°N	23.8–0.7
VI0322-06	2007-03-09T06:07:58.525	15.0–30.0°N	0.4–1.3
VI0324-06	2007-03-11T06:06:22.483	15.0–30.0°N	0.7–1.5
VI0371-10	2007-04-27T05:42:00.927	35.0–60.0°N	21.9–23.5
VI0383-12	2007-05-09T05:51:47.236	35.0–50.0°N	18.0–0.8
VI0715-02	2008-04-05T04:23:08.144	5°S–9°N	22.5–23.3
VI0718-03	2008-04-08T04:36:17.693	0.0–20.0°N	22.4–0.3
VI0724-02	2008-04-14T04:30:38.081	0.0–5.0°N	22.4–0.8
VI0792-02	2008-06-21T03:50:10.343	45.0–70.0°N	2.3–4.7
VI0806-02	2008-07-05T04:08:48.562	45.0–70.0°N	19.5–21.8

Data have been averaged over the 90–100 km altitude range, in order to increase the signal to noise ratio (SNR). Typical SNRs range from 60 to 300. Since the baseline of the observed spectra is not completely flat, a continuum subtraction was necessary prior to comparison with simulated spectra and analysis. Three different methods for baseline subtraction have been applied, in order to estimate the sensitivity of the procedure. The three different baselines have been obtained by fitting a first, second and third order polynomial, as follows:

(1) Straight line between 2.65 and 3.3 μm;
(2) Parabolic fit through three points: 2.6, 3.0 and 3.6 μm;
(3) Third order polynomial through four points: 2.0, 2.6, 3.3, 3.6 μm.

The points were chosen at wavelength values where no OH emission is observed. The emission values at the wavelengths used for the background subtraction are average values on 5–7 adjacent points. An example of the continuum estimation is shown in Fig. 1(left).

Synthetic OH spectra, including the contributions from the (1–0), (2–1), (3–2) and (4–3) bands, have been calculated by using the PGOPHER program (available at the following website: pgopher.chm.bris.ac.uk/) for 17 temperatures from 130 to 250 K, and convolved with the experimental line spread function (FWHM = 18 nm) following earlier analyses and also for consistency with previous works (Soret et al., 2012). For each of the rotational temperatures, the intensities of the rotational manifolds have been fitted in the range 2.64–3.29 μm, in order to obtain the best agreement with observations, thus providing the relative intensity of the different vibrational transitions. Higher vibrational levels in this band, with $v \geq 4$, were ignored since their spectral features were too noisy and not unambiguously identified. Successively, a chi-squared test has been performed to determine which rotational temperature provided the best fit, by fitting a third order polynomial through the chi-squared values obtained for each temperature. The fit for VIRTIS image VI0715-02 is shown in Fig. 1. In this case, the minimum χ^2 value is obtained for $T_{\mathrm{rot}} = 186.3 \pm 1.1$ K. A final value for the temperature has been obtained by averaging the values resulting from the three fits with a different continuum subtraction.

The statistical error in the determination of the temperature depends both on the baseline subtraction and on the SNR of the averaged spectra, as well as on other sources of error that are difficult to quantify. Here we estimate the error produced by the baseline subtraction as the standard deviation of the three fits with different baseline subtraction. The error due to the sensor noise has been estimated by using synthetic spectra with added noise for each spectrum taking into account the noise equivalent spectral radiance (NESR) of the detector and the number of observations averaged for the specific spectrum. The statistical variation in the