Icarus 299 (2018) 370–385

Contents lists available at ScienceDirect

Icarus

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

Long term evolution of temperature in the venus upper atmosphere at the evening and morning terminators

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A R T I C L E I N F O

Article history:
Received 21 September 2016
Revised 17 June 2017
Accepted 31 July 2017
Available online 8 August 2017

Keywords:
Venus
Atmosphere
Temperatures
Infrared observations
Spectroscopy

A B S T R A C T

This paper contains a comprehensive dataset of long-term observations between 2009 and 2015 at the upper mesosphere/lower thermosphere providing temperature values at different locations of the morning and evening side of the terminator of Venus. Temperature information is obtained by line-resolved spectroscopy of Doppler broadened CO_2 transitions features. Results are restricted to a pressure level of 1 µbar, ∼110 km altitude due the nature of the addressed non-LTE CO_2 emission line at 10 µm. The required high spectral resolution of the instrumentation is provided by the ground-based spectrometers THIS (University of Cologne) and HIPWAC (NASA GSFC).

For the first time upper mesosphere/lower thermosphere temperatures at the Venusian terminator derived from IR-het spectroscopy between 2009 and 2015 are investigated in order to clarify the local-time dependences, latitudinal dependences and the long-term trend. Measured temperatures were distributed in the range between 140 K and 240 K, with mean values equal to 199 K ± 17 K for the morning side of the terminator and 195 K ± 19 K for the evening side of the terminator. Within the uncertainty no difference between the averaged morning and evening terminator side temperature is found. In addition, no strong latitudinal dependency is observed at these near terminator local times. In contrast IR-het data from 2009 show a strong latitudinal dependency at noon, with a temperature difference of around 60 K between the equatorial and polar region (Sonnabend et al., 2012). Accord with the instruments of the Venus Express mission a northern-southern hemispherical symmetry is observed (Mahieux et al., 2012; Piccialli et al., 2015). The data shows no consistent long-term temperature trend throughout the six years of observation, but a variability in the order of tens of Kelvin for the different observing runs representing a time step of few month to two years. This is about the same order of magnitude as the variability within a single run with a typically time range of 2–10 days. This variation is not connected to the solar cycle. Submillimeter observations by Clancy et al. found a relation between temperatures and long-term variation in mesospheric water vapor, SO_2, and sulfate aerosols (Clancy and Muhleman, 1991; Clancy et al., 2012). SO_2 column densities observed by SOIR at the terminator are fairly stable over the time period of 2006–2011 (Mahieux et al., 2015), supporting the hypothesis of a relation between SO_2 and temperature variations.

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http://dx.doi.org/10.1016/j.icarus.2017.07.030

The temperatures derived from the infrared heterodyne spectroscopy (IR-het) are compared to results from the Venus Express space mission (VEx). A consistence with the temperatures from the VEx instruments SOIR, VIRTIS and SPICAV is found. As the instruments probe different local time, SPICAV probes the pure nightside, SOIR across the terminator and IR-het the pure dayside atmosphere it is not surprising that the IR-het temperatures are mostly on the warmer side compared to results from SPICAV and SOIR.

1. Introduction

Insight into physical and chemical processes in the atmosphere of Venus has increased in the recent years thanks to spaceborn and ground-based observations. Efforts have been put into the development of Global Circulation Models (GCMs) to describe and predict the behavior of atmospheric processes of the interesting atmosphere. At higher altitudes self-consistent models are limited, because relevant observational constrains are missing (Zalucha et al., 2013; Mendonça et al., 2012; Hoshino et al., 2012; Brecht and Bougher, 2012; Tingle, 2011; Lee and Richardson, 2010; Lebonnois et al., 2010; Bougher et al., 1986). An important parameter is the temperature in the upper mesosphere. The variation over the planet and short and long-term behavior is needed as input and validation for these models and consequently to understand the general circulation of the Venusian atmosphere.The thermal structure of the upper mesosphere is only poorly know, because of its difficult accessibility. Studying the thermal structure, in particular over a long-term, at these altitudes will help to verify and improve the performance of GCM.

This paper describes the temperature structure at Venus' dawn and dusk terminators, observed by mid-infrared heterodyne (IR-het) spectroscopy, which has a sensitivity to a pressure level of 1 μbar. This corresponds to an altitude of about 110 km ± 10 km, a complex and not very well characterized region in Venus' atmosphere. The Venus atmosphere is dominated by two large-scale wind systems (Schubert et al., 2007; Bougher et al., 2006). First, the retrograde super-rotating zonal flow (RSZ) between the surface and the cloud top at ∼70 km. The RSZ moves in the direction of the planets retrograde spin but rotates faster than the solid body. A subsolar-to-antisolar flow (SS-AS) takes place at altitudes above 120 km. The region between 70 km and 120 km is called the transition zone, where the dominance of the RSZ flow somehow fades with altitude and the SS-AS flow becomes more and more important. The thermal structure especially at the morning and evening terminator is of great interest because of the intense temperature changes that occur with rising/setting solar insulation. Knowing the thermal and dynamical structure of the terminator is essential towards the evaluating of the thermal day-night gradient, likely the main reason for the SS-AS flow. It is believed that the highly variable winds in the transition zone has implications for the underlying thermal structure. The upper atmosphere temperature structure must indeed be closely connected to the wind fields of the transition region. The detailed dynamical processes, like the effect of waves or planetary-scale tides at these altitudes is still an open question, since substantial variations emerge on short time scales and observations are limited in time, coverage, and spatial resolution (Clancy et al., 2008; Schubert et al., 2007; Lellouch et al., 1994; Sornig et al., 2012).

The thermal structure of Venus upper atmosphere has been investigated by previous spacecraft missions, like the Pioneer Venus orbiter (Taylor et al., 1980), Pioneer Venus probes (Seiff et al., 1985) and Venera 15 and 16 (Zasova et al., 2006, 2007). Findings from these missions were used to build the first Venus International Reference Atmosphere (VIRA) model (Keating et al., 1985). More recently, the European space mission Venus Express (VEx) (Svedhem et al., 2007, 2009) gave a huge boost for our understanding of the thermal structure. VEx has provided a closer look into the atmosphere, which has revealed a far more complex situation than had been considered (Mahieux et al., 2012; Mahieux et al., 2015; Piccialli et al., 2015; Gilli et al., 2015). The findings of these instruments about the thermal structure close to the terminator will be presented and compared to observations accomplished in the frame of this paper.

Ground-based observations in the sub-millimeter (Clancy et al., 2003, 2008, 2012; Rengel et al., 2008b, 2008a), millimeter (Lellouch et al., 1994) and mid-infrared wavelength ranges (Sonnabend et al., 2008b, 2010, 2012) with advanced technologies have been contributing for discovering significant variability of the thermal structure in Venus' upper mesosphere/lower thermosphere on various time-scales (Rengel et al., 2008a; Clancy et al., 2012; Sonnabend et al., 2010), also seen by spaceborn instruments (Mahieux et al., 2015). A strong local time and meridional dependence with temperatures up to 250 K at the subsolar point, decreasing to 160 K towards the terminator and poles are observed by IR-het spectroscopy (Sonnabend et al., 2010).

Despite observational and modeling efforts in the last decades, the dynamical behavior and the temperature structure of the Venusian atmosphere still pose questions. It is essential to continue, extend and coordinate observational investigations to improve the theoretical descriptions of the Venusian atmosphere in terms of GCMs. IR-het spectroscopy is a unique tool to observe highly resolved non-local thermodynamic equilibrium (non-LTE) CO_2 emission lines at 10 μm wavelengths which originate at a pressure of 1 μbar in Venus' upper atmosphere due to solar pumping. Such lines can be used to retrieve temperatures from the observed Doppler width of the emission feature. Moreover, IR-het spectroscopy provides the rare capability to probe the terminators on various time-scales from hours to years with a sufficed high enough spatial resolution and a narrow altitude resolution. The IR-het data presented in this work will therefore enlarge our knowledge of the thermal structure at the terminator and help to evaluate the performance of GCMs.

A brief description of the observation method, data acquisition, instrumentation and handling is given in Section 2. The comprehensive and detailed information about the instruments can be found in Sonnabend et al. (2008a), Kostiuk et al. (2005), Schmülling et al. (1999). Section 3 describes the observing situation. The temperature results are presented in Section 4, including a comparison to findings by instruments onboard Venus Express.

2. Instrument, data acquisition and handling

Temperatures can be derived from molecular Doppler line width of the emission line, in case these spectral lines are resolved and the line widths are measurable. Frequency resolution of finer than 40 MHz is needed to resolve the width of narrow non-LTE CO_2 emission lines at $\sim 1000\,cm^{-1}$. The Cologne Tuneable