Icarus 217 (2012) 779–793

Contents lists available at ScienceDirect

Icarus

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

Thermal structure and CO distribution for the Venus mesosphere/lower thermosphere: 2001–2009 inferior conjunction sub-millimeter CO absorption line observations

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ARTICLE INFO

Article history:
Available online 12 June 2011

Keywords:
Venus, Atmosphere
Atmospheres, Dynamics
Radio observations
Spectroscopy
Terrestrial planets

ABSTRACT

Sub-millimeter ^{12}CO (346 GHz) and ^{13}CO (330 GHz) line absorptions, formed in the mesosphere and lower thermosphere of Venus (70–120 km), have been mapped across the nightside Venus disk during 2001–2009 inferior conjunctions, employing the James Clerk Maxwell Telescope (JCMT). Radiative transfer analysis of these thermal line absorptions supports temperature and CO mixing profile retrievals, as well as Doppler wind fields (described in the companion paper, Clancy et al., 2012). Temporal sampling over the hourly, daily, weekly and interannual timescales was obtained over 2001–2009. On timescales inferred as several weeks, we observe changes between very distinctive CO and temperature nightside distributions. Retrieved nightside CO, temperature distributions for January 2006 and August 2007 observations display strong local time, latitudinal gradients consistent with early morning (2–3 am), low-to-mid latitude (0–40NS) peaks of 100–200% in CO and 20–30 K in temperature. The temperature increases are most pronounced above 100 km altitudes, whereas CO variations extend from 105 km (top altitude of retrieval) down to below 80 km in the mesosphere. In contrast, the 2004 and 2009 periods of observation display modest temperature (5–10 K) and CO (30–60%) increases, that are centered on antisolar (midnight) local times and equatorial latitudes. Doppler wind derived global (zonal and should be SSAS) circulations from the same data do not exhibit variations correlated with these CO, temperature short-term variations. However, large-scale residual wind fields not fit by the zonal, SSAS circulations are observed in concert with the strong temperature, CO gradients observed in 2006 and 2007 (Clancy et al., 2010). These short term variations in nightside CO, temperature distributions may also be related to observed nightside variations in O_2 airglow (Hueso, H., Sánchez-Lavega, A., Piccioni, G., Drossart, P., Gérard, J.C., Khatuntsev, I., Zasova, L., Migliorini, A. [2008]. J. Geophys. Res. 113, E00B02. doi:10.1029/2008JE003081) and upper mesospheric SO and SO_2 layers (Sandor, B.J., Clancy, R.T., Moriarty-Schieven, G.H., Mills, F.P. [2010]. Icarus 208, 49–60).

The retrieved temperature profiles also exhibit 20 K long-term (2001–2009) variations in nightside (whole disk) average mesospheric (80–95 km) temperatures, similar to 1982–1991 variations identified in previous millimeter CO line observations (Clancy et al., 1991). Global average diurnal variations in lower thermospheric temperatures and mesospheric CO abundances decreased by a factor-of-two between 2000–2002 versus 2007–2009 periods of combined dayside and nightside observations. The infrequency and still limited temporal extent of the observations make it difficult to assign specific timescales to such longer term variations, which may be associated with longer term variations observed for cloud top SO_2 (Esposito, L.W., Bertaux, J.-L., Krasnopolsky, V., Moroz, V.I., Zasova, L.V. [1997]. Chemistry of lower atmosphere and clouds. In: Bougher, S.W., Hunten, D.M., Phillips, R.J. (Eds.), VENUS II, 1362pp) and mesospheric water vapor (Sandor, B.J., Clancy, R.T. [2005]. Icarus 177, 129–143) abundances.

1. Introduction

The upper atmosphere of Venus encompasses critical photochemistry associated with sulfuric acid cloud formation (e.g., Esposito et al., 1997) and stability of the CO_2 atmosphere to photolytic dissociation (e.g., Yung and DeMore, 1982) in the mesosphere (70–95 km). Above the mesosphere, strong diurnal variation in atmospheric temperatures drives subsolar-to-antisolar (SSAS) transport of photolysis products (CO, O, NO, H, O_2 singlet delta) towards strong nightside enhancements (e.g., Bougher et al., 1986, 1988, 1990, 2006) in the thermosphere (95–200 km). A wide variety of observations from both ground-based and Venus spacecraft missions have addressed compositional variations in

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0019-1035/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2011.05.032

upper atmosphere of Venus, including mesospheric CO (Clancy and Muhleman, 1985; Gurwell et al., 1995; Lellouch et al., 1994; Vandaele et al., 2008) and H_2O (Sandor and Clancy, 2005; Gurwell et al., 2007; Bertaux et al., 2007; Fedorova et al., 2008; Vandaele et al., 2008), NO and O_2 airglow at 90–120 km altitudes (Stewart et al., 1980; Gérard et al., 2009; Crisp et al., 1996; Hueso et al., 2008), H and He nightside enhancements at 150–170 km altitudes (Niemann et al., 1980; Mayr et al., 1980; Grebowsky et al., 1996), and most recently SO and SO_2 abundances at 85–100 km altitudes (Sandor et al., 2010). Temperature measurements in the mesosphere and thermosphere of Venus have been surprisingly fewer, particularly in terms of defining what appear to be strong diurnal, secular, and spatial variabilities (Taylor et al., 1980; Seiff et al., 1980; Clancy and Muhleman, 1991; 2003; Bertaux et al., 2007; Bailey et al., 2008; Sonnabend et al., 2008).

Venus millimeter and submillimeter ^{12}CO and ^{13}CO absorption lines, formed within the mesosphere and lower thermosphere of Venus, support combined temperature and CO profile retrievals over the 75–115 km altitude region (e.g., Lellouch et al., 1994; Clancy et al., 2003, 2008). Venus inferior conjunction mapping observations of such CO absorption lines allow coarse latitudinal, local time, and vertical profile determinations of temperature and CO abundance variations across the Venus nightside disk (Lellouch et al., 1994; Gurwell et al., 1995). In the following, we present a unique temperature and CO abundance profile retrieval data set, encompassing multiple ^{12}CO and ^{13}CO absorption line maps of the Venus nightside disk at every inferior conjunction between 2001 and 2009. The correlations between the temperature and CO abundance fields, which is most pronounced in the lower thermosphere, indicates spatial and temporal variations in vertical and horizontal transport across the nightside upper atmosphere of Venus. These variations are considered in the context of simultaneous Doppler wind fields obtained from the observed CO line shifts (Clancy et al., 2010), as well as previous and contemporaneous temperature and compositional measurements of the upper atmosphere. We also present a more limited set of superior conjunction submillimeter CO line measurements, to provide disk-average dayside context to diurnal and secular variations observed in the extensive nightside observations.

2. Sub-millimeter ^{12}CO, ^{13}CO line observations

Table 1 presents the temporal, spatial, and measurement parameters of Venus sub-millimeter ^{12}CO, ^{13}CO line observations employed in this analysis (modified from Clancy et al., 2012, with the addition of superior conjunction observations in 2000 and 2007, 2008). A more detailed description of the observations, which were obtained with the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, is provided in Clancy et al. (2010, this journal). We present an abbreviated description of the observational parameters and techniques, and refer the reader to our companion paper for elaboration. JCMT is single dish sub-millimeter observatory, operating high sensitivity heterodyne receivers over the 330–360 gHz (B-band) frequency range of our targeted 330.588 gHz ^{13}CO and 345.796 gHz ^{12}CO rotational line transitions (Matthews, 2003). All of the presented observations were obtained with single-sideband (SSB), helium cooled receivers, with similar sensitivity characteristics. However, the degree of image sideband rejection varied from 13 dB over 2001–2006 to ⩾17 dB since 2007. In practice, this means that pre-2007 observed line absorption depths were scaled by 1.05 to account for the 5% added continuum associated with the imperfect image sideband rejection. Employed bandwidths and spectral resolutions of 150,250 MHz and 31,156 kHz, respectively (Table 1), are appropriate for sounding CO abundances and temperatures over the mesosphere and lower thermosphere of Venus. We also obtained Venus disk center (and occasionally full mapping) spectra with broader bandwidths (1 gHz) and coarser spectral resolution (500 kHz) to better constrain upper limits for CO abundances in the lower mesosphere (below 75–80 km, where higher pressure levels lead to increased collisional linewidth of CO absorption). Good or better B-band observing conditions, associated with low atmospheric water vapor over the Mauna Kea site, were obtained for one or more Venus disk mapping observations at every inferior conjunction between 2001 and 2009 (i.e., six annual periods). Terrestrial atmospheric water vapor is the primary variable with respect to noise present in each spectral observation, which is proportional to the system noise temperature (T_{sys} – Table 1).

The submillimeter line mapping observations consist of ^{12}CO and ^{13}CO absorption line spectra obtained for multiple pointing/integration positions on the apparent disk of Venus. All of the nightside observations were obtained very close to Venus inferior conjunctions when the Venus disk apparent size was 57–62 arcsec and the fraction of the disk illuminated was <3%. Consequently, all of these observations pertain to nighttime local times and provide optimum spatial resolution for disk-resolved observations. The JCMT diffraction-limited beam resolution is 13.5–14.5 arcsec at the observing frequencies of the B-band CO rotational lines, which allows 4–5 resolution elements across the nightside diameter of Venus. The basic observing method was to obtain separate ^{12}CO and ^{13}CO multi-beam-position mapping integrations over the Venus disk, as close in time as possible (from 15 min to 2 h), so that $^{12}CO/^{13}CO$ spectral pairs associated with identical pointing positions may be analyzed in terms of a single pressure–temperature–CO abundance (and Doppler wind) profile.

The number and position of beam integration positions over the nightside disk varied over of the 2001–2009 period, as indicated in Table 1. All of the mapping observations include a disk center position that provides local midnight, equatorial sampling as well as a zero Doppler wind reference (Clancy et al., 2010). For all of the observations except in 2001 (which includes only 5 mapping positions), beam integrations include E, W, N, S, NE, NW, SE, and SW positions around the limb of the Venus. Prior to the 2009 observations, they were positioned well within the Venus disk, offset 22 arcsec radially from disk center (Fig. 1A). Limb centered pointing positions, the analysis of which can be more sensitive to 2–4 arcsec commanded pointing uncertainties, were not employed until 2007 and, more extensively, in 2009 (Fig. 1B). We analyzed spectral continuum levels for the 2009 limb pointed positions to derive pointing corrections averaging less than 2 arcsec (similar to the millimeter CO analysis of Lellouch et al., 1994). Given the 14 arcsec FWHM beam-width, such pointing errors contribute minor uncertainties to retrieved temperature and CO abundance profiles. We also include in Table 1 a limited set of Venus superior conjunction observations, obtained in 2000, 2007, and 2008. Only disk center pointing positions are indicated for these dayside measurements (the disk is ⩾95% illuminated), as the apparent size of Venus near superior conjunction (10.5 arcsec) is substantially smaller than the JCMT beam resolution.

2.1. Venus ^{12}CO and ^{13}CO spectral line radiative transfer

Each ^{12}CO, ^{13}CO spectral observation pair supports combined temperature, CO profile retrievals over the 75–115 km altitude region (e.g., Clancy et al., 2003, 2008). Figs. 2 and 3 present ^{12}CO, ^{13}CO spectral pairs that demonstrate the spectral characteristics of CO line absorptions formed within the local midnight mesosphere and lower thermosphere on August 11, 2007. Solid lines indicate observed line absorptions, and symbols indicate radiative transfer (RT) synthetic line fits associated with retrieved temperature and CO abundance profiles within the mesosphere and lower