Carbon Monoxide Above and Below Venus’ Clouds

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Summary: Lower atmosphere Venusian carbon monoxide (CO) abundance at the polar collars, as measured in the infrared K-band (2.3 μm window), is elevated over the abundance at equatorial and mid-latitudes. Recently we have reported that this elevated abundance is confined to altitudes above ~40 km. We examine this result in the context of recent measurements of CO made in the middle atmosphere and find that the result is consistent with a planet wide over-turning of the atmosphere. CO that down-wells into the upper middle atmosphere appears to flow pole-ward as it down-wells further, eventually being consumed at the polar collars in the upper troposphere.

Keywords: Venus, Carbon Monoxide, CO, Troposphere, Mesosphere, Lower Atmosphere, Clouds, K-band.

Introduction

Carbon Monoxide in the Venusian Atmosphere

Venus is the solar system planet most similar to Earth in terms of size, mass and distance from the Sun and yet the atmospheric conditions of the two are vastly different [1]. Venus is the subject of a runaway greenhouse effect. The majority of the Venusian atmosphere is carbon dioxide (CO2) (96.5 %) and nitrogen (3.5 %) [1]. The most abundant trace gas, sulfur dioxide, is a precursor to the highly acidic Venusian cloud decks [2].

Venusian atmospheric chemistry is complicated with more than eighty different reactions taking place [3]. One of the most important atmospheric constituents is carbon monoxide (CO). CO is formed in the upper atmosphere by photo-dissociation of CO2, descending in the atmosphere, it is lost through chemical processes, including those important for the creation of the sulfuric acid clouds, as well as a conversion back into CO2 [3, 4]. As CO has a lifetime in the atmosphere of just 10’s to 100’s [5], it is important to studies of Venusian atmospheric dynamics [4, 6], providing particular insight into the Venusian Hadley cell in the lower atmosphere [4].

Recent Measurements of Carbon Monoxide

The infrared windows in Venus’ atmosphere were first discovered by Allen and Crawford in 1984 [7]. Spectra seen through the window at 2.3 μm (in the infrared K-band), in combination with atmospheric modelling [8, 9] allows the nightside abundance of carbon monoxide (CO) below the floor of the cloud layer at ~ 50 km to be gleaned. Studies using similar approaches have shown that CO is enhanced at these altitudes at the latitudes of the polar collars (around 60 degrees) [4, 9-14]; the enhancement has most often been interpreted as being representative of an altitude of 35 or 36 km where the measurement is most sensitive [4, 13], and is usually understood as being due to the overturning and down-welling of the atmosphere at the polar collars as part of the Venusian Hadley Cell [9, 11]. However, recently we have shown that enhancement in CO at the polar collars over the mid/equatorial regions actually occurs somewhat higher in the atmosphere at altitudes above ~40 km [11].
Recently a significant number of new measurements of upper middle atmosphere CO have been made with a variety of techniques [15-18]. Relatively few measurements of CO below ~75 km have been made previously, and these new measurements together with our own offer the potential for new insight into the dynamics of the middle and lower atmosphere. The purpose of the present paper is to discuss in more detail the results of recent measurements made of CO in the middle atmosphere.

What follows are two sections summarising measurements made of CO – above and below the clouds – with an emphasis on recent measurements and in particular our recent measurements, followed by a new discussion of these results. In essence this paper seeks to place the most recent measurements in context and in so doing present a new interpretation of the data.

Measurements of CO Above the Clouds

CO Origin in the Thermosphere

CO is created by UV photo-dissociation of CO$_2$ between 65 and 120 km [19], with a negative downward gradient associated with the main source region in the thermosphere [16, 19-22]. Above ~95 km CO abundance is enhanced by a factor of 2-4 on the nightside relative to the dayside, with the peak abundance very near the anti-solar point [21]. Between 80 and 90 km the peak abundance is shifted toward the morningside. Typically this nightside region of enhanced CO can extend down to around 70 km altitude to create what is know as the “CO bulge”, however there is considerable spatial and temporal variation in the CO mixing ratio at these altitudes [21, 22].

A significant number of microwave measurements have established the existence of a minimum in CO around 75 km [22], but the cause of this ‘CO depletion zone’ is not well understood [19]. Recently, by contrast with earlier ground based microwave measurements [20, 22], Vandaele et al. using SOIR on Venus Express found the minimum to be at 85 km altitude [18].

The dynamic of the upper atmosphere is dominated by thermal flow (dayside to nightside). In the middle atmosphere (below ~90 km) the dominant dynamic is that of the retrograde super-rotation. The mechanism by which gas is transported between the two regimes is not well understood, though it seems clear from oxygen air glow measurements that down-welling occurs around local midnight [23].

Middle Atmosphere CO Measurements

Until recently the dayside infrared spectroscopic measurement of Connes et al. [24]: 45 ± 10 ppmv at 65 km (later corrected by Young to 50 ± 1 ppmv at 58-66 km [25]), was the only notable measurement of CO made below the region sensitive to microwave measurements.

Measurements made in the last few years (published since 2008) of CO in the middle atmosphere support the Connes et al./Young measurement. Vandaele et al. found 30 to 50 ppmv at 75 km [18]. Iwagami et al. used dayside infrared spectroscopy (sensitive to 62–67 km) to measure a disc averaged mixing ratio of 58 ± 17 ppmv [16]. Krasnopolsky [17] produced three N-S trace measurements sensitive to slightly higher altitudes (68–71 km). Of those three traces one was near the evening terminator and returned 40 ± 4 ppmv. The two traces taken near the morning terminator returned 52 ± 5 and 51 ± 7 ppmv, with the latter having an equatorial enhancement up to 70 ppmv attributed to an extension of the nightside
“CO bulge” to lower altitudes. Krasnopolsky’s traces do not display a definite latitudinal trend, though there is a hint of an increase toward the polar collars. In contrast Iwagami et al. [16] report an enhancement of CO at equatorial latitudes in two of their four observations – in these cases the equatorial latitudes have a mixing ratio ~65 ppmv whereas the polar collars have ~30 ppmv.

A single nightside measurement of middle atmosphere (65–70 km) CO has been taken by Irwin et al. [15]. They used VIRTIS-M on Venus Express to take measurements in the 4.7μm window, finding 40 ± 10 ppmv for the southern mid-latitudes. Taken together with Krasnopolsky and Iwagami et al.’s results, this suggests that mid-latitude middle atmosphere CO may be slightly reduced on the evening/nightside compared to the morning/dayside, although the results are the same within error.

Measurements of CO Below the Clouds

Probe Based Measurements below the Clouds

The (sulfuric acid) Venusian cloud deck extends from 70 km down to ~48 km. Measurements of CO abundance below the clouds were first made by two probes in 1978. The Venera-12 mission, before landing at 7 ºS, 294 ºE, at ~10.30 LT [26], sampled the atmosphere 8 times between 42 km and ground level, recording ~30 ppmv in the range 42 to 36 km, and ~20 ppmv at 12 km [27], and being reported as 28 ± 14 ppmv overall [28]. Days before, the Pioneer Venus Large Probe impacted at 4.4 ºN, 304 ºE, at 7.38 LT [26], after sampling CO at three altitudes: 52 km (32.2 ± 7.2 ppmv), 42 km (30.2 ± 2.1 ppmv) and 22 km (19.9 ± 0.4 ppmv) [29]. Taken together the probe measurements describe a fairly steady drop off in CO abundance with altitude in the troposphere, but represent only equatorial latitudes during local morning and day times – although because of the opacity of Venus’ cloud layer little difference is expected between the night- and day-side below them.

Previous Tropospheric Polar Collar CO Measurements

The first to recommend a nightside altitudinal profile for carbon monoxide mixing ratios were von Zahn et al. [30]. Lower than 52 km this profile is wholly based on the probe measurements. Above that the profile has a very high mixing ratio at 100 km that is drawn to a minimum at 75 km based on the microwave measurements of Wilson and Klein [31]. Measurements of CO below the clouds that utilise the 2.3 μm K-band have utilised this profile [13, 14], or variants of it [9, 32, 33] that also include the Connes et al. measurement in the middle atmosphere and additional microwave measurements in the upper atmosphere such as those of Clancy and Muhleman [21] or Vandeaele et al. [18] (though these are not critical to determinations below the clouds). A typical altitudinal CO profile is shown later in this work.

Galileo and Ground Based Measurements

Ground-based observations using the 2.3 μm (K-band) window, in combination with spectral modelling – using the probe measurements as a basis – first retrieved a tropospheric CO mixing ratio as a linearly interpolated profile: {≤ 22 km: 30 ppmv, 42 km: 45 ppmv, 64 km: 75 ppmv} (~40 ppmv at 35 km) for a 5 arc-second diameter circular section of the nightside disk centred around 30 ºN [33]. Early maps of the nightside disk revealed no spatial contrast in CO [34]. These spectra [33, 34] were later reanalysed in combination to retrieve a linearly interpolated profile reported as a mixing ratio of 23 ± 5 ppmv with a gradient of 1.20 ± 0.45 ppmv/km at 36 km (i.e decreasing with depth into the troposphere) [35].
Variation in CO abundances with latitude was first inferred through analysis of Near-Infrared Mapping Spectrometer (NIMS) data from the Galileo flyby of the planet in 1990. North of 47°N CO abundance was found to be 135 ± 15 % of equatorial values [10]. Later, the latitudinal variation was confirmed from ground-based observations in the K-band spectroscopic window – interpreted through atmospheric models – by Marcq et al. who showed a ~15 % increase between the equatorial regions and latitudes 40°N/S [13]. Later reanalysis retrieved 24 ± 2 ppmv, at 36 km (with a gradient of 0.6 ± 0.3 ppmv/km), with an increase of 12 ± 4% by 40°N/S [14].

Venus Express Measurements

Since the arrival of Venus Express at the planet in April of 2006, both mapping (VIRTIS-M) and high resolution (VIRTIS-H) infrared instruments have been employed to retrieve tropospheric CO mixing ratios, all assuming similar linearly interpolated profiles, and all reported as mixing ratios at 35 or 36 km altitude. Sampling at various latitudes with VIRTIS-H revealed that CO abundances increased from the equatorial latitudes to at least 60°N/S (31 ± 2 ppmv (South), ~40 ppmv (North) as compared to the equatorial 24 ± 3 ppmv) [12]. Additionally dispersion in the measurements suggested a zonal or longitudinal variation of up to 20 % of the latitudinal mean [12]. Nightside maps produced with VIRTIS-M revealed that not only was CO increasing in abundance from the equator towards the poles, but that it reached a peak near 60°S (23 ± 2 ppmv at the equator to 32 ± 2 ppmv in the polar collar), and decreased at higher latitudes [4].

The pattern of CO past 60°S was explained as corresponding to the overturning of the atmosphere through the downward branch of the Hadley cell, while a dawn to dusk trend seen in two maps was initially ascribed to a combination of photo-chemistry and dynamical processes [4]. However, the most recent work, which includes North-South trace and southern hemisphere map data, has revealed temporal/zonal variability – and on a fast temporal scale not previously seen which may contradict the interpretation of the dawn to dusk trend [9].

Cotton et al. 2012 Measurements

Presented in this section is a summary of our most recent results. These results are presented in full elsewhere [11], but are detailed separately in summary here so as the reader might fully appreciate their significance for this review.

Observations and Analysis Method

The full details of the observations and analysis methods are available elsewhere [11]. In brief, we used the Anglo-Australian Telescope (AAT) at Siding Spring Observatory with the IRIS2 instrument [36] to acquire spatially resolved spectra of Venus at wavelengths between 2.0 and 2.4 μm in the near-infrared K-band. The spectrograph slit (1 arc second by 7.5 arc minutes) was scanned across the disk (typically ~40 arc seconds) to build up a spectral cube with R ~2400. These measurements were spread across 15 nights and three observing sessions between July 2004 until July 2007. We used the depth of the CO absorption band at 2.3 μm to map the two-dimensional distribution of CO across both hemispheres. VSTAR (Versatile Software for the Transfer of Atmospheric Radiation) radiative transfer models were used to relate the measured CO band depth to the volume mixing ratio of CO. We also modeled the detailed spectrum of the excess CO at high latitudes to determine the altitude of this extra CO.
2D Spatial and Temporal Variability

Our maps of the CO distribution confirm the results of previous studies in showing an enhancement of CO at latitudes of 60 °N/S. However, we saw significant variability in the details of the distribution pattern. Where observations were made over several nights we saw little indication of night-to-night variability in the distribution, but substantial changes were seen in the pattern over timescales of 20 days or longer.

Of the four disc maps, the one encompassing between 6LT and midnight showed the least variation, and displayed the clearest differentiation between polar collars and mid-latitudes. The other three maps display varying amounts of enhancement toward the mid-latitudes, and sometimes also a depletion in the polar collars toward the morning terminator (Fig. 1).

![Fig. 1: CO distribution by observing run showing the variation over time: (a) July 2004, (b) December 2005, (c) Early July 2007, (d) Late July 2007. These maps show CO mixing ratios at 35 km assuming an otherwise consistent altitudinal profile scaled by a multiplicative factor.](image-url)
We used the ratio of the spectra in regions of high CO concentration at high latitudes to low CO regions near the equator to determine the typical altitude of the extra CO responsible for the enhancements. Modelling (depicted in Fig. 2) revealed that the additional CO must be at altitudes of around 45 km, and not at the 35 km altitude assumed in previous studies. Because K-band measurements are less sensitive to CO at 45 km than at 35 km the amount of extra CO needed to account for the enhancements observed in these regions (in ppmv) is higher than had been determined previously (and presented in Fig. 1). This means that all other determinations of CO at the tropospheric polar collars will have to be revised (and for this reason they have been left off Fig. 3). By assuming a constant CO mixing ratio in the high latitude regions at altitudes above 38-40 km, mixing ratios in the range 54 to 83 ppmv were assigned for the map between 6LT and midnight, and the Southern hemisphere of the December 2005 map (Fig. 1). Around the equator the nominal mixing ratio of 27.5 ppmv at 45 km is presumed to still apply. However, where our maps show temporal variations around the mid-latitude and equatorial regions, the altitude of the enhancements in these regions has yet to be determined.

![Fig. 2: Ratio spectra of high to low CO regions (black dots) fitted with models (red lines) in which the CO mixing ratio in the high latitude high CO regions has a fixed value above 40 km and extending to the cloud tops (although we are not very sensitive to CO above about 50 km) as shown in the red line at right. The black line shows the nominal profile previously assumed to apply in the equatorial regions (and that was used for scaling in Fig. 1). Full detail including an error analysis for the fitting presented here is given in Cotton et al. 2012 [11], but it is worth noting here that the signal is attenuated somewhat at right of the plots in the left hand panel by the K-band filter used in collecting the data.](image)
Summary of CO Determinations below 75 km

**Table 1: CO Abundance Determinations Plotted in Fig. 3.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Altitude (km)</th>
<th>Abund. (ppmv)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vandeale et al. 2008</td>
<td>75</td>
<td>40 ± 10</td>
<td>Dayside, Sth Mid Lat Avg.</td>
</tr>
<tr>
<td>Krasnopolsky 2010</td>
<td>68-71</td>
<td>40 ± 4</td>
<td>Evening, N-S Trace Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52 ± 5</td>
<td>Morning, N-S Trace Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>51 ± 7</td>
<td>Morning, N-S Trace Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 ± 10</td>
<td>Morning, Eqi. Lat.</td>
</tr>
<tr>
<td>Irwin et al. 2008</td>
<td>65-70</td>
<td>40 ± 10</td>
<td>Nightside, Sth Mid-Lat Avg.</td>
</tr>
<tr>
<td>Young 1972</td>
<td>58-66</td>
<td>50 ± 1</td>
<td>Dayside, Disc Avg.</td>
</tr>
<tr>
<td>Iwagami et al. 2010</td>
<td>62-67</td>
<td>41 ± 18</td>
<td>Dayside, Disc Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>53 ± 14</td>
<td>Dayside, Disc Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70 ± 20</td>
<td>Dayside, Eqi. Lat. Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 ± 10</td>
<td>Dayside, Eqi. Lat. Avg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35-36</td>
<td>Nightside, Mid Lat Avg.</td>
</tr>
<tr>
<td>Marcq et al. 2006</td>
<td>35-36</td>
<td>24 ± 2</td>
<td>Nightside, Mid Lat Avg.</td>
</tr>
<tr>
<td>Marcq et al. 2008</td>
<td>35-36</td>
<td>24 ± 3</td>
<td>Nightside, Mid Lat Avg.</td>
</tr>
<tr>
<td>Tsang et al. 2008</td>
<td>35-36</td>
<td>23 ± 2</td>
<td>Nightside, Mid Lat Avg.</td>
</tr>
<tr>
<td>Oyama et al. 1980</td>
<td>52</td>
<td>32 ± 7</td>
<td>Morning, Eqi. Lat. (Probe)</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>30 ± 2</td>
<td>Morning, Eqi. Lat. (Probe)</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>20 ± 1½</td>
<td>Morning, Eqi. Lat. (Probe)</td>
</tr>
<tr>
<td>von Zahn and Morez 1985</td>
<td>42-36</td>
<td>30 ± 10</td>
<td>Dayside, Eqi. Lat. (Probe)</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>20 ± 1</td>
<td>Dayside, Eqi. Lat. (Probe)</td>
</tr>
</tbody>
</table>

Dynamical Implications

Overturning of the atmosphere transporting CO high in the atmosphere to the upper troposphere was first proposed by Taylor [19] as a way to both explain the enhancement of CO at higher latitudes and remove the requirement for a very large vertical diffusion rate at mid-latitudes. Taylor initially suggested transport via the polar vortices [19], whereas downwelling is now thought to take place at the latitude of the polar collars (around 60 °N/S) as part of a Hadley Cell [4].

The (mostly) recent measurements highlighted here provide increased support for the Hadley Cell picture. Lower atmosphere measurements made at equatorial latitudes suggest a steady decrease downward from 65-70 km in CO abundance in line with a moderate vertical diffusion rate. However, our recent determinations of tropospheric polar collar CO at 45-50 km are similar to – and possibly a little higher than – the abundances measured at 60-70 km; they are most similar to mid-latitude measurements made of Venus local morning or the...
dayside around 65 km. Such a result indicates a pole-ward flow followed by an over-turning (down-welling) of the atmosphere at the polar collars. Negligible net consumption of CO on this route until the cloud deck floor suggests that the over-turning is rapid.

Temporal Variations

Equatorial measurements of CO at 65-70 km in general tend to be higher than the disc average; these abundances measured at local morning or day are higher than those of the night or evening. This could be related to photo-dissociation still taking place at these altitudes, or it might be related to CO being sporadically transported through the depletion region via a morning extension of the CO nightside bulge down to lower altitudes similar to that hypothesised by Krasnopolsky [17]. The downward and morning-ward extent of the bulge has been known to vary [22], and the measurement of Vandaele et al. [18] placing the depletion zone much higher in the atmosphere than previously noted reinforces the variability of the atmosphere in this region. If tropospheric polar collar CO is directly sourced from above ~60 km then it seems likely that variability in the feeding of CO into this region plays a role in the temporal variations we see in the tropospheric CO distribution.

Mesospheric CO distribution have only been found to vary on “year-to-year” timescales (c.f [22]) using microwave measurements. Shorter timescale fluctuations have not been found, however most microwave measurements have been acquired from a run of 6 days or less (e.g. [22, 37]), a period over which we see little change in the tropospheric CO; and the observing has typically taken place only at inferior conjunction – meaning there has been little opportunity to observe variations on intermediate timescales. However, in 1977 measurements of the mesosphere made in February and April revealed a significantly different altitudinal distribution [38]. Though not as drastic, there are also differences in Vandaele et al.’s measurements taken ~1 month apart; they show a variation of 20 ppmv at 75 km [18]. So, it seems feasible that variations in the mesospheric CO distribution could occur on similar intermediate timescales – weeks to months – to those observed in the troposphere.

Conclusions

Our recent determinations of CO abundance in the tropospheric polar collars, and those of others in the upper-middle atmosphere, are suggestive of a more direct link between these two areas of the atmosphere of Venus than might previously have been considered. Similar concentrations in these regions indicate negligible net consumption of CO above the cloud deck in the collars and are suggestive of rapid down-welling. There is a possibility that temporal variations seen in the tropospheric CO could be related to irregular transport of mesospheric CO through the depletion zone around 75-85 km into the upper middle atmosphere.

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References


