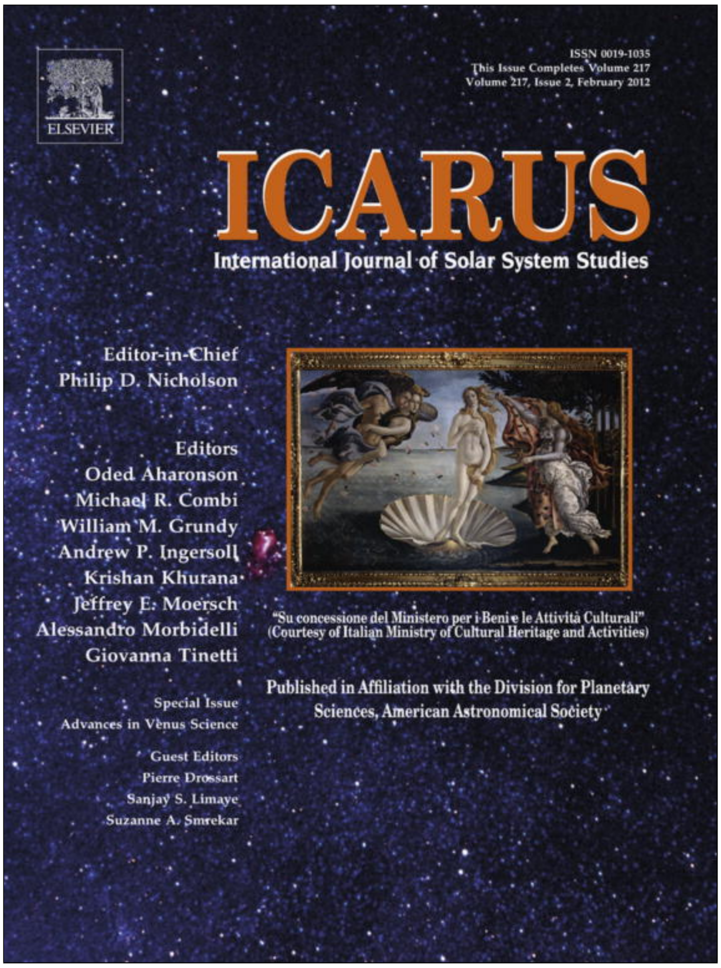
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Optical extinction due to aerosols in the upper haze of Venus: Four years of SOIR/VEX observations from 2006 to 2010

Valérie Wilquet [a,*], Rachel Drummond [a], Arnaud Mahieux [a], Séverine Robert [a], Ann Carine Vandaele [a], Jean-Loup Bertaux [b,c]

[a] Belgian Institute for Space Aeronomy, 3 Av. Circulaire, B-1180 Brussels, Belgium
[b] LATMOS, 11 Bd d'Alembert, 78280 Guyancourt, France
[c] Institut Pierre Simon Laplace, Université de Versailles-Saint-Quentin, 78280 Guyancourt, France

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ABSTRACT

The variability of the aerosol loading in the mesosphere of Venus is investigated from a large data set obtained with SOIR, a channel of the SPICAV instrument suite onboard Venus Express. Vertical profiles of the extinction due to light absorption by aerosols are retrieved from a spectral window around 3.0 μm recorded in many solar occultations (∼200) from September 2006 to September 2010. For this period, the continuum of light absorption is analyzed in terms of spatial and temporal variations of the upper haze of Venus. It is shown that there is a high short-term (a few Earth days) and a long-term (∼80 Earth days) variability of the extinction profiles within the data set. Latitudinal dependency of the aerosol loading is presented for the entire period considered and for shorter periods of time as well.

1. Introduction

Aerosols have been studied extensively because their optical properties impact the radiative balance through absorption and scattering of solar radiation. They also play a crucial role in heterogeneous chemistry. Important information on aerosol extinction can be obtained from satellite remote sensing measurements. However the retrieval of extinction coefficients is known to be difficult due to the lack of spectral signatures of aerosols.

The upper haze on Venus lies above the cloud layer surrounding the planet, ranging from the top of the cloud (∼70 km) up to as high as 90 km (Esposito, 1983). The ∼1.0 μm particles within the cloud layer were already identified in the early 1970s (Hansen and Hovenier, 1974) and are most likely composed of concentrated sulfuric acid (for a review see Esposito, 1983). This was confirmed later and the existence of a second species of smaller particles within and above the clouds with an effective radius of ∼0.25 μm was suggested from measurements obtained at relatively short wavelengths (<1.0 μm) by the Pioneer Venus Orbiter Cloud Photopolarimeter (OCPP) during the nominal mission in 1979 (Kawabata et al., 1980). The authors also explained that the differences they observed in the amount of haze between the polar regions and the rest of the disk is partly due to a variation of the altitude of the cloud top which is up to one scale height lower in the polar region.

Data on the climatology of the upper haze of Venus are rather sparse. Using OCPP polarization data, Knibbe et al. (1998) revisited later by Braak et al. (2002), pointed out long-term temporal variations of the haze layer, as they observed a gradual decrease of the haze particle column density during the Pioneer Venus Orbiter mission (from 1978 to 1990). From OCPP data of the beginning of the mission, Sato et al. (1996) also observed short-term variations of optical thickness of the haze particles in the polar regions. Since its arrival at Venus in 2006, several instruments on VEX have been accumulating new data of the Venus atmosphere over a broad range of wavelengths (Svedhem et al., 2009). It is worth mentioning that both VIRTIS-M IR on the nightside (de Kok et al., 2011) and SPICAV/SOIR at the terminators (Wilquet et al., 2009) are able to target the upper haze above the cloud layers for further investigation. Stellar occultations by SPICAV-UV on the nightside are also useful in this context.

SOIR stands for Solar Occultation in the InfraRed and is designed to measure the atmospheric transmission of the solar light in the infrared (IR). The instrument uses the self-calibrated technique of solar occultation for remote measurements of atmospheric gases. It gives access to important information about the vertical structure and composition of the Venus mesosphere and lower thermosphere. The instrument has proven its potential by obtaining densities and temperatures from CO_2 measurements (Mahieux et al., 2010), by detecting and retrieving vertical profiles of trace gases (Vandaele et al., 2008; Fedorova et al., 2008) and by identifying new CO_2 bands of isotopologues (Bertaux et al., 2008; Wilquet et al., 2008). In addition, we recently demonstrated the potential of the SPICAV/SOIR suite of instruments, which covers the spectral

* Corresponding author.
E-mail address: valerie.wilquet@aeronomie.be (V. Wilquet).

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region from 0.2 to 4.4 μm, to characterize the aerosol layer above the Venusian clouds (Wilquet et al., 2009).

The continuum of absorption in the SOIR spectra is primarily shaped by the extinction caused by the aerosol particles present in the upper haze (between ~70 and 90 km) of the Venus mesosphere. This information allows us to retrieve the aerosol slant opacity and the local extinction profiles. In this paper, we present an analysis of the optical extinction by aerosols in the upper haze over a period of 4 years of the VEX mission, covering the whole latitude range.

2. Measurements and data sets

2.1. The SOIR instrument

SOIR is an innovative echelle grating spectrometer onboard the ESA's Venus Express (VEX) spacecraft. All features, capabilities and characteristics of the instrument have been detailed in Nevejans et al. (2006), Bertaux et al. (2007) and Mahieux et al. (2008). Therefore, only a brief description is given here. SOIR operates in the solar occultation (SO) mode, i.e. the line of sight (LOS) of the channel points towards the Sun. As VEX is moving along its orbit, the LOS crosses the atmosphere of Venus at successive tangent altitudes.

The instrument is operating in the IR (2.3–4.4 μm) and its spectral resolution is of about 0.15 cm^{-1}. It includes a combination of an echelle grating and an acousto optic tunable filter (AOTF) to select one diffraction order at a time. The complete spectral window is divided into 94 useful diffraction orders of width ~20 cm^{-1}. During a typical occultation, four different diffraction orders are scanned sequentially by varying the radio frequency applied to the crystal of the AOTF filter every 250 ms. Therefore the same spectral window is scanned every second. The selection of orders has implication on the target molecules that are probed during an occultation.

The slit of SOIR is 2′ in the spectral direction, and 30′ in the spatial direction. The vertical resolution is comprised between 200 m and 700 m for SO at high northern latitudes and from 2.0 up to 5.0 km for measurements in the Southern hemisphere (Mahieux et al., 2010). The detector counts 256 pixel rows in the spatial direction but only the 24 central pixel rows are read. Due to telemetry constraints and in order to increase the signal to noise ratio, pixel rows are summed in two groups of 12 rows and called bin 1 and bin 2 (Mahieux et al., 2008). In this study, the vertical profiles obtained for each bin are combined (error weighted mean) resulting in one unique extinction profile for each orbit (called bin 0).

2.2. Spatial and temporal distribution of the measurements

For the purpose of studying the aerosol loading in the upper haze, in terms of time and location, we selected a window of wavelengths comprised between 2.96 and 3.02 μm and corresponding to the SOIR diffraction orders 148–150, recorded routinely between September 2006 and September 2010. Due to the orbit of VEX being fixed, periods for which solar occultations are possible are grouped within periods of about 85 orbits separated by about 35 orbits. There is one orbit per day. Each period is called a season of SO (Fig. 1), yet not all orbits of a season are favorable for SOIR observations. A total of 424 extinction profiles of the mesosphere were retrieved from the SOIR observations during seasons 2–15. Fig. 1 shows the latitudinal distribution of the observations considered for this study.

Observations in the northern hemisphere are mainly constrained to latitudes near the pole (the orbit of VEX is polar, with the pericenter near the North pole) while the coverage in latitude in the southern hemisphere is more widespread (see Fig. 1) and can be used to investigate possible latitudinal variations within the data set. Series of occultation events in the latitude ranges 60°–90°N and 60°–90°S allowed us to look for time variations on the long-term near the poles. In addition, SO seasons 4, 6 and 9–14 can be used to investigate the temporal variability near the equator (±30°).

3. Method of analysis

The spectra recorded for each bin (as defined in Section 2.1) are processed separately as described below, and the results of the retrieval are then combined (bin 0) into one vertical profile (i.e. density, temperature or extinction) obtained from the error weighted mean of bin 1 and 2.

The retrieval algorithm is called ASIMAT and is based on ASIMUT, both codes are described in detail in Mahieux et al. (2010) and in Vandaele et al. (2008), respectively. The onion peeling approach is used, in which the atmosphere is considered as an onion-like structure composed of successive homogenous spherical layers. Using this approach, temperature, pressure and mixing ratios of the constituents are considered constant within a layer. It simplifies the problem as the information obtained for the external layers is used for the analysis of subsequent layers deeper in the atmosphere.

To invert all the observed transmittances corresponding to one occultation in one go, the Optimal Estimation (OE) method developed by Rodgers (2000) has been implemented in ASIMAT, the procedure has been detailed in Mahieux et al. (2010). The general strategy of the OE is to constrain the parameters retrieved from a set of measurements (transmittances in the present case) within physically reasonable limits through the use of an a priori model. The error on the local extinction is directly obtained from the OE retrieval algorithm.

The contribution of each species to the molecular absorption is determined through a line-by-line model using the HITRAN 2008 spectroscopic parameters (Rothman et al., 2009) adapted to the venusian atmosphere mainly composed of CO_2 (Vandaele et al., 2008). As the aerosol signature is a continuum of absorption, the impact of aerosols on the observed spectra is therefore a decrease of the mean transmittance levels with decreasing altitude (Fig. 2), which is called the baseline of the spectra. The continuum is obtained by fitting the baseline of a spectrum, i.e. the observed transmittance T from which absorption lines have been removed, by a second degree polynomial as a function of the wavenumber (Fig. 2).

The aerosol optical depth (τ) was retrieved from the series of transmittances (T) averaged in the selected spectral window. Each transmittance is obtained by making the ratio of the solar spectrum seen through the Venus atmosphere (I) to the unattenuated solar spectrum measured above the atmosphere (I_0). Applying the onion-peeling method leads to the determination of the local extinction (β) in each atmospheric layer (see Eqs. (1) and (2))

$$\tau = -\ln(T) = -\ln\left(\frac{I}{I_0}\right) \tag{1}$$

$$\beta_N(\lambda) = \frac{\tau - \sum_{i=1}^{N-1} dz_i \beta_i(\lambda, z)}{dz_N} \tag{2}$$

where N is the number of atmospheric layers considered, i is the numbering of all layers above layer N and dz is the thickness of the layer under consideration.

4. The aerosol loading in the Venus' upper haze from 2006 to 2010

The considerable number of SOIR data obtained since the arrival of VEX at Venus in May 2006 allows us to present to a broad extent

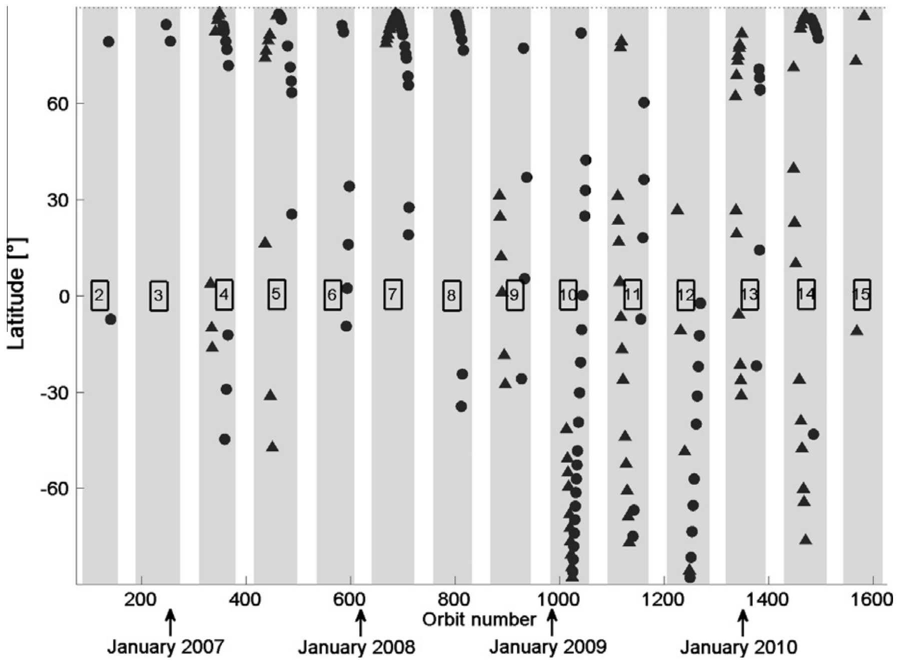

Fig. 1. Map of SOIR occultations considered in this study. The latitude is plotted as a function of the VEX orbit number. For clarity, a few dates are given. The gray boxes delimit the SO seasons (numbered in the middle of the figure). • are for SO at the morning terminator while ▲ are for SO at the evening terminator. There is one orbit per day.

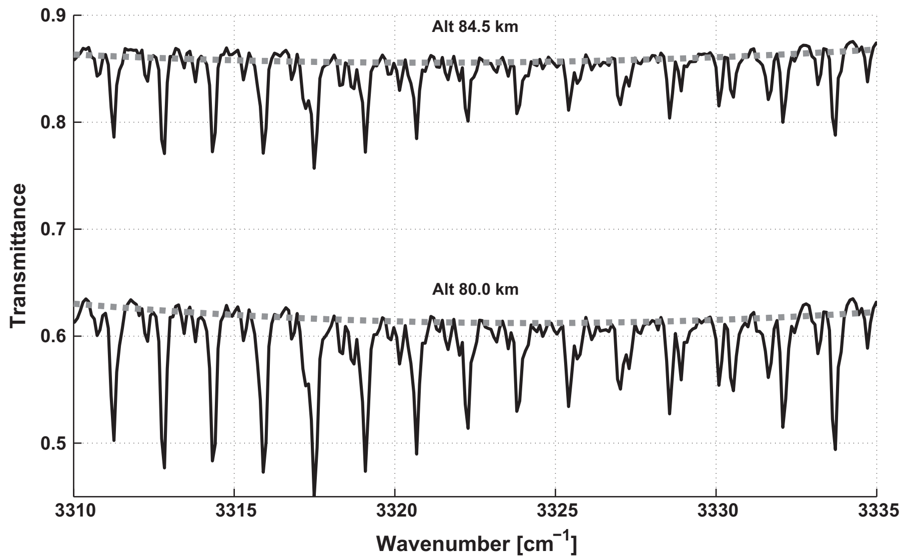

Fig. 2. Continuum of absorption. The spectra (black lines) were recorded on 24 February 2009, in the diffraction order 148 at altitudes of 80.0 and 84.5 km. The regularly spaced absorption lines are due to the main isotopologue of CO_2. The gray dashed lines are the 2nd order polynomial to fit the baseline of the spectra.

a recent geo-temporal variability of the upper haze of Venus. In the next section, a number of extinction profiles are presented as representative results. In order to compare numerous observations, values of the aerosol extinction at a given altitude (horizontal slices) are also plotted as a function of time or latitude.

4.1. Effect of the latitude

It is known that the altitude of the cloud top decreases when reaching the poles of Venus (Kawabata et al., 1980) and this has been recently confirmed by Ignatiev et al. (2009) and Fedorova et al. (2009). We therefore investigated the latitudinal variations of the extinction due to aerosols in the haze above the clouds. Seasons 10, 11 and 12 are considered as the coverage in latitudes is well spread (see Fig. 1).

As shown in Fig. 3, the local extinction profiles are shifted towards higher values of the extinction when the latitude of the tangent point of the observation (insets in Fig. 3) moves towards the equator. This is observed for the morning terminator (middle panels, seasons 10 and 12) and for the evening terminator as well (top panels, season 10 and 11). In contrast, the extinction profiles are grouped together for series of observations confined to high latitude (bottom panels, seasons 4 and 7) close to the North Pole.

Fig. 4 presents a global picture of all observations considered in this study regarding the latitudinal dependency of the extinction. For each profile, the value of the extinction at 80 km of altitude

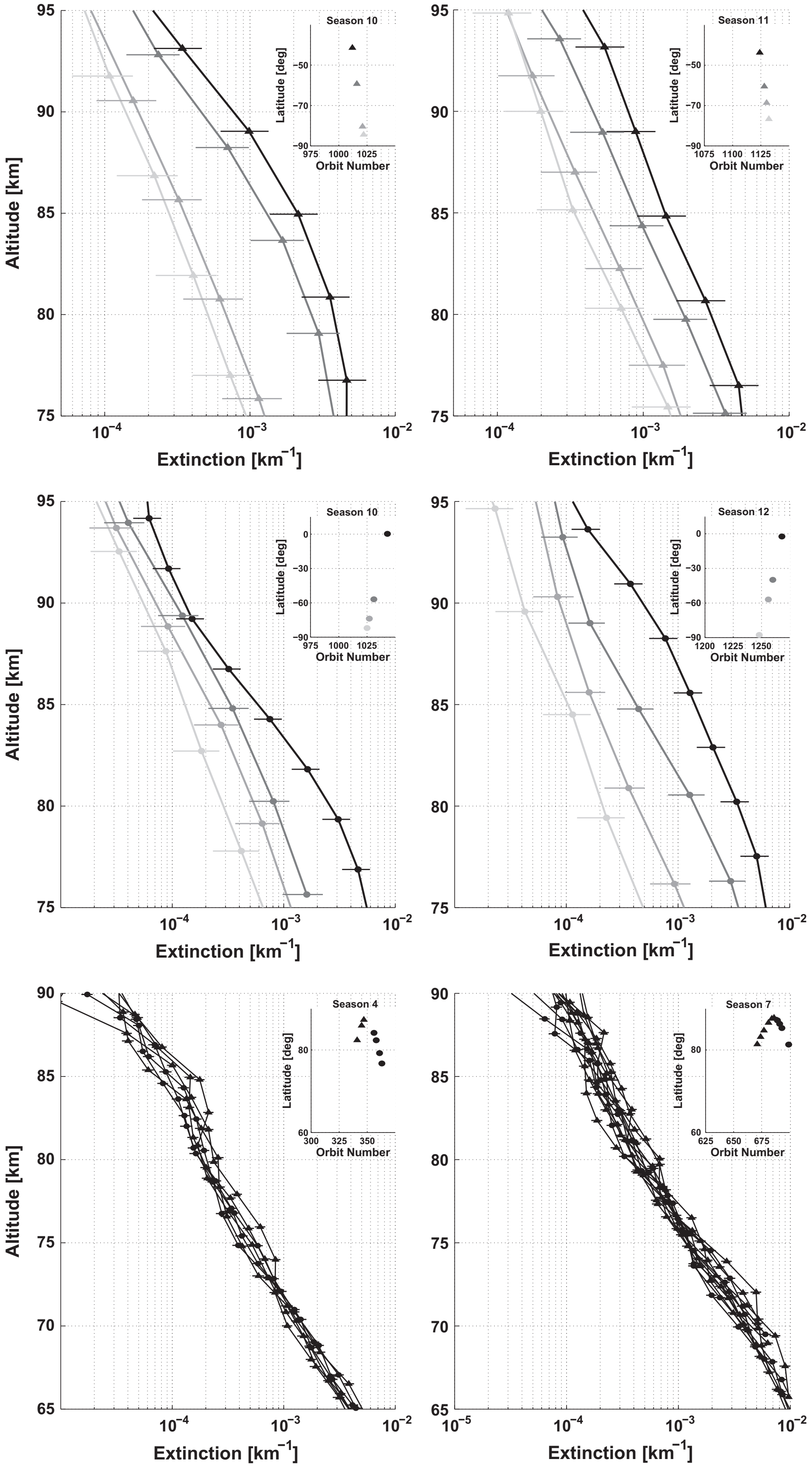

Fig. 3. Latitudinal variations of the extinction profiles during a number of seasons. For seasons 10 (February 2009), 11 (May–June 2009) and 12 (September–October 2009), the latitudinal coverage is spread (top and middle panels). On the bottom panels, extinction profiles are plotted for series of observations confined to high northern latitudes during seasons 4 (March–April 2007) and 7 (February–March 2008). • are for SO at the morning terminator while ▲ are for SO at the evening terminator. The horizontal bars represent the error on retrieved β.

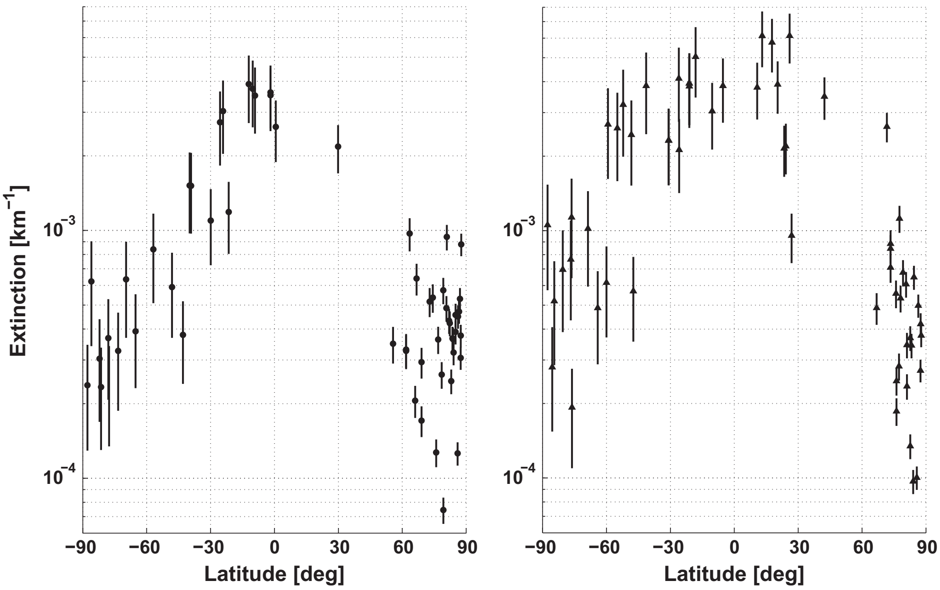

Fig. 4. Latitudinal variations of the extinction at 80 km of altitude for the all data set. On the left-hand panel, the values of the extinction for SO at the morning terminator (•) are plotted as a function of the latitude and on the right-hand panel, for observations at the evening terminator (▲). The vertical bars represent the error on retrieved β.

was plotted as a function of the latitude of the observation. For both terminators (morning on the left panel and evening on the right), it is observed that the extinction due to aerosols is significantly lower towards the poles (by a factor 10 at least) compared to the values around the equator, this is observed in both hemispheres. However, there is apparently no correlation between the extinction due to aerosols and the latitude in the region comprised between $-30°$ and $+30°$ around the equator (Fig. 4).

The altitude at which the aerosol slant opacity, τ, is equal to 1.0 (for $\lambda \sim 3.0$ μm) is 73 ± 2 km near the North pole and 82 ± 1 km at the equator and mid-latitudes (data not shown). The extinction values for the evening terminator is slightly higher (up to a factor of 2) than those for the morning terminator.

4.2. Time variation

In order to investigate the temporal variations within our measurements, we grouped together profiles retrieved at comparable latitudes. In this way, the effect of the latitude is substantially removed. Extinction profiles obtained at high latitudes (between +60° and +90°) during seasons 5 (11 profiles) and 7 (18 profiles) exhibited high and low short-term variability of the extinction, respectively. As one can observe in Fig. 5, the extinction measured at 77 km or 81 km of altitude during season 5 varies with almost a factor of 10 for occultations separated by a few Earth days (top right panels). This variability is also observed during season 13 (data not shown). It is not observed for all seasons, hence the variability is generally smaller. This is illustrated for season 7, for which values of the extinction differ by maximum a factor of 2 at most (bottom right panels). In consequence, the extinction profiles are grouped together (right-hand bottom panel of Fig. 5) compared to those obtained for season 5 (right-hand top panel).

The data are also analyzed for temporal effect on the longer-term, that is to say a period of more than 3 Earth years from season 4 (March 2007) to season 15 (August 2010). Again, only profiles within the same latitude range are compared, as shown on the maps, either latitudes between ±30° (bottom left panel in Fig. 6) or high southern and northern latitudes (bottom right panel). Data obtained for each terminator and for each season are grouped together. Within a group of profiles, the extinction at a given altitude is fitted using the method of error weighted least squares, resulting in one value of β.

These results are summarized in Fig. 6. Variations of the extinction (top panels) with time are different for the two ranges of latitudes and no obvious pattern can be deduced for this first data set regarding the long-term variability. Values of the extinction at 80 km for equatorial to mid-latitudes are confined between 1.3×10^{-3} and 5.5×10^{-3} km^{-1} with the exception of season 4 with a very low value of $\sim 2.0 \times 10^{-4}$ km^{-1}. In addition values for the evening terminator are either comparable or higher by a factor of maximum 2.5 than the one obtained for the morning terminator. For high latitudes, the extinction varies by a factor up to ~ 5 between seasons 7 and 14 for measurements at each terminator. The extreme value for season 5 was not taken into account for the long-term variability as it was shown that there is high short-term variability during this season. No significant differences in local extinction between the two terminators are observed at high latitudes except for season 5 which shows outstanding behavior for a number of SO (Fig. 5).

5. Discussion

The latitudinal behavior of the extinction due to aerosols described in the previous section, is also translated into a difference of ~ 9 km in the $\tau = 1$ altitude between the equatorial region and the poles. This range of altitudes is comparable to the differences in the altitude of the cloud top found with VIRTIS, ~ 66 km at low latitudes and ~ 74 km near the South pole (Ignatiev et al., 2009; Fedorova et al., 2009).

The slight asymmetry with respect to the equator that appears in Fig. 4 can be due to (1) the error on the extinction that is increasing with the latitude varying from +90° to $-90°$. Indeed the distance to the limb of SOIR is much greater and therefore the vertical resolution is worse going from the North to the South Pole, (2) the fact that the data set is latitudinally-biased as there is an over-representation of data at high northern latitudes and an underrepresentation of data between +30° and +60° of latitude. While the effect of the latitude on the local extinction is not disputable, the range of values of the extinction within 10° latitude windows is rather large (a factor of 10 in polar regions). It can be explained partly by the long-term variations; by constraining the

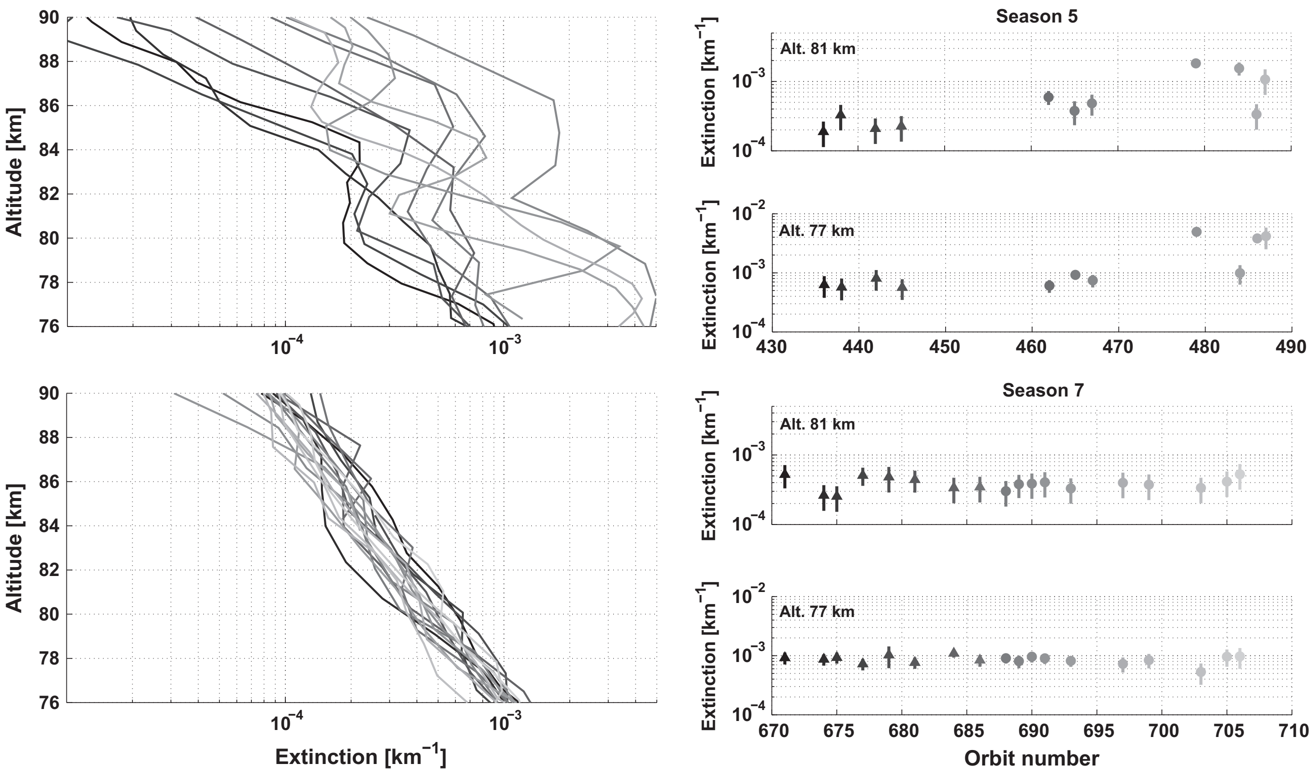

Fig. 5. Time variations of the local extinction. Occultation season 5 (July–August 2007) is presented on the top half and season 7 (February–March 2008) on the bottom half of the figure. The four right panels are horizontal slices at 81 km and 77 km, vertical bars represent the error on retrieved β. On the left panels, the extinction profiles considered are plotted. • are for SO at the morning terminator while ▲ are for SO at the evening terminator.

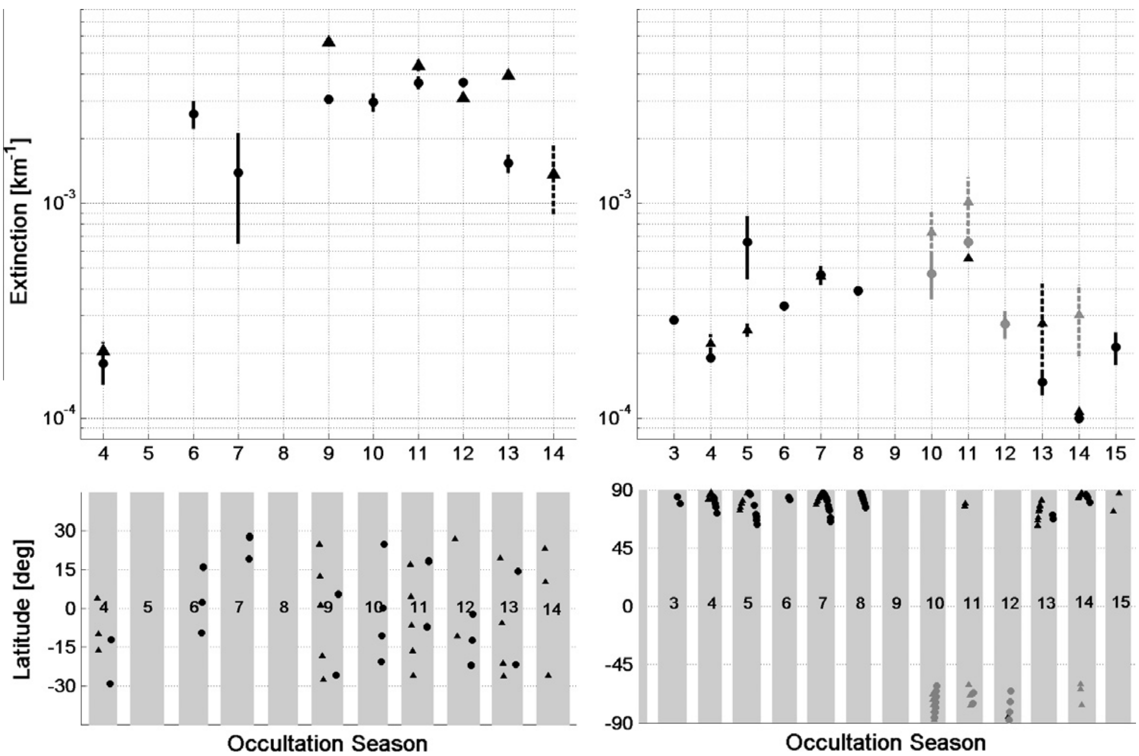

Fig. 6. Long-term variations. The error weighted mean of the extinction at 80 km of altitude for each season (top) is plotted as a function of time. The vertical bars are the standard deviation. • are for group of SO at the morning terminator while ▲ are for group of SO at the evening terminator. The bottom panels are maps of the occultations considered for each season. On the right panels, black is for observations at high northern latitudes and gray at high southern latitudes and on the left panels, SO from −30° to +30° are considered.

latitude range between 80° and 90°, the mean of the measurements during seasons 7 and 14 differ by a factor of ~5, for each terminator independently. In addition, the episodes of high short-term variability observed for seasons 5 and 13 do correlate with latitudes of the cold collars (60–75° in each hemisphere), known to differ thermally and dynamically from other regions.

Recently, Marcq et al. (2011) showed that the SO_2 mixing ratio derived from column density above the clouds obtained with SPICAV-UV dayside nadir viewing also presents latitudinal variation. It is even more correlated with the cloud top altitude obtained with SPICAV-IR. The highest values of SO_2 mixing ratio are found near the equator, which is in disagreement with results from previous missions and with the fact that SO_2 photolysis is more efficient at low latitudes for obvious reasons. In this special issue, a paper by Belyaev et al. (2012) presents vertical profiles of SO_2 obtained from SOIR spectra in the IR (altitude range between 65 and 80 km) and from SPICAV in the UV (altitude range from 85 to 105 km) both in the solar occultation mode. They also observe a decreasing SO_2 content when going from the Equator to the Pole. In addition, in the lowest atmospheric layer (probed with SOIR), SO_2 content decreases with increasing altitude while the reverse is observed at higher altitudes (probed with SPICAV-UV). Zhang et al. (2012) recently proposed a one dimensional photochemistry-diffusion model in order to reconcile these puzzling findings. It is generally accepted that H_2SO_4 aerosol particles are formed through SO_2 oxidation and hydration at the cloud top of Venus. It is now suggested (Zhang et al., 2011) that H_2SO_4 might be a source of SO_2 above 90 km through aerosol evaporation followed by SO_3 photolysis. Altogether, it shows the necessity for a careful examination of the relationship between SO_2 and aerosols content in the mesosphere of Venus.

Because SOIR was not operating at high southern latitudes during the first five seasons (see Fig. 1), we cannot investigate a possible long-term change as recently observed by Ignatiev et al. (2009). Indeed, VIRTIS detected a raise of the cloud top by ~3 km in this region between the first five seasons compared to the next ones. The further accumulation of SOIR data during the prolongation period of the VEX mission will allow us to detect possible trends of the aerosol loading in the upper haze if such trends would appear as it was the case during the Pioneer Venus Orbiter mission (Braak et al., 2002).

The time periods of the first data sets analyzed by VIRTIS, SPICAV and SOIR only partly overlap. It would be interesting to compare during future measurements: (1) the cloud top altitude as determined by VIRTIS, (2) the SO_2 content above the clouds as determined by SPICAV/SOIR, (3) the local extinction due to aerosols retrieved from SOIR data at the same altitude. SO_2 column abundance above the cloud top can be derived with SPICAV-UV in nadir mode on the dayside (Marcq et al., 2011). Vertical profiles of aerosol extinction (this work) and SO_2 vertical profiles (Belyaev et al., 2012), can be obtained with SPICAV/SOIR at the terminator. However, VIRTIS is measuring on the dayside only. Intercomparisons will have to take this difference into account.

6. Summary

A first data set of extinction profiles were retrieved from spectra obtained with the SOIR instrument onboard Venus Express for the period September 2006 to September 2010. This sample presents a high variability of the local extinction in the upper haze. SOIR also allows detection of events of high extinction variability, from orbit to orbit. An effect of the latitude on the aerosol extinction profiles is observed for several seasons of occultations individually. When grouping 4 years of measurements, a clear structure in the latitudinal distribution of the aerosol loading is observed, i.e. the value of the extinction at a given altitude within the upper haze is higher by at least a factor of 10 for observations near the equator compared to the those at the poles.

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