Study of the Venus' upper haze

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Abstract The Solar Occultation in the InfraRed (SOIR) onboard Venus Express (ESA) is designed to measure the atmospheric transmission at high altitudes (65–165 km) in the IR (2.2–4.3 μm) with high resolution by solar occultation. The SOIR data obtained in 2006-2009 are analyzed to examine the upper haze at altitude above 90 km. Vertical and latitudinal distribution of haze extinction, optical thickness and mixing ratio were calculated using statistics of the SOIR data. Extinctions and optical thickness due to aerosols at low latitude are two times thicker than those at high latitude. One of the notable results is the mixing ratio of aerosols increases at altitude above 90 km at both high and low latitudes. It is speculated that sources of haze are transported upward from altitude under 90 km and haze is produced at high altitude. From comparison with the vertical distributions of SO and SO_2 mixing ratios reported by Belyaev et al. (2012), it is speculated about the correlation between sulfur oxides and haze.

1. Introduction

The Venus cloud consists of a main cloud deck at 47–70 km, with thinner hazes above and below. 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 et al., 1983]. Relationship between haze and sulfur oxides is inferred from analogy of correlation between main cloud and sulfuric acid. For example, Belyaev et al. (2012) suggests from Venus Express observations that haze is related to SO and SO_2. SO and SO_2 mixing ratios increase with altitude from 85 to 105 km [Belyaev et al., 2012]. It suggests a new source of SO_2 at high altitude. One possible source of SO_2 in the upper haze layer could be photo-dissociation of SO_3 resulting from evaporation of H_2SO_4 droplets. However, recent upper limit of H_2SO_4 from sub-mm ground-based observation makes this theory less likely [Sandor et al., 2012]. The cause of the phenomena given above is still controversial. That is, the relationship between sulfur oxides and haze, and transport process are still unknown. The aim of this work is to examine the upper haze properties at altitude above 90 km, especially extinction, optical thickness and mixing ratio. This work also has aim to discuss the relationship between sulfuric compound and haze at high altitude. Although several studies have been made on haze layer, there is a poor understanding about it. For example, haze creation process, composition, global distribution, transport process, relationship with sulfuric compound and H_2SO_4 cloud, and so on. If the upper haze properties and relationship with sulfuric compound are cleared in this work, dynamic and chemical process could be cleared globally. This work could be the breakthrough to understand the dynamic and chemical process of overall Venus cloud including main cloud deck, not only confined to the haze layer.

2. Observation

2.1 Venus Express / SOIR instrument

SOIR is a compact and high resolution infrared echelle grating spectrometer. Descriptions of SOIR are summarized in Nevejans et al. (2006), Bertaux et al. (2007) and Mahieux et al. (2008). SOIR is a small volume of 414 × 254 × 210 millimeters. The instrument has a mass of 6.5 kg. SOIR observes Venus atmosphere in using the solar occultation method. It measures from 2.2 μm to 4.3 μm, or 4400 cm^{-1} to 2200 cm^{-1} and its spectral resolution is about 0.15 cm^{-1}. The width of the slit is 2′ in the spectral direction, and 30′ in the spatial direction. The apparent size of the Sun at Venus is 44′, which ensures that the slit will remain within the solar disk. The vertical distribution is comprised between 200 and 700 m at high northern latitudes and from 2.0 up to 5.0 km in the southern hemisphere [Mahieux et al., 2010]. Vertical structure and composition of the Venus atmosphere and cloud are obtained by SOIR with the solar occultation method. SOIR is looking toward the Sun and records spectra every one second. Solar occultations occur when the line of sight of the instrument crosses the Venus atmosphere. Tangent altitude is defined as the distance from the Venus surface to the center of the slit. SOIR observes Venus atmosphere during the spacecraft is moving along its orbit at different tangent altitudes. Two different configurations can be observed; one is the ingress case and the other is egress.

2.2 Transmittance observed by SOIR

Fig.1 gives an example of the observed transmittance (T_{obs}) through one occultation (03 Dec. 2007, order147, orbit591, lat.9 ° S, lon.209 °). Note that the vertical scale on Fig.1 is enlarged; the bottom of the vertical scale is 0.95. At the beginning of the one occultation, the light path is assumed not to cross the Venus atmosphere down to 220 km in tangent height h_{tg}. No absorption signature is assumed to be present and transmittances are equal to almost unity. As the Sun sets, the light path goes deeper and deeper into the atmosphere, and two absorption processes take place: continuum absorption due to aerosols and line absorption such as CO_2. At the end of an occultation, no light is captured anymore because the Sun disappears behind the cloud deck. As seen in Fig.1, solar spectrum has already been removed from observed spectra. It is found that the standard deviation on the observed transmittance is small enough to isolate an individual observed transmittance regardless of high-altitude observation. As an example, the difference between the spectra at 118.54 km and 115.77 km is 0.21 % while the standard deviation is 0.08 %. The average of the difference between two spectra at around 110 km and standard deviation are 0.3 % and 0.1 % at most, respectively. The total number observed occultation is 130. Most of these data are obtained from 2006 to 2009 at high latitude.

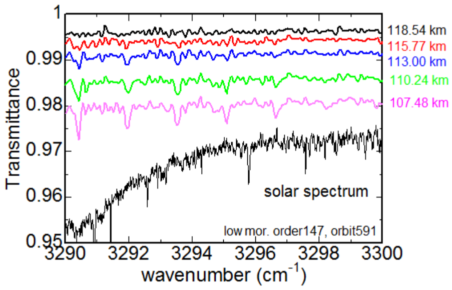

Fig.1 Example of observed transmittance (03 Dec. 2007, order147, orbit591, lat.9 ° S, lon.209 °). A solar spectrum (black) is also plotted. The standard deviation on the observed transmittance is small enough to isolate an individual observed transmittance regardless of high-altitude observation.

3. Method of Analysis

As described in Section 2.2, T_{obs} is obtained by taking the quotient between the atmosphere measured spectra and the spectra taken before the line of sight crosses the atmosphere. As the aerosol signature is a continuum absorption, the impact of aerosols on the observed spectra is a decrease of the mean transmittance levels with decreasing altitude (ex. Fig.1), which is called the baseline. To define the baseline, molecular absorption signatures due to Venus atmospheric molecules such as CO_2 are removed from observed transmittance. Molecular absorption (T_{molec}) is calculated by line-by-line method in using following equations,

$$T_{molec} = e^{-\tau_{total}} \tag{1a}$$

$$\tau_{total} = \sum \tau_i \tag{1b}$$

$$\tau_i = \sigma_i \int_{path} n_i \quad ds \quad (i = CO_2, H_2O, SO_2, HCl\ldots) \tag{2}$$

where τ_i, σ_i and n_i is optical thickness, absorption cross-section and number density of i-th gas respectively. σ_i s and n_i s are obtained from Venus atmosphere model, HITEMP 2000, VIRA 1985 model [Keating et al., 1985] and HITRAN 2008. An example of T_{molec} and T_{obs} is shown in left of Fig.2 (05 Sep. 2006, order149, orbit137, lat.79 °, lon.237 °, alt.110.26 km). The horizontal scale on the figure is enlarged for clarity. As shown in the left of Fig.2, overall T_{molec} level is equal to unity because no aerosol absorption is supposed. T_{molec} is decided in a way that is consistent with absorbed amount of T_{obs} by adjustment of CO_2 number density. At the same time, CO_2 number densities are decided. The standard deviation of CO_2 number density variety is estimated 30 %. The baseline (T_{base} on the right of Fig.2) is defined by dividing T_{obs} by T_{molec} (eq.(3)) at particular altitude.

$$T_{base} = \frac{T_{obs}}{T_{molec}} \tag{3}$$

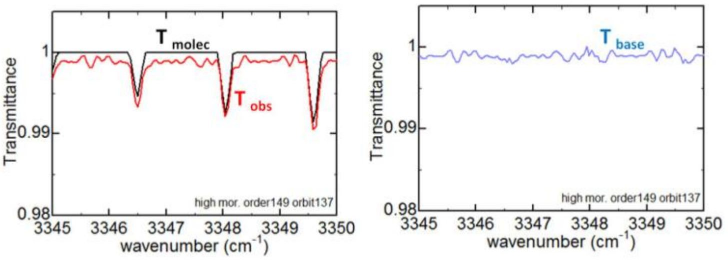

Fig.2 **(left)** Example of calculated transmittance (T_{molec}, black line) and observed transmittance (T_{obs}, red line, 05 Sep. 2006, order149, orbit137, lat.79 ° N, lon.237 °). T_{molec} level is equal to unity because no aerosol absorption is supposed. **(right)** Example of baseline (T_{base}, blue line).

Vertical distribution of extinction was derived by onion-peeling method from all selected data. Horizontal optical thickness at L_j layer (τ_j) is calculated by following equation,

$$\tau_j = -\ln(T_{base,\,j}) \tag{4}$$

where $T_{base,\,j}$ is calculated by eq.(3) at L_j layer. Local extinction k_j is calculated by dividing the $\tau_{j,\,in}$, the horizontal optical thickness at all the layers inner than L_j layer, by local length X_j (eq.(5)).

$$k_j = \frac{\tau_{j,\,in}}{X_j} = \frac{\tau_j - \sum_i^{j-1} 2dx_i \times k_i}{X_j} \tag{5}$$

where k_i is aerosol extinction of all the layers outer than the L_j layer, and dx_i is the horizontal length of outer the L_j layer. The errors of τ ($\Delta\tau$) and k_j (Δk_j) are estimated by using following equations,

$$\Delta\tau_j = \frac{\Delta T_{base,\,j}}{T_{base,\,j}} \tag{6}$$

$$\Delta\tau_{j,\,in} = \sqrt{(\Delta\tau_j)^2 + (\sum_{i=1}^{j-1}(\Delta k_i \times dx_i))^2} \tag{7}$$

$$\Delta k_j = \sum_{i=1}^{j} \frac{\Delta\tau_{i,\,in}}{X_i} \tag{8}$$

where ΔT_{base} is standard deviation of T_{base} and estimated almost 0.001. Example of vertical distribution of extinction is shown in the left of Fig.3. Vertical optical thickness (τ_{vert}) was obtained by integration in vertical direction. The normalized extinction at L_j layer, m_j, was equivalent to mixing ratio and calculated by dividing extinction by CO_2 number density. The errors of τ_{vert} ($\Delta\tau_{vert}$) and m_j (Δm_j) are estimated in using eq.(9) and eq.(10).

$$\Delta\tau_{vert} = \sum_{i=1}^{j} \Delta k_i \tag{9}$$

$$\Delta m_j = \sqrt{\left(\frac{\Delta k_j}{n_{co_2}}\right)^2 + \left(\frac{k_j \cdot \Delta n_{co_2}}{n_{co_2}}\right)^2} \tag{10}$$

where Δn_{co2} is standard deviation of CO_2 number density. Example of vertical distribution of normalized extinction is shown in the right of Fig.3.

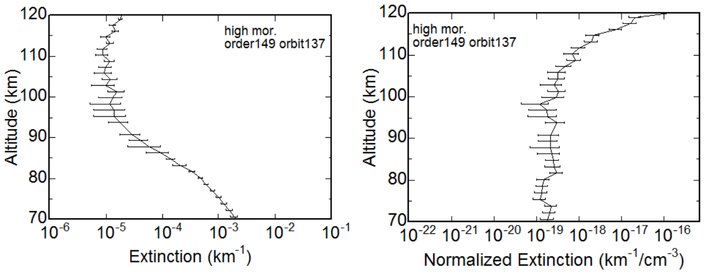

Fig.3 **(left)** Example of vertical distribution of extinction (05 Sep. 2006, order149, orbit137, lat.79°N, lon.237°). The average of error is 26.2 %. **(right)** Example of vertical distribution of normalized extinction (05 Sep. 2006, order149, orbit137, lat.79°N, lon.237°). The average of error is 41.6 %.

4. Results

4.1 Extinction

The mean of all extinction profiles is shown in Fig.4. For example, the value of extinction at 100 km at high latitude in the morning is 1.49×10^{-5}. For clarity, the error bar is plotted only at high latitude in the morning. The average of the error is 21.5 %. It shows that the upper haze is present at altitude above 90 km although it has long been recognized that the top of the upper haze is 90 km. Extinction profiles fold at around 95 km. At a given altitude, the values of the extinction at low latitudes are larger than those at high latitude.

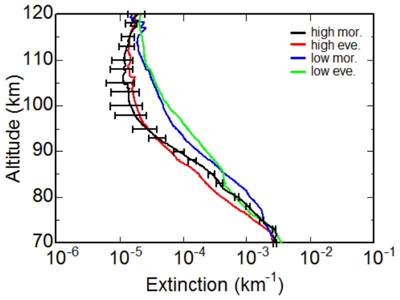

Fig.4 Mean of all extinctions; high lat. morning (black line), high lat. evening (red line), low lat. morning (blue line) and low lat. evening (green line). The error bar is shown only at high latitude in the morning. The average of the error is 21.5 % at high latitude in the morning.

4.2 Normalized Extinction

The vertical distributions of normalized extinctions are obtained from extinctions and correspondent CO_2 number densities. The mean of all normalized extinctions is shown in Fig.5. For example, the value of normalized extinction at 100 km at high latitude in the morning 1.81×10^{-19}. The error bar is plotted only at high latitude in the morning, for clarity. The average of error is 42.1 %. A significant increase of the normalized extinction is observed at altitudes above 90 km for both high and low latitudes. This is an unexpected finding because it was assumed that the upper haze extends till an altitude of 90 km. This is clearly due to the first statistic analysis at altitude above 90 km of the SOIR data in this study. Normalized extinctions at low latitude are almost one order of magnitude larger than those at high latitude.

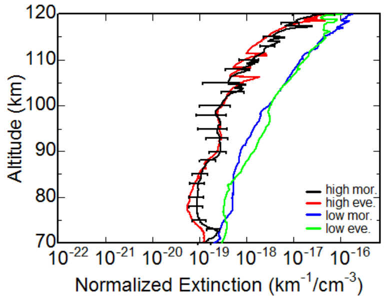

Fig.5 Mean of all normalized extinction; high latitude in morning (black line), high latitude evening (red line), low latitude in morning (blue line) and low latitude evening (green line). The error bar is shown only at high latitude in the morning. The average value of the error is 42.1 % at high latitude in the morning.

5. Discussion

The detection of the upper haze at altitude above 90 km on Venus is demonstrated for the first time as shown in Section 4. One of the notable results is that normalized extinctions increase with altitude above 90 km at both high and low latitudes. The following process is proposed to explain the increase of the normalized extinction at high altitude.

(1) Sources of haze are transported to high altitude from main cloud height. The upward transport velocity needs to be higher than the speed of gravitational sedimentation. Some transport processes are described in Bertaux et al. (2007), Liang and Yung (2009) and Piccialli et al. (2012).

(2) Transported sources will evaporate and SO・SO_2 will be produced at high altitude. Increases of SO and SO_2 mixing ratios at high altitude was observed in Belyaev et al. (2012).

(3) Haze will be produced by through any chemical processes related to SO and SO_2 at high altitude. Zhang et al. (2012) showed aerosol reaction rates in using two different 1-dimensional photochemistry–diffusion models to produce increases of SO and SO_2 mixing ratios at high altitude shown in Belyaev et al. (2012).

(4) The size of produced haze particles is considered to be smaller than that of the transported sources for the following reason. Extinction is obtained from the following expression:

$$k = \sigma \cdot N \tag{11}$$

where σ is the extinction cross section and N is number density of scattering material. When haze particles are reduced in size without changing the total amount of haze source material, the cross section becomes smaller and the number density increases. For example, when the size of a particle decreases by a factor of 2.0, the extinction cross section decreases by a factor of 4.0. As a consequence, the number density increases by a factor of 8.0. Under this circumstance, the extinction increases by a factor of 2.0.

It is therefore possible that the normalized extinctions increase at high altitude through the process described above. Given that normalized extinctions at low latitude are almost one order of magnitude larger than those at high latitude, it would imply that haze is more produced at low latitude than at high latitude.

6. Conclusions

The properties of the upper haze at altitude above 90 km were obtained for the first time. These new discovery concerning the upper haze was made possible cleared owing to the analysis of a wider range of altitude and latitude in this study than previous studies.

(1) Upper haze is present at altitude above 90 km although it has been recognized that the top of the upper haze is 90 km.

(2) Extinction profiles vary by an order of magnitude every occultations.

(3) Extinctions at low latitude are almost twice larger than those at high latitude. It would imply that aerosols are produced more at low latitude than at high latitude.

(4) Significant increases of normalized extinctions are observed at above 90 km at both high and low latitudes. From comparison with the vertical distributions of SO and SO_2 mixing ratios [Belyaev et al., 2012], it would imply that haze, is produced by any chemical reaction at high altitude after the sources of haze including sulfur, are transported to altitude above 90 km. This is clearly due to the first statistic analysis at altitude above 90 km of the SOIR data in this work.