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An uppermost haze layer above 100 km found over Venus by the SOIR instrument onboard Venus Express

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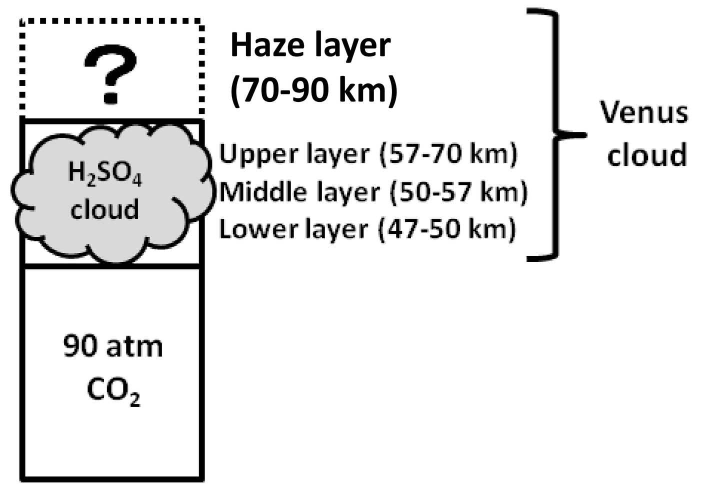
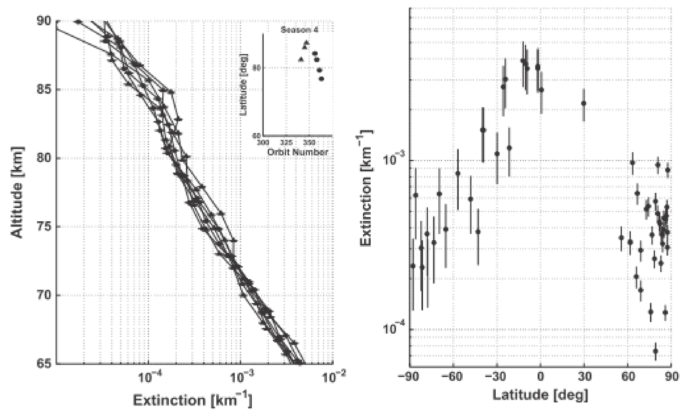
1. Introduction





(left) Fig.1 Example of vertical distribution of Extinction.
(right) Fig.2 Latitudinal distribution of the extinction [Wilquet et al., 2012].

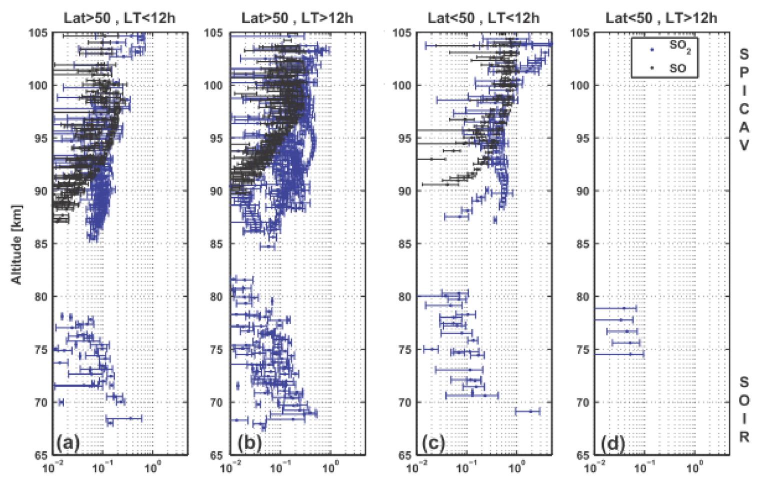
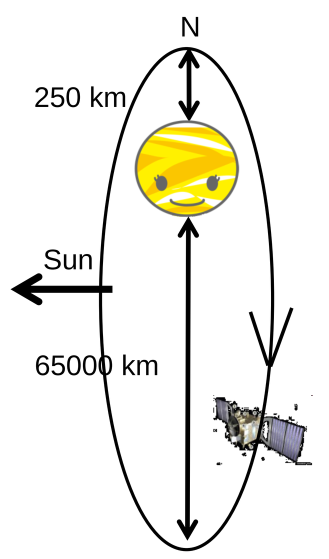


Fig.3 Vertical distributions of SO (black) and SO_2 (blue) mixing ratios [Belyaev et al., 2012].

- The clouds above Venus consist of a main cloud deck located between approx. 47 and 70 km surrounded by thinner hazes above and below. The upper haze layer was observed at altitudes as high as 90 km [Esposito et al., 1983].
- The haze optical properties up to 90 km were presented in Wilquet et al. (2009, 2012). Wilquet et al. (2012) reported that the aerosol extinction coefficient is significantly smaller at high latitudes than in the equatorial region.
- SO and SO_2 mixing ratios were shown to increase with altitude from 85 to 105 km [Belyaev et al., 2012; Mahieux et al., 2015]. These observations were tentatively explained by the existence of a still unknown source of SO and SO_2 at high altitudes. One possible source could be the photodissociation of SO_3, which results from the evaporation of H_2SO_4 droplets. For example, Zhang et al. (2012) showed important chemical pathways for sulfur species related to aerosols. Additionally, it has been speculated that aerosols and sulfur compounds are connected by condensation and evaporation [Zhang et al., 2012]. However, upper limit measurements of H_2SO_4 using submillimeter ground-based observations make this suggestion unlikely [Sandor et al., 2012]. Clearly, what occurs above 90 km is not yet understood.

2. SOIR / Venus Express



- **S**olar **O**ccultation at **I**nfra**R**ed (**SOIR**)
  - Wavelength: 2.3-4.2 µm
  - Wavelength resolution: 0.1-0.2 nm
- Venus atmosphere and haze at high altitude (70-220 km) are observed continually.

- At the beginning of an occultation, the solar light path does not traverse the Venus atmosphere. SOIR starts recording solar spectra at the outer region of the atmosphere to obtain at least 40 spectra and to define the reference Sun spectra. For tangent altitudes lower than 220 km, the observed transmittances are calculated by dividing the spectrum recorded at the current time by the reference Sun spectrum. At lower altitudes, the instrument line of sight penetrates deeper into the atmosphere, and continuum absorption occurs due to haze and atmospheric molecules such as CO_2. At the end of an occultation, the signal becomes zero, because the solar light is completely absorbed by the clouds and atmospheric species.

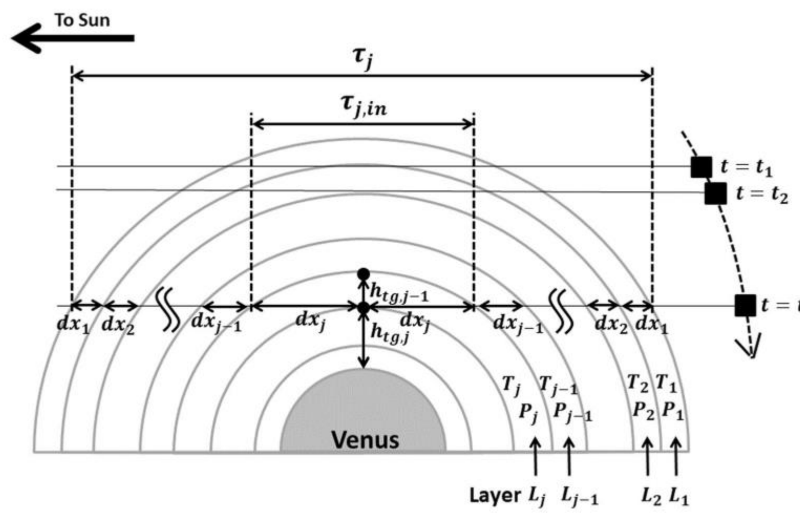


Fig.4 Geometry of solar occultation measurements and analysis method [modified from Fig.4 of Vandaele et al., 2008].

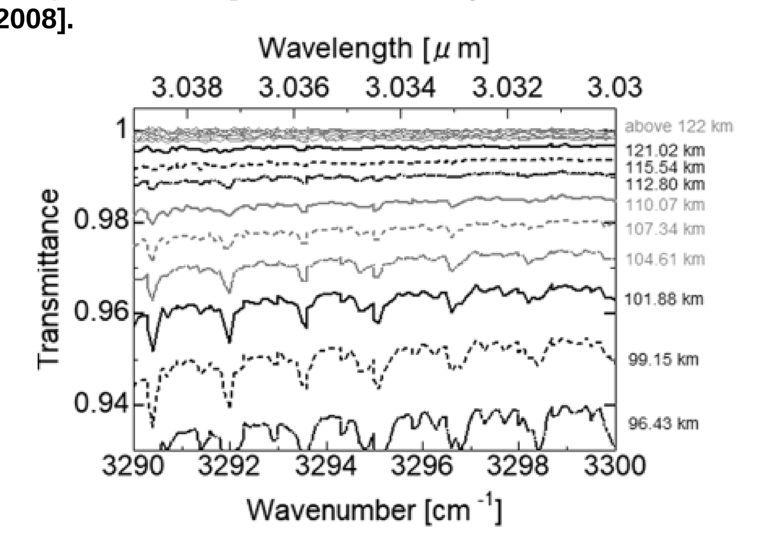


Fig.5 Example of observed transmittances above at altitude 95 km. The observed transmittances above 122 km are almost unity, because the solar light is not yet being absorbed by the atmosphere [Takagi et al., 2019].

3. Analysis

Removal of molecular absorption effect

The gas transmittance T_{gas} due to atmospheric molecules (i) is calculated as:

$$T_{gas} = e^{-\tau_{gas}}$$

where τ_{gas} is the total optical thickness due total species obtained as:

$$\tau_{gas} = \sum_i \tau_i$$

where τ_i is the total optical thickness of species i, integrated along the full line of sight (LOS):

$$\tau_i = \sigma_i \int_{LOS} n_i \quad (i = \mathrm{CO_2, H_2O, HCl\ and\ HF})$$

where σ_i and n_i are the absorption cross section and the number density of species i, respectively. T_{haze} is obtained by dividing T_{obs} (observed transmittance) by T_{gas} at each observed altitude as:

$$T_{haze} = \frac{T_{obs}}{T_{gas}}$$

Retrieval of the haze optical properties

τ_i, the horizontal optical thickness corresponding to layer Lj and all the above-located layers, is defined as:

$$\tau_j = -\ln(T_{haze,j})$$

$\tau_{i,in}$, the horizontal optical thickness of layer Lj, is obtained considering the so-called onion peeling method and can be written as:

$$\tau_{j,in} = \tau_j - \sum_{i=1}^{j-1} 2dx_i \times k_i$$

where k_i is aerosol extinction coefficient of layer Li and dx_i is the horizontal path length in layer Li, which is outside relative to layer Lj. We define the local extinction coefficient k_j, calculated as:

$$k_j = \frac{\tau_{j,in}}{2dx_j}$$

The normalized extinction m_j (in dimensions of the mixing ratio) is defined as:

$$m_j = \frac{k_j}{n_{co2} \cdot S}$$

where n_{co2} is total CO_2 number density in layer Lj and S is the extinction coefficient cross section.

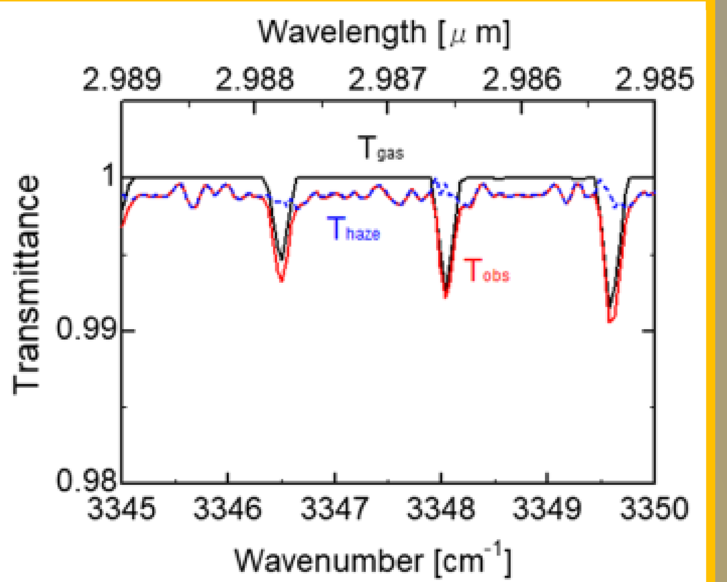


Fig.6 Example of a calculated transmittance (T_{gas}, black spectrum), and observed transmittance (T_{obs}, red sp.), and a residual transmittance (T_{haze}, dotted blue sp.) [Takagi et al., 2019].

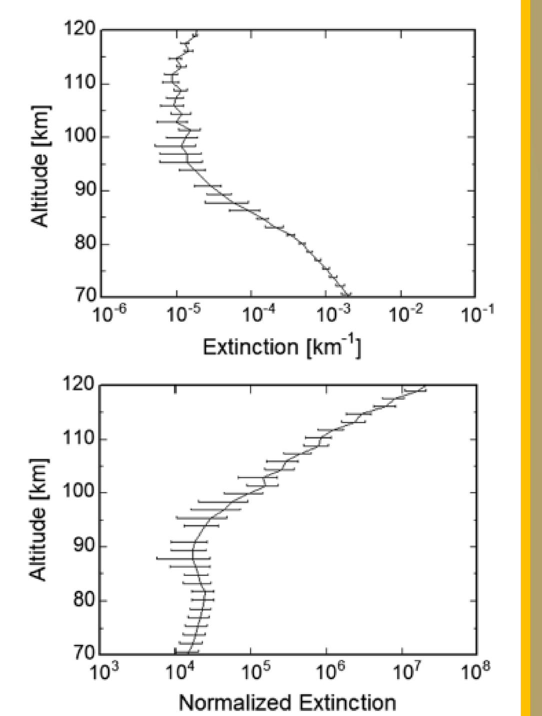


Fig.7 Example of vertical profile of extinction coefficients (top) and the corresponding normalized extinction coefficients (bottom) [Takagi et al., 2019].

4. Results

Extinction

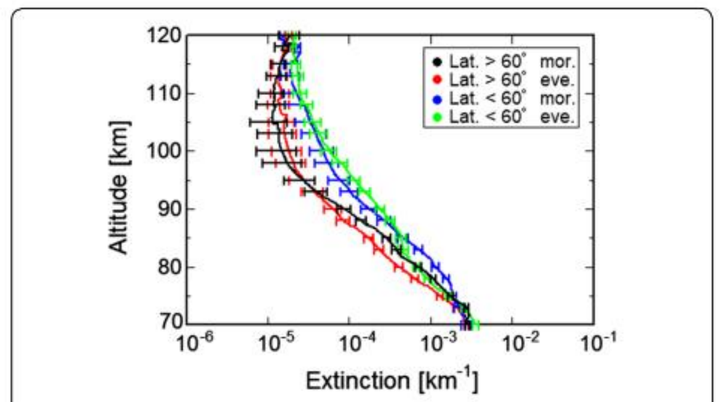


Fig.8 Average extinction coefficient profiles for morning high-latitude (latitude > 60°, black line), evening high-latitude (latitude > 60°, red line), morning low-latitude (latitude < 60°, blue line), and evening low-latitude (latitude < 60°, green line) observations. The average of the variability is 21.5% for the morning high-latitude observations [Takagi et al., 2019]

- Hazes appear to be present at altitudes above 90 km.
- Extinction coefficient profiles show an obvious change in the slope at ~95 km.
- Extinction coefficients at low latitudes are larger than those at high latitudes.

Normalized Extinction

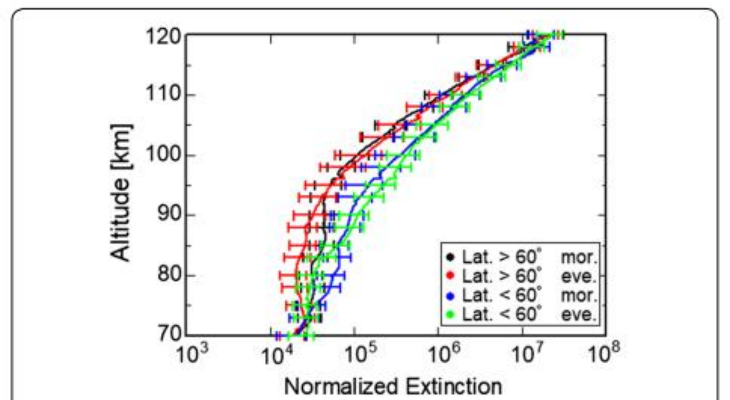


Fig.9 Average of all normalized extinction coefficients for morning high-latitude (latitude > 60°, black line), evening high-latitude (latitude > 60°, red line), morning low-latitude (latitude < 60°, blue line), and evening low-latitude (latitude < 60°, green line) observations. The average of the variability is 34.3% for the morning high-latitude observations [Takagi et al., 2019]

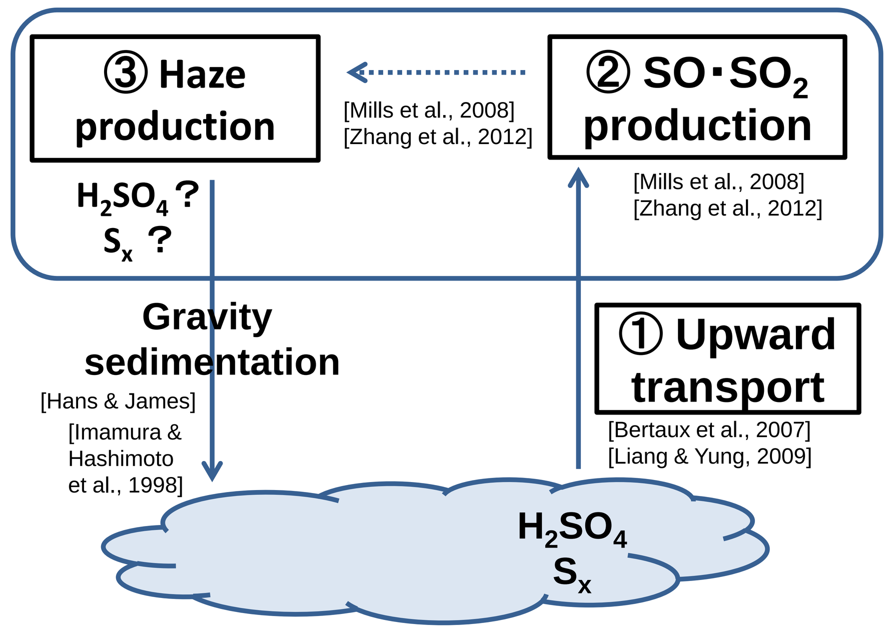
Above 90 km

- A significant increase in the normalized extinction coefficient with the altitude is observed above 90 km for both the high- and the low- latitude regions.
- The normalized extinction coefficients for both the morning and the evening occultations at low latitudes are almost one order of magnitude larger than those at high latitudes at altitudes above 90 km.

Under 90 km

- Normalized extinctions are constant at both high and low latitudes.

5. Discussion



② SO・SO_2 production

$H_2SO_4 \rightarrow SO_3 + H_2O$
$SO_3 + CO \rightarrow SO_2 + CO_2$
$S + O + M \rightarrow SO + M$
$S_x + O \rightarrow SO + S_{x-1}$
$SO + OH \rightarrow SO_2 + H$
$SO + O \rightarrow SO_2 + O$
…

③ Haze production

$SO_3 + H_2O \rightarrow H_2SO_4$
$SO + h\nu \rightarrow S + O$
$SO_2 + h\nu \rightarrow S + O_2$
$2S + M \rightarrow S_2 + M$
$S + S_2 + M \rightarrow S_3 + M$
…

Small Large

$$k = \sigma \cdot N$$

σ: Scattering cross section
N: Number density

① Upward transport

$$u = \left(1 + \frac{1.26\lambda_a}{r}\right) w_{sed} \quad \text{[Hans \& James]}$$

$$\lambda_a = \lambda_{a,0}\left(\frac{p_0}{p}\right)\left(\frac{T}{T_0}\right)$$

p_0=1013.25 mb
T_0=293.15 K
$\lambda_{a,0}=6.6 \times 10^{-6}$ cm

$$w_{sed} = -\frac{2}{9}\frac{g\rho r^2}{\eta}$$

g=8.7 m s^{-2}
$\rho = 1.8 \times 10^3$ kg m^{-3}
$\eta = 1.5 \times 10^{-5}$ kg m^{-1} s^{-1}

At 110 km (p=10^{-3} [mb], T=150 [K]),
radius r = 0.25 µm: u ∼ 2.5 m/s
r = 0.5 µm: u ∼ 5.0 m/s
r = 1.0 µm: u ∼ 10.0 m/s

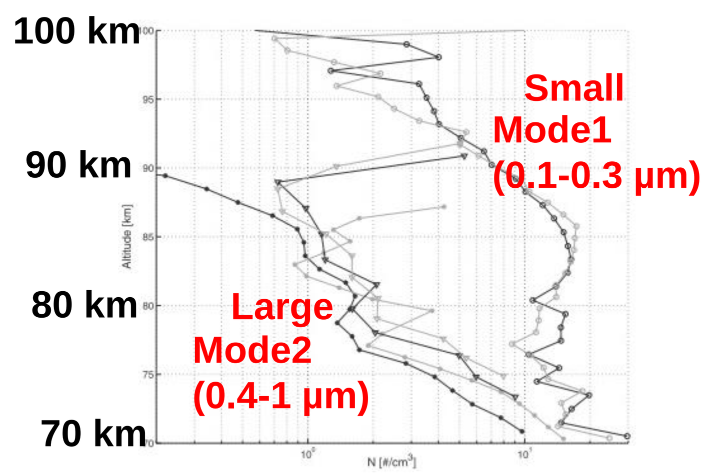
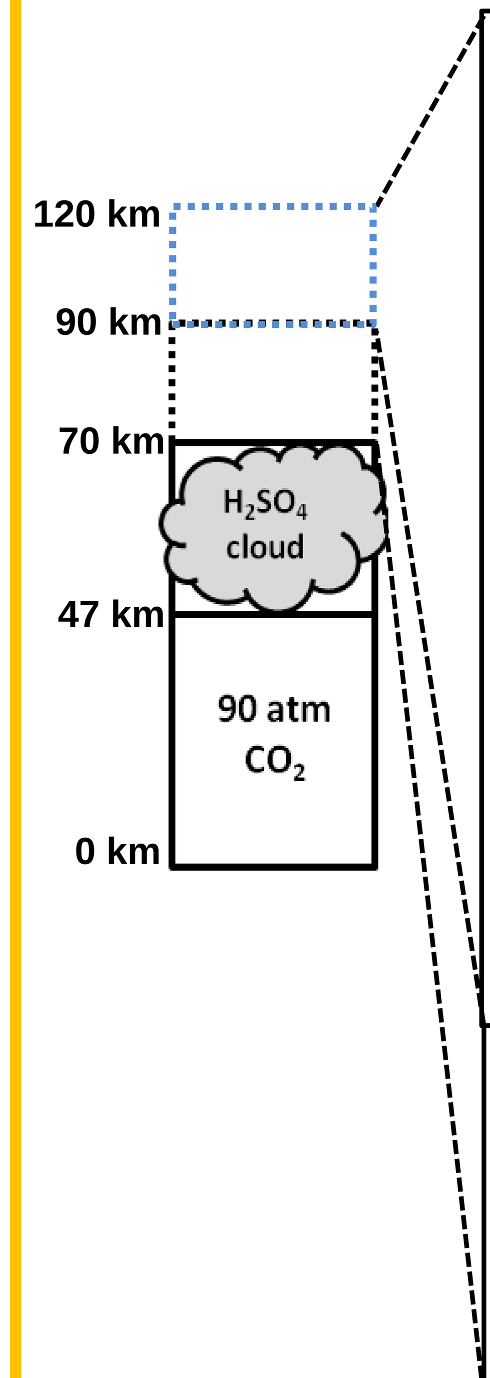


Fig.10 Number density of particles [Wilquet et al., 2009].

6. Summary



- The optical properties of the upper haze layer at altitudes above 90 km were studied in this work.
  - A significant increase in the normalized extinction coefficient was observed above 90 km at both high and low latitudes, which could be linked to the vertical profiles of SO and SO_2.
  - It is considered that sources of haze are transported upwards at a velocity larger than the sedimentation velocity from the cloud deck. The transported aerosols then evaporate or react to produce SO and SO_2 at high altitude.
  - At high altitudes, haze particles are produced by chemical processes involving SO and SO_2. Since the normalized extinction increases at high altitude, we propose that the size of the haze particles that are produced is smaller than those of transported aerosol particles.

- The optical properties of haze layer (70-90 km) were also obtained in this work.
  - Extinctions at low latitude are larger than those at high latitude.
  - Normalized extinctions are constant at both high and low latitudes.