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# Climatology of SO<sub>2</sub> and UV absorber at Venus' cloud top from SPICAV-UV nadir dataset.

Emmanuel Marcq<sup>a,\*</sup>, Kandis Lea Jessup<sup>b</sup>, Lucio Baggio<sup>a</sup>, Thérèse Encrenaz<sup>c</sup>, Yeon Joo Lee<sup>d</sup>, Franck Montmessin<sup>a</sup>, Denis Belyaev<sup>e</sup>, Oleg Korablev<sup>e</sup>, Jean-Loup Bertaux<sup>a,e</sup>

<sup>a</sup>LATMOS/CNRS/Sorbonne Université/UVSQ, 11 boulevard d'Alembert, F-78280 Guyancourt, France

<sup>b</sup>South West Research Institute, Boulder, CO, USA

<sup>c</sup>LESIA/CNRS/Observatoire de Paris, 5 place Jules Janssen, F-92195 Meudon, France

<sup>d</sup>University of Tokyo, Kashiwa, Japan

<sup>e</sup>Space Research Institute (IKI), Russian Academy of Sciences, Moscow 117997, Russia

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## Abstract

Following our previous work (Marcq *et al.*, 2011, 2013), we have updated our forward radiative transfer code and processed the whole SPICAV-UV/Venus Express nadir dataset (2006-2014) in order to retrieve SO<sub>2</sub> abundance at cloud top – assuming a SO<sub>2</sub> decreasing scale height of 3 km and a ratio SO/SO<sub>2</sub> tied to 10% – as well as the imaginary index of scattering mode 1 particles, representative of the remaining UV absorption, [since the OSSO vertical profile found by Frandsen \*et al.\* \(2016\) cannot account for our observations](#). Our main results mostly confirm and extend the validity of those discussed by Marcq *et al.* (2013), namely: (i) long-term variations of low latitude SO<sub>2</sub> at 70 km between  $\sim 100$  ppbv (2007, 2009) and less than 10 ppbv (2014); (ii) in average, decreasing SO<sub>2</sub> with increasing latitude and depletion near the sub-solar point, consistent with a competition between advection and

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\*E-mail: [emmanuel.marcq@latmos.ipsl.fr](mailto:emmanuel.marcq@latmos.ipsl.fr)

photo-chemical destruction; (iii) secular increase of mode 1 imaginary index at 250 nm, from  $10^{-2}$  to  $5 \cdot 10^{-2}$  between 2006 and 2010; (iv) if not related instead to long-term variability, a possible localized enrichment of SO<sub>2</sub> and UV brightness increase above the western slopes of Aphrodite Terra, consistent with Bertaux *et al.* (2016) supply mechanism through orographic gravity waves. This spatial and temporal variability underlines the need for a long term monitoring of Venus SO<sub>2</sub> and cloud top from ground-based facilities until the next generation of Venusian orbiters is operational.

*Keywords:*

Venus, atmosphere, Ultraviolet, observations, Atmospheres, composition

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## 1. Introduction

Sulphur dioxide is arguably the most variable species in Venus' cloud top atmosphere, on a large range of temporal and spatial time scales. The first attempt to detect it in UV only yielded a 0.1 ppmv upper limit (Jenkins *et al.*, 1969). Yet, a decade later, Barker (1979) found between 0.1 and 0.5 ppmv of SO<sub>2</sub> using the same UV spectral range. The most extensive data set before *Venus Express* was acquired with UVIS onboard *Pioneer Venus* (Esposito *et al.*, 1979; Esposito, 1984; Esposito *et al.*, 1988), and revealed an important short term variability, as well as a long term decrease between 1978 and 1988. These long-term variations were interpreted as possible evidence for active volcanism, which would alter the thermal buoyancy of the lower atmosphere and allow for an intermittent resupply of SO<sub>2</sub> above Venus' clouds, where it is photochemically destroyed. Meanwhile, IR measurements from *Venera 15* (Zasova *et al.*, 1993) and UV measurements from rockets (Na *et al.*, 1994)

15 also evidenced a latitudinal gradient, with SO<sub>2</sub> increasing with increasing  
16 latitude, consistent with a photochemical control of SO<sub>2</sub> since photolysis is  
17 less effective at higher latitudes.

18 After a blank decade (1995-2005), Venus exploration (including cloud top  
19 SO<sub>2</sub> monitoring) resumed with ESA *Venus Express*. Occultation measure-  
20 ments from SOIR (Belyaev *et al.*, 2008) allowed for a retrieval of SO<sub>2</sub> scale  
21 height above the clouds, confirmed that SO<sub>2</sub> had returned to the relatively  
22 high values of the early 1980s, and evidenced a reversal in the latitudinal gra-  
23 dient of SO<sub>2</sub>. These features were confirmed by our first SPICAV-UV nadir  
24 measurements (Marcq *et al.*, 2011, 2013), along with a long-term decrease  
25 of low latitude SO<sub>2</sub> similar to the one observed by *Pioneer Venus*. In par-  
26 allel, high spectral resolution measurements in the thermal IR using NASA  
27 IRTF (Encrenaz *et al.*, 2012, 2016, 2019), or in the UV using STIS/HST (Jes-  
28 sup *et al.*, 2015) have confirmed and supported this trend, with two possible  
29 SO<sub>2</sub> regimes above the clouds: a high abundance regime more prevalent in  
30 the early 1980s or late 2000s, with a large number of SO<sub>2</sub> plumes located  
31 at lower latitudes and a negative latitudinal gradient, and a low abundance  
32 regime with little to no SO<sub>2</sub> convective plumes, and a reversed latitudinal  
33 gradient more typical of the early 1990s or mid-2010s. The transition be-  
34 tween these regimes can occur within a few Earth days (Jessup *et al.*, 2015),  
35 and accounts for the large short-term dispersion of the measurements. [The](#)  
36 [long-term change in the relative prevalence of these two regimes explain the](#)  
37 [long-term change in the average SO<sub>2</sub> latitudinal gradient that we observed](#)  
38 [in our previous study \(Marcq \*et al.\*, 2013, Fig. 2\).](#) Nevertheless, the physical  
39 processes ruling both these regimes are still poorly known. Convective mix-

40 ing with the lower atmosphere where SO<sub>2</sub> is always abundant – more than  
41 100 ppmv near 30-40 km (Bézard *et al.*, 1993; Marcq *et al.*, 2008; Arney *et al.*,  
42 2014) is most certainly involved, but the reasons behind these variations of  
43 the convective mixing intensity are still debated, including possible episodic  
44 volcanism or other atmospheric processes.

45 Following the recent progress in our knowledge of Venus clouds and  
46 hazes (Luginin *et al.*, 2016), as well as in our processing of SPICAV-UV  
47 nadir spectra, we have completely rewritten our analysis pipeline and pro-  
48 cessed the whole of SPICAV-UV archive in order to complete and update  
49 our SO<sub>2</sub> climatology, as well as other derived observable parameters such as  
50 the mean UV brightness of the clouds. A short description of our data set  
51 is given in §2, and of our forward radiative transfer model in §3, since both  
52 were already extensively described in a previous paper (Marcq *et al.*, 2019).  
53 Our results about SO<sub>2</sub> and UV absorber variability is detailed in §4 and  
54 their scientific implications further commented in §5, before we summarize  
55 and conclude in §6.

## 56 **2. Observations**

57 Our data set and processing is detailed in our previous paper (Marcq  
58 *et al.*, 2019). For the convenience of the reader, we summarize the main  
59 points below.

### 60 *2.1. Data set*

61 Our data set consists in the whole archive of SPICAV-UV (Bertaux *et al.*,  
62 2007) nadir or near-nadir spectra, from 170 to 320 nm at a spectral resolution

63 of 1 nm. There are 1508 such observations, from 2006-06-01 up to 2014-11-  
64 20. Coverage in local time and latitude is extensive except for the south  
65 polar region (Marcq *et al.*, 2019, their Fig. 1), with southern hemisphere ob-  
66 servations dominated by ~~near nadir tracking pointing~~ mode observations over  
67 single ~~spots~~spot targets (implying continuously changing emission and phase  
68 angles along the orbit), whereas northern hemisphere observations consisted  
69 mainly in ~~nadir~~latitudinal scans (where emission angle is essentially zero  
70 along the orbital track).

## 71 2.2. Processing

72 The first steps of data processing are unchanged since Marcq *et al.* (2011),  
73 namely cosmic ray hit removal, dark subtraction, correction of electronic  
74 readout artifact, flat-fielding, wavelength assignment. Most recent progress  
75 come from a better knowledge of the instrument PSFPoint Spread Function  
76 (PSF), especially at large distances from the center (far wings). Richardson-  
77 Lucy deconvolution is now performed in order to clean the far wing con-  
78 tribution, which enables the scientific use of spectra from 200 nm instead of  
79 215 nm in our first analyses, which in turn enables to retrieve more observable  
80 parameters relative to Venus' clouds and SO<sub>2</sub>.

81 Photometric calibration of the spectral radiance spectra was performed  
82 from the CALSPEC catalog of bright UV stars observed in-flight (Bohlin  
83 *et al.*, 2014). From these calibrated spectral radiances, we computed the  
84 corresponding radiance factors  $\beta(\lambda) = \frac{I(\lambda) \times \pi \text{ sr}}{F_{\odot}(\lambda)}$  where  $I(\lambda)$  is the spectral  
85 radiance and  $F_{\odot}(\lambda)$  a reference top-of-atmosphere solar spectral irradiance.  
86 These solar spectral irradiance were extracted from the SOLSTICE II database  
87 (McClintock *et al.*, 2005) at the corresponding date to account for the solar

88 cycle variations. We also corrected a spectral feature in these solar spectra  
89 near 230-240 nm that our forward radiative transfer model was unable to  
90 reproduce, no matter the prescribed values of the atmospheric parameters.

### 91 3. Forward Model

#### 92 3.1. Overview

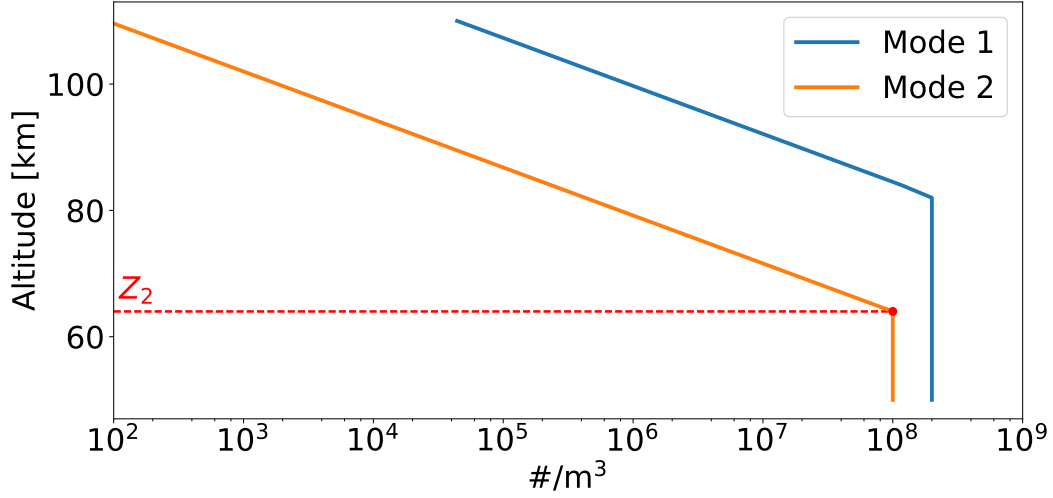
93 A detailed description of the forward radiative transfer we use is avail-  
94 able in Marcq *et al.* (2019). For the sake of convenience, we present below  
95 a summary of its features and free parameters. The radiative transfer equa-  
96 tion solver we use is the pseudo-spherical version of DISORT (Dahlback and  
97 Stamnes, 1991) using 16 streams.

##### 98 3.1.1. Aerosols

99 The model encompasses the 50-110 km altitude range. We consider a  
100 bimodal log-normal size distribution ( $r_{\text{eff}} = 0.12$  and  $0.8 \mu\text{m}$  respectively,  
101 with an effective dimensionless variance of  $\nu_{\text{eff}} = 0.15$ ) of aerosol particles  
102 following Luginin *et al.* (2016).

103 The vertical profiles for both modes that we consider are ~~simplified from~~  
104 ~~the same reference (Luginin *et al.*, 2016)~~ a simplification from the retrieved  
105 profiles derived by Luginin *et al.* (2016) and can be seen in Fig. 1. ~~Number~~  
106 ~~density is capped for both particles at in the lower part the model (respectively~~  
107  ~~$2 \cdot 10^8$  and  $10^8$  particles/ $\text{m}^3$  for mode 1 and mode~~ Above a altitude named  $Z_2$   
108 hereafter, mode 2 ), ~~and the number density ratio  $n_1/n_2 = 1000$  is fixed in the~~  
109 ~~upper~~ particle number density decreases following  $n_2(z > Z_2) = 10^8 \exp\left(\frac{Z_2 - z}{4.5 \text{ km}}\right)$  particles/ $\text{m}^3$ .  
110 Below this altitude, we have a constant, capped value  $n_2(z < Z_2) = 10^8$  particles/ $\text{m}^3$ .

Figure 1: Synthetic number density profiles for both particle modes.  $Z_2$  is a free parameter in our model, which captures cloud top altitude variations.



111 Mode 1 particles follow a similar profile, with a constant ratio  $n_1/n_2 = 1000$   
 112 in the upper part of the model, and a cap at  $2 \cdot 10^8$  particles/ $m^3$  in the  
 113 lower part of the model. The altitude  $Z_2$  above which mode 2 particles  
 114 decrease following a scale height of 4.5 km is a free parameter in our model,  
 115 representative of which is related to the cloud top altitude variations—  
 116 we find that  $Z_{TOP}(250 \text{ nm})$ , classically defined (Titov *et al.*, 2018) as the  
 117 altitude where nadir optical depth is equal to one (considering only particulate  
 118 opacity). Numerical intergration yields  $Z_{TOP}(250 \text{ nm}) = Z_2 + 4.95 \text{ km}$  for  
 119 the above described extinction profiles.

120 The real refractive index of both modes is taken from Hummel *et al.*  
 121 (1988) for a 75%-25%  $H_2SO_4$ - $H_2O$  mixture. Imaginary indices for both modes  
 122 are discussed in §3.2, the imaginary index of mode 1 particles at 250 nm being  
 123  $\alpha_i m_i(250 \text{ nm})$ , being another free parameter.



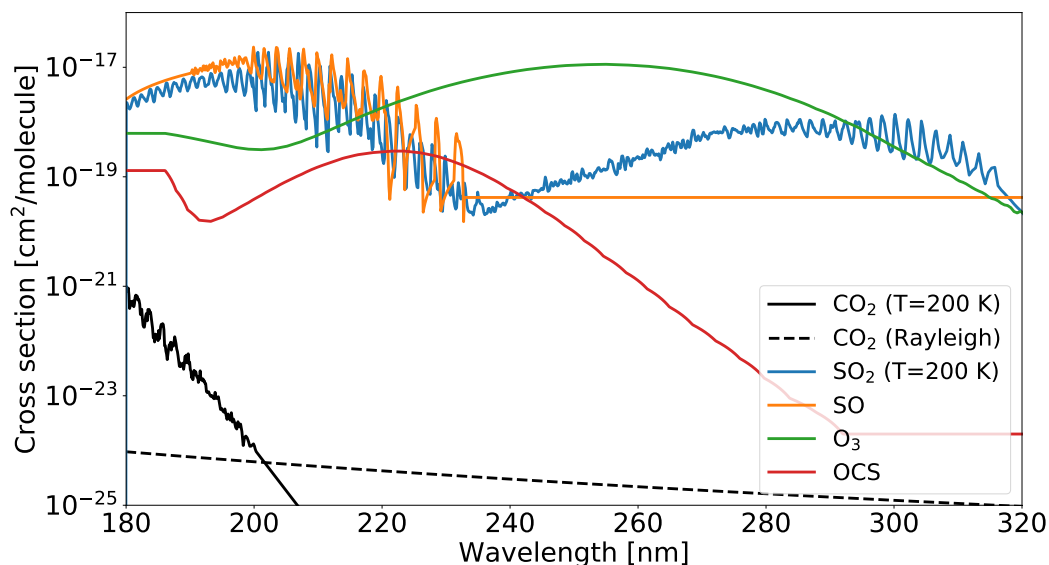
124 3.1.2. Gaseous Species

125 The gaseous species involved in absorption and/or scattering are dis-  
126 played in Fig. 2. CO<sub>2</sub> Rayleigh and absorption cross-section is unchanged  
127 since Marcq *et al.* (2013). SO<sub>2</sub> and SO cross-sections were compiled from  
128 various sources by Jessup *et al.* (2015), and we use the same. New gaseous  
129 species that we consider is O<sub>3</sub> and OCS, whose UV absorption cross-sections  
130 are taken from Sander *et al.* (2011).

131 CO<sub>2</sub> vertical profile is computed from hydrostatic equilibrium assum-  
132 ing VIRA-2 temperature profile (Moroz and Zasova, 1997). Following recent  
133 intercomparison between observations and models (Vandaele *et al.*, 2017a; Marcq *et al.*, 2018)  
134 , we consider that SO<sub>2</sub> vertical profile is capped at 150 ppmv in the lower  
135 part of the model, and decreases according to a scale height of 3 km in the  
136 upper part of the model. Its mixing ratio at 70 km is a free parameter of our  
137 model. Since we cannot distinguish individual SO and SO<sub>2</sub> absorption lines  
138 at SPICAV-UV spectral resolution, we have to assume that SO vertical profile  
139 is tied ~~at~~ to 10% of SO<sub>2</sub>, according to the average values dervied from higher  
140 spectral resolution HST/STIS measurements (Jessup *et al.*, 2015). OCS ver-  
141 tical profile is taken from Haus *et al.* (2015), and O<sub>3</sub> is considered uniformly  
142 mixed between 55 and 70 km. Its mixing ratio in this range is an optional  
143 free parameter of the model.

144 O<sub>3</sub> measurements is the main topic addressed by Marcq *et al.* (2019). O<sub>3</sub>  
145 absorption is considered only when including it yields a substantial reduction  
146 in the reduced  $\chi^2$  (namely, 5.5). We adopt the same criterion in the present  
147 study. Example of a fitted spectrum with and without O<sub>3</sub> can be found  
148 in ~~Marcq *et al.* (2019, their Fig. 2)~~ Marcq *et al.* (2019, their Fig. 3).

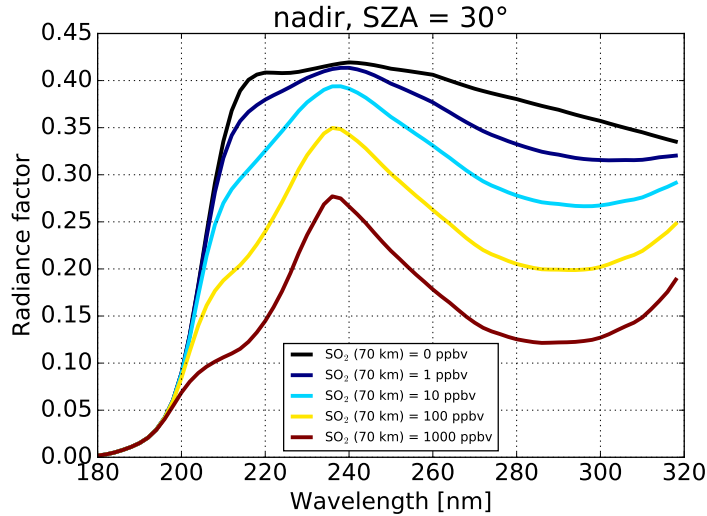
Figure 2: UV cross-sections of considered gaseous species



149 *3.2. Model Sensitivity*

150 The modeled effect of varying  $\text{SO}_2$  (Fig. 3) is easy to understand: since  
 151  $\text{SO}_2$  has two broad electronic absorption bands peaking near 215 and 280 nm,  
 152 respectively, these two absorption bands have a relative depth that becomes  
 153 more pronounced with increasing  $\text{SO}_2$  abundance. However, it is noteworthy  
 154 that the  $\text{SO}_2$  influence extends throughout the whole spectrum, even though  
 155 the cross-section is a continuum between 240 and 270; nm reaching a local  
 156 minimum near 240 nm. Sensitivity of the inferred radiance factor to  $\text{SO}_2$   
 157 absorption in the 240-270 nm region is a telltale sign that multiple scattering  
 158 is prevalent, so that most backscattered photons have traveled through long  
 159 enough optical paths into deep,  $\text{SO}_2$ -rich atmospheric layers that its smaller  
 160 absorption cross-section is partially offset. This is important when consider-  
 161 ing  $\text{SO}_2$  measurement proxies such as image ratios between 280 and 240 nm:

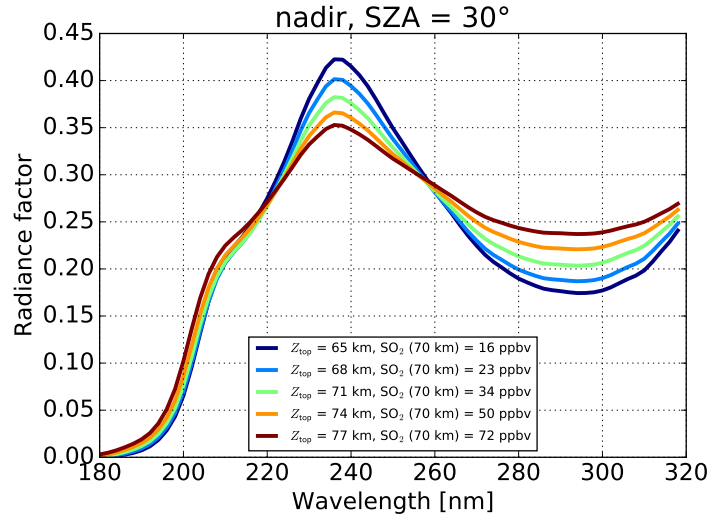
Figure 3: Synthetic radiance factors for a cloud top altitude of 74 km,  $m_i(250 \text{ nm}) = 10^{-2}$  and varying SO<sub>2</sub> abundances. The considered geometry is pure nadir viewing, with a solar zenith angle of 30°.



162 the image at 240 nm, though not dominated by SO<sub>2</sub> ~~gas~~gas absorption, is  
 163 also not independent from the spatial SO<sub>2</sub> variations.

164 At Venus' cloud top, the observed SO<sub>2</sub> absorption band is primarily re-  
 165 lated to the column density above the cloud top (Marcq *et al.*, 2011, 2013).  
 166 Thus, altering the cloud top altitude results in a change in the total SO<sub>2</sub> col-  
 167 umn density above the cloud top, according to the assumed vertical profile  
 168 of SO<sub>2</sub> number density. The primary effects of altering the cloud top alti-  
 169 tude while making no change to SO<sub>2</sub> vertical profile would therefore be very  
 170 similar to the results displayed in Fig. 3, because the direct outcome of the  
 171 change in the cloud top altitude is a change in the SO<sub>2</sub> column density above  
 172 that altitude. However, as Fig. 4 shows, changing the cloud top altitude will  
 173 impact the total absorption occurring in the two SO<sub>2</sub> electronic absorption

Figure 4: Synthetic radiance factors for  $m_i(250 \text{ nm}) = 10^{-2}$ , and varying  $\text{SO}_2$  abundances as well as cloud top altitudes ~~at~~ at 250 nm. The considered geometry is pure nadir viewing, with a solar zenith angle of  $30^\circ$ .



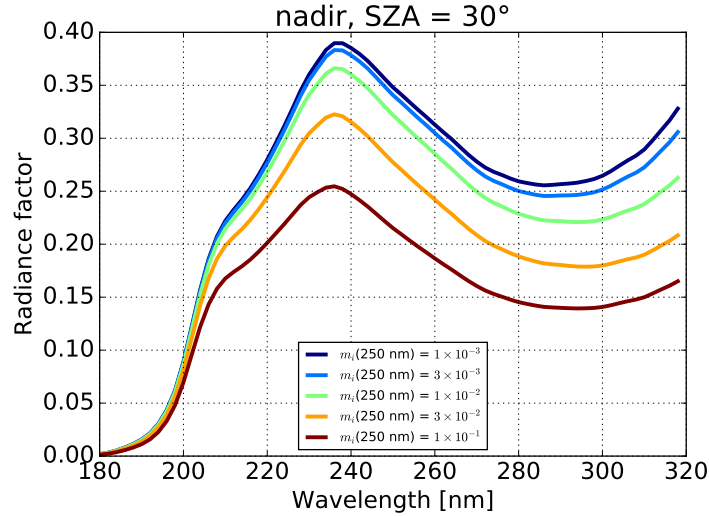
174 bands differently, because the 280 nm band has a lower cross-section than  
 175 the 215 nm band. Thus, for example, increasing the cloud top altitude re-  
 176 sults in a lower relative depth for the 280 nm  $\text{SO}_2$  absorption band compared  
 177 to the 215 nm band. Similarly, the lower cross-section of the 280 nm band  
 178 allows that band to probe deeper into the atmosphere than the 215 nm band.  
 179 Notably, at lower altitudes both Rayleigh scattering and  $\text{CO}_2$  absorption are  
 180 stronger.

181 Altering the imaginary part  $m_i$  of the refractive index of mode 1 parti-  
 182 cles yields the expected outcome, namely lowering the albedo when particles  
 183 are darker (Fig. 5). However, altering the spectral slope of this mode 1  
 184 absorption results in a spectral distortion very much alike that of chang-  
 185 ing the cloud top altitude. This resulted in a fitting degeneracy ~~when~~ if we

186 tried to fit both the mode-1 absorption spectral slope and cloud top altitude  
187 together. We therefore chose to keep only the cloud top altitude as a fit-  
188 ted parameter, and adopted a ~~spectral dependency fixed spectral slope for~~  
189  $m_i(\lambda) = m_i(250 \text{ nm}) \times \exp\left(\frac{\lambda - 250 \text{ nm}}{40 \text{ nm}}\right)$  ~~where the exponential function,~~ fitting  
190 only  $m_i(250 \text{ nm})$ . The 40 nm slope accounts for the decreasing mode 1 single-  
191 scattering albedo with increasing wavelength. Using this ~~relationship fixed~~  
192 40 nm value, our low latitude cloud top average altitude near 250 nm was  
193 then in agreement with the most recent IR measurements (Ignatiev *et al.*,  
194 2009) that do not suffer from this degeneracy. ~~The~~ This 40 nm value is  
195 slightly less steep than our previous estimate of about 34 nm (Marcq *et al.*,  
196 2011), which can be explained by our updates to the spectral calibration  
197 of radiance factors (Marcq *et al.*, 2019). At first, we assumed that this de-  
198 pendency applied to both particle modes, but this assumption resulted in  
199 spurious correlations between effective air mass and cloud top altitude as well  
200 as imaginary refractive index retrievals – mode 2 particles contribute more  
201 to backscattering at smaller air mass since they dominate at lower altitudes.  
202 Empirically, we found that assuming a constant, fixed imaginary refractive  
203 index of  $10^{-3}$  for mode 2 particles minimized such spurious correlations.

204 Since this fixed value is much larger than the imaginary refractive index  
205 of pure  $\text{H}_2\text{SO}_4\text{-H}_2\text{O}$  solutions in this wavelength range, this may be indica-  
206 tive of two different UV absorbers: one, well mixed with mode 2 and mode  
207 1 particles and with little spectral dependency between 200 and 300 nm,  
208 and the other one, mixed with mode 1 particles only and horizontally vari-  
209 able, absorbing more towards longer wavelengths. This latter absorber is  
210 likely the same absorber than the infamous near UV-blue absorber peaking

Figure 5: Synthetic radiance factors for a cloud top altitude of 74 km, SO<sub>2</sub> volume mixing ratio of 50 ppbv at 70 km and varying  $m_i(250 \text{ nm})$ . The considered geometry is pure nadir viewing, with a solar zenith angle of 30°.



211 near 365 nm, our retrieved imaginary indexes in the  $10^{-2}$ - $10^{-1}$  range and  
 212 spectral slope being in agreement with recent determinations of this imag-  
 213 inary refractive index over a larger spectral range extending to the visible  
 214 range (Pérez-Hoyos *et al.*, 2018).

215 We will further discuss the scientific implications in §5.1.

## 216 4. Results

### 217 4.1. Retrieval uncertainties

218 The above described forward model is then compared to 30-s binned  
 219 SPICAV-UV observations through a Levenberg-Marquardt iterative algorithm (Newville *et al.*, 2014).  
 220 Three parameters are always fitted, namely: SO<sub>2</sub> mixing ratio at 70 km,  
 221 Z<sub>2</sub> and  $m_i(250 \text{ nm})$ . O<sub>3</sub> mixing ratio is also fitted when its inclusion results

222 in a significant reduction in residual  $\chi^2$  – the interested reader should refer  
223 to Marcq *et al.* (2019) for further details about O<sub>3</sub> in the SPICAV-UV nadir  
224 data set.

225 The Levenberg-Marquardt algorithm yields a covariance matrix, from  
226 which  $1 \cdot \sigma$  statistical uncertainties are derived for each fit, along with the  
227 residual reduced  $\chi^2$ . The median reduced  $\chi^2$  of the whole dataset is 16.6  
228 (which indicates that systematic errors do exist, and/or that the observatoinal  
229 uncertainty may be underestimated). Hereafter, we only consider our fits  
230 valid if their  $\chi^2$  is less than 3 times this median value ( $\chi^2 < 50$ ).

231 In this valid dataset, the median relative  $1 \cdot \sigma$  uncertainty on SO<sub>2</sub> retrievals  
232 is 38%, substantially less than the 3-order of magnitude spatial and temporal  
233 variability of SO<sub>2</sub> (§4.2, §4.3.1): the lowest  $3 \cdot \sigma$  detection of SO<sub>2</sub> is about  
234 0.6 ppb, and the highest values on the order of 1000 ppbv. Similarly, the  
235 median relative  $1 \cdot \sigma$  uncertainty on  $m_i$  retrievals is 25%, also substantially  
236 less than its spatial and temporal variability (§4.2, §4.3.2). Finally, the  
237 median relative uncertainty on our cloud top altitude retrievals is on the  
238 order of 1 km.

#### 239 4.2. Temporal variability

240 The long term evolution over the whole extent of *Venus Express* of our  
241 retrieved cloud top SO<sub>2</sub> and imaginary index of mode 1 particles are shown  
242 respectively on Fig. 6 and 7. ~~We restricted the analysis of~~ Since most SO<sub>2</sub>  
243 ~~temporal variability to lower latitudes only so that we do not encompass any~~  
244 ~~bias in latitude~~, since SO<sub>2</sub> and latitude are correlated in our data set content  
245 is actually located below  $\pm 20^\circ$  in latitude (see §4.3), we will discuss hereafter  
246 the temporal variabilty of SO<sub>2</sub> temporal variability only in this low-latitude

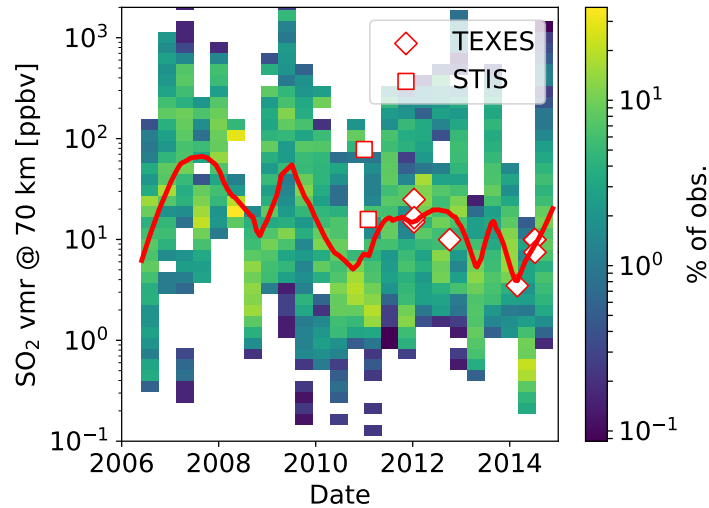
247 bin. The most striking features in both retrieved parameters are: (i) short-  
248 term dispersion is much larger than retrieval uncertainties, and spans two  
249 orders of magnitude for SO<sub>2</sub> and one for the imaginary index; (ii) despite  
250 this short-term variability, longer term trends can be observed.

251 For SO<sub>2</sub>, the overall trend consists in an overall decline by a factor 5 to  
252 10 from 2007 (about ~~80 ppbv~~ 80 ppbv in median) to 2014 (about 10 ppbv).  
253 This steady decline is not monotonous though: after the peak in 2007, surges  
254 in SO<sub>2</sub> can be observed in 2009, 2012, and late 2013. This trend is consistent  
255 with our previous findings for 2006-2012 (Marcq *et al.*, 2013), except for the  
256 2009 peak that was not noticed at the time, probably due to an insufficient  
257 number of analyzed observations compared to our extensive analysis pre-  
258 sented here. ~~Comparison with~~ STIS/HST retrievals (Jessup *et al.*, 2015) and  
259 ~~with~~ TEXES retrievals (Encrenaz *et al.*, 2012, 2016), extrapolated at 70 km  
260 assuming a scale height of 3 km ~~is excellent, and~~, are fully consistent with  
261 the statistical dispersion of SPICAV-UV retrievals, which highlights the fact  
262 that these “snapshot” observations are actually representative of the ~~median~~  
263 ~~state of~~ cloud top SO<sub>2</sub> as observed ~~statistically~~ by SPICAV. More gener-  
264 ally, these variations are in agreement with the inter-comparison of available  
265 SO<sub>2</sub> measurements detailed by Vandaele *et al.* (2017b), as well as recent  
266 UVI/Akatsuki results (Lee *et al.*, 2017).

267 Regarding UV darkness (as measured through mode 1 imaginary index  
268 at 250 nm), the long term trend can be divided in two time periods: first a 5-  
269 fold increase from 2006 ( $\sim 10^{-2}$ ) until 2010 ( $\sim 5 \cdot 10^{-2}$ ), and then a constant,  
270 darker plateau from 2011 onward until the end of the mission in late 2014.  
271 These variations are most pronounced at lower and mid-latitudes, latitudes

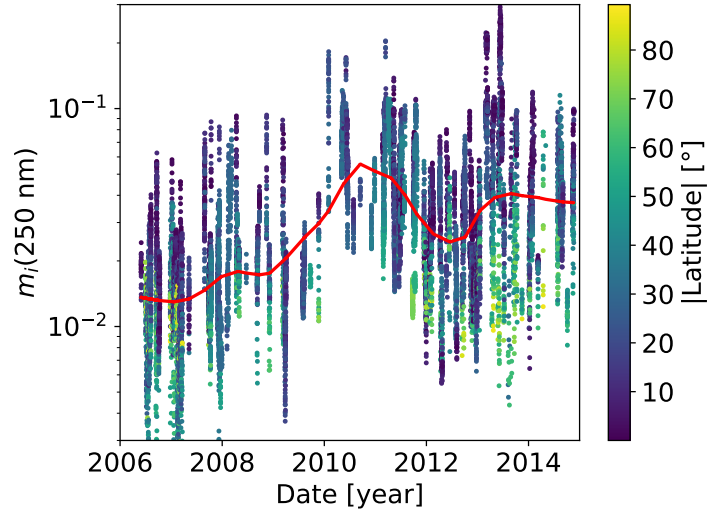


Figure 6: Temporal evolution of SO<sub>2</sub> mixing ratio at 70 km for latitudes lower than 30°. The red line stands for the moving median value, and white diamonds ~~are TEXES~~ /squares show other SO<sub>2</sub> ~~mixing ratios from Encrenaz *et al.* (2016)~~ measurements in the same time interval.



272 above 60° seem less affected by this trend. Here also, these results compare  
 273 well with our previous results (Marcq *et al.*, 2013) where we accounted for  
 274 this UV darkening through a fitted scaling factor, but also with the 40% UV  
 275 albedo darkening observed in 2006-2011 by *Venus Express*/VMC at 365 nm  
 276 (Lee *et al.*, 2015). This agreement between two different instruments (VMC  
 277 and SPICAV) and the fact that the albedo latitude variation trends inferred  
 278 from either the VMC and SPICAV data sets are consistent, even though  
 279 the binning and the reduction of the two data sets ~~is~~ are unique lead us to  
 280 believe that this darkening is genuine, and not an artifact from the aging of  
 281 the SPICAV UV detector.

Figure 7: Temporal evolution of mode 1 imaginary refractive index at 250 nm. The red line stands for the moving median value. Absolute latitude is color-coded.

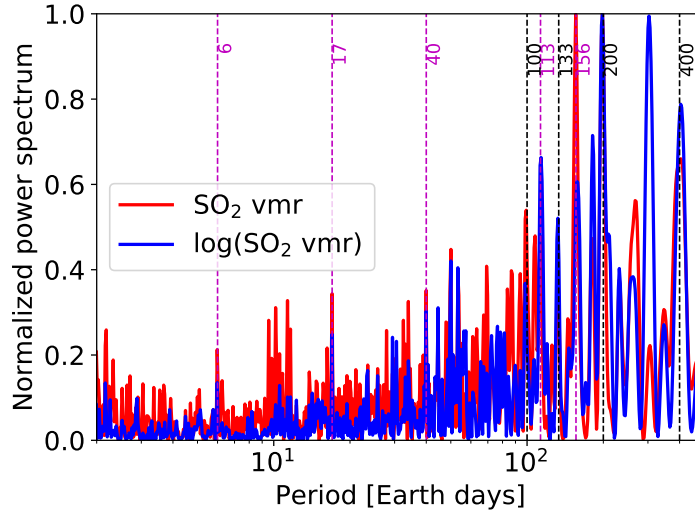


282 *4.2.1. SO<sub>2</sub> periodogram*

283 The SO<sub>2</sub> variations observed in Fig. 6 suggest they may exhibit some  
 284 periodicity. In order to discuss them more quantitatively, we computed a  
 285 Lomb-Scargle periodogram of both SO<sub>2</sub> mixing ratio as well as its logarithm  
 286 (since we present all of our SO<sub>2</sub> results in a logarithmic scale). Lomb-Scargle  
 287 periodograms are well suited when the temporal sampling of measurements  
 288 is uneven (as it is the case here), but may exhibit “ghost” harmonics for  
 289 integer multiple values of the genuine frequency.

290 These periodograms are shown in Fig. 8. Assuming that genuine fre-  
 291 quencies would show up in both SO<sub>2</sub> and log(SO<sub>2</sub>) periodograms, we find  
 292 that our frequency signal is dominated by a 400 Earth day period (and its  
 293 ghost harmonics near 200, 135 and 100 days) component, that can be seen  
 294 between the SO<sub>2</sub> surges in Fig. 6. A 110-day long component is also visible,

Figure 8: Lomb-Scargle periodogram of low-latitude  $\text{SO}_2$  in log and linear scales. Periods discussed in the main text are shown in dashed, with the 400-day period and its ghost harmonics shown in dashed black.



295 close to the solar day on Venus surface, suggesting a link between  $\text{SO}_2$  vari-  
 296 ations and local solar time at the surface reminiscent of the similar period  
 297 seen by Bertaux *et al.* (2016) for the UV brightness as observed by VMC.  
 298 We present the correlation between topography and  $\text{SO}_2$  in more detail in  
 299 §4.3.1.

300 Other possible periods that are significantly above noise include a 155  
 301 Earth day component, as well as medium term components (40, 17 and 6  
 302 Earth days). Noticeably, a 4-day period is absent, implying that  $\text{SO}_2$  patches  
 303 are shorter lived than the super-rotation period at cloud top.

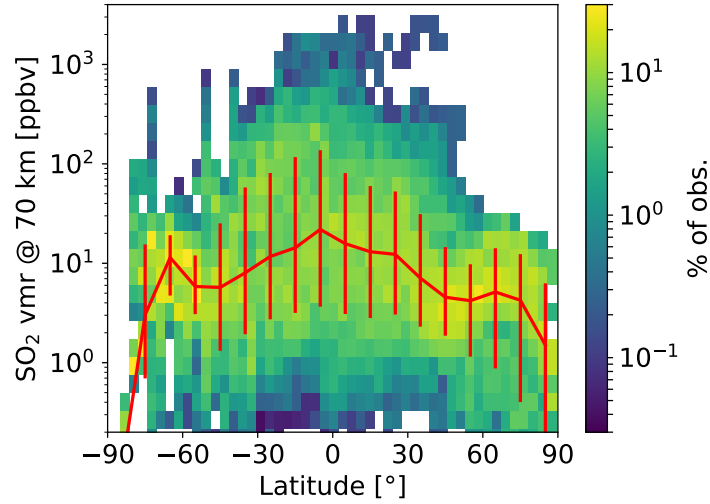
304 *4.3. Spatial variability*

305 *4.3.1. SO<sub>2</sub>*

306 The binned latitudinal distribution of our SO<sub>2</sub> retrievals is shown in Fig. 9.  
307 The main features from our previous analyses (Marcq *et al.*, 2013, 2011) are  
308 still valid, namely: (i) there is a large dispersion, spanning more than two  
309 orders of magnitude at lower latitudes and about one order of magnitude at  
310 higher latitudes (ii) the median SO<sub>2</sub> value is larger at lower latitudes (typ-  
311 ically 5 to 100 ppbv, median 20 ppbv below 30°), due to the occurrence of  
312 SO<sub>2</sub> “plumes” (above 100 ppbv) that do not occur at higher latitudes. The  
313 observed latitudinal pattern remains consistent with the SO<sub>2</sub> gas distribution  
314 being dominantly controlled by a Hadley-cell type circulation as reported pre-  
315 viously (Jessup and Mills, 2019; Vandaele *et al.*, 2017b; Jessup *et al.*, 2015;  
316 Marcq *et al.*, 2013, 2011) – thus is linked to large-scale (or deep) convective  
317 mixing process. The broad range of SO<sub>2</sub> abundance values observed at each  
318 latitude points to the perpetual competition between general circulation and  
319 the LST dependent photochemical destruction of SO<sub>2</sub> (Marcq *et al.*, 2013)  
320 which may produce order of magnitude changes in the cloud top abundances  
321 on a time scale of several Earth days (corresponding to 1-2 hours of LST  
322 considering the zonal super-rotation at cloud top) particularly at low lati-  
323 tudes. The SPICAV-observed variability patterns are fully consistent with  
324 other measurements in UV from HST/STIS (Jessup *et al.*, 2015) or in IR  
325 with IRTF/TEXES (Encrenaz *et al.*, 2012, 2016).

326 Our comprehensive data set also allows us to study the variability of  
327 SO<sub>2</sub> with respect to local solar time as shown in Fig. 10. A local minimum  
328 near noon (between 10am and 2pm) is evidenced. Interestingly, TEXES

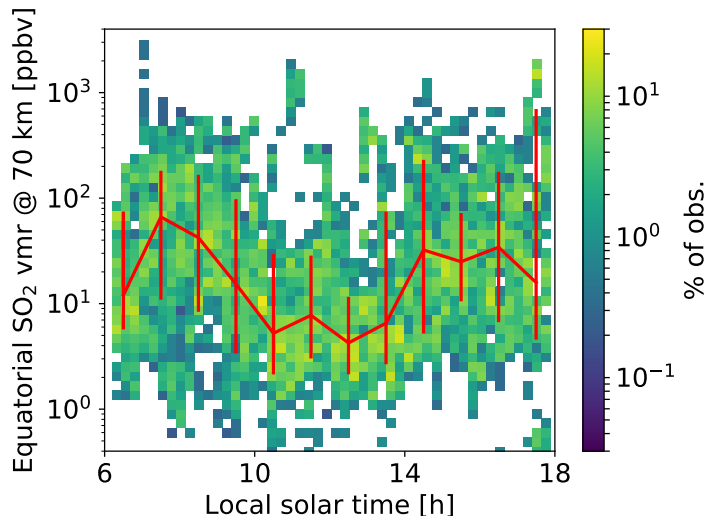
Figure 9: SO<sub>2</sub> mixing ratio at 70 km with respect to latitude [for all LSt values](#). The red line stands for the [moving-10°-moving boxcar](#) median value, and red error bars for the  $1 \cdot \sigma$  statistical dispersion.



329 measurements also confirm the inefficiency of upwelling SO<sub>2</sub> plumes in the  
 330 10h to 14h local time interval (Encrenaz *et al.*, 2019). We further discuss the  
 331 SO<sub>2</sub> and overall UV brightness variations with respect to local solar time in  
 332 §5.2.

333 The SO<sub>2</sub> periodgram (§4.2.1) suggest that SO<sub>2</sub> and surface topography  
 334 may be correlated. Therefore, we have mapped our SO<sub>2</sub> retrievals with re-  
 335 spect to latitude and geographic longitude in Fig. 11. Besides the latitudinal  
 336 trend already discussed, we notice a possible SO<sub>2</sub> enhancement located down-  
 337 wind of the western edge of [the large equatorial high-altitude plateau known](#)  
 338 [as Aphrodite Terra](#) in the 30°-45° range. Similarly, the SO<sub>2</sub> volume mixing  
 339 ratio observed by HST at low latitudes in the 0°-45°E longitude range was  
 340 an order of magnitude higher than directly over *Aphrodite Terra* (Jessup and

Figure 10: SO<sub>2</sub> mixing ratio at 70 km [for latitudes below 20°](#) with respect to local solar time. The red line stands for the [1-hour moving boxcar](#) median value, and red error bars for the  $1 \cdot \sigma$  statistical dispersion.

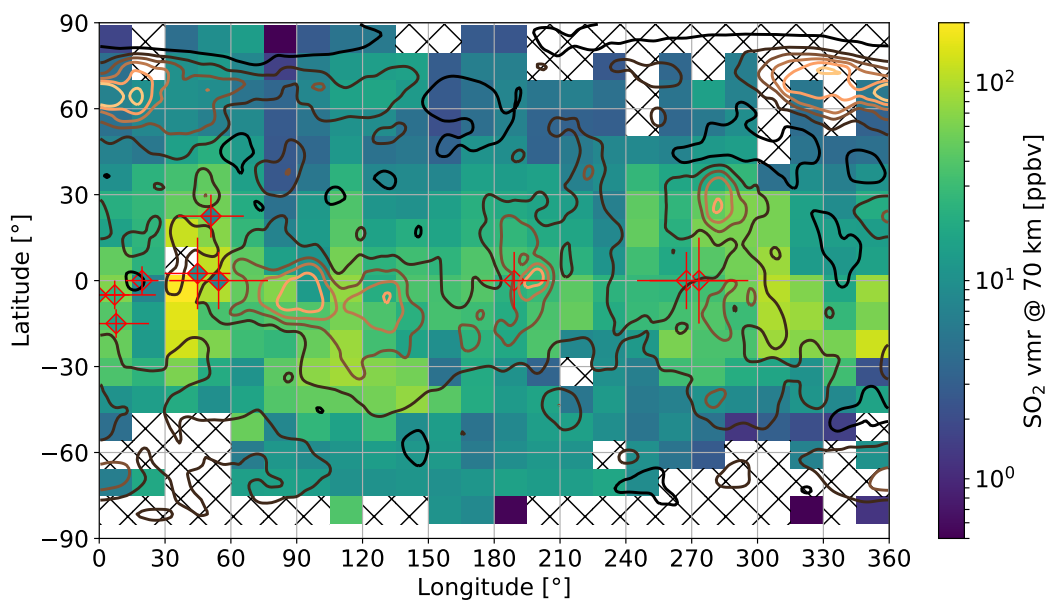


341 Mills, 2019). Yet TEXES measurements also displayed on Fig. 11 fail to re-  
 342 port such an increase of SO<sub>2</sub> over the same ground location. Although the  
 343 70 km values inferred from TEXES data do not match the statistical averaged  
 344 SPICAV values, a trend of increased SO<sub>2</sub> plumes at 0°-30°E vs. 60°-140°E  
 345 is distinctly evident in the TEXES data (Encrenaz *et al.*, 2019, their Fig.  
 346 8). One should also note that the polar orbit of *Venus Express* implies that  
 347 different longitudes were observed at different dates, so that longitudinal and  
 348 temporal variability cannot be retrieved separately from these maps.

#### 349 4.3.2. UV brightness

350 We have also investigated the correlation between topography and the  
 351 retrieved absorption of mode 1 particles shown in Fig. 12 to determine if

Figure 11: Map (latitude vs. longitude) of SO<sub>2</sub> mixing ratio at 70 km. The contour lines follow topographic elevation – *Aphrodite Terre is peaking near 90°E-0°*. Crossed hatching indicated lack of meaningful data. Red diamonds show co-located day side TEXES retrievals, with red crosses showing the TEXES observations footprint.



352 relationships between the albedo and the underlying topography proposed  
353 by Bertaux *et al.* (2016) are supported by our data, and to determine how  
354 the observed albedo trends might relate to the retrieved SO<sub>2</sub> abundances.  
355 We are able to do so, since the retrieved values of  $m_i(250\text{ nm})$  exhibit an  
356 anti-correlation with the UV brightness of the cloud top (once SO<sub>2</sub> absorption  
357 is taken into account). Comparison of Figures 11 and 12 highlights that  
358 directly over *Aphrodite Terra* (60°-140°E, 15°S) where relatively SO<sub>2</sub> VMRs  
359 have been retrieved, the  $m_i$  values are low, suggesting a bright cloud top –  
360 this results confirms that the cloud top is brighter over Aphrodite but the  
361 anti-correlation between the cloud top albedo and the SO<sub>2</sub> gas abundance  
362 does not support that the abundance of both components (SO<sub>2</sub> and UV  
363 absorber) is controlled solely by linked vertical transport process (see §5).

364 Fig. ~~H-12~~ 12 also indicates that high  $m_i$  values are retrieved at lower lati-  
365 tudes, which is expected since convective activity is strongest at these lati-  
366 tudes due to the enhanced solar heating (Peralta *et al.*, 2007; Titov *et al.*,  
367 2008, 2012). However, strong longitudinal variability in the cloud top bright-  
368 ness is observed within the low latitude region sampled by SPICAV; and the  
369 inferred brightness distribution is not symmetric with respect to the equator.  
370 Additionally, as already mentioned, the polar orbit of *Venus Express* leads  
371 to an uneven longitudinal sampling with respect to observation date, so that  
372 the observed distribution pattern may also be linked to long-term temporal  
373 variability.

374 In terms of local time and latitudinal variability, Fig. 13 shows that (i)  
375 UV brightness increases with increasing latitude, reaching a high plateau  
376 near 60°N; and (ii) UV brightness is lower between 10:00 and 16:00 at lower



Figure 12: Map (latitude vs. longitude) of mode 1 imaginary refractive index at 250 nm. The contour lines follow topographic elevation – [Aphrodite Terre is peaking near 90°E-0°](#). Crossed hatching indicates lack of meaningful data.

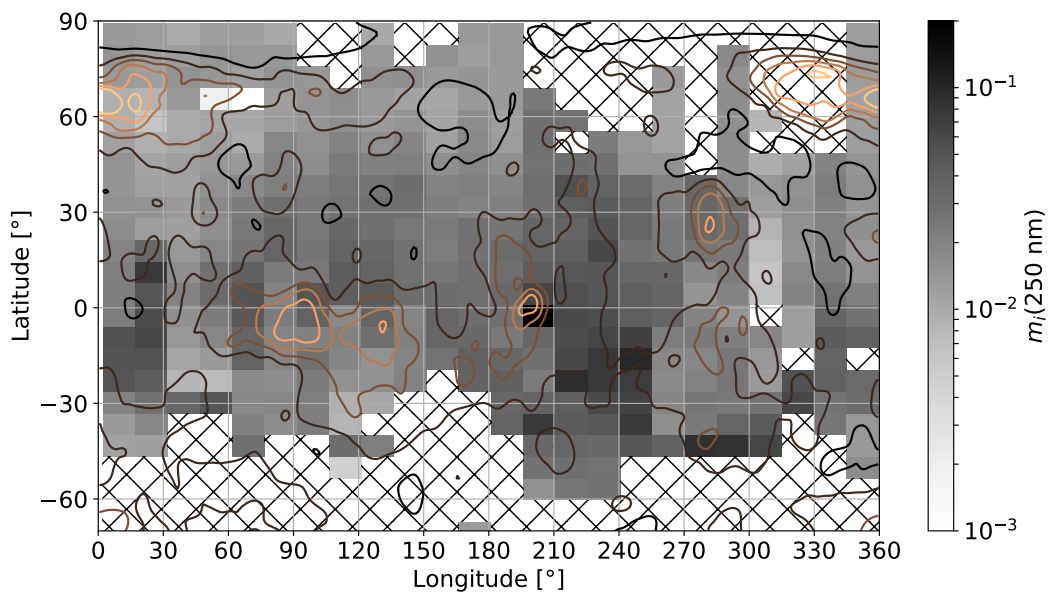
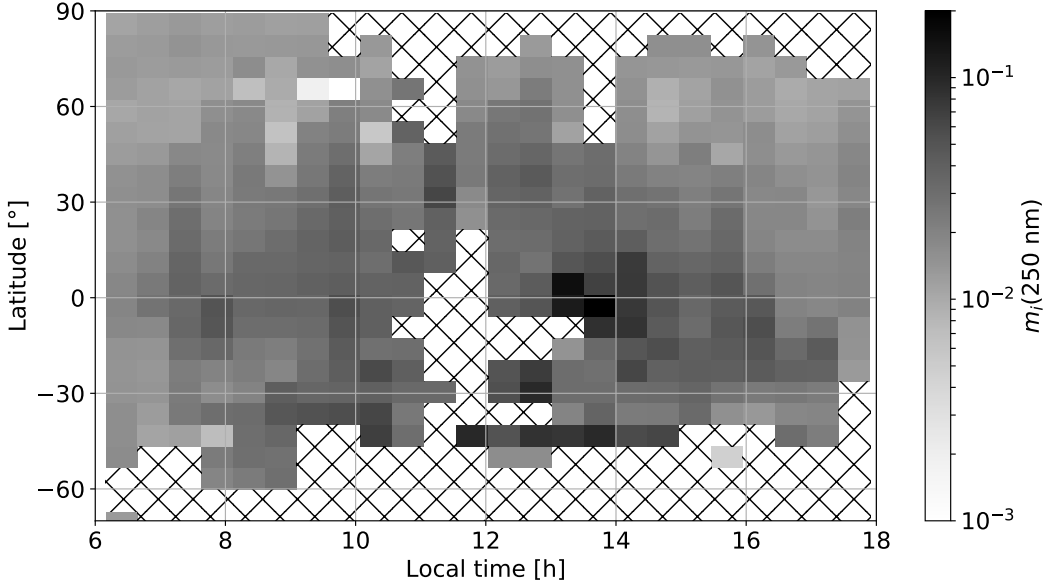


Figure 13: Pseudo-map (latitude vs. local solar time) of mode 1 imaginary refractive index at 250 nm. Hatched areas indicate lack of meaningful data



377 latitudes (below  $30^\circ$ ). Both these patterns in latitude and local solar time  
 378 are already known from previous studies (Titov *et al.*, 2008, 2012; Lee *et al.*,  
 379 2015). These already known trends, plus the fact that minimum UV bright-  
 380 ness (~~correlated with maximum  $m_i$  values~~) is reached near 14:00 and not  
 381 exactly at noon lead us to discard a spurious correlation of our retrievals  
 382 with respect to airmass, which may occur if the assumed extinction vertical  
 383 profiles are not representative of the real ones.

#### 384 4.3.3. Cloud top altitude

385 Variations of cloud top altitude with respect to latitudes are shown in  
 386 Fig. 14. The average low latitude cloud top altitude (defined as  $\tau(250 \text{ nm}) =$   
 387 1 nadir level) we find is  $73 \pm 2 \text{ km}$  in good agreement with already known

388 values (Ignatiev *et al.*, 2009; Pérez-Hoyos *et al.*, 2018). This is not surprising,  
389 since we adjusted the spectral slope of the UV absorber precisely to match  
390 this mean value (see §3.2). The already known decrease of cloud top altitude  
391 towards higher latitudes (Ignatiev *et al.*, 2009) is also observed, although  
392 the amplitude – about 10 km from equator to pole here instead of about  
393 3 km according to Ignatiev *et al.* (2009) – is somewhat larger, and starts  
394 at lower latitudes (30° instead of 50°). Nevertheless, due to the aforemen-  
395 tioned degeneracy between the spectral slope and cloud top altitude, reach-  
396 ing a qualitative agreement for this poorly constrained parameter retrieval  
397 is satisfactory, considering the need to keep as few free fitted parameters as  
398 possible in our forward model. [Please note that simultaneous and co-located](#)  
399 [IR cloud top measurements would remove such a degeneracy, and allow for](#)  
400 [a detailed investigation of the spatial and temporal variability of the aerosol](#)  
401 [spectral slope.](#)

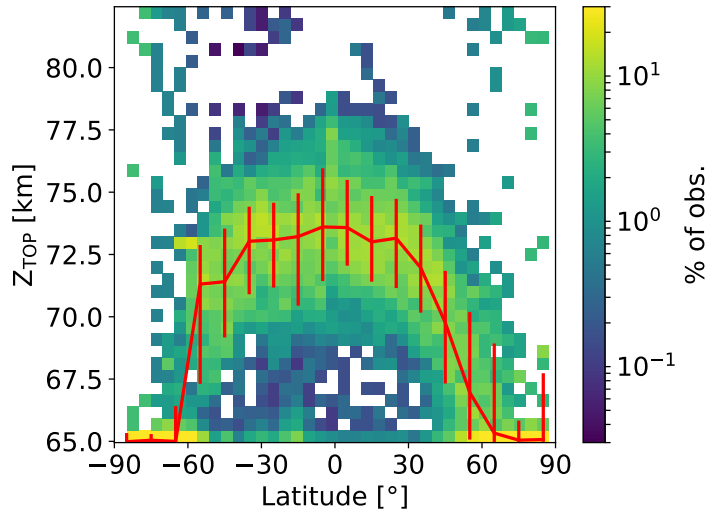
## 402 5. Discussion

### 403 5.1. UV absorption

#### 404 5.1.1. Nature of UV absorber

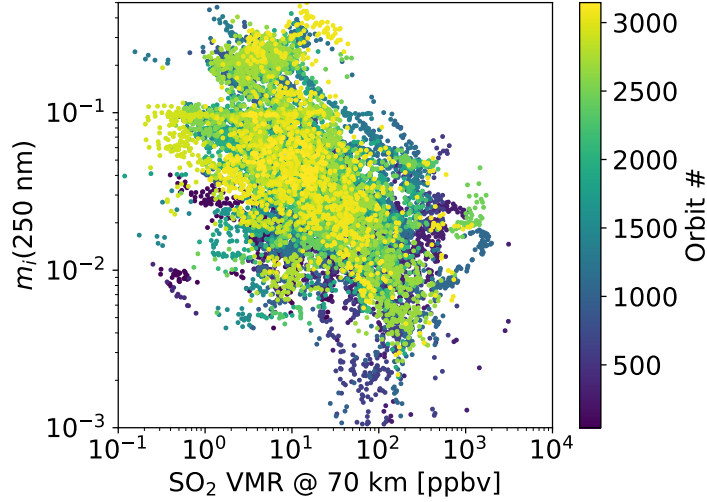
405 As already mentioned in §3.2, we suspect that our retrievals of the imagi-  
406 nary refractive index of mode 1 particles is directly related to the local abun-  
407 dance of the infamous UV absorber. Unfortunately, the only **spectropseopic**  
408 [spectroscopic](#) constraint we were able to derive is the spectral slope-related  
409 parameter of 40 nm. Such ~~an~~[a](#) decrease of UV single scattering albedo with  
410 increasing wavelength in the SPICAV UV range is compatible with a large  
411 number of candidates for the UV absorber, including the most recent mix-

Figure 14: Cloud top altitude with respect to latitude. The red line stands for the [10° binned moving boxcar](#) median value, and red error bars for the  $1 \cdot \sigma$  statistical dispersion.



412 ture of cis- and trans-OSSO suggested by Frandsen *et al.* (2016). Actually, we  
 413 first tried to fit the average UV brightness not through the refractive index  
 414 of mode 1 particles, but with peak OSSO concentration following the theo-  
 415 retical vertical profile given by Frandsen *et al.* (2016) peaking near 62 km. It  
 416 appeared then that we could not reach a satisfactory fit, the amount of OSSO  
 417 required to match the mean albedo was at up to two orders of magnitude  
 418 larger than the peak abundance given reported by Frandsen *et al.* (2016,  
 419 about 10 ppbv), and in such a case suppressed all other gaseous spectral  
 420 signatures (SO<sub>2</sub>, SO, O<sub>3</sub>) except for CO<sub>2</sub>. So, if the unknown UV absorber  
 421 were indeed OSSO, its vertical abundance profile and abundance would differ  
 422 significantly from the theoretical values given by Frandsen *et al.* (2016).

Figure 15: Scatter plot between imaginary index of mode 1 particles at 250 nm and SO<sub>2</sub> mixing ratio at 70 km



423 5.1.2. Correlation with SO<sub>2</sub>

424 We already reported (§4.3) that low SO<sub>2</sub> abundances were observed within  
 425 2 hours of the subsolar point, and similarly the lowest UV brightness (min-  
 426 imum absorber abundance) was detected in the afternoon hours. The long-  
 427 term trends are opposite too, with an observed secular decrease for SO<sub>2</sub>, and  
 428 secular increase of the UV absorption, see §4.2). This points to an anti-  
 429 correlation between SO<sub>2</sub> and UV absorption that is confirmed in Fig. 15:  
 430 although the statistical dispersion for both SO<sub>2</sub> and the imaginary refrac-  
 431 tive index  $m_i(250 \text{ nm})$  is large, there is an average decrease of one order  
 432 magnitude for  $m_i$  relative to an increase of SO<sub>2</sub> of two orders of magnitude.

433 Such an anti-correlation using VMC 365 nm observations with respect to  
 434 our previous estimates of SO<sub>2</sub> (Marcq *et al.*, 2013) was reported by Lee *et al.*  
 435 (2015), as well as using high spectral resolution (line-resolving) retrievals of

436 SO<sub>2</sub> and SO with HST/STIS from Jessup *et al.* (2015). Therefore, we can  
437 safely dismiss that correlation would be a spurious artifact due to parasitic  
438 trends in the photometric calibration of SPICAV-UV spectra. There are two  
439 possible, non-mutually exclusive physical explanations already reported (Es-  
440 posito, 1984; Jessup *et al.*, 2015) and supported by this study: (i) injections  
441 of SO<sub>2</sub> and H<sub>2</sub>O from the deep atmosphere lead to an increased formation  
442 rate of uncontaminated H<sub>2</sub>SO<sub>4</sub>, UV-bright haze particles above the UV ab-  
443 sorber; and (ii) on longer time scales, SO<sub>2</sub> is a precursor species to the UV  
444 absorber, so that there is a possible conversion of SO<sub>2</sub> into a sulfur-bearing  
445 UV absorber – SO<sub>2</sub> and the UV absorber being competing reservoirs of sulfur  
446 in such a case.

### 447 5.1.3. Comparison with VMC

448 Our SPICAV retrievals of  $m_i$  (mode 1 imaginary index) show a greater  
449 level of longitudinal variation of the unknown UV absorber than inferred  
450 from VMC (Lee *et al.*, 2015; Bertaux *et al.*, 2016); for example, Fig. 12 does  
451 not indicate that Aphrodite is a region where the cloud top albedo is uniquely  
452 bright compared to all other longitudes, unlike what is indicated by Bertaux  
453 *et al.* (2016). Similarly, the latitude variation at southern latitudes is more  
454 complex than what is seen in VMC at southern latitudes. On the other hand,  
455 the latitudinal variations inferred from the SPICAV analysis at northern lat-  
456 itudes shows the expected pattern of low latitudes darker than high ~~at~~for  
457 almost all longitudes. These ~~complexities~~complex spatial patterns are likely  
458 more readily discernible in the SPICAV data, because these data may be  
459 used to distinguish between different particle modes (effectively ~~segregating~~  
460 distinguishing between mode 2 H<sub>2</sub>SO<sub>4</sub> particles mostly conservative scatter-

461 ing ~~from~~ and mode 1 absorption), while VMC traces only the total absorption  
462 in the 365 nm band, thus likely to include both mode 1 and mode 2 contri-  
463 butions. Moreover, SPICAV reconstructed maps include long-term temporal  
464 variations due to the slow Venus Express orbital swath precession relative  
465 to longitude and/or local solar time, which may explain the overall larger  
466 variability seen by SPICAV compared to instantaneous VMC maps.

### 467 5.2. Requirements for deep vertical mixing

468 Since SO<sub>2</sub> transient enhancements and correlated UV brightenings are  
469 caused by local upwellings – also called “plumes” by e.g. Encrenaz *et al.*  
470 (2016)), clues to the processes that support the observed SO<sub>2</sub> spatial dis-  
471 tributions and the impact of SO<sub>2</sub> enhancement plumes can be derived by  
472 considering the LST, latitude and longitude patterns revealed in the statisti-  
473 cally averaged data. As described in §4.3 and shown in Fig. 11, regions of SO<sub>2</sub>  
474 enhancements have been observed primarily at latitudes smaller than 30° ex-  
475 cept at *Aphrodite Terra* longitudes (60°-140°E) where the SO<sub>2</sub> enhancement  
476 extends to 40°S so that on average the SO<sub>2</sub> abundance from 0° to 40°S is  
477 higher than observed at the same latitudes in the 160°-240°E region. Addi-  
478 tionally, on average a very strong enhancement region is typically observed  
479 downwind from Aphrodite at 30-45°E. On the other hand, depletion of SO<sub>2</sub>  
480 noted between 10:00 to 14:00 local solar time (Fig. 10) implies that at these  
481 local solar times replenishment of the cloud top SO<sub>2</sub> abundance via large-  
482 scale mixing cannot keep up with the high rate of photochemical loss that  
483 would dominate at these local solar times at low latitude.

484 The prevalence of Venus’ cloud top SO<sub>2</sub> abundance to peak at low lat-  
485 itudes was already noticed in our first analysis (Marcq *et al.*, 2011, 2013),

486 and was then linked to the general meridional circulation causing upwelling  
487 at lower latitudes and downwelling at higher latitudes. Therefore, the com-  
488 bined SPICAV, TEXES and HST results confirm that the mechanism driving  
489 transient plume formation differs distinctly from shallow sub-solar mixing  
490 and deep Hadley-cell circulation processes.

491 The observed increase in SO<sub>2</sub> abundance in the 0° to 40°S latitude re-  
492 gion at longitudes intersecting *Aphrodite Terra* relative to what is observed at  
493 similar latitudes upwind provides further evidence to the unexpected connec-  
494 tion between surface topography and cloud top (Bertaux *et al.*, 2016; Peralta  
495 *et al.*, 2017). In general, the current analysis shows that statistically on aver-  
496 age SO<sub>2</sub> is high at low latitudes from 40° to 120°E relative to other longitudes  
497 except at 30°-45°E (downwind from Aphrodite) where the SO<sub>2</sub> abundance is  
498 on average higher than at Aphrodite. We still do not completely understand  
499 what controls the overall SO<sub>2</sub> longitudinal variation (provided it is genuine  
500 and not an artifact from our temporal-longitudinal sampling). Nevertheless,  
501 the relative increase in SO<sub>2</sub> between the region downwind of Aphrodite and  
502 directly over Aphrodite are consistent with the differences in wind speed  
503 within those two specific regions and the anticipated vertical wind speed re-  
504 sponse proposed by Bertaux *et al.* (2016), [as we already suggested in §4.2.1](#)  
505 [while discussing the possible 110-day period in SO<sub>2</sub>](#). The differences in wind  
506 speed between these two regions are likely linked to the impact of gravity  
507 waves (Navarro *et al.*, 2018) momentum deposition on cloud top zonal wind  
508 speeds as proposed by Bertaux *et al.* (2016).

509 Interestingly, Encrenaz *et al.* (2016) does not see any SO<sub>2</sub> plume over this  
510 location (see Fig. 11), which highlights that while the discussed SO<sub>2</sub> enhance-



511 ment over the western slopes of *Aphrodite Terra* is on average higher than  
512 other longitude regions, other transient phenomena may also be relevant,  
513 such as local time effects shown in Fig. 13. In fact, TEXES measurements  
514 were acquired above *Aphrodite Terra* at 13:30 local time, further confirming  
515 that transient plume activity is suppressed directly over *Aphrodite* near local  
516 noon. Similarly, STIS observations from Jessup and Mills (2019) show that  
517 increased 245 nm cloud top darkening occurs over regions of low elevation 2  
518 hours LST prior to local noon, but these increases are not observed at similar  
519 local times directly over *Aphrodite Terra*.

## 520 **6. Conclusion**

521 Our analysis of the full SPICAV-UV nadir data set has been performed  
522 by fitting the observed radiance factors with respect to SO<sub>2</sub> abundance at  
523 cloud top and UV absorption of mode 1 particles. Our previous conclusions  
524 about SO<sub>2</sub> (Marcq *et al.*, 2011, 2013) are mostly confirmed: in average, SO<sub>2</sub>  
525 is found to be decreasing with increasing latitude, from typically 5-100 ppbv  
526 at 70 km near the equator to 2-20 ppbv polewards of 60°N and S. Statistical  
527 dispersion is therefore much larger at lower latitudes, consistent with the  
528 location of transient SO<sub>2</sub> plumes as seen by other observers (Encrenaz *et al.*,  
529 2016). The 5-fold secular decrease in equatorial SO<sub>2</sub> reported by Marcq  
530 *et al.* (2013) between 2007 and 2011 is now found to extend until 2015 at  
531 least, albeit with a previously unreported secondary maximum in 2009. A  
532 minimum near subsolar point is also found in average, likely caused by the  
533 locally higher photochemical depletion rate.

534 UV absorption (Fig. 13) displays the familiar pattern of comparatively

535 brighter mid-to-high latitudes compared to lower latitudes (Titov *et al.*,  
536 2018), along with an already known darkening in the 12:00-14:00 local time  
537 range at low latitudes (Titov *et al.*, 2012). Long-term evolution of UV dark-  
538 ness (Fig. 7) shows at first an increase between 2006 and 2011, followed by  
539 a variable, yet in ~~average~~ average darker UV albedo between 2011 and 2015.  
540 Such a behavior is reminiscent of the other UV-sensitive instrument on board  
541 ~~venus~~ Venus Express, namely VMC (Lee *et al.*, 2015, 2019).

542 We have also investigated possible correlations with topography. Since  
543 longitudinal and temporal sampling are correlated to the slowly precessing  
544 *Venus Express* polar orbit, such correlations are hard to disentangle from  
545 temporal variability. With this *caveat* in mind, topographic signature of  
546 *Aphrodite Terra* is possibly seen both in SO<sub>2</sub>, with high SO<sub>2</sub> levels reported  
547 directly downwind of *Aphrodite Terra* in the 30°-45°E zonal region, and in  
548 UV brightness with a comparatively brighter cloud top above and downwind  
549 from *Aphrodite Terra*. Both findings are consistent with VMC studies of UV  
550 albedo (Bertaux *et al.*, 2016) and SO<sub>2</sub> behavior as seen by STIS/HST (Jessup  
551 *et al.*, 2015), and explained through coupled variations in vertical mixing and  
552 zonal wind speed through momentum deposition from topography-induced  
553 gravity waves over the western edge of *Aphrodite Terra*.

554 In any case, the high temporal and spatial variability of both SO<sub>2</sub> and  
555 UV absorption over a large span of temporal (from days to decades) and  
556 spatial (from regional to planetary) scales highlight the need to continue  
557 the monitoring of Venus after the end of *Venus Express*, from orbiters like  
558 *Akatsuki* and Earth-based observations, at least until the next generation of  
559 UV instruments on board Venus orbiters may take over the legacy of *Venus*

560 *Express* at some point in the late 2020s to early 2030s.

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