Sulfur Dioxide variability in the Venus Atmosphere

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Introduction - SO_2 is strongly related to the formation of the clouds and haze on Venus, which are composed of sulfuric acid combined to water complexes. Presence and variations of SO_2 could be the proof of a possible volcanism on Venus. The most intriguing are discrepancies among different observations, and the suspected long-term variations of the SO_2 abundance observed on the scales of several years, in particular during Pioneer Venus Orbiter and Venus Express missions. Similar trends are also observed in the super-rotation period and circulation patterns, which suggest that these aspects may be more strongly coupled than expected.

An ISSI international team has been built in view of considering different aspects of sulfur chemistry on Venus. This includes comparison and validation of observations, from past missions, from Venus Express, from the Earth, and from Hubble Space Telescope, modeling of photochemistry and of other processes in which the sulfur family is involved. In this work, we will consider not only SO_2, but also SO and other constituents involved in the sulfur cycle. Reference density and vmr fields will be constructed from the detailed analysis and comparison of data. These will be included into the next generation of the VIRA reference atmosphere.

Observations - Different observations were considered: previous measurements performed by the Venera probes and Pioneer Venus, as well as more recent observations carried out from Earth or from space-borne instruments, where the latter encompasses instruments on board Venus Express and the Hubble Space Telescope. Table 1 summaries the observations considered in this study, and Figure 1 and 2 illustrates the spatial coverage of these observations.

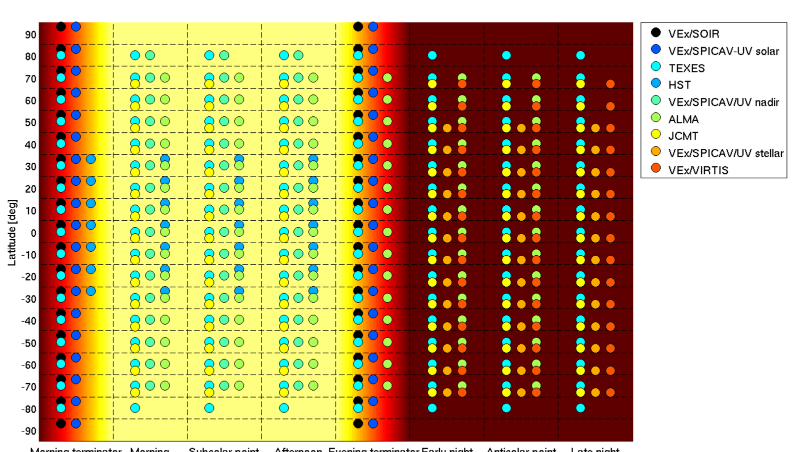

Figure 1: Coverage in terms of Latitude/Local Solar Time

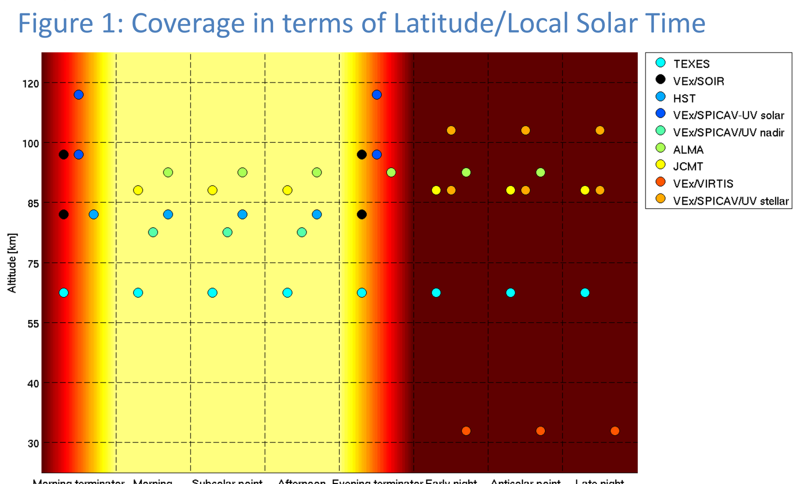

Figure 1: Coverage in terms of Altitudes/Local Solar Time

Observation	Resolving power, λ/Δλ	Altitude range, km	$[SO_2]$, ppbv	[SO],ppbv	Concerns/notes
IRTF, 7.5 µm	80 000	60-80	75-125	yes	High variability [Encrenaz et al., 2014]
IRTF, 19 µm	80 000	Below the clouds	75-125	yes	High variability [Encrenaz et al., 2014]
ALMA 346.6 GHz	80 000	60-80	75-125	yes	High variability [Encrenaz et al., 2014]
IRTF, 4 µm	40 000	70-80	200-600	--------	SO_2 and OCS [Krasnopolsky, 2010]
SPICAV UV nadir, 190-300 nm	150-200	70-80	40-400	assumed $0.1*SO_2$	Vmr decreases from 2007 to 2012 (peak suspected in 2007) [Marcq et al., 2013]
UV HST, 190-300 nm	700-1000	70-80	6-200 above z=75 km;	1-15	Dayside &near terminator values (i.e. SZA = 15-75°) derived from the HST data obtained between 30N and 35S latitude region, for SO_2 and SO gas; VMR derived assuming VIRA CO_2 profile, 0.965 CO_2 abundance [Jessup et al., 2015]
SOIR, 4 µm	20 000	66-80	20-500	--------	Terminator; Mostly polar coverage [Mahieux et al., 2015]
		80-90	10-200	--------	Terminator; Coincide with SPICAV-UV assuming no SO [Belyaev et al., 2012]
JCMT, 346.6 GHz	10^3-10^4	70-100 (84)	0-70 @ >85 km, 0 @<83 km	0-30	Time variable [Sandor et al., 2010]
SPICAV UV occultations, 190-300 nm	150-200	85-100	80-100 on avg, Variable up to 500	20-200	Depends on SO retrieval - Total amount of SO_x is 10-100 times higher than expected from µwave [Belyaev et al., 2012]
VIRTIS, 2.4 µm	2000	30-40	130±50	--------	Spectral resolution is not enough to clarify variations with latitude and time [Marcq et al., 2008]

Table 1: Observations/Instruments considered in this study

Models - Different models were also considered :

- 1-D photochemical models
- 3-D Global Circulation Models

with different photochemistry schemes, number of species considered , etc. (see Table 2)

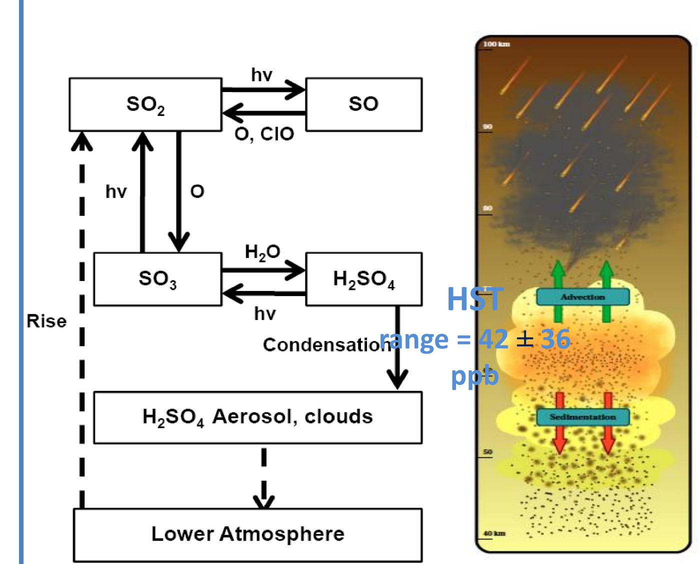

Figure 3: SOx photochemistry

Model	Type	diurnal cycle	Description	Altitude range	T	Type of chemistry	Dynamics	Cloud microphysics
Caltech/JPL Photochemical Model (KINETICS) [Mills and Allen, 2007]	1 (,2,3)-D	N	50 species - 400 Reactions - T dep XS	58-112	specified	Comprehensive oxygen photochemistry	N	N
[Zhang et al., 2010]	1-D v3	(Y)	50 species - 350 Reactions - T dep XS	58-112	specified	Simplified sulphur photochemistry	N	N
[Zhang et al., 2012]	1-D v4	N	35 species - 200 Reactions - T dep XS	58-112	specified	Comprehensive sulphur photochemistry	N	N
[Parkinson et al., 2015]	1-D v4	N	51 species - 300 Reactions - T dep XS	58-112	specified	Comprehensive sulphur and water photochemistry	N	N
[Jessup et al., 2015]	1-D v4	N	35 species - 200 Reactions - T dep XS	58-112	specified	Simplified sulphur photochemistry	N	N
VTGCM + Caltech/JPL Photochemical Model (KINETICS) [Parkinson et al., 2015]	3-D	N	51 species - 300 reactions	70-250	calculated	Simplified sulphur photochemistry	N	Y (CARMA)
LMDz Venus GCM + photochemistry	3-D	Y	33 species - 140 reactions - T dep XS	0-100 (140)	calculated	comprehensive	Explicit	Y (simplified)
Krasnopolsky Model [Krasnopolsky, 2012]	1-D	N		47-112	specified	Comprehensive photochemistry	N	N

Table 2: Models considered in this study

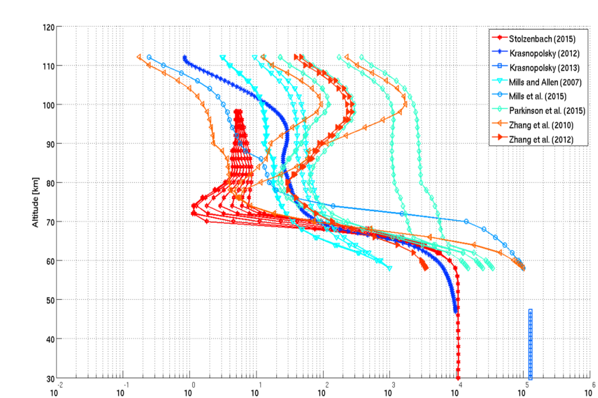

Figure 4: Vertical vmr profiles obtained by the models

Comparisons between datasets - Vertical profiles -

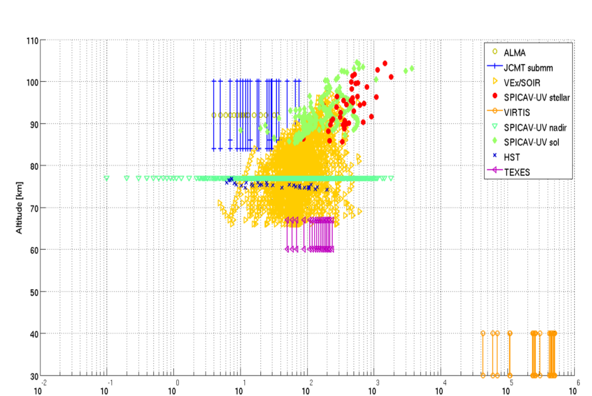

Figure 5: VMR profiles from the different experiments as a function of the altitude

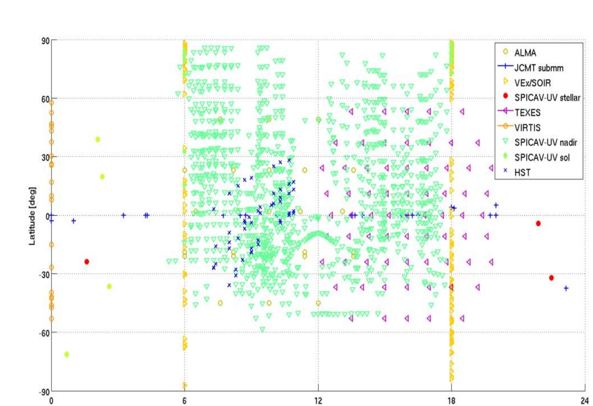

Figure 6: Geolocalisation of the datasets, latitude as a function of local solar time

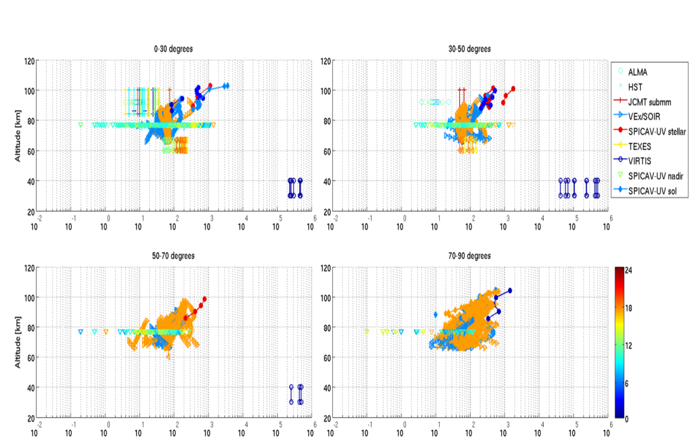

Figure 7: VMR as a function of altitude for different absolute latitude regions, from 0 to 30° (Panel A), 30 to 50° (Panel B), 50 to 70° (Panel C) and 70 to 90° (Panel D). The color code is the local solar time

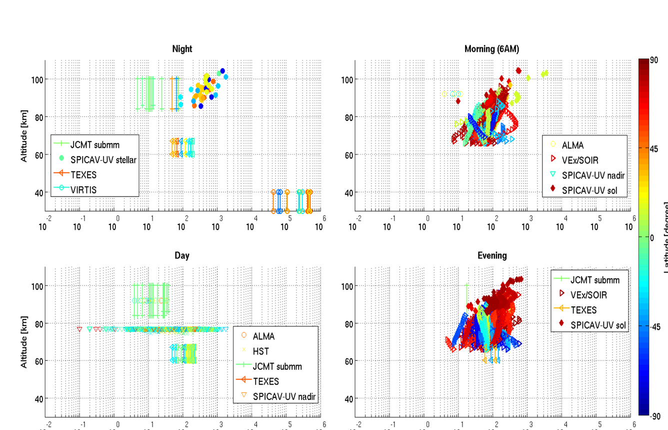

Figure 8: VMR as a function of altitude for different local solar time regions, night side (Panel A), morning side of the terminator (Panel B), day side (Panel C) and evening side of the terminator (Panel D). The color code is the latitude

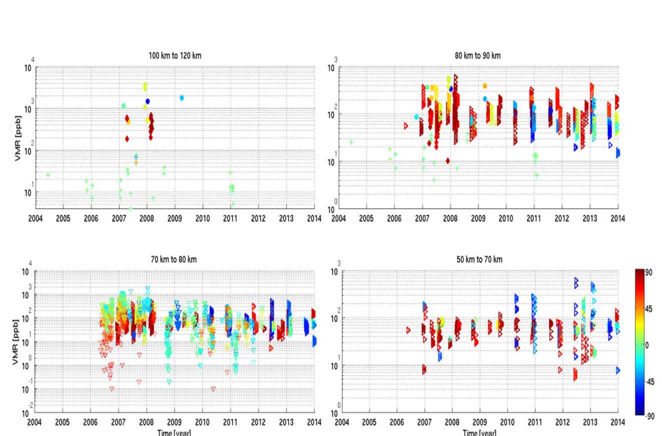

Figure 9: VMR as a function of time for different altitude regions, from 100 to 120 km (Panel A), 80 to 90 km (Panel B), 70 to 80 km (Panel C) and 50 to 70 km (Panel D). The color code is the latitude

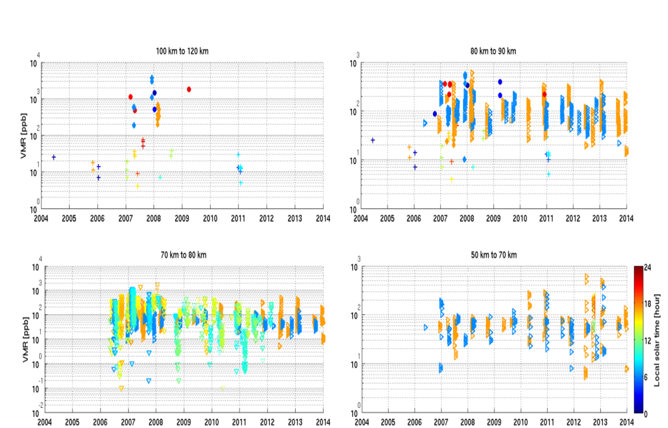

Figure 10: VMR as a function of time for different altitude regions, from 100 to 120 km (Panel A), 80 to 90 km (Panel B), 70 to 80 km (Panel C) and 50 to 70 km (Panel D). The color code is the local solar time

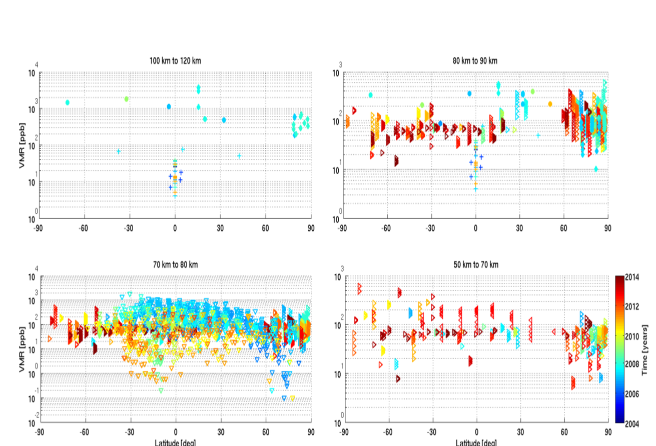

Figure 11: VMR as a function of latitude for different altitude regions, from 100 to 120 km (Panel A), 80 to 90 km (Panel B), 70 to 80 km (Panel C) and 50 to 70 km (Panel D). The color code is the time

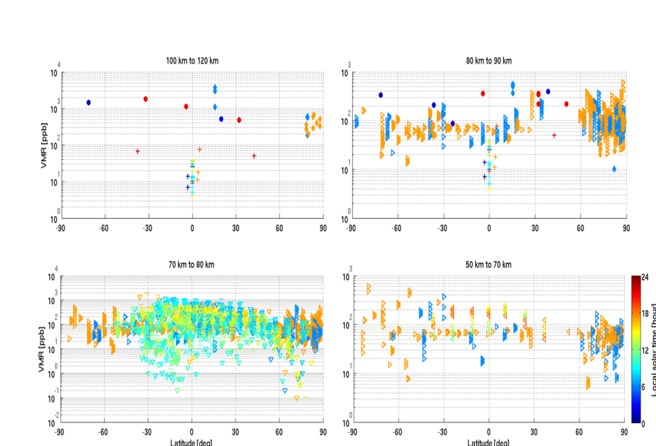

Figure 12: VMR as a function of latitude for different altitude regions, from 100 to 120 km (Panel A), 80 to 90 km (Panel B), 70 to 80 km (Panel C) and 50 to 70 km (Panel D). The color code is the local solar time

Short-scale & short-term variations - Spectroscopic imaging of the Venus disk, as observed from the ground or from Earth orbit, allows us to track short-scale and short-term variations of minor species abundances. This information is fully complementary to the Venus Express observations. TEXES observations [Encrenaz et al., 2014] have shown evidence for short-scale variations of SO_2 over the observed Venus disk with local time. As shown in Figure 13, the SO_2 variations at the cloud top show a contrast of about 5 across the disk (in the 7 µm data) ; within the clouds a contrast of about 3 has been inferred from the 19 µm data. Characterization of the short-term SOx gas distributions are primarily derived from the TEXES, SPICAV-UV nadir and ALMA datasets. The SPICAV/UV nadir dataset records significant variability in the SO_2 gas abundance and distribution within a few orbits (i.e., within a few Earth days). In these cases, variability in the SO_2 abundance range tends to be larger during epochs where the SO_2-abundance is low. For example, order of magnitude drops in the 70-80 km cloud top SO_2 levels to values below the SPICAV/UV nadir detection threshold have occurred within just four VEx orbits (see Figure 14).

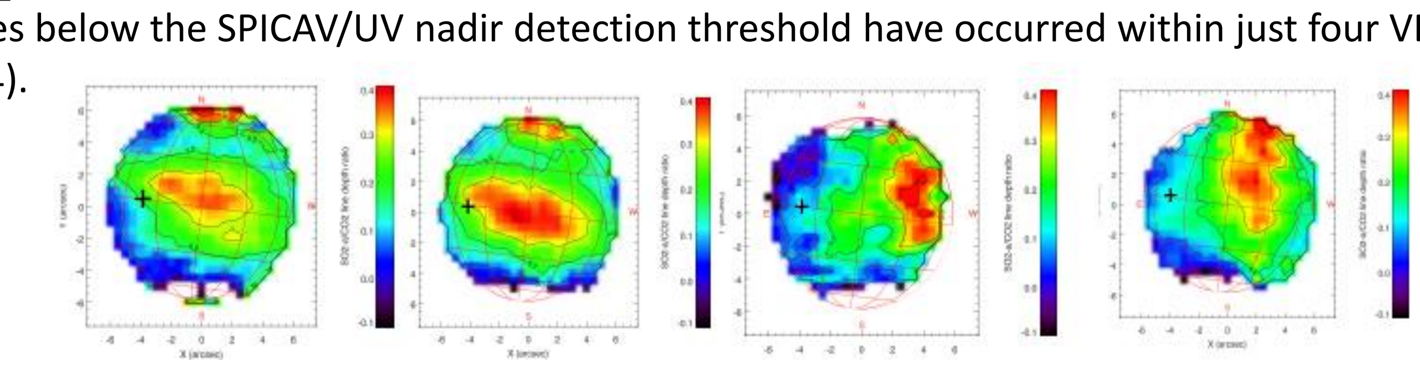

Figure 13: Variations of the SO_2/CO_2 line depth ratio in July 2014 as measured by TEXES. From left to right: July 7, 17:00 UT; July 7, 20:00 UT; July 8, 17:00 UT, July 8, 20:00 UT. The SO_2 transition is at 1345.12 cm^{-1}, the CO_2 transition is at 1345.25 cm^{-1}. The disk-integrated SO2 mixing ratio is about 100 ppb. The morning terminator is observed on the right side of the disk. The subsolar point is indicated with a black cross

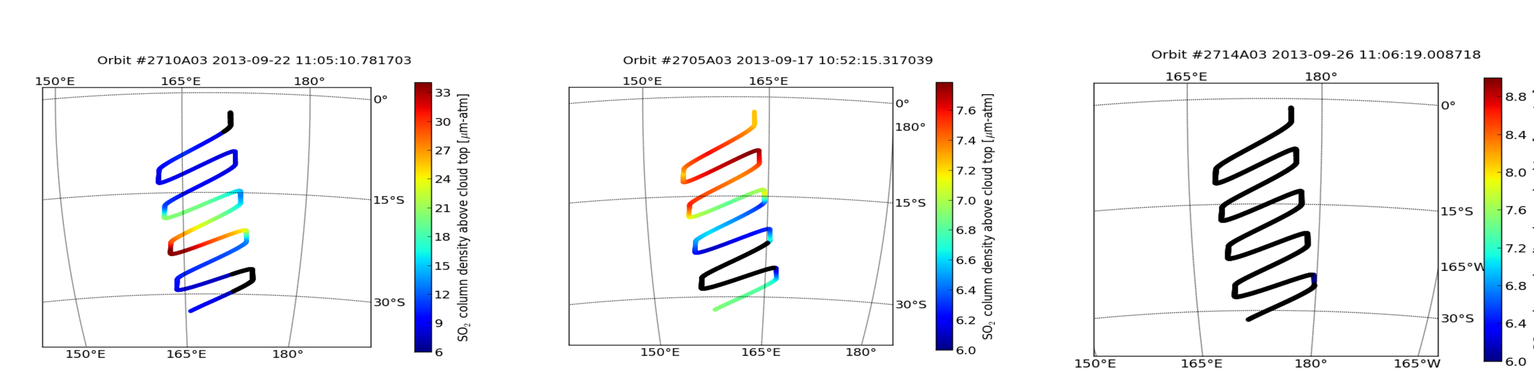

Figure 14: SPICAV/UV maps of SO_2 column densities obtained in late September 2013, exhibiting significant short-scale spatial and temporal variability

Long-scale & long-term variations - The cloud top SO_2 abundance derived from the 2010 and 2011 HST observations [Jessup et al., 2015] varied from date to date, indicating that the cloud top SO_2 abundance is also highly variable on long-term time scales. SPICAV-UV nadir observations seems to indicate that variations in SO_2 gas density are related to changes in convective mixing in the atmosphere (perhaps driven by temperature change) at low latitudes.

Figure 15: More than thirty years of SO_2 measurements at Venus's cloud top. Black: previous measurements [Esposito et al., 1997]. Red: 8-month moving average of SPICAV data. Error bars are 1σ random uncertainty, and dotted red error bars represent measurement dispersion in each temporal bin. Figure adapted from [Marcq et al, 2013]