The recent PAST and the coming FUTURE of HUBBLE OBSERVATIONS of VENUS

ADVANCING VEXAG SCIENCE GOALS THROUGH EARTH-BASED OBSERVATIONS of VENUS

Kandis-Lea Jessup (SwRI);

Emmanuel Marcq; Franklin Mills; Arnaud Mahieux; Sanjay Limaye; Colin Wilson; Mark Allen; Jean-Loup Bertaux; Wojciech Markiewicz; Anthony Roman; Ann-Carine Vandaele; Valerie Wilquet; Yuk Yung, Tibor Kremic, Eliot Young

VEXAG 2015

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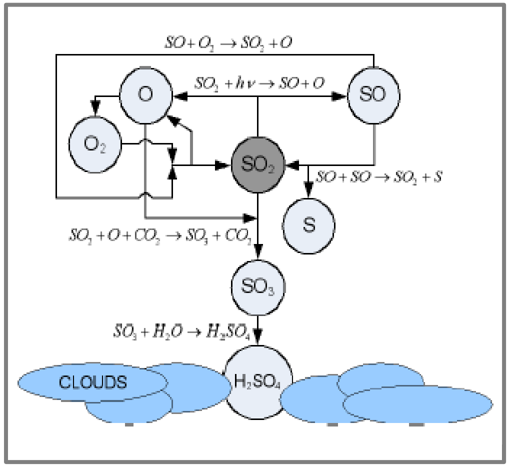
THE BIG PICTURE

VEXAG wants to define the processes that control Venus' atmospheric greenhouse and the chemical makeup and variability of Venus' clouds

Sulfur Chemistry Cycle:



Photolysis of SO_2 → SO, S, O

Kinetic reaction with photolysis components → O_2, SO_2, SO_3

H_2SO_4 is formed from kinetic reaction of SO_3+H_2O

Venus' H_2SO_4 formation cannot be understood independent of the sulfur chemistry cycle

Greenhouse Mechanism:

The H_2SO_4 clouds reflect 75% of incoming solar, while trapping heat between surface and cloud tops

HST Observing Goal:

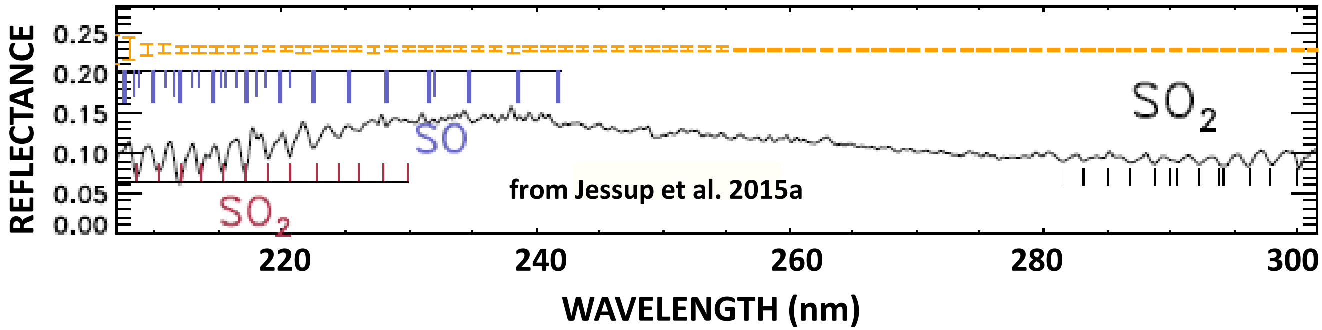
measure and study the abundances of SO_2 and SO which are the parent gas species for the cloud aerosols, and indicators of the sulfur-cycle

Rationale:

H_2SO_4 is at the center of Venus' greenhouse heating and climate evolution

Why observe in the UV

Both SO_2 and SO gases (parent species for H_2SO_4 gas) absorptions conspicuous between 200-300 nm

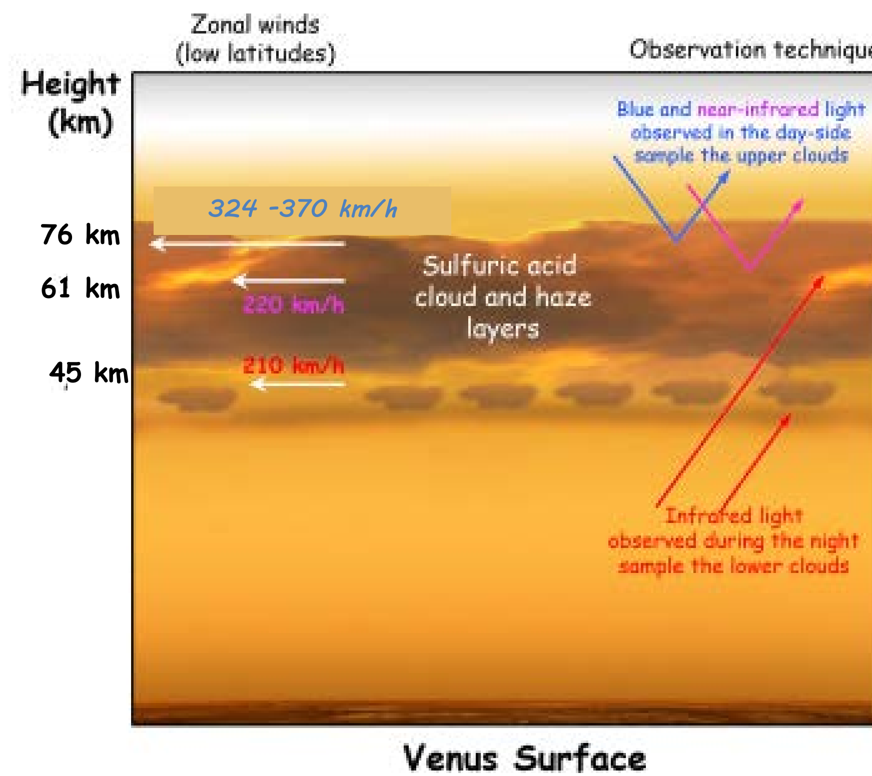


SO_x signatures not convolved with other prominent (or trace) Venus gases

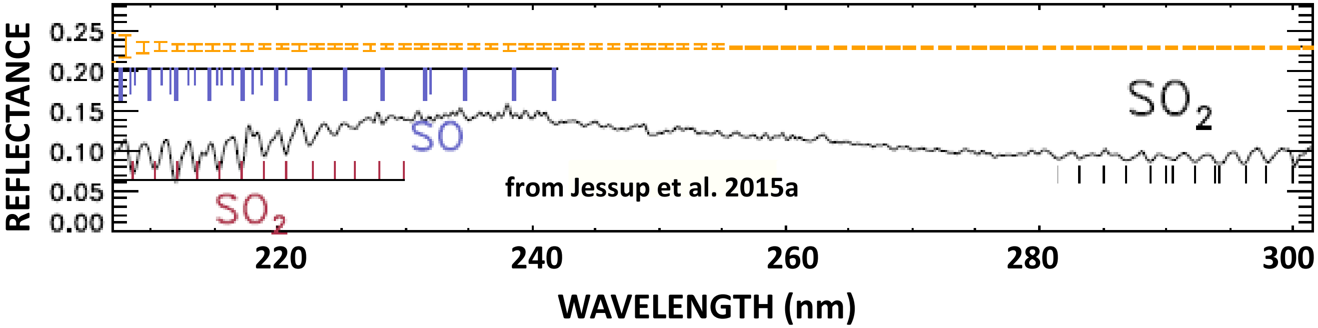
Records SO_2 and SO gases absorption originating from between 70 and 80 km

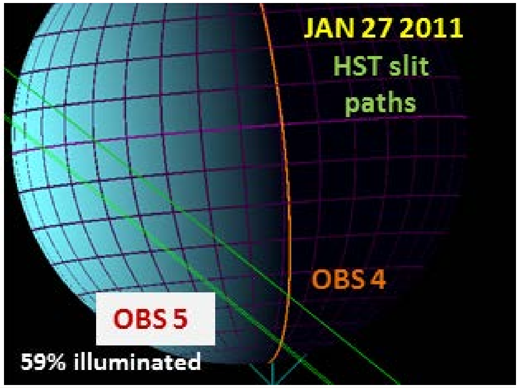
If* photolysis products can be mapped simultaneously as function of local time *then

SO_2 and SO gas distribution can be used to define relative role of photochemistry and dynamics in maintaining reservoir of parent H_2SO_4 gases at H_2SO_4 cloud altitude.



Why HST





0.1″ HST slit records gas signature between ~15 and 75±5° SZA with ~50 km/pixel spatial resolution

Currently HST is the ONLY:

- Earth-based Telescope has access to $\lambda < 280$ nm where both SO_2 and SO absorptions are seen

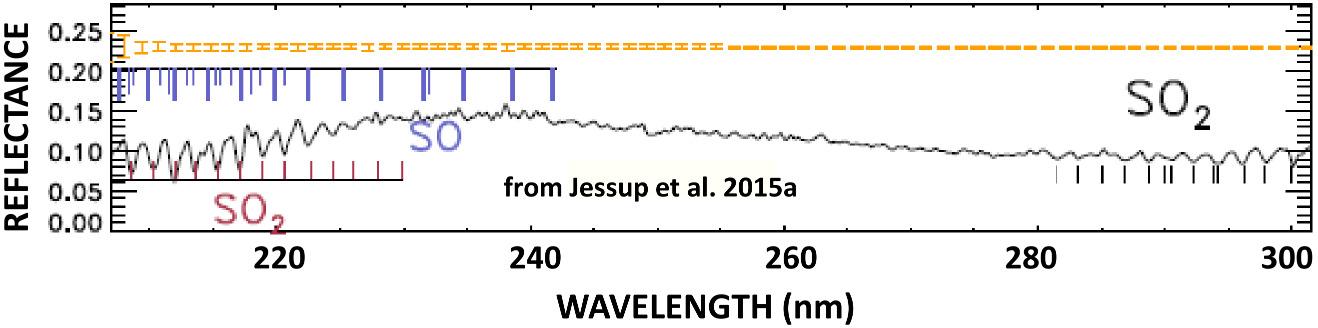
Currently ONLY HST :

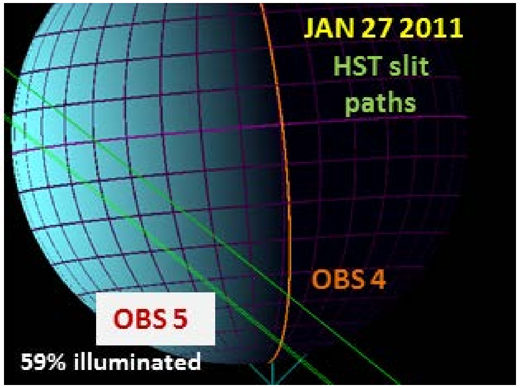
- Houses a UV spectrograph with spectral resolution required to make distinction retrievals of SO_2 and SO gases simultaneously.

During Venus Express ONLY HST :

- Had field of view adequate for documenting SO_2 and SO variation over ~60° SZA in a single exposure—so that instantaneous local time variation could be mapped

Why HST



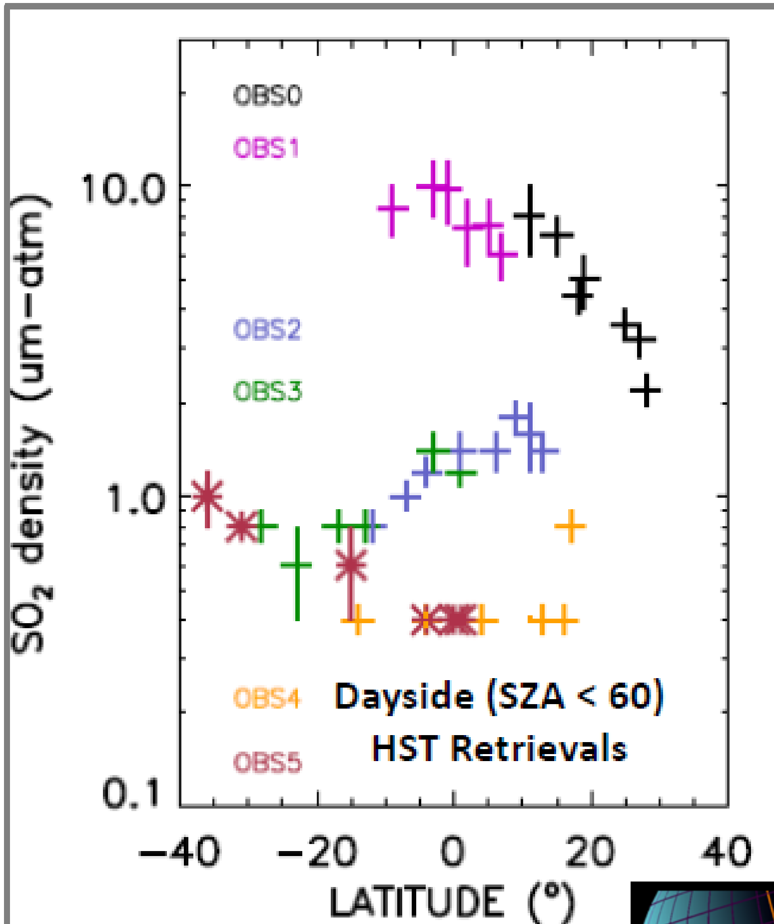


These capabilities meant that HST/STIS was the *only* instrument that could constrain SO_x photolysis process between 70 and 80 km altitude during entire Venus Express Mission.

Thus HST provided the only data that could be used to study (parameterize) the relative role of photochemistry, zonal and vertical transport between 70 and 80 km.

The coordinated HST and Venus Express HST/STIS observations were the
***first and (thus far) only* spectrally and spatially resolved observations of Venus made with Hubble Space Telescope**

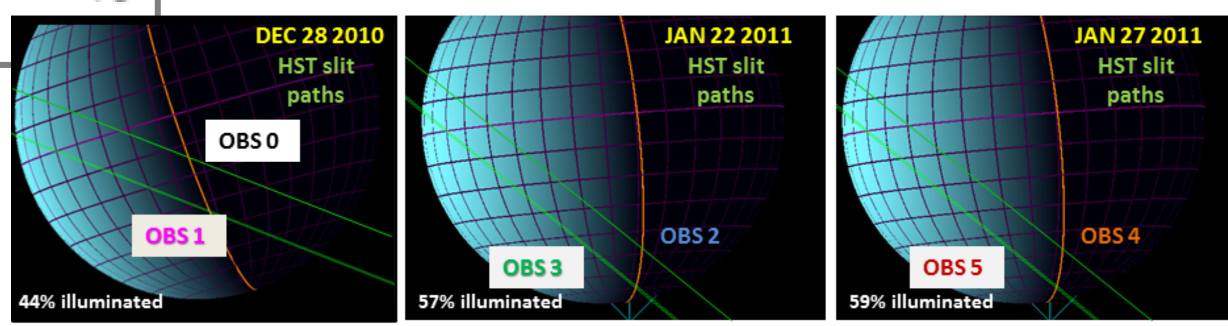
HST Results: Strong but Variable Latitudinal Gradients



- SO_2 density observed to ***decrease away from the equator***, even when factor of 5 difference in equatorial SO_2 density observed.

- ***Reversed*** SO_2 density gradient ***increasing away*** from equator was observed when equatorial density 20x lower than highest equatorial density observed

- If latitudinal gradient linked to density, must require low SO_2 densities



OBS 0: 15S, L65° DEC 28
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OBS 2: 45S, L145° JAN 22
OBS 3: 65S, L145° JAN 22

OBS 4: 45S, L160° JAN 27
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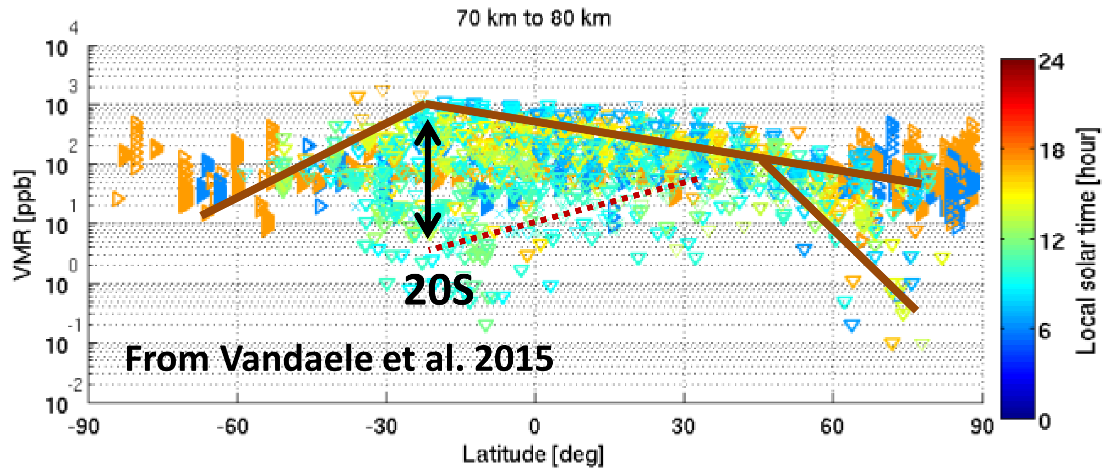
HST results relative to SPICAV

SPICAV observed SO_2 latitudinal gradient typically decreased away from equator

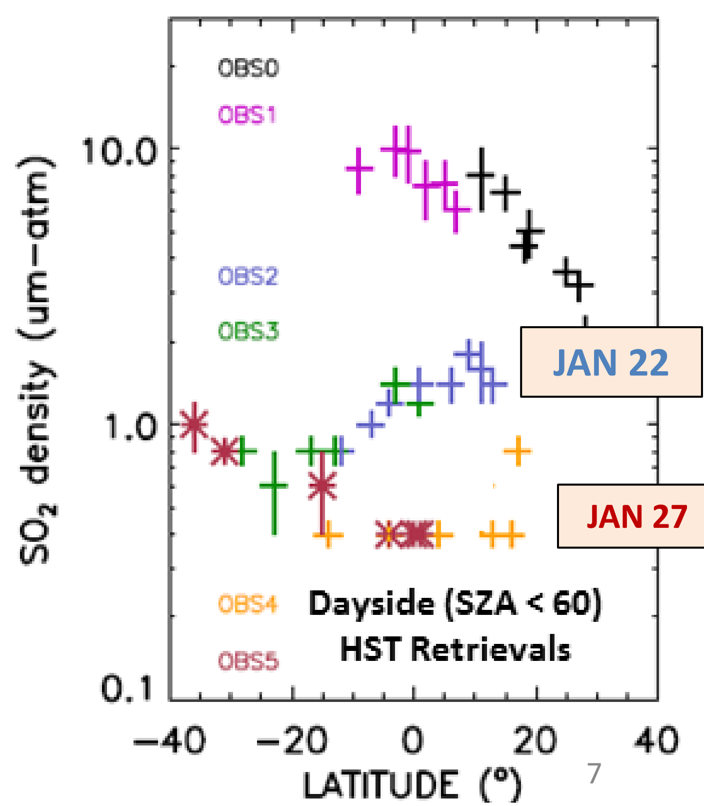
SPICAV observed latitude gradient showed sensitivity to SO_2 density



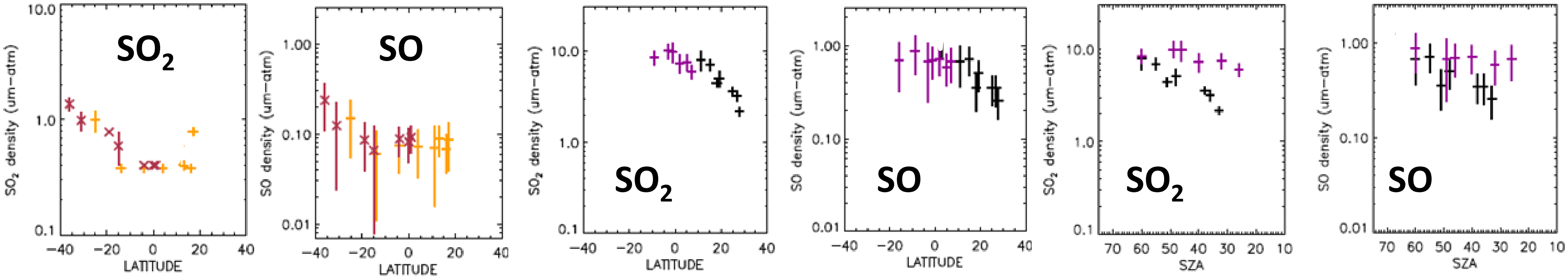
Marcq et al. model predicts:
when the equatorial SO_2 supply level is at a minimum, efficient SO_2 photolysis at low-latitudes over a 5-day period produces a reversal of typical latitudinal gradient

HST results fit pattern predicted by Marcq et al. model

Marcq et al. model implies latitudinal gradient dependent on:
SO_2 supply from lower altitudes &
relative photolysis strength as function of SZA and latitude.



HST Results: SO Latitudinal (and Local Time) Variation Mimics SO_2



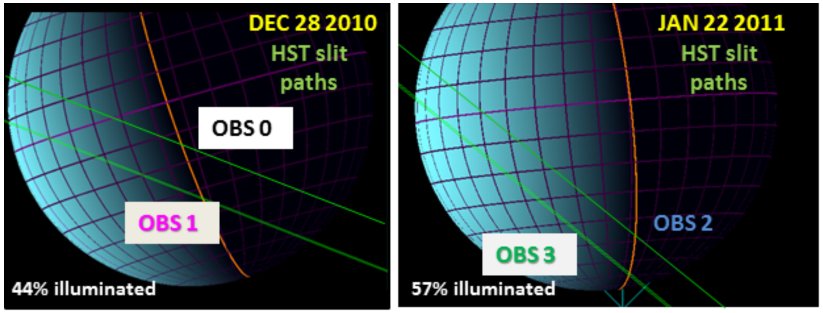
Correlation of SO_2 and SO densities between 70 and 80 km contradicts expected photochemical behavior

Correlation ***requires process other than SO_2 photolysis*** dominates (controls) relative sulfur and oxygen budget between 70 and 80 km

This means processes that control reservoir of gas species responsible for (and contributing to) H_2SO_4 formation are not well constrained

HST results provide clear empirical constraint must be meet to improve understanding of H_2SO_4 formation process.

Additional HST Local Time Variation Results



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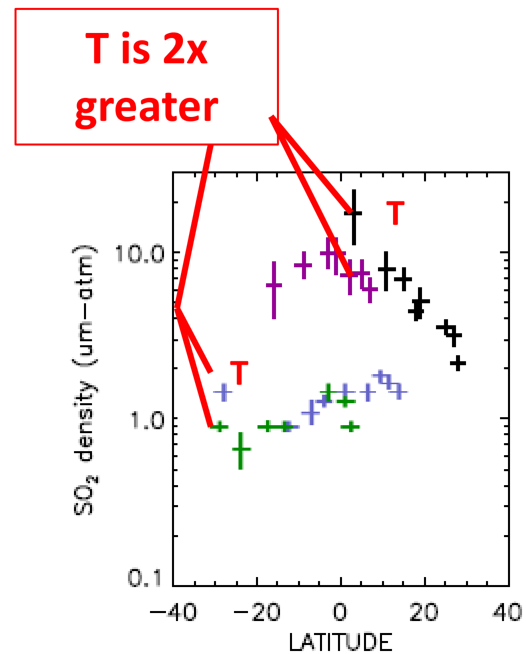
On two dates there was sufficient data to compare at a unique latitude the SO_2 retrievals derived from the near -terminator (SZA =60-75°) region and a smaller SZA.

The near morning terminator SO_2 retrievals were a factor of 2 (not 10) higher than that observed at the same latitude at smaller SZA

when

the equatorial SO_2 density was $\geq \sim 1.4$ μ-atm

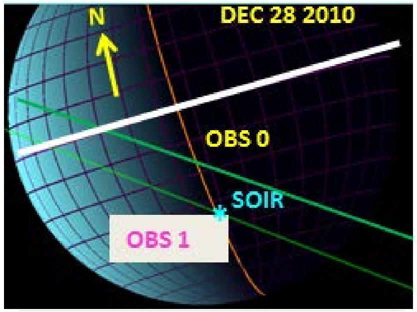
(VMR $\geq \sim 20$ ppb)



T = near-terminator

Additional HST Local Time Variation Results

Coincident HST nadir and SOIR occultation data provided the **first record of local time SO_2 density variation from pre-dawn to near-noon in the 70 and 80 km altitude region**



OBS 0: 15S, L65° DEC 28
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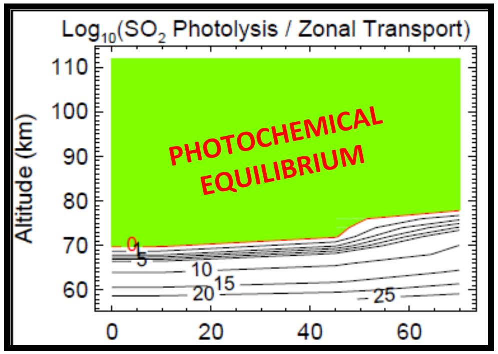
The SO_2 number density inferred from HST at ~ 7:40 LT
was equivalent to the
SO_2 density retrieved from SOIR at 78.5±3.5 km at LT ~ 5:30-6:30

This suggests the nightside SO_2 gas density was transported to the early a.m. dayside, with no significant modification to its abundance due to any chemical processing within a ~ 2 hour period

Relative roles of chemistry and dynamics in supplying parent H_2SO_4 gas species

New 1-d Photochemical modeling effort: (diurnally variant solar flux model)

Explores relative significance of zonal and vertical transport on SO_2 and SO distribution , and SO_3 formation



Indicates that zonal transport dominates over SO_2 photolysis at SZA > 55° between 60 and 78 km altitude

This ***confirms*** that the pre-dawn nightside SO_2 gas density is transported across terminator with minimal chemical processing over 2 hours between dawn and 8 a.m. local time at these altitudes

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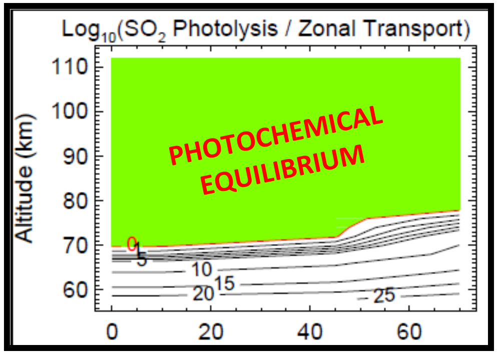

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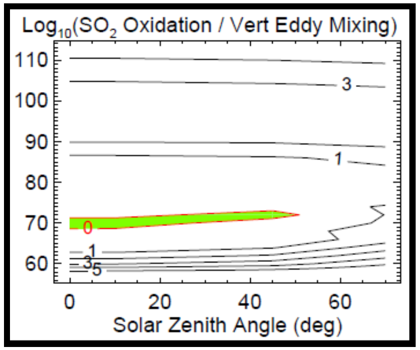

Indicates **SO_3 (and thus H_2SO_4) formation is at a minimum in the near-terminator region AT ALL ALTITUDES**; i.e., the near terminator SO_3 formation timescale is > than vertical and zonal transport timescales.

On the dayside the SO_3 (and H_2SO_4) formation is easiest at 68-74 km, but in competition with zonal transport.

i.e., vertical transport timescale>SO_3 formation timescale > zonal transport time scale, on dayside at these altitudes

Relative roles of chemistry and dynamics in supplying parent H_2SO_4 gas species

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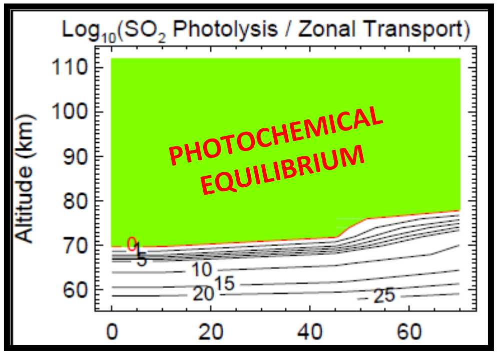

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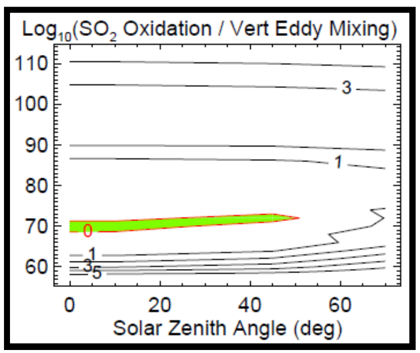

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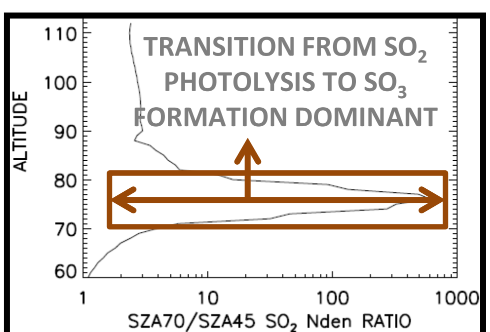


Confirms that SO_2 density near the terminator (SZA > 60°) is inflated a minimum of a factor of 2 over density anticipated at smaller SZA for altitudes >65 km

HST and Model Results Relative to Observations at Other Altitudes

Together, UV (70-80 km), submm (80-100 km) and IR (60-67 km) data indicate
inflation of SO_2 abundance at terminator *transiently* observed throughout 60-100 km region

Transience seems linked to observed SO_2 abundance

Diurnally variant 1-d model does **NOT** predict transience in terminator enhancement—SO_3 production always at a minimum SZA > 55°

In current model photolysis at high altitude always most efficient

TO ANSWER WHY TRANSIENCE OBSERVED

*****additional loss and production mechanism for SO_x must be found*****

Implies impact of microphysical processes on sulfur budget must be explored

--AND/OR--

- additional chemistry—e.g., a process that would alter O oxidation rates, changing SO_2 & SO_3 formation rates
- vertical transport—e.g., local convective cells, temperature driven eddy mixing

HST and Model Results Relative to Observations at Other Altitudes

ABOVE 80 KM:

Total sulfur present at 80-100 km based on submm greater than predicted by a simple model where SO_2 photolysis and determines sulfur budget

The combined HST and submm results indicate that SO_2 photolysis does NOT solely determine sulfur budget in full 70-100 km altitude region

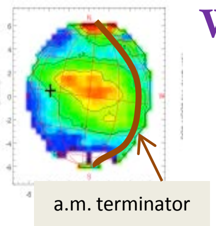
No photochemical predicts this, this is a new empirical constraint that must be met

BELOW 70 KM:

SO_2 behavior from IR data (lower adjacent altitudes) shows that SO_2 variability is high, but too rapid to result from zonal transport.

1-d model indicates SO_2 photolysis rates also too slow to explain rapid variations
Thus vertical transport/oxidation chemistry and/or microphysical processes are the likely sources

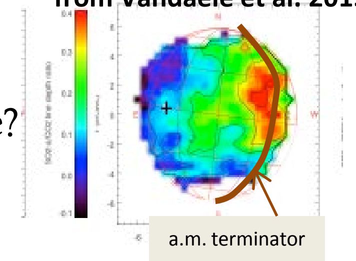
New Questions:



Why is terminator inflation transient, in each altitude regime?

i.e., what eradicates the SO_2 loss at small SZA in each altitude regime?

and/or what increases SO_2 loss at high SZA in each altitude regime?



What really determines the 70 to 80 km SO_2 abundance?

The Marcq et al. model suggests SO_2 supply from lower altitudes

the HST observations indicate an additional sulfur source (chemical/microphysical and/or dynamical) exists between 70 and 80 km

The IR data also supports that the 60 to 67 km SO_2 distribution is dependent on chemical/microphysical/ and/or dynamical SO_2 source yet to be fully studied or identified.

Considering these results together, raises these questions:

are the species responsible for balancing out the loss and production SO_x at 70 and 80 km directly upwelled from lower altitudes, and if so from how low in the atmosphere, and through what process?

--or--

--is it a fluctuation in the upward flux of SO_2 itself that determines the SO_2 density?

--or--

--is the 70 to 80 km behavior intimately linked to the 60 to 70 km region, and if so by what species/and or processes ?

in the absence of in-situ observations, contemporaneous UV and IR observations of both altitudes are needed to further study these questions

- **How does the p.m. quadrant behave as function of local time, especially at the terminator?**

The NEW1-d photochemical model implies the SO_2 density at high SZA should reflect gas behavior at earlier local times. For the a.m. terminator, this means the nightside, for the p.m. terminator this means early afternoon.

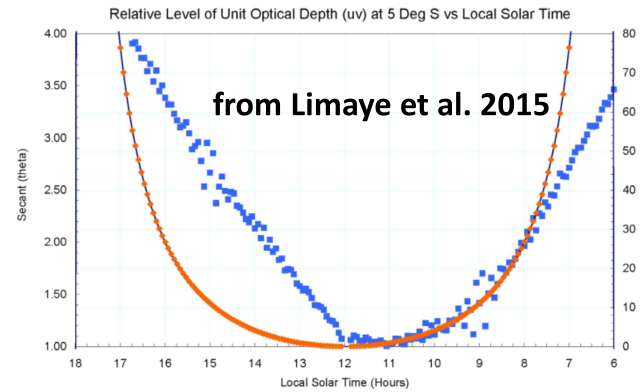
-- are the predicted differences observable on the p.m. quadrant

-- what can differences between a.m. and p.m. quad tell us about relative importance of zonal transport and vertical transport of SO_2 and/or species that control the SO_2 distribution?

FUTURE Observing Plans:

Observing Venus P.M. Quadrant

VMC shows haze local time behavior not the same on a.m. and p.m. quadrants



Pioneer Venus also showed that a.m. and p.m. terminators haze not the same (Esposito et al. 1983)

Photochemical model predicts relative chemical and zonal transport behavior at high SZA that should produce differences in the gas distribution on a.m. and p.m. terminators

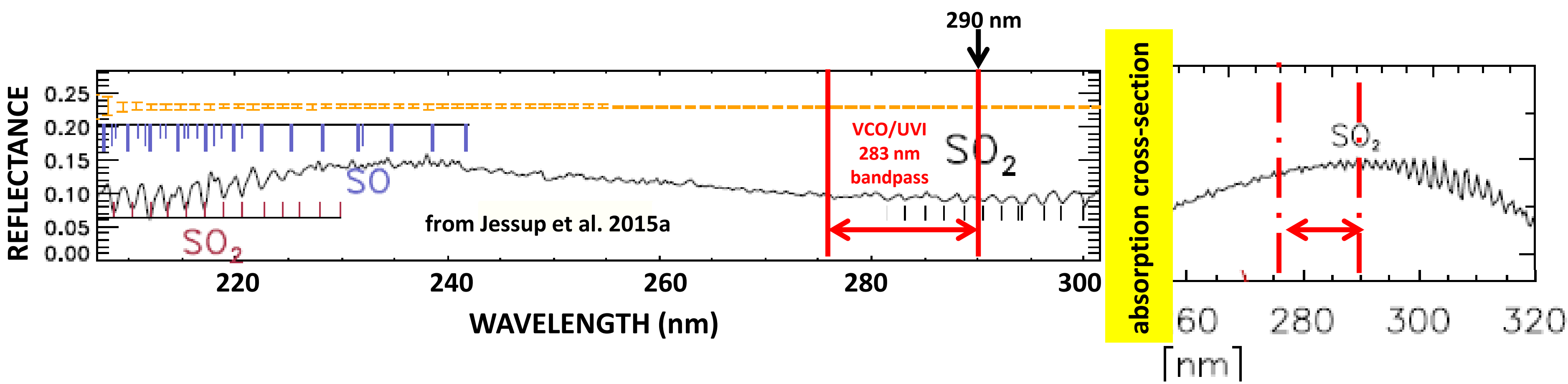
must OBSERVE to know if true

Previous observations obtained on 5 day periodicity bore much fruit
Want to repeat similar periodicity on PM quad for 2 or 3 rotation cycles

FUTURE Observing Plans: *Coordination with AKATSUKI*

Coordinated HST and AKATSUKI observations strengthens science return of both

The VCO bandpass extends from 276 to 290 nm, which is challenging:



HST/STIS spectral resolution, can be used to cross-calibrate UVI 283 nm SO_2 retrievals.

During the HST/STIS observing window can observe every 4.4 days, plan to observe for 3 rotation cycles to align with 9 day AKATSUKI orbit period, and Venus orbit period, v_{zonal}=~100 m/s

AKATSUKI will provide long term monitoring results, that can contextualize new HST observations

FUTURE Observing Plans:

Coordinated Ground Based Observing

Provides increased altitude sampling of SO_2 (submm, and IR), H_2O/HDO (IR/submm) and H_2SO_4 (submm)

this extends the degree to which models of the sulfur cycle and H_2SO_4 formation can be validated/constrained/parameterized.

Coincident observations without temporal disparity from directly adjacently lower altitudes may provide a straightforward way to study how SO_2 variability between 70 and 80 km is linked to fluctuation of SO_2 supply from below, and/or the fluctuation of SO_2 reservoir source/controller from below.

Coordinated High Altitude Balloon Observing

Near future: can provide opportunity to observe across the terminator in two altitude regimes (UV:65-80 km, IR:30-40 km), potentially allowing to study/parameterize chemical and vertical mixing links between regions

OBSERVATIONS DURING AKATSUKI mean data taken while zonal wind field WELL measured

Far future: can open up 200-240 nm region from the ground

Summary

HST observations provide detailed measurement of the latitude and local time variation of Venus' SO_x products between 70 and 80 km, these data:

- Show that the SO_x products have strong latitudinal gradients & are correlated in spatial distribution
- Allowed an empirical study of relative roles of photochemistry, vertical and zonal transport

New modeling efforts by Jessup et al. 2015 and Marcq et al. 2013 indicate:

- The SO_2 abundance between 70 and 80 km impacted by influx of SO_2 (or SO_2 controlling species) from lower altitudes
- latitude gradient dependent on SO_2 supply from lower altitudes & relative photolysis strength as function of SZA and latitude.
- The correlation of the SO_2 and SO gas distribution contradicts expectations for a system where SO_2 photolysis determines the sulfur and oxygen budget
- Transience in the inflation of the SO_2 terminator density is contrary to a system where SO_2 source and loss mechanisms are dependent primarily on SO_2 photolysis and SO_3 oxidation
- Zonal transport should dominate in the near terminator region between 60 and 80 km.
- Rapid variations observed between 60 and 67 km are not consistent with currently expected photolysis times scales

Consideration of the HST UV observations with available submm and IR data implies that microphysical processes are a likely source for the vertical and local time gas distributions detected between 60 and 80 km, but vertical mixing, and other oxidation processes also need to be explored.

Observations obtained at multiple wavelengths could help to further explore/resolve relative roles of vertical transport and alternate chemistry in maintaining observed vertical and latitudinal SO_2 gas distributions.

Coincident and coordinate observations made at multiple wavelengths would improve our understanding of the sulfur-cycle and its role in the H_2SO_4 formation process.

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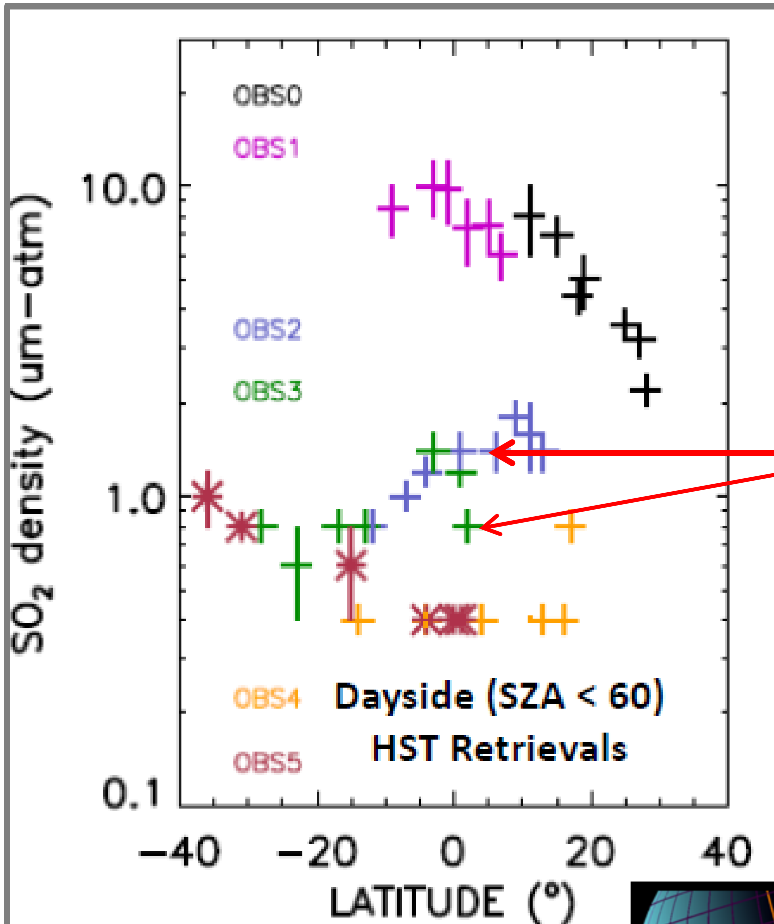
Extras follow

HST Results: Strong but Variable Latitudinal Gradients

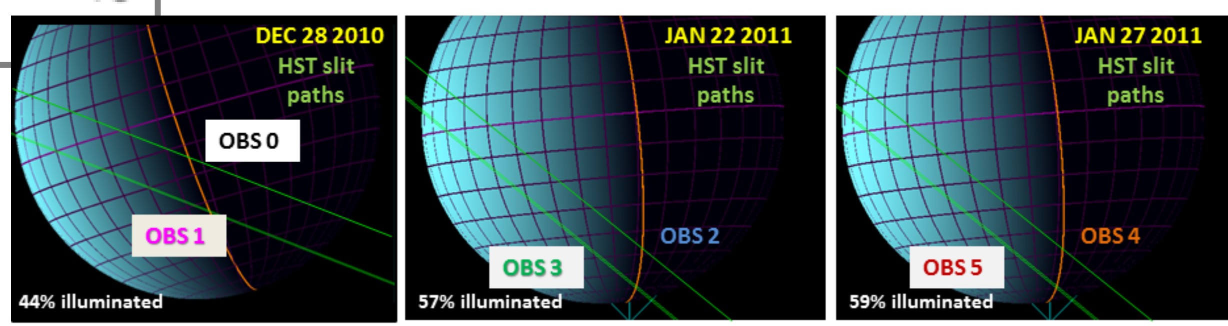


limited local time sensitivity

On each date, for most latitudes 2 local times were observed.

On the ***dayside (i.e. SZA=0-60 °)***, the SO_2 density retrieved at each latitude was insensitive to the observed SZA--**except** at the equator, where a sensitivity to small (<20° SZA) was evident

The SO_2 density at the equator at small SZA 2x < than observed at 20 ° < SZAs <60 °



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HST can distinctly observe spectral signature of the unknown UV absorber allowing for a unique solution for the most likely refractive index for the unknown UV absorber :