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Sulfur Dioxide in the Atmosphere of Venus

II. Modeling Results

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We have analyzed the results from the UV sounding rocket observations of Venus made on 15 September 1988 and 29 March 1991 which obtained high-resolution spectra of Venus clouds from 190 to 230 nm. The albedo of Venus in this wavelength range is dominated by absorption features of sulfur dioxide and sulfur monoxide. We estimate that the mixing ratio of SO_2 above the clouds of Venus is 80 ± 40 ppb for 1988 and 120 ± 60 ppb for 1991. The scale height of SO_2 at the same altitude region is 3 ± 1 km for both 1988 and 1991. These numbers are in good agreement with both Pioneer Venus and IUE observations made around the same time period, and indicate that no large change in SO_2 above the clouds occurred from 1982 to 1991.

In addition, the SO mixing ratio above the clouds derived from the 1991 observations is 12 ± 5 ppb, and the scale height of SO above the clouds is close to that of the bulk atmosphere. Our analyses indicate that the mixing ratio of SO decreases sharply below the 64-km level, which is in good agreement with the photochemical models.

The mixing ratio of SO_2 at the cloud top level derived from the 1988 observation ranges from 60 ± 30 ppb at the equator to 300 ± 150 ppb near 50°S. The scale height of SO_2 at the cloud top region ranges from about 3–4 km at the equator to ~2 km near 50°S. Venera 15 observations show similar latitudinal variation of SO_2.

INTRODUCTION

SO_2 was first detected in the atmosphere of Venus by Barker (1979) with groundbased observations, and it was subsequently confirmed by Stewart *et al.* (1979) and Conway *et al.* (1979). These observations indicated that the abundances of SO_2 in 1978–1979 period were larger than the previously established upper limits (Owen and Sagan 1972) by an order of magnitude. Continuous observations by Pioneer Venus from 1978 to 1986 showed a steady decline in the cloud-top SO_2 abundance toward values consistent with previous upper limits (Esposito *et al.* 1988). This decline has been confirmed by IUE observations (Na *et al.* 1990). Explanations that have been advanced for the observed decline of SO_2 include active volcanism and changes in atmospheric dynamics.

The episodic nature of the change in SO_2 abundance led Esposito (1984) to conclude there was a significant injection of SO_2 into the Venus middle atmosphere prior to Pioneer Venus arrival at Venus. Esposito suggested the buoyant thermal flux from an immense volcanic eruption as a natural physical mechanism for the injection. The case for active volcanism in Venus' geologic past is supporting by a number of arguments, including (i) the Magellan orbiter observations of numerous volcanic features such as domes and lava flows (e.g., Head 1991); (ii) detections by both Pioneer Venus and *Galileo* of strong radio signals, suggested widespread and recurring lightning on Venus, particularly lightning associated with the mountainous regions (Ksanfomaliti 1980, Scarf *et al.* 1980, Gurnett *et al.* 1991); and (iii) decline of SO_2 at the cloud-top region of Venus observed by Pioneer Venus and IUE (Esposito *et al.* 1988, Na *et al.* 1990).

However, the evidence of lightning associated with mountainous regions on the planet's surface has been challenged by Taylor and Cloutier (1986), who suggested that SO_2 variation could be explained in terms of changes in atmospheric circulation. This explanation for the decline in SO_2 abundance had been considered by Esposito (1984) but rejected on the grounds that the time scale for atmospheric phenomena at the cloud tops is on the order of months, while the inferred injection event had a time scale of decades.

Based on the analysis of Pioneer Venus Cloud Photo-Polarimeter (OCPP) data, Del Genio and Rossow (1989) suggested that the cloud level dynamics may be cyclic with a time scale of 5–10 years. In addition, Clancy and Muhleman (1991) showed a similar time scale for the change in CO mixing profiles in the mesosphere of Venus. They suggested that the variation of CO and the decline

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of SO_2 are related phenomena and that the decline of SO_2 could be explained without invoking active volcanism.

Furthermore, the changes in SO_2 above and within the clouds of Venus may have a significant effect on the photochemistry of the clouds of Venus. Pioneer Venus observations have shown that the clouds of Venus are created by the photochemical processes that oxidize upwelling SO_2 (Winick and Stewart 1980, Yung and DeMore 1982). Thus, any significant changes in SO_2 may have an effect on the chemistry and dynamics of the clouds.

In this paper, we have analyzed the results from two sounding rocket observations of Venus made in the wavelength range 190–230 nm (McClintock *et al.* 1994; hereafter Paper I). Our objectives are (1) to extend the time base of observations to look for changes in SO_2 abundance in the Venus atmosphere, (2) to observe Venus with a high spatial resolution to study the horizontal variations of SO_2 above the clouds, (3) to provide a check on the results of Pioneer Venus and IUE by making independent measurements of SO_2 abundance, and (4) to search for other UV absorbers such as SO, OCS, and CS_2 which are important in constraining the photochemical studies of Venus atmosphere.

OBSERVATIONS

Rocket observations of Venus were made on 15 September 1988 and 29 March 1991. Figure 1 and Table 2 in Paper I summarize the parameters for both the 1988 and the 1991 observations. The rocket payload consists of a Cassegrain type telescope and an Ebert–Fastie spectrograph equipped with a CODACON microchannel plate detector. The detector has 1024 elements and provides a spectral coverage of approximately 375 Å with a spectral resolution of 2 Å. A detailed description of the spectrograph performance can be found in McClintock *et al.* (1982, 1994).

Pointing of the rocket telescope is accomplished by a star tracker located in front of the secondary mirror of the telescope. The star tracker points the telescope to within 1 to 2 arcmin of the target, and more precise pointing (1–2″) is achieved by an internal motion compensation system. The 1988 observations included a succession of spatially resolved spectra of Venus. In 1991, data were taken from a single pointing centered on the equator of Venus (see Paper I).

ANALYSIS

Model Procedure

The model atmosphere of Venus, which is based on the groundbased and Pioneer Venus observations, is composed of CO_2 gas and sulfuric acid aerosols which are mixed uniformly with the gas from about the 50- to the 80-km level. The aerosols have a radius of ~ 1 μm and are assumed to have a single scattering albedo of 0.98 (Kawabata and Hansen 1975). In addition, a pure absorbing layer with an optical depth of 0.2 is added at an altutide of 75 mbar (Esposito *et al.* 1979). Then, absorbers such as SO_2 and SO are added to the clear atmosphere with distributions given by two parameters, the mixing ratio and scale height at the cloud top (40 mbar). Table I lists the range of values for the parameters used in the present analysis.

TABLE I

Model Parameters Used in the Analysis

SO_2 mixing ratio (ppb)	SO mixing ratio (ppb)	SO_2 scale height (km)
12.5	1.25	1
25	3.125	2
50	6.25	3
100	12.5	4
125	25	5
250	50	
500		
1000		

After the absorbers are added to the model atmosphere, the optical depth, single scattering albedo, and Rayleigh scattering fraction are calculated at each wavelength. These values are then used with a multiple scattering radiative transfer code based on the Markov chain method (Esposito and House 1978, Esposito 1979) to calculate the model brightness. The model spectra are calculated at 2-Å intervals, which is the effective wavelength resolution of the rocket spectrograph. We derived the mixing ratio and the scale height of SO_2 by choosing the models that minimize the root mean square (rms) differences between model spectra and the rocket data.

Observing Geometry

As shown in Fig. 1 of Paper I, the entrance slit covers the entire length of the disk of Venus in one dimension; therefore, the flux reaching the detector is from an entire latitudinal zone of Venus. Within that latitudinal zone, the solar zenith angles and the observation angles vary greatly. Thus, modeling of this flux through the slit involves dividing the latitudinal zone of Venus into small areas where the observing geometry is assumed to be constant. At the center of each area, the local solar zenith angle and the observation angle are calculated and are used in the model calculation. The brightness for the entire latitudinal zone is the average of the brightnesses calculated at the center of the small areas.

Rapidly varying geometry near the limb introduces uncertainty, and it can be reduced by making each area small enough. To determine the optimum number of areas, we track the difference in brightness (I/F) caused by each finer subdivision:

$$\left(\frac{I}{F}\right)_N - \left(\frac{I}{F}\right)_{N-1} < \varepsilon,$$

where

$$\left(\frac{I}{F}\right)_N = \frac{\sum_{i=1}^{N} (I/F)_i}{N}.$$

$(I/F)_N$ is the brightness for the entire latitudinal zone calculated with N number of areas. The calculation is repeated until the difference (ε) between $(I/F)_N$ and $(I/F)_{N-1}$ becomes less than 10^{-5}.

The entrance slit used for the 1991 observation was wider than the slit used for the 1988 observation. Combined with the smaller angular diameter (13″) of the disk of Venus at the time of observation, the entrance slit projected a much larger area on the disk of Venus. Since the slit covered more than 20° in latitude of Venus, we divided the equatorial area of Venus projected by the slit into three strips, and on each of these three strips we repeated the analysis as described above. The model brightness for the observation is obtained by averaging the brightness from all three strips.

RESULTS

Cloud Top Abundance of SO_2

The derived global mixing ratio of SO_2 at the cloud tops was 80 ± 40 ppb for September 1988. For the 1991 observations, the derived SO_2 mixing ratio is 120 ± 60 ppb. The error estimates given above include the systematic error resulting from the absolute calibration uncertainties (see Paper I). The average scale height of SO_2 at the cloud top was 3 ± 1 km for the 1988 observation, and the scale height of SO_2 derived from the 1991 observation is also 3 ± 1 km.

The mixing ratio and scale height of SO_2 in 1988 represents the average value from all latitudes, and the values for the 1991 observation is from the ±15° of the equator. Nevertheless, the SO_2 abundance derived from two separate rocket experiments agrees well with the results from Pioneer Venus (Esposito *et al.* 1988) and IUE observations (Na *et al.* 1990) made around the same time.

As shown in Fig. 1, the SO_2 mixing ratios derived from four different instruments show remarkably good agreement: they all overlap within their their respective error bars. It is clear from Fig. 1 that the SO_2 abundance above the clouds has not experienced any large change from 1982 to 1991, and the mean abundance of SO_2 above the clouds is around 100 ± 20 ppb.

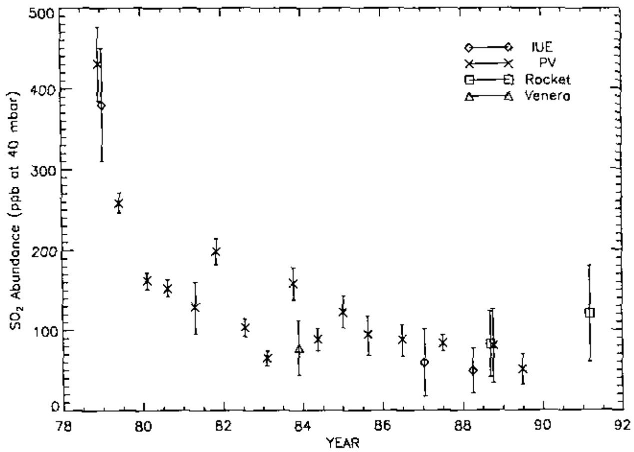

FIG. 1. SO_2 mixing ratios above the clouds of Venus derived from Pioneer Venus, IUE, and Venera-15 are plotted along with the values from the sounding rocket observations made in 1988 and 1991. These four different observations show good agreement.

Vertical Profile of SO

Figure 2 shows comparison of the best fit models to the 1991 rocket spectrum. As seen in the figure, the model that includes SO and SO_2 is a much better fit than the model containing just SO_2. Since SO absorption features are embedded within the prominent SO_2 absorption features, a detailed modeling of a SO profile requires the data to have a high spectral resolution and a high signal to noise ratio (SNR). The SNR of the rocket data is much higher than that of Pioneer Venus and IUE, due to higher sensitivity and greater dynamic range of the rocket instrument. This high SNR of the rocket data together with a high spectral resolution allowed a much more detailed analysis of the SO profile in the Venus atmosphere.

In the analysis of IUE data (Na *et al.* 1990), SO was limited to the top 10 layers in the model atmosphere and was assumed to be well mixed with the atmosphere. In the present analysis, the number of layers that contain SO was varied, as was its mixing ratio and scale height at 40 mbar. First, we put SO in the top 10 layers in the amount determined by the mixing ratio and the scale height at 40-mbar level. Next, we increased the number of layers containing SO, and at each increment, we varied the mixing ratio and the scale height of SO. The best fit to the data was obtained when the model atmosphere had 12 ppb of SO with its scale height close to that of the bulk atmosphere down to about 64 km in altitude. Thus, we conclude that SO is well mixed with the atmosphere above ~64 km, and below 64 km, the mixing ratio of SO is greatly diminished. Figure 3 shows the derived vertical profile of SO from the 1991 observations along with the

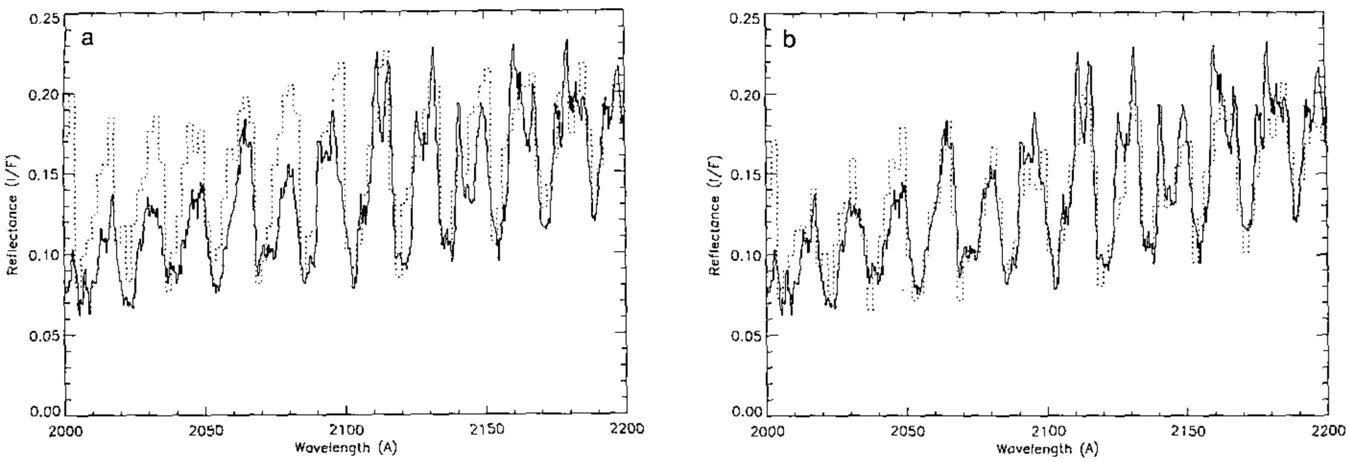

FIG. 2. The 1991 rocket spectrum is plotted with a model containing 100 ppb of SO_2 (a) and a model containing 100 ppb of SO_2 and 12.5 ppb of SO (b). The model with SO gives a much better fit to the data.

vertical profiles of SO from photochemical models by Winick and Stewart (1980) and by Yung and DeMore (1982). It shows that the derived SO profile is in good agreement with the models. The SO mixing ratio of 12 ± 5 ppb above 64 km level is in good agreement with the value derived from the IUE observation (Na *et al.* 1990), and it is also consistent with the upper limits established from goundbased observations by Wilson *et al.* (1981).

Latitudinal Variation of SO_2

The rocket observation carried out in September of 1988 made a vertical scan of the disk of Venus in subarcsecond steps. The derivation of SO_2 abundance was carried out for each of the steps by direct comparison with the model spectra. As shown in Fig. 4, there is a sizable variation in the abundance and scale height of SO_2 with latitude. The SO_2 mixing ratio is at a minimum near the equator (60 ± 30 ppb) and increases with latitude in both directions (300 ± 150 ppm at 50°S). The scale height of SO_2, on the other hand, decreases with latitude from about 4 km near the equator to ~2.5 km near 50°S.

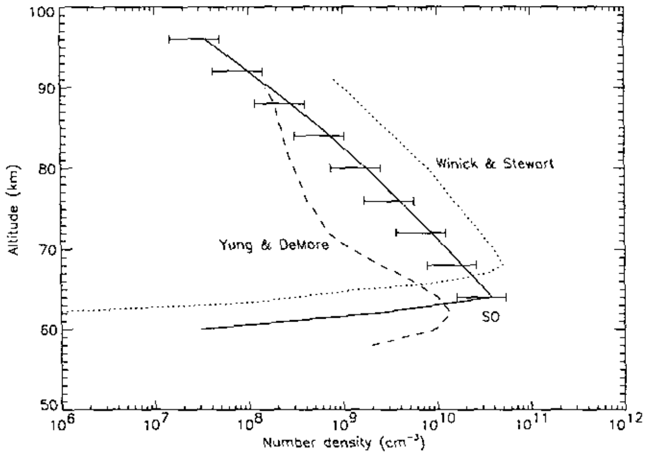

FIG. 3. The vertical profile of SO derived from the 1991 observations is plotted with the predicted vertical profiles of SO from photochemical models by Winick and Stewart (1980) and Yung and DeMore (1982).

We note that the derived value of the SO_2 mixing ratio at high latitudes could be influenced by uncertainty in the pointing of the telescope. However, it is estimated that the pointing was accurate to ~0.4″ during the flight. This small pointing error has negligible effect on the drived amount of SO_2 at low latitudes (<40°). Even at high latitudes, a pointing error has to be much greater than 0.4″ for it to have a significant effect on the derivation of the SO_2 abundance. In Fig. 5, the brightness of Venus at 2100 Å is plotted against latitude along with five models. The models have different SO_2 mixing ratios, but the scale height was fixed at 3 km. As seen in the figure, the data within 40° latitude are well matched by the models that have 50 and 100 ppb of SO_2, whereas the data between 40° to 60° lie between models that have 250 and 500 ppb of SO_2. It is clear from the figure that the latitudinal variation of SO_2 cannot be explained by errors in pointing alone.

As was seen in Fig. 4, the latitudinal variation of the mixing ratio of SO_2 and its scale height seems to be anticorrelated. At low latitudes, the scale height of SO_2 is at maximum while the mixing ratio is at a minimum. The variation of SO_2 above the clouds may be due to differences in atmospheric mixing above the clouds. The larger scale height of SO_2 around the equatorial region indicates that atmospheric mixing is more vigorous there than at the mid latitude region.

Comparison with Venera-15 Observations

The Fourier spectrometer on board Venera-15 made the first detection of SO_2 in the infrared spectral region

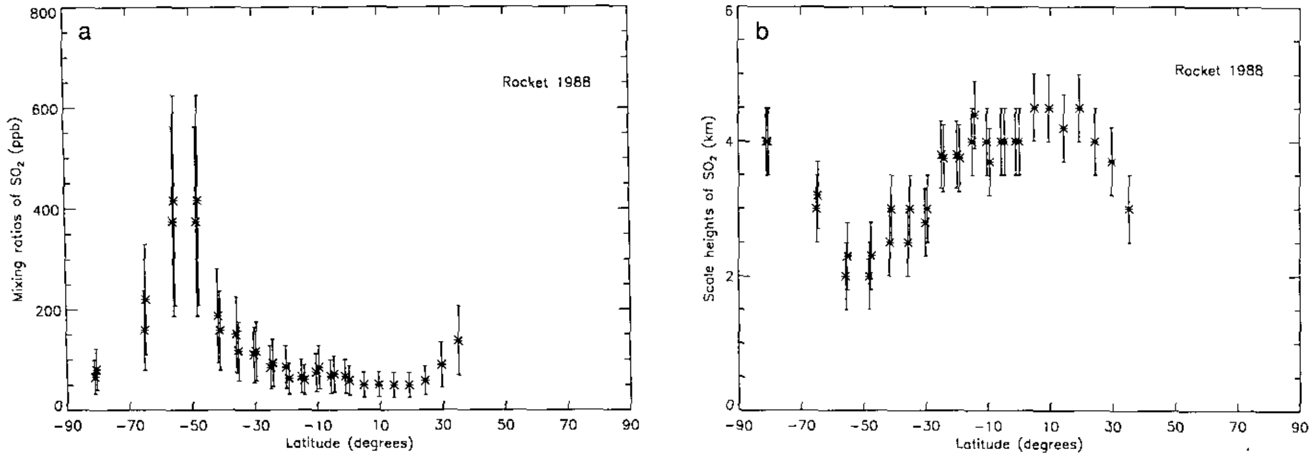

FIG. 4. Mixing ratio and scale height of SO_2 derived from the 1988 rocket observation are plotted against latitude. The SO_2 mixing ratio at mid-latitude is much higher than at other latitudes, and the scale height of SO_2 shows an opposite trend.

from the spacecraft (Zasova *et al.* 1993). The Venera-15 spacecraft arrived at Venus in September 1983; the standard observing session lasted from October 12, 1983, to December 14, 1983. The infrared measurements were made along the viewing tracks which started at low latitudes, went through the north pole, and finished at low latitudes again. More than 1500 spectra were obtained for latitudes from 65°S to 87°N. There was one session with a special (nonnominal) spacecraft orientation, when the nadir observations of the equator were conducted (Zasova *et al.* 1993).

The IR observations by Venera-15 probe the altitude region from 58 to 72 km, depending on cloud scale height and SO_2 scale height. Thus, the results from this infrared experiment can be compared to the UV rocket observations which are sensitive above the clouds. Figure 6 shows the mixing ratio and scale height of SO_2 derived from the Venera-15 observations, along with the results from our rocket observations. The results from both UV and IR observations were binned into latitudinal bins that are 15° wide to reduce the scatter in the data. As seen in the figure, both the IR and UV data show a large variation of SO_2 abundance with latitude. The variation of SO_2 seen in the IR data is even higher than seen by UV observations. The mixing ratio of SO_2 derived from the IR observations increases from about 20 ± 10 ppb in the equatorial region to about 400 ± 100 ppb at high latitudes.

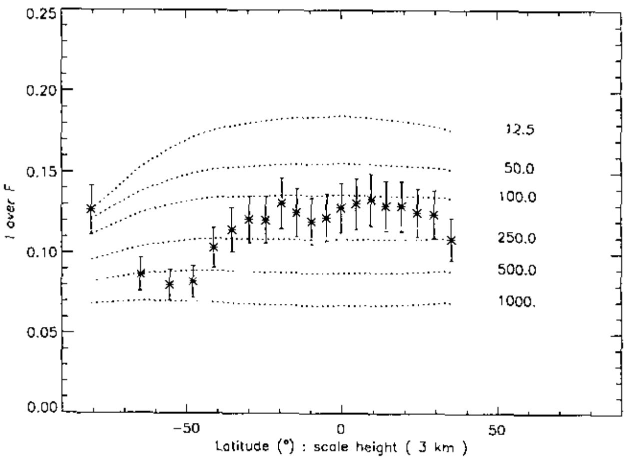

FIG. 5. Rocket reflectances at 2100 Å are shown in solid lines. Dotted lines are model reflectances at 2100 Å that were calculated with different mixing ratios of SO_2 with the scale height fixed at 3 km. It is clear that the horizontal variation is not due to pointing errors.

The difference in mixing ratio of SO_2 between UV and IR observations may result from uncertainty in the absolute flux calibration for both experiments and the fact that the observations are separated by about 6 years in time. However, the general dependence of SO_2 mixing ratio with latitude is similar for both UV and IR observations. On the other hand, the scale height of SO_2 derived from the UV and the IR observations show opposite behavior. The differences in scale height of SO_2 between the two experiments may be due to the different vertical profile of the cloud aerosol used in the model calculations. For UV model calculations, the aerosol is assumed to be mixed uniformly with the bulk atmosphere at all latitudes. For the IR observations, the scale height of cloud aerosols was measured by Venera-15, and it was used in deriving the SO_2 mixing ratio and scale height. Venera-15 saw a significant variation in cloud aerosol scale height at high latitudes (Zasova *et al.* 1993). Thus, the differences in SO_2 abundance from UV and IR observations may be an indication that the Venus atmosphere is considerably more complex than the two-parameter model atmospheres used in the present analyses.

Now that the Pioneer Venus is no longer operational

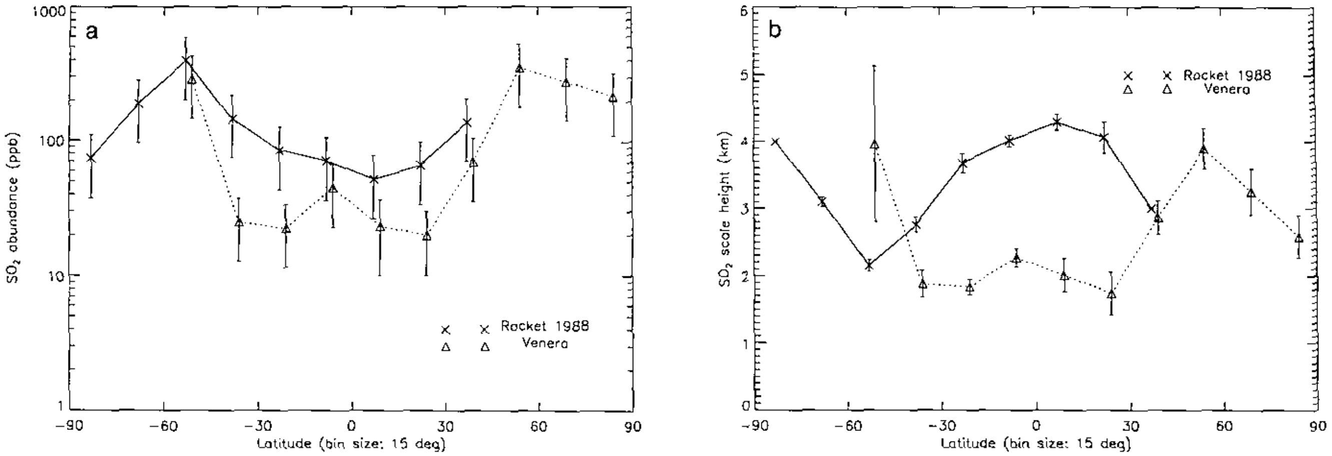

FIG. 6. SO$_2$ mixing ratios and scale heights derived from Venera-15 and the sounding rocket observations are plotted against latitude. The results are binned in 15° bins to reduce the scatter in the data.

and IUE and HST are limited to observing Venus at greatest elongations, the only platform capable of regularly monitoring the UV absorbers in the Venus atmosphere is a sounding rocket. SO$_2$ and SO are important indicators of cloud-top dynamics, chemistry, and possibly surface geological activity on Venus as well. Regular observations are vital in documenting any long-term changes in SO$_2$ and SO above the clouds of Venus and in understanding the physical mechanism responsible for the change.

CONCLUSION

The mixing ratio of SO$_2$ at the cloud top of Venus, derived from rocket observations made on 15 September 1988 and on 29 March 1991, is 80 ± 40 and 120 ± 60 ppb, respectively, and the scale height of SO$_2$ is 3 ± 1 km. The mixing ratio of SO above the cloud derived from the 1991 observation is 12 ± 5 ppb above the clouds. The scale height of SO is nearly the same as that of the bulk atmosphere, and the mixing ratio of SO decreases below the 64-km level. The derived mixing ratios and the scale height of SO$_2$ and SO are in good agreement with results from Pioneer Venus, IUE, and Venera-15 observations.

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