

Reports

Sulfur Dioxide: Episodic Injection Shows Evidence for Active Venus Volcanism

Abstract. *Pioneer Venus ultraviolet spectra from the first 5 years of operation show a decline (by more than a factor of 10) in sulfur dioxide abundance at the cloud tops and in the amount of submicron haze above the clouds. At the time of the Pioneer Venus encounter, the values for both parameters greatly exceeded earlier upper limits. However, Venus had a similar appearance in the late 1950's, implying the episodic injection of sulfur dioxide possibly caused by episodic volcanism. The amount of haze in the Venus middle atmosphere is about ten times that found in Earth's stratosphere after the most recent major volcanic eruptions, and the thermal energy required for this injection on Venus is greater by about an order of magnitude than the largest of these recent Earth eruptions and about as large as the Krakatoa eruption of 1883. The episodic behavior of sulfur dioxide implies that steady-state models of the chemistry and dynamics of cloud-top regions may be of limited use.*

Venus is entirely shrouded in highly reflective clouds, featureless at visible wavelengths. In the ultraviolet, dark markings are seen; these markings show the location of upwelling SO_2 , which sunlight converts into cloud particles (1, 2). The chemistry of the production of the Venus clouds is thus plainly visible. The missing solar photons that make the dark markings dark at wavelengths of 2000 to 3200 Å are those that drive the conversion of SO_2 to H_2SO_4 .

The cycle of cloud formation on Venus bears many similarities to the production of acid rain on Earth (3). Nonetheless, several unresolved puzzles remain. One

is the recent discovery of SO_2 in the Venus atmosphere (4) by several observers independently over a period of several months in 1978. The measured amounts of SO_2 exceeded by orders of magnitude earlier upper limits (5). A second puzzle was the observation by the Pioneer Venus orbiter of an extensive haze of submicron particles overlying the planet (6). The absence of such particles in the late 1960's was shown convincingly by polarimetric analysis (7). It has been difficult to reconcile the diverse observations with photochemical models (8). Presumably unrelated to these puzzles are several arguments im-

plying recent volcanic activity on Venus: topographic features (9), lightning (10), and geochemical evidence (11).

Observations of the Venus cloud tops made by the Pioneer Venus orbiter from 1978 to 1983 show a steady decline in the amount of both SO_2 and haze toward pre-1978 upper limits. I conclude that the explanation of this phenomenon was a single injection of SO_2 into the Venus middle atmosphere prior to the Pioneer Venus encounter in 1978. The absence of any similar Venus phenomena from the late 1960's through the mid-1970's and the observation of a similar phenomenon in the late 1950's (12) implies a time scale of several decades. A natural physical mechanism for this injection is major volcanic activity on the surface.

The Pioneer Venus orbiter has been in Venus orbit since December 1978 (13). The ultraviolet spectrometer of the orbiter regularly takes spectra of sunlight reflected from the planet in the wavelength region from 1100 to 3500 Å (14). These spectra are inverted to yield the SO_2 abundance and vertical distribution at the time of observation in the following way (15).

The instantaneous observing geometry and Venus brightness are extracted from each spectrum for wavelengths of 207 and 237 nm. The average SO_2 absorption coefficient averaged across the instrument bandpass differs by a factor of 100 at these two wavelengths (16). This difference allows inference of both abundance and scale height. These brightness values for each spectrum are compared to a set of 20 models computed at both wavelengths. The models include values for SO_2 abundance at 40 mbar [essentially the cloud top, see (17)] of 0, 3, 6, 12, 25, 50, and 100 parts per billion (ppb) and

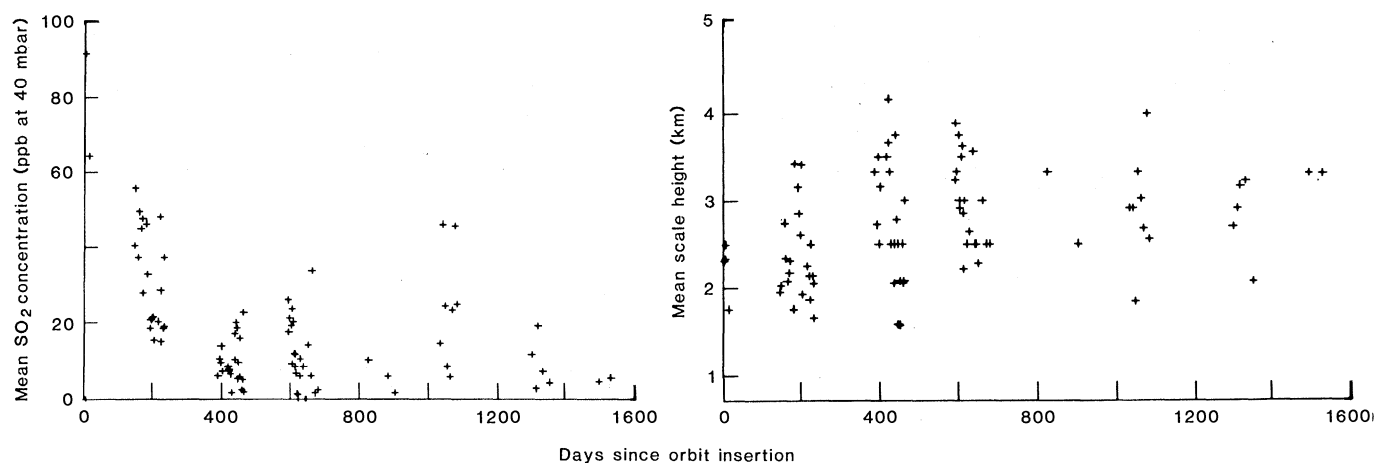


Fig. 1 (left). Time variation of the derived SO_2 concentration at 40 mbar from ultraviolet spectra. Global means are shown, derived from spectra fit within 15 percent. Fig. 2 (right). Time variation of the derived SO_2 scale height in the cloud-top region. Global means are shown, derived from spectra fit within 15 percent.

values for the SO₂ scale height of 1.25, 1.7, 2.5, and 5.0 km. The basic type of model is similar to that used by Esposito (2); the outgoing reflected brightness, including multiple scattering, vertical inhomogeneity, and observing geometry, is calculated explicitly by the Markov chains method (18). The best combination of values for abundance and scale height is that which minimizes the mean-square difference between the actual brightness and the model brightness at the two wavelengths. If this root-mean-square difference is larger than 15 percent of the observed brightness, no model is deemed a satisfactory fit. Of 1179 spectra taken by the ultraviolet spectrometer in the first 1600 orbits, for 925 (78 percent) a satisfactory fit was found. For each of the 90 orbits containing spectra, the derived values are averaged to give global means for SO₂ abundance and scale height. These means are plotted against orbit number in Figs. 1 and 2 (orbit insertion was on 4 December 1978). Figure 1 shows a clear decline from approximately 100 ppb on orbit 2 to less than 10 ppb by orbit 1500.

Belton has criticized (19) earlier work in which this method was used to derive the SO₂ distribution. He stated that the SO₂ spectrum is not continuous but is actually composed of lines unresolved by current laboratory studies. If this is true, then the models used in this analysis will be in error since they take into account only known structure in the SO₂ cross section (16). On the other hand, no laboratory spectra of high enough resolution exist in this wavelength region (2000 to 2400 Å). Furthermore, because of predissociation at these wavelengths (20), there is good reason to expect a continuum, consistent with the models used.

Lacking a laboratory determination on this matter, we can check to see if the models used here show any systematic variations consistent with Belton's hypothesis. Because the complicated line structure suggested by Belton would be interpreted according to the above inversion as an inhomogeneous vertical distribution of SO₂, we could expect systematic failures as we viewed higher in the atmosphere, that is, as the line of sight went toward the limb. These would be in the sense of deriving larger SO₂ concentrations for observations closer to the limb. Figure 3 shows the derived SO₂ amount as a function of μ , the cosine of the emission angle. For radial viewing $\mu = 1$; as we go to the limb μ goes to 0. No effect of the sort predicted by Belton's hypothesis is seen. In fact the

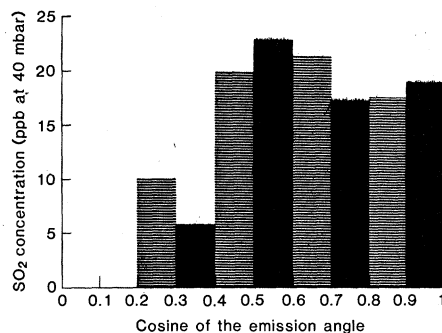


Fig. 3. Histogram of the mean SO₂ concentration as a function of μ , the cosine of the emission angle (data from 925 spectra fit within 15 percent). No observations for $\mu < 0.2$.

opposite effect is seen, with slightly lower derived values of SO₂ abundance at smaller μ values. Lacking laboratory data on which to base more complicated models and finding no evidence of systematic errors, I conclude that the current models are satisfactory.

Other possible ways to explain the data without requiring that the global amount of SO₂ in the cloud-top region decrease by an order of magnitude also lack force. The SO₂ is not covered up by haze: the haze decreases as rapidly over the same period (6). Moreover, the SO₂ is not hidden by an uplift of the main cloud. To the inversion algorithm, this would appear as a smaller scale height (21). Figure 2 shows that the scale height increases over this time. Furthermore, on theoretical grounds it appears that the SO₂ scale height is maintained by photochemical destruction at the cloud tops (1, 2, 8). Thus, if the SO₂ were hidden by a brighter layer above it, this destruction would cease and the SO₂ would be rapidly transported upward by mixing into the previously pristine layer. The time scale for the transport is only months, given derived eddy mixing rates (22). Thus, such a situation could not persist for years unless the supply of SO₂ is decreased at a lower level in the Venus atmosphere.

All that is clearly shown by the ultraviolet spectrometer data is the disappearance of SO₂ from the cloud-top region. However, earlier upper limits (5) are much lower than the amount seen at Pioneer Venus encounter in 1978. This result, coupled with the sudden multiple observations (4), provides strong evidence of a rapid increase in the amount of SO₂ at the cloud tops before the Pioneer Venus encounter.

Esposito and Travis showed (17) that there is a negative correlation between the submicron haze (6) at any given instant and the amount of SO₂. The

natural interpretation of this is a conservation of sulfur atoms between the gas (SO₂) and the haze aerosol (H₂SO₄). Since the particles are produced from the SO₂ gas, this would naturally explain the observed long-term positive correlation: as the global amount of SO₂ declines, so should the production of haze aerosols. Indeed, Kawabata *et al.* show (23) that the amount of submicron haze decreased by an order of magnitude over the first 1000 days of the Pioneer Venus mission.

Like the SO₂, this submicron haze was at a historic high in 1978 (24). The especial brightness of the polar regions at this time is also accounted for by the haze. The last major occurrence of bright polar caps in 1959 has also been associated with submicron particles at the cloud tops (12). The conclusion from these facts is straightforward: (i) SO₂ is episodically injected above the Venus cloud tops; (ii) this SO₂ is rapidly converted to new, small aerosols of H₂SO₄, seen as a haze and especially bright polar regions; and (iii) these aerosols rapidly grow and fall out into the main cloud deck, which would give rise to decade-long periods during which neither small aerosols nor SO₂ is seen.

An appealing explanation for the observed SO₂ injection and resulting haze formation is episodic volcanism. Radar studies by the Pioneer Venus orbiter (9) have detected topographic features on Venus that resemble terrestrial volcanic landforms. Prinn (11) argues that the observed amount of SO₂ in the lower atmosphere is out of equilibrium with the surface composition measured by the latest Venera landers (25). This current imbalance requires a geologically recent source of sulfur compounds at the surface.

It is well known that major volcanic eruptions give rise to a haze layer of submicron particles in Earth's atmosphere. The mass of aerosols in the earth's stratosphere after the eruptions of El Chichón in 1982 approached 10¹³ g (26). Vertical optical depths measured in Earth's polar regions exceeded 0.1 (27). The total mass of the Venus polar haze inferred by Kawabata *et al.* (6) is 2 × 10¹⁴ g; the optical depth of the Venus polar haze exceeds 1.0. Thus the amount of aerosols injected into the Venus middle atmosphere is greater by at least an order of magnitude than that associated with the most recent volcanic episodes on Earth.

Volcanism is not the only possible cause for middle atmospheric injection on Venus. The SO₂ abundance (28) differs by an order of magnitude above and

below the stable layer in the Venus atmosphere at 40 to 50 km (29). Any large-scale mechanism that mixes SO₂ across this layer would result in a massive injection into the cloud-top region. A satisfactory mechanism must account for both the long time scale (decades) and the method of breaking through the stable layer below the clouds.

Volcanic eruptions fit with the long time between such injections. The time scales for atmospheric phenomena would seem much shorter, that is, about 1 month (28) at the cloud tops. In a volcanic eruption, the emitted gases (and the entrained atmosphere) have positive buoyancy (30). The heated column of gases is a convective plume, which can rise to great heights even in a stable stratified atmosphere (31), as on Venus.

A plume must rise to a height of about 50 km to reach the unstable region in the Venus middle cloud at 50 to 57 km (29, 30). At this altitude, no further expenditure of buoyancy is required: the warm column of erupted gases and entrained air does not lose heat as fast through expansion as the atmospheric temperature falls with altitude. Thus, any injected gases reaching this height would rise through the middle cloud and be mixed into the region of photochemical production of H₂SO₄ in the upper cloud (57 to 70 km), where they are "visible" to remote-sensing devices (30).

The ability of a buoyant plume to rise in a stably stratified medium has been studied by Morton *et al.* (31). The height, H , attained by a buoyant plume is proportional to the fourth root of the input of buoyant flux, F , at the surface, and inversely proportional to the 3/8 power of the atmospheric stability, s :

$$H \sim F^{1/4} s^{-3/8} \quad (1)$$

The buoyant flux is given by the thermal input \dot{Q} multiplied by the coefficient of expansion ($1/T$ for gases, where T is the surface temperature) divided by the thermal capacity and multiplied by the gravitational acceleration, g :

$$F = \frac{g \dot{Q}}{T \rho c_p} \quad (2)$$

where ρ is the atmospheric density and c_p is the specific heat. The atmospheric stability is

$$s = \frac{g \Gamma (1 + n)}{T} \quad (3)$$

where Γ is the adiabatic lapse rate and n is the ratio of the observed atmospheric lapse rate to Γ (for an adiabatic atmosphere, $n = -1$). The proportionality constant in Eq. 1 is given by a numerical calculation of the upward velocity de-

pendence on height and an experimental measurement of the entrainment rate (the speed at which ambient gas is mixed into the rising column). For a standard Earth atmosphere (31, 32),

$$H = 8.2 \dot{Q}^{1/4} \quad (4)$$

where H is measured in meters, and \dot{Q} is the rate of thermal energy release in watts. Although it is simplistic and ignores radiative cooling, Eq. 4 gives a satisfactory explanation for the height of volcanic plumes from recent terrestrial eruptions (32, 33).

For Venus, the average observed lapse rate between the surface and 50 km is 7.7 K/km and the mean adiabatic lapse rate is 8.9 K/km (29). Correcting Eq. 4 for the conditions at the Venus surface (29), we find that a plume on Venus will rise ~ 0.6 as high as one on Earth created by a volcano with the same thermal output. Thus, to reach a height of 50 km on Venus, the volcanic eruption must have a thermal output $\dot{Q} \geq 10^{16}$ W. This rate of heat production is about 10 to 100 times that from well-documented major terrestrial volcanic eruptions of the last century (32–34). Such large heat production has been supplied by historical eruptions, including Krakatoa (1883) (35) and Tambora (1815) (36). On Earth, such massive explosions might occur only once per century or less.

Phillips and Malin (37) have suggested that volcanic activity may be more vigorous on Venus than on Earth because of the lack of organized plate tectonics on Venus. The more vigorous volcanic activity on Venus might be due to larger volcanoes, a greater number of volcanoes, or more frequent eruptions. The last two of these possibilities could account for a higher frequency of SO₂ injections into the visible Venus atmosphere.

This recent injection can account for the current geochemical imbalance between the surface and atmosphere noted by Prinn (11) and also the failure of steady-state photochemical models to match both the small scale height of SO₂ and the upper limits on O₂ (8, 38). Since SO₂ is the major precursor of the Venus clouds and an important absorber of solar radiation, steady-state models of the chemistry and dynamics of the cloud-top region must be used cautiously. The abundances of other chemically active constituents such as Cl₂, CO, and polymorphic sulfur must also experience coupled episodic variations.

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39. I am grateful for useful discussions with H. Masursky, R. Prinn, A. Young, W. B. Rossow, C. A. Barth, J. L. Bertaux, A. I. F. Stewart, R. A. West, G. E. Thomas, and B. M. Jakosky. I thank M. Copley, who reduced the spectral data. This research was supported by the Pioneer Venus Project office and the NASA Planetary Atmospheres Program (NAGW-389).

20 September 1983; accepted 4 January 1984