Venus: Dead or Alive?

Harry A. Taylor, Jr., and Paul A. Cloutier

In situ nightside electric field observations from the Pioneer Venus Orbiter have been interpreted as evidence of extensive lightning in the lower atmosphere of Venus. The scenario, including proposed evidence of clustering of lightning over surface highland regions, has encouraged the acceptance of currently active volcanic output as part of several investigations of the dynamics and chemistry of the atmosphere and the geology of the planet. However, the correlation between the 100-hertz electric field events attributed to lightning and nightside ionization troughs resulting from the interaction of the solar wind with the ionosphere indicates that the noise results from locally generated plasma instabilities and not from any behavior of the lower atmosphere. Furthermore, analysis of the spatial distribution of the noise shows that it is not clustered over highland topography, but rather occurs at random throughout the latitude and longitude regions sampled by the orbiter during the first 5 years of operation, from 1978 to 1984. Thus the electric field observations do not identify lightning and do not provide a basis for inferring the presence of currently active volcanic output. In the absence of known evidence to the contrary, it appears that Venus is no longer active.

The evidence for the possible occurrence of widespread and continuing lightning at Venus is based primarily on two sources of observations: the Soviet results from Venera 11 and 12 and the U.S. results from the Pioneer Venus Orbiter (PVO). The initial suggestion that lightning might be present at Venus is attributed to Ksanfomaliti (*1*), who interpreted radio noise measurements obtained during the descents of the Venera 11 and 12 probes as evidence of lightning discharges. These data were limited in time to a few hours and restricted in spatial extent to the latitudes near $-10°$ and longitudes near 300° that were traversed during the descents of the two probes.

The interpretation of the Venera 11 and 12 data and subsequent PVO data led Krasnopol'skii (*2*) to reexamine optical measurements from the Venera 9 and 10 probes; he identified possible but isolated evidence for lightning, although measurement artifact was not completely ruled out. An independent search for optical evidence in the nightside from the PVO had negative results (*3*). Nevertheless, Ksanfomaliti *et al.* (*4*) depended on the PVO electric field measurements attributed to lightning (*5*) for support for their interpretation.

The Venera 11 and 12 measurements encouraged the interpretation of lightning as the source for 100-Hz noise observed by the Orbiter Electric Field Detector (OEFD) on the PVO (*5, 6*). Subsequent measurements of several thousands of individual 100-Hz noise bursts, each attributed to lightning, have been reported from measurements accumulated among many of the nightside orbits of Venus during the first 5 years of the PVO mission, beginning in December 1978 and extending to March 1982 (*7–9*). The numerous PVO observations constitute the majority of the observational data proposed as evidence of lightning at Venus.

In analyzing the reported spatial distribution of the 100-Hz electric field noise, Scarf and Russell (*7*) called attention to what they described as "dramatic evidence for topographical clustering of the lightning sources," over the Atla, Beta, and Phoebe regios. They proposed that since the Venus cloud cover is typically observed to be rather widespread, normal atmospheric disturbances were not generating the lightning signals; rather they inferred that a topographic clustering of the events suggested active volcanic output from the mountainous regions as the particular stimulus for the lightning.

The PVO lightning interpretation has stimulated numerous investigations in wide-ranging areas, including crustal evolution and gravitation (*10, 11*), mechanisms for lightning on different planets (*12–16*), and perturbations of Venus cloud and aerosol composition (*17–19*). Moreover, the prior results encouraged attempts to detect lightning above prominent highland regions with lightning detectors on the VEGA balloon experiments (*20*). On 11 June 1985 the VEGA-1 balloon drifted along a path near 7°N after its injection near local midnight into the dayside region; it sampled the nightside for about 33 hours. Four days later, the VEGA-2 balloon conducted a similar sampling along a track near 7°S. Both balloons were inserted near 180° longitude and drifted west over much of the surface regions where lightning had been reported from the PVO results (*7*). Neither instrument detected evidence of lightning activity anywhere in this region.

We have examined the characteristics of an extended set of OEFD electric field results observed between 1978 and 1984. We show that the 100-Hz signals are not clustered over mountains, but rather are randomly distributed within the latitude and longitude regions traversed by the PVO during periapsis passes. Topographic clustering of the 100-Hz events, if present, would be important for the interpretation of lightning and essential for the interpretation of present-day volcanic output. Our evidence is consistent with the interpretation that the 100-Hz signals are actually generated in the vicinity of the PVO, resulting from instabilities inherent in the interaction of the solar wind and ionosphere (*21, 22*), and supports our proposal that the electric field noise is not related with either the lower atmosphere or the mountain regions.

Although the PVO electric field observations provide no evidence for inferring that Venus is volcanically alive, support for assuming present-day volcanic activity has been stimulated by the PVO electric field results, including the interpretation of variations in atmospheric SO_2 (*17*). We propose that this interpretation of cloud chemistry and dynamics, as well as speculation about the existence of volcanic activity during the 1978–1984 epoch, should be reconsidered.

H. A. Taylor, Jr., is at Goddard Space Flight Center, Greenbelt, MD 20771. P. A. Cloutier is in the Department of Space Physics and Astronomy, Rice University, Houston, TX 77001.

Observations

The PVO orbit and the nightside sampling characteristics. The PVO exploration of the Venus environment began in December 1978 with daily orbits about the planet. The orbit has a period of about 24 hours, a near polar inclination, and a periapsis located near 15°N latitude. The height of periapsis varies from a low of about 140 km to more than 1900 km within the data we examined. The periapsis height was controlled by on-board propulsion and maintained below about 200 km for the first three excursions of the spacecraft through the nightside of the planet and thereafter was allowed to rise to increasing heights. The nightside ionosphere typically extends to heights near 1000 km and the orbiter thus passes through the ionosphere in a latitude band extending from about 60°N to about 30°S. In each orbit of Venus about the sun, different longitude zones were traversed by sequences of nightside passes of the PVO. In each nightside sequence, 112 daily orbits were recorded, from dusk across midnight to dawn, extending across a longitude interval of about 160°. Between 1978 and 1984, nine sequences of nightside orbits were recorded (Fig. 1). The orbit segments depict the ionosphere traversal portions of the first and last orbits in each sequence. The rotation of the planet is such that the motion of orbits moves from right to left across the longitude scale, sweeping across the successive regions of the surface. In the first nine excursions, all longitudes were traversed at least once. However, the frequency of occurrence of near-midnight orbits varies with longitude, with a minimum occurring between about 300° and 30°, where mostly dawn or dusk region orbits were obtained. The surface areas outlined in Fig. 1 indicate highland topography including some mountainous regions, suggested to be of possible volcanic origin, as judged from radar observations also made from the PVO (*23*).

The distribution of 100-Hz noise attributed to lightning. Scarf and Russell (*7*) and Scarf (*9*) have proposed that the PVO electric field noise is directly associated with mountainous regions and thus indicative of volcanic activity. Some of the evidence for the clustering of the electric field noise over mountain regions proposed by Scarf and Russell (*7*, figure 3 and plate 1) and Scarf (*9*, figure 4) are shown in Fig. 2. The topographical outline map (Fig. 2A) shows the locations of highland areas identified from radar observations. The locations of selected, relatively more frequent 100-Hz noise bursts, attributed to lightning by Scarf and Russell (*7*) are shown in Fig. 2B superimposed on a more detailed shaded relief map with the same latitude-longitude format.

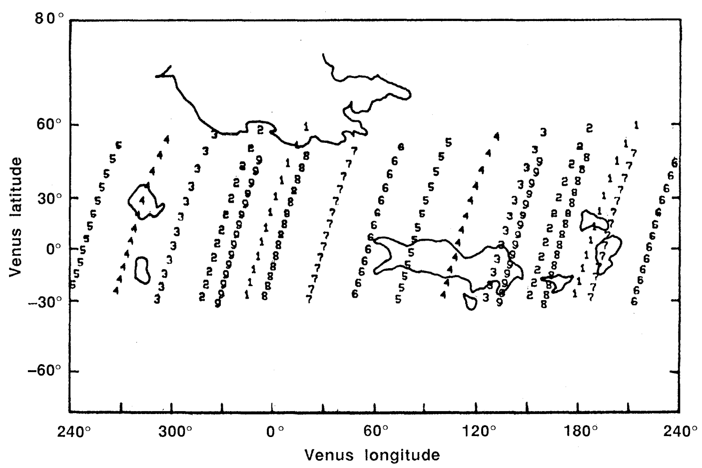

Fig. 1. Map indicating progression of longitude coverage provided from the first nine sequences of nightside Pioneer Venus Orbiter orbits up to orbit 1895, from 1978 to 1984. Each line segment indicates the PVO path inbound from 1000 km before periapsis to 1000 km outbound after periapsis, corresponding approximately to traversals of the ionosphere. The first (dusk) and last (dawn) orbit of each sequence of 112 nightside orbits is shown, labeled 1, 2, and so on for each of the nine sequences. The first sequence begins with segment 1, crossing the equator near 0° longitude. The motion of the planet is such that each sequence progresses across longitude from right to left, covering a longitude interval of about 160° in 112 days, so that sequence 1 begins near 0°, moves to the left past 240° and ends near 195°. The midnight orbit would occur in the middle of each sequence, with the near terminator or dawn and dusk orbits being located near the boundaries of each sequence. These nine sequences provide coverage of all prominent middle and low latitude highland regions shown in outline. However, in the region from about 330° to about 30° the coverage is mostly by near terminator orbits, with few late night orbit passes.

As reported by Scarf and Russell (*7*), the data exhibited in Fig. 2B include a symbol for each 5° by 5° latitude-longitude surface segment in which three or more distinct 100-Hz noise bursts were detected at the PVO. These results were reported from the analysis of all 100-Hz "lightning" events recorded by the OEFD during the first 1185 daily orbits of PVO about the planet. Each 100-Hz "lightning" burst was mapped down from the PVO position to the surface of the planet and assigned a corresponding latitude and longitude position. The first 1185 orbits extended up to the sixth nightside sequence shown in Fig. 1, so that the region between about 0° and 60° longitude was not traversed by nightside orbits. Also, on either side of this region, the nearest orbits are from either dawn or dusk portions of nightside sequences.

The mapping to the surface was based on the premise that the near-radial component of the draped interplanetary magnetic field lines, encountered coincident with the 100-Hz signals, provides the ducting path for lightning-stimulated whistler waves from the lower atmosphere continuously upward to the PVO orbit. The surface was then divided into 5° by 5° squares and the number of bursts (from multiple orbits) tabulated in each square. Squares in which only one or two events occurred were eliminated; 33 remaining squares with more frequent bursts were identified with black dots (Fig. 2B). This result was the basis for the interpretation of "dramatic topographic clustering" of the noise that was proposed as being regionally stimulated from volcanic eruptions in the highland regions.

We disagree with several key points of the results presented in Fig. 2, and the interpretation of the electric field data in terms of lightning and active volcanism. First, Fig. 2 does not reveal the distribution of all the 100-Hz signals attributed to lightning and detected during the first 1185 orbits. Figure 3A shows the distribution in latitude and longitude of all 100-Hz signals identified for orbits 1 to 1185; the specific surface coordinates assigned to each "lightning" event are also shown (*24*). The gap in noise observations between about 330° and 90° longitude results from the lack of late night orbits crossing the region. As discussed below, the late night orbits are the most favorable for observing the noise. Otherwise, where the 100-Hz noise is observed, it appears that the individual 100-Hz noise events are randomly distributed over latitude with no tendency for clustering of points over any of the prominent low latitude mountainous regions outlined in Fig. 3.

The frequency distribution of these points is indicated in Fig. 3B; we applied the same criterion as Scarf and Russell in identifying events (*7*). That is, we disregard regions containing isolated examples of only one or two events and plot a symbol within each 5° by 5° region containing at least three or more 100-Hz noise bursts. There is no tendency for the more frequent events to cluster over any of the prominent highland regions. There are a total of 260 5° by 5° regions with three or more events lying outside the outlines of the highlands, accounting for more than 85% of all of the regions with frequent events.

We identified considerably more surface regions with three or more events than those shown in Fig. 2. The majority of the 271 additional points that we identified, using the documented database, do not support the interpretation of "dramatic topographic clustering" of the 100-Hz events. The distributions of both the total set of events, as well as the set with three or more events, show that the 100-Hz noise is randomly distributed with respect to the surface highland regions. Moreover, the frequency distributions for 5, 10, and 15 points per surface region show the same results; there is no evidence for clustering.

We also examined the distribution of 100-Hz events attributed to lightning for all orbits up to orbit 1895 (Fig. 4), corresponding to the interval December 1978 to February 1984. In this interval the PVO traversed all of the middle and low latitude surface regions, passing above all of the low latitude mountainous regions. The observed 100-Hz events are widely distributed in longitude, although there is still a noticeable infrequency of events between about 330° and 30°. Two factors contribute to the lack of events in this region. First, as noted earlier, phasing of the local times of orbits relative to longitude is such that this region is traversed by orbits with relatively lower solar zenith angles, that is, near the dawn and dusk terminators. We show later that the ionospheric disturbances responsible for the electric field perturbations are relatively infrequent near the terminators because of the typical configuration of the draped interplanetary magnetic field. Second, many of the orbits traversing this region are late sequence orbits having high periapsis altitudes, often above the ionosphere, again where the 100-Hz events are infrequently observed. It is the compound restriction of these factors that precludes more frequent detection of noise in the particular longitude region.

Throughout the wide range of longitudes where the noise is frequently observed, including all of the designated highland regions, there is no evidence of particular clustering of the electric field events over the highland areas. Of the total of 461 5° by 5° regions with events, only 72 regions, or only about 16% of the frequent 100-Hz results, are located within the boundaries of the more prominent highlands (Fig. 4B).

The association of 100-Hz noise and ion troughs. The evidence that the 100-Hz signals are randomly distributed above the surface might suggest to some that the lightning, if real, was simply occurring in naturally cloudy regions, which are in general widely distributed in latitude and longitude (*25*). Such speculation, however, is not supported by the additional evidence that the 100-Hz noise is in fact the signature of in situ plasma noise generated from instabilities associated with ionization troughs which mark the interaction of the solar wind with the nightside ionosphere (*21, 22*). The close correlation of the two phenomena is illustrated in Fig. 5. This sampling of nightside orbits shows a close association between the onset and duration of prominent ion troughs and the detection of the 100-Hz noise bursts.

Figure 5 illustrates some of the most prominent "lightning" signal sequences, prominent in that many closely spaced individual noise events are observed along a given PVO orbit, in contrast to some

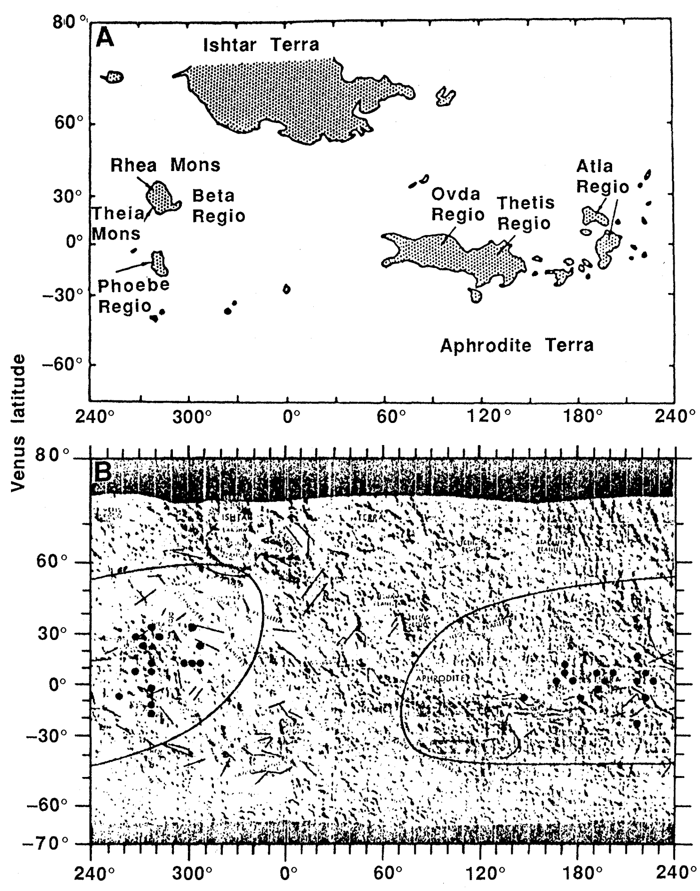

Fig. 2. (A) Venus map with outlines of prominent highland regions. (B) Same topography as in (A) except a shaded relief map of surface elevations is substituted, and black dots are superimposed to identify those 5° by 5° surface regions having multiple "lightning" events on the basis of data from orbits 1 to 1185. A total of 33 surface regions with three or more noise bursts (from multiple orbits) are evident. Solid lines indicate surface regions covered by PVO through orbit 1185 (*7, 9*).

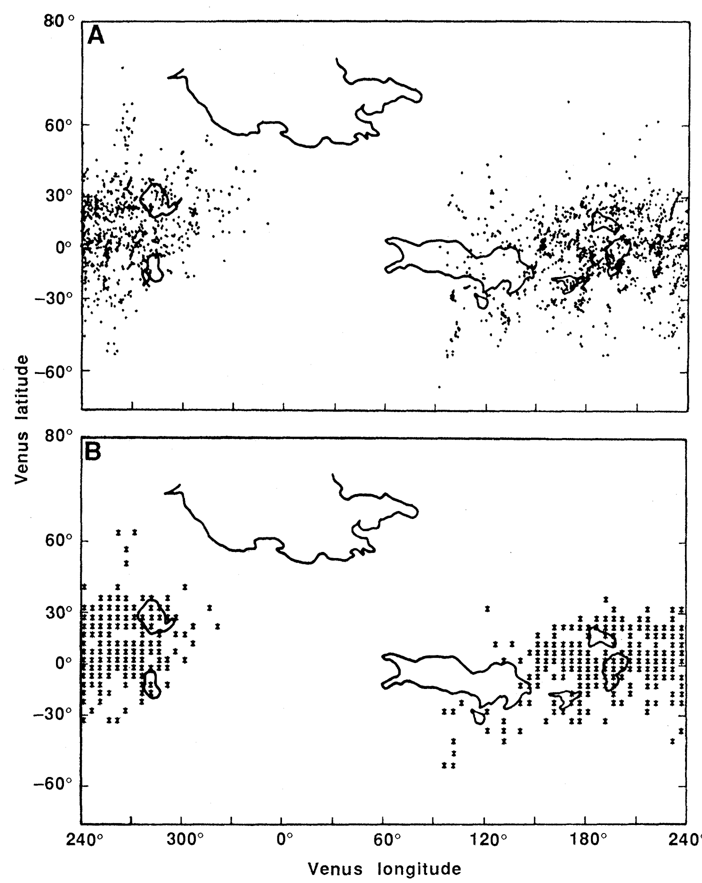

Fig. 3. (A) Venus map showing surface locations corresponding to all overhead 100-Hz "lightning" bursts reported for orbits 1 to 1185, with background outlines showing prominent highland surface regions. Locations of individual points are determined by assuming that the magnetic field direction evident at the time of the 100-Hz burst detection can be traced down from the PVO to the planet surface. (B) Locations of individual 5° by 5° latitude-longitude regions containing three or more of the events shown in (A).

other orbits on which isolated individual noise bursts are detected. The corresponding ion troughs on individual orbits are also persistent in time (and thus in subsatellite latitude and longitude). Also, the abruptness of the onset or cessation, or both, of the ion troughs is matched by a similarly abrupt onset or cessation in the 100-Hz noise; this is indicative of the common origin of these disturbances and suggests the interpretation that the 100-Hz signals are the signature of ion-acoustic noise generated by the local plasma instabilities (*21, 22*).

It is the occurrence of numerous persistent events such as those illustrated in Fig. 5 that contributes to the high frequency of 100-Hz events in particular 5° by 5° regions noted in Fig. 4. A close spatial relation exists between the associated planetary surface distributions of the ion troughs and the 100-Hz noise events. A replotting (Fig. 6A) of the data of Fig. 4A shows the subsatellite track corresponding to that portion of each individual orbit in which three or more 100-Hz signals were identified. Thus, Fig. 6A shows the surface over which the PVO passed while the 100-Hz data were being recorded, rather than the result of projecting the signals back to the surface with the assumption of magnetic field continuity and whistler wave ducting. Consequently, the 100-Hz events are distributed according to the satellite motion, and sequences of events from a given orbit are aligned along slightly inclined tracks, as shown in Fig. 1.

We also plotted the subsatellite tracks of PVO corresponding to a total of 114 of the more prominent ion troughs detected among orbits 1 to 1895 (Fig. 6B). These trough events were visually identified from plots of the total ion density detected by the orbiter ion mass spectrometer, with the requirement that the ion depletion be sufficiently large and continuous to be identifiable as a distinct departure from relatively quiet undisturbed plasma distributions evident in the general vicinity of the trough signature. It is seen that the distribution of the 100-Hz events is much the same as that of the ion troughs, both being randomly distributed in latitude and longitude. Some differences occur because the ion and electric field measurements were not always operated simultaneously. Also, numerous isolated 100-Hz noise bursts contribute relatively more detail (Fig. 6A) than do the tracks associated with ion troughs, since isolated, very small-scale ion trough events were not included in our sample. No topographic clustering is evident for either of these associated phenomena.

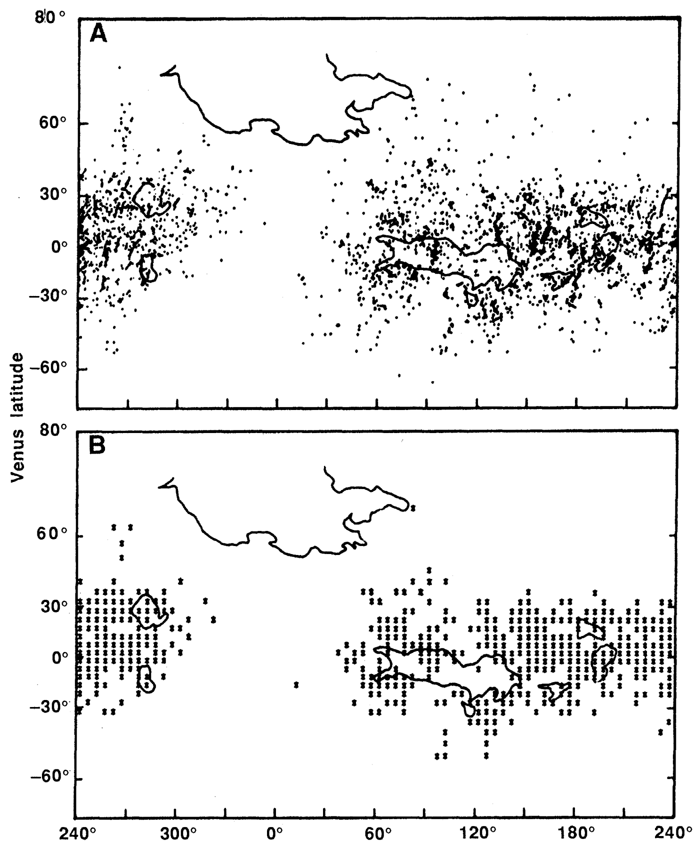

Fig. 4. Locations of 100-Hz noise bursts attributed to lightning from all orbits 1 through 1895, 1978 to 1984. Format of (A) and (B) are the same as described in the legend to Fig. 3.

Discussion

The coincidental relation of 100-Hz signals and topography. Although we are concerned with the volcanic implications of the nonclustering of 100-Hz noise over mountains, for clarity we have included observations documenting the field and particle correlations in the ion troughs, since this is fundamental to understanding the underlying physics involved. We have illustrated two prominent characteristics of the PVO electric field observations bearing on the critical issue of active volcanism at Venus: (i) there is no clustering of the 100-Hz noise over mountainous regions, and (ii) the spatial distribution of 100-Hz noise events is associated with that of ion troughs that result from direct solar wind interactions with the ionosphere. These characteristics may be more fully appreciated by considering the mechanisms responsible for the nightside plasma perturbations and the associated motion of PVO in surveying the nightside.

The presence of nightside ion depletions is well established (*26–30*). There are several common characteristics of these plasma depletions, variously referred to as "holes" or "troughs," including the following: (i) they are associated with enhanced magnetic field intensity, with a near radial configuration; (ii) they tend to occur at moderately low latitudes, in a band extending from about 30° to −30°; and (iii) they may be encountered over most of the nightside, with the latitude and local time of individual troughs on a specific orbit determined by the configuration of the interplanetary magnetic field and the solar wind pressure; statistically, more troughs are encountered at the higher solar zenith angles relative to positions closer to the dawn and dusk terminators.

Recognizing these characteristics, Marubashi *et al.* (*30*) analyzed the relation of the distribution of ion troughs to the configuration of the interplanetary magnetic field and concluded that these plasma depletions are signatures of crossings of the ionopause; that is, the sudden decrease in plasma density occurs as the PVO moves from the main body of the ionosphere into the ionosheath–solar wind regions and then back into the ionosphere. In this sense, the crossing of the ion trough is analogous to the crossing of ionospheric troughs associated with the auroral regions of the earth's ionosphere (*31*). In the earth auroral zones, the magnetic field lines are also connected to the solar wind and thus ionization gradients and associated plasma instabilities are typically encountered.

There are two distinct reasons for expecting frequent detection of electric field noise in the nightside ionosphere. First, it has been shown that ion-acoustic noise at the frequencies detected by the electric field detector is prevalent at altitudes below about 160 km at night, the noise resulting from impact ionization at the spacecraft (*32*). Second, noise within the frequency range of the electric field detector also results from the plasma instabilities inherent in the ion trough regions, where sharp density gradients, fast ion flows, and field aligned particle acceleration are encountered. The subsatellite segments depicted in Fig. 6B thus indicate regions in which one or both of the mechanisms capable of generating low-frequency noise are to be expected.

As noted by Brace *et al.* (*26*) and by Marubashi *et al.* (*30*) the nightside ion trough regions may be displaced significantly in latitude and solar zenith angle, from orbit to orbit. Further, because of the draping of interplanetary magnetic field lines about the planetary obstacle, the ionospheric depletions form in both nightside hemispheres. Because the solar wind and imbedded magnetic field vary from day to day, the PVO naturally encounters ion troughs over a wide range of local times, with relatively more troughs encountered as the PVO moves closer to midnight. Also as a consequence of the field draping, the troughs are typically encountered within about 30° above and below the equator. The trough structure encountered on a given orbit may range from moderate to extensive, depending on the solar wind conditions. Within these restrictions, the distribution of the ion troughs within latitude and longitude is essentially random, consistent with the distribution of the electric field noise.

Thus, we find no evidence for clustering of either the electric field or the associated ion events over the highland areas. Both the field and particle events are manifestations of the solar wind interaction with the ionosphere and are unrelated to the lower atmosphere and to the mountains. Similar reasoning applies to field and particle disturbances regularly observed above auroral regions of the earth—regions that also contain elevated topography in some longitudes, but topography that is not actively volcanic and thus is not stimulating the instabilities encountered in the ionosphere.

Arguments opposing the occurrence of lightning. There has been considerable skepticism concerning the Venus lightning interpretation, involving physical concepts important in associating the electric field noise with the surface topography. On the basis of the cloud physics, it has been argued that the presence of both natural lightning as well as the stimulation of lightning by volcanic output are unlikely processes. Noting that probe measurements show that the lower atmosphere is free of large aerosols (*33*), it has been argued that the atmosphere could not support strong charge buildup (*14, 16, 34, 35*). In particular, sedimentation rates for observed particle sizes were shown to be sufficient to produce charge separation yielding electric fields of only about 200 V m^{-1}, corresponding simply to fair-weather cloud electrification at the earth (*34*). It has been emphasized (*36*) that for an atmospheric density 50 times as large as that at the earth, the dielectric constant of the Venus atmosphere would be proportionately higher, requiring unreasonably large charge buildup, particularly in view of the documented absence of aerosols. It has been argued that the same massive atmospheric pressure would also restrict the ejection of any volcanic output to high altitudes, mitigating the opportunity for charge separation and lightning development (*14*).

The lightning-volcanism scenario has also been questioned on the basis of the inherent uncertainties in using ray tracing to relate the noise detected along the PVO orbit to specific surface locations (*14, 36*). Because the waves are present only in the 100-Hz channel, lack of spectral information prevents positive identification of the wave mode. However, the tentative identification of this noise as whistler waves propagating upward along magnetic field lines seems doubtful. In particular, because the noise sequences are often closely correlated with ion trough structures in which the magnetic field geometry changes significantly within a distance of much less than the 3000-km wavelength of the 100-Hz waves, it is unlikely that effects of ducting could be seen. Even if ducting were to occur, the

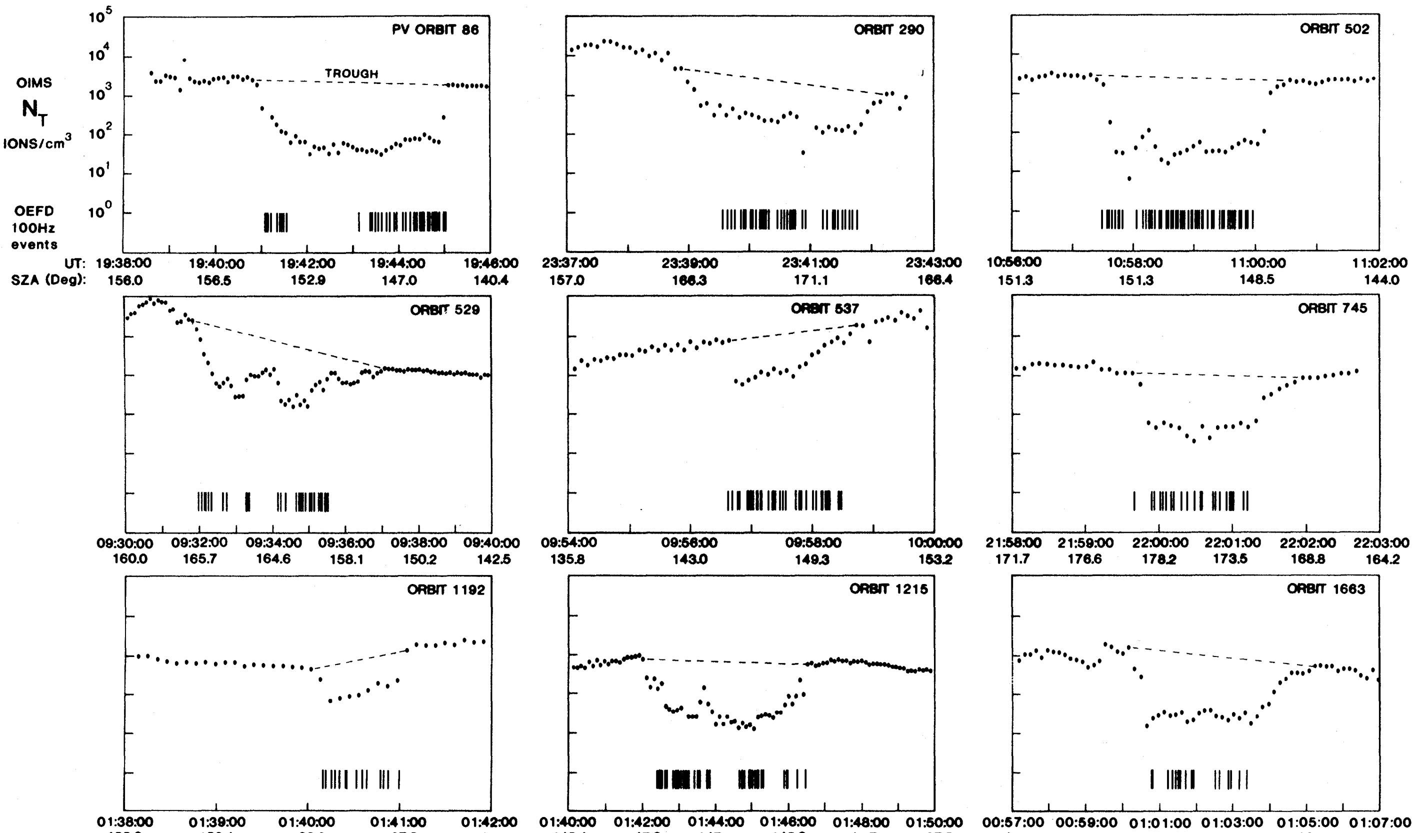

Fig. 5. Examples of the close correlation between troughs in the total ion density (N_T) and sequences of 100-Hz noise bursts attributed to lightning. Individual 100-Hz noise bursts are identified by vertical line segments located at times of each observation. All 100-Hz events are taken from tabulations of specific "lightning" signals (*24*). Examples are for a number of nightside observing periods, showing the persistence of the correlation over the several years of observations. OIMS and OEFD refer to the Orbiter Ion Mass Spectrometer and Orbiter Electric Field Detector, respectively.

configuration of the draped interplanetary magnetic field is both variable and unknown, and consequently large uncertainties are involved in inferring the paths of propagating signals and in associating such long wavelengths with specific surface locations.

Influence of the proposed topographic clustering of the 100-Hz noise. The technical questions raised in the foregoing arguments have not been answered. Rather, the proposed topographic clustering of the noise has encouraged speculation about the possibility of volcanic activity and even assumptions that the highland regions not only suggest volcanic construct formations, but apparently are actually currently active (*9, 10, 17, 19*). From independent theoretical investigations of the evolution of the planet body, relating to the observed topographic elevations and surface composition characteristics, arguments for past volcanic activity have been developed, but how recent such activity may have been has not been determined (*10, 23, 37, 38*). Neither the PVO radar (*23*) nor the considerably higher resolution radio telescope observations from the Arecibo Observatory (*38*) are capable of confirming surface evidence of volcanic output in the past few years. Thus many of the references to "active volcanism" at Venus have only been made in the context of geologic time and are not to be interpreted as indicative of current conditions.

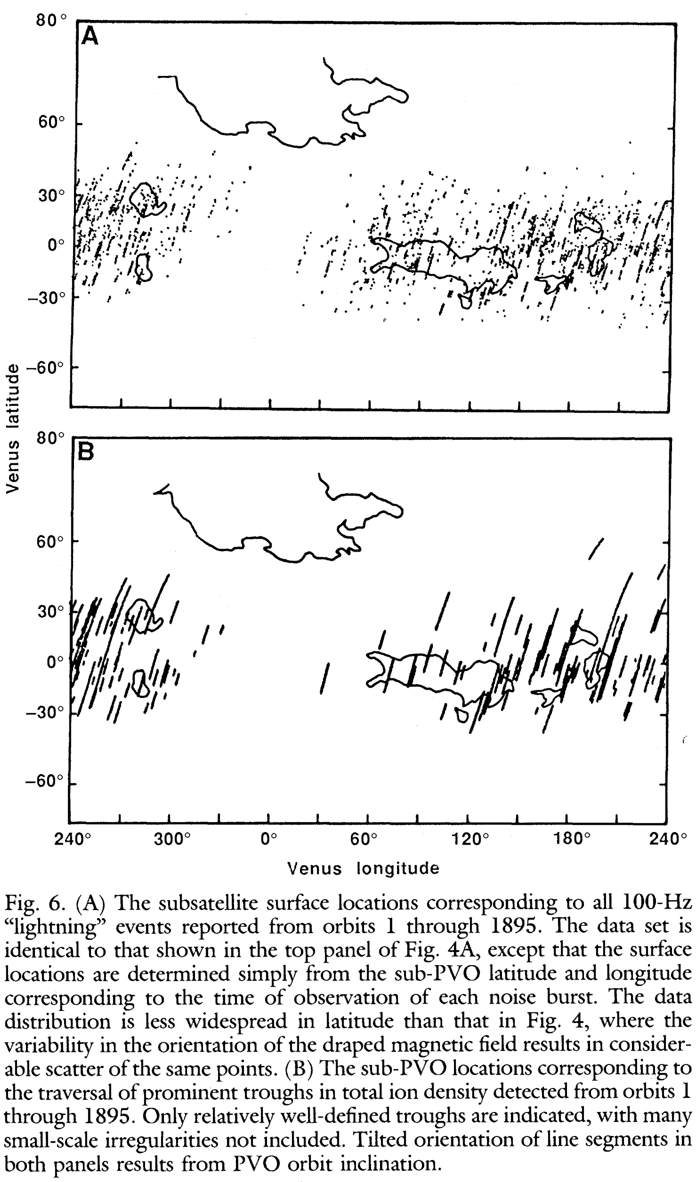

Fig. 6. (A) The subsatellite surface locations corresponding to all 100-Hz "lightning" events reported from orbits 1 through 1895. The data set is identical to that shown in the top panel of Fig. 4A, except that the surface locations are determined simply from the sub-PVO latitude and longitude corresponding to the time of observation of each noise burst. The data distribution is less widespread in latitude than that in Fig. 4, where the variability in the orientation of the draped magnetic field results in considerable scatter of the same points. (B) The sub-PVO locations corresponding to the traversal of prominent troughs in total ion density detected from orbits 1 through 1895. Only relatively well-defined troughs are indicated, with many small-scale irregularities not included. Tilted orientation of line segments in both panels results from PVO orbit inclination.

Investigations of cloud physics have been noticeably influenced by the lightning-volcanism scenario. Analyses of unexplained short-term changes in Venus cloud composition and haze (*17, 19, 39*) and in cloud particle size distributions (*18*) are examples in which the interpretation of unresolved atmospheric variations have to varying degrees been linked with the assumed credibility of persistent lightning and currently active volcanic output.

Using infrared emission observations from the PVO, Esposito (*17*) derived the cloud top SO_2 concentrations and found that from 1978 to 1983 a decrease of more than an order of magnitude was apparent. The time-series of SO_2 identified suggests that much of the decrease occurred during the first year of the PVO measurements, although the evidence of large concentrations is limited to only several isolated observations. After 1979 the concentration exhibits considerable short-term variability, remaining at relatively low levels during the ensuing 4-year interval. Esposito noted that earlier observations of Venus, before the PVO encounter, had shown much lower SO_2 levels; he attributed the anomalous increase apparent in 1978 to an episodic volcanic output and the subsequent decrease in SO_2 to previously indicated levels to a decline in volcanic activity. Esposito noted that the evidence for extensive lightning, clustered over the mountainous regions, provided evidence supporting the inference of active volcanism.

The SO_2 scenario and the PVO "lightning" results were identified by Prinn (*19*) as providing two independent pieces of evidence supportive of the inference that Venus must have been volcanically active during 1978–1979. However, it is apparent that the interpretation by Esposito was at least encouraged by the PVO results, and thus we do not consider these as strictly independent pieces of evidence. Moreover, the fact that the 100-Hz noise attributed to lightning persists in the period 1982 to 1984 is in conflict with the assertion that the decrease in the SO_2 concentration in these years signaled the end of the volcanic output. Thus, even if the 100-Hz signals were to originate from lightning, these events are not only not topographically clustered but, moreover, the "lightning" would presumably have had to continue to occur without the stimulus of significant volcanic output, as interpreted from the continuing low level of SO_2 in the same years.

Implications for investigation of the earth's atmosphere. Because earth-related physical concepts provide much of the foundation for theoretical interpretation of planetary conditions, our new evidence may have implications for understanding comparable processes at the earth. As a case in point, the SO_2 variation, rather than reflecting volcanic injections, may well result from as yet unexplained changes in the general circulation of the Venus atmosphere. Esposito (*17*) noted that atmospheric mixing might also produce the SO_2 variations, but reasoned that the episodic nature of the variation, as well as a proposed region of stability below the clouds, challenged an explanation on the basis of dynamics.

Variable distributions of trace constituents in the upper atmosphere of the earth are closely linked to the nonlinear variability of the circulation. At Venus, the SO_2 detected by Esposito (*17*) represents a small fraction of the total SO_2 budget, and it seems likely that as at the earth, circulation may be responsible for the observed changes in both the SO_2 and the atmospheric haze. As discussed by Prinn (*19*), the time cycle of the evolution of SO_2 to H_2SO_4 and back to SO_2 is on the order of 1 year, and yet significant short-term variations are clearly evident in the inferred SO_2 variation reported by Esposito. Furthermore, we know from the analysis of the cloud and haze data that the intensity of zonal winds as a function of latitude exhibits significant interannual variation, with strong mid-latitude zonal wind jets appearing and disappearing in time (*40*). It seems plausible that variations in the atmospheric circulation may well be responsible for the changes in the global distribution and apparent concentration of the inferred SO_2 and that it is not necessary to invoke arguments for present-day volcanism.

Conclusion

A scenario with the assumption that there is evidence of lightning and associated present-day active volcanism at Venus has evolved, stimulated primarily by the PVO electric field measurements. We find from examination of more than 5 years of data that the 100-Hz signals attributed to lightning are randomly distributed across much of the low latitude surface traversed at night and are not clustered over mountains. The 100-Hz signals are thought to be noise generated near the PVO, resulting from plasma instabilities arising from solar wind–ionosphere interaction. Due to the pattern of draping of the interplanetary magnetic field about Venus, this region of plasma instability characteristically appears at middle and low latitudes and is prominent over a wide range of nightside local times. Due to the motions of the PVO orbit and of the planet and the variation of the geometry of the interplanetary magnetic field, the associated 100-Hz noise events and associated ion troughs are sometimes coincidentally detected over mountainous terrain. We find that the noise events are not physically associated with the surface or lower atmosphere and conclude that the PVO results are indicative neither of lightning nor of current volcanic activity.

We know of no geological evidence for currently active volcanism at Venus. Moreover, since we have not identified compelling arguments to the contrary, we suggest that the SO_2 and associated haze variations previously attributed to volcanic output may well be linked to changes in atmospheric circulation. Also, we note that the interpretation of the Venera 15 and 16 radar observations of northern hemisphere surfaces indicates that once active volcanic structures appear to have been dormant for about 1 billion years (*41*). Although limitations of observations preclude a definitive answer to the question of whether Venus is geologically dead or alive the available evidence appears to indicate that it is inactive. In either case, we find that the PVO electric field results provide no basis for inferring that Venus is currently volcanically alive. Related investigations of both planetary geology and atmospheric variations should be reexamined wherever the PVO results have been accepted as evidence that the planet lives.

REFERENCES AND NOTES

1. L. V. Ksanfomaliti, *Nature (London)* **284**, 244 (1980).
2. V. A. Krasnopol'skii, *Kosmich. Issled.* (transl., *Cosmic Res.*) **18**, 325 (1980).
3. W. J. Borucki *et al.*, *Geophys. Res. Lett.* **8**, 233 (1981).
4. L. V. Ksanfomaliti *et al.*, *Pis'ma Astron. Zh.* (transl., *Sov. Astron. Lett.*) **8**, 230 (1982).
5. F. L. Scarf *et al.*, *J. Geophys. Res.* **85**, 8158 (1980).
6. W. W. L. Taylor, F. L. Scarf, C. T. Russell, L. H. Brace, *Nature (London)* **279**, 614 (1979).
7. F. L. Scarf and C. T. Russell, *Geophys. Res. Lett.* **10**, 1192 (1983).
8. L. V. Ksanfomality, F. L. Scarf, W. W. L. Taylor, in *Venus*, D. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Ariz. Press, Tucson, 1983), pp. 565–603.
9. F. L. Scarf, *Adv. Space Res.* **5** (no. 8), 31 (1985).
10. C. Bowin, *Icarus* **56**, 345 (1983).
11. ——, G. Abers, L. Shure, *J. Geophys. Res.* **90** (suppl.), C757 (1985).
12. A. F. Cook II, T. C. Duxbury, G. E. Hunt, *Nature (London)* **280**, 794 (1979).
13. J. A. Burns, M. R. Showalter, J. N. Cuzzi, R. H. Durisen, *Icarus* **54**, 280 (1983).
14. Z. Levin, W. J. Borucki, O. B. Toon, *ibid.* **56**, 80 (1983).
15. W. J. Borucki, R. L. McKenzie, C. P. McKay, N. D. Duong, D. S. Boac, *ibid.* **64**, 221 (1985).
16. K. Rinnert, *J. Geophys. Res.* **90**, 6255 (1985).
17. L. W. Esposito, *Science* **223**, 1072 (1984).
18. R. G. Knollenberg, *Icarus* **57**, 161 (1984).
19. R. G. Prinn, *Sci. Am.* **252**, 46 (March 1985).
20. R. Z. Sagdeev *et al.*, *Science* **231**, 1411 (1986).
21. H. A. Taylor, Jr., J. M. Grebowsky, P. A. Cloutier, *J. Geophys. Res.* **90**, 7415 (1985).
22. ——, *ibid.* **91**, 4599 (1986).
23. H. Masursky *et al.*, *ibid.* **85**, 8232 (1980).
24. F. L. Scarf, personal communication.
25. L. D. Travis *et al.*, *Science* **205**, 74 (1979).
26. L. H. Brace, R. F. Theis, H. G. Mayr, S. A. Curtis, J. G. Luhmann, *J. Geophys. Res.* **87**, 199 (1982).
27. J. G. Luhmann *et al.*, *ibid.*, p. 9205.
28. J. G. Luhmann and C. T. Russell, *Geophys. Res. Lett.* **10**, 409 (1983).
29. H. A. Taylor, Jr., *et al.*, *Adv. Space Res.* **2** (no. 10), 291 (1983).
30. K. Marubashi *et al.*, *J. Geophys. Res.* **90**, 1385 (1985).
31. H. A. Taylor, Jr., and W. J. Walsh, *ibid.* **77**, 6716 (1972).
32. S. A. Curtis, L. H. Brace, H. B. Niemann, F. L. Scarf, *ibid.* **90**, 6631 (1985).
33. R. G. Knollenberg and D. M. Hunten, *ibid.* **85**, 8039 (1980).
34. W. J. Borucki, *Icarus* **52**, 354 (1982).
35. M. A. Williams, E. P. Krider, D. M. Hunten, *Rev. Geophys.* **21**, 892 (1983).
36. W. J. Borucki, *Seventh International Conference on Atmospheric Electricity* (American Meteorological Society, Boston, 1984), preprint vol., pp. 476–480.
37. S. C. Solomon and J. W. Head, *J. Geophys. Res.* **87**, 9236 (1982).
38. D. B. Campbell, J. W. Head, J. K. Harmon, A. A. Hine, *Science* **226**, 167 (1984).
39. V. A. Krasnopolsky, *Planet. Space Sci.* **31**, 1363 (1983).
40. A. D. Del Genio and W. B. Rossow, *Icarus* **51**, 391 (1982).
41. V. L. Barsukov *et al.*, *J. Geophys. Res.* **91**, D378 (1986).