Evidence of Lightning and Volcanic Activity on Venus: Pro and Con

H. A. Taylor, Jr., and P. A. Cloutier (*1*) address the question of present-day volcanic activity on Venus largely in terms of a proposed re-interpretation of certain plasma wave observations from the Pioneer Venus Orbiter (PVO). They assert that the subset of plasma wave data attributed by us and our colleagues to Venus lightning (*2–4*) forms the primary basis for the concept of active volcanism on Venus. They then reiterate their concept that statistical correlations with ion spectrometer observations can be used to identify plasma wave modes (*5*), and they argue that the waves we identify as electromagnetic whistler signals from atmospheric discharges are actually associated with local plasma instabilities. They then present deductions about Venus topography based on their interpretation of a previously unpublished table of PVO wave events; from this they propose that the impulsive noise bursts are detected in regions that are distributed randomly around the planet and conclude that "Venus is no longer active."

We believe that the impulsive 100-Hz noise bursts detected with the use of the electric field antenna on the PVO have plasma wave characteristics that can only be explained if they are whistler mode signals of a type that can be produced by atmospheric discharges. These waves tend to exhibit clustering in the Aphrodite highlands, as we originally noted (*3*).

The PVO was inserted into Venus orbit on 4 December 1978, but the spacecraft did not make measurements in the planetary shadow until January 1979. During these Venus nightside traversals, solar array noise was absent and the electric field instrument detected impulsive noise bursts with wave frequencies less than the local electron cyclotron frequency. The wave investigators (*2–4*) related a subset of these bursts to the impulsive electromagnetic noise bursts previously detected within the Venus atmosphere by the magnetic loop antennas on the Soviet spacecraft Venera 11 and 12 (*6*). Taylor and his associates have proposed (*1, 5*) that these 100-Hz noise bursts represent other plasma wave modes (specifically ion acoustic oscillations) generated by local plasma instabilities. However, when we try to identify the wave mode in a conventional manner by using plasma physics and concentrating on actual characteristics of the waves themselves (the frequency spectra and the polarizations), we conclude that the Pioneer events are electromagnetic whistler mode signals of the type commonly associated with detection of lightning signals above a planetary ionosphere.

Figure 1 shows the amplitudes detected in the four plasma wave bandpass channels, along with the density of heavy ions and the magnetic field strength measured during a 1979 nightside traversal when the PVO periapsis was low (altitude = 146 kilometers). The results are typical of the designated data set in the sense that (i) the impulsive 100-Hz waves are only detected when the electron cyclotron frequency, f_c^-, exceeds 100 Hz and (ii) no corresponding signal appears in the more sensitive higher frequency channels. These characteristics demonstrate that Doppler shifts do not affect the waves in question; that is, as the PVO travels through the plasma medium with a speed *V*(orbiter), the frequency measured in the spacecraft frame is Doppler-shifted to

$$f' = f[1 + V(\text{orbiter})\cos\theta/V(\text{phase})] \quad (1)$$

where *V*(phase) is the phase speed of the wave as it propagates through the plasma, and θ is the angle between the spacecraft velocity vector and the direction of wave propagation. Since Doppler shifts are not important, and since cos θ is generally finite (*8*), we conclude that *V*(phase) is much greater than *V*(orbiter). This indicates that the 100-Hz impulses are whistler mode waves because, for the parameters of Fig. 1, *V*(orbiter) is near 10 km per second, *V*(phase) for whistlers is approximately 100 to 1000 km per second, and *V*(phase) for local plasma waves is near 1 km per second (*9*). The point is reinforced by a quantitative calculation of the Doppler shift for presumed local plasma waves; we derived the numerical values for $\Delta f = f' - f$ shown at the top of Fig. 1 using the exact velocity vector for the PVO, the measured value of the magnetic field vector, and the calculated value for *V*(phase) for an ion acoustic wave. If the 100-Hz noise bursts had actually been ion acoustic waves, they would have readily

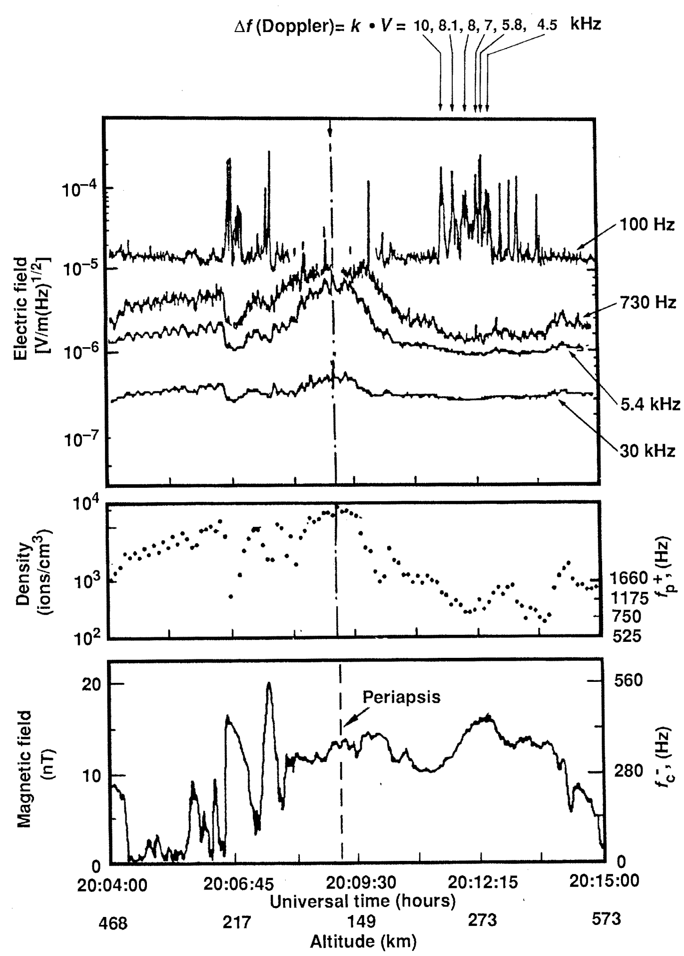

Fig. 1. PVO data for an early orbit (66) when periapsis was low. Four channel electric field measurements are plotted on a common amplitude scale with the ion density from Taylor's mass spectrometer (*1*) and the magnetic field strength (*B*) in nanoteslas. The characteristic frequencies of a plasma, the electron cyclotron frequency, f_c^-, and the ion plasma frequency, f_p^+, are shown on the right (*7*); Doppler frequency (Δf) is also indicated.

appeared in the 730-Hz and 5.4-kHz channels; since the bursts were not detected in these channels, we conclude that V(phase) is high and that the waves are whistlers (*10*).

In a magnetized plasma, the primary low-frequency wave modes (whistlers and ion acoustic waves) both tend to propagate in the direction of the magnetic field vector **B** (*6*), but the two modes have different polarizations. Whistlers are electromagnetic and the electric field vector **E** is perpendicular to **B**, while ion waves are compressional and **E** is essentially parallel to **B**. Thus, the mode is readily identified by examining the actual wave polarization with respect to **B** (*11*).

Figure 2 shows how the polarization analysis yields a conclusive whistler mode identification for the 100-Hz signals. Panels A and B have plots of electric field strength versus angle with respect to the magnetic field. These waves have **E** perpendicular to **B** and thus are electromagnetic (*12*); since $f < f_c^-$, they are designated as whistlers (*13*).

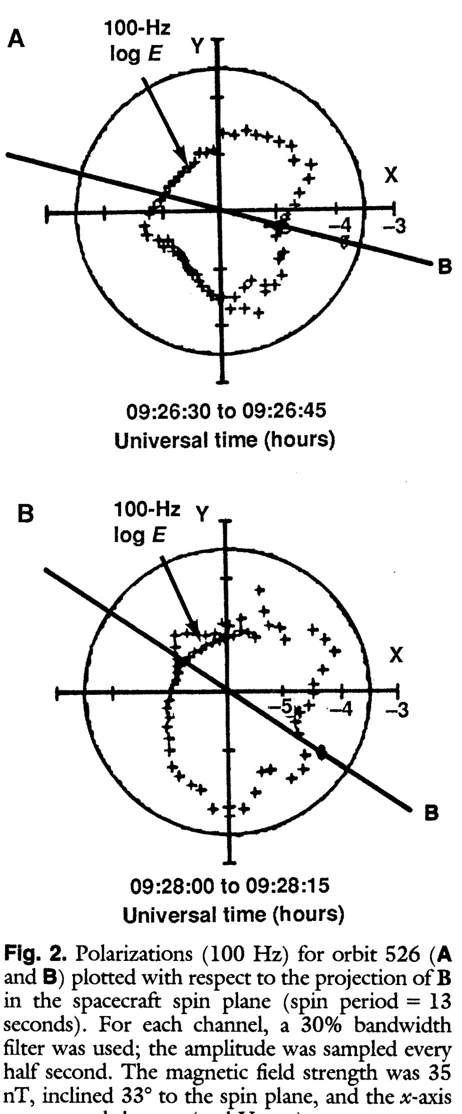

Fig. 2. Polarizations (100 Hz) for orbit 526 (**A** and **B**) plotted with respect to the projection of **B** in the spacecraft spin plane (spin period = 13 seconds). For each channel, a 30% bandwidth filter was used; the amplitude was sampled every half second. The magnetic field strength was 35 nT, inclined 33° to the spin plane, and the x-axis was toward the sun (and Venus).

Panels A and B in Fig. 3 show a Mercator projection of the Venus surface. We (*3*) used a plasma wave data set from orbits 1 through 1185 and tried to identify lightning sources by tracing rays along **B** from the PVO down to the surface. Panel A shows the 5° by 5° regions that contained three or more intense and persistent whistler mode events, with each "event" defined as a sequence of closely spaced bursts with intensities at least one order of magnitude above instrument background.

The map derived from this data set (Fig. 3A) suggests clustering of these strong signals near Beta and Phoebe and at the eastern edge of Aphrodite. In order to test the sensitivity of this result to the way in which these events were counted, we repeated the analysis in 1984 and 1985 using a new definition of an event; we selected a fixed threshold level (minimum value) of the electric field E(min), near 20 microvolts per meter per root hertz, and made a separate tabulation of all the points with electric fields greater than E(min) that satisfied the lightning whistler criterion (that is, activity in the 100-Hz channel only, with the magnetic field magnitude high enough so that f_c^- was greater than 100 Hz and **B** oriented toward the planet; we made these determinations using high-resolution data records identical to those on file at the National Space Science Data Center). According to the new definition, a strong single event from the "original" list can correspond to a large number of events from the "new" list. The uniform distribution of points in figures 3 and 4 of Taylor and Cloutier (*1*) appears to be caused by an "over-exposure" of the plots, as the "new" data set has many more points.

Figure 3B shows the results derived from the "new" data set for a total of 15 events in a 5° by 5° square. As expected, a 15-event accumulation from the new list is comparable to a 3-event accumulation from the original list; and for each map we have roughly the same number of total points. Comparison of the two maps reveals some significant changes, especially in the Beta-Phoebe region; that is, with the new definition of an event, there is no real indication that these western highlands are favored source regions. However, our reanalysis reinforces our initial conclusion that the eastern edge of Aphrodite Terra is a likely source region for clusters of whistler mode noise bursts.

The tabulation of the "new" data set was furnished to Taylor in February 1985, and Taylor and Cloutier used the list to make up their maps (*1*); but they do not note crucial distinctions between the event definitions in the original and the new data sets. For instance, in (*1*) they reproduce the upper map of Fig. 3 (their figure 2B) and com-

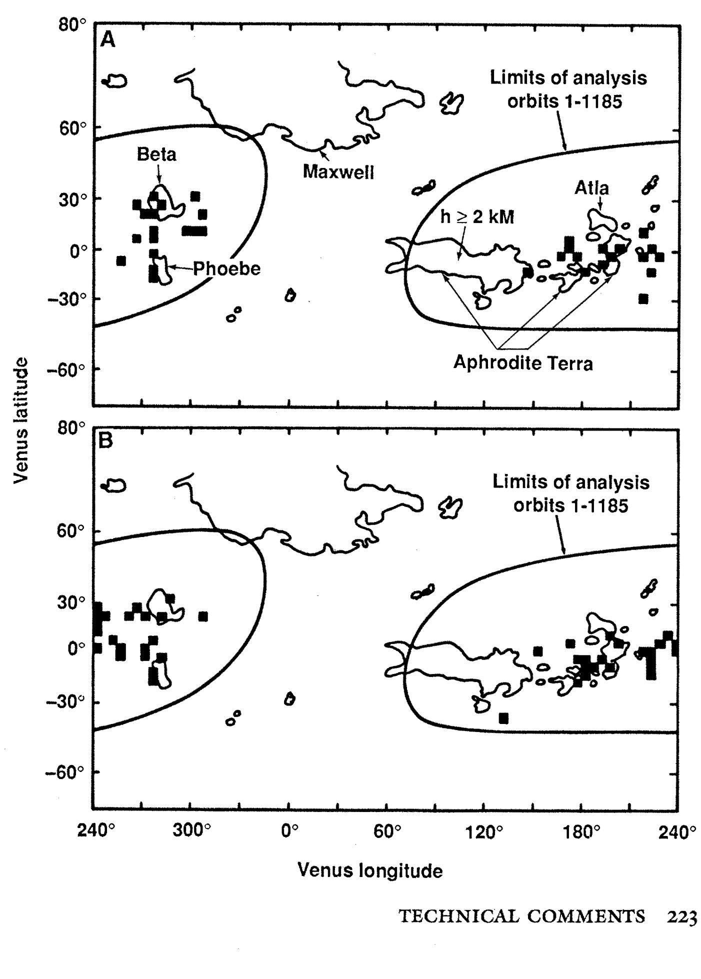

Fig. 3. (**A**) Map showing outlines of the Venus highlands and 5° by 5° squares with three or more large events (PVO orbits 1 through 1185). (**B**) "New" map for PVO orbits 1 through 1185 based on a new way of counting individual events (both large and small).

ment correctly that it contains 33 points with three or more events in a 5° by 5° square. However, they then state, "We identified considerably more surface regions with three or more events than those shown in Fig. 2," and in their figure 3B they show a map in which the same numerical criterion is used (three events in a 5° by 5° square), but with the new data set. They end up with a map containing more than 250 "clustered events" that they compare with the one we produced (*3*). They then state that "the frequency distributions for 5, 10, and 15 points per surface region show the same results; there is no evidence for clustering"; in fact, as shown in Fig. 3, the 15-point distribution from the new data set continues to show clustering.

Taylor and Cloutier state that the PVO plasma wave "scenario, including proposed evidence of clustering of lightning over surface highland regions, has encouraged the acceptance of currently active volcanic output. . . ." However, the first suggestion of active volcanism on Venus was published in 1967 (*14*); Ksanfomaliti commented on the possibility of lightning from an erupting volcano in his 1979 papers on the Venera wave measurements (*15*, *6*). In the period from 1979 to 1982 more discussions of this concept arose because of direct measurements in the interior, surface, and atmosphere of Venus (Venera landing photographs; radar maps for Arecibo, PVO, and Venera 15 and 16 showing volcanic structures, absence of plate tectonics, and high radar reflectivity; and observations of atmospheric sulfur content). Critical information suggesting present-day volcanism includes discussions of gravity anomalies (*16*) and, in their discussion of heat transport on Venus, Solomon and Head (*17*) stated, "the Venus surface, if most of the heat loss occurs by volcanism, should be densely covered with thousands of distinct centers of current or recent volcanic activity." These concepts are supported by subsequent detailed analysis of the ages of the volcanic structures on the Venus surface (*18*) and by PVO measurements of SO_2 variability since 1978 (*19*).

Indirect but significant support for the volcano concept also comes from ray tracing with the Venera and PVO wave data, studies of atmospheric chemistry, and variations in the haze characteristics (*20*), and from a re-analysis of one Venera 9 optical event originally discussed by Krasnopol'skii in terms of detection of lightning flashes (*21*). The intensity of the Venera event detected on 26 October 1975, however, was much too high to have indicated lightning, and Venera may have detected a volcanic eruption that could have served to initiate the SO_2 enhancement subsequently observed by the PVO. In short, there are many reasons to believe that Venus has active volcanism, quite independent of the wave observations.

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REFERENCES AND NOTES

1. H. A. Taylor, Jr., and P. A. Cloutier, *Science* **234**, 1087 (1986).
2. W. W. L. Taylor, F. L. Scarf, C. T. Russell, *Nature (London)* **279**, 1979; L. V. Ksanfomaliti, F. L. Scarf, W. W. L. Taylor, in *Venus*, D. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, AZ, 1983), pp. 565–603; F. L. Scarf, *Adv. Space Res.* **5** (no. 8), 31 (1985).
3. F. L. Scarf *et al.*, *J. Geophys. Res.* **85**, 8158 (1980).
4. F. L. Scarf and C. T. Russell, *Geophys. Res. Lett.* **10**, 1192 (1983).
5. H. A. Taylor, Jr., J. M. Grebowsky, P. A. Cloutier, *J. Geophys. Res.* **90**, 7415 (1985); *ibid.* **91**, 4599 (1986); H. A. Taylor, Jr., *Eos* 67, 501 (1986); *ibid.*, p. 644 (1986); see also *Sci. News* **129**, 214 (5 April 1986) and *New Sci.* **110**, 35 (15 May 1986).
6. L. V. Ksanfomaliti, *Nature (London)* **284**, 244 (1980).
7. For electrons, f_c^{-1}, in hertz, equals 28 *B*, where *B* is the magnetic field magnitude in nanotesla; f_p^- equals 9000 $(N)^{1/2}$, where *N* is the number density in cubic centimeters. For positive ions with mass number *M* (in proton masses), we find $f_c^+ = f_c^-/1846\,M$ and $f_p^+ = f_p^-/[1846\,M]^{1/2}$.
8. In a magnetized plasma, the wave modes of interest all propagate nearly parallel to **B**.
9. For whistlers, *V*(phase) is approximately $c\,[f_c^-]^{1/2}/f_p^-$, where *c* is the speed of light; for local plasma oscillations such as ion acoustic waves, *V*(phase) is approximately $[kT/m_i]^{1/2}$, where *k* is Boltzmann's constant, *T* is the electron temperature, and m_i is the actual ion mass, which we take to be the mass of an oxygen ion. See, for instance, *The Theory of Plasma Waves* by T. H. Stix (McGraw-Hill, New York, 1962) for further details about the wave characteristics.
10. True examples of ion acoustic waves are readily found in the Orbiter data set. One type appears in Fig. 1; the relatively smooth high-frequency peak centered around periapsis has been explained by S. A. Curtis *et al.* [*J. Geophys. Res.* **90**, 6631 (1985)] in terms of ion acoustic waves generated by CO_2 impact ionization. F. L. Scarf *et al.* [*Adv. Space Res.* **5**, 185 (1985)] have provided additional examples of ion acoustic waves associated with auroral-type field-aligned currents. In all of these cases the spectrum extends to the upper channels in a manner consistent with the Doppler shift analysis.
11. The analysis of the wave amplitude as a function of the angle between the electric antenna and the projection of **B** in the spin plane can be carried out when (i) **B** has a large component in the spacecraft spin plane and (ii) the duration of the wave sequence is comparable with the 13-second Pioneer Venus spin period. Since most of the 100-Hz bursts occur on time scales that are short when compared with 13 seconds, we have not used this technique in previous publications.
12. For real ion acoustic waves, such as the broadband enhancements detected near periapsis and attributed to CO_2 impact ionization, we find a polarization peak parallel to **B**.
13. The correlation of the occurrence of these waves with the presence of ion (and electron) troughs has a simple explanation in terms of lightning-generated whistler waves. That is, the radial magnetic configuration that allows the signals to propagate upward through the ionosphere also tends to allow plasma diffusion away from the planet, as noted by Scarf *et al.* (*3*). These density depletions can form whistler ducts that help guide the signals to the spacecraft.
14. G. T. Davidson and A. D. Anderson, *Science* **156**, 1729 (1967).
15. L. V. Ksanfomaliti, *Kosmich. Issled* 17, 747 (1979).
16. R. J. Phillips and M. C. Malin, in *Venus*, D. Hunten, L. Colin, T. M. Donahue, Eds. (Univ. of Arizona Press, Tucson, AZ, 1983), pp. 159–214. This paper, prepared before publication of the Scarf-Russell map (*4*), contains a drawing showing an active volcano at Beta Regio.
17. S. C. Solomon and J. W. Head, *J. Geophys. Res.* **87**, 9236 (1982).
18. D. B. Campbell, J. W. Head, J. K. Harmon, A. A. Hine, *Science* **226**, 167 (1984).
19. L. W. Esposito, *ibid.* **223**, 1072 (1984).
20. L. V. Ksanfomaliti, in *Advances in Space Research*, vol. 4 (Pergamon, Elmsford, NY, 1985), pp. 91–98.
21. V. A. Krasnopol'skii, in *Venus*, D. Hunten, L. Colin, T. M. Donahue, Eds. (Univ. of Arizona Press, Tucson, AZ, 1983), pp. 459–483.
22. Research at TRW supported by the Pioneer Project at NASA Ames Research Center under contract NAS2-12319; research at UCLA supported under Pioneer contract NAS2-12383 and NASA Headquarters grant NAGW-995.

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Response: Scarf and Russell (*1*) raise issues that may distract the reader from the central theme of our article (*2*), namely, that the electric field measurements by the Pioneer Venus Orbiter (PVO) are unrelated to either the lower atmosphere or the surface of Venus. In addition, Scarf and Russell make several assertions that we believe are inconsistent with past interpretations and are incorrect. Our specific responses are as follows.

Scarf and Russell contend that the PVO electric field noise is topographically related. In our article, we emphasized that the 100-Hz noise attributed to lightning and volcanism was not, as Scarf and Russell state, uniquely clustered over highland topography, but rather that the noise appears randomly across the nightside of Venus. We provided ample evidence to support this perception in our figures 3 and 4. In their figure 3, Scarf and Russell present noise distributions from only a portion of the complete data set and state that these noise events are clustered over the highlands. However, these restricted results do not provide convincing evidence for highland clustering of the noise.

When a more extensive set of data is shown, it is readily apparent that the noise distribution is widespread, not clustered. To verify this point, we show in Fig. 1 the distribution of 100-Hz noise attributed to lightning by Scarf and Russell for all PVO orbits up to orbit 1895. By comparing panels A and C of this figure it may be seen that the vast majority (~85%) of the 100-Hz events are observed outside the outlines of the highland regions. Figure 1 also illustrates the nightside tracks of the Soviet Vega 1 and 2 balloons, which traversed regions