SIGNATURES OF SOLAR WIND INTERACTION WITH THE NIGHTSIDE IONOSPHERE OF VENUS

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(Received 23 January, 1995)

Abstract. Plasma and field relationships observed across the nightside of Venus evidence a chaotic variety of interactions between the ionosphere and the combined effects of the solar wind and interplanetary magnetic field draped about the planet. Close examination of these data reveal within the chaos a number of repeatable signatures key to understanding fundamental field-plasma interactions. Observed from the Pioneer Venus Orbiter, (PVO), nightside conditions range from extensive, "full-up" ionospheres with little evidence of dynamic or energetic perturbations, to an almost full depletion, sometimes described as "disappearing ionospheres". Between these extremes, the ionospheric structure is often irregular, sometimes exhibiting well-defined density troughs, at other times complex intervals of either abundant or minimal plasma concentration. Consistently, large B-fields (typically exceeding 5–10 nanoteslas) coincide with plasma decreases, whereas stable, abundant plasma distributions are associated with very low-level field. We examine hundreds of nightside orbits, identifying close correlations between regions of elevated magnetic fields featuring polarity reversals, and (a) exclusive low-frequency or distinctive broadband noise, or both, in the electric field data, (b) turbulent, superthermal behavior of the the ions and electrons. We review extensive studies of nightside fields to show that the correlations observed are consistent with theoretical arguments that the presence of strong magnetic fields within "normal" ionospheric heights indicates the intrusion of magnetosheath fields and plasma within such regions. We find abundant evidence that the "ionosphere" is frequently disrupted by such events, exhibiting a chaotic, "auroral-like" complexity appearing over a wide range of altitude and local time. We show that field-plasma disturbances, widely suggested to be similar to conditions in the Earth's auroral regions, are tightly linked to the electric field noise otherwise attributed to lightning. Owing to the coincidence inherent in this relationship, we suggest that natural, predictable plasma instabilities associated with the plasma gradients and current sheets evident within these events produce the E-field noise. The data relationships argue for a more detailed investigation of solar wind induced E-field noise mechanisms as the appropriate scientific procedure for invoking sources for the noise previously attributed to lightning. Consistent with these views, we note that independent analyses have offered alternative explanations of the noise as arising from ionospheric disturbances, that repeated searches for optical evidence of lightning have found no such evidence, and that no accepted theoretical work has yet surfaced to support the inference of lightning at Venus.

1. Introduction

Well in advance of the arrival of the Pioneer Venus Orbiter (PVO) at Venus, in December, 1978, investigators speculated about how the long Venus night and the suspected weak or absent magnetic field, might affect the formation and stability of the ionosphere. Those of us involved with the design and testing of the Orbiter Ion Mass Spectrometer (OIMS), were challenged by the perception, suggested by or Co Investigator R. Hartle, (Goddard Space Flight Center) that owing to the predicted

Earth, Moon and Planets **69:** 173–199, 1995.

lack of shielding by a strong intrinsic magnetic field, The PVO might encounter an ionosphere of auroral-like complexity over much of the planet. Such a possibility was sobering, in view of known difficulties encountered by direct measurement plasma instruments used to investigate perturbations common in the auroral regions of the Earth ionosphere. For example, we had found earlier that retarding potential analyzers flown on the Orbiting Geophysical Observatories often were unable to "track" abrupt and highly structured plasma depressions, detected as "troughs", in the high-latitude ionosphere (e.g. Taylor and Walsh, 1972).

At Earth, troughs mark the boundary between the normally thermal, undisturbed ionosphere distributed across latitudes below about 60 degrees, and the high-latitude regions where often chaotic field and particle variations result in the formation of auroras, and related polar ionospheric disturbances, including superthermal ions, and fast flowing plasmas. Even rather sophisticated thermal ion mass spectrometers designed to accommodate a greater degree of fluctuations were challenged to detect accurately the details of such complex regions. Consequently, considerable effort was invested to design and test the OIMS to enable it to cope as fully as possible with such conditions (Taylor *et al.*, 1980).

On arriving at Venus, the PVO plasma instruments did indeed encounter a highly variable ionosphere. The evident absence of an intrinsic field results in a direct and complex interaction between the interplanetary magnetic field (IMF) and the Venus ionosphere. Owing to the long Venus night direct photoionization of the nightside is absent, yet a substantial nightside ionosphere was often observed, understood to result primarily from convection of dayside ions into the night (e.g. Taylor *et al.*, 1979), and secondarily from in-situ impact ionization by precipitating electrons (e.g. Spenner *et al.*, 1981). Since the plasma flow is interactive with the highly variable solar wind and IMF structure, it is understandable that rapid, complex variations appear in both the dayside and nightside regions. Since the nightside plasma, both transported and locally produced, is totally responsive to the changing solar wind/IMF variability, it follows that the degree of ionospheric variability is largest there, and particularly in regions where the flowing plasma and entrained draped magnetic field divert toward midnight and lower altitudes, to fill-in the wake region. Consequently ionospheric complexity familiar at high latitudes at Earth appears at Venus in analagous, chaotic forms across much of the nightside. This view is supported in repeated analyses of the Venus data, as will be discussed in later sections.

Numerous studies have reported experimental results and theoretical models attempting to sort out the nightside complexity (e.g. Luhmann and Cravens, 1991; Luhmann, 1992; Luhmann and Russell,1992). In these and earlier studies, it was recognized that during periods of increased solar wind pressure, the dayside ionosphere is compressed and interplanetary field lines may penetrate within the otherwise thermal plasma envelope. Luhmann, (1992) emphasizes that in analogy with the dayside field intrusions, the appearance of anomalously strong magnetic fields ranging from about 5–40 nanoteslas, within the "normal" nightside ionospheric envelope indicate a disruptive anomaly. Intruding B-field enhancements were confirmed by Luhmann to be directly correlated with thermal plasma depletions, labeled variously as either "troughs" or "holes." Luhmann interpreted these regions as marking the penetration of ionosheath-ionotail magnetic fields and associated disturbances to very low altitudes deep within the nominal nightside ionosphere. In the next section, we illustrate "classic" examples the field-plasma relationships associated with these types of intrusions.

2. Observed, Repeatable Field-Plasma Relationships

2.1. IONOSPHERIC STATES: "FULL-UP, TROUGHED, AND DISAPPEARING"

Owing to the extreme variability of the solar wind/IMF, the nightside ionosphere is so variable that for the most part, only relatively large-scale, quasi-repeatable "signatures" have usually been recognized and discussed. However as one examines large-scale features more closely, still smaller structures become evident as repeatable events, and are found to be widespread. However, as background for addressing the significant smaller-scale events, we first illustrate three field-plasma relationships identified in earlier studies as semi-repeatable large-scale conditions.

Three ionospheric states to which we refer as (a) the "full-up" ionosphere, (b) the "troughed ionosphere", and (c) the "disappearing ionosphere" are shown in Figure 1. In the upper panel, orbit 547 is an example of a dense, wide ranging ionosphere usually occupying much of the shadowed nightside of the planet, extending from about 60 °N latitude across periapsis to about 60 °S latitude. Except for the ionopause regions, near 1000 km inbound and 1500 km outbound in this example, the "full-up" ion profile exhibits regions of a steady "thermal", or undisturbed character, as would frequently be observed at mid to low latitudes in the Earth ionosphere during quiet, stable solar wind conditions.

On orbit 547 significant ion depletion events are encountered on either side of periapsis. These events are often marked by distinct density gradients, and have horizontal scales which can range from several to hundreds of kilometers. These plasma depressions, recognized as ion composition anomalies linked with B-field enhancements were reported by Taylor *et al.* (1980), and considered as troughs in the thermal concentrations. Subsequent studies found these depressions to be widespread throughout the nightside data, (e.g. Brace *et al.*, 1982; Marubashi *et al.*, 1985; Taylor *et al.*, 1985, Luhmann and Russell, 1992, and Hartle and Grebowsky, 1993). In some cases, authors refer to these regions as "holes", while others identify them as "troughs." Owing to (a) their analogy with well-known "trough" events in the Earth ionosphere, and (b) the fact that the evidence indicates that these events consist of depressions, not a total absence of plasma, we shall refer to the events hereafter as "troughs."

Authors investigating troughs consistently identify these events as resulting from direct interaction of the solar wind with the ionosphere. Marubashi *et al.* inter-

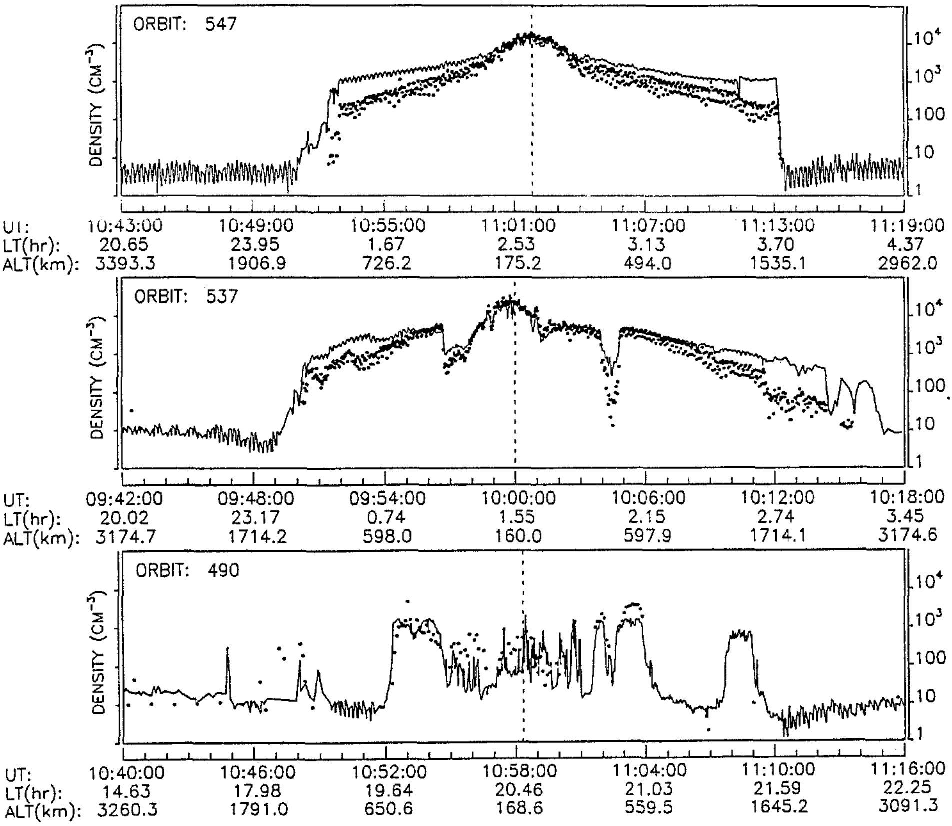

Fig. 1. Three states of the Venus nightside ionosphere: (top) full-up and quiet, (middle) troughed, and (bottom) disappearing with highly disturbed structure. Solid line shows electron density (Ne) from high resolution OETP. Dots show total unflagged (nominal measurements) of OIMS ion density (Ni). Short period spacecraft spin modulation is evident. Apparent offset between Ne and Ni in this and later figures may result from differences in instrumental response to varying plasma flow. Dashed line shows periapsis location.

preted the troughs as resulting from PVO crossings of the ionopause, in regions where the action of anti-sunward flow of plasma and magnetosheath fields compress the ionopause, below the PVO orbit. Thus as the PVO enters the trough it temporarily exits the thermal ionosphere into a zone of variable dimension, accessible to the field and particle disturbances associated with the ionosheath-magnetotail regions.

In orbit 490, a classic example of a "disappearing ionosphere" (hereafter referred to as "DI") exhibits a profile dramatically different from the prior two examples. In this pass, the sense of reference sometimes provided by the undisturbed ionospheric arc is totally absent, replaced with a chaotic series of structures. Of course, since the PVO samples only a narrow arc spanning nightside latitudes, the overall status of the nightside plasma distribution cannot be known. Marubashi *et al.* reasoned that the Dl appears on orbits coinciding with sufficiently high solar wind pressures that the normally encountered ionosphere is compressed below the orbit, throughout the pass, i.e. an extension of the trough, to affect all or much of the nightside pass.

As in the case of orbit 490, the DI plasma profile is typically quite structured. Often, plasma densities may either drop to background levels or at most attain levels of 10/cm^3 as seen near 10:51 and 11:11 UT. At other times, significant increases in plasma appear, such as near 10:47 and 11:03 UT, but these may be found to be composed of superthermal plasma. We will discuss the field and plasma details of this orbit and two other DI passes in Section 2.3.

2.2. TROUGHS AND ASSOCIATED LOW-FREQUENCY E-FIELD NOISE

Interdisciplinary investigations of the ion troughs reported by Taylor *et al.*, (1985) and Taylor and Cloutier (1986) have shown that these events are widespread across the nightside, exhibiting no planetographic bias. The troughs are singularly correlated with the appearance of "low-frequency" electric field noise appearing exclusively at 100 Hz. This noise is usually characterized by a "turn-on, or off", coincident with the trough boundaries. Figure 2 presents examples of the field-plasma relationship in well-defined troughs. In some, the depth of depletion indicated in the ions exceeds that of the electrons, an effect which may be linked to the inability of the OIMS to accommodate fast, off-axis ion flows which may appear within the troughs. As reported by Hartle and Grebowsky (1993), troughs are found to consistently exhibit strong outward ion flows. Of course, the presence of such flows testifies directly to the anomalous character of the troughs, and to the inevitable association of plasma instabilities and resultant field noise in these regions.

Typically, O_+ is the dominant species outside the troughs. Within troughs, O_+ drops off quickly leaving H_+ as the dominant constituent. We add the caveat however that there exists some uncertainty in abundance measurements resulting from instrument limitations within the troughs. Unambiguous characteristic troughs are typically found above 400 km and in these cases, the magnetic field is essentially characterized by a dominant vertical component. We have found, among many passes, similar, but less well defined trough structures at lower altitudes. At the lower altitudes, the trough field polarity becomes increasingly horizontal.

It is evident from Figure 2, and many other examples too numerous to illustrate that the appearance of the 100 Hz noise and the plasma depressions are persistently coincident. As reported by Taylor and Cloutier (1986) the vast majority of thousands of impulsive noise events tabulated by F. Scarf as evidence of lightning appear within ion troughs, whereas outside the ion trough-field enhanced regions, the appearance of similar noise exclusively at 100 Hz is insignificant, and has never been reported to our knowledge as providing evidence for lightning. From our recurrent examination of hundreds of nightside orbits, the evidence is clear: *when a noticeable ion trough is encountered, the 100 Hz noise ubiquitously appears.*

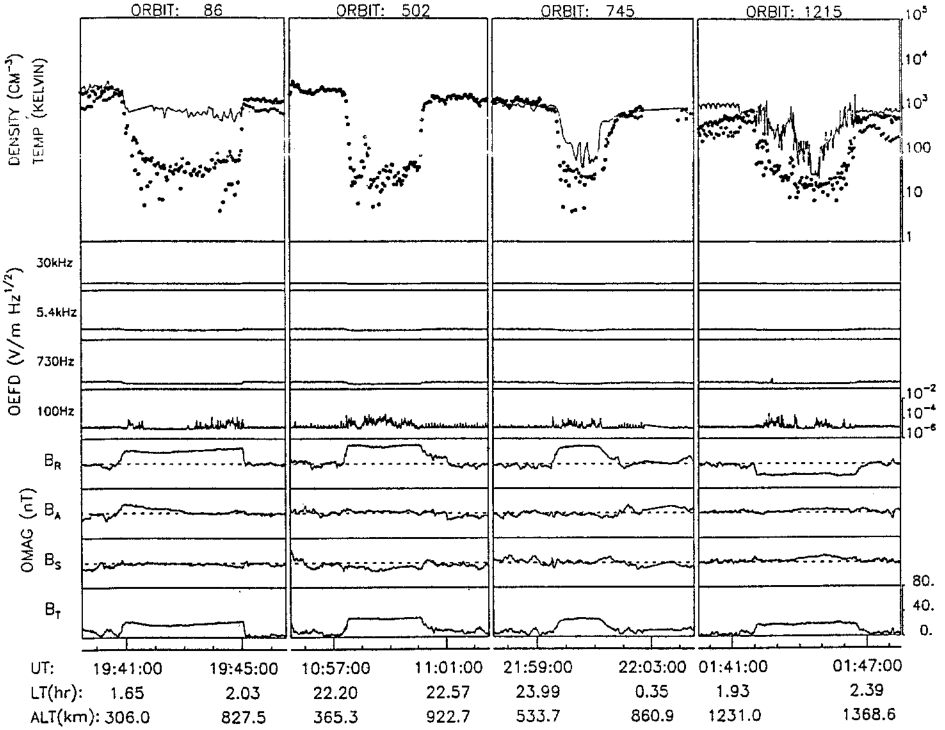

Fig. 2. Four examples of well defined plasma troughs tightly correlated with strong steady vertical magnetic field and impulsive 100 Hz electric field noise. Ne (solid line) is not available for orbit 502. Dots show Ni.

The coincidence between strong fields and plasma troughs is so well established that detailed studies of the large-scale magnetic fields on the nightside by Luhmann and Russell (1992) have concluded that "magnetic signatures" of troughs are readily apparent, and extend to the lowest periapsis altitudes, down to at least 145 kilometers. This recent result provides a new perception for the plasma stability expected for low-altitude periapsis regions, since earlier studies (e.g. Brace *et al.* 1981; Grebowsky and Curtis, 1981; Luhmann *et al.*, 1982) reported that troughs were not present below 200 kilometers. Luhmann and Russell substantiate their report with illustrations of several examples of these very low-altitude magnetic signatures, noting that the electron density measurements have confirmed the presence of troughs for each of the field signatures. In this and earlier studies, (Luhmann *et al.* 1982; Grebowsky *et al.*, 1983; Marubashi *et al.*, 1985, etc.) authors have consistently attributed the combined strong field-plasma depletion signatures as evidence of the incursion of magnetotail fields deep into "ionospheric" heights. We concur, noting that this interpretation of the trough signature and its connection with conditions outside the thermal ionosphere is consistent with our earlier studies of this phenomenon, (e.g. Taylor *et al.*, 1985; 1987, and Taylor and Cloutier, 1986).

We emphasize that the report of Luhmann and Russell (1992) details "well-defined" troughs, illustrating, for example, B-field variations across periapsis of orbit 526 as a prominent, low altitude event. It is remarkable therefore, that a recent investigation of factors controlling the 100 Hz E-field noise bursts by Ho *et al.* (1992) concludes that plasma concentration is "not a significant factor". Ho *et al.* support this conclusion with "case-studies" of just two key 100 Hz noise sequences, on orbits 526 and 538, stressing in particular that orbit 526 exhibits no important overall change in either total ion or electron density. Not only is this description incorrect, but in particular, it contradicts the very specific identification of a trough across periapsis of orbit 526 by coworkers Luhmann and Russell (1992) and Luhmann *et al.* (1982), as well as the statistical evidence of trough-noise relationships documented in our own studies (e.g. Taylor and Cloutier, 1986).

We confirm the report of orbit 526 by Luhmann and Russell with the illustration of the multi-parameter field and plasma behavior across the pass, in Figure 3. As seen, an anomalously strong magnetic field appears across periapsis, standing-out as an unmistakable "magnetic signature" of a an incursion of the draped magnetotail field into what would otherwise be a normal ionospheric region. Coincident with this magnetic intrusion, the noise in the 100 Hz channel turns on and off, as is often observed, in PVO crossings of more than 100 other well-defined plasma troughs. The associated disturbance in the ion and electron densities is easily seen, particularly if compared with the smooth cross-periapsis plasma distribution seen in Figure 1a. Whereas both the Ni and Ne distributions partially recover across periapsis, compared to an undisturbed pass these profiles are obviously disturbed. Further, we note that the presence of impact ionization effects at this low altitude (as discussed by Brace, 1991) could be contributing to an "apparent" recovery of thermal plasma. Clearly, either the magnetic field appearing across periapsis is of magnetotail origin or, more remotely, a planetary intrinsic field. We, as do Luhmann and Russell interpret it as magnetotail intrusion, inconsistent with nominal plasma concentrations. As a consequence of these results, we are forced to conclude that the study of Ho *et al.* (1992) was performed without adequate perception of the nature of the field-plasma relationship in troughs, resulting in an an invalid interpretation. Thus, it is evident that the study and the reported conclusions of Ho *et al.* are compromised by the failure to properly recognize this phenomenon.

Remarkably, another "magnetic signature" of a trough across periapsis illustrated by Luhmann and Russell (1992), on orbit 501, is featured as a key example of broadband E-field noise inferred as independent evidence of lightning by Russell *et al*, (1989). In opposition to this interpretation, the impulsive broadband noise on across periapsis on this orbit will be shown in Section 2.4 as evidence of the intrusions of similar field and particle disturbances encountered in DIs and troughs.

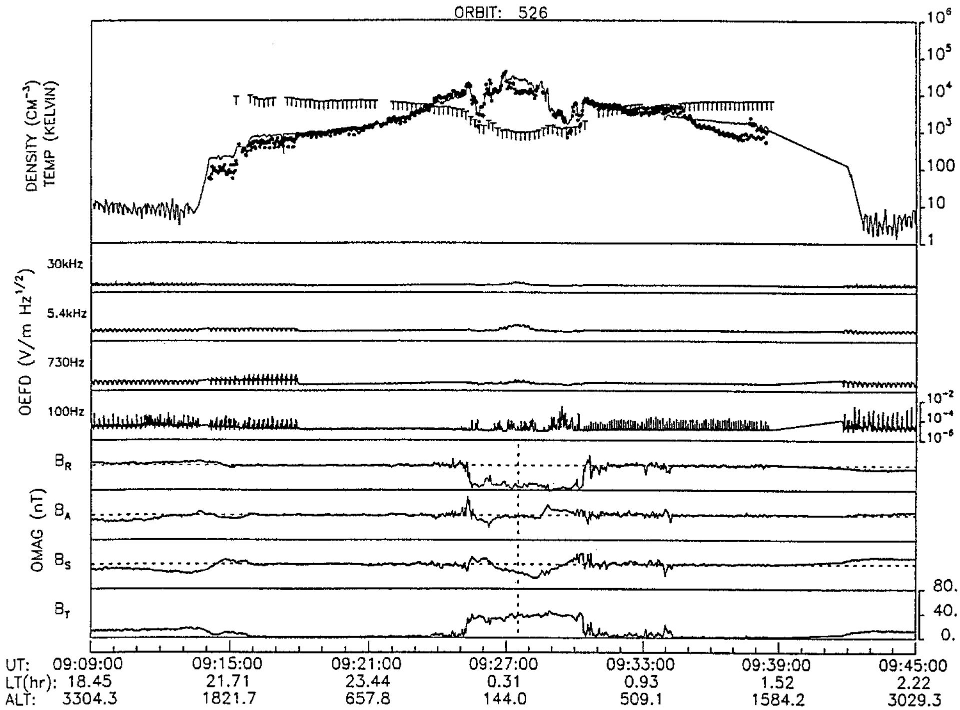

Fig. 3. Field and plasma distributions exhibiting signature of plasma trough across orbit 526. Plasma depletions coincide with boundaries of enhanced B-field and 100 Hz noise. Partial recovery of Ne and Ni at periapsis is unusual and perhaps artificial. Electron temperature (T) shows fluctuations near trough boundaries. Bulges at periapsis in E-field indicate neutral atmosphere impact ionization which interferes with interpretation.

2.3. FIELD-PLASMA EVENTS ASSOCIATED WITH DISAPPEARING IONOSPHERES

Since the flow and associated pressures exerted on the nightside plasma are so variable, it is understandable that in the case of the troughs as well the DI, the “signatures” of these events will not always be revealed as neatly defined “square-wave” events, and thus may be overlooked. During high-pressure solar wind periods, when the ionopause is lowered, the PVO track may graze the compressed ionosphere-ionosheath region. In such cases, the plasma exhibits multiple trough-like features, some very narrow, some wide, and all generally featuring evidence of superthermal, fast flowing plasma. These features are all interpreted as irregularities common to the ionopapuse region, affected by the frequently chaotic solar wind interaction. Since the development and decay times of individual depressions and flowing stream regions vary, some events will appear stronger and better developed than others which happen to be growing or dissipating.

Notwithstanding an often confusing array of irregularities, a closer inspection of the field and plasma details provides evidence that discrete field-aligned disturbances appear along many orbits which may either be designated as widespread,

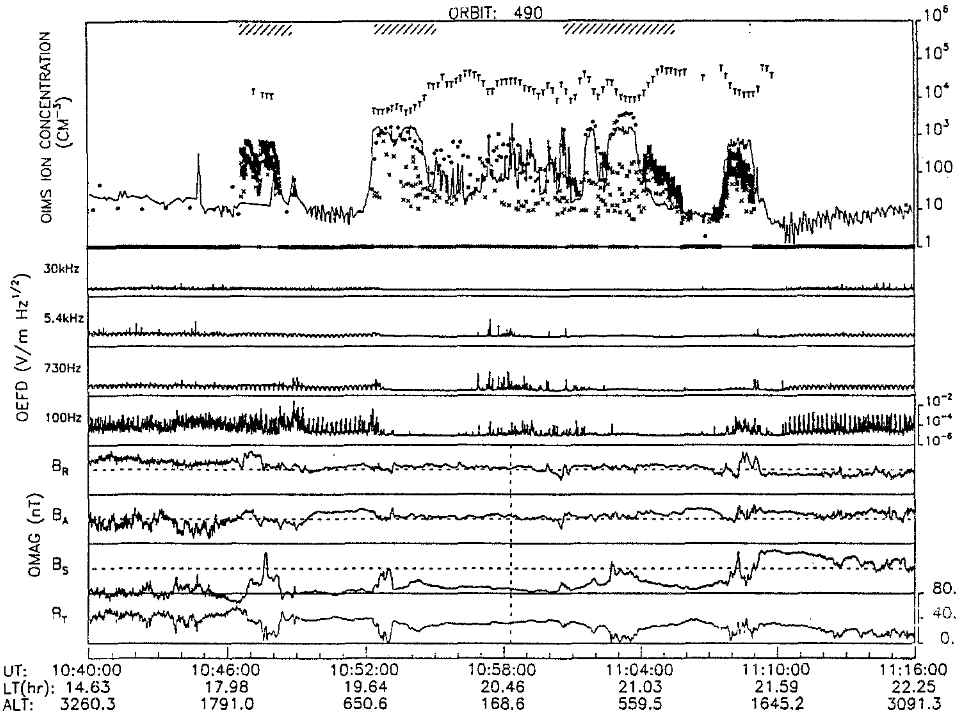

Fig. 4. Three examples of disappearing ionospheres. (a) orbit 490 is highly disturbed with sufficient fluctuations in both Ne and Ni to suggest most plasma is superthermal. Strong superthermal activity possibly involving fast flows is indicated by appearance of anomalous masses (24, 40, 44, and 56 AMU)-plotted as X's, beginning near 10:47, 10:53, 11:04, and 11:08. Each interval coincides with (1) "FAP" signatures in B, (2) impulsive noise bursts in E, and (3) ONMS detection of superthermal ions (hatched bars). Note anomalously elevated and disturbed electron temperature over most of pass. Across periapsis, wideband impulsive E-noise coincides with chaotic gradients in Ne and Ni, all appearing within the "magnetic signature" of a trough (i.e. anomalously strong, pervasive B- field within "normal"ionospheric heights.)

or partial, DI passes. In Figure 4a–c, multiparameter variations observed across orbit 490 (seen earlier in Fig. 1) and two additional DI passes, orbits 85 and 77, are presented.

Noting first the data for orbit 490, it is seen that the magnetic field is strong throughout much of the pass, at times relatively stable and horizontal in direction, at other times exhibiting sharp reversals in horizontal polarity, or even more complex changes. The ion and electron data generally appear highly disturbed particularly where the B-field either reverses or is quite strong. Coincident with several of the marked B-field reversals (which we later identify as FAP events) the OIMS, the Orbiter Electric Field Detector (OEFD), the Orbiter Electrostatic Probe (OETP), and the Orbiter Neutral Mass Spectrometer (ONMS) all provide evidence of very disturbed conditions, including superthermal plasma responses and associated wideband impulsive E-field noise.

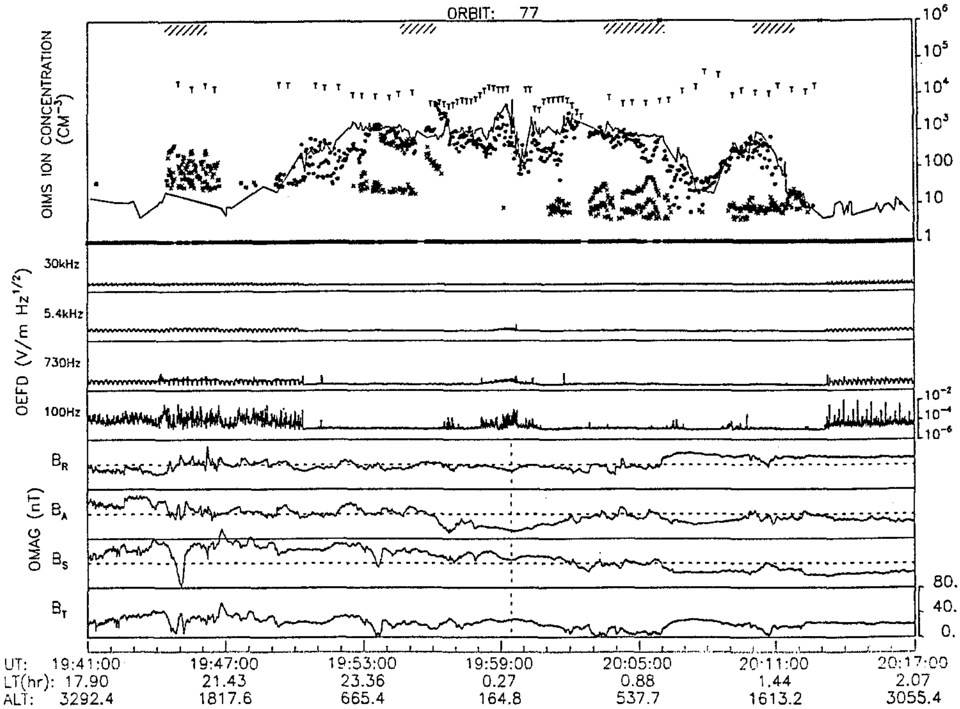

Fig. 4b. Orbit 77 also exhibits regions of coinciding perturbations in field and plasma distributions near 19:45, 19:53, 20:05, and 20:11. Although these "FAP" events are not as neatly defined as on orbit 490, the reversal in B-field polarity and associated drop in magnitude indicate current sheet configuration.

To illustrate characteristics of the associated magnetic field observations, we have presented the three magnetic field components in a coordinate system reflecting a radial component, BR, oriented vertical to the planet surface, and two horizontal components, one of which is designated BS and is the component parallel to a "great circle" arc connecting the spacecraft position to the Venus subsolar point. BS is selected to be nearly anti-parallel to the solar wind flow direction assuming the flow diverges from the subsolar point on the dayside along paths that stream around the planet, across the terminator to the spacecraft position on the nightside. The last component, BA, is orthogonal to both BR and BS in the sense that the vector B = (BR, BS, BA) are components in a right handed coordinate system.

In the case of the OIMS, anomalous ion composition ratios, and/or appearance of unexpected heavy molecular ions, constitute evidence that the plasma is superthermal in many regions of orbit 490. This interpretation is confirmed in several locations, with the coincident measurements of irregular impulsive events or appearance of ions with energies greater than 40 ev by the ONMS. Whereas neither of these instruments was designed to fully interpret the composition and energy of non-thermal particles, we infer that anomalous ion signatures in the OIMS, such as

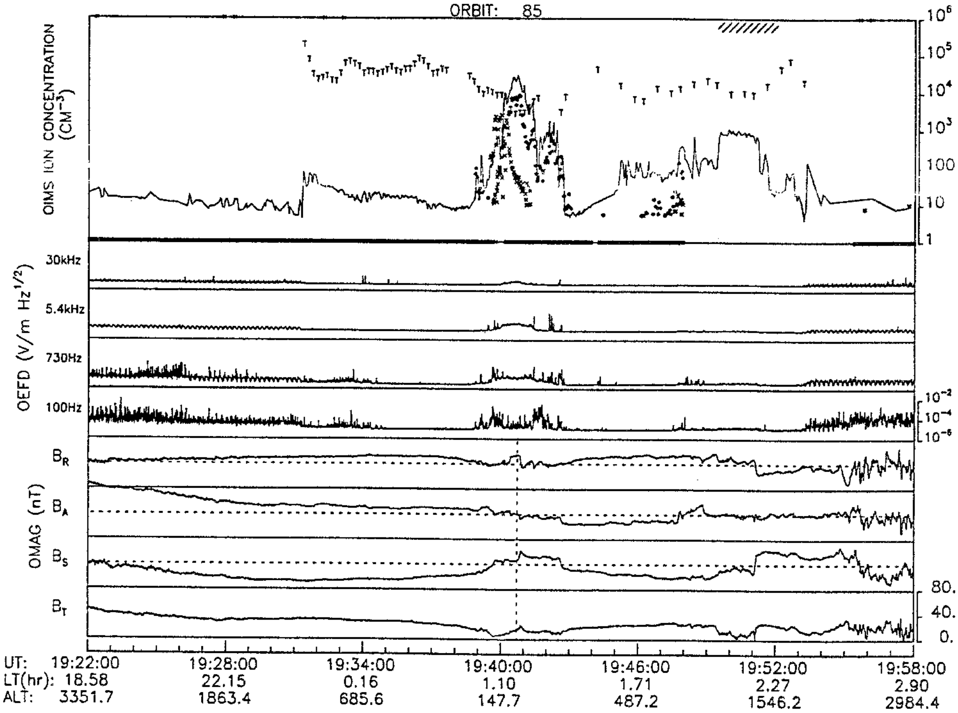

Fig. 4c. Orbit 85 also exhibits the reversal in horizontal B-field polarity and associated dips in field magnitude near 19:40, 19:42, and 19:51, indicating intrusions of non-thermal conditions to ionospheric heights. The strong asymmetry in distribution of anomalous ions (X's) across periapsis suggests that even as the lowest altitudes, the plasma is highly disturbed, and possibly superthermal.

unexpected activity in mass channels 40 and 44, which abruptly appear in plasma recovery regions near 10:47 and 11:08 UT are either accelerated by a pick-up process involved with the field-flow activity, or alternatively the ion currents at these mass positions may in part arise from mass "aliasing". For example, a lighter ion, such as the abundant atomic oxygen ions, accelerated to velocities of tens of kilometers, will have kinetic energies causing them to be detected within the OIMS at mass positions "shifted" to those of heavier ions, as for example, mass 44 The response of the OIMS to superthermal ions has treated in detail by Grebowsky *et al.* (1993) and in work now in progress.

Examination of ONMS engineering data provided courtesy of W. Kasprzak reveals a highly disturbed condition in the neutral measurements of mass 16 on orbit 490. Although the instrument was commanded into an ion mode 5 minutes after periapsis, we are able to detect impulsive indications of ion counts strongly reminiscent of similar appearing superthermal signatures is the OIMS, seen in this, and other intervals. Unfortunately, the appropriate ONMS engineering data were not completely archived, due in part to the complexity of documenting the raw data. Consequently, our examination and interpretation of possible superthermal activity cannot be as complete as desirable. We did obtain a summary listing of ONMS superthermal event intervals which are shown in Figure 4 as cross-hatched bands along the top of the figure. It is seen that these events correspond quite closely to the superthermal signatures seen in the other parameters. Adding further to the evidence of disturbed conditions along this pass, strong modulation (greater than an order of magnitude) appears in either the ion or electron densities, or both, between about 10:54 and 11:03 UT.

The second DI example, orbit 77, also exhibits a highly structured plasma distribution, across which the OIMS measurements generally indicate superthermal conditions. Across 19:44-19:47 UT strong instabilities in the B-field, including a sharp reversal in the Venus-Sun horizontal component are accompanied with increases in the E-field noise (superimposed upon a background of modulated solar-induced noise) and by a coincident appearance of a superthermal response in the OIMS, energetic ions by the ONMS and an elevated electron temperature. Unfortunately, a gap appears in the Ne distribution in this interval, possibly due to difficulty in tracking the plasma disturbance. The electron temperatures are high throughout the pass, particularly in a trough signature region, centered near 20:08. At periapsis, at altitudes below 180 kilometers, broadband E-field noise appears in the midst of anomalously high level B-field, and erratic superthermal plasma conditions, detected by both the OIMS and ONMS. Again the results from the ONMS show 4 superthermal episodes in approximately the same location as the anomalous counts in the OIMS.

In Figure 4c, orbit 85 illustrates another dramatic DI pass. The Ne profile shows moderate concentrations only at periapsis, and there the OIMS indicates what may be superthermal plasma. On the outbound leg, the highly irregular Ne profile suggests non-thermal conditions, with only a narrow indication of a "normal" plasma distribution seen near 19:51, where the B-field magnitude drops to quite low levels for several minutes. Unfortunately a gap in the OIMS data precludes verification of the nature of the ions in this region. However, an examination of ONMS pulse count data shows impulsive superthermal characteristics and the ONMS event interval database also provides evidence of a supertermal episode, indicated by the cross-hatched bar. Across periapsis, reversals in the polarity of the horizontal B-field and associated drops in the field magnitude are accompanied by broadband, impulsive E-field noise. The impulsive noise is superimposed upon a bulge-shaped offset in the dc level of the OEFD channels. We will discuss the impulsive noise below, in relation to the field aligned irregularities, or FAPs. The background level offset in the OEFD channels (not to be confused with the impulsive noise) has been interpreted by Curtis *et al.* (1985) as an instrumental response to neutral atmosphere impact ionization.

Each of the foregoing DI passes features particular field-plasma signatures, in which reversals of field direction and associated drops in field magnitude coincide with E-field noise and superthermal plasma conditions. Similar events were first discussed in detail by Scarf *et al.* (1985) and interpreted as field aligned particle precipitation events. Hereafter, we will refer to these events as FAPs, first showing further evidence of their distribution in the nightside, then discussing them in the context of the related E-field noise.

More than 1500 nightside orbits have been examined for evidence of the same type of FAP events evident in the foregoing DI events. Our results indicate hundreds of these events, confirming that the reversal of the Sun-Venus component of B, the depression in total field, and associated appearance of broadband E-field noise are widespread events, evident within and above the ionospheric heights, in darkness and in sunlit regions Most significantly, although these events have not been reported at low altitudes previously, we often find at low altitudes events exhibiting characteristics similar to the FAPs seen at higher altitudes.

In Figure 5, we illustrate a sampling of a variety of the FAP signatures illustrative of the wide-range of altitudes and times over which they are observed. Like the reversal events highlighted in Figure 4a–c, in some of the FAP events, the OIMS detects highly irregular ion distributions which appear to be superthermal. This response in the OIMS is in some regions confirmed with related clusters of superthermal ions detected by the ONMS. Unavailability of ONMS data restricts possible confirmation in other cases.

In analogy with the ion troughs, some events in Figure 5 do not exhibit the neatly-defined signature which characterizes some others. The corresponding depression in the total B field generally reflects these same variations. In some events, such as in orbits 541, 663, 1220, and 1883, the B-field polarity reversal is relatively sharp and singular, occurring primarily in the stream-directed BS component. The appearance of the other field and plasma disturbances is coincident with the center of the reversal excursion. In other examples, such as orbits 77, 783, and 2096, the reversal may be more complex and the alignment of E-feild and plasma responses is shifted. This variability in the complexity of the B-field structure is suggestive of variations in the intensity and relative temporal alignment of associated disturbances in the E-field and the plasma. There appears to be some correlation between the slope of the magnetic field changes and the occurrence of 100 Hz noise bursts within these FAP regions, indicating the possible role of currents or beam-driven instabilities in producing the 100 Hz noise, perhaps triggered by lower energy ions and electrons than those believed responsible for the superthermal ion detection events.

As cited earlier, the signatures we identify as FAP events was reported in detail by Scarf *et al.* (1985), who extended an earlier study by Russell *et al.* (1982). Russell *et al.* reported evidence of detached “plasma clouds” interacting with the draped IMF, in a “slingshot fashion” to produce anomalous plasma acceleration. Scarf reported a total of 33 of these “diamagnetic cavity” events from a wide search of nightside orbits. Figure 6 is reproduced from the Scarf *et al.* paper, illustrating four FAP events. It may be seen that, the details of these events are comparable with the events of Figure 5. The distinctions between the study of Scarf *et al.* and our own are: (1) we have extended the multiparameter evidence of plasma instability

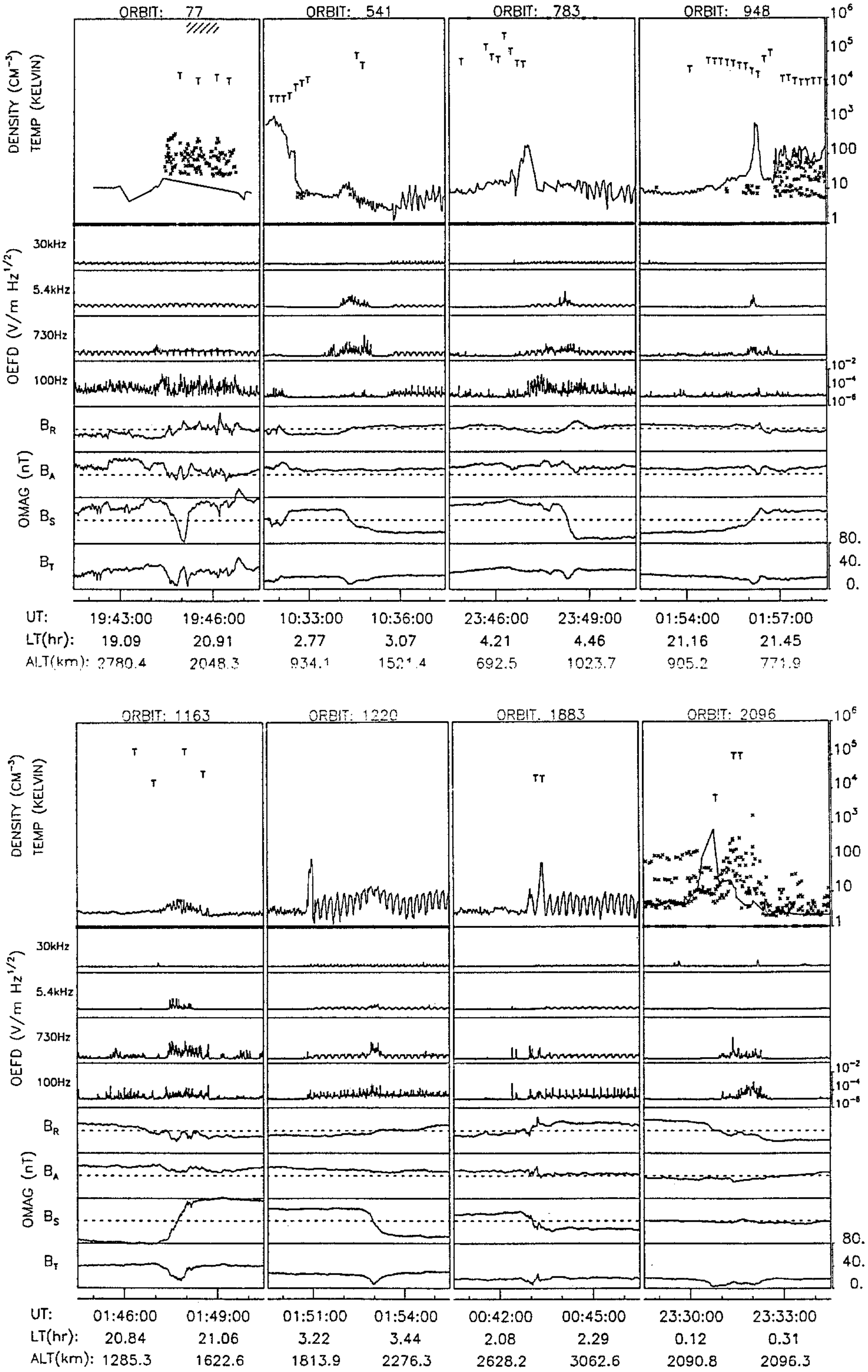

Fig. 5. Eight nightside FAP events selected from mid to high altitude. Reversals in horizontal field with coincident dips in field strength relate to onset of broadband E-field noise and plasma disturbances appearing either as anomalous offsets in Ne background levels or appearance of superthermal activity from OIMS (X's)or ONMS (hatched bars). Spacecraft spin modulation is evident in Ne.

to show the OIMS AND ONMS superthermal ion results, and (2) significantly, we have scrutinized many low altitude passes featuring complex field and plasma irregularities, identifying many low-altitude incursions of these events.

Scarf and colleagues studied the field-aligned disturbance events in detail, apparently perceiving them as primarily upper, or high-altitude (up to 3000 kilometers) events. Whereas they speculated that such events are likely sources of auroral disturbance in the atmosphere, the authors did not illustrate any examples at the lowest altitudes. Although they reported only 33 events, Scarf *et al.* noted that they, as do we, observed many others, and accordingly characterized these events as statistically significant for the nightside region. In fact these authors evaluated event frequency relative to time spent in regions studied, and reported that the PVO evidence of such disturbances was even greater than that reported from a study of analogous field aligned disturbances detected over the auroral and polar regions of the Earth ionosphere.

Scarf *et al.*, 1985 interpreted the FAP events as evidence of very disturbed plasma and field conditions, stating:...*"In many ways these waves and field measurements resemble those obtained at Earth, above the auroral oval, within the polar cusp, and at the boundary of the plasma sheet. The intense broadbanded turbulence (in the E-field) is detected near a current layer that is essentially field-aligned and this suggests that the current drives some sort of ion acoustic mode (of field noise)."*...The authors further interpreted these events as "auroral-type" energy deposition into the upper atmosphere of Venus, and inferred their evidence as consistent with reports of nightside auroral emissions (Fox and Stewart, 1990: Phillips *et al.*, 1986). We emphasize the fact that the nightside data exhibits hundreds of these examples, indicates that the ionosphere is frequently disturbed by such conditions, and discuss implications of this in Sections 2.4, and 3.

We wish to emphasize a feature common to both the ion troughs and the FAPs, namely that each is in part identified with the appearance of one or more distinct changes in orientation and magnitude of the B-field. In the case of the ion troughs, the B-field may either increase or reverse polarity rapidly, at the onset of the anomalously strong field encountered within these regions. In the case of the FAPs, when a strong horizontal field reverses polarity, the reversal signature is the same as would occur at the intersection of two "magnetic signatures" of troughs, of opposing field polarity-a condition observed on a number of orbits. At other times as the PVO approaches a FAP, the field may be of modest level, and of one polarity, then the field subsequently reverses direction and strengthens significantly. In such cases, also observed on numerous orbits, the FAP signature is the same as would be observed as the PVO crosses the boundary of signatures we, and Luhmann and Russell (1992) refer to as the "magnetic signature" of a trough. These B-field signatures appear to be the same events reported by Luhmann (1992) and Luhmann and Cravens (1992) who interpreted them as evidence of current sheet boundaries, predicted to feature particle acceleration and instabilities. This perception of field-

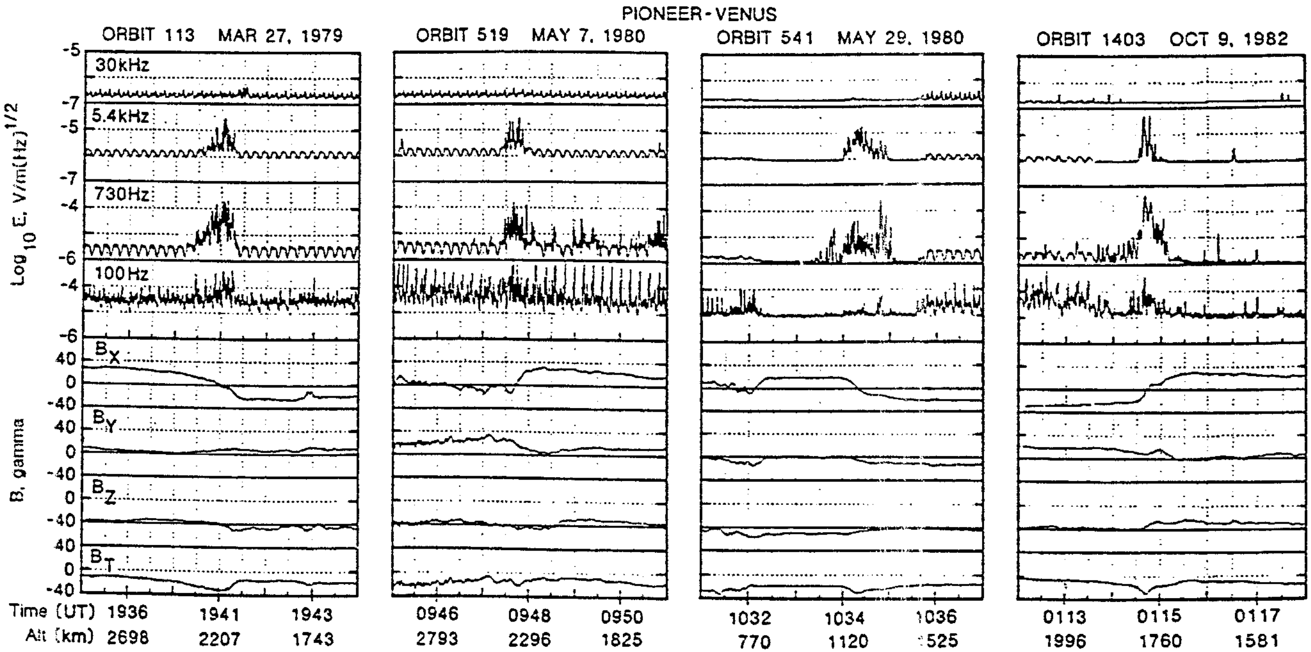

Fig. 6. A selection of four FAP events reported earlier by Scarf *et al.* (1985).

plasma relationships is understood to be consistent with our observations reported herein.

2.4. FIELD AND PLASMA DISTURBANCES AT LOW PERIAPSIS ALTITUDES

As we have referenced, B-field studies show that anomalously strong magnetic field signatures of troughs intrude to very low altitudes (145 km or lower), during periods of enhanced solar wind pressure. Since the presence of anomalously strong B-field is interpreted as indicating the connection of the magnetotail-ionosheath region to the region indicated, then the presence of these events at very low altitudes appears consistent with the suggestions of Scarf *et al.* that the FAP events may be responsible for the auroral-like disturbances across the nightside, and supports the argument, that under such conditions, the plasma must be considered subject to turbulence and instability.

In Figure 7, we illustrate periapsis FAP events for four low-altitude periapsis passes, which feature quite disturbed plasma profiles. In each case, the onset of distinct regions of plasma disturbance, highly variable B-fields, and turbulent impulsive E-field noise all coincide. The rise in broadband noise is particularly evident where abrupt FAP events are evident in the B-field polarity reversals. These FAP events have the same characteristics as those included in the illustrations of Figure 6. Comparing the wave-like perturbations in the ion and electron total density profiles in these examples with the "undisturbed" periapsis crossing shown in Figure 1(a), the anomalous behavior of the plasma stands out as evidence of very anomalous conditions.

The ONMS data we have been able to access for orbits 515, 522, and 531 generally reveal weak superthermal components on either side of periapsis but more prominently on the outbound leg of the pass. In the area very close to periapsis, the criterion for establishing superthermal activity above the dominant background of the neutral atmosphere is not well established. There is also a theoretical expectation that as the plasma becomes collision dominated in the dense low altitude neutral atmosphere, any superthermal component will be quenched causing the plasma to assume a pure thermal distribution. Whereas these factors complicate identification of superthermal evidence, the low altitude plasma is clearly most disturbed.

3. B-Field and Plasma Implications for Sources of E-field Noise

Responding to many reports linking both low frequency and broadband E-field noise with speculations on the occurrence of lightning in the Venus atmosphere, we have in turn suggested in the numerous papers referenced that the E-field noise detected within anomalously disturbed B-field and plasma disturbances surely arises from the natural instabilities resulting from the solar wind interaction with the nightside ionosphere. By analogy, we have argued that as in the Earth ionosphere,

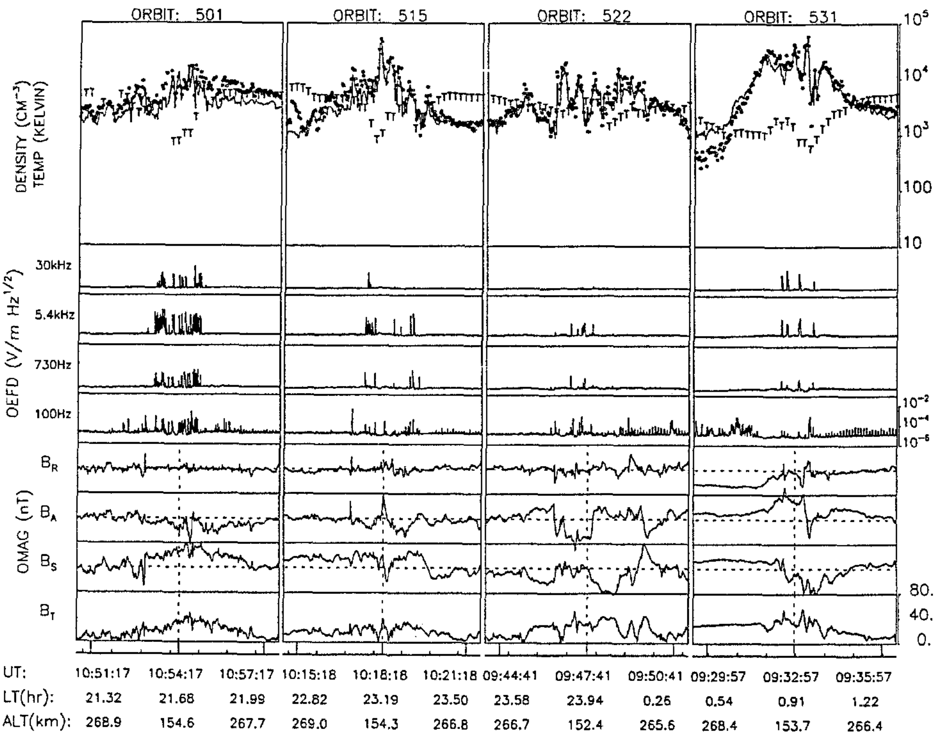

Fig. 7. Illustration of complex FAP-like events appearing across periapsis on four low-altitude passes. Although complex, each pass exhibits associated anomalous fluctuations in strength and polarity of B. FAP signatures clearly seen on orbits 522 and 531, are more complex on orbits 501 and 515. Presence of anomalously strong B-field is consistent with highly irregular non-thermal gradients in the ions and electrons, B-field characteristics similar to "magnetic signatures" in troughs.

the appearance of E-field noise within chaotic auroral disturbance regions must first be considered as associated with those disturbances, prior to searching for unlikely and unpredicted alternative sources. By examining several details of the foregoing illustrations of field-plasma disturbances, the argument for interpreting the E-field noise as resulting from sources near the PVO, or above, and not the lower atmosphere, is even further strengthened.

3.1. LOW FREQUENCY 100 HZ NOISE

During the extensive debate over interpreting the actual source of the 100 Hz noise attributed to lightning, this particular noise form has consistently been reported as being associated with the plasma troughs (e.g. Taylor *et al.* 1986). As noted earlier, those analyzing the characteristics of the nightside magnetic field, and also the troughs, have consistently reported that these plasma depressions are sites for the intrusion of large fields, i.e. incompatible with the presence of a "normal" thermal ionosphere (e.g. Marubashi *et al.*, 1985; Luhmann,1992). In addition, the evidence of anomalous ion composition within the troughs reinforces the view expressed by Marubashi *et al.* that these regions feature conditions normally encountered "outside" the ionosphere, i.e. that the boundaries of the troughs are equivalent to crossings of the ionopause.

It is established that as the PVO crosses the ionopause, several associated forms of field-plasma disturbance are encountered, including (a) the appearance of superthermal ions, detected by both the OIMS and ONMS, coincident with (b) impulsive E-field noise (Taylor *et al.*, 1981; Kasprzak *et al.*, 1982). In some examples the E-field noise is low-frequency, in other examples, broadband. The superthermal ions and associated noise were interpreted as resulting from energetic processes involved in the interaction of the strongly flowing ionosheath particles, energizing thermal ions and driving plasma instabilities and generation of electrostatic waves and noise.

Other studies of the ion troughs have provided evidence of the anomalous composition changes noted in Figure 2, and have been interpreted as evidence of strong upward escape flows of ionospheric ions (Hartle and Grebowsky, 1993). These observations, plus the clear indication that some trough boundaries are comparable to the same form of sharp reversals in B-field polarity marking the FAP events, combine to indicate that troughs, DIs, and FAPs are all consequences of the solar wind/IMF interaction with the ionosphere. These disturbances, accepted within the PVO literature as indicative of natural plasma instabilities, directly confront the speculation that the E-field noise detected in the midst of these disturbances, originates from atmospheric "lightning".

Independent study of the low frequency noise by Huba (1992) and Walker (1992) have shown that the majority of well-identified ion trough-E-field noise events occur within an ionospheric region where the lower-hybrid-drift instability would occur, thus providing a likely source mechanism for the 100 Hz noise. Walker performed a study of over 3000 100 Hz E-field events selected by Scarf and Russell (1983) as indicative of lightning events, and found that 89.7% of these events occurred in regions unstable to the lower-hybrid -drift instability studied by Huba. A study of the minority of the events (10.3%) which were not unstable to the lower-hybrid drift indicated a correlation with either magnetic field or plasma density structure. The results of the study are shown in Table I. As can be seen, the vast majority of the stable cases (95.8%) occurred when the magnetic field was fluctuating. It is interesting to note that the original criteria stated by Scarf and Russell for a well-defined trough//E-field noise event called for a steady magnetic field. The remaining few events either occurred at the edge of an ion trough, just after a trough, or inside an ion density dip. A density dip is a regions where the plasma concentration falls with respect to the background density, but not to a great enough extent to be classified as a trough. Thus, Walker found that nearly 100% of these events are either in regions of a defined instability, or spatially coincident with ionospheric plasma or magnetic field structure, again pointing to a local origin for the waves.

TABLE I

Summary of Walker (1992) analysis of E-field trough noise events. Vast majority of events (89.7%) otherwise attributed to "lightning" are in unstable zone conducive to growth of lower-hybrid waves, ad developed by Huba (1992)

Type of event	Number	% of 3027
Beta < 1 Unstable	2715	89.7
Beta > 1 Stable	312	10.3

Density characteristics of stable points

	Number	% of 312	% of 3027
Fluctuating	161	51.9	5.4
Dip	65	20.8	2.1
Edge of Trough	28	9.0	0.9
No Structure/Other	57	18.2	1.9
Total	312	100.0	10.3

B-Field characteristics of stable points

	Number	% of 312	% of 3027
Fluctuating	299	95.8	9.9
No Structure/Other	13	4.2	0.4
Total	312	100.0	10.3

Related investigations reported by Huba and Grebowsky (1993) conclude that the lower- hybrid-drift instability is most likely to be generated in low-beta regions, i,e. within the ionospheric troughs. While those arguing for the lightning interpretation (e.g. Russell, 1991) assert that other studies (e.g. Ho *et al.*, 1992) have discounted the noise source suggested by Huba, we have shown that in particular, the report of Ho *et al.* failed in its "case studies" to recognize the "magnetic signatures" of troughs already certified by the detailed studies of Luhmann and Russell (1992).

Even among those who have supported arguments for the E-field noise-lightning interpretation, there are recent reports of alternative explanations, consistent with our own interpretations. Specifically, Strangeway (1991) discusses the ion trough-100 Hz noise event of orbit 502 shown earlier in Figure 3, as ..."*a counter example to impulsive whistler-mode waves.*"... Strangeway notes that the noise is not primarily impulsive, and that it may be due to in-situ instabilities, citing the plasma cloud events reported by Scarf *et al.* and which we illustrate in Figures 5 and 6. Whereas Strangeway illustrates just one plasma trough-100 Hz noise example, we can postulate that within the many hundreds of orbits exhibiting the ion trough-100 Hz noise correlation, there are surely other such examples, which if the case, would be another rationale for discounting the repeated statistical results drawn from the 100 Hz noise data base.

In an investigation of wave propagation characteristics of the low-frequency noise by Sonwalkar *et al.*, 1991, the polarity and dispersion features of a limited sample of published "lightning-noise" events found some which did, yet others which did not, exhibit characteristics required for whistler mode waves, postulated to propagate upward to the PVO from an atmospheric source. Whereas Russell (1991) cites the results of this investigation as consistent with the lightning interpretation, the results of Sonwalkar *et al.* is readily citeable as evidence contrary to the lightning interpretation. In particular the test-sample analysis performed by Sonwalkar *et al.* leads to the conclusion that prior published reports based upon statistical studies of the noise-(studies using data sets selected without benefit of the polarity and dispersion selection tests), are not scientifically rigorous. These authors acknowledged that their tests could not confirm the presence of lightning, and consistent with this, noted alternative sources for local generation of the noise, resulting from the solar wind interaction.

The lightning interpretation is further weakened by the fact that the morphology of the events which were ruled out by Sonwalker *et al.* as lightning-generated is identical to that of events which were not ruled out. Since the non-lightning events prove the existence of a generation mechanism within the ionosphere and do not fit tests for instabilities studied to date, clearly the challenge to further examine plasma instability mechanisms, not to continue to pursue a lightning hypothesis. An interesting possibility which has not been adequately pursued, perhaps because of excessive emphasis on the lightning scenario, is that the 100 Hz events are downward propagating whistler waves generated in the distant magnetotail by the solar-wind-driven processes similar to those at the ionopause, and that the ion troughs mark the lower boundary of the whistler ducts.

Significantly, papers speculating on the interpretation of the 100 Hz noise in troughs as evidence of lightning have consistently failed to address one inevitable, yet incredible implication of this speculation. The evidence supporting this strong conclusion is as follows. First, the observational data first reported by Taylor *et al.* (1985) confirming that the noise in question is highly correlated with the plasma depressions is now widely accepted, (e.g. Strangeway, 1991). Second as we have reported, the noise often begins and ends coincident with the gradients of the magnetic field enhancement. This significant characteristic is confirmed, even by those supportive of the lightning interpretation (Ho, *et al.*, 1992). From the evidence, it follows that lightning, if present and responsible for the 100 Hz noise, would necessarily be essentially incessant. The probability that a lightning generated sequence of noise bursts would "happen" to almost always appear coincident with the crossing of a trough, is so low as to discount the lightning interpretation, alone. Not only has no proponent for possible lightning suggested that its occurrence would be incessant, but on the contrary, cloud physicists most familiar with the electrification processes required, argue that the atmospheric conditions at Venus discount the probability for any occurrence of lightning, whatsoever (e.g. Esposito *et al.*, 1983).

3.2. BROADBAND MULTIFREQUENCY NOISE

After many published reports interpreting the exclusive 100 Hz noise as evidence of lightning, those studying the OEFD data instead began to report that a subset of so called "broadband" E-field noise detected at low altitudes, is the more likely indicator of such activity (e.g. Russell *et al.*,1989). We place the term broadband in quotes, since the reported broadband characteristics have been challenged, showing that reported noise groups did not exhibit predicted broadband characteristics (Taylor and Cloutier, 1991; 1992). Russell *et al.* reported that the multifrequency noise appears most often near dusk, leading them to speculate that inferred atmospheric instabilities similar to Earth-like thunderstorm processes might provide the otherwise unpredicted stimulus for lightning. They also reported the noise exclusively at the lower periapsis altitudes, further encouraging their speculation on the lightning source. We emphasize that although the multifrequency noise-lightning interpretation is repeated in a number of published studies (e.g. Scarf *et al.*, 1989; Russell, 1991), such reports do not adequately address alternative sources for the noise. Specifically, in lieu of defending criticisms of prior published work based on specific data sets, new data selection criteria are introduced, leaving a substantial body of published work unresolved. Moreover, the authors do not address the combined implications of B-field amplitudes and fluctuations, and accompanying plasma anomalies associated with their selected event.

In particular, we note two specific examples of conflict in the interpretation of the broadband noise at periapsis identified by Russell *et al.* (1989). The authors illustrate a series of key examples of the broadband impulsive noise, argued by them to constitute the most convincing evidence of lightning. We can show that four of their illustrated examples are coincident with evidence of B field and plasma disturbance conditions which confront the lightning interpretation. First, orbit 85, shown in Figure 4b is a DI, appearing in the special list of DI events certified by Luhmann (1992) as an example of anomalous intrusion of high B-fields, inconsistent with normal, thermal ionospheric conditions. Second, as we have shown in Figure 7, the periapsis portions of orbits 501, 515, and 531, also key examples of "lightning" noise illustrated by Russell *et al.*, exhibit anomalous B-field and plasma characteristics inconsistent with thermal ionospheric conditions. Further, the periapsis broadband E-field noise on orbit 531 has been independently interpreted by Luhmann *et al.* (1982), as noise "*believed to be current-driven electrostatic turbulence similar to that detected in the Earth's polar cusp and auroral region*", (Fredericks *et al.*, 1973; Scarf *et al.*, 1973).

Whereas his co-authors have apparently not recognized the significance of the B-field-plasma relationships for the interpretation of the low-altitude broadband E-field noise, one report of F. Scarf certainly did. In particular, the field-plasma irregularities of the type evident in the DI events of Figure 4, were also recognized by Scarf. In Figure 8, we reproduce Figure 5 from Scarf *et al.* (1986) in which Scarf specifically characterizes the broadband E-field noise across periapsis on orbit 490- (the same noise we show in Figure 4a) as "*a case with intense broadband electrostatic noise in a region with variable electron and ion characteristics*", also labelling the noise in question as "*not lightning*".

Since important portions of the evidence of superthermal activity now interpreted from the OIMS, OETP, and ONMS were not included in Figure 8, Scarf was unable to appreciate fully the very convincing correlation between what he recognized as turbulent E-field noise, and the obvious evidence of plasma instabilities across this pass, which appears to be grazing the complex upper boundary of a strongly compressed ionosphere. Nevertheless, his interpretation of the multifrequency noise remains viable and consistent with our own past and present reports: *the multifrequency noise attributed to "lightning" is instead locally produced, as a consequence of the solar wind interaction with the ionosphere, and thus unrelated to any possible existence of lightning*. Finally, further evidence for a local source for the broadband noise is the observation of Sonwalker *et al.* (1991) that these events show no dispersion and could not have propagated through the refractive lower ionosphere.

3.3. THE SIGNIFICANCE OF E-FIELD NOISE AT THE LOWEST ALTITUDES

During the time that the appearance of either low-frequency noise (e.g. Scarf *et al.*, 1988) or broadband noise (e.g. Russell *et al.*, 1989) was being defended as evidence of lightning, it was perceived that the ionospheric troughs did not penetrate below about 200 km. Thus impulsive noise reported as most prevalent at the lowest altitudes, and attributed to lightning, was not challenged by evidence of solar wind disturbances penetrating to the same low altitudes. Now, however, given recent (Luhmann and Russell, 1992) and our present evidence for significant field-plasma disturbances down to 145 kilometers or lower, there is an even more compelling basis for considering alternative sources for both forms of the E-field noise. These newer perceptions clearly favor the likelihood that the turbulent noise, whether at 100 Hz, or multifrequency, is linked to field-aligned interactions between the solar wind and the ionosphere.

4. Conclusions

We conclude our study of hundreds of nightide PVO orbits and a closely related review of an extensive reporting of nightside field and plasma conditions, with several perceptions which are fundamental to understanding both the maintenance of

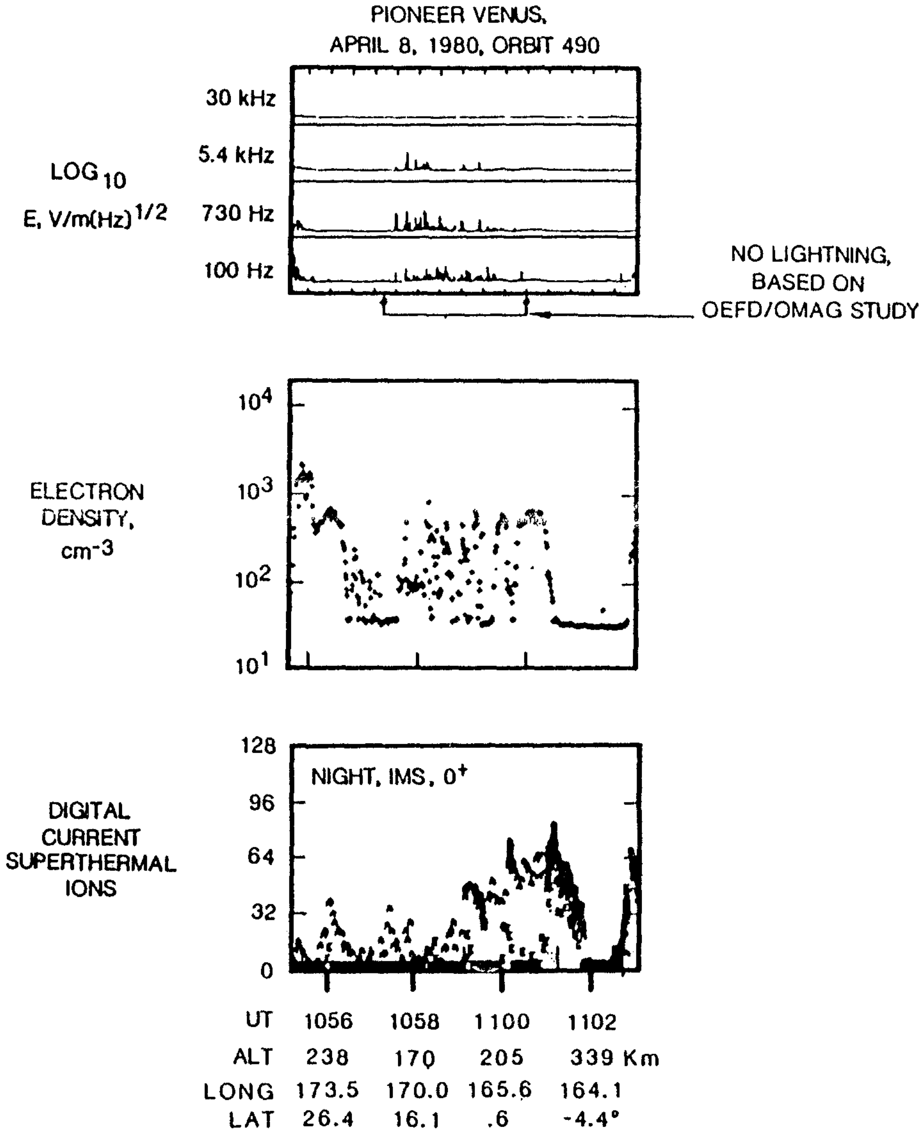

Fig. 8. Low-altitude broadband E-field noise analysis reported and illustrated by Scarf *et al* (1986) for orbit 490. Noise is interpreted as resulting from current driven electrostatic turbulence and thus "not lightning".

the nightside ionosphere, and the conjecture on the possible existence of widespread lightning about the planet. The clear and repeatable field-plasma signatures in the data convince us that in analogy with the auroral regions of Earth, widespread portions of the nightside ionosphere are frequently chaotic, often featuring abrupt changes in field direction and intensity, and in plasma concentration, composition, and energetics.

We have noted two fundamental examples of non-credible statistical coupling between the impulsive E-field noise and field-particle aberrations independently reported to be randomly driven by erratic variations in the solar wind interaction with the ionosphere. These are: (a) the persistent turn on and turn off of the 100 Hz noise in plasma troughs, and (b) the tight correlation between the impulsive broadband noise and B-field-plasma anomalies. Together these repeatable relationships alone argue very strongly for seeking the explanation of the E-field noise in the form of plasma instabilities occurring near the PVO.

We firmly believe as reported previously, that both the low frequency and broadband electric field noise detected by the OEFD result from plasma instabilities driven by the solar wind/IMF interaction with the plasma convected from day to night. We recognize that some arguments have been extended by lightning advocates to dismiss reports of plasma instability processes, such as proposed by Huba (1991), but we submit that since these studies do not confront the obvious coincidence between the field and particle events, they are peripheral to the core of the problem. Lightning induced noise even if present, cannot be expected to appear coincident with the wide variety of field and particle disturbances we have identified, and thus alternate explanations must be sought. We further note that the implications of our investigations are supported by the negative results of repeated searches for any optical evidence of lightning across the Venus nightside, reported by Borucki *et al.* (1981; 1991); Taylor and Cloutier (1994).

Finally, we submit that the reported association of the OEFD E-field noise with lightning is simply speculation. In the face of the associated field-plasma irregularities, the scientific obligation of those interpreting the actual origins of the electric field noise is to consider fully the noise generation mechanisms co-existent with the intrusion of ionosheath-magnetotail processes, appearing regularly at the ionopause, in ion troughs, and often intruding to the lowest altitudes sampled by the PVO. Lightning may or may not exist at Venus: we remain convinced that the PVO instruments have detected no evidence of that possibility.

Acknowledgements

We acknowledge substantial and timely assistance from Ralph Post and Dave Guell of NSSDC/Goddard Space Flight Center, in supplying archived data, and from Wayne Kasprzak of NASA/Goddard for supplying ONMS data and assisting in its interpretation.

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