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INITIAL PVO EVIDENCE OF ELECTRON DEPLETION SIGNATURES DOWNSTREAM OF VENUS

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Abstract. This first analysis of Pioneer Venus Orbiter (PVO) plasma analyzer electron measurements obtained in early 1992 during the PVO entry phase of the mission indicates the presence downstream from the terminator of a depletion or "bite out" of energetic ionosheath electrons similar to that observed on Mariner 10. There is more than one possible explanation for this energetic electron depletion. If it is due to atmospheric scattering, the electrons traveling along draped magnetic flux tubes that thread through the Venus neutral atmosphere would lose energy from impact ionization with oxygen. The cross-section for such electron impact ionization of oxygen has a peak near 100 eV, and it remains high above this energy, so atmospheric loss could provide a natural process for electrons at these energies to be selectively removed. In this case, our results are consistent with the Kar et al. (1994) study of PVO atmospheric entry ion mass spectrometer data, which indicates that electron impact plays a significant role in maintaining the nightside ionosphere. Although it is appealing to interpret the energetic electron depletion in terms of direct atmospheric scattering, alternatively it could result from strong draping which connects the depletion region magnetically to the weak downstream bow shock and thereby reduces the electron source strength.

Introduction

The Mariner 10 plasma detector (Bridge et al., 1974) observed in the ionosheath downstream of Venus a reduction in flux of electrons with energies > 100 eV. They interpreted this as "evidence for some direct interaction with the exosphere" and suggested that the flux decrease or "bite-out" was caused by depletion of the electron population on magnetic flux tubes which passed close to the ionopause. The cross section for electron impact ionization of oxygen has a peak near 100 eV and remains high above that energy so that penetration into the neutral oxygen exosphere is a natural way for electrons at these energies to be selectively removed (Bridge et al., 1976). Hartle et al. (1982) reported a strong decrease for electrons with energies > 700 eV on draped magnetic field lines in Titan's tail. They attributed this depletion to the scattering of Saturn's magnetospheric electrons by the neutral atmosphere through which the magnetic field lines thread.

In the present paper we provide the first analysis of PVO electron observations obtained in the entry phase in the nightside ionosheath by the OPA, orbiter plasma analyzer (Intriligator et al., 1980). The OPA measures electrons in sixteen logarithmically spaced energy steps ranging from 0 volts to -250 volts. The electron data we discuss were obtained in the scan mode where the energy step (i.e., voltage) is changed once per spacecraft revolution. The OPA scans 360° in azimuth on each revolution and identifies the maximum flux at that energy step, the azimuthal (longitudinal) flow direction, and polar (north-south) flow direction associated with the maximum flux.

Observations

Figure 1 shows electron energy spectra obtained on orbit 4775 in the Venusian ionosheath and ionotail between 0002 and 0107 UT on January 2, 1992. Each spectrum is plotted from right to left. The start time refers to the time of initiation of the first (0 volts) energy step. A reference trajectory is shown. The first two spectra (start times 0002 and 0008 UT) were measured in the outer ionosheath. These spectra show two peaks - a lower energy photoelectron peak and a higher energy peak associated with shocked solar wind electrons. The next two spectra (0014 and 0020 UT) show the lower energy photoelectron peak and a progressive diminution in the higher energy shocked solar wind electron peak. Since PVO entered the Venus optical shadow at ~0024 UT and exited it at ~0046 UT, there is an absence of the low energy photoelectrons in the 0026 UT spectrum. The shocked solar wind electrons also are absent in this spectrum. There is a data gap from 0031 UT to 0044 UT. The 0044 UT spectrum also shows the absence of both electron peaks. The 0050 UT spectrum is similar to the 0014 UT spectrum. It was obtained in the ionosheath and displays the fully developed lower energy photoelectron peak and a reduced amplitude in the higher energy peak. The last two spectra (0056 and 0102 UT) were obtained in the outer ionosheath and are similar to the 0008 and 0002 UT spectra, respectively, and show both electron peaks. The spectra in Figure 1 are consistent with those in Intriligator et al. (1979).

In Figure 1 the depletion of the shocked solar wind electron peak (the higher energy peak) begins in the 0014 UT spectrum and continues through the 0050 UT spectrum. It is tempting to associate this depletion or "bite out" with the electrons' scattering by the atmosphere, as inferred for Mariner 10. If this were the case, then these depleted electrons were on draped magnetic field lines that threaded through the atmosphere or reduced the electron source strength. The PVO magnetometer only can obtain one component of the magnetic field (the Z-component perpendicular to the ecliptic plane), so we assume a draped magnetic field geometry as is typical for these orbits (C.T. Russell, private communication). This configuration for orbit 4775 is compared below with that observed on orbit 87 and supports our assumption of the draped magnetic field being associated with the energetic electron depletion. We discuss several possible explanations of the energetic electron depletion in the next section.

To further study the depletion, in Figure 2 we show the OPA electron flux for each of the 16 electron energy steps for the nine electron spectra in Figure 1. At the top of Figure 2 we show the electron density profile obtained by the OETP Langmuir probe. The inbound ionopause was crossed near 1800 seconds and the outbound ionopause was crossed during the OETP data gap, but we do not know when. To use it as a reference point we show it as near 2700 seconds prior to OETP restart. This is adequate for our purposes considering the scale of the energetic electron depletions we are studying. The shaded region along the OETP bottom horizontal axis shows when PVO was in optical shadow (~0024 to ~0046 UT). Other trajectory information (e.g., spacecraft altitude, latitude, longitude, solar zenith angle, and local time) are shown at the bottom of Figure 2. The OPA measurements at the lower energy steps (0, -3, -4 volts) show the initial presence of the photoelectrons, their absence in the optical shadow when the electron flux drops to background levels, and their abrupt reappearance after PVO exits the shadow.

The electron fluxes at -37, -51 volts show the initial presence of the higher energy electrons,

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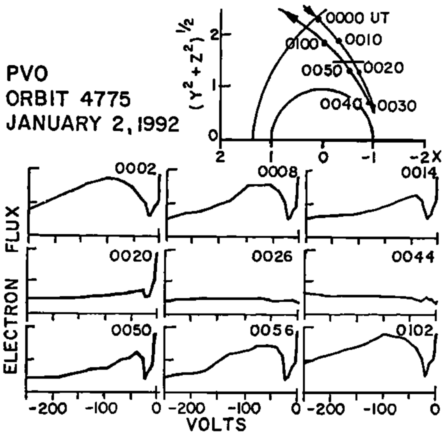

Fig. 1 OPA electron energy spectra near periapsis on orbit 4775. The start time of each spectrum is the initiation time of the 0 volts step (i.e., the first electron energy step) and is indicated in the upper right above each spectrum. The dots on the trajectory plot show 10 minute time intervals (0100 is 0060). The horizontal line intercepting the trajectory indicates the location of the energetic electron depletion boundary.

their gradual depletion starting before the optical shadow, and their gradual reappearance after PVO exits the shadow. The duration of the flux depletion increases with increasing energy of the electrons: the duration of the depletion for -182 volt electrons begins at ~660 seconds and extends to ~3660 seconds while the flux depletion of the -37 volt electrons starts at ~1260 seconds and ends just after 3060 seconds. The start and stop times of the depletion for the higher energy (e.g., -182 volts) electrons also do not coincide with the times of the ionopause crossings. The -182 volt electron depletion begins 19 minutes before the inbound ionopause is crossed and ends at least 16 minutes after the outbound ionopause crossing.

The increased duration with increasing energy of the flux depletion is emphasized in Figure 3 which displays for the same time interval as that shown in Figure 2, the color map for the 16 energy steps for the nine electron spectra in Figure 1. The high energy electron "bite out" is evident.

It is useful to examine another orbit where the OPA also was in the electron mode for more than one or two electron spectra so that the presence of the electron depletion can be investigated. Figure 4 presents for orbit 4819 eight electron energy spectra. Only the outbound electron depletion profile is available on this orbit since the inbound electron spectra in the ionosheath were not obtained. The first spectrum (0010 UT) was obtained when the OPA was first switched to the electron mode. This initial spectrum appears to be artificially enhanced (or riding high) from a transient due to mode switching. This transient is observed on other orbits. This spectrum is included in Figures 4, 5, and 6 for completeness but it does not affect our results since we base our conclusions only on the outbound electron data. The 0016 UT spectrum shows the low energy photoelectron peak. The 0028 UT spectrum follows a data gap (0022 to 0028 UT). This spectrum and the 0034 and 0041 UT spectra show no photoelectron peaks since they were obtained in the Venus optical shadow. The small peak at -27 volts in the 0041 UT spectrum may be due to PVO exit from shadow. The 0047 UT spectrum and the subsequent spectra show the low energy photoelectron peak. The higher energy peak is just beginning to show in the 0047 UT spectrum. In the 0052 and 0058 UT spectra it is very evident.

In Figure 5 the OETP profile shows the inbound ionopause crossing near 0024 UT (1440 sec) and the outbound crossing near 0041 UT (~2500 sec). The bottom portion of Figure 5 shows the OPA electron flux for each of the 16 electron energy steps for the eight electron spectra shown in Figure 4. As in the orbit 4775 case, the lower energy (0, -3, -4 volts) electrons are present initially, drop to background levels in the optical shadow, and then abruptly reappear when PVO exits shadow. The higher energy (-37, -96 volts) electrons show the depletion in the optical shadow and then gradually reappear until eventually they obtain a higher flux when PVO is well into the ionosheath. The duration of the depletion is longer at the higher energies in agreement with the orbit 4775 measurements. On orbit 4819, for example, the -182 volt electrons recovered from their depletion after 3340 seconds or 14 minutes after the ionopause crossing. Thus, the high energy electron depletion extended beyond the optical shadow and also beyond the ionopause. This prolonged high energy electron depletion is similar to that observed on orbit 4775. The depletion on both PVO orbits is consistent with that observed on Mariner 10.

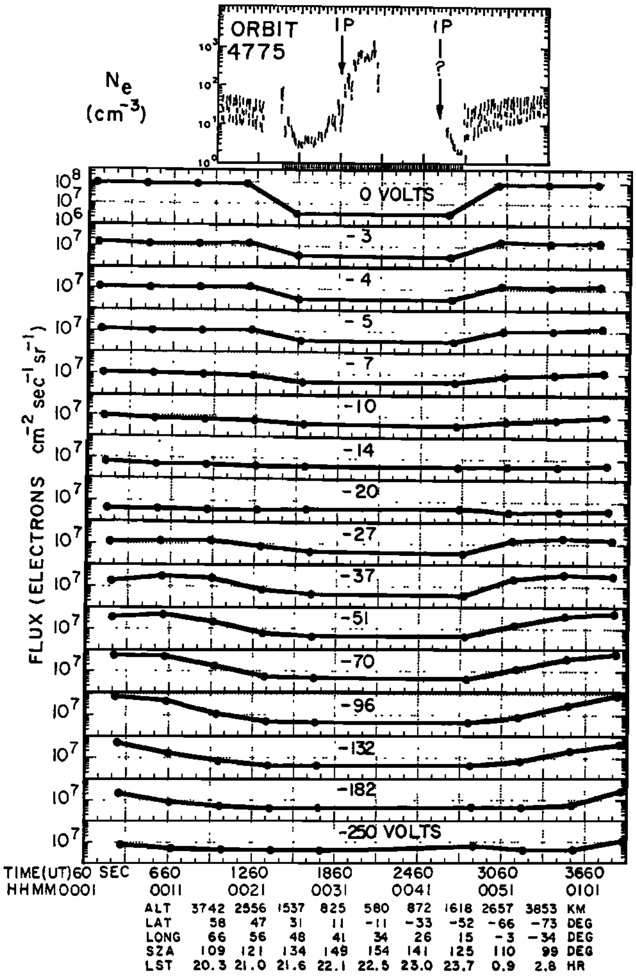

Fig. 2 Time series measurements near periapsis on orbit 4775 of OETP electron density (upper plot) and OPA electron flux (lower plots) for each of the 16 energy steps. The voltage for each is indicated above its plot. The ionopause (IP) crossings are marked. On this orbit the exact time of the outbound crossing is unknown. Its arrow is a reference point (see text). The shaded region just below the upper plot shows when PVO is in the Venus optical shadow. The six lowest OPA energy step (0 through -14 volts) data show the absence of photoelectrons in optical shadow. The energetic electron depletion or "bite out" is evident in the -37, -51, -70, -96, -132, -182, and -250 volt steps. The duration of the depletion increases with increasing energy. The energetic electron depletion begins and ends when PVO is in the ionosheath presumably on draped magnetic field lines.

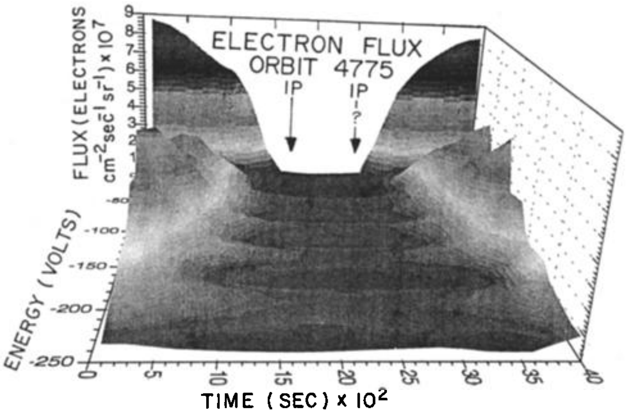

Fig. 3 Color map for orbit 4775 showing for the same time interval as Figure 2 the OPA electron flux for each energy step. A linear interpolation was used to fill in between data points. Ionopause crossings marked are the same as those used in Figure 2. The energetic electron depletion or "bite out" is evident.

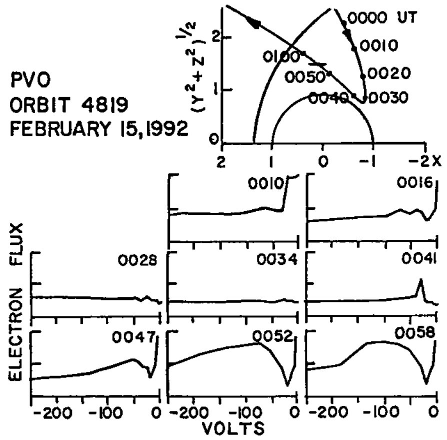

Fig. 4 Same as Figure 1 for orbit 4819. On orbit 4819 both ionopause crossings are observed.

The color map for orbit 4819 (Figure 6) is based on the electron flux data in the eight electron spectra in Figure 4. The higher energy electron flux depletion is evident in Figure 6.

In Perez-de-Tejada et al. (1993) Figures 1, 2, and 4 show the location of the "intermediate transition" on orbit 87 and the draped magnetic field configuration in this region. Comparison of the locations of the depletion boundary (our Figure 1) for orbit 4775, for example, with the location of the "intermediate transition" on orbit 87 shows that the two boundaries are nearly coincident. Based on this comparison it is tempting to conclude that the energetic electron depletion boundary and the "intermediate transition" are coincident and that the energetic electron depletion boundary is the signature in the plasma electrons for the intermediate transition. The electron data support the suggestion that the "intermediate transition" may be the signature of atmospheric scattering for the electrons or of the reduction in electron source strength.

Discussion

We present first analyses of OPA electron measurements obtained during the PVO atmospheric entry. Our study of two cases in 1992 shows there is a depletion or "bite out" in the energetic electron population downstream of Venus. There is more than one possible explanation for this depletion. It is tempting to attribute it to their being lost to the atmosphere when they travel along draped magnetic field lines. By draped, we mean field lines becoming strongly U-shaped, concave tailward, because the interaction with the planet retards the motion of the middle relative to the sides (McComas et al., 1986). Previous studies of

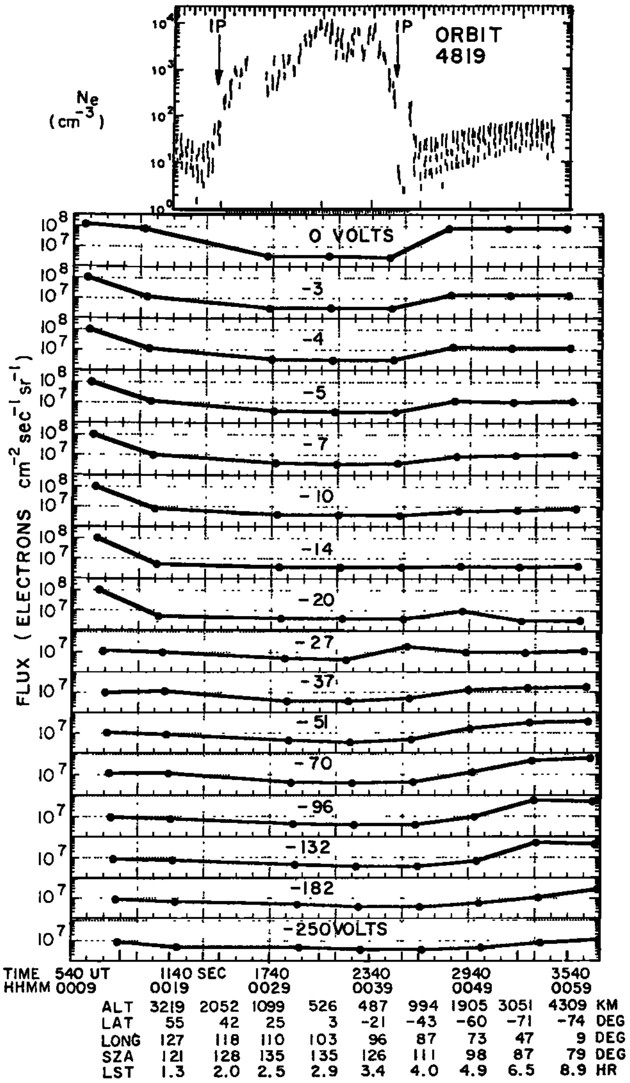

Fig. 5 Same as Figure 2 for orbit 4819.

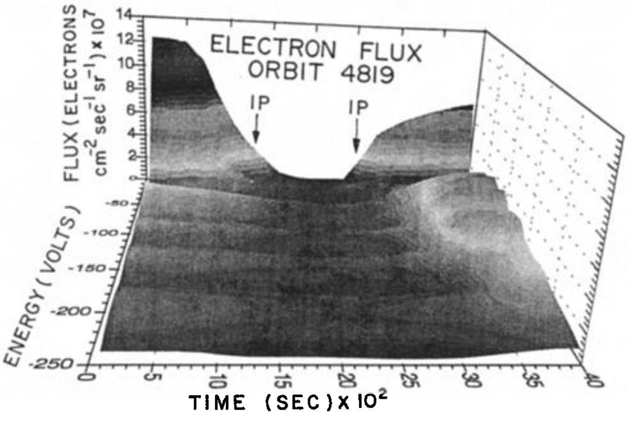

Fig. 6 Same as Figure 3 for orbit 4819.

the intermediate transition (Perez-de-Tejada et al., 1993) often showed that in the ionosheath in regions comparable to those studied here, there is an abrupt rotation of the ionosheath magnetic field to the draped configuration.

If the electron depletion observed in the higher energy channels is due to energy loss resulting from impact ionization of the neutral atmosphere, then the collision mean free path, $\lambda = 1/\sigma L$ should be less than or equal to L, the length of the column of neutral atmosphere attaining a density N. This means that the magnetic field lines on which the electrons travel must thread through regions of the atmosphere where the density $N \geq 1/\sigma L$. If L is as large as a planetary radius, then $N \geq 3 \times 10^6 \text{ cm}^{-3}$ when the cross section $\sigma = 5 \times 10^{-16} \text{ cm}^2$ for oxygen, the dominant neutral constituent in the dayside upper atmosphere. Oxygen densities of this magnitude occur at altitudes below 300 km on the dayside, an altitude usually below the ionopause. Since the electron depletion in the higher energy channels is first observed at distances almost two planetary radii above the ecliptic plane, the bite out is not likely due to impact ionization when the magnetic flux tubes lie in a plane ~ parallel to the ecliptic plane, because the oxygen densities on such field lines are orders of magnitude less than 10^6 cm^{-3}. However, the observed bite out might be due to electron impact ionization if the plane of the magnetic field lines is skewed to the ecliptic plane in such a way as to permit them to drape around the dayside ionosphere and penetrate to depths where the oxygen density is sufficient to produce the depletion. The oxygen density would not need to be as high as $3 \times 10^6 \text{ cm}^{-3}$ if the electrons in the solar wind interaction region undergo multiple passes through the atmosphere by "mirroring" or being reflected by wave particle scattering. There appears to be no work on these processes. Centrifugal drift and gradient B drift are too weak at Venus to account for the bite out.

While it is appealing to interpret the depletion in terms of atmospheric scattering, it also could be that in the case of strong draping - which apparently accompanies the bite outs - the field lines intersect the bow shock far downstream, where the shock is relatively weak. Therefore, the electron depletions might not be "bite outs", but "turn downs" of the energetic electron source at the bow shock.

The two depletion cases studied were obtained in January and February 1992 during the declining phase of the solar cycle. Kar et al. (1994) report evidence near solar minimum of electron impact ionization on the nightside of Venus from their examination of the PVO ion mass spectrometer data for ~3 months starting in August 1992. They present the first clear evidence of an ionosphere maintained mainly by electron impacts. They find a drastic decrease in the O^+ abundance in 1992 compared with solar maximum (the first three PVO Venus years ~1979, 1980) and a steady O_2^+ peak in 1992 that changed little from solar maximum conditions "can be understood only in terms of electron impact ionization with the electrons originating in the solar wind." Thus, if our evidence (on presumably draped magnetic flux tubes) of a depletion in the energetic electrons of solar wind origin were due to atmospheric loss, it would be consistent with the conclusions of Kar et al. (1994) and it would support their results.

Our PVO OPA electron measurements are consistent with the Mariner 10 data. Both Mariner 10 and PVO results show a depletion in the higher energy electron flux in regions of the Venusian ionosheath where draped magnetic field lines typically exist. Mariner 10 was in the downstream ionosheath and a draped magnetic field was measured. For both PVO examples, PVO was in the downstream ionosheath and also in the nightside ionosphere and in the optical shadow. On these orbits energetic electron depletion occurs in the ionosheath where the draped magnetic field geometry is typical but the available magnetic field data cannot confirm this geometry. Nevertheless, it is tempting to assume that this typical draped field configuration is present during the two PVO passages, particularly since the Perez-de-Tejada et al. (1993) study of the magnetic field properties of the intermediate transition in the Venus ionosheath are consistent with this configuration. It is possible that for both PVO and Mariner 10 the energetic electron depletions result from depletion by atmospheric scattering or from a reduced source strength.

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