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RESULTS OF THE FIRST STATISTICAL STUDY OF PIONEER VENUS ORBITER PLASMA OBSERVATIONS IN THE DISTANT VENUS TAIL: EVIDENCE FOR A HEMISPHERIC ASYMMETRY IN THE PICKUP OF IONOSPHERIC IONS

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Abstract. Pioneer Venus Orbiter plasma and magnetometer observations from the first nine tail seasons of crossings of the Venus wake are used to study ion pickup in the far wake of an unmagnetized object embedded in the solar wind. This first statistical study treats all of the plasma spectra containing pickup ions in the vicinity of the Venus tail. We find a hemispheric asymmetry in the pickup of ionospheric ions, with approximately four times more O^+ events observed in the "northern" magnetic hemisphere (where Z" > 0), i.e., the induced electric field points outward, (away from the ionopause boundary) than in the "southern" (Z" < 0) magnetic hemisphere. Out of a total of 167 large O^+ events, 125, or 75%, occurred in the northern hemisphere when position is calculated in terms of Venus radii and 129 or 77% occurred in the "northern" hemisphere when position is expressed in gyroradii. This hemispheric asymmetry in ion pickup is consistent with the prediction of the Cloutier et al. (1974) mass loading model for Venusian ions above the ionopause boundary.

Introduction

Ion pickup by the solar wind at Venus and at comets (e.g., Giacobini-Zinner, Halley), and for interstellar helium is an important physical process central to our understanding of the solar wind interaction with non-magnetic objects. Cloutier et al. (1974) developed a mass loading model for Venus. They examined two cases, corresponding to the electric field $E = -v \times B$ in the post-shock flow directed away from and toward the ionopause boundary. They found for the case of the E-field directed away from the ionopause boundary (and v perpendicular to B) that the ions produced above the ionopause are drawn outward by the E-field, and execute cycloidal motion as seen in the planetary rest frame, drifting at an average speed $v = E/B$ with the post-shock solar wind plasma. When the E-field is directed into the ionopause boundary (with $v \perp B$), they found that photoions are drawn toward the ionopause boundary by the E-field and that those created within $2a_c$ (where a_c is the ion gyroradius) of the boundary will penetrate into the region below the ionopause. Thus in this hemisphere within $2a_c$, they predict that most of the ions are concentrated near the ionopause boundary and drift with speeds less than the local plasma velocity. They found that photoions created at distances greater than $2a_c$ from the ionopause will undergo the same cycloidal motion as photoions produced where E is directed outward (the first case) and will drift with the local plasma velocity. The present paper summarizes the results of the first statistical analysis of PVO plasma observations to study the pickup of Venus ions downstream of the planet and to ascertain the evidence for a hemispheric asymmetry.

First we review some previous studies in this area. In the Observations section we summarize our criteria for identifying the Venus tail and O^+ pickup in the plasma data; then we show the results on the location of the O^+ events in the $v \times B$ coordinate system for some specific orbits; and finally we present the results for all of the O^+ events in this coordinate system.

Vaisberg et al. (1976) reported that Venera 10 data in the Venus optical shadow in the near wake (< 1.3 R_v) showed the presence of low-energy (50 eV) ions flowing from the limbside of Venus. They concluded that the peak of the energy spectrum was below 50 eV.

Previous PVO studies including plasma observations used only a limited data base. Intriligator (1982) studied the tail by analyzing the simultaneous heavy ion and proton data for the first (June 1979) tail season. This study provided clear evidence for the intermittent presence of heavy ions near the boundary of the tail and identified O^+ as the prevalent constituent of the heavy ions. The O^+ number densities were of the order of 1% of those of the protons. The speeds and flow angles (azimuthal and polar) of the heavy ions and the protons were found to be similar. Perez-de-Tejada et al. (1982) examined plasma and magnetic field data for the June 1979 tail season and found that the accelerated planetary O^+ ions tend to move in the shocked solar wind flow direction and not along the local magnetic field direction as predicted for ion pickup in comets (Alfven, 1957). Mihalov and Barnes (1982) examined the June 1979 plasma data and reported the xenographic locations of the O^+. Intriligator and Scarf (1984) used June 1979 data from the plasma analyzer, magnetometer, and plasma wave detectors to study wave-particle interactions in the Venus tail. Luhmann (1986) numerically calculated ion trajectories in the magnetosheath. Phillips et al. (1987) studied the finite Larmor radius effect on ion pickup at Venus in the near-planet magnetosheath using 10 pickup events and numerical calculations. More recently Intriligator (1988) and Slavin et al. (1989) studied additional plasma and magnetic field data in the tail region.

Russell et al. (1985) reported the first examination of field polarities in the tail.

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Saunders and Russell (SR) (1986) extended this study and found possible evidence of a hemispheric asymmetry in the cross-tail magnetic field with larger cross-tail fields in the upper magnetic hemisphere. They emphasized that an important remaining question concerns this asymmetry and its relation to the pickup of ionospheric ions. Our study employs the same first nine PVO tail seasons (through May 1984) of the Venus wake and we investigate statistically the mass loading of ionospheric ions in this region for those orbits where there is evidence of the Venus tail in the plasma data (see Observations).

In the present paper all the O^+ events we identify occur considerably further downstream ($x \sim 5$ to 12 R_v) than those recorded at Venera. While it is possible that on occasion the peak of the O^+ distribution in this relatively far Venus wake occurs below 50 eV, we do not observe the peak at these low energies. We usually observe the peak at considerably higher energies as reported in Intriligator (1982) and as presented in the next section.

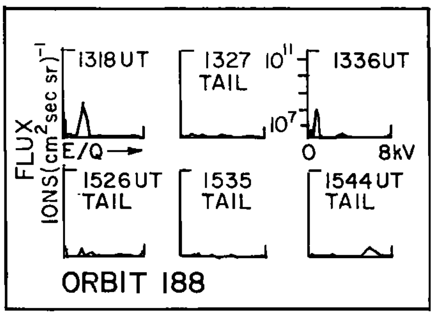

Fig. 1. Examples of intervals identified as the distant Venus tail in the PVO plasma data.

Observations

In identifying the Venus tail (see Figure 1) in the plasma analyzer data we employ one criterion: the absence of or substantially reduced levels of measurable ion flux. As first discussed in Intriligator and Scarf (1984) this leads to different times for the plasma tail as compared with the magnetic tail (based on only magnetometer data) for the same orbit. SR state that the identification of tail encounters based only on the magnetometer data is sometimes uncertain. We believe that the identification of the tail using plasma data is more reliable and less ambiguous than that based solely on magnetometer data.

We have carried out this first statistical study of mass addition downstream of Venus by examining each plasma analyzer ion spectrum obtained downstream of Venus on all orbits of the first nine tail seasons where there is evidence in the plasma data (see above) of the Venus tail. Our criteria for identifying "large" ion pickup (O^+) events are that the peak O^+ flux exceeds 1.6×10^7 ions (cm^2 sec sr)$^{-1}$ and that there are at least two points in the O^+ spectrum (see Figure 2) except in the few cases when the spectrum is part of a series of continuous spectra (1602 UT, 1612 UT, etc.) containing O^+ and the evolution of the spectra is such that in a particular spectrum

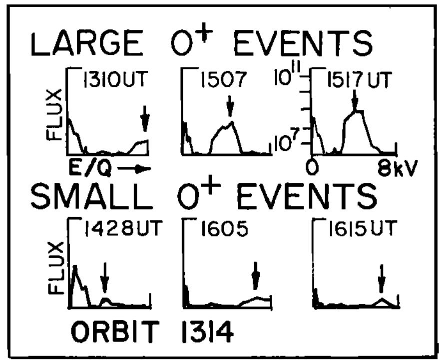

Fig. 2. Examples of "large" O^+ events and "small" O^+ events in the PVO plasma data.

only one point of the O^+ spectrum is within the energy per charge range of the detector (e.g., it is at the highest energy step). We do not include "small" O^+ events (see Figure 2) where the peak flux is less than 1.6×10^7 ions (cm^2 sec sr) in this study. It is evident in Figure 2 that the O^+ peaks occur at > 50 eV. If a peak occurs at < 50 eV (as in the Venera data) it is not observed by the PVO plasma analyzer since at times it may be "masked" or "swamped" by what appear to be low energy protons and/or the fluxes are so low that they are not observed.

To investigate ion pickup by the $v \times B$ electric field, we transform the location of the O^+ pickup ion from the xenographic Venus Solar Orbital (VSO) coordinate system $(X,Y,Z)_{VSO}$, to the aberrated VSO coordinate system $(X',Y',Z')_{VSO}$ and finally to the magnetic coordinate system $(X'',Y'',Z'')_{VSO}$ as employed in SR. The VSO system is analogous to GSE coordinates since it employs the Venus orbital plane for the X - Y plane where the Venus orbital motion is in the $-Y_{VSO}$ direction. In the aberrated VSO coordinates there is a 5° rotation (corresponding to the 5° aberration angle for the Venus tail) in the XY plane such that $-X'_{VSO}$ aligns with the aberrated tail axis. In the magnetic coordinates the Y''_{VSO} coordinate is aligned with the $B\perp$ or cross-flow component of the upstream interplanetary magnetic field so that it differs from the aberrated VSO coordinates by the rotation about the X'_{VSO} axis.

Figure 3 shows examples of the location of the O^+ events in the VSO coordinate system (upper panel) and in the magnetic coordinate system (lower panel). Figure 4 shows in the magnetic coordinate system all the large O^+ events observed in the first nine tail seasons. There are a total of 167 large ion pickup events during this time. The ellipse shows an average tail boundary from SR. The numbers in Figure 4 denote the number of O^+ events in each bin, where a bin is $1/3\ R_v \times 1/3\ R_v$. From Figure 4 it is evident that most of the large pickup ion or O^+ events occur above $Z'' = 0$. Specifically 125 large O^+ events occur at $Z'' > 0$ and 29 large O^+ events occur at $Z'' < 0$. The 13 large O^+ events that occurred at $Z'' = 0$ were not included in either the $Z'' > 0$ or $Z'' < 0$.

Figure 5 shows the location of each of the O^+ events in the magnetic coordinate system plotted in the north-south (Z'') direction as a function

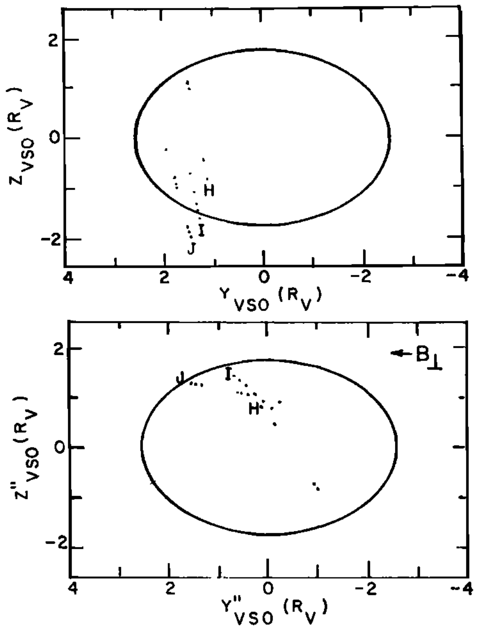

Fig. 3. Examples of the location of the large O^+ events in the VSO coordinate system (upper panel) and in the magnetic coordinate system (lower panel).

of the Z" position in gyroradii (Cloutier et al.) and in the east-west direction as a function of the Y" position in R_V. The bin size is 1/3 by 1/3 in the units of the respective axes. In this figure it is also evident that most of the events occur at Z" > 0. In this case 129 events occur at Z" > 0, 9 occur at Z" = 0, and 29 occur at Z" < 0. From Figure 5 we can also see that most events (i.e., 127) occurred between 0 and $\pm 2a_c$.

Discussion

We carried out the first statistical analysis of plasma observations downstream of Venus.

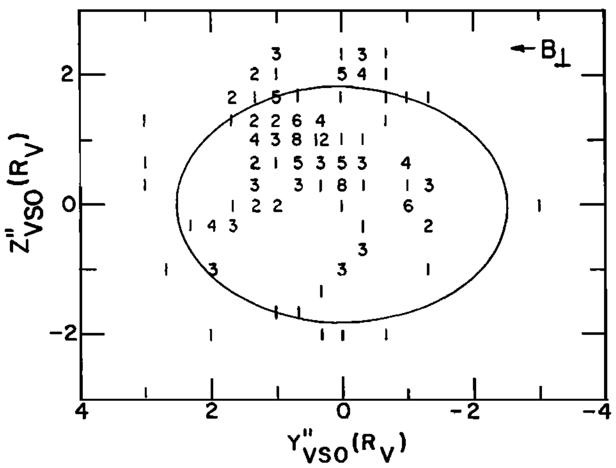

Fig. 4. Summary of all the large O^+ events in the magnetic coordinate system on orbits where the tail was observed in the first nine tail seasons. The numbers denote the number of large O^+ events in each bin (see text).

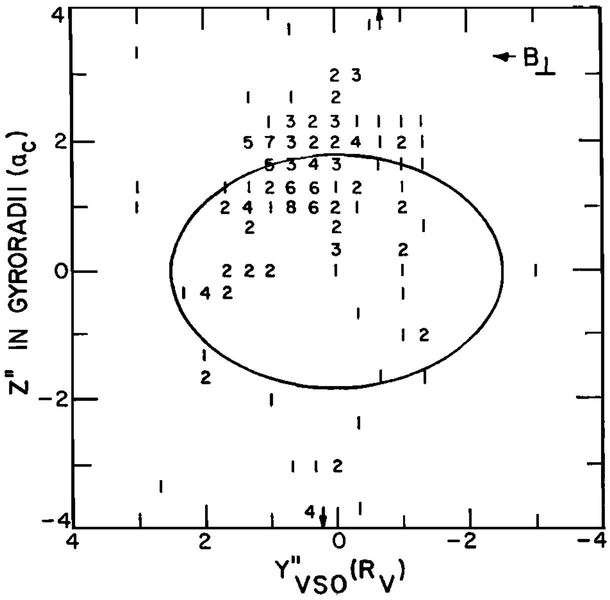

Fig. 5. Summary of all the large O^+ events as a function of gyroradii in the Z" (north-south) direction in the magnetic coordinate system. The Y" direction is expressed in terms of R_V. The numbers denote the number of large O^+ events in each bin (see text). Note the clustering of events within ±2 gyroradii. The arrows at the top and at the bottom of the figure denote that the position of 1 and 4 events, respectively, lie outside the plot.

Using the first nine tail seasons, we examined each plasma spectrum and identified orbits where the plasma data show evidence of the tail. For each of these orbits we examined each plasma spectrum to determine if there was evidence of ion pickup. We then selected all of the 167 large pickup events for this study. It is possible that some of the ions in these "large O^+ events" are not O^+ (rather He^+, etc.), but they are all ions that have been picked up at Venus.

Our analysis clearly indicates that there is a hemispheric asymmetry in the pickup of ionospheric O^+ ions on orbits where the tail has been evident in the plasma data and that approximately four (i.e., 4.3) times more O^+ events (i.e., 125 events versus 29 events) are observed in the "northern" (Z" > 0) magnetic hemisphere than in the "southern" (Z" < 0) magnetic hemisphere when the north/south distance is expressed in R_V. When it is expressed in terms of gyroradii there are still approximately four times (i.e., 4.4) more events observed (i.e., 129 versus 29) in the northern magnetic hemisphere. Since 125 (129) large O^+ events out of a total of 167 large O^+ events occurred at Z" > 0 this indicates that 75% (77%) of the O^+ events occurred in the "northern" hemisphere where the v × B field is outward.

This hemispheric asymmetry in ion pickup is consistent with the predictions of Cloutier et al. (1974) who found a hemispheric asymmetry in Venusian ions above the ionopause boundary. In the hemisphere where the v × B electric field points outward (i.e., the "northern" hemisphere) they calculated almost a constant density of ions (of a given species) from the ionopause boundary out to two gyroradii ($2a_c$) above the ionopause. At distances greater than $2a_c$ they found that the density decreased exponentially with the species neutral scale height. In this hemisphere all ions are accelerated up to post-shock solar wind ion speeds. In contrast, in the other hemisphere (i.e., the "southern" hemisphere), where the induced electric field is directed inward, they predict that the ions are concentrated much closer to the ionopause boundary and that their density falls off rapidly with height above it. In this hemisphere within two gyroradii of the ionopause boundary, they find that the average drift velocity of the ions is less than the flow velocity of the post-shock solar wind ions (varying with distance, the drift velocity is zero at the ionopause boundary and equal to the post-shock solar wind flow velocity at $2a_c$ above the ionopause). Since we find that approximately 75% of the O^+ events occur in the hemisphere where the $v \times B$ field is outward we present the first statistical verification of the prediction of Cloutier et al. (1974). The clustering of the O^+ ions within ± 2 gyroradii in Figure 5 is quite dramatic (127 events occur between 0 and $\pm 2a_c$) and is also consistent with the predictions of Cloutier et al. The hemispheric asymmetry in the O^+ pickup we observe in the tail is also consistent with the possible asymmetric hemispherical magnetic flux reported by Saunders and Russell.

Perez et al. (1982) found that the flow direction of the O^+ in this region tends to be in the direction of the shocked solar wind flow and not necessarily along the local magnetic field direction. The clustering of the O^+ ions within ± 2 gyroradii in Figure 5 implies that these O^+ ions have only recently been picked up. We believe that the hemispheric asymmetric of the picked up O^+ we report here is indicative of only the initial gyrotropic pickup of the O^+ at the Venus source region as predicted by Cloutier et al. (1974) and not necessarily of the dominance of gyrotropic processes in the plasma flow downstream of the planet (Perez-de-Tejada, private communication).

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