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Venus/Mars pickup ions and ionosheath wave structures

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Abstract

A search for ULF waves associated with pickup ions was undertaken for Venus and for Mars. The Pioneer Venus Orbital Plasma Analyzer (OPA) measurements of ion energy per unit charge spectra provided signatures of the probable presence of pick-up ions. At the locations of these energetic ion signatures we derived power spectra and propagation characteristics of structures in the local magnetic field from measurements by the Pioneer Venus Orbiter Magnetometer. Some of these features are characteristic of effects previously identified in the ionosheath of Venus, analogous to wave activity properties in the Earth's magnetosheath. However, for the first time examples have been found at Venus of ULF waves near the ion gyrofrequencies in the ionosheath and in the far magnetic tail. Both linear and elliptically polarized waves are found in the vicinity of ion pickup detections. The signatures of these features are presented using one orbit of Pioneer Venus Orbiter data. The same wave analysis techniques are applied to the magnetic field data measured on one characteristic orbit from the Mars Global Surveyor Magnetometer. This is used to demonstrate how a comparative analysis of the two planets can be useful.
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1. Introduction

The atmospheres of Mars and Venus extend into the shocked solar wind region. Hence the ionosheaths of these planets as well as their magnetic tails have ion components of atmospheric origin that are accelerated by the electromotive electric field deriving from the solar wind. These planetary ions, either created in the midst of the high-speed solar wind plasma or as directed ion beams, are potential sources for the generation of ULF magnetoplasma waves with frequencies below ~1 Hz from waves generated at the ion gyrofrequencies of the planetary ions. The Earth's magnetosheath, where pickup ions are not important, is characterized by strong ULF wave activity that is predominately produced by solar wind/bow shock processes. Hence in order to show that atmospheric derived ions are actually stimulants of wave activity for Mars and Venus one must look for wave signatures and/or ion measurements, such as wave packets at the pickup ion cyclotron frequencies that are clearly distinct from the well-studied magnetosheath/solar wind induced wave activity at Earth. For example, comet studies (Tsurutani, 1991) have found clear magnetic wave signatures at the gyrofrequency of water-derived ion species. For Venus and Mars one might anticipate similar signatures for H^+ and O^+ – the much more minor, heavier molecular ions that exist near these planets are not likely significant sources of wave activity.

Magnetic field observations from Pioneer Venus Orbiter (PVO) provided the first in depth analysis of MHD wave activity for a planet with an extensive atmosphere and no intrinsic magnetic field. Discrete ULF wave frequencies were detected in association with the planetary bow shock (Greenstadt et al., 1987) which have been identified as whistler waves (Orlowski and Russell,

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1995) analogous to the "1 Hz" waves seen upstream of the Earth's bow shock (e.g., Fairfield, 1976). The waves have right hand polarization in the solar wind reference frame, but because of their low phase velocity relative to the solar wind are Doppler shifted, and frequently have left-handed polarization in the spacecraft reference frame of PVO. Similar waves were observed upstream of Mars' bow shock (Russell et al., 1990).

Also within the ionosheath of Venus, ULF waves with 10–40 s periods have been traced along convection streamlines to the bow shock and their turbulence levels correlate with upstream solar wind turbulence (Luhmann et al., 1983). These waves arise in the vicinity of, or upstream of, the shock with turbulence levels associated with quasi-parallel shock regions. Terrestrial magnetosheath observations also show ULF wave activity in the magnetosheath that is directly related to solar wind wave activity with localized peaks in the ULF power spectrum, at ~0.1 Hz or less, that parallel those in the solar wind. At Venus, even though accelerated ions of ionospheric origin have been detected above the thermal ionosphere there has been no experimental evidence thus far for activity different than at Earth that would indicate the presence of pickup ion stimulated ULF waves. For Mars, Brain et al. (2002) recently demonstrated, from Mars Global Surveyor magnetometer measurements, the prevalence of H^+ ion cyclotron frequency waves upstream of the Martian bow shock. The existence of such waves at Mars attributed to pickup ions was first reported by Russell et al. (1990), on the basis of Phobos measurements. Their prominent presence at Mars compared to Venus is considered to be the result of the extension of Mars' exosphere much further into the solar wind than at Venus. In this paper an orbit of measurements from PVO will be discussed that has ULF wave signatures that appear to derive from such ionization. The same analysis technique will be applied to one orbit of MGS data at Mars to show the differences in the way PVO and MGS view the ULF wave activity.

2. Approach

PVO ion measurements from the ARC Orbiter Plasma Analyzer (OPA) were surveyed to identify orbits that appeared to encounter pick-up ions. For the orbits of interest, the trajectories were examined and time intervals were selected for study and for availability of other data sets. Time-series spectral and phase analyses of the magnetic field measurements from UCLA's Orbiter Magnetometer (OMAG) were made looking for coherent wave trains near the ion cyclotron frequencies. For comparison samples at Mars taken from the GSFC magnetometer (MAG) on Mars Global Surveyor (MGS) were also investigated. In this brief paper we will describe one complete orbital analysis for both planets showing some new facets of the low frequency wave activity in the ionosheaths of these planets. Our analysis approach employs the computation of ULF power spectra and perturbation B vector phase angle plots using PVO and MGS high-resolution magnetic field measurements. The two techniques complement one another. The power spectra are based on only the amplitude of the B fluctuations – hence directional information on the wave polarization is obtained by comparison of the power of different field components observed over a finite time interval. On the other hand the phase of the instantaneous vector disturbance field depends only on the direction of perturbation magnetic field vector. Sometimes ULF waves may have a coherent rotation, but if the rotation rate varies, no distinct frequency peak will be seen in the power spectrum integrated over time while the temporal variation of the phase of the perturbation vector will reveal the discrete wave component. On the other hand if multiple wave modes exist (e.g., at O^+ and H^+ gyrofrequencies simultaneously) the superposition of the two modes may obscure the cycling in a phase-time plot, so a spectral analysis would best separate the two components. This phase analysis technique, first used for Mars by Cloutier et al. (1999), is an excellent mechanism for delineating the wave train scale sizes.

3. Results

For Venus PVO, analysis of measurements by the OPA (Intriligator et al., 1980) provided evidence of the presence of pick-up ions. These measurements provide a reference point for focusing the study of wave activity in regions where pickup ions might lead to ULF wave stimulations. The instrument is a quadrispherical electrostatic analyzer with five north–south collectors that utilized the spacecraft longitudinal spin (12 s period) to make 3-dimensional measurements of ion fluxes as a function of energy per unit charge from 50 eV to 8 keV in 32 steps. In this study only the maximum flux mode of the instrument was employed – i.e., the mode which selected the maximum ion flux detected from all view angles for each 12 s E/Q step.

One complete orbit, number 638, of OPA measurements will be described in which the orbit plane of the nearly polar-orbiting PVO was in the noon-midnight meridian, with periapsis near noon. This orbit was selected because it provided clear evidence of energetic atmosphere related ions in the magnetotail and some traces in the dayside ionosheath. The trajectory for this orbit is plotted in Fig. 1 in which the locations of orbital segments to be singled out for wave analysis are labeled (A–E and 1–3). The regions of interest chosen correspond to periods upwind of the bow shock (both in and

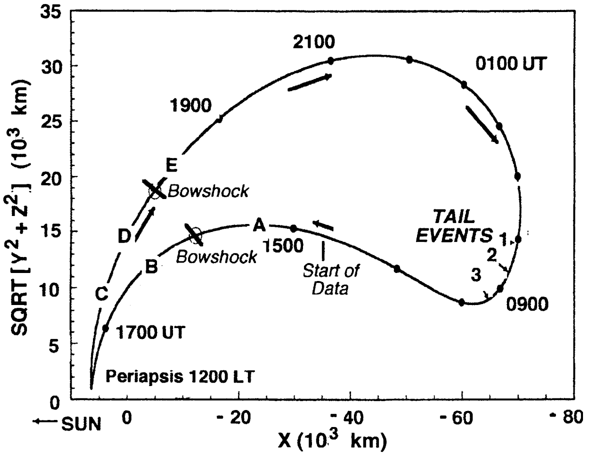

Fig. 1. PVO trajectory for Orbit 638 on September 3, 1980 in cylindrical coordinates with respect to center of Venus. Locations of bow shock crossings are indicated along with regions to be examined in detail. Periapsis was ~330 km altitude.

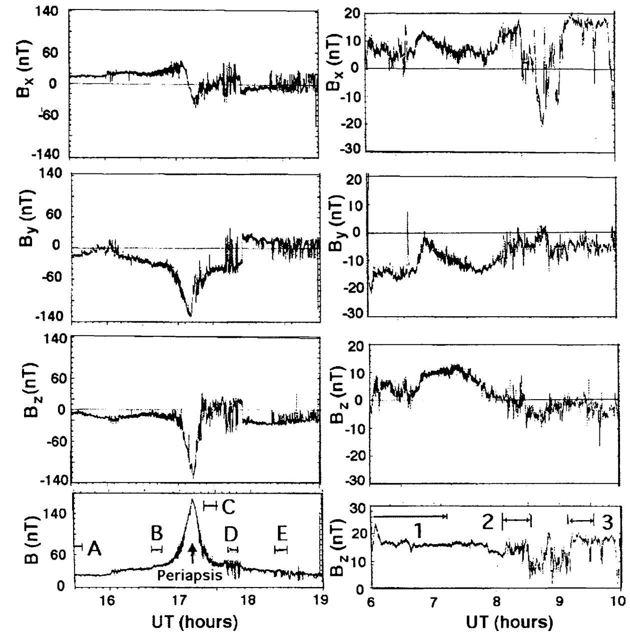

Fig. 3. PVO orbit 638 magnetic field data.

out-bound), ionosheath segments, and periods near apoapsis in the far magnetotail of the planet. The ionopause on this orbit occurred at or below periapsis.

A comprehensive set of OPA measurements taken on orbit 638 are plotted in Fig. 2. The time sequence of data plotted starts on the inbound leg when the spacecraft is far out in the solar wind, continuing as PVO moves through the bowshock, traverses the ionosheath, down to periapsis and then back up and out into the solar wind. There is subsequently a 12 h gap in the plot and then continuous spectra are shown as the spacecraft enters the far magnetotail. The corresponding magnetic field components for the orbit are plotted in Fig. 3. Solar wind conditions changed from the inbound and outbound crossing of the shock, as is seen in the change of the inbound and outbound magnetic field *X* and *Y* components. In the magnetotail traversal the events 2 and 3 were selected because the interesting OPA signatures happened to be located on nearly radial field lines – i.e., the *X* component of the field was dominant. Inbound the OPA sequence of measurements in the solar wind show characteristic solar wind spectra of H^+ and a higher energy peak or bump due to He^{++}.

The time periods corresponding to the spectra at A, and E on the outbound leg are study event intervals in the solar wind. Going inbound through the bowshock and into the ionosheath one sees only the shocked solar wind ions initially until the spectrum "B" where distinct higher energy shoulders/peaks appear that may be accelerated planetary ions, H^+ or O^+. Full ion pickup would introduce plasma energies up to twice the shocked solar wind speed. But since the atmospheric scale height is less than the ion gyroradii, the pickup ion

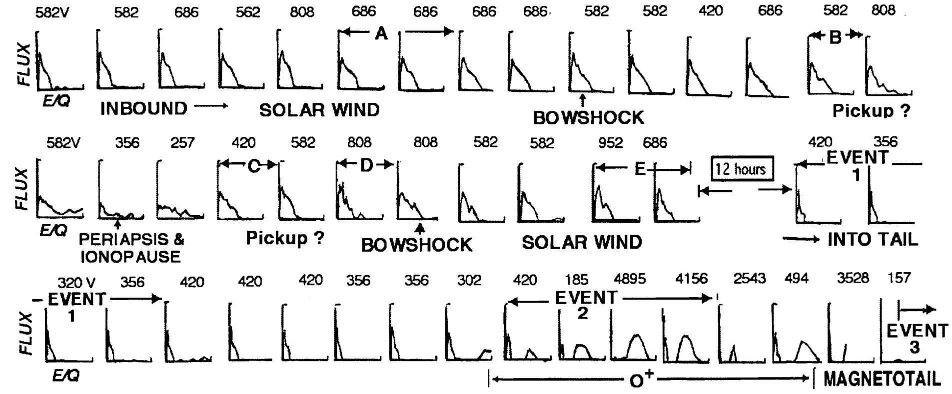

Fig. 2. Continuous OPA measurements for PVO orbit 638. Data start at 143456 UT and each frame plots Flux (ions/cm²-s-sr) vs. energy/Q (50 eV–8 keV). Data correspond to measurements in the solar wind inbound, traversal of the ionosheath inbound and outbound and then back into the solar wind and far into the tail emergence into the magnetotail.where high energy ions are detected, presumably O^+. The labels above each curve depict the energy of the maximum flux in each spectrum.

distributions are characterized by lower energies than this (Hartle et al., 2001). Unfortunately, due to limited project resources, the instrument did not have the capability to identify the masses of the ion species. Outbound, similar ionosheath spectra were seen before PVO again entered into the solar wind. When the spacecraft entered the magnetotail the ion temperatures cooled and, where the magnetic field became radial, a prominent high-energy ion component with a peak flux at an energy exceeding 4 keV was encountered. This (e.g., event 2) has the characteristic signatures of heavy ions, presumably O^+ as was deduced in earlier studies of pickup ions (e.g., Intriligator, 1989).

The magnetic field power spectra for the selected OPA event time intervals are depicted in Fig. 4. A routine was used for the analysis of unevenly sampled data developed by Lomb (1976). This eliminated the need to make algorithm approximations for data gaps or changes in telemetry rates as must be done with the Fast Fourier Transform technique. The upper cutoff frequencies in the plots are at the Nyquist frequencies corresponding to the average of the time interval between samples. The spectra shown are only for the transverse magnetic field fluctuations (relative to the average *B* vector over 256 consecutive data points) for the *B* vector components in the planet orbit plane. This was typically the component with the highest power for the PVO time segments considered here. Inset on each power spectrum plot is a short sequence of the instantaneous phase angle of the perpendicular perturbation field vector for intervals within the power spectrum time range. Phase plots were singled out which showed the presence of clear localized packets of oscillations. Polarization plots of the perturbation vectors were also obtained, but not shown here.

The ULF wave power in the solar wind (A) was generally greater than in the outer ionosheath inbound (B), but in the latter region a prominent enhancement is seen in a frequency region straddling the local H^+ gyrofrequency. Inbound the IMF direction was such that the shock orientation was quasi-perpendicular. The inset time sequence plot of the transverse perturbation phase angle confirms the presence of a wave train with repetition frequencies in the same range as the power spectrum peak. The slope of the phase angle-time curves indicates left hand polarization in the spacecraft rest frame. In conjunction with the OPA measurement of a bump in the shocked solar wind ion spectrum, which could be atmosphere derived H^+, the wave activity in the ionosheath offers evidence for an association of these ions with proton cyclotron components in the wave distributions. After passage through perigee on the outbound traversal of the ionosheath the wave power is enhanced and

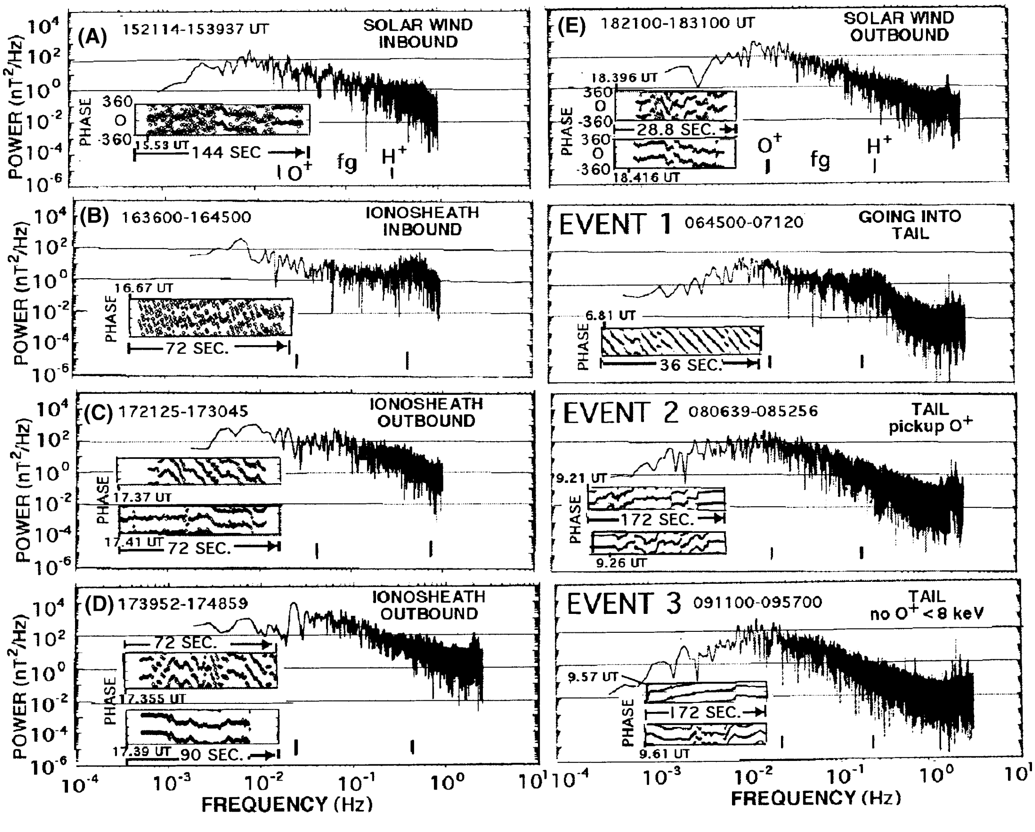

Fig. 4. Power spectra and phase angles for PVO orbit 638. Progression is from out in the solar wind on top left, as the spacecraft moves inbound (downward on left) to perigee and then outbound into the tail (on the right), Phase angles are plotted from −360 to 360 to better see the cyclic behavior.

spectral peaks near the O^+ ion gyrofrequency appear in the outer sheath (D) that are significant to the 1% level. In the outbound inner ionosheath region C the perturbation vector phase momentarily, for ~40 s (400 km along PVO's orbit), becomes oscillatory with a repetition frequency less than 0.1 Hz. In region D just inside the bow shock a distinct tone at the O^+ gyrofrequency appears and there is evidence of a short coherent burst at such a frequency in the phase angle plot segment shown. Polarization is left-handed. These are the first Venus wave examples found, supported by the ion measurements, which could be related to atmospherically derived ions. Distinct peaks are also seen at a few hertz in the outer sheath and solar wind. These are consistent with the characteristic 1 Hz signals associated with quasi-parallel shocks.

Other interesting examples of ion cyclotron frequency waves are seen in the magnetotail crossings shown in Fig. 4 (right) where in event 1 prominent left hand polarized waves are encountered going into the tail with a spectral peak at the H^+ cyclotron frequency. Later when energetic O^+ ions are detected the low frequency power level near the O^+ gyrofrequency is intensified and distinct wave trains are seen in the phase angle plots near the same frequency with right hand polarization. The right hand polarization suggests a different source mechanism than the proton cyclotron frequency waves.

The more extended atmosphere of Mars and the lower magnitude of the interplanetary magnetic field at Mars produce differences in the wave environments from that at Venus. In particular waves near the H^+ ion cyclotron frequency are clearly evident upstream of the bow shock. Space does not permit a detailed discussion of the Mars environment, but one example for general comparison to the Venus discussion is shown in Fig. 5. This event was selected because of the very prominent cyclical activity in the magnetic field. Planetward of the magnetic pileup boundary, in the ionosphere, very low ULF frequencies dominate, indicating the presence of ionospheric magnetoacoustic activity. The phase plot indicates a long period wave with possibly a right hand polarization component. In the ionosheath and in the solar wind very coherent left hand polarized wave trains of frequencies less than a few tenths of an Hz are seen with a broad power peak straddling the proton cyclotron frequency. In the solar wind the power spectrum has a similar peak but is above the average local proton gyrofrequency. Whether related to pickup ions or simply the Mars analogue of magnetosheath/solar wind behavior seen at Earth needs further evaluation. The waves appear to be much more coherent for longer periods in MGS data than for PVO. Since MGS's speed (2.5 km/s for event C, 3.7 km/s for B, and 5.6 km/s for A) is slower than PVO's speed near periapsis 10 km/s) a comparison of both spacecraft observations of the same wave feature could be used to explore frequency-wavelength characteristics of some wave processes.

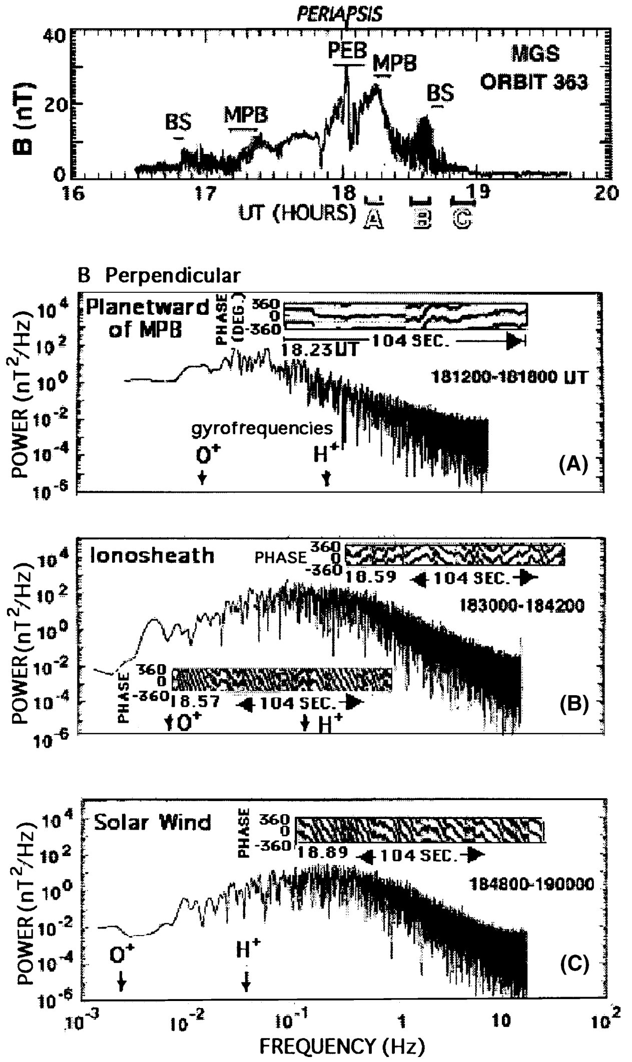

Fig. 5. MGS orbit 363 outbound. Power spectra and segments of transverse disturbance phase angles. The locations of the power spectra windows relative to the Photoionization Boundary, the Magnetic Pile-up Boundary and the Bow Shock are labeled on the too plot.

4. Summary

Examples of power spectra and transverse magnetic disturbance phase angles show the presence of bursts of left-hand polarized waves in the ionosheaths of Mars and Venus. For Venus the ion measurements support the presence of ion cyclotron frequency waves related to pickup ions. In the tail of Venus right-hand polarized waves with frequencies near the O^+ gyrofrequency were observed. The narrow energy distributions of O^+ in the tail are "cold" relative to the "hot" distributions expected from pickup ions, consistent with the concept that tail ions are of ionospheric origin (e.g., Hartle and Grebowsky, 1993, Brace et al., 1995), being accelerated directly from the dayside and/or nightside ionosphere. Such "cold" Venus ions have been observed at 1 AU from SOHO (Hartle et al., 2001). At Venus, throughout the ionosheath and out into the solar wind, the H^+ and O^+ pickup ions energy densities are less than those in the observed cyclotron frequency waves. Such waves may have been generated in the solar wind before being influenced by the planet. However, following Sauer et al. (2001), the few pickup ions may have acted as "seed" ions for the generation of the waves. In contrast, the H^+pickup energy density in the ionosheath and the near solar wind at Mars is on the order of the wave energy, making a good case that such ions can drive the proton cyclotron waves.

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