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Comparison of Observed Plasma and Magnetic Field Structures in the Wakes of Mars and Venus

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Plasma and magnetic field observations from the Phobos 2 spacecraft at Mars and the Pioneer Venus orbiter (PVO) at Venus show that there are some notable similarities in the structure of the low-altitude magnetotails at both of these weakly magnetized planets. In particular, it is found that when conditions in the interplanetary medium are steady and the orbit sampling geometry is appropriate, two magnetic tail lobes, with an intervening "plasma sheet" or "central tail ray" in the approximate location of the dividing current sheet, are present. This behavior is seen in both the Phobos 2 ASPERA plasma analyzer data and in the PVO Langmuir probe data. In the Phobos 2 data, the tail ray is found to be composed primarily of antisunward streaming oxygen (O^+) plasma which has a bulk velocity consistent with an energy close to that of the upstream solar wind plasma. The PVO Langmuir probe experiment also detected two (or more) additional cold plasma structures flanking the central feature; Phobos 2 data, on the other hand, show a proton plasma "boundary layer" flanking the central (mostly O^+) tail ray or plasma sheet, with sporadic fluxes or rays of O^+ ions. If the latter considered is to be the magnetosheath (solar wind plasma) at the tail boundary, it is mainly the common central tail O^+ features that suggest that there are common planetary ion acceleration and magnetotail formation processes at work in the low-altitude wakes of Mars and Venus. On the other hand, an important contribution from picked-up exospheric hydrogen in the wake at Mars cannot be ruled out.

INTRODUCTION

Until Phobos 2 arrived at Mars in 1989, the only detailed view of the region where the magnetotail of a weakly magnetized planet is formed came from the Pioneer Venus orbiter (PVO) spacecraft. PVO was equipped with instrumentation for making both aeronomical and plasma physical measurements [see *Colin* 1980]. The PVO data of most value for studying the "roots" of the Venus magnetotail were obtained during the extended mission, when the orbit periapsis was allowed to rise from ~150 km altitude to ~2300 km altitude (about 1.3 R_V from the center of Venus). For these orbits, the magnetometer and Langmuir probe (electron temperature probe) experiments provided the most continuous and directly interpretable data. (The PVO plasma analyzer had only ~ 9 min temporal resolution, operated in a variety of modes, and was frequently turned off at periapsis.) Together, the magnetic and plasma electron measurements hinted at the complicated nature of this region [*Brace et al.*, 1987].

Experiments on Phobos 2 have now provided observations behind Mars at ~2.7-2.9 R_M. The complement of plasma instruments on Phobos 2 was different than that on PVO, with greater emphasis on energetic plasma composition measurements [cf. *Lundin et al.*, 1989; *Rosenbauer et al.*, 1989]. Here we examine selected samples from the Phobos 2 data obtained by the ASPERA (automatic space plasma experiment with a rotating analyzer) [*Lundin et al.*, 1989] and MAGMA (magnetic fields near Mars) magnetometer experiments [*Riedler et al.*, 1989], and we consider the parallels that exist between the features seen at Mars and those seen with the Pioneer Venus Langmuir probe and magnetometer experiments at 1.3 R_V behind Venus [*Brace et al.*, 1987]. Comparisons with the Phobos 2 Langmuir probe data, and between the Mars and Venus plasma wave data in these regions, will be described elsewhere by other authors.

DESCRIPTION OF THE DATA

For the purpose of the present analysis, we selected a subset of the available wake passes, some of which were used by *Luhmann et al.* [this issue] to demonstrate the similarity between the Mars and Venus induced magnetotails. These data were generally chosen because of their clear bipolar signatures in the x (planet-Sun axis) component of the magnetic field. The appearance of this signature requires both a fairly steady interplanetary field orientation and an appreciable angle between the plane of the spacecraft trajectory (an almost polar orbit, in the case of PVO; a more nearly equatorial orbit for Phobos 2) and the plane of the current sheet dividing the induced tail lobes. It was considered that if the plasma behavior in the wake was related to that of the magnetic field, the relationship should be apparent in these particular passes.

As mentioned above, the PVO data used here were obtained with the magnetometer and Langmuir probe experiments during the extended mission. Although higher temporal resolution is available, sufficient detail was obtained by examining 15-s magnetic field averages within ±1 hour of periapsis, and the corresponding 12-s resolution electron density and temperature data from the Langmuir probe. It is assumed that the Langmuir probe is measuring the electrons associated with the "cold" ionospheric plasma, which is primarily O^+ and H^+. Only data obtained in the optical shadow of Venus were used because the Langmuir probe can best measure low densities in darkness (the "noise" level from spacecraft photoelectrons

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when in sunlight is at about the 10 cm^{-3} level). However, we consider that most of the ion tail structure lies within the shadow. The Phobos 2 plasma data were obtained by the ASPERA plasma spectrometer [*Lundin et al.*, 1989], which gives both the energy per charge and mass of ions in the range 0.5 eV/charge to 24 keV/charge. (Here it is assumed that all ions are singly charged.) Although ASPERA nominally has a 360° field of view, the fluxes in the detector sector pointing toward the Sun were used since the majority of counts occur in this sector. The angular resolution is roughly 36° per sector. Two- minute averages of the density moments obtained during both circular and elliptical orbit phases of the mission are used for the present investigation. These moments are given separately for O^+ ions and for protons.

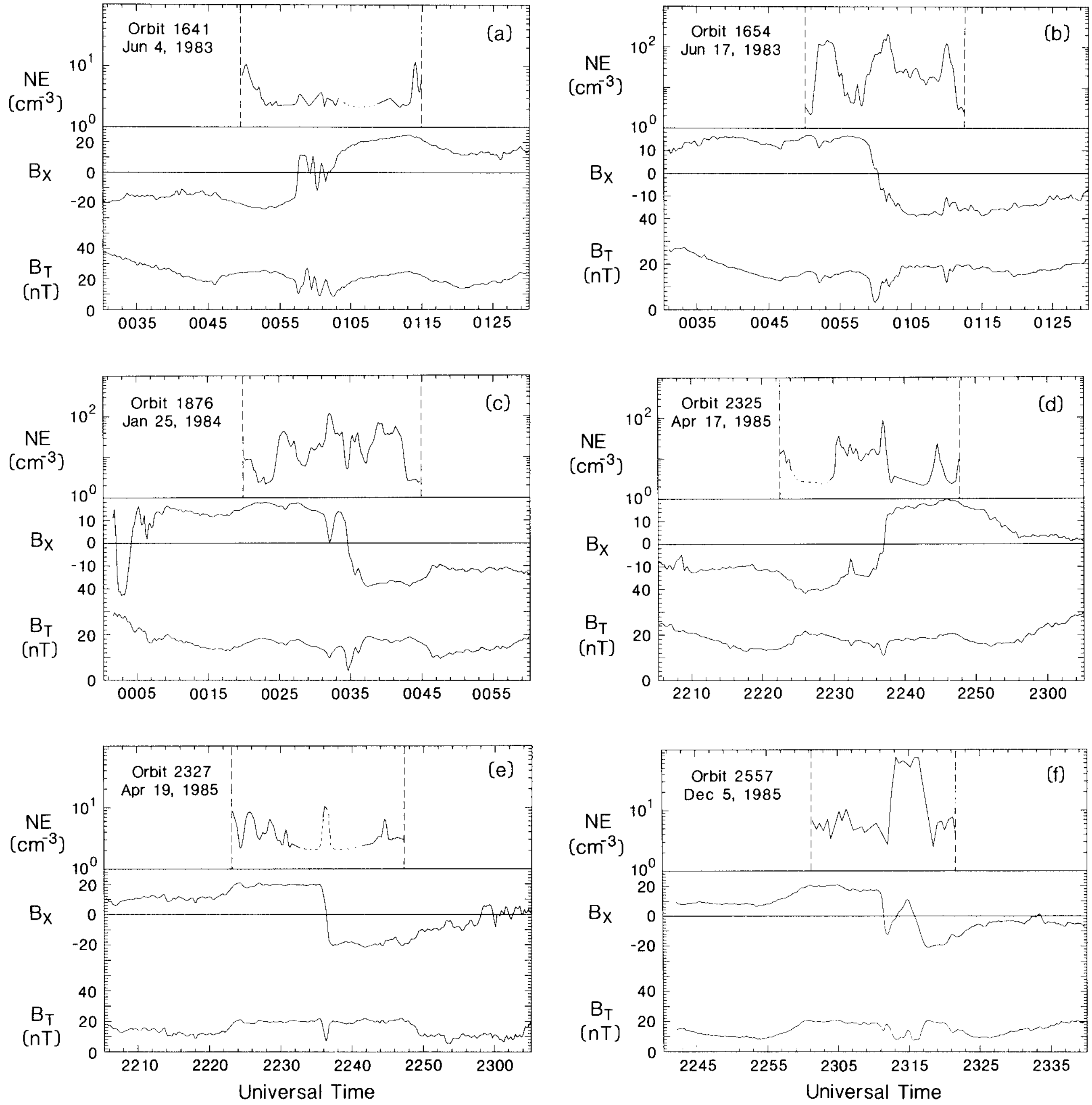

Fig. 1. Selected time series of electron density (NE) and the magnitude (B_T) and x component (B_x) of the magnetic field vector in the near wake of Venus measured by the PVO Langmuir probe and magnetometer, respectively. The dashed lines mark the optical wake within which the density measurements were possible. Dotted lines in the data are drawn where the density fell below the limit of detection. The x component of the magnetic field points toward or away from the Sun. For these particularly clear examples of the double-lobed magnetic structure at tail positions of about -1.3 R_V, three separate features ("tail rays") are generally seen in the electron density near the center of the tail. Their apparent widths, deduced from their durations of ~ 1-5 min (full width at half maximum) and a nominal spacecraft velocity of ~ 10 km s^{-1}, are ~ 600 to 3000 km. The central features roughly coincide with the current sheet B_x reversal.

COMPARISONS

Figures 1*a* through 1*f* show simultaneous PVO magnetometer and Langmuir probe time series for four selected passes through the wake of Venus. Only the magnetic field *x* component (B_x) and total field (B_T) for the hour around periapsis are shown since these contain the key information for the present study. (*Luhmann et al.* [this issue] show the same magnetometer data for a 2-hour period that includes the bow shock crossings.) All of the magnetic time series show the distinctive B_x signature of two tail lobes (fields pointing sunward and antisunward) separated by a reversal in B_x which we interpret as a current sheet. The "polarity" of these lobes changes when the interplanetary field component transverse to the upstream flow reverses. The corresponding Langmuir probe data likewise show distinctive features. For almost all of the examples in Figure 1, a central "tail ray," or "plasma sheet," was observed at the location of the central current sheet

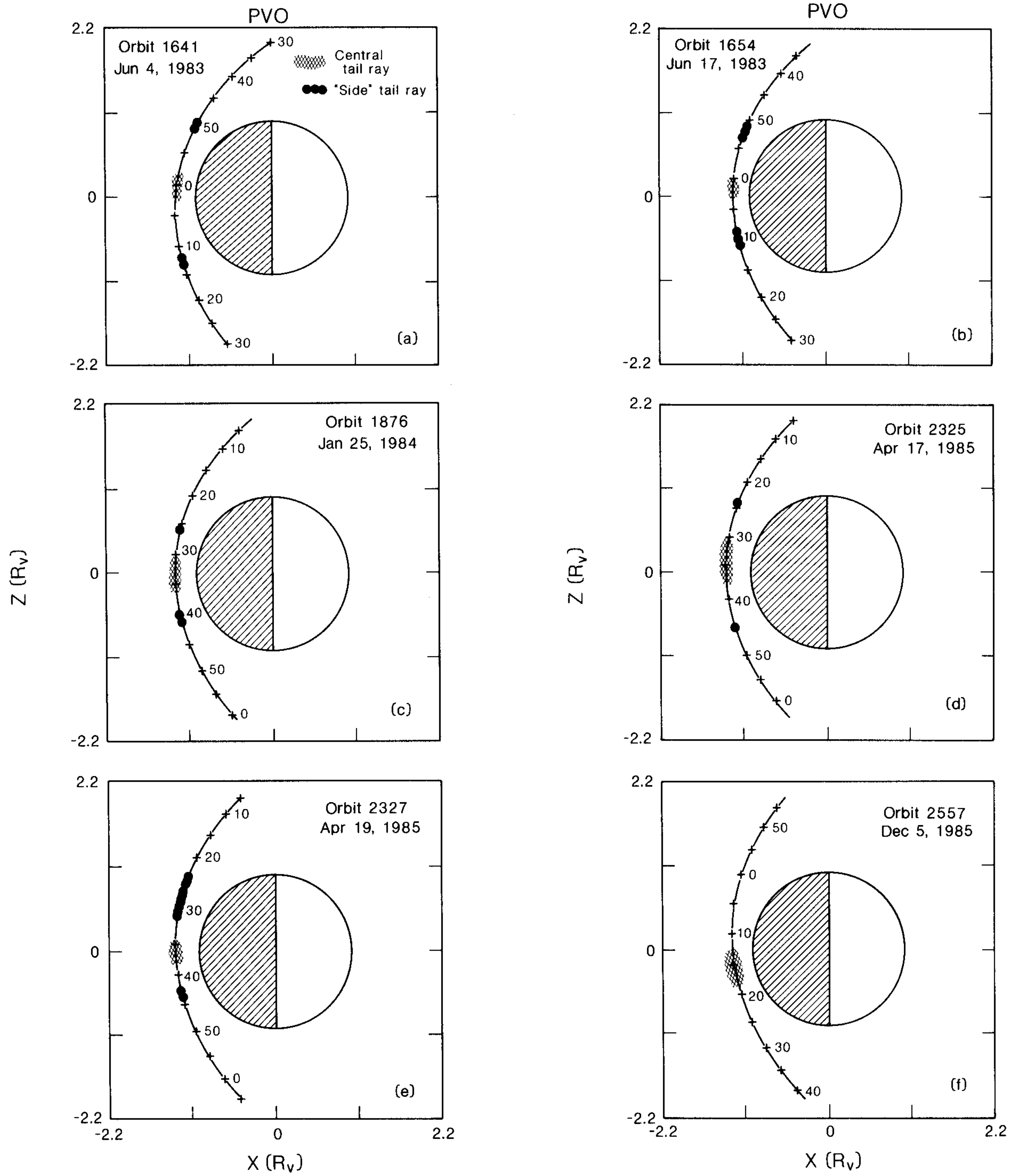

Fig. 2. Noon-midnight meridian plane views of PVO orbit segments for the passes used in Figure 1, showing the location of the plasma structures relative to the optical shadow. The numbers on the spacecraft trajectory correspond to the minutes in the time series in Figure 1.

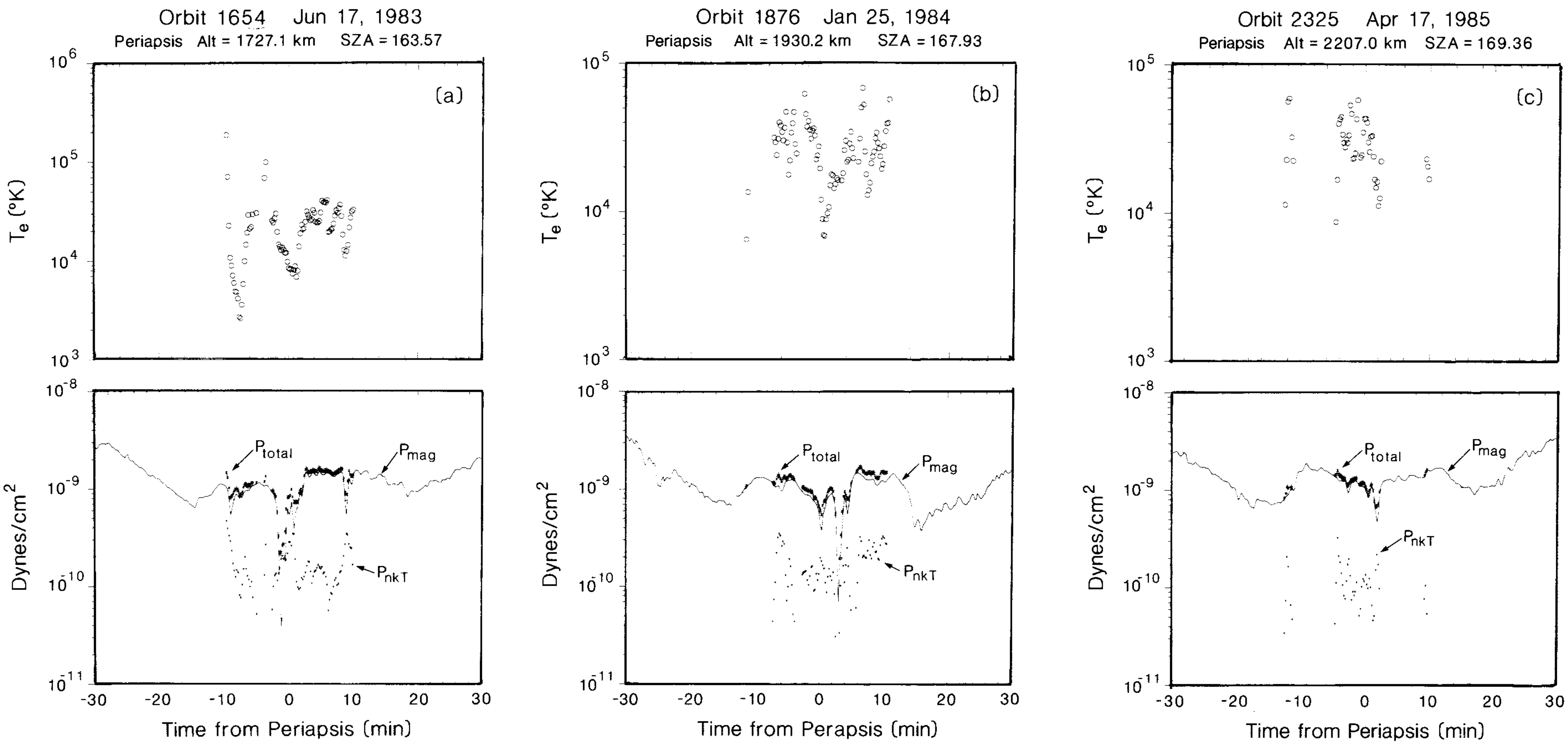

Fig. 3. Comparison of various pressures in the central near wake of Venus, computed from the magnetic field strength (magnetic pressure, P_{mag}) and the observed plasma density and electron temperature (thermal pressure, P_{nkT}, assuming the ion temperature is one-half the observed electron temperature) for several of the passes shown in Figure 1. Total pressure is also shown for those points where thermal pressure makes a contribution. For the above assumptions concerning the ion temperatures, the magnetic pressure appears to dominate throughout most of the near wake.

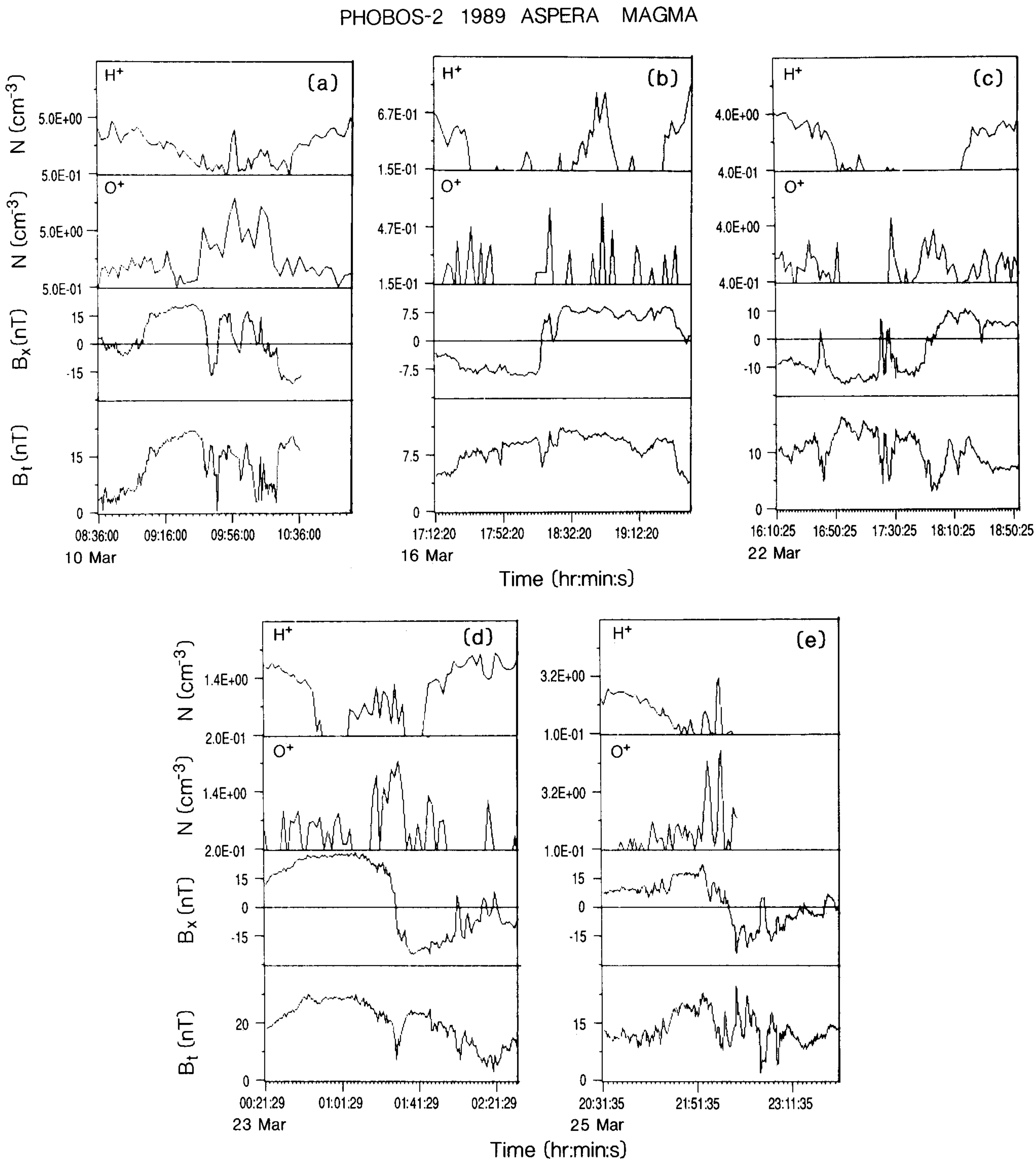

Fig. 4. Examples of Phobos 2 plasma and field data obtained behind Mars at -2.7 to -2.9 R_M. The oxygen (O^+) and proton (H^+) density moments are from the ASPERA experiment, and the magnetic field data are from the MAGMA experiment. Only the B_x component and total field are shown, but these are sufficient to illustrate the correlation between the presence of oxygen (and sometimes proton) plasmas and the crossings of the central tail current sheet.

crossing (although it is fairly weak in orbit 1641, Figure 1*a*). (*Brace et al.* [1987] had previously examined PVO Langmuir probe and magnetometer measurements from a number of near-tail passages of Venus and had noted that there was a relationship between the electron density and the magnetic field.) In all cases but orbit 2557 (Figure 1*f*), two or more "side" tail rays flank the central ray. The locations where these features were seen along the spacecraft orbit are indicated in Figure 2. In contrast to the central plasma structure, there are no particularly significant current sheets observed together with the side tail rays. On the other hand, there is usually a coincident dip in the magnetic field magnitude although it is less than that accompanying the central feature.

The electron temperature data for these tail plasma structures are not always reliable because of the low electron densities. However, for three of the passes (orbits 1654, 2325, and 1876) the tail rays were sufficiently dense that temperatures could be determined and the pressure balance with the magnetic field examined. Figure 3 shows the temperatures and pressure comparisons derived from them, assuming that the ion temperature is half the electron temperature. These displays show that the plasma thermal or kinetic pressure determined from the measured electron temperature in the central feature (but not the side rays) is insufficient to cause the diamagnetic effects in the total field by pressure balance. Since the magnetic field is rather sharply curved in the current sheet, however, curvature forces may invalidate the simple pressure balance picture. In addition, as will be seen from the Phobos 2 data, hot ions (hotter than half the electron temperature) might contribute substantially to the ion pressure in the central current sheet.

Some Phobos 2 data with analogous magnetic field behavior are shown for comparison in Figure 4. It is worth remembering, in considering the comparisons with the Venus data described above, that Phobos 2 is somewhat farther down the tail (~2.7-2.9 planetary radii as opposed to 1.3 planetary radii for the Venus data). It is also worth remembering that Mars has a more extended (but less dense) neutral exosphere due to its lower gravity and that its exosphere composition is primarily hydrogen instead of oxygen [e.g., *Nagy and Cravens*, 1988]. The time series of the ASPERA ion density moment data are shown in place of the Langmuir probe electron densities. The ASPERA data also provide a separate record of hydrogen and oxygen (O^+) ion flux. While the temporal resolution of these data (2 min versus 12 s) is somewhat lower than for the PVO Langmuir probe data, they still show a tendency for plasma densities to be enhanced at the current sheet between the two tail lobes. Moreover, they show that at Mars the plasma in this central current sheet structure is primarily O^+ of planetary origin. The side tail rays seen in the Venus Langmuir probe data are not always seen, or possibly not resolved, in the Mars ASPERA data. However, in some cases (orbits on March 10 and 25) side structures distinctly appear. The locations of the central and side tail plasma features on the Phobos 2 orbit are shown in Figure 5, for comparison with Figure 2.

In place of temperatures, the energy per charge spectra of the ions in Figure 4 are shown in Figure 6. (The conversion factor is 1 eV ≈ 1.16×10^4 degrees Kelvin.) The pressure balance was not examined here since the data required to determine the electron and thermal ion contribution to the plasma pressure are not available for the present study. However, Figure 7, which shows a plot of the oxygen ion energy at the peak of the energy per charge spectrum for the central wake feature versus the energy of the upstream solar wind protons (H^+), suggests that there is a correlation between the two.

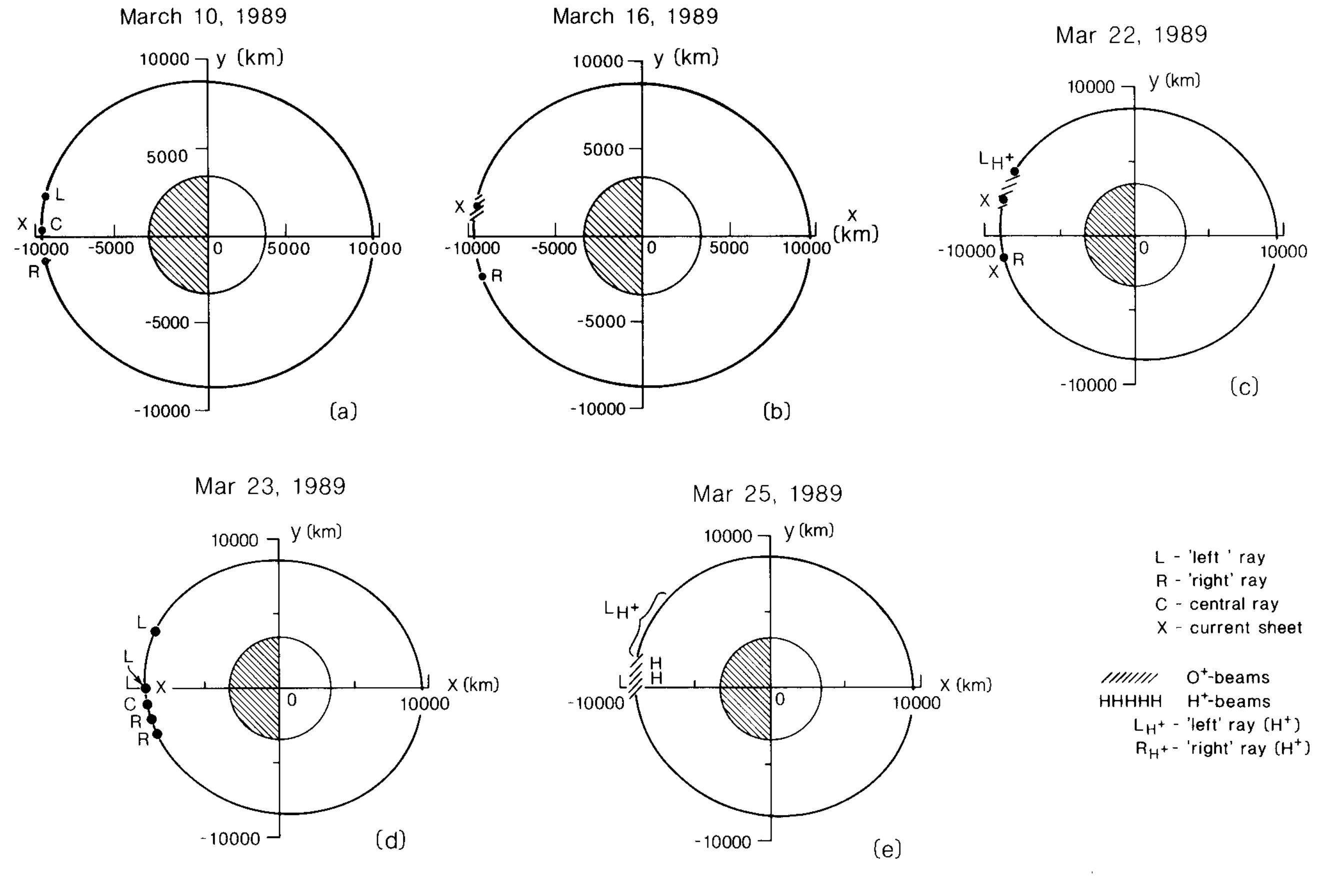

Fig. 5. Equatorial plane view of the Phobos 2 orbit, showing the locations of the plasma structures in Figure 4 relative to the optical shadow. Note that a different symbol key is used than that in Figure 2.

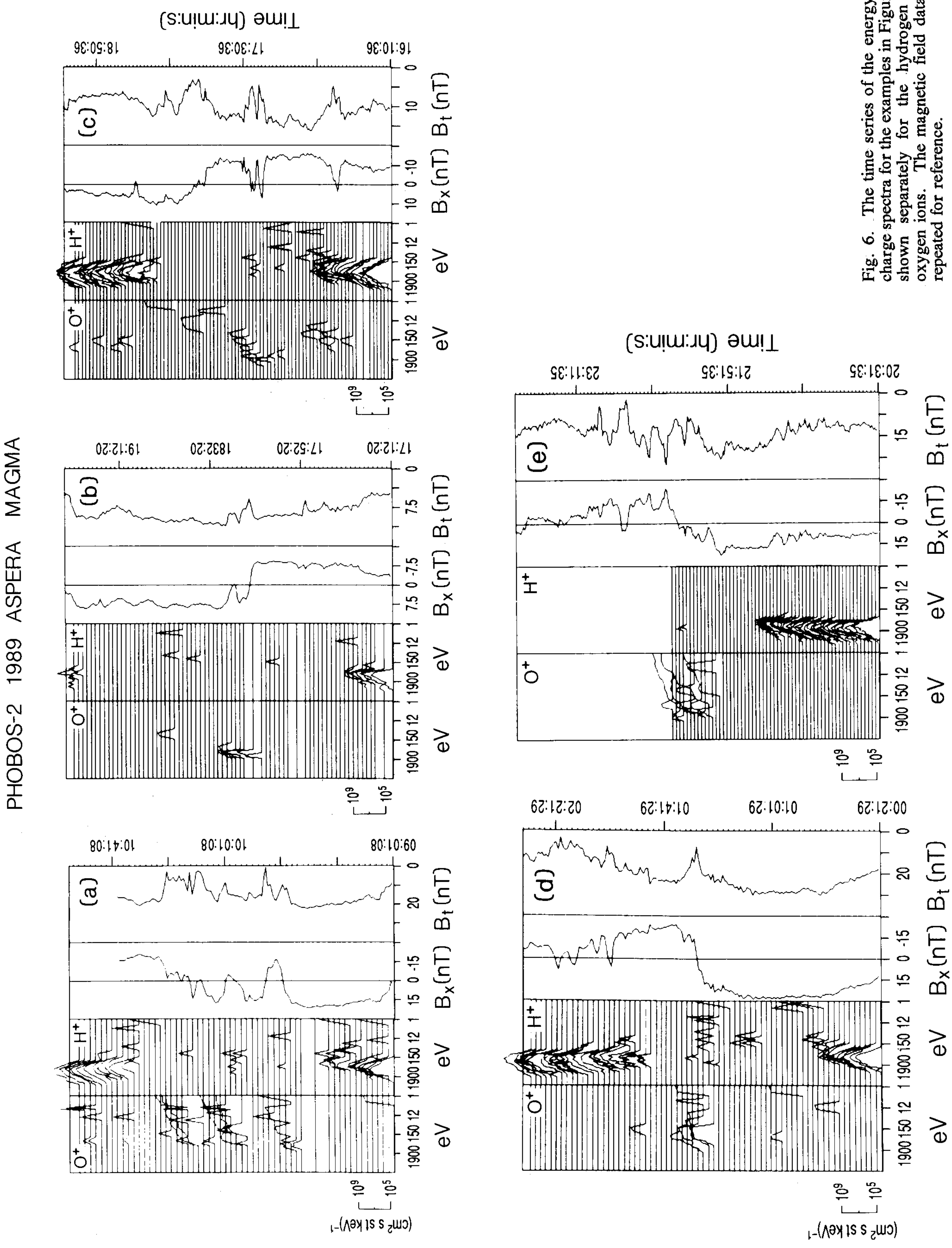

Fig. 6. The time series of the energy per charge spectra for the examples in Figure 4, shown separately for the hydrogen and oxygen ions. The magnetic field data are repeated for reference.

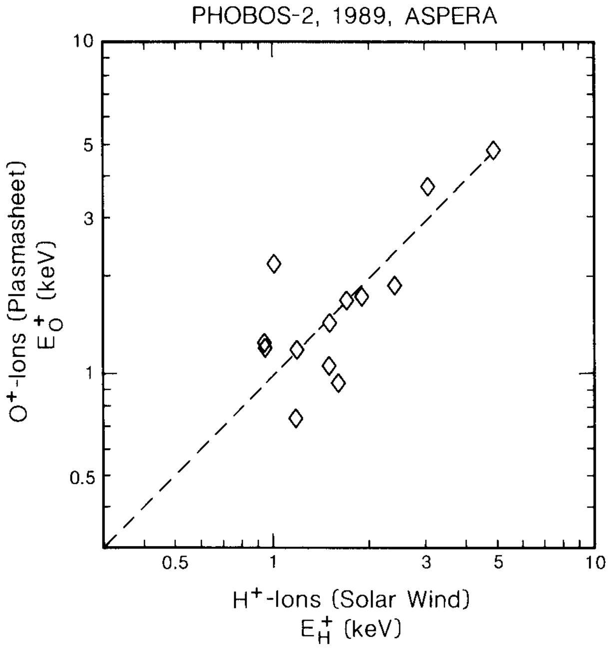

Fig. 7. Comparison of ion energies (E_{O^+}) at the peaks of the average oxygen energy per charge spectra in the central wake, with those obtained for protons in the upstream solar wind (E_{H^+}). Note that this figure includes more passes than are shown in Figure 4, since oxygen ions were observed in the wake even when the magnetic field structure did not appear as a simple double-lobed configuration.

DISCUSSION

The details of the formation of "induced" planetary magnetotails are poorly understood. The tail rays are presumably made up of mass-loaded interplanetary flux tubes (e.g., see the review by *Russell*, [1986]). In particular, the physical process of "mass loading" can involve either the very large gyroradius pickup ions described by *Moore et al.* [1990] or a more "fluid" planetary ion population in the event that plasma instabilities and scattering by ambient field fluctuations are important. It can also involve "bulk" scavenging processes such as those which produce irregularities on the ionopause [e.g., *Brace et al.*, 1982], where plasma can subsequently be moved tailward by the **J**x**B** force associated with the draped magnetosheath field geometry. Indeed *Russell et al.* [1982] argued that the "clouds" of cold plasma observed above the ionopause at Venus were attributable to the latter. Because any or all of these processes might contribute to the observed magnetotail magnetic field geometry, the coordinated analysis of the plasma and magnetic field measurements is essential. The comparisons described above are only a first attempt at this, since many other plasma parameters, such as distribution functions, can eventually be derived and examined (at least for the ASPERA data) and comparisons with Phobos 2 Langmuir probe [*Grard et al.*, 1989], Phobos 2 TAUS (proton and alpha-particle spectrometer) plasma analyzer [*Rosenbauer et al.*, 1989], and plasma wave data [*Grard et al.*, 1989] can be included. Nevertheless, they already tell us something about the Mars and Venus magnetotails.

The detection of many of the discrete tail rays in only the sunward looking sector of ASPERA suggests that the observed oxygen ions may not be gyrating with very large gyroradii in the central tail at Mars. The presence of dips in the total field magnitude in conjunction with the central tail rays at both Venus and Mars indicates either that the curvature force associated with the draped field precludes pressure balance in the tail current sheet or that there is an extra (so far undetected) plasma contribution to the total pressure there. More work, using the results from the other Phobos 2 experiments, needs to be done to determine the electron plus ion pressure in the Martian tail. The reason for the appearance of side tail rays is not understood, but interpretations should be reserved until the Phobos 2 Langmuir probe data of *Grard et al.* [1989] are examined. New data currently being obtained by the PVO plasma analyzer (D. Intriligator, personal communication, 1990) may soon allow comparisons of energetic plasma energy spectra in the near wakes of Mars and Venus. In this regard, the apparent correlation of the energy of the central plasma feature O^+ spectral peak with that of solar wind protons, in Figure 7, deserves further mention.

The narrowness of the observed spectra of the O^+ ions behind Mars (see Figure 6) indicates that most of the energy in these ions is in their bulk motion instead of in gyrational or thermal motion. A similar characteristic was observed in O^+ spectra in the distant ($x \approx -12\ R_V$) Venus magnetosheath and wake [*Mihalov and Barnes*, 1981, 1982; *Intriligator*, 1982]. The O^+ speeds were found to be comparable to local H^+ speeds. The speeds of O^+ ions in the Martian tail are much less than H^+ ion speeds, and the O^+ energy is similar to the upstream proton energy. Simple convection electric field acceleration of the particles should produce spectra that vary from zero energy to twice the energy for the underlying plasma convection speed (e.g., see the model by *Luhmann* [1990]). On the other hand, it is considered that the **J**x**B** force associated with the draped tail field should not fully accelerate "fluid" ionospheric plasma up to the solar wind speed until much further down the tail [e.g., *McComas et al.*, 1986]. Thus the reason for the correlation in Figure 7 remains a question. It can be assumed, for example, that ions in the "central ray" are extracted from low altitudes by the electric field. The **J**x**B** force acts on the magnetized electrons (ions, having much larger Larmor radii, are not tied to the magnetic field). The electric field arising due to charge separation will accelerate heavy ions up to energies similar to the proton energy. (The electric field will be determined approximately by the number density of the most abundant O^+ ions.) The bulk energy of the solar wind protons is transferred to the magnetic field compression on the dayside. On the night side, where the field is depressed, the magnetic field energy is transferred via the electrons to the extracted ions. Thus the observed similar energies of H^+ and O^+ ions are not physically unreasonable. The motion of ions at greater distances from the planet will be more complicated. For example, ions may gain energy during several crossings of the current sheet. Future analyses, which will include a broader set of plasma and field data, at least from Phobos 2, will perhaps give new information about the acceleration processes in the Martian tail. Nevertheless, the similarity in the appearance of the magnetic field behind Mars and Venus, together with the existence of apparently ionospheric plasma structures associated with the central current sheets, suggests that a common process of induced tail formation is occurring at both planets.

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