GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 6, PAGES 727-730, JUNE 1982

OBSERVATIONS OF MASS ADDITION TO THE SHOCKED SOLAR WIND OF THE VENUSIAN IONOSHEATH

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Abstract. Analyzed are the proton and heavy ion populations observed by the Pioneer Venus Orbiter plasma analyzer in the region downstream (11.5 R_V) of Venus. The ion energy per unit charge (E/Q) ratios for protons and heavy ions are consistent with the identification of oxygen (0^+) as a prevalent constituent of the heavy ions. The speeds of the heavy ions and protons are often comparable with the number densities of the heavy ions being 1% of those of the protons. The azimuthal flow angles for the heavy ions and the protons are similar and the polar flow angles of both are usually within $\pm$ 7½° of the ecliptic plane. The apparent intermittent nature of the heavy ion fluxes may be an indication that erosion of the ionosphere is taking place over a limited spatial range and that the orbit of the Pioneer Venus spacecraft is such that it does not intercept the "layers" of heavy ions in a continuous manner. The efficiency of the erosion process may be time variable, e.g., dependent on external ionsheath flow conditions, the state of the ionosphere. Evidence is found of a shear layer, the presence of oxygen ions of varying speeds or of other ionospheric constituents. The heavy ion observations are consistent with a viscous interaction and several other processes that have been suggested as giving rise to the removal and acceleration of ionospheric ions. The analyses reported here may be relevant to an understanding of the plasma interactions associated with comets and Mars and perhaps even with the subsonic interaction at Io and at Titan.

Introduction

We have continued our study (Mihalov et al. 1980) of the heavy ion component in the plasma observations downstream from Venus by the plasma analyzer experiment on the Pioneer Venus Orbiter (PVO). The present paper is based on our analyses of the first season of PVO orbits with apoapsis in the tail—orbits 180 through 195 (June 2, 1979 through June 17, 1979)—and provides clear evidence for the presence of heavy ions. We present information on the heavy ions including intensities, energy distributions, speed, flow directions, and the relation of the heavy ion observations to the simultaneous proton observations. A second component in the flow was first reported by Vaisberg et al. (1976).

The solar wind interaction with a non-magnetic body such as Venus is of considerable interest. The weakness of the Venus planetary magnetic field permits direct interaction of the shocked solar wind in the ionosheath with the ionosphere and the upper atmosphere. This leads to the removal of momentum from the shocked solar wind and mass addition to the shocked solar wind flow. A number of processes (e.g., charge-exchange, photoionization) are responsible for creating heavy ions. A viscous interaction (Dryer, 1970; Perez-de-Tejada, 1980), a Kelvin-Helmholtz instability (Wolff et al., 1980) or local turbulence and large-scale electric fields, or other mechanisms may be responsible for the removal of ions/neutrals from the ionosphere and their acceleration to ionosheath speeds. The erosion of ionosphere plasma by the ionosheath flow may have large-scale planetary atmosphere consequences and interactions with the neutrals may also effect the evolution of the upper atmosphere of the planet.

The laboratory results of Intriligator and Steele (1982) may imply that the many structures (e.g., regions of plasma depletion, regions of plasma enhancement, and regions of strong turbulence) downstream of Venus are relatively permanent features of the interaction and that the general downstream locations of these features are relatively permanent for typical solar wind conditions.

The analyses reported here may be relevant to understanding the solar wind interaction at Mars (Intriligator and Smith, 1979) and comets and to the subsonic interaction of the Io torus plasma with the atmosphere/ionosphere of Io and the subsonic plasma interaction at Titan. In each case there is an interaction of the flowing plasma with the planetary body and its associated atmosphere/ionosphere.

Observations

Figure 1 shows ion energy per unit charge (E/Q) spectra that were obtained downstream of Venus at a distance of 11.5 R_V on June 11, 1979 (day 162, orbit 189) from 1211 through 1351 UT. The spectra show both the proton and the heavy ion components from 1211 through 1342 UT. There is a variability in the E/Q location and the shape of both peaks. This variability is indicative of the real variability and intermittent nature of the proton and heavy ion populations in this region. Another example of this variability is the absence of measurable ion fluxes at the times of the angular scans (Intriligator et al., 1980) associated with the energy spectra at 1306 and 1315 UT. From comparison of only the energy scans at 1306 and 1315 UT one could erroneously conclude that the ion fluxes are rather steady. But there is no doubt from the 1306 UT angular scan obtained between these two energy scans that just before the 1315 UT energy scan there was a complete absence of measurable ions at the energies associated with the peak in the 1306 UT and 1315 UT energy scans.

On the basis of the relatively high intensity of the protons and heavy ions during some of the time (e.g., 1200 to 1330 UT) in Figure 1 we identify this region as the ionosheath. The magnetometer team (Russell et al., 1981) identified this as the magnetotail. Figure 2 shows the trajectory plot for orbit 189.

Figure 3 shows a plot from 1000 to 2100 UT on June 11, 1979 of the peak proton intensity, the E/Q location of this proton peak, the speed associated with this proton peak, and the azimuthal flow direction of this peak proton intensity, and the corresponding parameters for the heavy ions. All of the quantities shown in Figure 3 were obtained from our analyses of the plasma analyzer energy scans (Intriligator et al., 1980). The heavy ion speeds calculated assume that these ions are 0^+ ions. The absence of data points in Figure 3 indicates the absence of measurable plasma or that the peak intensity of the measured plasma was below 5 x 10^7 ions/cm^2 sec sr. The azimuthal flow angle is zero (0°) when the flow is from the solar direction; when the flow is from the west it is positive; when the flow is from the east it is negative (Intriligator et al., 1980).

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Paper number 2L0738.
0094-8276/82/002L-0738$3.00

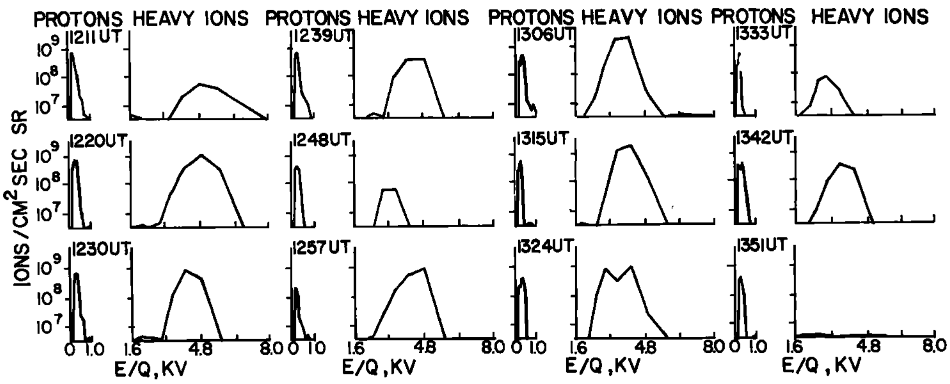

Fig. 1. Ion energy per unit charge (E/Q) spectra measured by the PVO plasma analyzer downstream of Venus on June 11, 1979. To aid comparison, the proton component and the heavy ion component are plotted separately. The vertical axis is the same for both components. The times in Figure 1 denote the beginning of each energy scan. The figure clearly shows the presence of both the proton component and the heavy ion component in most spectra (e.g., 1211 UT through 1342 UT).

Figure 3 shows that the proton fluxes were steadier in intensity and E/Q than the heavy ion fluxes; and both the proton and the heavy ion intensities decreased to much lower levels from 1500 to 1650 UT. From 1340 to 1500 UT there is a decrease in energy associated with the peak intensity of the heavy ions. These lower energies could be associated with lower peak speeds of the oxygen (e.g., a shear layer) or they could indicate the presence of other ion species. The implications of these observations are discussed below. Following the decreased level of proton intensity from 1500 to 1650 UT there is a long period of increased proton intensity accompanied by depressed heavy ion intensity.

Figure 3 shows that the azimuthal flow directions are similar for the protons and the heavy ions. With respect to the polar (north-south) angular distributions, the peak intensities of both the protons and the heavy ions are usually recorded on Collector 3, the central collector which measures flows within ± 7½° of the equatorial plane.

Figure 4 is similar to Figure 3 and shows the correspond ing proton and heavy ion parameters from 0700 to 2000 UT on June 8, 1979 (orbit 186). The trends in the data in Figure 4 are similar to those in Figure 3. The decrease in the E/Q of the heavy ion peak from 1130 to 1230 UT is similar to that observed on orbit 189.

Figure 5 presents some statistics from the first tail passage. The scatter plot indicates for the downstream region of each orbit the average heavy ion speed (V_{0^+}) associated with the peak intensity of heavy ions versus the average proton speed (V_p) associated with the peak intensity of protons. The ordinate extends to 310 km/sec, which corresponds to 8 kv the maximum range of the instrument. The upper panels in Figure 5 indicate the number of samples in the downstream region used to obtain the average heavy ion speed and the average proton speed.

It is possible that additional heavy ions, moving at speeds comparable to those of the protons, were present on these orbits and not included in our samples since the E/Q of the 0^+ ions would have been above the range of the instrument. Figure 6 illustrates this point further. Figure 6 is a scatter plot for each spectrum of the heavy ion speed associated with the peak heavy ion intensity versus the proton speed associated with the peak proton intensity. Figure 6 shows that in many spectra the proton and heavy ion speeds are comparable. Thus, it is likely that the instrument's 8 kv range limited its ability to detect accelerated heavy ions.

Discussion

The heavy ion peaks in Figure 1 are consistent with their identification as oxygen ions (0^+). Since the plasma analyzer

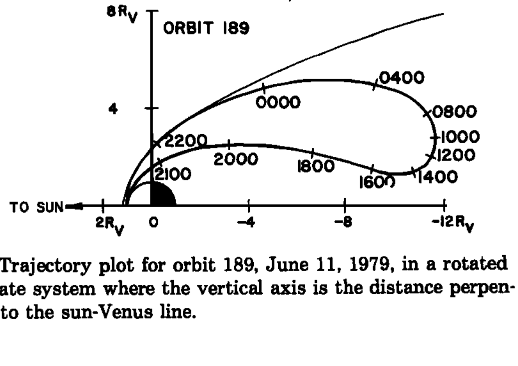

Fig. 2. Trajectory plot for orbit 189, June 11, 1979, in a rotated coordinate system where the vertical axis is the distance perpendicular to the sun-Venus line.

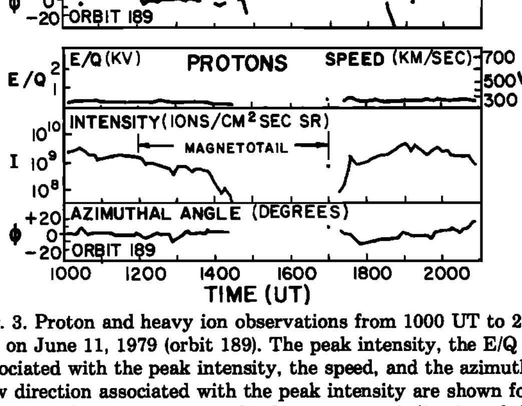

Fig. 3. Proton and heavy ion observations from 1000 UT to 2100 UT on June 11, 1979 (orbit 189). The peak intensity, the E/Q value associated with the peak intensity, the speed, and the azimuthal flow direction associated with the peak intensity are shown for the protons and the heavy ions. The data gaps are indicative of the absence of measurable plasma or peak plasma intensities below 5 x 10^7 ions/cm² sec sr. The approximate boundaries of the magnetotail region identified from the PVO magnetometer data (Russell et al. 1981) are also shown.

separates particles only by energy/charge (E/Q), it is not possible to separate particles with the same mass/charge ratio and the same speed (Intriligator and Miller, 1981). However, based on our knowledge of the solar wind and of solar wind/planetary interactions we identify the low energy peak as protons. From our knowledge of the composition of the atmosphere and ionosphere of Venus and the E/Q ratios of the protons and the heavy ions, $(E/Q)_{\text{heavy ion}} \approx 16\ (E/Q)_p$, it is likely that the heavy ions in Figure 1 are oxygen ions.

The continuous presence of the heavy ions in the spectra from 1211 through 1342 UT is compelling evidence for mass addition to the ionosheath flow. Oxygen ions or other heavy ions are not noticeably present in the solar wind. While there is evidence for the occasional presence of ions other than hydrogen and helium ions in the solar wind the fluxes associated with these additional ions are very low—less than those of the heavy ions in Figure 1. Therefore, the Venus atmosphere and/or ionosphere is the source of these heavy ions.

With regard to relative densities, the proton number densities associated with the intervals of appreciable flux on June 11, 1979 (e.g., 1000 to 1300 UT, 1800 to 2000 UT) are 20-40 protons/cm^3. The heavy ion number densities are about 1% or less of the proton number densities. The proton temperatures are about 10^5 °K. At times the 0^+ temperatures are comparable to this and at other times (e.g., 1220 UT on orbit 189) the 0^+ temperature is almost four times higher. We calculated proton and 0^+ densities and temperatures by a moment calculation similar to that used in Wolfe et al. (1974) since the NASA Ames data reduction program used for solar wind data is not directly usable for the protons and oxygen ions in this region. We calibrated the moment method by comparing parameters for solar wind spectra obtained from the moment method with the NASA Ames program's calculated parameters for these same spectra.

In comparing relative intensities at various E/Q's to infer relative densities one should recall (Intriligator et al., 1980) that the range of energies accepted at an E/Q step is a constant percentage of the nominal energy of that step so the "energy window" is larger at higher energies. Thus an energy correction must be made before relative densities can be inferred. Since we assume the heavy ions are singly charged oxygen ions travelling at the same speed as the protons, no charge or speed corrections need be made.

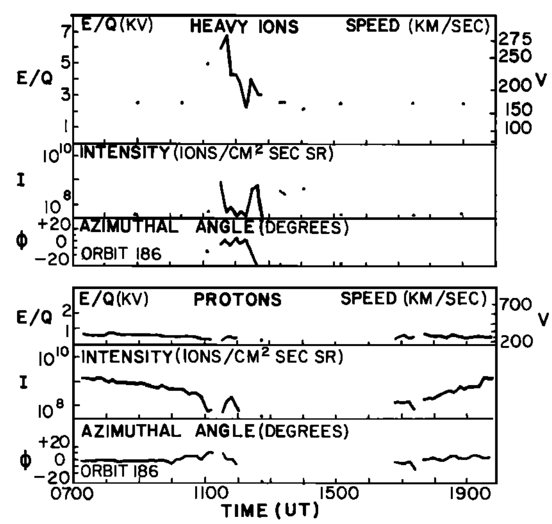

Fig. 4. Proton and heavy ion observations from 0700 UT to 2000 UT on June 8, 1979 (orbit 186). See Figure 3 caption. The magnetometer was turned off during this time (Russell et al. 1981).

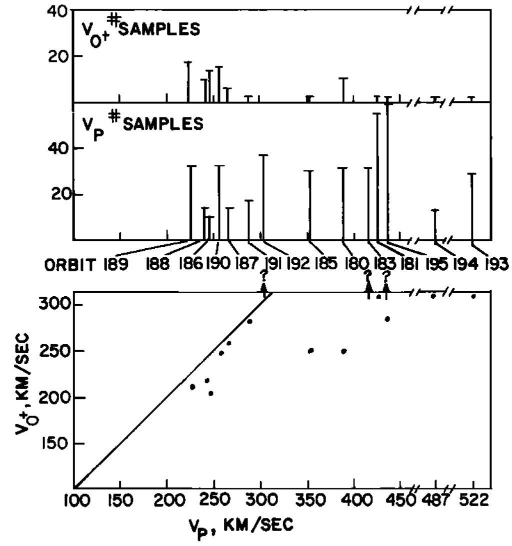

Fig. 5. Scatter plot for each tail orbit studied of the average heavy ion speed (V_{0^+}) associated with the peak heavy ion intensity versus the average proton speed (V_p) associated with the peak proton intensity in the downstream region. The number of samples of V_{0^+} and V_p are shown. The highest 0^+ speed measurable by the plasma analyzer is 310 km/sec.

On the basis of the plasma observations in Figures 1 and 3 we associate the measurements made on orbit 189 from 1000 to 1330 UT or even to 1400 UT with the Venusian ionosheath. The exclusion of measurable plasma from 1430 to 1700 UT we associate with the tail cavity. As shown in Figure 3, the "magnetotail" has been defined from 1200 to 1700 UT on the basis of the magnetometer observations (Russell et al. 1981).

The continuous and prolonged observations of the heavy ion component on orbit 189 by the plasma analyzer were aided by the relatively low speeds of the solar wind and ionosheath flow. The spectrum of the heavy ions can only be measured when it is present below 8 kv. The proton and heavy ion speeds during this period were below 250 km/sec (see Figure 3). Thus the geometry of the orbit and the low ionosheath speeds combined to provide us with advantageous conditions for observing mass addition to the ionosheath flow.

The spectra in Figure 1 clearly indicate that at 1248 UT there is a definite shift to a lower E/Q of the heavy ion peak. At 1248 UT the proton peak also shifts, but it does not decrease proportionately. As a result at 1248 UT, $(E/Q)_{\text{heavy ions}} \approx 14(E/Q)_{\text{protons}}$. We associate these changes in E/Q with a decrease in the bulk speed of flow of the ions.

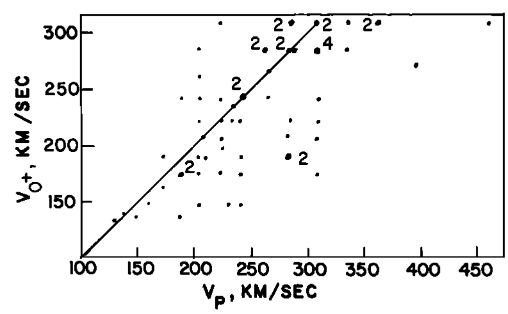

Fig. 6. Scatter plot for each spectrum of the heavy ion speed associated with the peak heavy ion intensity versus proton speed associated with the peak proton intensity. The numbers beside some dots denote the number of overlapping dots.

While it is possible that this shift and the change in the E/Q ratio of the heavy ions to the protons (i.e., it is 14 not 16) is indicative of an absence of oxygen ions and the presence of a different heavy ion species, it appears unlikely. Thus, we tentatively associate this shift in the high energy peak as a decrease in speed of the observed oxygen ions: at 1239 UT the oxygen ion speed (corrected for aberration) was 230 km/sec and at 1248 UT it was 200 km/sec.

The slow rather continuous change in E/Q of the peak heavy ion intensity from 1340 to 1500 UT shown in Figure 3 could also be associated with the change in speed of heavy ions or a change in composition or both. Figure 2 indicates that during this time the spacecraft is traversing a limited spatial region. It is also quite close to the optical shadow. A similar change in E/Q location of the peak heavy ion intensity is also evident in Figure 4 between 1130 and 1230 UT. Therefore, it is possible that these observations are indicative of a shear layer or some other boundary layer or a viscous interaction region (Dryer, 1970; Perez-de-Tejada, 1980). It is also possible that these observations are indicative of some temporal variation and may imply a change in the rate or location of acceleration of ionospheric ions and/or a change in composition of the accelerated ionospheric ion population. The Venus ionospheric ions, initially having low speeds, must undergo acceleration to attain speeds comparable to those of the shocked solar wind protons. If there is a direct interaction between the shocked solar wind and the neutral atmosphere, charge-exchange can occur leading to the production of a fast neutral. The E/Q and flux variations in both the solar wind component and the Venus component of the ion flow could reflect the varying characteristics of the regions in which these interactions are taking place.

Figures 3 and 4 indicate the similar azimuthal flow angles associated with the peak intensities for protons and heavy ions. With regard to the polar (north-south) flow, most of the proton and heavy ion fluxes in this region are observed on collector 3, the collector detecting flows within $\pm 7\frac{1}{2}°$ of the spacecraft equatorial plane.

Conclusions

The analyses presented indicate that a heavy ion component was added to the ionosheath flow for a prolonged period on June 8 and 11, 1979 while the spacecraft was downstream from the planet. The heavy ion component was identified as oxygen ions (O^+). Heavy ions were detected on most of the orbits in the first season of apoapsis tail passages. The small number of observable heavy ions on some orbits may be due to the limited range (≤ 8 kv) of the instrument.

Oxygen ions or other heavy ions are not noticeably present in the quiescent solar wind. In contrast, on June 11 the oxygen ion density was as high as 1% of the proton density, implying that the oxygen ions are the result of the direct interaction of the shocked solar wind with the Venusian ionosphere or atmosphere.

It is tempting to speculate that there are a number of eddies, layers or other specific spatial regions associated with the interaction of the solar wind with the planetary environment and the resulting mass addition to the flow. There also may be some temporal variability. In the downstream region the speeds of the protons and the heavy ions are quite variable. At times there is a change in the speed of one or the other component. The intermittent fluxes and variability of the E/Q and angular distributions of both the protons and heavy ions are consistent with a dynamic interaction giving rise to the spatial and temporal changes.

It is anticipated that future analyses of the plasma observations associated with subsequent seasons of PVO tail passages and comparisons with the simultaneous plasma wave, magnetic field, and ionospheric/atmospheric observations will contribute to our understanding of the significant physical mechanisms involved in this interaction and of the resulting structures.

Acknowledgement. This paper represents one aspect of research carried out by Carmel Research Center for NASA Ames Research Center under Contract NAS2-10926. All of the analyses reported in this paper were performed at Carmel Research Center.

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(Received August 27, 1981;
accepted May 4, 1982.)