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Measurements of Electron Fluxes in the Shadow Region of the Martian Magnetotail with the HARP Spectrometer aboard the *Phobos-2* Spacecraft

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Abstract—Data of electron observations from the HARP instrument on the night side of circular orbits of the *Phobos-2* spacecraft are summarized and studied in detail. Electron fluxes with energies greater than the electron energy of undisturbed solar wind, which are observed in the transition region behind the shock wave, show existence of the acceleration processes. Characteristic features of the electron fluxes measured in the Martian magnetotail cannot be classified in the framework of modern views; however, a correlation between intensities of these fluxes and the undisturbed solar wind is shown.

INTRODUCTION

Orbital parameters of the *Phobos-2* spacecraft, launched on July 7, 1988, allowed the Martian magnetotail to be investigated in detail for the first time. All previous spacecraft that studied solar wind interaction with the Martian plasma did not cross the shadow part of the Martian magnetosphere. *Mariner-4* in 1965 only crossed the bow shock, and *Mars-3* entered the transition region of the Martian magnetosphere in 1972. The first observations of the magnetotail plasma took place in 1971 aboard the *Mars-2* spacecraft, when it crossed the boundary region at a distance of about 25 000 km from the planet, considerably above its optical shadow [1]. The Martian magnetotail was also observed by *Mars-5* in 1975 at a distance of 10 000 km from the planet. *Mars-2* and -5 had three axis stabilization and electrostatic analyzers, and wide-view electron and ion traps with deceleration potential were mounted aboard them [2, 3]. Gringauz *et al.* [2, 4] identified the magnetotail as a region where ion flux intensity decreases and showed that, in the magnetotail boundary region, this ion intensity decrease is more pronounced than the decrease of the electron flux intensity. The authors of [2, 4] also noted that electron energy distributions broaden considerably, after the shockwave inside the transition region is crossed. Electrons of higher energies and strong fluctuations of intensity were observed. Vaisberg *et al.* [5] noted that the boundary between the transition region and the magnetotail may be rather wide. They also cited cases in which ions were scarcely detected in the magnetotail.

Phobos-2 came close to Mars on January 29, 1989. The flights ended on March 29, and in the last 57 days, *Phobos-2* conducted measurements on five elliptical Martian orbits and more than 100 circular orbits. The radii of the circular orbits were higher by 300 km than the orbital radius of the Martian moon Phobos. One turn on the circular orbit took 8 hours. This orbit allowed detailed investigations of the shadow side of the Martian magnetotail at a distance of three planetary radii.

Luhmann *et al.* [6] compared magnetic field measurements from the Martian magnetotail on circular orbits with magnetic data obtained aboard the *Pioneer Venus Orbiter* spacecraft as it crossed the Venus magnetotail. The authors suggest that the similarity of these magnetograms is evidence of the wrapping structure of the magnetic field lines in both cases; however, the Venus magnetotail field is less inclined to the magnetotail axis than the Martian field. According to the results of statistical data analysis [6, 7], the Martian magnetotail is induced. Correspondingly, plasma processes in the magnetotail should be mainly governed by the solar wind.

A plasma sheet is in the vicinity of the neutral layer in the Martian magnetotail [8]. It is similar to the plasma sheets of the Earth and Venus magnetotails, which have increased values of ion energy and density. Fluxes of ions accelerated up to energies of several kiloelectronvolts were observed in the central part of the Martian magnetotail as well. A more

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†Deceased.

detailed analysis of the Martian magnetosphere is presented in [8].

Phobos-2 measured electron fluxes near Mars with the hyperbolic electrostatic spectrometer HARP. The HARP, which is fully described in [11], was mounted on the back side of solar batteries to measure energy distributions of electrons for eight coplanar directions symmetrically relative to the antisolar axis. The energy range was 1–800 eV. A field of view for each angular sector was 10° x 20°. For the circular orbits considered in this article, the spacecraft was spinning at approximately one turn per ten minutes around an axis perpendicular to the solar battery plane and directed at the Sun. Thus, the spectrometer was directed at the antisolar hemisphere. The analyzing voltage was increased from 1 to 800 V by 25 or 75 steps. The duration of information accumulation for each energy step was 1 s. Because of limits in information transmission by telemetry, the energy spectrum was recorded once every 40 minutes. The HARP spectrometer worked periodically on circular orbits from February 21, 1989 to March 25, 1989.

This work reflects the results of measurements obtained for 24 orbits under undisturbed solar wind conditions. We will not consider the features of the electron plasma component in the magnetosheath, in the magnetotail, behind, or in front of the shock wave; however, simultaneous measurements of ions and magnetic field will be compared with electron observations.

RESULTS OF MEASUREMENTS

The data discussed correspond to small parts of circular orbits situated in the optical shadow of the planet.

Figure 1 presents energy spectra obtained on March 2, 1989 in one of the eight angular sectors of the HARP instrument. The upper part of this figure shows a projection of the circular orbit on the X–Y plane of the solar-ecliptic coordinate system centered on Mars with the X-axis pointing to the Sun. Actually, the orbital plane was inclined by 25° to the ecliptic plane. The radius of the circular orbit was 9600 km, i.e. it was a little less than three Martian radii. Radial dashes show the spacecraft positioned along the orbit according to universal time (UT). Temporal dynamics of the measured energy spectra (from bottom to top) reflects the motion of the spacecraft from the region of undisturbed solar wind to other regions of the near-Martian plasma. For comparison, variations of the B_x magnetic field component [7, 12] are presented in the right part of the figure.

In the obtained energy spectra, the solar wind spectra broaden visibly, and an additional, more energetic component appears in the region between the bow shock and the Martian optical shadow. As expected, there are no solar wind electrons modified by the bow shock in the Martian optical shadow, but existence of a high energetic component is evident. Two components in the energy distribution of electrons appear again during the re-entry into the transition region.

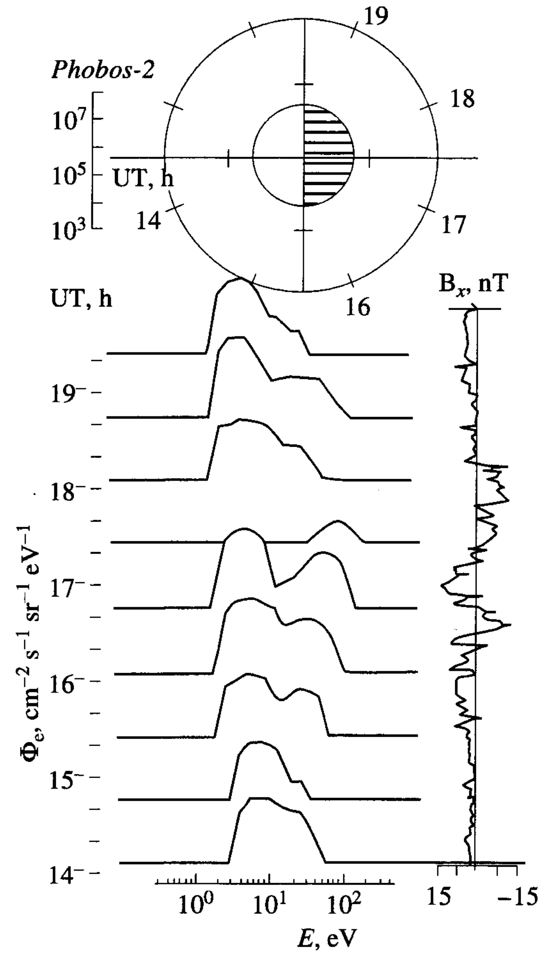

Fig. 1. Energy spectra of electrons measured within one of the angular sectors of the HARP instrument and simultaneous measurements of the magnetic field on a circular orbit on March 2, 1989 at 13:45:04–19:25:04 UT.

Energy spectra similar to those presented in Fig. 1, namely, distributions with a maximum average energy of 100–200 eV, were observed eight times in the Martian optical shadow. Electron fluxes were not recorded in this region during four orbits, and in the other seven orbits their energy did not exceed 50 eV. In four other cases, both high and low energy electrons were present.

We studied correlations between electron fluxes observed in the planetary shadow, along with simultaneous measurements of magnetic field [7, 12] and heavy ion fluxes from the TAUS experiment [10, 13]. Simultaneous measurements of magnetic field and electrons are available from 10 orbits, and there are data on electrons and ions from 6 orbits. Data of

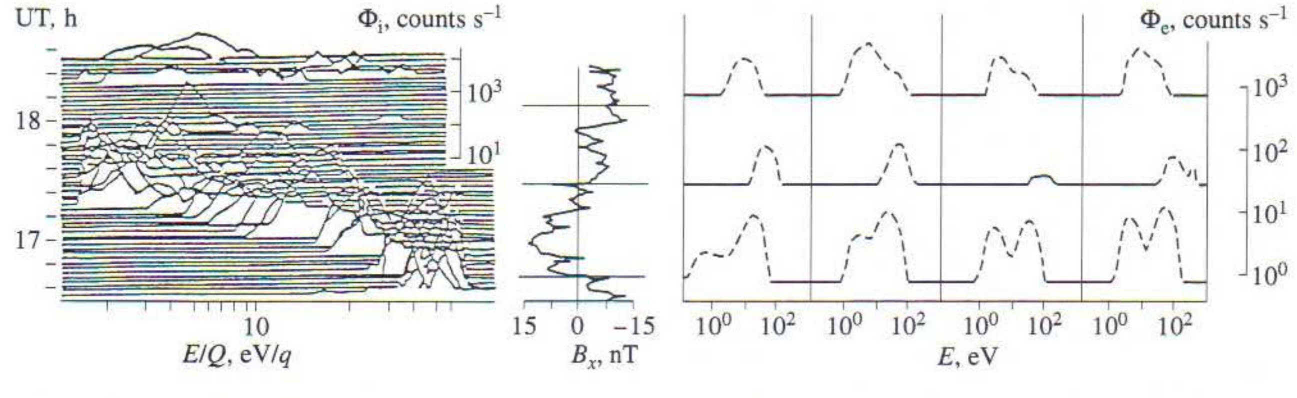

Fig. 2. Results of simultaneous measurements of electrons within four angular sectors (on the right), the magnetic field (in the center), and heavy ions (on the left) on February 3, 1989.

simultaneous measurements of electrons, ions, and magnetic field were obtained in four cases.

Figure 2 demonstrates the results of simultaneous observations of electron fluxes Φ_e by the HARP instrument, the B_x magnetic field component by the MAGMA instrument, and heavy ion fluxes Φ_i by the TAUS instrument. The left scale of this figure shows the time of measurements (UT). This figure has three time series of energy spectra measured by the HARP instrument in four angular sectors. Contrary to the results of electron measurements presented in Fig. 1, the electron intensity is given using arbitrary units (counts/s) for a more informative comparison with the measurements of heavy ions expressed in the same units. It is clear from this figure that, as the spacecraft was moving from the bow shock to the region of optical shadow (from bottom to top), the energy of heavy ions decreased from 6 keV (the upper limit of the TAUS instrument) to several hundred electronvolts. Note that the TAUS instrument measured heavy ion fluxes moving from the planet. According to the magnetic field data, the spacecraft crossed the bow shock and entered the magnetosphere at 15:25 UT, and at 19:21 exited it. Variation in the *X* magnetic field component shows that the sign of the longitudinal component changed several times.

The largest electron energies were observed in the region of optical shadow, during which time the intensity of low energy ions escaping from the planet was most considerable and the magnetic field polarity changed. High energy electrons were detected together with changes of magnetic field polarity in 5 out of 10 orbits, in which these instruments worked simultaneously at shadow parts of the magnetotail. Because of limited availability of data on simultaneous observations of ions and high energy electrons, it is difficult to make final conclusions regarding cause-and-effect connections between electron-ion fluxes.

DISCUSSION

As was pointed out above, definitions of different regions and boundaries of the Martian magnetotail are not yet universally agreed-upon. Before the *Phobos* flight, a description of complex effects in the Martian magnetotail was presented by Vaisberg and Smirnov [14]. Analyzing results of the *Phobos-2* flight, Verigin *et al.* [13], Shutte *et al.* [15, 16] classified, in a similar manner, different regions where ion fluxes and magnetic field were observed. A clearly defined zone separates the regions where solar wind protons modified by the bow shock are dominant and where there are practically no protons and heavy ions, apparently of planetary origin, are dominant [6, 10, 13]. This transition zone is also characterized by variations in the magnetic field parameters [13]. Verigin *et al.* [13] named the outer part of this zone the magnetosheath and the inner part the tail. The central part of the tail, as was mentioned above, is called the plasma sheet.

The results of measurements by the HARP instrument presented in this work, as well as previous observations on elliptical orbits [15], clearly show that electrons with energies of several hundred kiloelectronvolts exist in the transition region. These energies are higher than the electron energy of undisturbed solar wind. This is new and interesting evidence of the effective acceleration processes in this region. We suppose that an appropriate acceleration mechanism has been proposed by Sagdeev *et al.* [17]. Cold Martian ions penetrate into the transition layer and interact with solar wind protons crossing the bow shock, as a result, waves are generated. These waves accelerate electrons up to the observed energies. The accelerated electrons discovered at the day side [15, 16] were also detected by Jonson and Hanson [18] using the analyzer with deceleration potential aboard *Viking-1* in 1976.

It is difficult to classify the energy distributions of electrons measured by the HARP instrument in the Martian magnetotail from a traditional standpoint. We considered a possible correlation between the dynamic

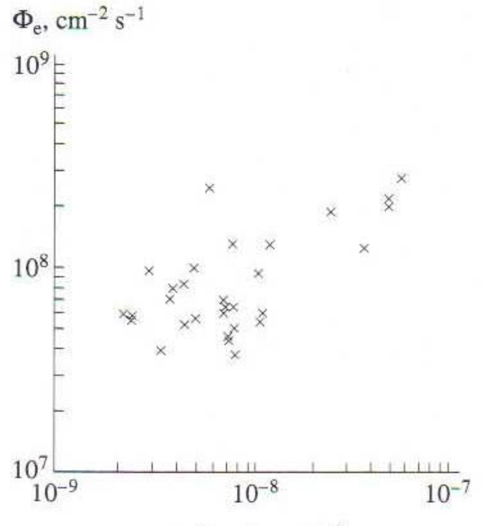

Fig. 3. Electron fluxes Φ_e in the shadow region of the Martian magnetotail versus the dynamic pressure of undisturbed solar wind P_{sw}.

pressure of undisturbed solar wind and the electron flux intensity measured in the central part of the tail. Figure 3 shows the electron fluxes (integrated over energies and pitch-angles) obtained by the HARP instrument, at the parts of the circular orbits within 30° relative to the antisolar direction, as a function of the solar wind dynamic pressure. Higher solar wind pressure values correspond to greater electron flux intensities close to the anti-solar direction. Therefore, it may be supposed that the efficiency of the acceleration mechanism is governed by the solar wind. When analyzing this correlation, we should keep in mind that the time interval between measurements in the undisturbed solar wind and the tail was 2–4 hours. As was mentioned above, the detection of high-energy electrons by the HARP instrument, in 5 out of 10 cases, coincides with reversals of the B_x magnetic field component. The results of ion measurements [9, 10] show that the largest ion fluxes in the central part of the tail also correlate with reversals of the X magnetic field component. However, according to a more detailed analysis [13], all changes in B_x polarity were accompanied by strong ion fluxes, whereas enhanced ion fluxes were not always accompanied by changes in B_x polarity.

CONCLUSION

The energy distributions of electrons measured by *Phobos-2* in the transition region of the Martian magnetosphere on circular and elliptical orbits are similar, though they were obtained at different points and times. The two-peak spectra may be considered a characteristic feature of the Martian transition layer. The accelerated component of electron flux is interpreted as a result of the particle-wave interaction. Our interpretation of plasma observations, made with the HARP instrument and other plasma devices mounted aboard the *Phobos-2* spacecraft, does not yet provide a simple picture of the phenomena. The available data show the existence of intensive plasma fluxes in the shadow region of the tail, but direct correspondence between the fluxes and the plasma layer position is not found. However, we did find a correlation between electron flux intensity and the dynamic pressure of undisturbed solar wind.

ACKNOWLEDGMENTS

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