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Nightside electron flux measurements at Mars by the Phobos-2 HARP instrument

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Abstract. All the available nightside electron data obtained during circular orbits at Mars from the Phobos-2 HARP instrument have been examined in detail and are summarized in this paper. An electron flux component with energies exceeding that of the unperturbed solar wind was observed inside the magnetosheath, indicating the presence of acceleration mechanism(s). The character of the electron fluxes measured in the magnetotail cannot be classified in any simple manner; however, there is a correlation between the electron fluxes measured well inside this region and the unperturbed solar wind ram pressure.

Introduction

The Phobos-2 spacecraft, launched on 12 July, 1988, was the first one which explored in detail the tail region of Mars. Previous missions launched to study the solar wind interaction with the plasma environment of Mars never entered into the Martian umbra. The Mariner 4 flyby in 1965 barely crossed the bow shock, and the Mars 3 trajectory in 1972 stayed only in the magnetosheath. It was the Mars 2 mission in 1971 which provided the first observation of the Martian plasma tail when it crossed the boundary region surrounding the tail at about 25,000 km from the planet, but well above the optical shadow of the planet [*Vaisberg and Bogdanov,* 1974]. Mars 5 made observations in the same general tail regions in 1975, about 10,000 km from the planet. Both Mars 2 and 5 were three-axis stabilized spacecraft carrying onboard electrostatic analyzers and wide-angle electron and ion retarding potential analyzers [*Gringauz,* 1976a; *Vaisberg*, 1992]. *Gringauz et al.* [1976b] identified the tail as the region where the ion flux drops; the decrease of the ion flux at the boundary of the tail was much stronger than the decrease of the electron flux. The same investigators reported significantly broadened electron spectra downstream of the bow shock, inside the sheath. Electron fluxes of higher energies were observed, and strong fluctuations were also seen in the flux intensity. *Vaisberg et al.* [1975] showed that the boundary between the magnetosheath and the tail was an extended one, and they reported that in the tail there were cases with and without a detectable ion flow.

The Phobos-2 spacecraft reached Mars on 29 January, 1988. For 57 days, until the end of the mission on 29 March, Phobos-2 made five elliptic equatorial orbits around Mars, followed by more than 100 circular orbits. The circular orbits had a radius 300 km beyond that of the Martian moon Phobos; one revolution was almost equal to 8 hours. This circular orbit was advantageous for the exploration of the tail region at three Mars radii.

Luhmann et al. [1991] compared the magnetic field data obtained in the Martian tail during the circular orbits with the magnetograms obtained during wake crossings of Venus by the Pioneer Venus Orbiter. These authors concluded that these two sets of magnetograms resemble one other in many respects; both show a draping structure, though the Venus tail field seems to be more strongly draped close to the planet than that at Mars. Based on statistical analyses of the magnetic field data, *Luhmann et al.* [1991] and *Yeroshenko et al.* [1990] concluded that the Martian magnetic tail is induced. Accordingly, plasma phenomena in the tail are governed by solar wind conditions.

The Martian tail in the vicinity of the magnetic neutral sheet has a plasma sheet [*Zacharov,* 1992] similar to the plasma sheets in the magnetic tails of Earth and Venus, which contain plasma with increased energies and densities. In the central part of the Martian tail, accelerated ions up to several keV were observed [*Lundin et al.*, 1989, *Rosenbauer et al.*, 1989]. Further details of the Martian magnetosphere are summarized by *Zacharov* [1992].

In order to obtain information on the electron fluxes in the plasma environment of Mars, a Hyperbolic Retarded Potential Analyzer (HARP) was carried onboard the Phobos-2 Soviet space probe. The instrument was described in detail by *Szucs et al.* [1990]. This instrument measured the electron spectra in a fan of 8 coplanar view directions, symmetrically arranged with respect to the antisolar axis. The energy range covered by the instrument was approximately 1 - 800 eV. The field of view of each angular sector was 10x20 degree; the sensor package was mounted on the backside of the solar panels. During the circular orbit segments, from which we are presenting data in this paper, the spacecraft was slowly rotating (1 rotation per about 10 min.) along an axis perpendicular to the solar panels; this axis was pointing towards the Sun. Therefore, in time, the instrument covered the antisolar hemisphere. The energy range of 1-800 eV was covered in either 25 or 75 steps, the integration time for each step was one second. Telemetry rate limitation allowed the transmission of only one spectra every 40 minutes. The HARP instrument operated intermittently during the circular orbit phase of the mission which extended from 21.02.89 to 25.03.89. In this paper we include data from all those orbits for which the upstream HARP electron spectrum had the characteristics typical of the undisturbed solar wind. This means we have available for examination useful data from 24 orbits.

Our objective is to characterize the electron population of the magnetosheath and magnetotail of Mars, bow shock or upstream related data will not be discussed here. We also

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present relevant ion and magnetic field data along with our own results.

Experimental observations

In this section we present and summarize the observations. The physical location of each measured electron spectrum will be characterized only with respect to the bow shock and the optical shadow in order to avoid any potential controversies concerning the definitions of various regions. We will comment on our observations in terms of commonly used boundaries/regions in the discussion section.

Figure 1 shows the observed spectra from one of the eight angular sectors of the HARP during an orbit on March 2, 1989. The top of the figure shows the projection of the circular orbit onto the x-y plane of the Mars centered solar ecliptic coordinate system (the x axis points towards the Sun). The plane of the actual orbit was tilted approximately 25 degrees about the x axis relative to ecliptic plane. The radius of the circular orbit was 9600 km, slightly more than three Mars radii. The location of the spacecraft as a function of time (in UT) is also shown along the orbit. The location of the typical bow shock crossing of the spacecraft is along the day-night terminator plane. The time sequence of the measured electron energy spectra (from bottom to top) shows the characteristic changes as the spacecraft moved from the region of the unperturbed solar wind through the Martian plasma environment. In the right of this figure the variation of the x component of the magnetic field is shown for comparison [*Riedler et al.*, 1989; *Yeroshenko et al.*, 1990].

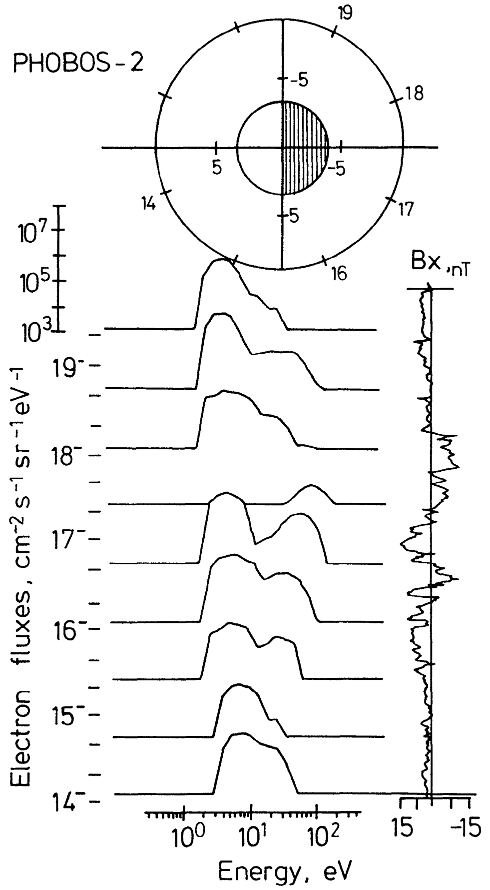

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Figure 1. Observed electron spectra from one of the eight angular sector of HARP. See text for details.

This sequence of HARP data shows how the spectra of the solar wind electrons broaden, and an additional energetic component appears in the region between the bow shock and the optical shadow of Mars. As expected, in the optical shadow of Mars the shocked solar wind component is not present, but there is still a clear high energy component. As the spacecraft moves back into the magnetosheath, the two component distribution reappears.

There were differences in the apparent fluxes measured by the eight HARP sensors. At the lower energies (<10 eV) the fluxes may, at times, be contaminated by photo- or secondary emissions. However, in this paper we do not discuss the low-energy electron fluxes, and thus we do not address this problem.

While the spacecraft was in the optical shadow of Mars, we observed during 8 orbits electron spectra similar to the one shown in Figure 1, i.e. a single, fairly narrow peak centered in the range of 100-200 eV. During 4 orbits no electron flux was observed, while on the remaining 7 orbits electrons below 50 eV were observed. There were 4 cases when both the high- and low-energy electrons were present.

Simultaneously obtained magnetic field data [*Riedler et al.*, 1989; *Yeroshenko et al.*, 1990] and heavy ion results from the TAUS experiment [*Rosenbauer et al.*, 1989; *Verigin et al.*, 1991] were examined to establish any observable correlation and for possible clues about the physical processes involved. Such simultaneous magnetometer data are available for 10 orbits, and TAUS data for 6 orbits. In 4 cases both magnetometer and TAUS data are available.

Figure 2 shows a simultaneous data set of HARP electron fluxes (on the right), the B_x component of the magnetic field from MAGMA (in the middle), and the heavy ion fluxes obtained by the TAUS instrument (on the left). The time scale on the left applies to all three data sets. The HARP data are from the same orbit as the one shown in Figure 1. In this figure we show data only from three of the time segments, but we also present spectra from four central sensors. The data from the third sensor are shown in Figure 1. In order to be consistent with the data available from the TAUS instrument, the HARP data are given in counts/s as opposed to Figure 1. As the TAUS results indicate, as the spacecraft moves away from the bow shock towards and into the optical shadow (from bottom to top in the figure) the energy of the heavy ion flux decreases from about 6 keV (top energy range of the instrument) down to a fraction of a keV. It is important to note that the TAUS instrument measures ion fluxes moving away from the planet along this portion of the orbit. The bow shock was crossed at 15:25 on the inbound portion of the orbit and the spacecraft moved out through the bow shock at 19:21 as was established by the total magnetic field values. The x component of the observed field shows that the spacecraft encountered a number of field reversals as it moved from bow shock to bow shock. During this orbit the highest energy electron fluxes were observed in the optical shadow region, and at the same time there was also a significant low energy heavy ion flux flowing away form the planet, and a magnetic field reversal was also observed. A field reversal in B_x and the presence of high energy electron fluxes are seen simultaneously on 5 of the 10 orbits during which simultaneous data are available in the shadow. Although ion and high energy electron fluxes were observed

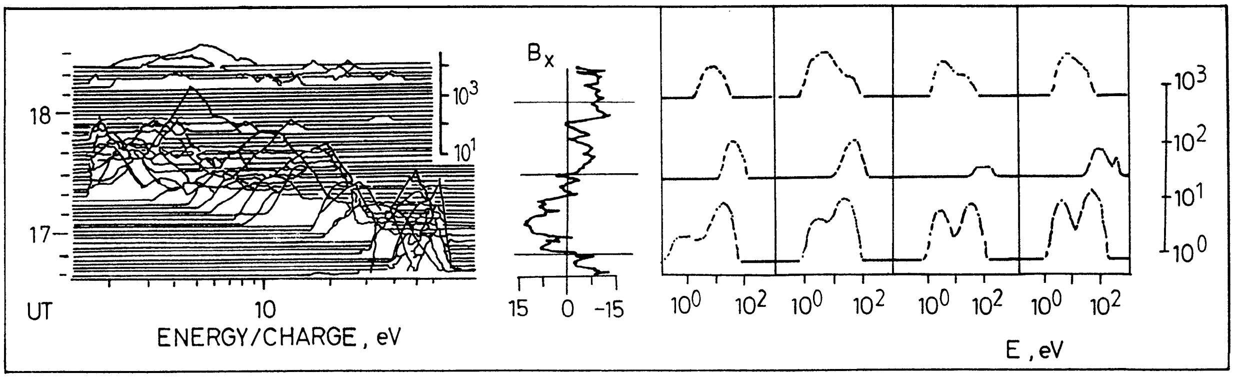

Figure 2. Simultaneous data set of HARP electron fluxes (on the right), magnetic field data (in the middle), and heavy ion fluxes obtained by the TAUS (on the left) instruments. See text for details.

simultaneously not only on this orbit, the general significance of this coincidence cannot be confirmed because there were only a few (~4) orbits with simultaneous observations.

Discussion

As stated in the previous section, there is no uniformly accepted definition of the various regions and boundaries of the Martian magnetosphere. A summary of our pre-Phobos understanding of the composite nature of the tail was given by *Vaisberg and Smirnov* [1986]. *Verigin et al.* [1991] and *Shutte et al.* [1989, 1991] used the additional results from the Phobos-2 mission to classify the various regions according to ion flux and magnetic field observations, as it was described before. A clear distinction can be made between the region populated by shocked solar wind protons and a region where this population is not significant and heavy ions, believed to be of planetary origin, are present [*Rosenbauer et al.*, 1989; *Lundin et al.*, 1990; *Verigin et al.*, 1991]. This transition is also generally characterized by changes in the character of the magnetic field. *Verigin et al.*, [1991] called the outer region, where the shocked solar wind is present, the magnetosheath, and the inner region the tail. The central part of the tail, as mentioned earlier, has been called the plasma sheet.

The HARP measurements presented in this paper, as well as measurements from the initial elliptic orbit of Phobos-2 [*Shutte et al.*, 1989] have shown clearly that in the magnetosheath there is an electron flux component with energies exceeding that of the unperturbed solar wind, reaching values of a few hundred eV. This is a new and interesting result, suggesting the presence of an accelerating mechanism in this region. One mechanism which has been suggested and could explain this observation was put forward by *Sagdeev et al.*, [1990]. As cold, heavy Martian ions penetrate into the magnetosheath, they interact with the shocked solar wind. The interaction excites waves, which in turn accelerate electrons up to the energies observed. Accelerated electrons were also seen on the dayside [*Shutte et al.*, 1986], and *Johnson and Hanson* [1991] found similar accelerated electrons in the data obtained by the retarding potential analyzer carried on the Viking 1 lander in 1976.

The character of the HARP data in the magnetotail cannot be classified in any simple manner. First, we examined the possibility of a correlation between unperturbed solar wind ram pressure and the electron fluxes measured in the center of the tail region. In Figure 3 we plotted the HARP electron fluxes (integrated over energy and pitch angle) measured within a cone of 30 degrees in the antisolar direction versus the unperturbed solar wind ram pressure. It can be clearly seen that high solar wind pressure corresponds to large electron fluxes near the antisolar direction. This could be an indication of an acceleration mechanism, which depends on the solar wind conditions. In considering this correlation one has to remember that there is a 2 to 4 hour time difference between the unperturbed solar wind measurements and the tail observations. We reported above that in the case of the HARP measurements a field reversal in B_x is observed when high energy electron fluxes are present only on 5 of the 10 orbits during which simultaneous data were available. We believe that there are also some unresolved issues associated with the interpretation of the ion data observed in the central tail. *Lundin et al.* [1989] and *Rosenbauer et al.* [1989] reported earlier that the most intense ion fluxes were observed where the x-component of the magnetic field is reversing. However, the more detailed analysis of *Verigin et al.* [1991], showed that the enhanced ion fluxes were not always accompanied by a change in B_x; whenever B_x reversed, increased ion fluxes were seen, but not vice versa.

In summary, we wish to reemphasize that the electron spectra measured in the magnetosheath during the circular and

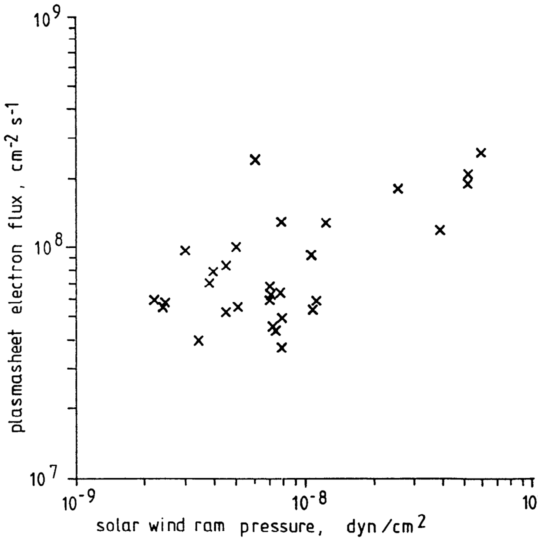

Figure 3. Correlation between unperturbed solar wind pressure and the electron fluxes in the Martian tail for several orbits. See text for details.

elliptic orbital phases of the Phobos-2 mission are similar, although they were obtained at different times and locations. The nature of these spectra appears to be characteristic of the Martian magnetosheath in general. The accelerated electron population was interpreted, previously, in terms of wave-particle interaction processes. In the central tail region the interpretation of the plasma data observed by the HARP and the other plasma instruments carried onboard the Phobos-2 spacecraft do not provide a simple picture. Our available database and published results from other instruments show the general presence of enhanced plasma fluxes in this region, but no clear-cut correlation with the location of the current sheet has been found. We did find a good correlation between the intensity of the electron flux and the unperturbed solar wind ram pressure.

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