JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A5, PAGES 9101–9111, MAY 1, 1998

# On the dayside region between the shocked solar wind and the ionosphere of Mars

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**Abstract.** The objective of this paper is to explore the structure and properties of the region between the shocked solar wind and the planetary plasma on the dayside of Mars. This study is based on the observations obtained by the plasma instruments carried on board the Phobos 2 spacecraft. These instruments have independently identified several plasma boundaries in the dayside magnetosphere of Mars, the boundaries are located close to each other but exhibit different plasma features. This investigation leads us to conclude that a dayside region exists on Mars with the following characteristics: (1) the bulk of the shocked solar wind protons are deflected, (2) the total magnetic field increases, (3) a plasma depletion region is formed, (4) both shocked solar wind and planetary plasma are present, (5) accelerated electrons and heavy ions are also present, (6) intensive wave activity is seen in the 5 to 150 Hz frequency interval, and (7) a current layer and associated magnetic shears can be identified. We name this region, located between the ionosphere and the shocked solar wind, the dayside boundary layer or dayside mantle. Its key features are similar to those of the Venus mantle; the variety of names given to the Martian plasma boundaries merely reflects its complicated structure. We conclude that the two boundary layers at Venus and Mars are very similar and that the physical processes (i.e., the interaction of the shocked solar wind with the planetary plasma) at work within these boundary layers are probably similar.

## 1. Introduction

In this paper we investigate the region between the shocked solar wind and planetary ions in the dayside of Mars. The objective is to collect and examine its key physical features and compare it to the similar plasma region around Venus in order to find similarities and differences in the measured data. This study is based on the observations made by the plasma instruments carried on board the Phobos 2 spacecraft; we take this opportunity to summarize these data coherently. It is well known that these instruments have identified several plasma boundaries in the dayside magnetosphere of Mars and named them differently. The presence of these boundaries was always derived from single instrument measurements; the boundaries appear to be located close to each other, but they exhibit different plasma features. We conclude that these seemingly independent boundaries form a complex region (which we name the dayside boundary layer), that the two boundary layers at Venus and Mars are very similar, and that therefore the physical processes (i.e., the interaction of the shocked solar wind with planetary plasma) inside them are most likely similar.

We compare Mars to Venus, despite the fact that there are many proven and proposed differences between these planets. In the majority of studies both planets are believed to be nonmagnetic, though some indirect observations and theoretical models indicate the presence of a small, intrinsic magnetic dipole field on Mars [*Axford*, 1991; *Verigin et al.*, 1993]. Applying simple scaling laws to the observations made on Venus does not lead to what has been observed on Mars; for example, the subsolar location of the bow shock is farther upstream from the planet than would follow from an appropriately scaled Venus-type model [*Brecht*, 1993, 1997], and the flare angle of the shock is larger on Mars than Venus [*Verigin et al.*, 1993]. In the foreshock region of Mars the solar wind is considerably decelerated [*Verigin et al.*, 1991; *Kotova et al.*, 1997], but no similar effect was reported on Venus. It was also proposed that the solar wind interaction with Mars is more cometlike [*Breus et al.*, 1989] owing to the extended neutral corona. We recognize all of these differences, and we also note that during the revision period of this paper, information was released that Mars may have a weak magnetic field. However, the coupling of the planetary plasma with the solar wind on Mars still appears to be similar to that on Venus.

The solar wind interaction with the planet Venus was explored extensively during the 14 year lifetime of the Pioneer Venus Orbiter (PVO), which provided an excellent database for this comparison. It has long been recognized that Venus has a special plasma region above the dayside ionosphere, called the dayside mantle. The first measurements that indicated the existence of this dayside boundary layer were the electron energy spectra obtained by the PVO retarding potential analyzer (ORPA) [*Spenner et al.*, 1980]. The Bennett ion mass spectrometer (OIMS) carried by PVO indicated the existence of a superthermal ion layer [*Taylor et al.*, 1981]; intensive wave activity was also reported there [*Scarf et al.*, 1980]. Recent investigations [*Szego et al.*, 1991; *Perez de Tejada et al.*, 1995; *Shapiro et al.*, 1995; *Strangeway and Russell*, 1996] have proven that this plasma region is a

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Paper number 98JA00103.
0148-0227/98/98JA-00103$09.00

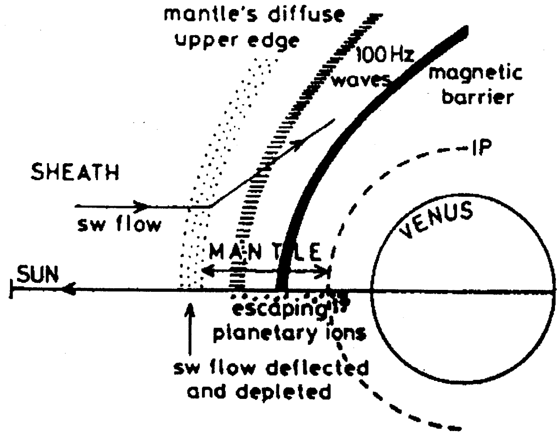


**Figure 1.** Structure of the dayside mantle of Venus, taken from *Shapiro et al.* [1995]. Solar wind is deflected at its diffuse upper boundary, and a plasma depletion region develops. Magnetic field piles up; the peak value is always reached above the pressure balance ionopause. The peak value of the 100-Hz wave intensity is observed at higher altitudes than the peak value of the magnetic field. Energetic electron currents are observed to be colocated with the peak wave activity. As indicated, the plasma features form an ordered sequence in altitude.

permanent feature of the magnetosphere of Venus, surrounding the planet and extending far in a tailward direction.

We summarize the structure of the dayside mantle of Venus in Figure 1, taken from *Shapiro et al.* [1995]. This structure was based on the analysis of about 70 PVO orbits and was further confirmed by the more extended statistical analysis of *Strangeway and Russell* [1996] concerning the ordering of magnetic fields, waves, and the ionopause (these authors did not consider other features). As we approach the planet from the direction of the shocked solar wind, we first reach a depletion region where the shocked solar wind is deflected and depleted by the obstacle. The peak of the magnetic barrier (defined as the place where the ionospheric pressure balances the solar wind) is formed above the ionopause; intensive wave activity is detected in the mantle higher above the planet than the magnetic barrier, with a peak intensity in the 100-Hz channel of the instrument. Accelerated and heated electrons were found at the same location [*Szego et al.*, 1997], and suprathermal ions were also observed in the region [*Taylor et al.*, 1981]. Similarities and differences between the dayside mantle of Venus and the appropriate region of Mars have been studied [*Nagy et al.*, 1990]; at that time, however, only a limited amount of data was available, and to some extent, theoretical models were also lacking. The current study eliminates many of the questions posed by *Nagy et al.* [1990].

It should be emphasized that the physical processes inside the dayside mantle differ substantially from the processes inside the mantle, behind the terminator line. It is in the dayside region of the mantle where the shocked solar wind encounters plasma of ionospheric origin, and the interaction between these two plasma populations deflects the solar wind flow. The plasma that populates the dayside region consists essentially of the hot, shocked solar wind and the cold planetary plasma; both components are equally important. Tailward in the mantle, the "mature plasma" is the result of the dayside interaction and possesses many of the features observed on the dayside, but it is a distinct plasma region with different plasma populations. The mantle is much broader in the tail than on the dayside. The distant tailward mantle was observed both on Venus and Mars during early missions, such as Mariner 5 and Mars 2, 3, and 5 [*Breus and Verigin*, 1976]. The difference between the dayside and nightside mantle is not recognized by many authors, leading to some confusion in the terminology.

The Phobos 2 mission, launched in 1989, is still, as of today, the best equipped spacecraft that has explored the Martian plasma environment. In this paper, we analyze the data collected by the plasma instruments carried by Phobos 2 spacecraft during the first three elliptic orbits, identified as E1, E2, and E3. We focus our attention on the region located between the shocked solar wind and the inner plasma. No magnetometer data are available from the fourth elliptic orbit, and the fifth orbit, a transfer orbit for the next phase of the mission, did not cross the region we investigate. The first three elliptic orbits are particularly suitable to the analysis of the interaction between the shocked solar wind and planetary plasma because the spacecraft spent a long time inside or in close vicinity to the dayside boundary layer. During the first two elliptic orbits the spacecraft was spinning around an axis pointing approximately toward the Sun (*x* axis) with a period of about 10 min, and it was also nutating with a half cone angle up to 15°. The three orbits are very similar, therefore only E1 is shown in Figure 2 that indicates the different plasma regions as well. The pericenter of these orbits was reached at 1839:37, 0015:47, and 0551:47 UT, at altitudes of 865, 859, and 852 km, respectively.

We use data from the magnetometer experiment (MAGMA) [*Riedler et al.*, 1989] and from the plasma wave system (PWS) [*Grard et al.*, 1989] that covered the frequency range 0.2 Hz - 150 kHz in 25 channels. One spectrum was sampled every 2 s, and we use 6-s running averages. The dipole antenna of PWS consisted of two spherical sensors; it measured the spacecraft potential with respect to that of one sphere (referred to as $\Delta V$).

The differential hyperbolic retarding potential analyzer (HARP) measured electron and ion spectra in a fan consisting of eight coplanar view directions, symmetrically arranged with respect to the antisolar axis [*Shutte et al.*, 1989]. The field of view of each angular sector was 10° x 20°; the sensor head was mounted on the backside of the solar panels. The ion energy range, 0.3-550 eV, and the electron energy range, 3.4-550 eV,

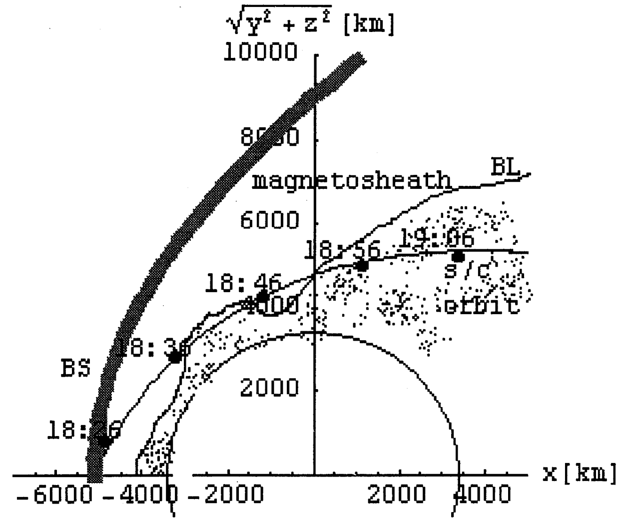


**Figure 2.** Spacecraft orbit around Mars on February 1, 1989. Vertical and horizontal axes are distances, in kilometers, in the orbital plane; the horizontal axis is the Sun-Mars line. The dots on the orbit mark time, 1826, 1836, 1846, 1856, and 1906 UT; BS and BL denote the bow shock and boundary layer, respectively.

were covered in 42 and 25 steps, respectively; the integration time of each step was 1 s in both cases. In this study, we use two perpendicular channels of the HARP instrument pointing at 34° and -56° relative to the $x$ axis.

The TAUS instrument [*Rosenbauer et al.*, 1989] measured protons and heavy ions in the 30 eV to 6 keV range, covering a 40° x 40° sunward field of view centered on the nominally aberrated solar wind direction, divided into 8 x 8 separate channels both in elevation and azimuth. We also refer with some cautions to published data of the automatic space plasma experiment (ASPERA), because that experiment had a very narrow field of view, 5° x 360° in a plane perpendicular to the solar panels [*Lundin et al.*, 1989].

As mentioned previously, these various instruments identified several plasma boundaries in the dayside magnetosphere of Mars that were called by different names, such as magnetopause, planetopause, mass-loading boundary, ion composition boundary, etc. [see, e.g., *Grard*, 1994]. These boundaries appeared to be close to each other, but they exhibited distinct features. We show that these observations can be ordered to reveal the existence of an interaction region on Mars, the Martian dayside boundary layer or mantle, which is very similar in structure to the dayside mantle of Venus.

## 2. Data Analysis

Here we present and discuss the results of the plasma measurements made in the different regions in the Martian dayside magnetosphere. Figures 3-5 summarize the field and particle data obtained during E1; Figures 6-8 show the equivalent data set from E2; while Figures 9 and 10 show the same for E3. Though we focus on the dayside boundary layer (BL) between the magnetosheath (MS) and the ionosphere, we also describe results obtained in the magnetosheath. Phobos 2 did not penetrate the ionosphere; only the Viking landers provided in situ information about it. These probes, however, carried only a retarding potential analyzer [*Hanson et al.*, 1977], and no other plasma instruments. Radio occultation measurements [*Kliore*, 1992] revealed the existence of a robust dayside ionosphere with peak electron densities of a few times $10^5$ $cm^{-3}$ and a uniform vertical extent, independent of the solar zenith angle.

### 2.1. Magnetosheath

The region bounded by the bow shock and the next "inward boundary" is the magnetosheath. The high-resolution magnetic field data (with a 1.5-s sampling period) are characterized by intensive fluctuations that disappear inside the dayside boundary layer. As anticipated, the energy spectrum of the solar wind protons is broader in the MS than upstream of the bow shock. TAUS did not detect continuously the shocked solar wind on E1; we do not attach any physical significance to this anomaly because it is probably due to spacecraft nutation. In the MS, $\Delta V$ is smaller than in the undisturbed solar wind ([c.f. *Grard et al.*, 1991, Figure 2], reproduced here partially as the top panels of Figures 4, 7, and 10), indicating a denser solar wind population. It was pointed out by *Kallio* [1996] that the ASPERA proton densities decrease when Phobos 2 crosses the bow shock and enters the MS, but this effect is probably due to the very constrained view direction of the instrument.

The HARP ion and electron data show peculiar features in the magnetosheath, i.e., between 1825-1835, and 0001-0013, along E1 and E2, respectively. The HARP electron spectra are shown in Figures 5 and 8; in both cases the shocked solar wind electron component is seen in the spectra, but a high-energy tail can also be identified, extending to the upper energy limit of the instrument. These high-energy tails are present in both perpendicular channels and do not seem to be affected by the

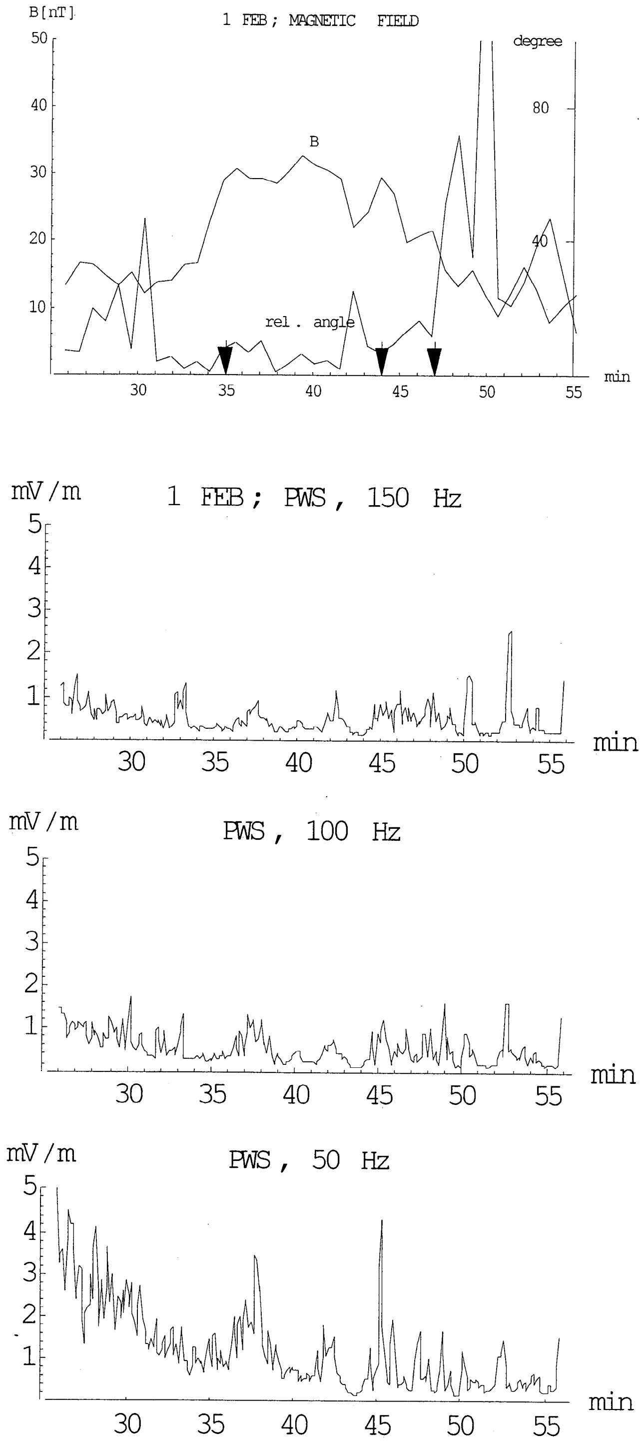


**Figure 3.** Summary plots of magnetic field and wave data measured on February 1. Horizontal axes show time in minutes past 1800 UT, beginning right after the bow shock crossing. Arrows denote the time of the boundary layer crossings. (top) Total magnetic field $B$ and its variation, showing the angle between two consecutive field vectors ("angle"). Also shown (top to bottom) the electric fields in the (b) 5-50, (c) 50-100, and (d) 100-150 Hz channels, in millivolts per meter. PWS is the plasma wave system.

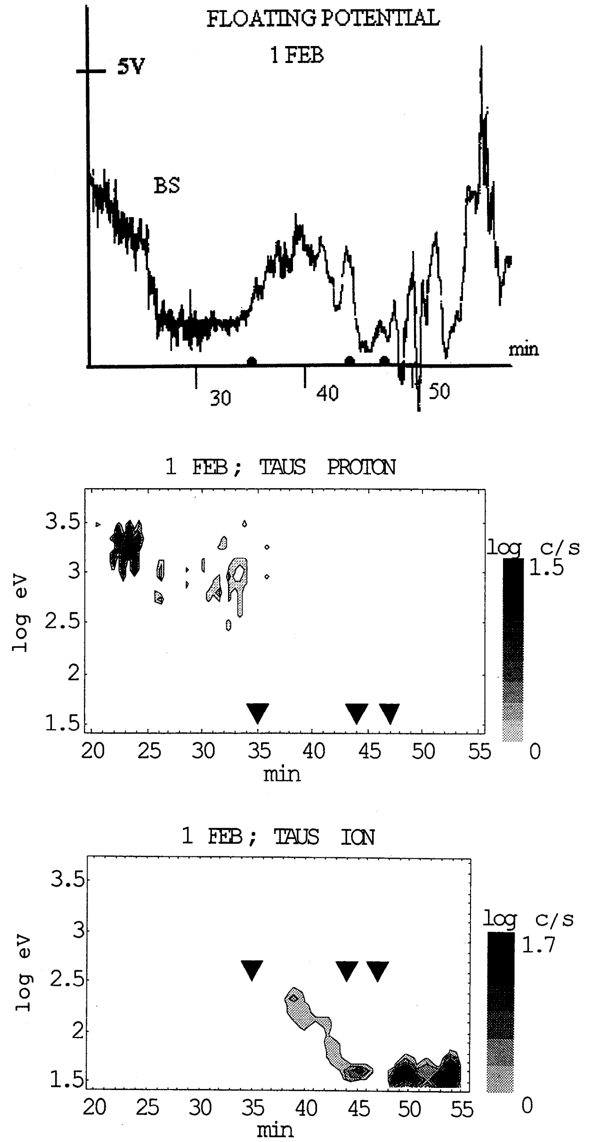


**Figure 4.** Summary plots of the (top) floating potential, (middle) TAUS proton, and (bottom) TAUS ion data measured on February 1. The horizontal axes show time in minutes past 1800 UT, beginning 5 min before the bow shock crossing. The arrows denote the time of the boundary layer crossings. The TAUS plots exhibit log counts/s.

direction of the magnetic field. The orientations of the two HARP sensors relative to the magnetic field direction are also shown in Figures 5 and 8. No high-energy electron component has been reported either in the Venus sheath (the electron detector on board the Pioneer Venus Orbiter had an upper limit of only 60 eV) or from earlier missions to Mars.

Figures 5 and 8 also exhibit the HARP ion data. Only ion fluxes with energies greater than 10 eV are shown; at these higher energies the effects due to spacecraft charging become small. Ion flux enhancements were detected in the antisunward direction, after the bow shock crossing up to 1833:45 UT on E1 and 0012:45 UT on E2, when the spacecraft entered the BL. The flux increase is also present at the lower energies, with some gaps around 2 to 3 eV. HARP measured all ions with approximately equal sensitivity (no ion mass dependence). The ion flux measured with HARP may also include ions freshly created from the neutral corona. These observations are consistent with the relevant ASPERA results [*Dubinin et al.*, 1993]. No significant heavy ion flux was detected by TAUS in this region.

### 2.2. Boundary Layer

There is one or possibly more transition layers between the magnetosheath and the planetary ionosphere, depending on whether or not Mars is weakly magnetic. On Venus the unique transition zone was called mantle by some authors and magnetic barrier by others; its characteristic features were summarized in Section 1. Both shocked solar wind and planetary plasma are present and equally important in this layer; their interaction leads to physical processes that makes the BL peculiar compared with other plasma regions.

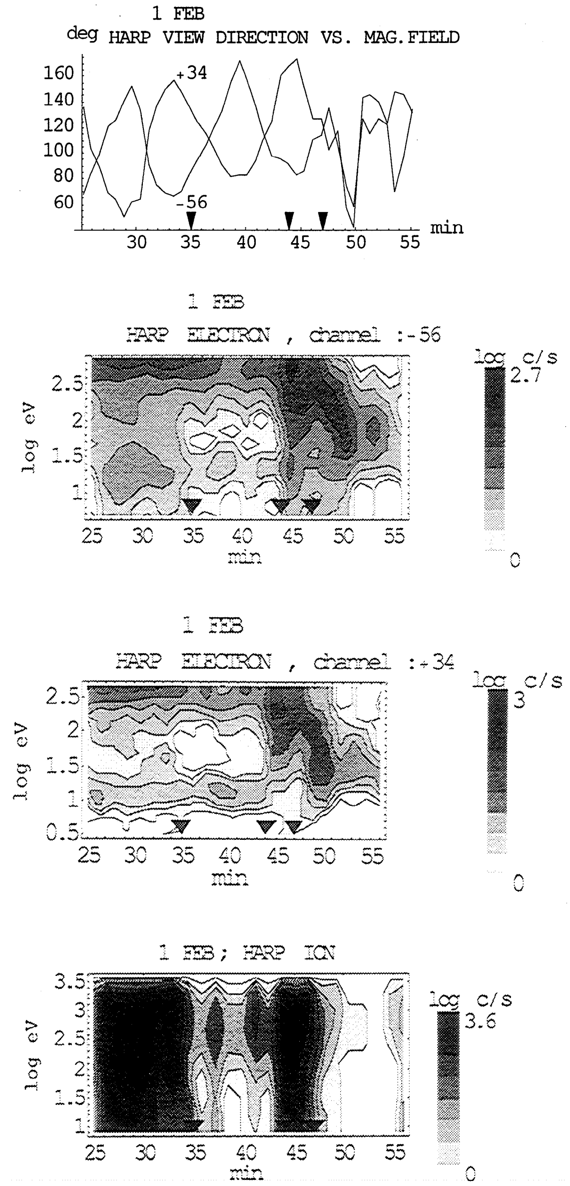


**Figure 5.** Summary plots of the hyperbolic retarding potential analyzer (HARP) data and (top) the angle between the view directions of the HARP sensors and the magnetic field, measured on February 1. Horizontal axes show time in minutes past 1800 UT, beginning right after the bow shock crossing. Arrows denote the time of the boundary layer crossings. The HARP plots exhibit log counts per second for (top to bottom) data collected in the look directions (b) 34° and (c) -56° and (d) ion data.

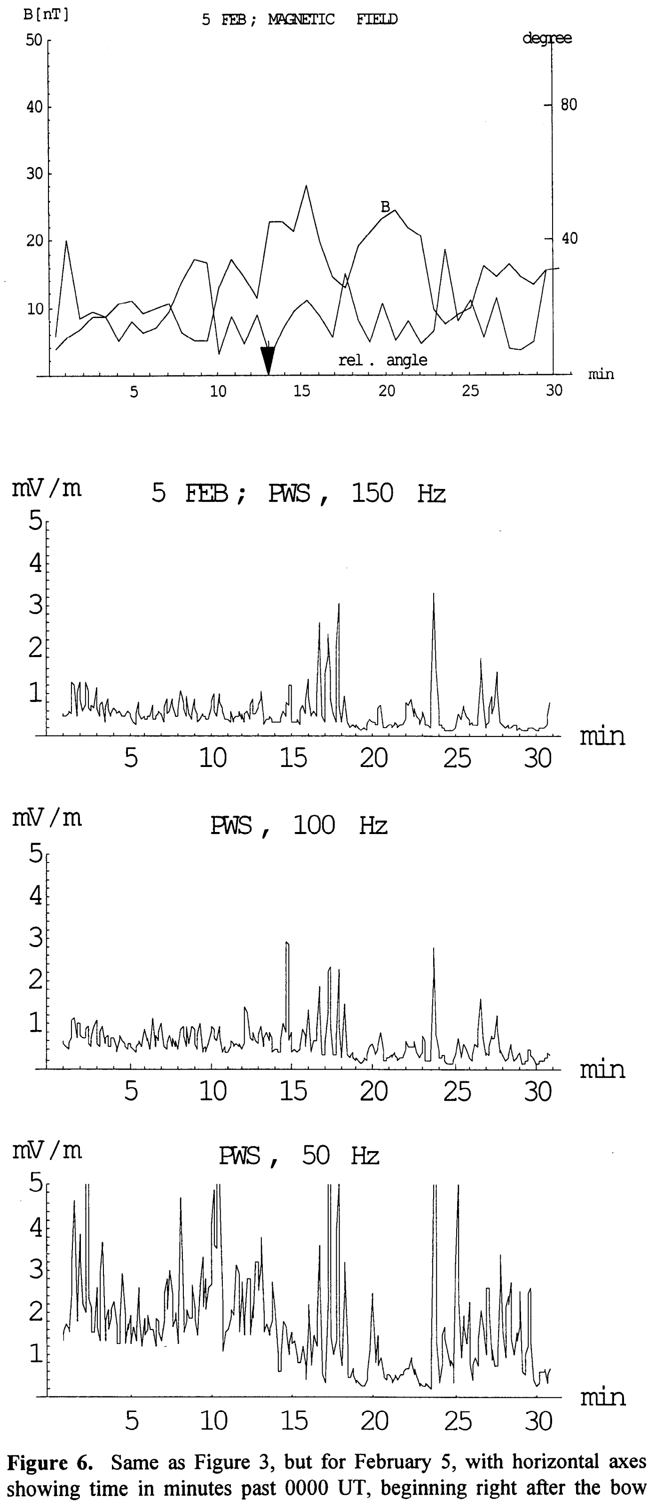


**Figure 6.** Same as Figure 3, but for February 5, with horizontal axes showing time in minutes past 0000 UT, beginning right after the bow shock crossing.

The Phobos 2 spacecraft penetrated the BL on all three elliptic orbits, although in various ways, because the solar wind conditions were different. The solar wind velocities (and the proton density per cubic centimeter) were 790 km/s (2.1), 542 km/s (1.8), and 451 km/s (1.7) on E1, E2, and E3, respectively. The solar wind pressure was the highest during E1, 2.19 x $10^{-8}$ dyn/$cm^2$, and accordingly, the BL was compressed closer to the planet. Therefore the spacecraft stayed close to its upper edge for a long period of time while the solar zenith angle (SZA) increased considerably, and the spacecraft also reemerged from it for short period(s). Along E2 and E3 the spacecraft entered the BL only once.

**2.2.1. Foot of the boundary layer.** The crossing of the outer (upper) edge of the BL is very clear from the particle data. On E1 the solar wind proton flux disappeared from the field of view of TAUS at 1834:55 UT (see Figure 4), with a one-time reappearance at 1837:02 UT when the high-resolution measurements of $B_{tot}$ show a significant drop in magnitude of the magnetic field (seen only in the high resolution data). The HARP ion spectra (Figure 5) changed significantly between 1833:46 and 1835:46, and in the same time interval the HARP electron spectra also changed. Between 1833:22 and 1835:37, while the spacecraft altitude dropped from 1000 to 916 km, $B_{tot}$ increased from 16.76 to 29.02 nT; this is the location at ~1835 UT that we identify as the outer edge or the foot of the BL.

On E2 (Figure 7) the bulk of the solar wind disappeared between 0008:58 and 0011:30 (there are no data between these two observations in the proton spectrum). The HARP ion detector

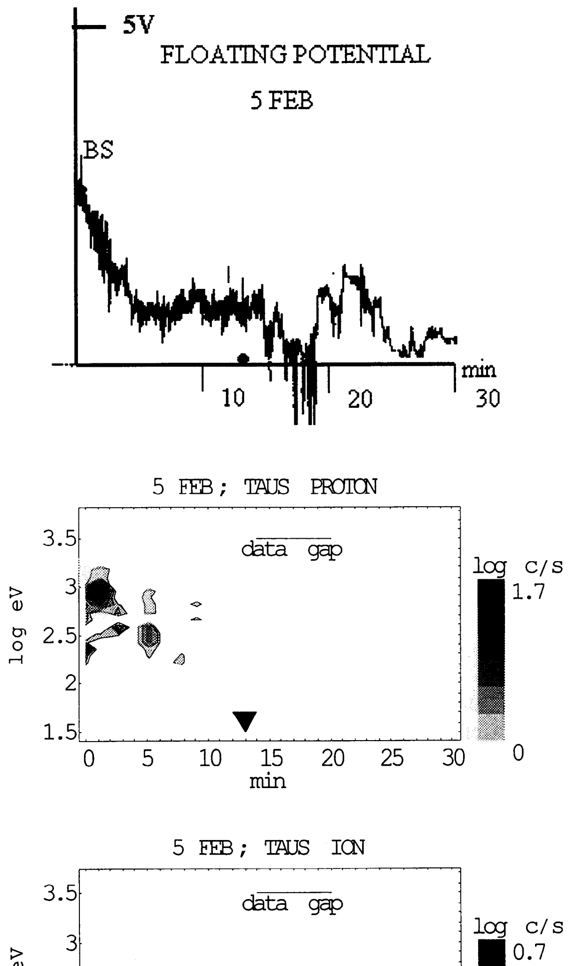


**Figure 7.** Same as Figure 4, but for February 5, with horizontal axes showing time in minutes past 0000 UT, beginning right after the bow shock crossing.

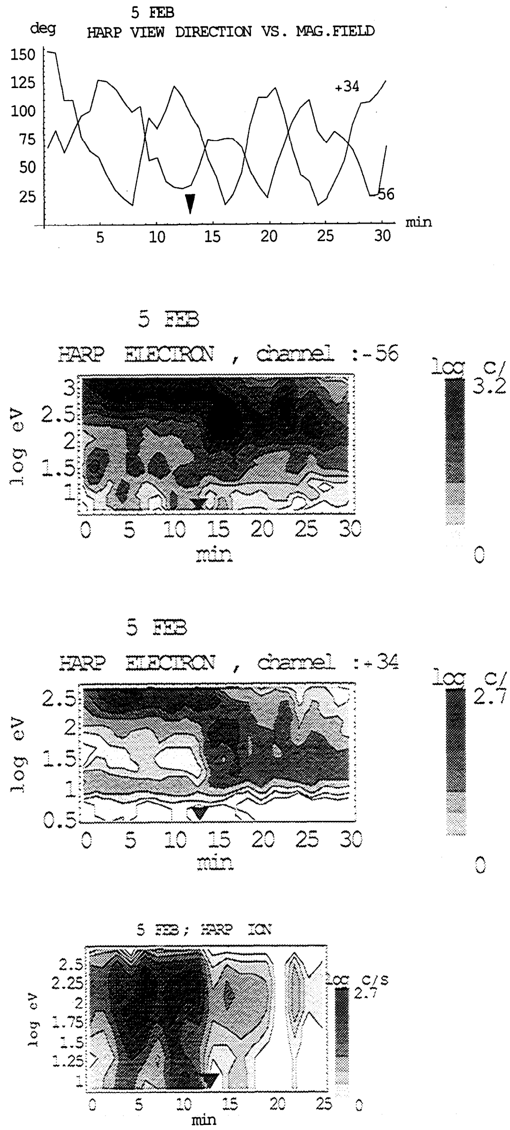


**Figure 8.** Same as Figure 5 but for February 5, with horizontal axes showing time in minutes past 0000 UT, beginning right after the bow shock crossing.

did not see the sheath ions after 0012:45 UT, and the electron spectra also changed significantly between 0012 and 0014 UT (Figure 8). In this interval, $B_{tot}$ increased by about 10 nT (Figure 6). We identify ~0013 UT as the foot of the BL.

On E3 the HARP was switched off. The TAUS data (Figure 10) indicate that the bulk solar wind was stopped around 0543 UT, though a few particles were detected somewhat later as well. The increase of the magnetic field was quite smooth, the peak was reached at 0547:40 UT. As HARP ion data are lacking, we invoke the floating potential and the TAUS ion data (Figure 10) to identify the foot of the BL. We concluded that it was crossed at ~0544 UT.

**2.2.2. Plasma depletion region.** Around the outer edge of the BL the formation of the plasma depletion region is evident from the $\Delta V$ measurements. On E1 the $\Delta V$ potential (Figure 4) started to increase around 1835 UT from its low value measured in the MS; on E3 the $\Delta V$ data (Figure 10) indicate the onset of depletion region around 0544 UT. The width of the depletion region is much smaller than the width observed along E1. On E2 (Figure 7), however, it is difficult to find this region; probably the spacecraft did not penetrate deep enough into the BL. In all cases the onset of the depletion region is smooth; we suspect that the foot of the BL is not a sharp plasma boundary.

**2.2.3. Accelerated ions.** Behind the foot of the boundary layer, accelerated heavy ions were detected by TAUS along E1, after 1838:30 UT (Figure 4). These heavy ions have energies up to 300 eV. The average ion energy possibly correlates with the distance from the foot of the BL, the heavy ions closer to the foot

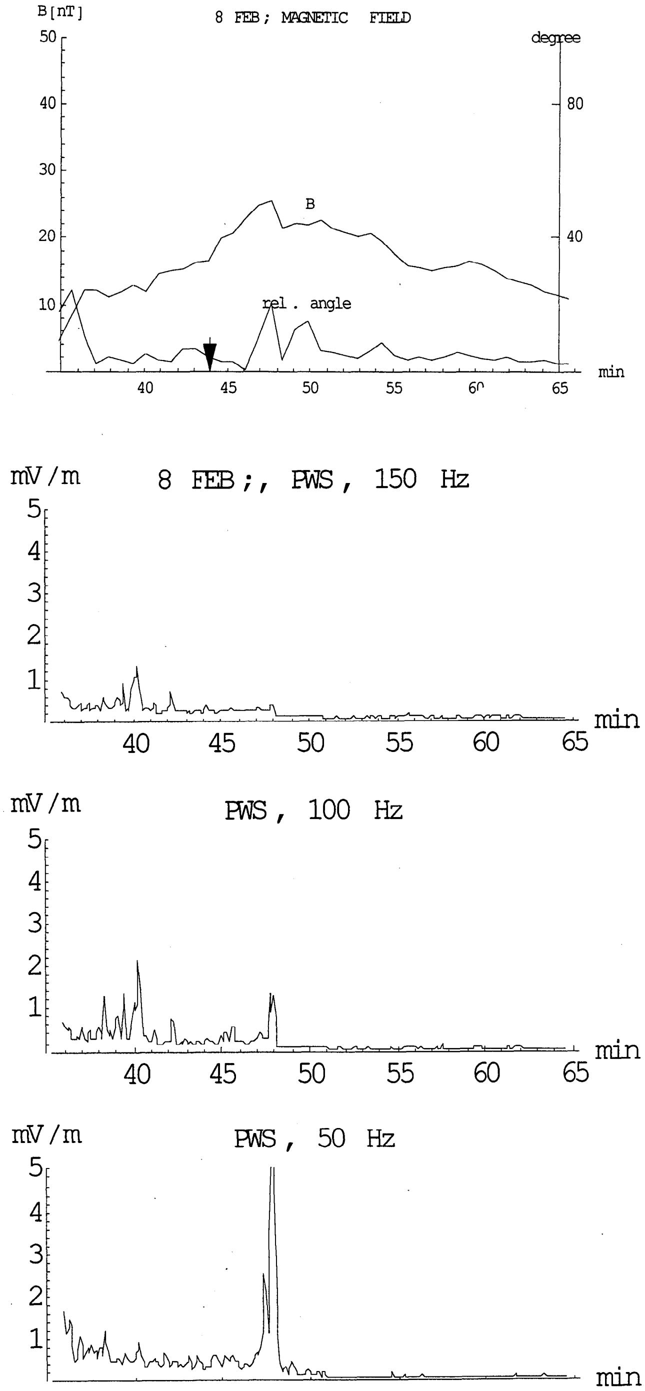


**Figure 9.** Same as Figure 3, but February 8, with horizontal axes showing time in minutes past 1700 UT, beginning right after the bow shock crossing.

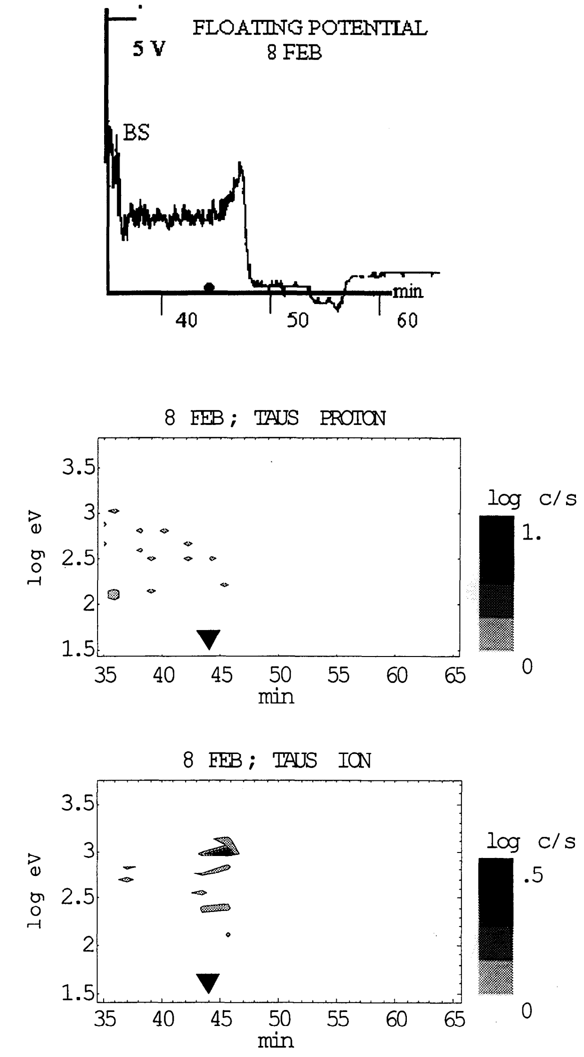


**Figure 10.** Same as Figure 4, but February 8, with horizontal axes showing time in minutes past 1700 UT, beginning right after the bow shock crossing.

having higher average energy. These heavy ions are moving tailward; we conclude this from the two-dimensional TAUS ion distribution measurements (not shown here) and also from the fact that the HARP ion sensor did not detect them.

During E2, accelerated ions were seen by TAUS after 0020 UT (Figure 7), but we must note a data gap between 0014 and 0020 UT. As the spacecraft approached the terminator and its altitude became higher, the accelerated heavy ions disappeared from the field of view of TAUS. Later on, however, as the distance of the spacecraft from the Sun-Mars line decreased again, TAUS detected these tailward moving accelerated ions before the spacecraft entered into the geometric shadow of the planet. During E3, heavy ions were seen before 0546 UT (Figure 10); consequently, the onset of the BL is very smooth.

ASPERA reported a change in the density ratio between the $O^+$ and $H^+$ number densities [*Lundin et al.*, 1990] both on E1 and E2 and called it a "mass loading boundary". However, neither the crossing time, nor the altitude of this boundary has been clearly stated. ASPERA reported that the mass loading boundary was seen at 0548 UT during E3 [*Dubinin et al.*, 1996]. It is very likely that this change occurred during the same interval when TAUS lost protons but started to see heavy ions; that is, the mass loading boundary is probably identical to the foot of the boundary layer. The 4-min difference between the ASPERA observation and our identification is very likely due to the smoothness of the foot on this particular orbit.

**2.2.4. Wave activity.** During E1, between 1835 and 1844 UT, the spacecraft altitude varied only ~100 km and the solar zenith angle (SZA) changed from 37° to 68°. We conclude from the $\Delta V$ measurements (Figure 4) that for ~9 min the spacecraft traveled inside the BL; peak $\Delta V$ was reached near periapsis, around 1840 UT, then dropped back around 1844 UT to the MS value. The HARP ion spectra clearly indicate that the spacecraft was in a different plasma region after 1843:45 UT.

During this period of time, i.e., from 1835 until 1844 UT, strong wave activity was observed in the 5-50 Hz, 50-100 Hz, and 100-150 Hz channels of the PWS. The details of the wave measurements are given by *Grard et al.* [1991]; a recent summary is provided by *Trotignon et al.* [1996]. The peak wave intensity was reached at 1838 UT. As can be seen in Figure 3, the most intensive waves were observed in the 5 to 50 Hz frequency range and at those places where the spacecraft was close to the foot of the BL.

Significant wave activity was present during orbit E2 (Figure 6). The waves excited between 0016 and 0019 UT are believed to be generated close to the foot of the BL because the total magnetic field values also drop in this interval, probably indicating that the spacecraft moved toward the foot. The peak field value was registered at 0024 UT, more than 4 min after periapsis.

During E3 there was only one significant wave event, namely, around 0548 UT (Figure 9), shortly after the spacecraft crossed the foot of the BL, i.e., after the solar wind disappeared from the field of view of the TAUS spectrometer.

Whereas, in general, waves are most intense in the 50-100 Hz channel, there was an event during E2, at 0014:40 UT, when the peak frequency was in the 100-150 Hz channel. The integral electron flux measured by HARP also reached maximum at this location; there the plasma $\beta$, the ratio between the kinetic and magnetic energy, is much higher than in the other cases. This frequency dependence on $\beta$ might restrict the possible wave excitation mechanisms.

The overall picture derived form the wave activity described above is consistent with a model in which the interaction between the shocked solar wind and planetary plasma is most intense close to the foot of the boundary layer, similar to what was seen on Venus.

*Grard et al.* [1991] and following them, *Trotignon et al.* [1996], have identified the planetopause as the place where the short timescale turbulence of the floating potential disappear. Other characteristics of the planetopause crossings may vary from orbit to orbit, such as the wave intensities reaching high values from nearly *dc* to 6 kHz and the spacecraft potential $\Delta V$, exhibiting further decrease; this definition of the planetopause uses field data only. Grard et al. and Trotignon et al. have identified planetopause crossings at 1842 UT on E1, at 0024 UT on E2, and at 0548 UT on E3. The last two are colocated with the peak of the wave activities; however, on E1 there is no other particular plasma event exactly at 1842 UT. We note that the high-resolution magnetic field data also exhibit turbulent structure in the MS, which also disappears inside the BL, but at locations other than the planetopause.

**2.2.5. BL crossings on E1.** The HARP ion spectra clearly show that the spacecraft was in a different plasma region between 1843:45 and 1847:45 UT during E1 (Figure 5, bottom). As the ion spectra are very similar to that observed in the MS, it is possible that the spacecraft returned the magnetosheath. The TAUS proton sensor did not detect solar wind protons in this time interval. However, this might be due to spacecraft nutation; therefore we are cautious about drawing definite conclusion from this.

The $\Delta V$ measurements are consistent with the ion data because around 1844 UT $\Delta V$ dropped back to the MS value and stayed there for awhile. The $\Delta V$ values dropped significantly further only after 1847 UT, indicating that the spacecraft was in a dense plasma region. The HARP electron spectra obtained between 1843 and 1847 UT are consistent with those in the magnetosheath (Figure 5). These facts lead to the conclusion that between 1844 and 1847 UT the spacecraft returned into the MS. However, the observations after 1847 show many new features, therefore we cannot rule out that in the given time interval, the spacecraft left the BL not toward the sheath but rather, toward the planet.

**2.2.6. Electrons in the BL.** To clarify the events registered after 1847 UT, we turn to the HARP electron data (Figure 5). If we compare the obtained spectra in the two different view directions and disregard some differences in intensity, the spectra of the two channels are very similar, except for the high-energy peaks inside the BL; that is, on E2 the electron spectra do not exhibit high-energy peaks. We correlate this with the fact that in this region the sensors were not parallel to the magnetic field, whereas the high-energy electrons are very likely field aligned. (We note that the 45-s averages of the magnetic field data give only general indications about the field direction; the exact orientation can be obtained from the 1.5-s high-resolution data.) After 1850 UT the distribution function has a new shape, we assume that this characterizes the lower region of the BL (or that it is a new plasma region).

The integral of HARP electron flux (that is $env$, where $n$ is the number and $v$ is the velocity of the electrons in the given sensor channel) reached maximal values twice, at 1845 and 1850 UT, with a drop around 1848 UT (Figure 11). Earlier interpretations suggested that at this point the spacecraft entered the topside ionosphere. However, if we analyze the electron energy in the vicinity of the second peak, it turns out that the increase is mostly due to high-energy electrons in the 10-100 eV range. The direction of the magnetic field in this region changed drastically (Figure 3); consequently, the spacecraft crossed an intensive current layer. HARP detected energetic electrons in this layer. The $\Delta V$ drop requires a density of 60 el/cm$^3$ for >30 eV electrons, and less density for higher energy electrons (A. Pedersen, private communication, 1996). The peak of the electron flux at 1845 UT is due to electrons below 10 eV, similar to other BL crossings.

We turn now to the HARP electron data obtained during E2. Between 0014 and 0017 UT the integral electron flux (Figure 11) shows the same behavior what we experienced along E1 between 1847 and 1851 UT, that is, the electron flux peaks and $\Delta V$ take negative values, indicating a dense plasma region. The interpretation of the magnetic field and HARP measurements on E2 in the time interval between 0014 and 0017 UT is very likely the same that we suggested for E1; that is, the spacecraft crossed an intense current layer.

The characteristics of the HARP electron data after 0022 UT are similar to those on E1 after 1850 UT. Accordingly, the electron spectra measured inside the BL fell into two distinctly different categories.

**2.2.7. Particles of ionospheric origin.** Next we discuss whether ionospheric plasma was observed inside the BL. The accelerated heavy ions seen by TAUS are very likely of planetary origin. Cold planetary ions were repelled from the HARP ion detector; though in the case of ions heavier than oxygen, the spacecraft motion might compensate the repelling potential. (During E1 the spacecraft velocity at the bow shock crossing was ~4 km/s, with $v_X$ = -2 km/s, and at the periapsis of the orbit it was 4.3 km/s, with $v_X$ = -3.5 km/s.) Along E1, ~1836 and ~1842 UT, small ion fluxes were observed briefly by HARP (Figure 5). These observations correlate well with the ASPERA cold ion measurements [*Lundin et al.*, 1989]. We assume that these ions were of planetary origin.

The case for planetary electrons is complicated. As can be seen from Figures 5 and 8, the lower limits of the electron spectra more or less follow the variation of the spacecraft potential. Accordingly, it is possible to argue that the lowest nonzero counts detected by HARP are due to cold electrons, accelerated to spacecraft potential. Such cold electrons must be of planetary origin.

This result can be compared to the retarding potential analyzer data of the Viking 1 lander. During its electron scans the potential

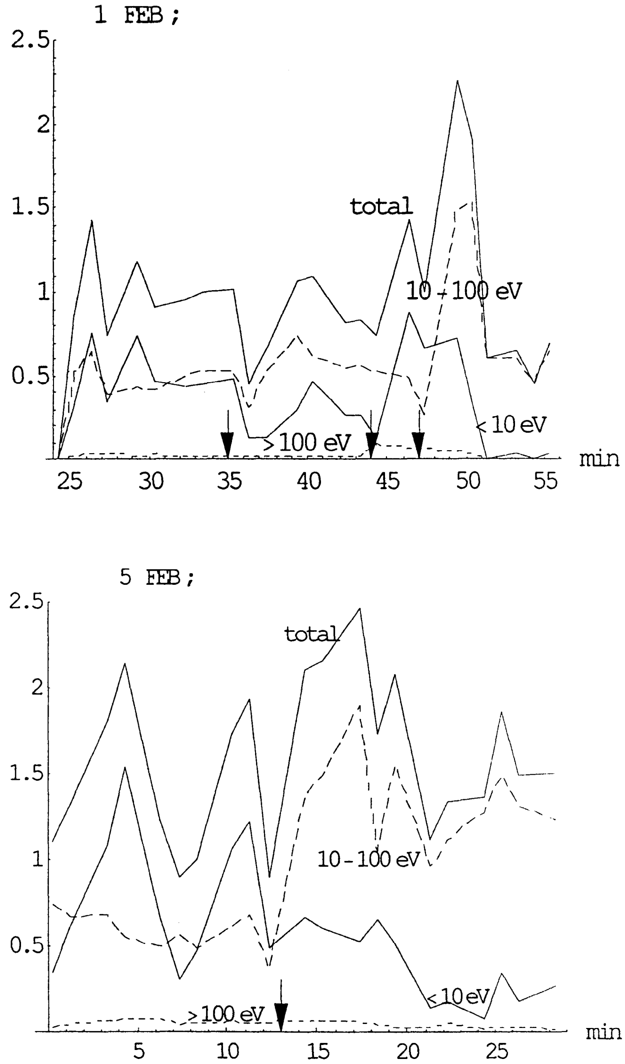


**Figure 11.** The integral electron flux in the look direction of the sensors of HARP during (top) E1 and (bottom) E2, summed over different energy ranges, in arbitrary units. Horizontal axes show time in minutes past 1800 and 0000 UT, respectively, beginning right after the bow shock crossing. Solid dark curves show the total electron flux, long-dashed curves denote the electron flux in the 10 eV-100 eV range, the solid light curves denote the flux of electrons less energetic than 10 eV, and short-dashed curves denote the electron flux of >100 eV electrons.

on the retarding grids varied from -78 to 0 V, and for each scan an *I-V* curve was obtained. In most of the cases two Maxwellians were fitted to the data; the results are shown by *Johnson and Hanson* [1991, Figure 12], who summarize the density and temperature values between 0 and 5000 km. The temperature of the colder component around the likely location of the top of the ionosphere was approximately a few times $10^4$ K; inside the BL, from 500 km altitude, it reached a value 6 times higher, and in the magnetosheath the temperature of the colder component increased further to $\sim 2 \times 10^5$ K. The density at the possible ionopause was $\sim 10$ cm$^{-3}$, and this value was more or less constant within the BL.

Taking into account that according to the HARP measurements, the real spectra are much broader than Maxwellian, we believe that these observations are in agreement with our previous conclusions that electrons below a few eV energy are actually present in the whole BL.

## 3. Discussion and Summary

It is a well-established fact that at Venus, on the dayside, there is an extended boundary region between the magnetosheath and the ionopause; this region is called the dayside mantle. The lower boundary of the mantle is the Venusian ionopause, and the upper boundary is diffuse; this is the region where the shocked solar wind is deflected and depleted due to the obstacle. It was suggested by *Zhang et al.* [1991] that the ionopause cannot be the obstacle boundary, and they identified the magnetic barrier as the obstacle. According to their definition, this is a region bounded from below by the ionopause and from above by a surface where the magnetosheath magnetic pressure is equal to half of the upstream dynamic pressure, corrected by the boundary normal angle, and the magnetic barrier is always within the mantle. Inside the mantle both the shocked solar wind and plasma of planetary origin are present. An objective of this study is to investigate whether a similar region exists on Mars. Our investigation was based on the data obtained by the plasma instruments on board of the Phobos 2 spacecraft, which did not enter the ionosphere of Mars, therefore this study is limited in that respect.

On Venus a few hundred orbits provided information about the dayside mantle. The 6xx orbits are particularly interesting for this comparison because they just grazed the Venusian boundary layer, similar to the Phobos 2 elliptic orbits. For Mars, however, we can use only data taken along three orbits, where the solar wind conditions are different. Therefore we compare the Phobos 2 measurements to the mantle model of Venus shown in Figure 1 and try to understand some of the similarities and differences. This approach has an inherent danger that could cause a bias in favor of a given model, but we tried to avoid this trap. A quantitative model on the shape of the outer boundary of this region is given by *Verigin et al.* [1997].

We believe that we have found ample evidence that around Mars, on the dayside, there exists a plasma region with the following characteristics.

1. In the upper part of the region, about 1000 km altitude from the surface at 37° SZA, the total magnetic field increases sharply compared with values observed in the MS. We call this point the foot of the boundary layer. We cannot claim that this is the obstacle boundary because the magnetic pressure at this point is less then what would be required by the definition of *Zhang et al.* [1991] (see above). However, both the electron and ion spectra, as measured by HARP, indicate that this is a real plasma boundary. Along E1 the measured magnetic field never reaches the value (45 nT) required to balance the upstream solar wind pressure ($2.19 \times 10^{-8}$ dyn/cm$^2$, which follows from the relation $\rho_p v_p^2 \cos^2 \psi \sim k\, B^2/8\pi$, where $k \sim 0.88$ and $\psi \sim 60°$). However, the peak magnetic field value was obtained just at the pericenter; therefore it is conceivable that the field had not yet reached its maximum value. Along E2 and E3 the measured field had values large enough to correspond to the solar wind pressure. The term "magnetic barrier" is justified if, inside the BL, the dominant pressure is magnetic; when the kinetic pressure is also important, this is a different type of boundary layer. The term "mass loading boundary" refers to such a situation. However, it has not yet been proven that this is the case, either on Venus or Mars; therefore we believe that in the boundary layer the dominant pressure is very likely to be magnetic.

2. The bulk of the shocked solar wind protons is deflected above the foot of the boundary layer, though a fraction of them might penetrate through the BL.

3. Below the foot of the BL the plasma is depleted compared with the MS densities. This is clearly indicated by the measurement of the spacecraft potential relative to the ambient plasma. On Mars the depletion region begins at the foot of the BL; on Venus it is known that the depletion region is above the Venusian magnetic barrier.

4. Accelerated electrons and tailward moving heavy ions were detected unambiguously by HARP and TAUS. The electrons are field aligned, as the correlation between the magnetic field and sensor directions shows. A possible explanation of this (as well as of the phenomena described below) in the case of Mars was given by Quest et al. [1997], developing further the model of *Shapiro et al.* [1995], which was introduced for Venus. According to that model, inside the boundary layer a two-stream instability develops owing to the presence of both the shocked solar wind and the cold planetary plasma population. The excited waves interact with the planetary plasma heating and accelerating it, yielding the observed electron and ion populations. Similar energetic ion and electron populations were seen at Venus, above the mantle/magnetic barrier [*Taylor et al.*, 1981; *Szego et al.*, 1997].

The location of the mass-loading boundary or the ion composition boundary reported by the ASPERA investigators falls between the region where TAUS saw the disappearance of the bulk of the solar wind protons and the appearance of heavy ions. There appears to be good agreement as far as the location of the measurements is concerned.

The structure of the dayside Venusian mantle indicates that if there had been an appropriate instrument aboard PVO, a change in the ion composition would have been seen as the spacecraft moved into the mantle. Therefore we do not think that such a composition boundary is specific to Mars.

5. Ionospheric plasma is present below the foot of the BL at Venus; oxygen ions of planetary origin were seen in the mantle, both by the electron temperature probe and the ion mass spectrometer of the Pioneer Venus Orbiter. These instruments measured the altitude variation of the oxygen ions, and the distribution clearly extends beyond the ionopause. Electrons, believed to be of planetary origin, were identified by the retarding potential analyzer on PVO.

Concerning the Phobos 2 data, the situation is more complex. Cold plasma could be detected, in principle, by ASPERA and HARP. As the energy gained by the oxygen ions due to the spacecraft motion compensate approximately the repelling spacecraft potential, the counts observed around 1 eV by HARP in its ion mode can probably be associated with cold planetary ions. The observed ASPERA oxygen energy spectra also support this. We believe that the comparison of HARP electron and

Viking 1 retarding potential analyzer data demonstrates the presence of electrons of planetary origin in the BL.

6. Intense wave activity was seen in the 5-150 Hz region, concentrated in regions close to the foot of the BL. In general waves, in the 5 to 50 Hz channel were the most intense, except for one wave burst along E2. We saw evidence of a correlation between the plasma density (plasma beta) and the frequency of the excited waves. The location of the intense wave activity was always higher in altitude than the location of the peak value of the magnetic field. These observations correlate well with the presence of the intense 100-Hz waves in the dayside mantle of Venus. The wave activity is an important indicator/component of the complicated boundary layer structure. We believe that wave excitation is due to the interaction of the shocked solar wind and planetary plasma.

The wave activities described above do not necessarily contain the highest peak, associated sometimes with the planetopause. The planetopause, in our understanding, might be a transition from a less dense plasma region to a more dense one (though this is not the case on E2); it is part of the boundary layer discussed here, but it does not have a clear analogy to Venus. It is difficult to interpret the planetopause in the framework of our model, and we cannot suggest a valid explanation for why the turbulence of the magnetic field disappears in the BL, but at a location other than the planetopause. On Venus the location of the peak wave activity is not a plasma boundary; we suspect that Venus and Mars do not differ in this respect.

7. The electron spectra observed inside the boundary layer have two characteristic shapes, separated by an intense current layer, as shown by the change of the magnetic field direction. The planetopause, however, is in a different location than where the change in electron spectra was observed.

## 4. Conclusions

We have shown that there is a dayside region between the ionosphere and the shocked solar wind around Mars that possesses properties 1-7 outlined in section 3. We call it the dayside boundary layer. The key signatures of this layer are similar to those observed inside the Venus mantle. The various names given to Martian plasma boundaries reflects only the complicated structure of this, and do not indicate special, new, never seen before plasma regions. We conclude therefore that the two boundary layers on Venus and Mars are very similar with similar physical processes inside them.

A particular feature of the data is the observed, denser plasma region around 1000 to 1300 km altitude between 60° to 90° SZA. HARP indicated that here the high electron flux is due to an energetic population >10 eV. If we compare the change in the magnetic field direction and the location of peaks in the current densities, the correlation is evident. The electron detector on board PVO had an upper energy limit of 60 eV; therefore no similar data are available for Venus. We associate these observations with the presence of an intense electron current; such a current layer was not seen at lower SZA. The HARP electron spectra changed significantly behind it. These features may lead to the conclusion that below the boundary layer, but above the ionosphere of Mars, there are also other plasma regions. However, the data presently available cannot confirm this possibility.

**Acknowledgments**. The authors are indebted for useful discussions with M. Delva, A. F. Nagy, A. Pedersen, K. Schwingenschuch, and T. Zhang. The work of K. Sz. was supported by the Hungarian OTKA, grant T-15868.

The Editor thanks R. J. L. Grard and another referee for their assistance in evaluating this paper.

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(Received June 16, 1997; revised December 31, 1997; accepted December 31, 1997.)