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Ion and electron heating at the Martian bow shock. Common for bow shocks or not?

A. Skalsky[1,5], E. M. Dubinin[1,2,5], A. Petrukovich[1], K. Sauer[2,5], P. Kiraly[3], and K. Schwingenschuh[4]

[1]*Space Research Institute, Profsoyuznaya 84/32, 117810, GSP-7 Moscow, Russia*
[2]*Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany*
[3]*Central Research Institute for Physics, H-1525 Budapest, P.O. Box 49, Hungary*
[4]*Institut fur Weltraumforschung/OAW, 8010 Graz, Inffeldgasse 12, Austria*
[5]*International Space Science Institute (ISSI), Hallerstrasse 6, 3012 Bern, Switzerland*

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Two typical bow shock crossings recorded by the Phobos-2 spacecraft in 1989 are considered in the present paper in order to demonstrate that the Martian bow shock is the shock of "common sense" in spite of peculiarities due to the pick-up ions of the Martian origin and their Larmour radius comparable to the scale size of the interaction region between the planet and solar wind. The incident plasma flow is decelerated and plasma species are heated within the relatively thin layer upstream the planet. The observed changes of plasma density, velocity and temperature are comparable with values expected for the MHD shock waves. Moreover, the dynamics of ion and electron energy distributions observed in the shock transition region indicates that mechanisms responsible for the energy dissipation seems to be similar to those operating at the Earth's bow shock.

1. Introduction

The plasma and magnetic field measurements performed by the Phobos-2 spacecraft have confirmed previous observations made on Mars-3, 5 and Mariner-4 that the bow shock exists near Mars (Riedler *et al.*, 1989; Schwingenschuh *et al.*, 1990). Barabash and Lundin (1993) have distinctly observed a foot of reflected protons at the subsolar bow shock, and evaluated that about 30% of solar wind protons might be reflected at the electrostatic barrier of the shock. Trotignon *et al.* (1991) have compared spectra of plasma waves at Earth's and Mars's bow shocks that were measured by similar instruments onboard Phobos-1 and Phobos-2 spacecraft. The similar features of electric-field amplitude spectra were found. Tatrallyay *et al.* (1997) have analyzed magnetic field overshoots in the terminator Martian bow shock and found features which are similar to those observed at Earth and Venus. The height of overshoot increased with the Mach number, and the thickness was typically 0.5–2.5 proton gyroradii. Barabash and Lundin (1993) have identified the well developed ion foreshock upstream of the Martian bow shock which was very similar to that known from observations around the Earth. Ions reflected from the bow shock and streaming back to the solar wind generate ULF waves which resemble those reported for the Earth foreshock (Delva and Dubinin, 1998). The wave measurements performed by the Plasma Wave System (PWS) allowed to identify the electron foreshock at Mars (Skalsky *et al.*, 1992). Skalsky *et al.* (1992) reported observations of the emissions at frequencies around the local electron plasma frequency after the spacecraft crossed the magnetic field line tangential to the bow shock surface. These high frequency waves, previously discovered in the near Earth's space, are generated by electrons reflected at the bow shock (Feldman *et al.*, 1983, Fitzenreiter *et al.*, 1990). Simultaneous measurements of electrons at Mars revealed also the enhanced level of particles with energies between 100 and 530 eV reflecting from the Martian bow shock (Skalsky *et al.*, 1993). All these observational facts provide an evidence that physical processes ongoing at the Martian bow shock and in its upstream region are very similar to those known for the Earth environment.

On the other hand, some new features of the Martian bow shock were also found. Because the shock is immersed an extended neutral exosphere, a new population of ions may be originated in front of shock. Barabash *et al.* (1991) observed pickup protons outside the foreshock. Russell *et al.* (1990) measured wave emissions at proton gyrofrequency and attributed them to pick-up ions. Delva and Dubinin (1998) found ULF fluctuations of the magnetic field upstream of the foreshock. Dubinin *et al.* (1993, 1995) showed that picked-up exospheric protons reflected from the bow shock contribute significantly to the population of backstreaming ions. Moses *et al.* (1989) pointed out another interesting feature of the Martian bow shock. Because of the large gyroradius of reflected solar wind protons, a partial overlapping of quasi-parallel and quasiperpendicular shocks may happens. Moreover, small scale of Mars gives rise to doubts about the existence of the traditional collisionless bow shock. Brecht and Ferrante (1991) and Brecht (1997) argued that ion dissipation caused by ion reflection does not exist around Mars, because of the lack of room. Solar wind gyroradius 1200–2900 km is comparable with a scale of obstacle ($R_{\mathrm{M}} \sim 3380$ km) and could exceed the thickness of the magnetosheath at subsolar region. Based on 3-D hybrid simulations on interaction be-

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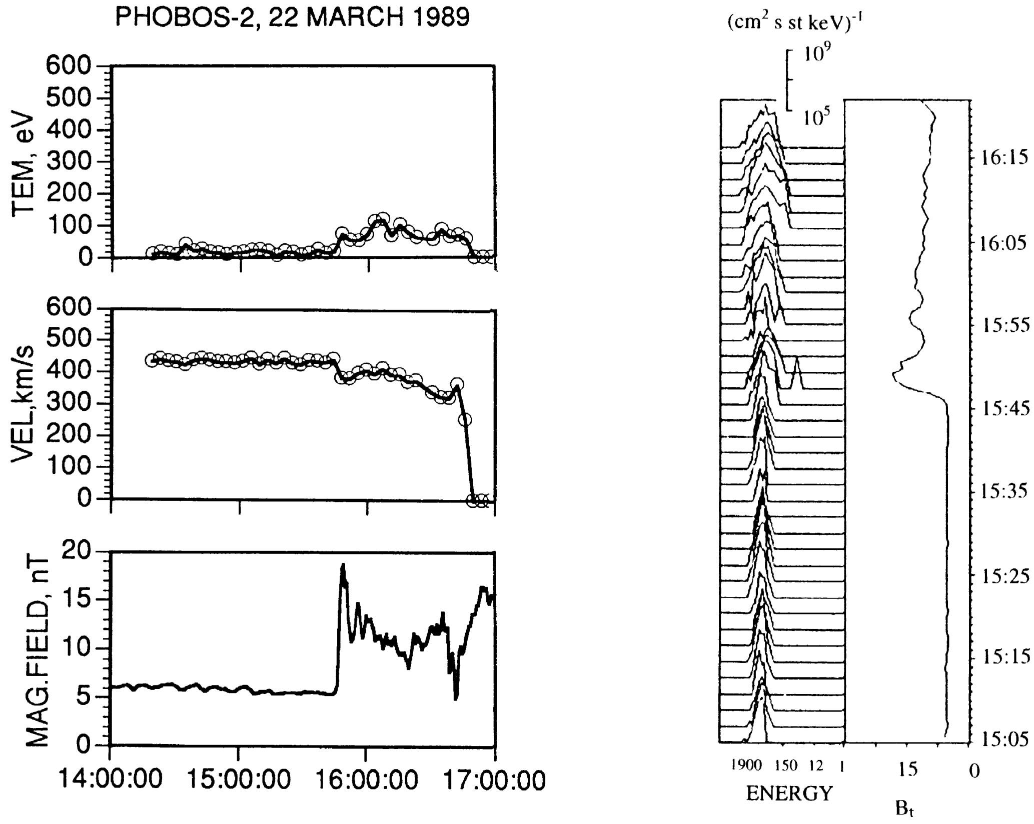

Fig. 1. Proton observations made with the ASPERA instrument on 22 March 1989 when the Martian bow shock is crossed. Energy-time spectrogram of proton fluxes along with the magnetic field strength are presented at the left side; proton temperatures, proton velocities and magnetic field value are shown from top to bottom at the right side.

tween the solar wind and Mars, Brecht (1997) concluded the difference of 'the kinetic wave-like behavior of the Martian bow shock and standard hydrodynamic paradigm'. The main topics of the paper are to present two typical crossings of the Martian bow shock and to consider the dynamics of electrons and ions through the shock transition region at Mars with an emphasize on how they agree with expectations for the MHD shock and observations at the Earth's bow shock.

2. Ion Heating

The ASPERA ion spectrometer onboard the Phobos-2 spacecraft, comprised the toroidal (E/q) analyzer placed in front of cross-field mass separator, was able to measure energy and mass distribution of ions. A set of ten detectors was used to measure energy spectra (0.5 eV/q–25 keV/q) of ions coming from 10 directions. The field of view of the spectrometer system was $5^\circ \times 360^\circ$. The absence of reliable attitude measurements significantly entangled the 'despinning procedure' of onboard moment calculations (Kallio *et al.*, 1994). To avoid this problem, only 'spectral' data of the ASPERA were used to evaluate fluid parameters of protons. E/q-spectra of protons were measured every 1 min from sunward, antisunward and side directions. Figure 1 presents observations of the solar wind protons carried out with the ASPERA during the inbound crossing of the Martian bow shock at 15:47 UT on 22 March 1989. At this time, the Phobos-2 spacecraft was in the evening sector at the distance of $\sim$2.8 R_M from the center of the planet; the zenith angle was about 90°. The solar wind conditions on 22 March lead to the following 'shock' parameters: $M_A \sim 5.9$, $M_{MS} \sim 5.5$, $\beta_i \sim 0.25$, $\beta_e \sim 0.35$. The observed profile of the magnetic field magnitude shown in Fig. 1 is typical for the quasiperpendicular shock. The foot region can be identified between 15:45 UT and 15:47 UT; the shock ramp is encountered at 15:47 UT. The solar wind protons are mainly heated at the shock ramp simultaneously with the sharp deceleration of the solar wind plasma (Fig. 1). The gyrating ions with energies higher than those of the undisturbed solar wind are observed in the downstream between 15:47 and 16:05 UT. Those ions were reflected from the bow shock and gained energy in $\mathbf{V} \times \mathbf{B}$ field. Then, they passed through the shock and contributed to the further ion heating. The temperature of protons slightly increases at 16:05 UT and the high-energy tail appears at energies at which the gyrating ions are observed earlier. Dubinin *et al.* (1993) considered this bow shock encounter with an emphasize on how the exospheric ions can influence the physical processes ongoing at the Martian bow shock. The ions at low energies, recorded by another detector and interpreted as those of the Martian origin, appear near the shock front with an increase at about 16:05 UT, i.e. after the solar wind ions have been heated in the shock transition region. Thus, the Martian ions are mostly affected the solar wind flow in the depth of the magnetosheath. Ion kinetic parameters presented in Fig. 1 (left

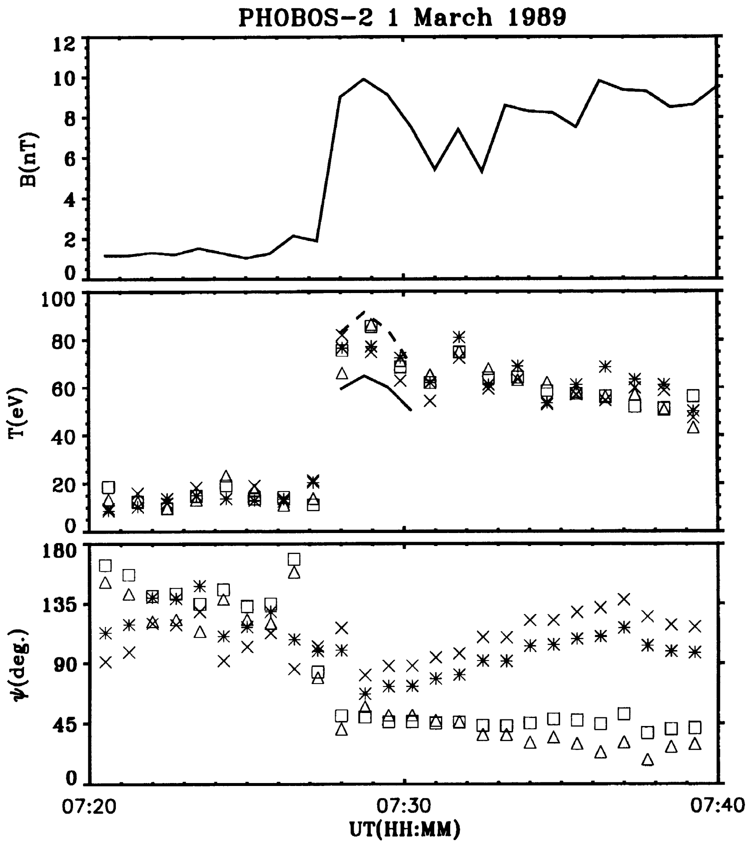

Fig. 2. A bow shock crossing on 1 March 1989. The magnetic field magnitude, the temperatures calculated with measurements of four slits of the HARP instrument (namely, those making angles of −56° (squares), −33° (triangles), 33° (stars) and 56° (crosses) with the anti-solar direction) and the respective pitch-angles ψ of electrons entering these slits are shown from top to bottom. The solid and dashed lines in the middle panel indicate the limits of the electron heating under the assumption of $T_{e\perp}/B$ conservation (see explanation in the text).

panel) are obtained with the moment calculations. The ratio of ion heating (T_d/T_u, the subscript "u" denotes upstream values; the subscript "d" is used for downstream values) is about 18 for the shock crossing presented. The value of ion temperature in the downstream region, which is used to estimate the ratio of heating, is taken after 16:05 UT when the relaxation of gyrating ions completes. The value of 18 for the heating ratio of ions is rather typical for observation at the Martian bow shock. The part of the energy dissipated in the shock which transforms into the thermal energy of ions is about 20%. The jump of the magnetic field B_d/B_u is about of factor 2 if the value of B_d is taken after the relaxation of the gyrating ions, and does not exceed a factor of 3 for B_d taken in the overshoot at 15:48 UT. It implies that the ion heating is strongly non-adiabatic, i.e. its ratio significantly exceeds the jump in the magnetic field value at the shock front.

3. Electron Heating

The hyperbolic electrostatic analyzer HARP have measured the energy spectra of electrons in eight viewing sectors arranged in a fan configuration with the symmetry axis pointing in the anti-solar direction. The plane of the fan was perpendicular to the ecliptic plane when the spacecraft was in a three-axis stabilized mode. Each slit covered a field of view of 10° × 20° within and across the fan plane, respectively. The electron spectra were measured in 25 energy steps in the range from 3.4 to 550 eV. The inbound bow shock crossing on 1 March 1989 was detected at 07:28 UT. Data on the solar wind conditions on 1 March 1989 lead to the following plasma parameters: $M_A \sim 21$, $M_{MS} \sim 6$, $\beta_i \sim 1.1$ and $\beta_e \sim 3.5$. The complanarity theorem and the model of the shock shape (Trotignon *et al.*, 1991) are used to derive the angle φ between the normal to the shock and the magnetic field in the solar wind. The angle, estimated with both methods, is between 25° and 40°. However, the increase of the magnetic field magnitude after 07:33 UT (Fig. 2) seems to depend on the variation of the magnetic field in the solar wind. It makes the evaluation of the angle somewhat uncertain. Nevertheless, the profile of the magnetic field allows to consider at least, this bow shock crossing as the intermediate one ($\varphi = 45°$). Figure 2 presents, from top to bottom, the magnetic field magnitude B, the electron temperatures T_e measured with different slits of the HARP instrument (namely, those making angles of −56, −33, 33 and 56° with the anti-solar direction) and the pitch-angles ψ of electrons entering these slits. The electron temperatures were calculated with algorithms described by Montgomery *et al.* (1970) and Scudder *et al.* (1973). The electron temperature upstream of the shock front was obtained by fitting the measured distributions with a Maxwellian function. The Maxwellian shape of the electron distribution function in the solar wind was proved by many authors (see, for example, Feldman *et al.* (1975) and Rosenbauer *et al.* (1976)). The similar conclusion with regard to the electron measurements in the solar wind near Mars has been delivered by Shutte *et al.* (1991). The measure of temperature in the magnetosheath was evaluated by calculating the second moment of the electron distribution function in view of its non-Maxwellian form. The electron flux at energies below 25 eV was probably affected by the spacecraft potential and measurements in this energy range were excluded from calculations.

Figure 2 shows that the electron heating occurs in the thin region around the shock front simultaneously with a sharp increase in the magnetic field magnitude. The curve segments shown in the middle panel has been evaluated with the following relations: $T_{eu}(B_d/B_u)$ (dashed line) and $(2T_{eu}B_d/B_u+T_{eu})/3$ (solid line) where T_e is the electron temperature and B is the magnetic field value. The subscripts "u" and "d" denote parameters upstream and downstream the shock front respectively. The first relation defines the $\Delta T_{e\perp}$ with the assumption of the $T_{e\perp}/B$ = const. The second relation gives the estimate of the temperature increase under the following assumptions: $T_{eu\perp} = T_{eu\|}$; an absence of any heating parallel to the magnetic field and a certain redistribution of the electron energy in the pitch angles downstream the shock front is due to, for example, the magnetic field turbulence (Schwartz *et al.*, 1988). Behind the shock front, the values of temperature derived from observations are in the margins defined with these two relations which leads to the conclusion that the observed increase in the electron temperature is mostly adiabatic at the shock front.

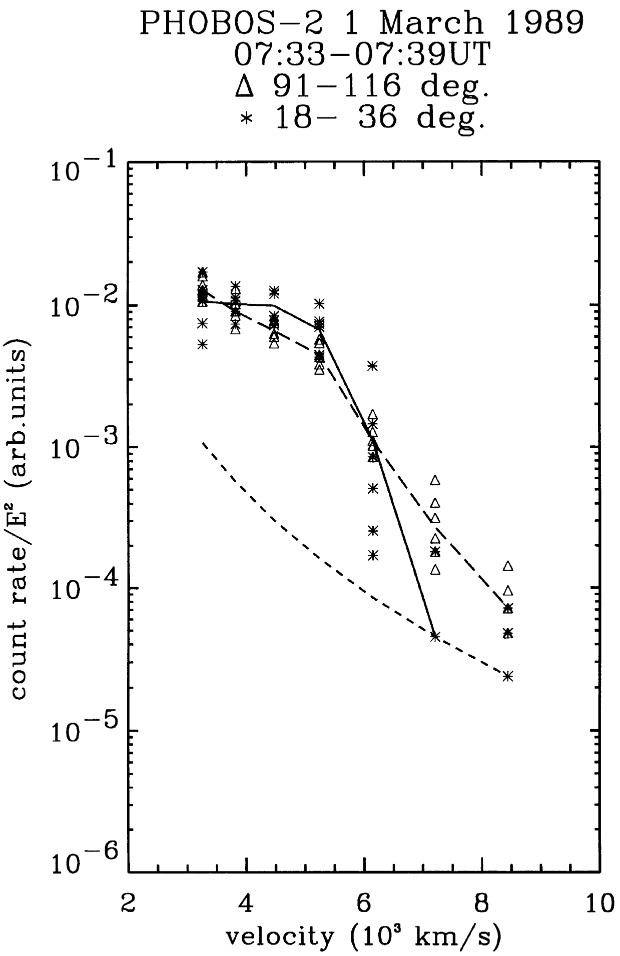

Fig. 3. Electron velocity distributions observed with two slits of the HARP spectrometer in the magnetosheath in the time interval 07:33–07:39 UT on 1 March 1989. The pitch-angles intervals in which distributions are detected are indicated at the top. The median shapes of the electron velocity distributions in the pitch-angle intervals 91–116° and 18–36° are shown with dashed and solid lines respectively. The reference level corresponding to 1 count/sec is shown with a small dashes.

Figure 3 presents the compilation of electron velocity distribution functions measured by two slits of the HARP instrument in the magnetosheath throughout the time interval 07:33–07:39 UT on 1 March 1989. The two slits, covering the pitch angles closest to 0° and 90°, are chosen and median shapes are presented with solid and dashed lines respectively. It is seen that the electron distribution measured closer to the magnetic field reveals the flat-top shape at low energies with a break in slope at the energy of about 60 eV ($4.6 \cdot 10^3$ km/s). The electron distribution in the pitch-angle range 91–116° is less flat at low energies and, beyond 60 eV ($4.6 \cdot 10^3$ km/s), its slope is less steep than that of the spectrum measured closest to the magnetic field direction.

4. Discussion and Conclusion

Earlier studies on the ion dynamics at the Earth's bow shock point out that the following features are commonly observed for both critical and supercritical shocks (Thomsen *et al.*, 1985; Sckopke *et al.*, 1990 and references in these papers): (1) ions reflected from the shock rump and accelerated by the solar wind electric field in the foot region; (2) sharp broadening of ion distribution (heating) at the shock rump; (3) gyrating ions in the downstream region; (4) their relaxation leading to the high energy non-Maxwellian tail in the depth of downstream region; (5) the observed ratio of proton heating exceeds the adiabatic level. These phenomena typically observed in the near-Earth space resemble those presented in this paper. Moreover, the proton heating ratio at Mars, which is typically of 18, can be compared to that of 16 usually observed at the Earth's bow shock with similar Mach numbers (Formisano *et al.*, 1973a,b). For both planetary shocks, the part of energy of incoming solar wind which is converted to the thermal motion of protons is within 20%. Further, Formisano *et al.* (1973a,b) have also shown that the plasma behavior at the Earth's bow shock, particularly jumps of plasma densities, velocities, temperatures, fraction of dissipated energy follow expectations for the MHD shock waves. The resemblance between ion dynamics at Martian and terrestrial bow shocks allows to conclude that MHD theory is generally applicable for the Martian bow shock, at least, at the terminator region. Similar conclusion was made by Vaisberg *et al.* (1990) who compared the observed jumps of the proton temperature with values predicted by the MHD theory. Study, based on ion data from the Mars-2, 3, 5 spacecrafts shows that although the observed jumps are less than expected (an electron temperature is not included in calculations), the solar wind is deflected by the strong bow shock without significant absorption of the flow by planet. The bow shock encounter on 22 March 1989 allows to demonstrate the most typical features of ion dynamics observed in the shock transition region near the terminator of Mars. Ion deceleration and heating inside the shock transition are not strongly influenced by exospheric ions. The "cold" ions reported by Dubinin *et al.* (1993) are 'mixing' in velocity space with the solar wind protons deeply inside the magnetosheath when the solar wind ions are already heated (see, for example Fig. 3 from Dubinin *et al.*, (1993)). A total thermalization affecting the whole community occurs over the magnetosheath and plasma mantle. However, there is a limited set of observations, particularly near the subsolar point, when the solar wind ions reveal the unusual dynamics at the shock front. These events are associated with the enhanced fluxes of the exospheric ions, large Mach numbers and ion gyroradius (Dubinin *et al.*,1994). The full ion kinetic treatment performed by Brecht and Ferrante (1991) and Brecht (1997) under the solar wind conditions similar to those observed during these unusual shock crossings indicates the absence of the pronounced overshoot in the quasi-perpendicular subsolar region. Even so, in-situ ion measurements carried out near the subsolar point reveal the relatively sharp change of the solar wind flow kinetic parameters which allows to state the crossing of the bow shock (Lundin *et al.*, 1989).

The electron heating at the oblique Martian bow shock encountered near the terminator occurs in the thin layer around the shock ramp and is mostly adiabatic. This result can be compared with observation at the Earth's bow shock where the electron heating is ongoing at the shock front being also adiabatic for the most part of quasiperpendicular crossings with different Mach numbers considered by Schwartz *et al.* (1988) and Thomsen *et al.* (1985). The spectra shapes measured downstream the front of the Martian bow shock are obviously reminiscences of those in the the Earth's magnetosheath reported by Montgomery *et al.* (1970), Scudder *et al.* (1973) and, by Feldman *et al.* (1983). Indeed, electron distribution in the earth magnetosheath has a flat top at energies below, roughly 100 eV which is the most evident along the magnetic field. The electron distribution function diminishes and the slope measured perpendicular to the magnetic field is less steep than that of distribution along the magnetic field above this energy. Both features are quite similar to those presented in this paper. Unfortunately, the data base of the electron observations in the vicinity of the Martian bow shock is limited to three sequences recorded when the HARP instrument have been operated with the relatively high telemetry rate. Two other records of electron data measured at the Martian bow shock and described by Shutte *et al.* (1991) and Kiraly *et al.* (1991) were collected during crossings of the quasiperpendicular region of the planetary bow shock, near the subsolar point on 1 and 4 February 1989. The electron flux exhibits maximum values at energies of about or higher 530 eV downstream the shock front in both cases (530 eV is the upper energy limit of the HARP instrument). This fact implies a very strong heating of electrons which exceeds the adiabatic level provided by the jump of the magnetic field strength (Schwingenschuh *et al.*, 1990). However, it could be explained by rather high solar wind with bulk velocities of 790 km/sec and 550 km/sec on 1 February 1989 and 4 February 1989, respectively. Indeed, a few observations made in the near-Earth under the high-speed conditions in the solar wind ($V_{sw} > 550$ km/sec) reveal also very large increase of the electron temperature ($T_d/T_u > 10$) at the bow shock which exceeds the jump of the magnetic field (Thomsen *et al.*, 1987). In spite of poor statistics of electron observations onboard the Phobos-2 spacecraft, general similarities between the electron behavior at Earth and Mars can be stated. In particular, it is related to the mechanism of electron thermalization. It appears that the electron heating is the same in nature for both planetary shocks and is governed in the same way by the solar wind conditions.

The planetary environment at Mars has certain features, particularly pick-up protons and cold ionospheric ions, which makes it different from that of the Earth (Dubinin *et al.*, 1993, 1995; Barabash *et al.*, 1991). Even so, the ion and electron dynamics in the vicinity of two planetary bow shocks are very similar. It leads to the conclusion that the Martian bow shock is indeed the "shock". Moreover, the microscopic processes responsible for the energy dissipation, ion and electron reflections in the shock region at Mars are believed to be similar to those operating at the Earth's bow shock.

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A. Skalsky (e-mail: askalsky@vm1.iki.issi.ru), E. M. Dubinin (e-mail: dubinin@helene.mpae.gwdg.de), A. Petrukovich, K. Sauer (e-mail: sauer@linax1.mpae.gwdg.de), P. Kiraly, and K. Schwingenschuh