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Solar wind plasma protrusion into the martian magnetosphere: ASPERA-3 observations

E. Dubinin [a,*], D. Winningham [b], M. Fränz [a], J. Woch [a], R. Lundin [c], S. Barabash [c], A. Fedorov [d], R. Frahm [b], J.R. Sharber [b], A.J. Coates [e], N. Krupp [a], J.-A. Sauvaud [d], M. Holmström [c], H. Andersson [c], M. Yamauchi [c], A. Grigoriev [c], J.-J. Thocaven [d], K. Asamura [f], C. Curtis [g], K.S. Hsieh [g], B. Sandel [g], H. Koskinen [h], E. Kallio [i], P. Riihelä [i], W. Schmidt [i], T. Säles [i], J. Kozyra [j], J. Luhmann [k], S. McKenna-Lawler [l], R. Cerulli-Irelli [m], S. Orsini [m], M. Maggi [m], E. Roelof [n], D. Williams [n], S. Livi [n], P. Wurz [o], P. Bochsler [o], C. Dierker [p], M. Grande [q], M. Carter [q]

[a] *MPI für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany*
[b] *Southwest Research Institute, San Antonio, TX 7228-0510, USA*
[c] *Swedish Institute of Space Physics, Box 812, S-98 128 Kiruna, Sweden*
[d] *Centre d'Etude Spatiale des Rayonnements, BP-4346, F-31028 Toulouse, France*
[e] *Mullard Space Science Laboratory, University College London, Surrey RH5 6NT, UK*
[f] *Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamichara, Japan*
[g] *University of Arizona, Tucson, AZ 85721, USA*
[h] *Department of Physical Sciences, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland*
[i] *Finnish Meteorological Institute, Box 503, FIN-00101 Helsinki, Finland*
[j] *Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109-2143, USA*
[k] *Space Science Laboratory, University of California in Berkeley, Berkeley, CA 94720-7450, USA*
[l] *Space Technology Ireland, National University of Ireland, Maynooth, Co. Kildare, Ireland*
[m] *Istituto di Fisica dello Spazio Interplanetari, I-00133 Rome, Italy*
[n] *Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723-6099, USA*
[o] *Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland*
[p] *Technical University of Braunschweig, Hans-Sommer-Strasse 66, D-38106 Braunschweig, Germany*
[q] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK*

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Abstract

The ASPERA-3 experiment onboard the Mars Express spacecraft revealed, near the wake boundary of Mars, a spatially narrow, strip-like plasma structure composed of magnetosheath-like electrons and planetary ions. The peak electron energy often exceeds the peak energy at the bow shock that indicates a significant heating (acceleration) during the structure formation. It is shown that this structure is formed during efficient plasma penetration into the martian magnetosphere in the region near the terminator. The penetration of sheath electrons and their gradual heating (acceleration) is accompanied by a change of the ion composition from a solar wind plasma to a planetary plasma dominated by oxygen ions. A possible mechanism of plasma inflow to the magnetosphere is discussed.

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* Corresponding author.
E-mail address: dubinin@mps.mpg.de (E. Dubinin).

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1. Introduction

Due to the absence of a global intrinsic magnetic field at Mars the solar wind directly interacts with its upper atmosphere/ionosphere. Therefore, the solar wind induced escape of planetary ions could be an effective dehydration mechanism at Mars over cosmological time scales (Lundin et al., 1989; Lundin, 2001). Indeed, planetary atoms ionized by solar UV radiation, charge-exchange or electron-impact processes can be effectively picked up by the solar wind and escape the martian environment. On the other hand, although Mars at present has no intrinsic field, the solar wind induces a magnetosphere by the pile up of the interplanetary magnetic field. This induced magnetosphere, in a certain sense, can screen the ionosphere from the direct exposure to the solar wind. The arisen magnetic barrier separates the solar wind from the ionosphere and acts as the effective obstacle deflecting the magnetosheath plasma (Zhang et al., 1990). Possible mechanisms of the barrier formation are discussed, e.g., in Biernat et al. (1999), Nagy et al. (2004). Previous missions to Mars, with complete onboard plasma packages, have not approached the planet closer than ∼850 km (the instrument package on Mars Global Surveyor (MGS) spacecraft which penetrates closer to Mars did not have any experiments capable of measuring ions of solar wind or planetary origin). Therefore, the altitude range 300–800 km at which the processes of scavenging of the planetary matter are expected to be most efficient, and where a magnetic barrier is formed, were not yet explored. The first measurements carried out by the ASPERA-3 (Analyzer of Space Plasma and Energetic Atoms) experiment onboard the Mars Express (MEX) spacecraft have already shown that solar wind plasma may be observed down to ∼300 km and that the ionospheric ions at these altitudes can gain energy up to several keV (Lundin et al., 2004). This suggests an effective interaction between the solar wind and the upper atmosphere/ionosphere, at least during periods of intense solar wind. However, mechanisms of ion extraction and their energization remain poorly known. Moreover, the motional interplanetary electric field and the small characteristic scale of the martian magnetosphere (more precisely, the small value of the ratio R/r_i, where R and r_i are respectively the characteristic scale of the system and the gyroradius of pickup O^+ ions) as compared to other planets imply a strong asymmetry of the induced magnetosphere and pickup ion fluxes (see, e.g., recent 3D hybrid simulations by Bößwetter et al., 2004, and Modolo et al., 2005). Therefore, the processes of ion scavenging at Mars may be different at different interaction sites. In this paper we discuss one of the important mechanisms of solar wind intrusion into the induced magnetosphere of Mars accompanied by effective extraction of planetary ions.

2. Observations

The ASPERA-3 experiment is a unique combination of in situ and remote diagnostics of atmospheric escape induced by the solar wind. It comprises the Ion Mass Analyzer (IMA), ELectron Spectrometer (ELS), Neutral Particle Imager (NPI), and Neutral Particle Detector (NPD) (Barabash et al., 2004). In this paper we discuss the results obtained from the ELS and IMA sensors. The ELS instrument measures 2D distributions of the electron fluxes in the energy range 0.4 eV–20 keV ($\delta E/E = 8\%$) with a field of view of $4^\circ \times 360^\circ$ and a time resolution of ∼4 s per energy spectrum. The IMA sensor measures 3D-fluxes of different ion species with m/q resolution (m and q are respectively mass and electric charge) in the energy range 10 eV/q–36 keV/q with a time resolution of ∼3 min and a field of view of $90^\circ \times 360^\circ$. In fact, ions with energy less than 300 eV are usually below the measurement threshold.

Fig. 1 shows a spectrogram of the electron fluxes obtained by the ASPERA-3 instrument along the MEX orbit on June 24, 2004. Positions of the bow shock (BS), the induced magnetospheric boundary (IMB), and the ionosphere (IS) are indicated by arrows. The orbit (the bottom panel) is given in cylindrical coordinates with the x (horizontal) axis directed from the Mars center toward the Sun and the radial distance r (vertical axis) taken from the x axis. The nominal positions of the bow shock and the magnetic pileup boundary (MPB) which can referred as the boundary of the induced magnetosphere (IMB) are also shown (Vignes et al., 2000). At ∼20:52 UT the spacecraft crosses the bow shock (BS) and enters the transition region (magnetosheath) that is clearly defined by the appearance of the strongly heated electrons. At 21:28 UT MEX enters into the magnetosphere as confirmed by a drop of magnetosheath electrons. The electron spectra in a region crossed at ∼21:33–21:42 UT contain clear signatures of ionospheric photoelectrons (the peaks in the electron fluxes in the range between 20 and 30 eV appear due to absorption of the strong solar HeII line at 304 Å in the carbon dioxide dominated atmosphere of Mars) (Frahm et al., 2006). At ∼21:45 UT the spacecraft crosses the boundary of the geometrical shadow and moving further along the outbound leg of the orbit records all these characteristic regions in the opposite order. A remarkable feature is the observation of a narrow strip of magnetosheath-like electrons on the spectrogram just near the wake boundary (∼21:45 UT). The peak energy of the electron fluxes exceeds the peak-energy at the BS. Although a similar strip in the spectrogram is not observed at the outbound crossing of the wake boundary (∼22:10 UT), it is not a transient but, as will be shown subsequently, a permanent, spatial structure of the martian magnetosphere.

Fig. 2 shows other examples of the localized strip-like structure near the wake boundary in ELS spectrograms obtained on a number of MEX orbits. The first (second) line corresponds to the inbound (outbound) orbits. Note that there are also cases when the strip signature was observed in both inbound and outbound passes. In all cases one can see the same features as in Fig. 1. Fig. 3 depicts the electron fluxes recorded by the ELS instrument at the energy $E_e = 80$ eV (a typical energy of the magnetosheath electrons) in cylindrical coordinates (the x axis is directed from Mars toward the Sun and r is the radial distance from the x axis). A strip-structure stretched roughly parallel to the wake boundary and the magnetosheath region can be easily recognized.

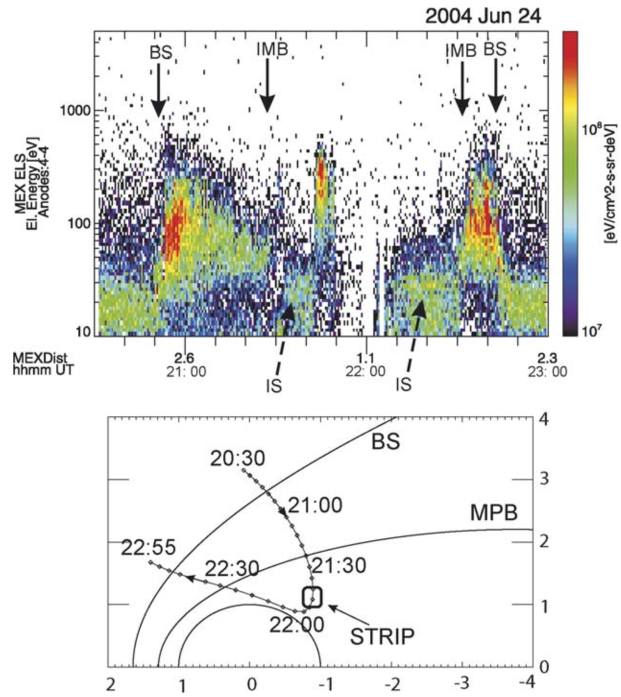

Fig. 1. Spectrograms of electron fluxes along the orbit of MEX shown on the bottom.

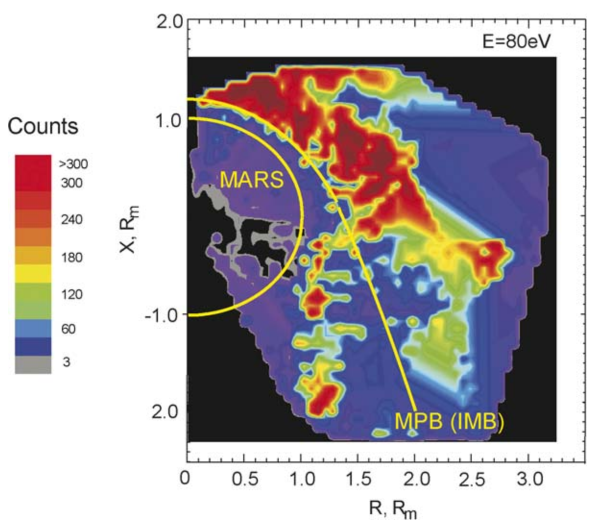

Fig. 3. Image of the electron fluxes at a fixed energy ($E_e = 80$ eV) near Mars in cylindrical coordinates (∼50 MEX orbits). MPB denotes the magnetic pileup boundary found from the MGS observations.

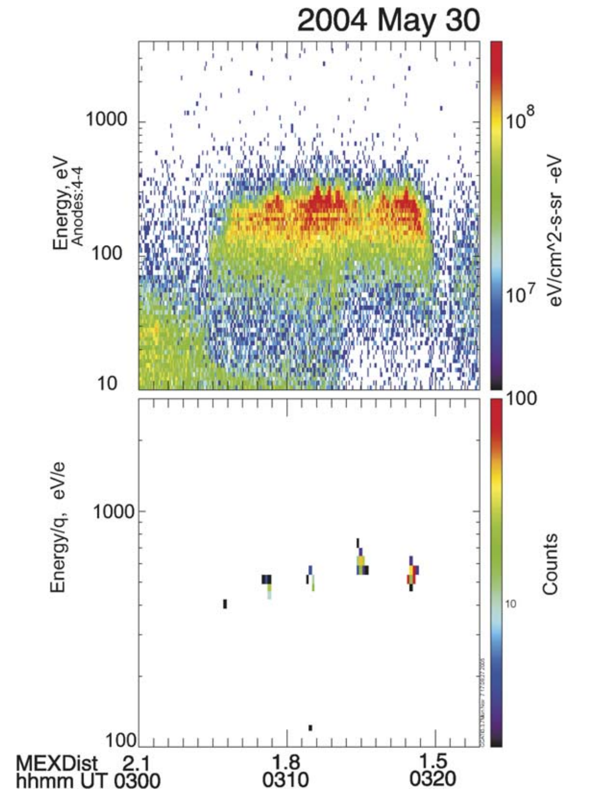

Fig. 4. The ion and electron fluxes (ion fluxes are integrated over all 32 mass channels) within a ‘strip’ structure.

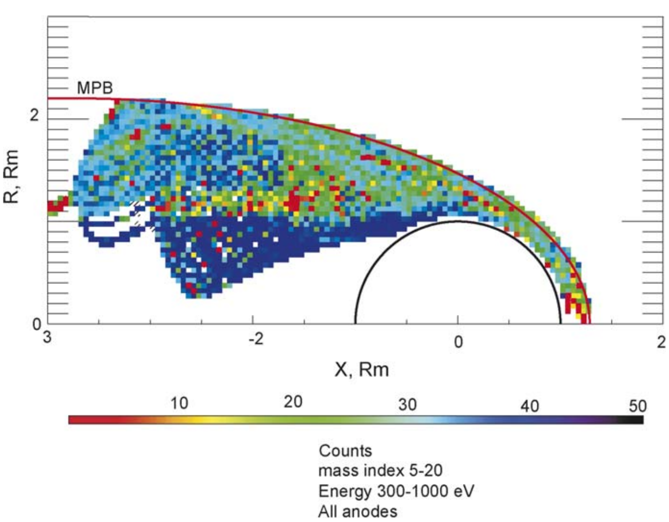

Fig. 5. Image of O^+ ion fluxes in the energy range $E_i = 300$ eV–1 keV at Mars in cylindrical coordinates made by using the dataset from all MEX orbits during the time period 01.04.2004–20.04.2005 (sum of counts from all angular sectors for the mass channels 5–20).

The important point is that plasma in these structures carry large fluxes of planetary (primarily O^+) ions in the form of narrow energy ion beams with a characteristic energy ⩽1 keV (Fig. 4). Fig. 4 depicts an example of simultaneous ion and electron measurements within such structures. The strip structure observed during almost 15 min is accompanied by beams of ions with energy of ∼500 eV. Analysis of an ion composition shows that the ions have a planetary origin (primarily oxygen and molecular ions). It is interesting to note that strip structures often contain periodic oscillations of the electron intensity typical for the magnetosheath plasma (see, e.g., Fig. 8 in Winningham et al., 2006) that indicates a topological connection between both regions.

Fig. 5 shows the image of the fluxes of planetary ions measured by the IMA sensor in the energy range 100 eV–1 keV based on the data set from April 1, 2004 to April 20, 2005. The intensity describes the ion fluxes from all sectors for the mass channels 5–20 (which approximately correspond to O^+

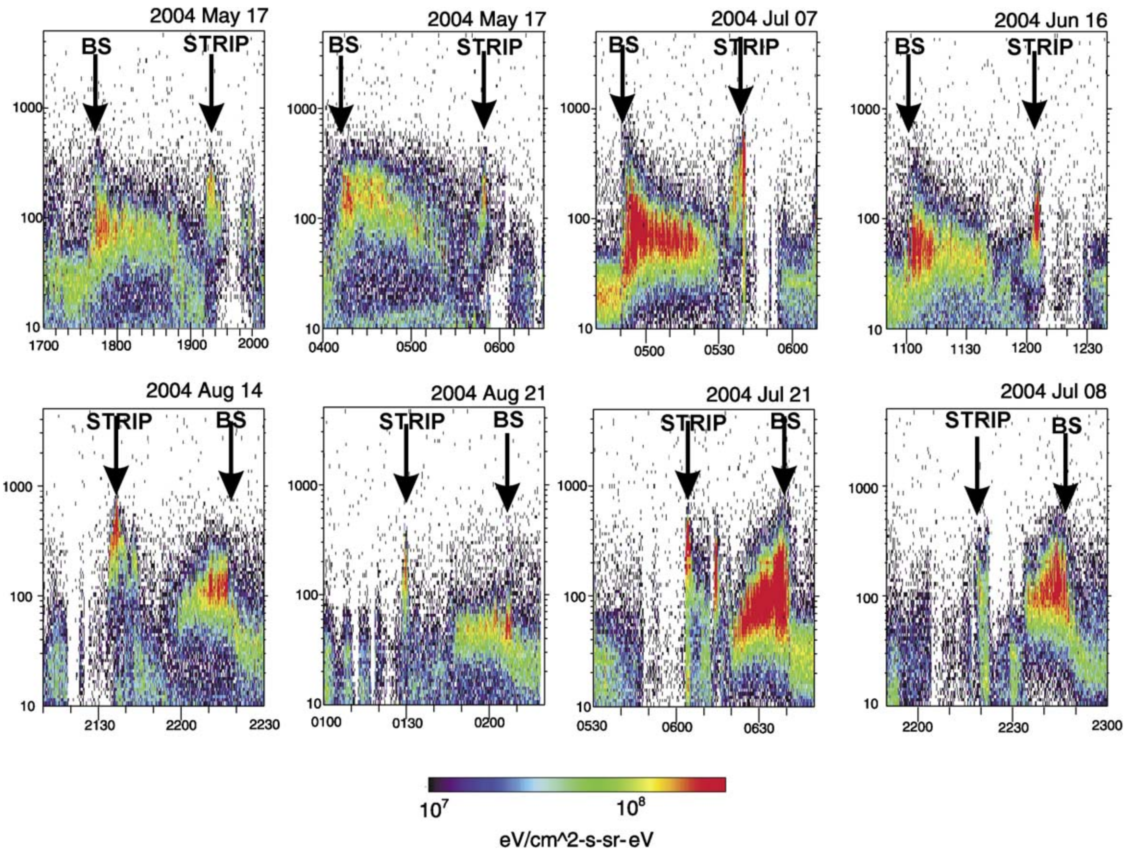

Fig. 2. Spectrograms of electron fluxes with clear signatures of a localized structure near the wake boundary.

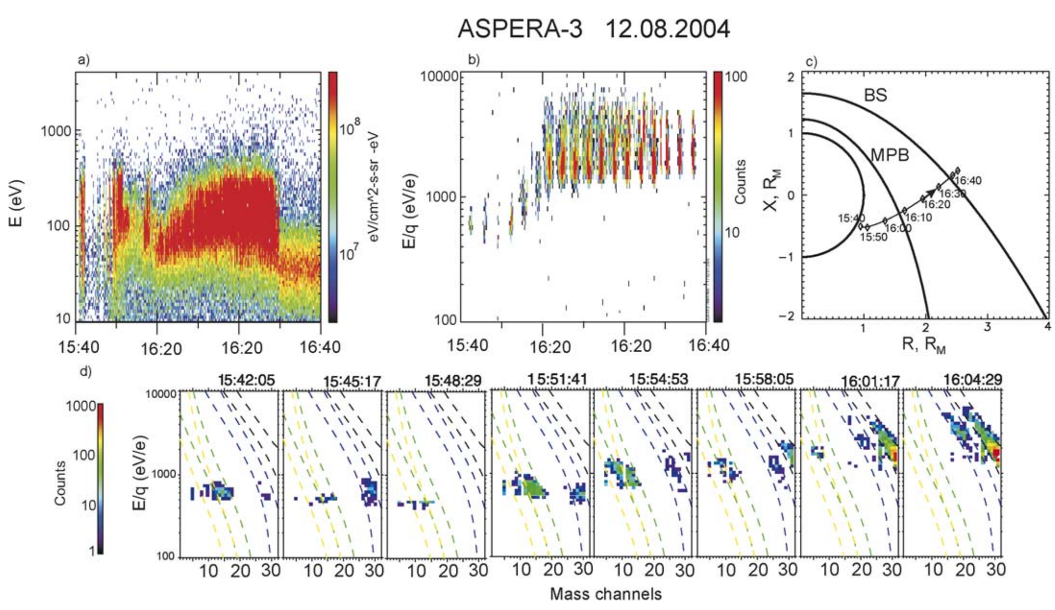

Fig. 9. (a) Spectrogram of the electron fluxes along an almost radial trajectory (in cylindrical coordinates) in the terminator region (c). (b) Spectrogram of the ion fluxes measured at all azimuthal and polar angles and also summed over the whole range of mass (m/q) channels. (d) Energy–m/q matrixes measured at different times. One matrix is built during ∼3 min. Dashed reference curves indicate identifications of mass-bands for m/q of 1 (black), 2 (blue), 16 (green), and 32 (yellow), respectively.

and molecular ions). A focusing of the fluxes of planetary ions near the wake boundary becomes more clear while moving tailward. Comparison of the electron and ion images shows that the observed strip-like structures can be an important channel for the transportation of planetary ions to the tail.

3. Discussion

Fig. 6 shows the spatial distribution of the events from February 2004 through November 2004 in the YZ (MSO) plane. The structures are observed close to the limb in the $-Z$ hemi-

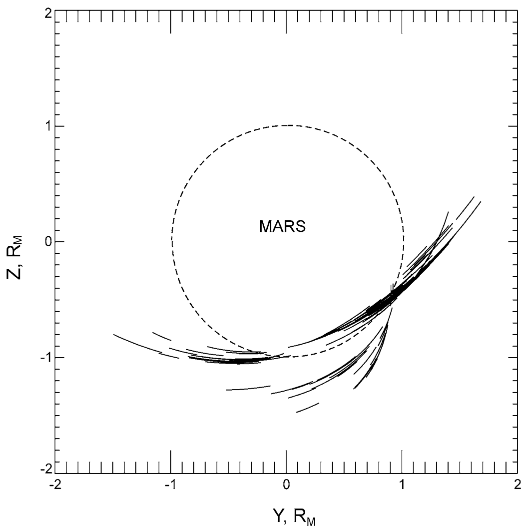

Fig. 6. Distribution of the events in the YZ-plane (MSO reference frame with the upward X axis toward the Sun).

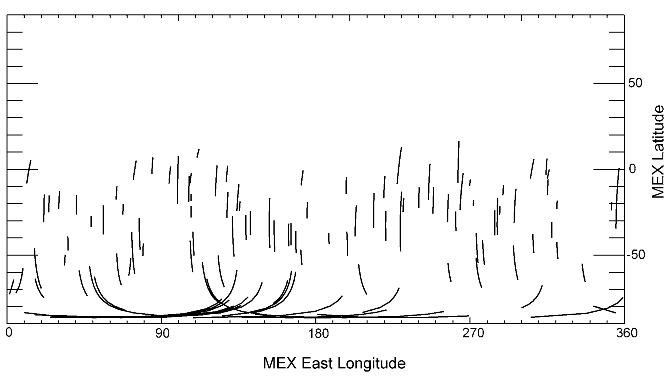

Fig. 7. Latitude–longitude distribution of the 'electron strips.'

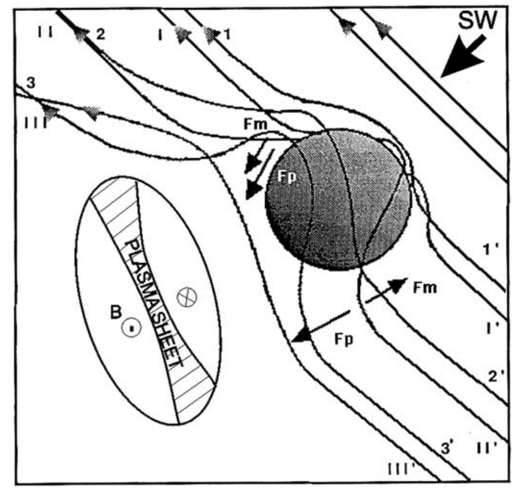

Fig. 8. 3D-configuration of the magnetic field on the dayside of the induced magnetosphere. Successive positions of two field lines (1–1′, I–I′, 2–2′, II–II′, 3–3′, III–III′, ...) slipping around the 'northern' pole are shown. The force F_m related to the magnetic field tension and the pressure force F_p act in the same direction in polar regions pushing a plasma into the wake. This inflow leads to the formation of plasma sheet. Near the magnetic equatorial plane the forces F_m and F_p act in the opposite direction. This provides a strong asymmetry in 'plasma intrusion.'

sphere. Note that similar regions in the $+Z$ hemisphere ($X < 0$) were not yet covered by the MEX orbits. Note that in future the orbits will be more favorable to the northern hemisphere. The appearance of strip structures near the wake boundary and their stretching in the tailward direction is similar to the features of rays, composed of escaping suprathermal ionospheric O^+ ions, observed at Venus (Brace et al., 1987). Luhmann (1993) suggested that these structures appeared from a thin source region around the terminator where the solar wind convection electric field penetrates into the oxygen-dominated high altitude terminator ionosphere.

We have studied a possible relation between these events and the UV sunset features. As a proxy UV sensor an integral of the 5 to 10 eV electrons (sensor 15) was used. However no evident correlation was observed. Moreover there are orbits with 'strip' structures when the MEX spacecraft did not cross the UV sunset (sunrise) boundary.

Comparison of the spectra of magnetosheath and strip electrons indicates a close relation between these regions. It could be, for example, a magnetic connection (interconnection between the crustal and IMF field lines). Indeed, penetration of the sheath electrons into the martian magnetosphere may be caused by interconnection between the draped IMF and the magnetic field from crustal sources. The interconnection can open the inner magnetospheric regions up to solar wind electrons. To check on a possible relation between the appearance of the observed structures and the crustal fields we analyzed their positions in latitude–longitude coordinates (Fig. 7) by using a simple radial mapping.

Although no preference to the regions with strong crustal magnetization, which are supposed to be the first candidates for interconnection, is observed we cannot exclude this mechanism because the magnetic field topology may be very tangled to trace the roots of the field lines. Note also that the structures were observed mainly in the southern hemisphere (Fig. 6) where most of the magnetic anomalies persist. Future measurements when the MEX orbits will cross the appropriate regions in the northern hemisphere help us to evaluate better a role of crustal magnetizations.

Another possible scenario for the formation of the observed 'intrusion structure' is associated with the specific features of an induced magnetosphere. It is known that although the localized crustal magnetic fields can influence the solar wind/Mars interaction, the global characteristics are well described in terms of an induced magnetosphere and draping of interplanetary magnetic field (IMF) carried by the solar wind around the obstacle (Acuña et al., 1998). After passing the BS the flow is accelerated at the flanks under the action of plasma pressure forces. The magnetic field tension of the draped field lines accelerates plasma in the polar region and slows it down in the equatorial part (in this description, the position of the equatorial plane is controlled by the IMF direction, the plane contains the solar wind velocity vector and the IMF vector in the undisturbed solar wind) (Fig. 8). Magnetic field tensions become dominant near the boundary of the induced magnetosphere (IMB) (Bertucci et al., 2003). Note that this boundary was called the magnetic pileup boundary (MPB) after the MGS magnetic field measurements at Mars (Acuña et al., 1998). As a result, the magnetic field lines are slipping around the poles pushing the shocked plasma into the wake. This is a probable mechanism of filling the plasma-sheet which separates two magnetic field lobes with different orientations of the magnetic field. Planetary plasma which loads the shocked solar wind will be also pushed to the tail by the magnetic field tension of the draped magnetic field lines which gradually 'sink' into the wake. Note that the observations made by the Phobos spacecraft have shown that the martian plasma-sheet is indeed dominated by oxygen ions of planetary origin (Rosenbauer et al., 1989; Lundin et al., 1990; Dubinin et al., 1996).

The MEX trajectories in August 2004, passing almost radially through the induced magnetosphere boundary (IMB) near the terminator were very favorable for the study of plasma intrusion. Fig. 9 (the top left panel) reveals in the electron flux spectrogram an almost continuous transition of the sheath-like electrons from the magnetosheath to a strip structure near the wake boundary deep inside the magnetosphere. The mean electron energy gradually increases if an observer moves from the magnetosheath into the magnetosphere. In contrast, the mean ion energy in the ion spectrogram (panel b) decreases. In fact, a decrease of the ion energy is accompanied by a change of ion composition. The plasma of solar wind origin is 'replaced' by planetary plasma. This is well demonstrated in the panels d of Fig. 9 which show energy–m/q ion spectra. Skewed curves depict nominal mass identification bands for $m/q = 1$ (H^+), 2 (He^{2+} or H_2^+), 16 (O^+), 32 (O_2^+), respectively. Although at low altitudes, the planetary ions dominate, the ions of solar wind origin also contribute to the plasma composition. This is, for example, indicated by the presence of ions with $m/q = 2$ (probably He^{2+}) within the magnetosphere. A lack of information about the fluxes of protons with $E_i < 1$ keV, due to instrument limitations, does not allow accurate estimations of the amount of solar wind plasma protruding into the magnetosphere. Effective penetration of magnetosheath-like electrons accompanied by their heating and a drastic change of the ion composition (plasma of solar wind origin is replaced by planetary plasma) implies that the processes of solar wind intrusion and extraction of planetary ions with their subsequent transport are closely connected. Indeed the $\boldsymbol{j} \times \boldsymbol{B}$ force associated with the tension of the magnetic field lines acts on the electrons, while the protons are dragged by the electric field to maintain quasineutrality. The presence of planetary ions can strongly modify this process since planetary ions essentially contribute to charge neutralization. In fact, it is a unique self-consistent process and presently there is no theory which quantitatively describes it.

A heating of the electrons may be related to adiabatic (plasma contraction during penetration) or nonadiabatic ('inelastic' interaction between the plasma of the solar wind and ionospheric/atmospheric origin) processes. The latter can be due to a 'friction' between the shocked solar wind and planetary plasma (viscous-type of the interaction) (see, e.g., Perez-de-Tejada, 1995). A gradual decrease of the ion energy in the process of plasma intrusion accompanied by a strong heating of the electrons can be described in terms of the momentum exchange between the solar wind and planetary plasma mediated by the magnetic field tensions. Such a mechanism was discussed in Lundin et al. (1991), Lundin and Dubinin (1992) and suggests a mass-loading process initiated either already in the solar wind/magnetosheath or in the subsolar interface between both plasmas near the IMB. In this case, a decrease of the ion energy while approaching the planet is associated with an increase in the amount of planetary matter carried by the loaded solar plasma. Transport of sheath electrons down to low altitudes and observations of energization of planetary ions imply an effective penetration of the solar wind electric field deep into the martian magnetosphere (Dubinin et al., 2006). Another mechanism of energization is discussed in (Lundin et al., 2006). Interconnected with the IMF, the crustal magnetic field lines can be stretched in the antisunward direction producing field configurations with 'auroral' field lines similar as at Earth. The upward (downward) ion (electron) acceleration in the parallel electric fields related with a 'V'-shaped electric potential distribution typical for the auroral field lines can produce ion and electron beams which can give rise to the observed structures.

4. Conclusions

The observations made by the ASPERA-3 experiment onboard the Mars Express spacecraft found an intense penetration of magnetosheath electrons into the induced magnetosphere. The penetration is accompanied by a significant broadening of the electron spectra that probably indicates a heating. Intruded electrons form a narrow strip-like structure stretched parallel the wake boundary which can gradually be transferred into the plasma sheet in the magnetospheric tail. Ion composition in this structure is dominated by planetary ions (primarily O^+ ions). This implies that the processes of penetration and extraction of planetary ions from the ionosphere/atmosphere are closely related. It is suggested that plasma penetration accompanied by mass loading by planetary matter is maintained by the magnetic field tensions generated by draping of IMF lines around the planetary obstacle. Slipping around the 'magnetic poles' the draped field lines push plasma into the deep magnetosphere. Such a mechanism suggests a strong asymmetry in plasma intrusion and, correspondingly, an asymmetry of ion scavenging controlled by the IMF orientation.

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