

## Electric fields within the martian magnetosphere and ion extraction: ASPERA-3 observations

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### Abstract

Observations made by the ASPERA-3 experiment onboard the Mars Express spacecraft found within the martian magnetosphere beams of planetary ions. In the energy ( $E/q$ )–time spectrograms these beams are often displayed as dispersive-like, ascending or descending (whether the spacecraft moves away or approach the planet) structures. A linear dependence between energy gained by the beam ions and the altitude from the planet suggests their acceleration in the electric field. The values of the electric field evaluated from ion energization occur close to the typical values of the interplanetary motional electric field. This suggests an effective penetration of the solar wind electric field deep into the martian magnetosphere or generation of large fields within the magnetosphere. Two different classes of events are found. At the nominal solar wind conditions, a ‘penetration’ occurs near the terminator. At the extreme solar wind conditions, the boundary of the induced magnetosphere moves to a more dense upper atmosphere that leads to a strong scavenging of planetary ions from the dayside regions.

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## 1. Introduction

Ion pick-up escape of planetary ions is one of the most important mechanisms of nonthermal losses of volatiles at Mars (Lundin et al., 1989; Rosenbauer et al., 1989; Luhmann and Bauer, 1992; Lundin and Dubinin, 1992; Lundin, 2001; Nagy et al., 2004 and references therein). Neutral atoms ionized by solar UV, charge-exchange and electron impact begin to gain energy in the motional electric fields and swept out of the upper atmosphere (exosphere) (Luhmann, 1990). However, it is not clear yet whether effective or not such mechanism at closer distances to Mars, in the region screened from the solar wind by the induced magnetic field barrier. Although extraction and subsequent scavenging of planetary ions by electric fields is assumed to be one of the most important escape processes, a question of penetration of the motional electric field into the martian magnetosphere was not explored yet by in situ observations. 3D hybrid simulations of the solar wind/Mars interaction show that the  $-\mathbf{v} \times \mathbf{B}$  electric field almost vanishes within the induced martian magnetosphere (Böswetter et al., 2004). However already the first measurements made by the ASPERA-3 on the Mars Express (MEX) spacecraft showed that solar wind plasma and energization of the planetary ions may be observed at rather low altitudes (Lundin et al., 2004). Penetration of the solar wind electrons down to the ionopause altitudes was also reported from analysis of the MGS observations (Mitchell et al., 2001). Dubinin et al. (2006) have observed an effective penetration of the magnetosheath electrons near or tailward of the terminator plane. Moving across the magnetic field a protruded plasma induces the electric field which can accelerate and sweep out the ionized atmospheric/ionospheric matter. In this paper we analyze the characteristics of the beams of planetary ions within the magnetosphere measured by the ASPERA-3 experiment. It is shown that energy gained by planetary ions is proportional to the distance to the planet that indicates an acceleration in electric fields. The estimated values of the fields are close to the value of the motional electric field in solar wind that suggests its effective penetration or generation within the magnetosphere.

## 2. Observations

The ASPERA-3 (Analyzer of Space Plasma and Energetic Atoms) experiment is a 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 IMA and ELS sensors. 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/ $q$ –30 keV/ $q$  with a time resolution of  $\sim 3$  min and a field of view of  $90^\circ \times 180^\circ$  (electrostatic sweeping provides elevation coverage  $\pm 45^\circ$ ). Note that ions with energy less than 300 eV are usually below the measurement threshold. Mass ( $m/q$ ) resolution is provided by combination of the electrostatic analyzer with deflection of

ions in a cylindrical magnetic field set up by permanent magnets. 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  $4^\circ \times 180^\circ$  and a time resolution of  $\sim 4$  s.

Fig. 1 (the top panel) shows the energy–time spectrogram of the electron fluxes (the energy flux of electrons recorded from all angular sectors) obtained by the ASPERA-3 instrument along the MEX orbit on October 9, 2004. The bottom panel shows the orbit of the spacecraft in cylindrical reference frame (the  $x$  axis is directed from the Mars center toward the Sun and the radial distance  $r$  is taken from the  $x$  axis). The nominal positions of the bow shock (BS) and the magnetic pileup boundary (MPB), which can be referred as the boundary of the induced magnetosphere are also shown (Vignes et al., 2000).<sup>1</sup> At  $\sim 00:50$  UT the spacecraft enters from the magnetosheath into the martian magnetosphere that is clearly defined by a drop of the shocked solar wind electrons. Closer to the planet, at altitudes  $\sim 450$  km, the spacecraft crossed the ionosphere with a clear signature of ionospheric photoelectrons, the narrow peak in energy spectra at  $\sim 28$  eV due to absorption of solar HeII line at  $304 \text{ \AA}$  in the  $\text{CO}_2$  atmosphere (Frahm et al., 2006). An abrupt drop of the photoelectrons is observed when the spacecraft crossed the terminator and occurred on the nightside. The outbound crossing of the nominal MPB was at  $\sim 02:00$  UT on the nightside, at  $x \sim -1.5 R_M$ . The middle panel depicts the energy–time spectrogram of ions fluxes measured by the IMA sensor. The intensity shows the total number of counts integrated over all angular sectors, the energy range 100 eV–4 keV and all mass-channels. At 01:25–01:55 UT, when MEX was inside the magnetosphere but above the ionospheric altitudes, ion beams were observed. Energy of the ions increases from  $\sim 650$  eV at 01:35 UT up to 3.5 keV at 01:55 UT. ‘Onset’ of an ion ‘fountain’ is approximately coincides with appearance of a strip-like structure in the electron spectrogram (01:20–01:25 UT). Plasma in these beams consist of planetary ions. Fig. 2 shows energy spectra of ions as a function of mass channels. Skewed dashed curves depict the bands of nominal mass identifications for  $m/q = 1$  ( $\text{H}^+$ ) (black), 2 ( $\text{He}^{2+}$  or  $\text{H}_2^+$ ) (blue), 16 ( $\text{O}^+$ ) (green), 32 ( $\text{O}_2^+$ ) (yellow), respectively. It is observed that oxygen ions dominate with a certain contribution of the molecular  $\text{O}_2^+$  ions.

We analyzed about twenty similar events of ion fluxes with ascending (descending) tones in energy–time spectrograms. Fig. 3 presents the orbit segments on which ion fluxes were observed. The ion fountains are mostly localized in the post terminator sector. Fig. 4 shows six examples of the ion observations within the magnetosphere. The dashed curves depict the altitude of the spacecraft over the Mars surface (the scale in kilometers is given on the right vertical axes). A remarkable feature is almost a linear increase of the ion energy ( $E/q$ ) in beams with altitude. Consider these cases in more detail.

<sup>1</sup> Summarizing the Phobos-2 and MGS observations Nagy et al. (2004) have concluded that MPB and several other boundaries observed in the inner magnetosheath are one and the same plasma boundary.

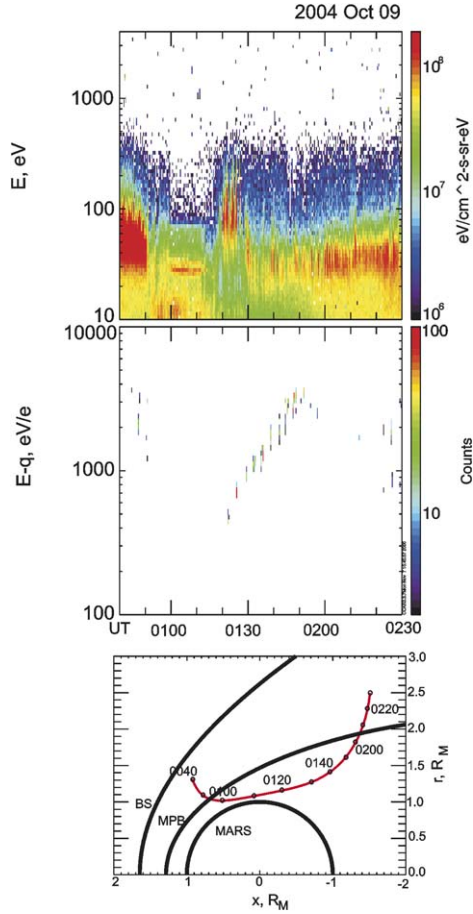


Fig. 1. (Top) Spectrogram of electron fluxes along the orbit of MEX on October 9, 2004. (Middle) Spectrogram of ion fluxes. (Bottom) MEX orbit in cylindrical coordinates.

#### August 9 (panel a)

The spacecraft almost radially crosses the magnetosphere near the terminator. The ions observed at 07:13–07:16 UT at the altitudes of  $\sim 700$ – $950$  km are molecular ions,  $\text{CO}_2^+$  and  $\text{O}_2^+$ , extracted from the ionosphere. Their energy ( $\sim 350$  eV) remains almost constant in this altitude range. At larger distances ( $>1200$  km) energy of the ions, identified mainly as  $\text{O}^+$  with a certain contribution of molecular ions, linearly grows with altitude and reaches 1.7 keV at  $\sim 2700$  km. After 07:42 UT the IMA sensor records ions of the solar wind origin that indicates entry of MEX to the magnetosheath.

#### July 31 (panel b)

The spacecraft moves on a similar trajectory but in the opposite direction. Ion energy decreases with approaching Mars, varying from  $\sim 720$  eV near 2000 km above the planet to  $\sim 350$  eV at 950 km. From comparison with the previous event one can infer that the observed variation in energy is not associated with a time-of flight effect when particles with higher velocities reach an observer at earlier times, but is caused by a change of a distance from Mars. Analysis of ion composition shows that  $\text{O}^+$  ( $\text{O}_2^+$ ) ions dominate at higher (lower) altitudes. Another typical feature is that energy width in the beams increases with altitude.

#### October 9 (panel c)

This event was discussed in Fig. 1. The ion energy increases from 400 eV up to 3 keV when MEX moves from 800 to 3000 km.

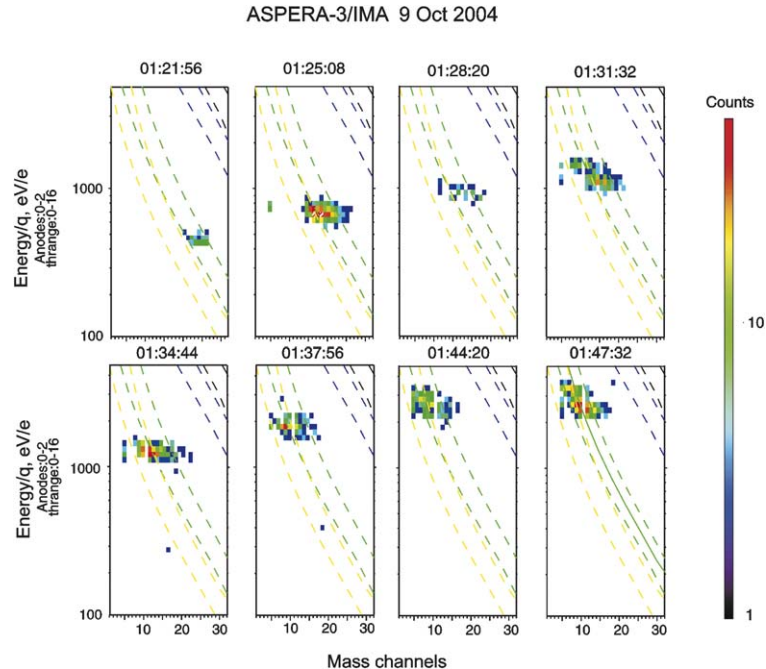


Fig. 2.  $E/q$ - $m/q$  spectra of ions. Dashed reference curves indicate identifications of mass-bands for  $m/q$  of 1 (black), 2 (blue), 16 (green), and 32 (yellow), respectively.

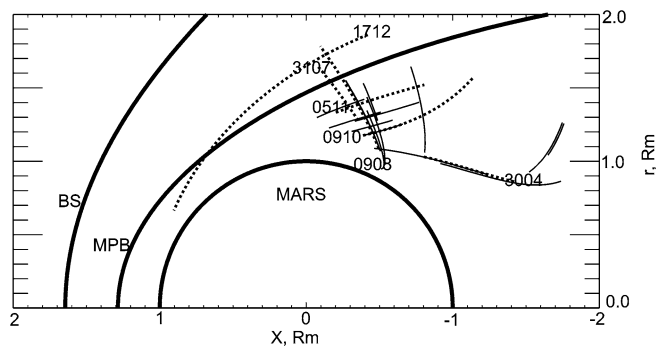


Fig. 3. Segments of MEX orbits, in cylindrical coordinates, in which outflowing fluxes of martian ions with ascending (descending) ‘tones’ in the energy–time spectrograms were observed. The dotted curves correspond to the orbits discussed in the text.

#### November 5 (panel d)

Ion (primarily  $O^+$ ) fluxes on November 5 were observed when the MEX spacecraft crossed approximately the same regions within the magnetosphere as in the previous case. An increase of ion energy ( $E/q$ ) in the outflowing beams is accompanied by a gradual energy spreading.

#### April 30 (panel e)

The spacecraft moved from the tail to the sunward magnetosphere. Ion fluxes were observed on the descending leg of the orbit. Correspondingly, the ion energy in the beams decreases. Ions have  $m/q = 16$ –32, i.e., they are most likely  $O^+$  and  $O_2^+$  ions. In the altitude range  $\sim 900$ –1700 km, the ion energy varies almost linearly with distance. At larger altitudes, a contribution from molecular ions increases and they gain additionally 0.5 keV between 1850 and 2100 km.

#### December 17 (panel f)

In this case the fluxes of oxygen ions were already observed when the MEX was in the magnetosheath. The band near 1 keV, in the ion energy–time spectrogram, corresponds to the ions of the shocked solar wind. In this extreme case, the magnetospheric boundary was crossed at  $\sim 17:57$  UT at  $\sim 500$  km at the solar zenith angle  $\sim 35^\circ$ , i.e., at much closer distances to the planet than the nominal MPB position. The energy of planetary ions extracted from such altitudes grows almost linearly with distance from  $\sim 600$  eV up to  $> 7$  keV.

### 3. Discussion

An almost linear increase of the ion beam energy with altitude suggests acceleration in the electric field. Fig. 5 depicts the energy of ion beams measured within the magnetosphere along the nine MEX orbits as a function of altitude. The data from different orbits are shown by different color. The length of vertical bars corresponds to the energy width in the beams. Most of the data points are clustered around the dashed curve. Linear increase of the energy begins approximately at the altitude of  $\sim 900$  km. The value of the electric field readily evaluated from a slope of the dashed curve and

assumption of single-ionized ions yields  $\sim 0.84$  mV/m. Note for comparison that the value of the interplanetary motional electric field  $\mathbf{v} \times \mathbf{B}$  in the solar wind at typical upstream conditions,  $v = 500$  km/s,  $B = 2$ –3 nT,  $\phi = 45^\circ$  is about 0.63–0.95 mV/m. There are different mechanisms which can be responsible for generation of large electric fields within the martian magnetosphere. For example, one can see a certain analogy between ion beams at Mars and ion beams observed on the cusp and auroral field lines at Earth. Although, presently, Mars has no a dynamo magnetic field, the localized crustal fields found by the MGS (Acuña et al., 1998) can influence a global martian induced magnetosphere (Mitchell et al., 2001; Brain and Mitchell, 2006). As a result, localized intrinsic mini-magnetospheres, with ‘cusp-like’ regions between neighboring crustal sources with the oppositely directed vertical magnetic fields, can be formed at the favorable conditions. Reconnected 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 ion acceleration in the parallel electric fields related with a ‘V’-shaped electric potential distribution typical for the auroral field lines can produce ion beams whose energy is proportional to the distance from the planet (Lundin et al., 2006). However a preliminary analysis of ‘fountain’ type of events shows that ‘foots’ of these structures are mainly observed in the regions with weak crustal fields. Note also that energization of the ionospheric ions up to  $\sim 1$  keV at Earth usually requires larger distances ( $\geq 6000$  km).

The electric field may have its origin in the solar wind, associated with a plasma motion across the magnetic field. The important feature of the martian environment is that the gyroradius of pickup  $O^+$  ion can be much larger than the characteristic size of the system. For example,  $O^+$  ions originated from the hot oxygen corona and picked up by the solar wind will move on cycloidal trajectories with the gyroradius  $> 10 R_M$ , where  $R_M$  is the planetary radius. Although this value decreases if ions start their motion at smaller radial distances, where the magnetic field increases due to a pileup of the field lines, energization of oxygen ions will be also approximately proportional to the distance. If the observed ion acceleration is associated with a deep penetration of the interplanetary electric field then one may expect that in the hemisphere in which this field is directed toward the planet the ion energy would decrease with the altitude. Fig. 6 depicts such example when the energy of planetary ions increases with approaching the planet.

Since the solar wind interaction with Mars much resembles that with Venus, mechanisms of ion energization and escape, widely discussed for the Venus environment, can be also relevant for Mars (see reviews Phillips and McComas, 1991; Brace and Kliore, 1991, and references therein). For example, the penetration of the motional solar wind electric field into the oxygen-dominated high altitude terminator ionosphere at Venus was proposed by Luhmann (1993) and Luhmann et al. (1995) to explain a removal to the tail of both thermal  $O^+$  ions and molecular ions.

The motional electric field with a strong tailward component can be also enhanced due to a tension of the magnetic field



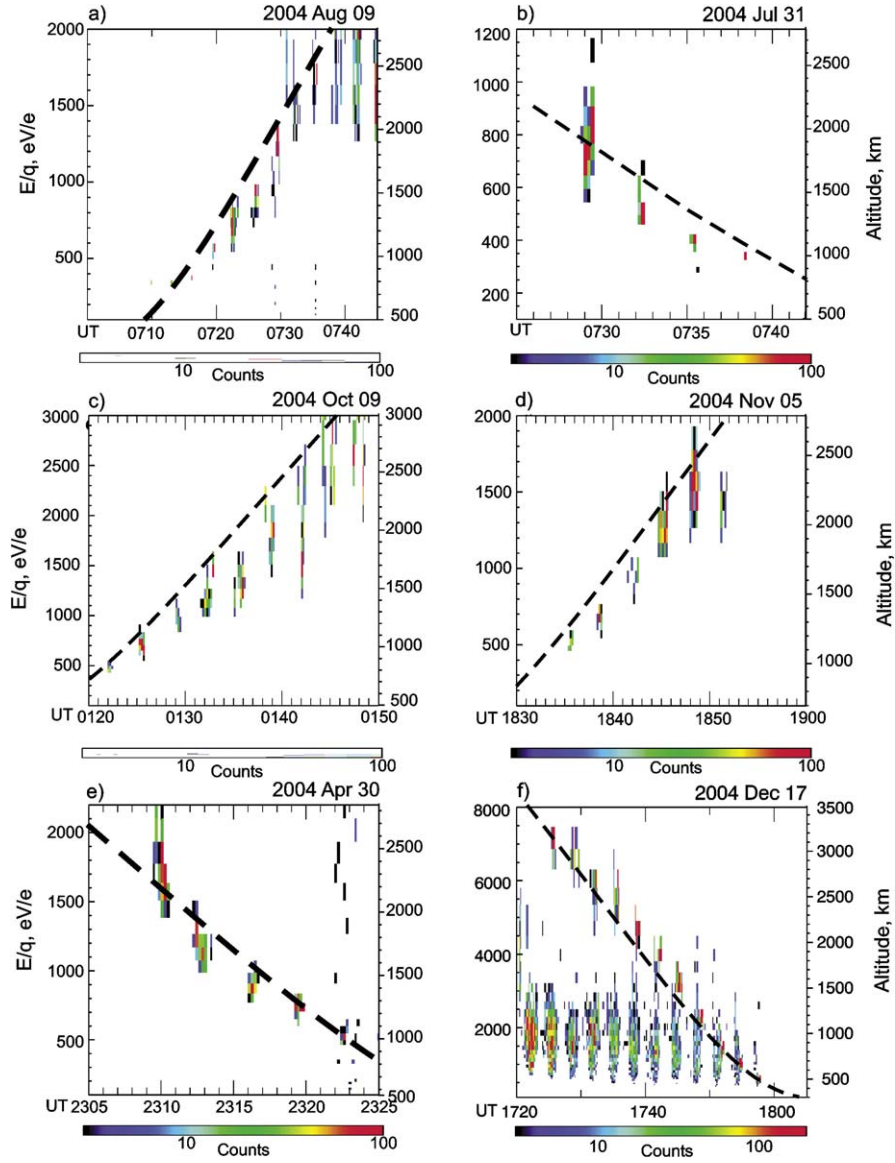


Fig. 4. Energy-time spectrograms of the ion fluxes on several MEX orbits. Dashed curves depict the distance from the Mars surface.

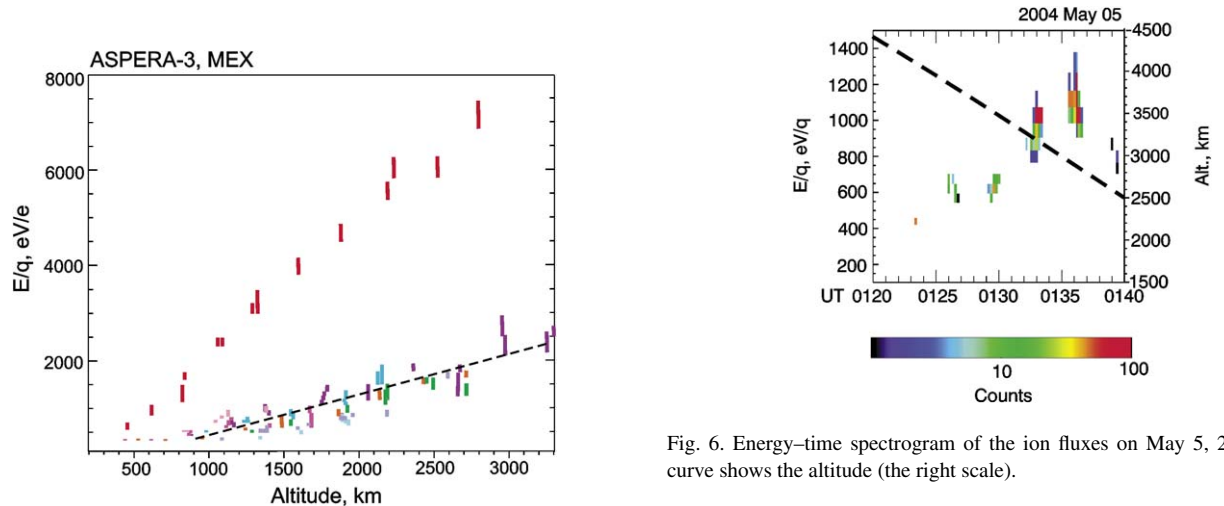


Fig. 5. Energy ( $E/q$ ) as a function of altitude for nine MEX orbits. The data from single orbits are given by different color.

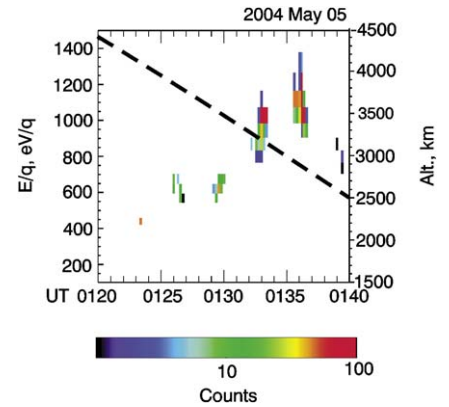


Fig. 6. Energy-time spectrogram of the ion fluxes on May 5, 2004. Dashed curve shows the altitude (the right scale).

lines draped around the planet. The electrons, accelerated by the  $\mathbf{j} \times \mathbf{B}$  force associated with a bending of the magnetic field

lines, pull the ions transferring them the magnetic field energy contained in a draping (Dubinin et al., 1993). Fig. 3 shows that the most of events are observed near and downstream of the terminator. Therefore the electric fields at low altitudes and effective scavenging of planetary ions can be closely related with process of plasma intrusion observed in this region (Dubinin et al., 2006).

At the nominal solar wind conditions, ions observed at the altitudes 400–700 km are weakly influenced by the electric field. However a high-speed solar wind can penetrate at such distances (where the number density of atmospheric atoms is higher) and sweep out planetary matter. A group of the data points apart from the main cluster data in Fig. 5 corresponds to such extreme event on December 17. The electric field in this case reaches 2.9 mV/m and results in a strong ‘fountain’ of the planetary ions.

The energy width of ion beams increases with altitude. Such broadening of the ion spectra can be caused either fluctuations in the magnetic field strength, contributions from other narrow beams due to a finite extent of a source and ‘mixing’ of different ion species (e.g.,  $O^+$  and  $O_2^+$  ions).

#### 4. Conclusions

The observations made by the ASPERA-3 experiment onboard the Mars Express spacecraft found dispersive ascending or descending (whether the spacecraft moves away or approach the planet) structures on the energy ( $E/q$ )–time spectrograms of the beams of planetary ions within the martian magnetosphere. A linear dependence between ion energy and the distance suggests acceleration in the electric field. The evaluated electric fields occur very large ( $\sim 0.8$ – $3$  mV/m) that indicates on either an effective local penetration of the solar wind induced electric field deep into the magnetosphere or generation of large fields in the process of the effective momentum exchange between the solar wind protons and planetary ions mediated by the magnetic field tensions. At the nominal solar wind conditions, a ‘penetration’ occurs near the terminator plane while in the extreme cases when the boundary of the induced magnetosphere moves much closer to the planet, ion extraction is also observed at the dayside.

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