Energisation of O^+ and O_2^+ ions at Mars: An analysis of a 3-D quasi-neutral hybrid model simulation

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We have studied the loss of O^+ and O_2^+ ions at Mars with a numerical model. In our quasi-neutral hybrid model ions (H^+, He^{++}, O^+, O_2^+) are treated as particles while electrons form a massless charge-neutralising fluid. The employed model version does not include the Martian magnetic field resulting from the crustal magnetic anomalies. In this study we focus the Martian nightside where the ASPERA instrument on the Phobos-2 spacecraft and recently the ASPERA-3 instruments on the Mars Express spacecraft have measured the proprieties of escaping atomic and molecular ions, in particular O^+ and O_2^+ ions. We study the ion velocity distribution and how the escaping planetary ions are distributed in the tail. We also create similar types of energy-spectrograms from the simulation as were obtained from ASPERA-3 ion measurements. We found that the properties of the simulated escaping planetary ions have many qualitative and quantitative similarities with the observations made by ASPERA instruments. The general agreement with the observations suggest that acceleration of the planetary ions by the convective electric field associated with the flowing plasma is the key acceleration mechanism for the escaping ions observed at Mars.

1. Introduction

Mars does not have a strong global intrinsic magnetic field and, therefore, the solar wind can flow close to the planet where the density of atmospheric neutrals is high. Because of the direct interaction between the atmosphere/exosphere and the solar wind some of the particles ionised from the neutral exosphere and atmosphere can be accelerated by electromagnetic forces and escape the system. This non-thermal escape is one of the loss mechanisms for atmospheric particles. The role of non-thermal escape processes at Mars at present and at times in the past has received attention when the evolution of the Martian atmosphere has been studied (see e.g. *Lammer et al., 2006*, and ref. therein).

The Mars Express (MEX) spacecraft has observed Mars and the properties of near-Mars space since December 2003. So far the most comprehensive data set for studying ion escape at Mars has been provided by the MEX Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment [*Barabash et al.*, 2004]. This experiment contains four individual instruments one of which, the Ion Mass Analyser (IMA), can distinguish escaping planetary ions (O^+, O_2^+, CO_2^+) from the solar wind ions (H^+, He^{++}). IMA has measured planetary ions near Mars on the dayside [*Lundin et al.*, 2004] and on the nightside (e.g., *Fedorov et al.* 2006).

Energisation of planetary ions at Mars has been a subject of intense investigations since the Phobos-2 mission in 1989 when distinction between heavy planetary ions and the lighter solar wind ions was performed. Various modelling approaches have been used to interpret Phobos-2 observations, such as a test particle simulation (e.g. *Kallio and Koskinen*, 1996), a gas dynamic (GD) model (e.g. *Kallio et al.*, 1994), a magnetohydrodynamic (MHD) model (e.g., *Liu et al.*, 1999) and a quasi-neutral hybrid (QNH) model (e.g., *Brecht at al.*, 1993). In this paper we continue to study the ion escape at Mars with a three dimensional (3-D) QNH model. So far the model results have been compared with ASPERA/Phobos-2 ion measurements and Phobos-2 magnetic field measurements [*Kallio and Janhunen,* 2002], and recently with IMA/ASPERA-3/Mars Express observations [*Kallio et al.*, 2006]. In the QNH-IMA/ASPERA-3 comparison, macroscopic plasma parameters based on QNH simulation were compared with IMA energy spectra [*Kallio et al.*, 2006]. In this paper we study the properties of escaping O^+ and O_2^+ ions in more detail by analysing the ion velocity distribution functions and by generating energy spectrograms in a similar format as used to display IMA measurements.

The paper is organised by first presenting some basic features of the QNH model and the particular methods used in this paper are introduced. Then the density of O^+ and O_2^+ ions in the tail region and the properties of the magnetic field near Mars based on a QNH model run are presented. Several analyses of the properties of the planetary ions on the nightside at three planes with x = constant (x = -1.1 R_M, -2.1 R_M and -3.1 R_M) are presented: (1) spatial distribution on each plane, (2) the particle flux, (3) the total outflow rate and its temporal variations, (4) an example of a 3-D O^+ ion velocity distribution function, (5) the direction of the velocity of escaping ions compared with the undisturbed velocity of the solar wind, (6) acceleration of the planetary ions versus the distance from the centre of the tail and, finally, (7) IMA-type of time energy spectrograms generated at the three planes along and perpendicular to the interplanetary magnetic field, IMF.

2. QNH Model

The description of the 3-D QNH model can be found elsewhere (see *Kallio and Janhunen*, 2002; *Kallio et al.,* 2006) and here we briefly list some basic features of the model that are of special importance for the present study.

The size of the simulation box is -4.2 R_M < x, y, z < 4.2 R_M (R_M = 3393 km, the radius of Mars) in Mars-centered Solar Orbital (MSO) coordinates (Figure 1). The simulation box contains three cell sizes, 720 km (~0.2 R_M), 360 km (~0.1 R_M) and 180 km (~0.05 R_M). The grid is refined in a spherically symmetric pattern both in dayside and nightside. The inner obstacle in the simulation box is a sphere of radius r = $r_{obstacle}$ = 3600 km that approximates the position of the exobase above which ion-neutral collisions are not frequent. An ion is removed from the situation if it moves inside the obstacle or out of the simulation box. The total number of ions in the simulation is ~11.2 million, the average number of particles per a cell is 30, and the time step, *dt*, is 0.02 s. The solar wind density(n_{sw}), velocity($\mathbf{U}_{sw}$) and the interplanetary magnetic field($\mathbf{B}_{sw}$) are $n_{sw} = n(H^+) = 3$ cm^{-3}, $\mathbf{U}_{sw} = \mathbf{U}(H^+)$ = [-450, 0, 0] km s^{-1}, and $\mathbf{B}_{sw}$ = [cos(55°), -sin(55°), 0] 1.12 nT = [0.64, -0.92, 0] nT. These parameters were adopted in order to use the same upstream parameters than in our previous study [*Kallio et al.*, 2006]. The solar wind contains also 4% of He^{++} ions ($n(He^{++}) = 0.04 \times n(H^+)$) which have the same velocity as the solar wind H^+ ions. The model does not contain a Martian crustal magnetic field. The simulation has to run up to t ~ 300 s in order to reach a (quasi) stationary state. In the present study the simulation was continued up to t = 800 s in order to collect enough ions to the x = const. planes and to study temporal variations.

The model uses so called ion splitting and joining technique. In the analyzed run one ion is split to two if the number of ions becomes much smaller than 30 and three ions are joined to two if the total number of ions within a cell becomes much higher than 30. These methods were chosen to constrain the number of ions in the computer memory and to keep the simulation computationally feasible. These techniques conserve the total energy and the total momentum of ions but the disadvantage of the joining method is that it artificially changes the velocity distribution function. Therefore, one should avoid making strong conclusions from every detail that can be seen in the 3D ion velocity distribution function. We are working to remove this artifact from our forthcoming model versions.

The velocity and energy of the escaping planetary ions are studied in detail by introducing three planes with x = const. into the simulation box and recording the position and the velocity of O^+ and O_2^+ ions when the escaping planetary ions, that is, $v_x < 0$ ions, cross these planes. The planes represent therefore imaginary detectors that collect escaping ions from the 2π angular space. It is also worth noting that, in this study escaping ions are collected by three planes, that is, they are not ions collected inside to a specific volume *dV*. As a consequence of the ion collection procedure, the number of collected ions which have high $|v_x|$ is larger than the number of collected ions which have small $|v_x|$ although the number of low velocity ions within *dV* would be same as the velocity of high velocity ions. Also only the ions which have $v_x < 0$ were recorded (escaping ions). Therefore in this study the point where the ion 3-D velocity function was analyzed was far in the tail ($x = -3.1\ R_M$) where most ions move antisunward ($v_x < 0$).

The ions are collected during the time interval 400 s < *t* < 734 s from the beginning of the simulation, or until the number of collected ions at a plane exceeded 10^5. The collected ions were divided in four groups depending on the angle, Θ, between the direction of the ion velocity($\mathbf{v}_i$) and the direction of the undisturbed solar wind($\mathbf{U}_{sw}$): $\Theta = \arccos[(\mathbf{v}_i/|\mathbf{v}_i|) \bullet (\mathbf{U}_{sw}/|\mathbf{U}_{sw}|)]$, (see Fig. 1). Therefore, Θ = 0° (90°) corresponds to ions that move exactly parallel (perpendicular) to the undisturbed solar wind.

Figure 1.

Ions are treated as particles accelerated by the Lorentz force. The model contains four ion species: H^+, He^{++}, O^+ and O_2^+. These ions have three sources. The protons are mainly solar wind protons launched into the simulation box at the front face x = 4.2 R_M. Protons are also generated from the hydrogen corona with scale height 2.61×10^4 km (from *Barabash et al.*, 2002, Table 1), but with a low total ion photoionization production rate 1.8×10^{24} s^{-1}. H^+ ions from the charge exchange and electron impact ionization are not included in the simulation. In this study we do not distinguish solar wind protons from protons originating from the neutral hydrogen corona. Alpha particles are only launched into the simulation box from the face at x = 4.2 R_M. The velocity distribution of the solar wind H^+ and He^{++} ions was assumed to be Maxwellian.

Atomic oxygen ions are produced by two sources: (1) the neutral exosphere with a probability that depends linearly on the neutral density and (2) the obstacle boundary that models the exopause. The neutral scale height is 1.78×10^4 km (from *Barabash et al.,* 2002, Table 1). The molecular oxygen ions are emitted from the obstacle boundary without a neutral exosphere. The total ion production rates from the neutral corona, q_{corona}, and the total ion emission rate from the obstacle boundary, q_{iono}, were as in our previous study [*Kallio et al.*, 2006]: q_{corona} (O^+) = 2.7×10^{23} s^{-1}, q_{iono}(O^+) = 1.4×10^{25} s^{-1} and q_{iono}(O_2^+) = 2×10^{25} s^{-1}. The used probability function, $f_{exobase}$, to generate the position of a planetary O^+ or $O2^+$ ion on the surface of the obstacle had a solar zenith (SZA) dependence on the dayside but not on the nightside: $f_{exobase}$ ~ cos(SZA) + 0.1 on the dayside (i.e. at SZA < 90°) and 0.1 on the night side (i.e. at SZA> 90°). The velocity distribution function of the planetary ions formed in the neutral corona and emitted from the exobase was Maxwellian. The temperature of ions from the neutral corona and the ions from the exobase was chosen to be 6.5 ×10^3 K and 10^5 K, respectively. The average total ion loss rates from the simulation box are 1.38×10^{25} O^+ ions s^{-1} and 1.38×10^{24} O_2^+ ions s^{-1}, implying that almost all of the O_2^+ ions emitted from the obstacle boundary return back to the obstacle.

3. Results

In this section we present an overview of the properties of plasma and magnetic field based on the analysed run, the properties of the plasma on the three analysed planes and simulated energy spectrograms.

3.1 Overview of the run

Figure 2 shows the density of O^+ and O_2^+ ions on the XY-plane (z = 0) and on the XZ-plane (y = 0) at the time t = 675 s. The highest densities are near the planet and an ionotail is formed behind the planet. A notable feature on the XY plane is the formation of “tail-ray type” or filamentary structures behind the planet. Furthermore, only a slight dawn-dusk asymmetry, i.e. asymmetry between the y > 0 and y < 0 hemispheres, can be seen. The dawn-dusk asymmetry is caused by the non-zero IMF x component. In contrast, on the XZ plane there is a clear asymmetry between the z < 0 hemisphere and the z > 0 hemisphere. The former (latter) hemisphere is the one where the convective electric field in the undisturbed solar wind points away from (towards) the planet, respectively. In this paper as in our previous studies these hemispheres are referred to as the +Esw and $-E_{sw}$ hemisphere. The convective electric field **E** (= – $\mathbf{U}_e$ x **B**, where $\mathbf{U}_e$ is the electron bulk velocity and **B** is the magnetic field) accelerates planetary ions away from the planet near the surface in the $+E_{sw}$ hemisphere, resulting in “erosion” of planetary ions in that hemisphere and non-zero planetary ion densities relatively far away from the planet in the $+E_{sw}$ hemisphere. Note that the localised O^+ ion enhancements in the solar wind seen in Figures 2a and 2b are ions originating from the oxygen corona and that the number of O^+ ions in the simulation is not optimised to resolve accurately the properties of that ion population overall in the simulation box.

Figure 2.

Figure 3 illustrates how the density of O^+ ions shown in Fig. 2 is associated with the morphology of the magnetic field. In Fig 3a-b the grey colour shows the density of O^+ ions on the y = 0 and z = 0 planes and the red vectors show the direction of the magnetic field (**B**/|**B**|). Fig. 3a provides a 3D view of the direction of the magnetic field on the two planes while Fig. 3b gives a view along the z axis and Fig. 3c along the y axis. Note that the B-vectors are out of the planes. Also note the formation of the magnetic tail lobes in the nightside with the magnetic field pointing away from (towards) the sun at $y < 0$ ($y > 0$) hemisphere (Fig. 3b). Furthermore, the magnetic field is “piled up” against Mars, it being tangential to Mars near the planet. The XY plane is therefore a cut through the magnetic tail lobes (Fig. 3b) while the XZ plane is a cut near the cross tail current sheet (Fig. 3c). Furthermore, Fig. 3b and 3c show the density of O^+ ions in the magnetotail where the magnetic field is highly draped and different than in the solar wind.

Figure 3.

3.2 Values at the x = constant planes

3.2.1 Spatial distribution, temporal variations and the particle flux

The position of 5000 O^+ and O_2^+ ions that hit the three analysis planes are given in Figure 4. Note that on the $x = 1.1\ R_M$ plane the hits of O^+ ions are clustered around ~ [-1.1, 0, 1] R_M and ~ [-1.1, 0, -1] R_M, that is, near the so called magnetic “poles” at [0, 0, ±1] R_M . The spatial distribution is axially asymmetric in all three planes but the asymmetry is relatively small at $x = -3.1\ R_M$. However, a clear asymmetry with respect to the direction of $\mathbf{E}_{sw}$ can be seen at all three planes in the O_2^+ ions. One reason for the clearer asymmetry in Fig. 4a than in Fig. 4b can be the fact that the plotted 5000 O^+ ions are originating both from the oxygen neutral corona and from the ionosphere while the 5000 O_2^+ ions are coming only from the ionosphere. Another reason for the differences between the atomic and molecular oxygen ions is the different mass of ions and, consequently, different ion gyroradius. In fact, that is the only difference between O^+ and O_2^+ ions originating from the exobase because these two ion species are emitted in the same way from the model exobase (see Section 2). Note also that escaping O_2^+ ions are concentrated close to the y = 0 plane, i.e., near the cross tail current sheet.

Figure 4.

The QNH model contains a finite number of ions and the plasma and field parameters never fully reach stationary values. The non-stationary nature can be seen in Figure 5 that shows the average outflow rate of O^+ ions through plane 3 during the time interval 400 s < t < 505 s. The average outflow rate through plane 3 is ~3.4×10^{24} s^{-1}, but fluctuations over 10% can be seen in the 150 time step running mean values. One reason for the fluctuations is the finite number of ions that cross the planes at each individual time step dt (= 0.02s). On the other hand, as noted in our previous study [*Kallio et al.*, 2006], the model can result in density enhancements or plasma “clouds” that are generated near the surface of Mars and thereafter move tailward. For example, in Figure 5 a periodicity of about 17 s (~ 0.06 Hz) can be found by Fourier analysis, which can also be identified by visual inspection. For a comparison, the gyroperiod of H^+, He^{++}, O^+ and O_2^+ ions in the solar wind (IMF = 1.12 nT) is 60 s, 120 s, 940 s and 1870 s, respectively. In fact, H^+, He^{++}, O^+ ions and O_2^+ ions had to be in the magnetic field of 4 nT, 8 nT, 62 nT and 123 nT, respectively, in order to have the gyroperid of ~17 s. In the simulation several tens of nT magnetic field can be found only near Mars while a few nT magnetic field can be obtained at x ~-3.1 R_M (see, *Kallio et. al.* 2006, Fig, 7). This suggests that if the fluctuation is associated with the gyromotion of O^+ or O_2^+ ions, the fluctuations may be originating near Mars while H^+ and He^{++} ions may generate ~17 s fluctuations far in the tail. Figure 5 illustrates that “snapshot” values based on the QNH model run, i.e. values at a given time t, can vary from one time to another.

Figure 5.

Figure 6 shows the average particle flux, j_x[s^{-1} cm^{-2}], of the O^+ and O_2^+ ions at the three planes. The flux is derived by using ions that hit the planes during the time period 400 s < t < 734 s. Note that the maximum particle flux in both ion species is found at all planes within the optical shadow or close to the limb. Moreover, the maximum flux is found near the y = 0 line, that is, near the cross tail current sheet. In both ion species a $+E_{sw}$ hemisphere/$–E_{sw}$ hemisphere asymmetry exists, j_x being higher on the $+E_{sw}$ hemisphere (z < 0) than on the opposite hemisphere. Furthermore, there is a slight dawn/dusk asymmetry caused by the non-zero IMF x-component.

Figure 6.

3.2.2 Velocity vectors and energisation

In this section we study in detail the velocity distribution of the escaping ions as well as their energy. Figure 7 gives the angle Θ, that is, the angle between the solar wind direction and the direction of O^+ and O_2^+ at the three planes. As already shown in Fig. 1, Θ = 0° corresponds ions that move exactly parallel to the undisturbed solar wind and Θ = 90° ions that move exactly perpendicular to the undisturbed solar wind U_{sw}. Fig. 7 illustrates that predominantly antisunward (Θ ~ 0°) moving ions can be found within or close to the optical shadow. At the x = -1.1 R_M plane, the ion velocities can differ notably from the antisunward direction, i.e., Θ >> 0°, near the optical shadow corresponding to the convergence of the planetary ions into the tail. Note that the velocity of O_2^+ ions becomes more and more perpendicular (Θ increases) the further the ion resides from the x-axis. Recall that an additional source of O^+ ions is the neutral oxygen corona which causes larger spread in the Θ angle distribution than for O_2^+ ions (which originate only from the ionosphere).

Figure 7.

Figure 8 shows in detail the velocity of the O^+ ions that hit plane 2 (x = -2.1 R_M) near [y, z] = [0, 0], i.e. around the x-axis at the centre of the tail. At this point the magnetic field is **B** = [B_x, B_y, B_z] = [-1.4, -3.0, -1.4] nT and the bulk velocity **U**(O^+) = [-77, 17, -40] km s^{-1}. At this point the O^+ ions flow away from Mars (antisunward) but they also posses a notable velocity component in the direction of the $\mathbf{E}_{sw}$. The direction of **B** at the point is also indicated in Figure 8, but no clear organisation of the O^+ velocities with respect to the direction of **B** can be seen. Note that every dot corresponds to an ion passing through the plane and that the distribution of the velocity points in a plot like in Fig. 8 would not be Maxwellian even if the velocity distribution functions were Maxwellian (see Section 2).

Figure 8.

The energy of the ions versus the distance from the x-axis is given in Figure 9. The red solid lines show the average energy of ions where only ions from the $+E_{sw}$ hemisphere, that is, at $z < 0$, are taken into account. The average energy of ions located on the opposite $–E_{sw}$ hemisphere at $z > 0$ are shown by blue dashed lines. In all panels the average energy is higher on the $+E_{sw}$ side than on the $–E_{sw}$ side. Also, the energy of O_2^+ ions increases almost linearly with the increasing distance from the x-axis. If one approximates the increase by a straight line that passes through the points $[(y^2 + z^2)^{-1/2}$ (in R_M), E (in keV)] = [0.5, 0] and [3.5, 4] at plane 1, the points [0, 0] and [3.5, 4] at plane 2 and the points [0, 0.5] and [4, 4] at plane 3, the value of $d\langle E_{kin}\rangle/(e \times d\rho)$ ($\rho = (y^2 + z^2)^{-1/2}$, e is the unit charge, $\langle E_{kin}\rangle$ is the average kinetic energy) is 0.39 mV m^{-1}, 0.34 mV m^{-1} and 0.26 mV m^{-1}, respectively. Such an increase of the kinetic energy would be obtained if the ions were accelerated away from the x axis by the electric field $E_\rho = d\langle E_{kin}\rangle/(e \times d\rho)$. In the model the electric field in the magnetotail is a non-axially symmetric 3D vector but it is worth noting that the values of E_ρ are close to the value of E_{sw} (= 0.41 mV m^{-1} = 450 km s^{-1} × 1.12 sin(55°) nT). The decrease of E_ρ from a plane to another results from the fact that the energy of the ions within the centre of the tail have increased more rapidly than the energy of the ions far away from the x axis. It is finally worth noting that there are two O_2^+ ion populations near the optical shadow at $\rho = 1$ R_M: fast (E ~ keV) ions in the $+E_{sw}$ hemisphere and low (E ~ few hundred eV) in the $–E_{sw}$ hemisphere.

Figure 9.

3.2.3 Simulated energy spectrograms

In this section we study in detail the energy of the escaping ions in the magnetic lobes and near the cross tail current sheet by generating IMA-type energy spectrograms. Figure 10 gives the density of O^+ and O_2^+ ions, the magnetic field, and the simulated energy spectrum on the x = -3.1 R_M plane along the y-axis.

The ion density and the magnetic field in Fig. 10a and 10c are derived at t = 675 s. The energy spectrum in Fig. 10b and 10d gives the particle flux j_x(# s^{-1} sr^{-1} cm^{-2})

calculated by collecting ions on plane 3 that have $|z| < 0.2\ R_M$ and dividing the number of hits by the energy intervals $[E_i, E_{(i+1)}]$ where $E_i = 3\ \text{eV} \times (1 + 0.08)^i$ (i = 0, 1, ..., 95). These energy intervals were chosen to mimic the energy steps used in IMA measurements that have an energy resolution of dE/E ~ 0.08 (*see Barabash et al.,* 2004, for the details of the IMA instrument). The energy spectra were also calculated separately in the four directions shown in Fig. 1: direction No. 1 (0° < Θ < 22.5°), direction No. 2 (22.5° < Θ < 45°), direction No. 3 (45° < Θ < 67.5°) and direction No. 4 (67.5° < Θ < 90°). These Θ intervals were chosen because IMA has a field of view (FOV) of 4.5° × 22.5°. Note that the simulated energy spectra do not represent any individual IMA measurement because the simulated FOV is not identical to the FOV of the IMA instrument, and also because the direction of FOV of IMA depends on the MEX orientation. In the simulation, the directions of the FOVs are fixed in the MSO frame. Moreover, MEX never crosses the tail along the y or z-axis, resulting in more complicated energy spectra than those presented here.

The magnetic field in Figures 10a and 10c shows that when an imaginary spacecraft moves along the y-axis, the maximum magnetic field associated with the magnetic tail lobes is observed at $|y| \sim 1\ R_M$, and that the cross tail current sheet is crossed near y ~ 0. There is a slight asymmetry resulting from the positive IMF x-component that has boosted the magnetic field in the magnetic tail lobe where B_x is positive, compared with the tail lobe where B_x is negative. More details of the properties of the magnetic field can be found in our previous work [*Kallio et al.,* 2006] when the macroscopic parameters for the same case than presented in this work was analyzed. Also note that there are three local maxima in $n(O^+)$ and $n(O_2^+)$, one maximum being associated with ions in the cross tail current sheet, the two other maxima being associated with the escaping ions within the magnetic tail lobes. The properties of $n(O^+)$ on the XY plane, as well as the position of the analysis line, can be seen in Figures 2a and 2c.

As seen in Figures 10b and 10d the highest particle fluxes are located within the optical shadow near the cross tail current sheet. The energy dispersion of the fluxes show that the average energy within the optical shadow is higher at the centre of the optical shadow (“inverted U shape”). One possible reason for differences between O^+ and O_2^+ energy spectra is the fact that O^+ ions are originating both from the neutral corona and from the exobase while O_2^+ ions are originating from the exobase only. The other possible source for the differences can be associated with the different mass of the atomic and molecular oxygen ions. The properties of $n(O_2^+)$ on the XY plane, as well as the position of the analyses line, can be seen in Figures 2b and 2d.

Figure 10.

Figure 11 presents similar simulated parameters as these given in Fig. 10, but now they are calculated along the z-axis. In this case, the tail is crossed near the cross tail current sheet and the magnetic field is weaker than in the previous case when an imaginary spacecraft crossed the magnetic tail lobes (Figs. 11a and 11c, bottom panels). The increase of the average energy with increasing distance from the x-axis on the $+E_{sw}$ hemisphere ($z < 0$) is clearly seen in the O_2^+ energy spectra. The highest O^+ count rates can be found within the optical shadow or near it, as was also the case in Figure 10. It is worth of noting that it is not obvious that such a correlation should exist in the Martian tail because the convective electric field depends on the magnitude and the direction of the magnetic field and the bulk velocity of all ion species. These are fully 3D parameters in the Martian tail, their values depending on how the solar wind is decelerated, accelerated and deviated around Mars.

Figure 11.

Figure 12 shows the simulated energy spectrograms at the three planes along the z-axis and along the y-axis. The highest fluxes are observed in the antisunward direction (dir. No. 1) near or within the optical shadow, and the highest flux values correspond to a few keV energy. A clear increase of the average energy of O_2^+ ions can be seen in Figs. 12a-c when z is decreased, i.e. when one moves toward the $+E_{SW}$ hemisphere (Figs. 12a-c; panels on the right hand side). A similar increase, although not as intense as in O_2^+, is observed in the O^+ energy spectra which contains ions both from the ionosphere and from the neutral oxygen corona (Figures 12a-c; panels on the left hand side). It is worth noting that O_2^+ ions are concentrated within the optical shadow or close to the limb when the path is along the y-axis (Figures 12d-f; panels on the right hand side). Notice also that the energy of O^+ and O_2^+ ions increase notably near the optical shadow at plane 1 when moving along the z axis (the current sheet) away from the x axis. In that case the energy of the escaping ions is in a wide energy range from a few tens of eV's to a few kilo eV's (Fig. 12a). Finally, the flux of planetary ions seems to be higher near points [-1.1, 0, ±1] R_M than points [-1.1, ±1, 0] R_M. This effect probably results from the $j \times B$ "slingshot" force caused by the magnetic tension at the highly draped magnetic field lines near the so called magnetic poles, that in the analyzed IMF case are at [0, 0, ±] R_M (see *Tanaka*, 1993, for more discussions about the $j \times B$ slingshot force). In the analyzed case the $j \times B$ slingshot force can accelerate planetary ions effectively near the XZ plane near the magnetic poles.

Figure 12.

4. Discussion

4.1. Similarities with observations

In this paper several properties of the escaping O^+ and O_2^+ ions in the Martian tail have been analysed. The main motivation for this study is to interpret ASPERA-3/Mars Express ion observations, especially the observations of escaping planetary ions in the tail. In a very detailed IMA data - QNH model comparison the energy spectra should be generated by using the positions of MEX, the attitudes of IMA instrument, and the accurate IMA FOV but this is beyond the present study.

Figs. 2-12 represented some parameters based on the analysed run. The following similarities between the simulated values and the observations made by ASPERA-3/Mars Express and ASPERA/Phobos-2 (measurements in 1989) are worth noting.

4.1.1 About keV planetary ions at the centre of the tail

ASPERA/Phobos-2 ion measurements near Mars in 1989 showed that there was a beam of ~keV planetary ions in the centre of the Martian tail (see, for example, *Kallio et al.*, 1995). Also ASPERA-3/MEX has measured ~1 keV planetary ions in the nightside (see, for example, *Kallio et al.*, 2006, Fig. 1). The present study as well as our previous study [*Kallio and Janhunen*, 2002] showed that our self-consistent QNH model produces a few keV planetary ions to the tail (see Figs. 10-12). In addition, the model resulted in energy dispersion and "inverted U" type of energy spectra (see Fig. 10b and d) being, at least qualitatively, in agreement with energy spectra observed by ASPERA/Phobos-2 (see, for example, *Kallio and Koskinen*, 1999, Fig. 9b, the bottom panel). In fact planetary ions with energies near 1 keV have also been produced in test particle simulations [*Kallio and Koskinen*, 1999].

4.1.2 Energisation of planetary ions outside of the optical shadow

ASPERA-3 ion observations suggest that the energy of the planetary ions can increase with increasing distance from the planet and that there are events when the increase of energy with altitude is linear in the magnetosheath [*Dubinin et al.*, 2006]. The observed linear increase of the energy can be obtained if the ions are accelerated by the electric field whose magnitude is about the magnitude of the convective field in the undisturbed solar wind [*Dubinin et al.*, 2006]. It is therefore notable that in this study the QNH model was found to result in a linear energy increase of planetary ions with increasing distance from the x-axis (see Fig. 9). Furthermore, the magnitude of the derived electric field, E_ρ, was found to be close the value of the $|\mathbf{E}_{sw}|$ (see Section 3.2.2). It is worth of noting that it is not obvious that such a clear correlation between E_ρ and $|\mathbf{E}_{sw}|$ should exists in the Martian tail because the convective electric field depends on the magnitude and the direction of the magnetic field, B, and the bulk velocity of all ions species, $U(H^+)$, $U(O^+)$ and $U(O_2^+)$. These B and U fields are fully 3-D in the Martian tail their values depending on how the solar wind was decelerated, accelerated and deviated around Mars.

4.1.3 Spatial distribution of the escaping ions in the tail.

A statistical study of the spatial distribution of the escaping planetary ions in the Martian tail suggests that the planetary ions are escaping asymmetrically with respect to the direction of the undisturbed convective electric field, $\mathbf{E}_{sw}$ [*Fedorov et al.*, 2006]. More ions were found to be lost on the $+E_{sw}$ hemisphere than in the -

E_{sw} hemisphere [*Fedorov et al.*, 2006]. Similar type of $+E_{sw}/–E_{sw}$ asymmetry can be also seen in the QNH model simulation (see Figure 6).

It should also be noted that the "clustering" of the escaping planetary ions in the tail (see Fig. 4, top and middle panels) have some similarities with the earlier test particle simulations that was developed to interpret ASPERA/Phobos-2 observations [*Kallio and Koskinen*, 1999]. Although a comparison of the test particle simulations and the present study is not straightforward because of different input parameters and different collection surfaces for ions (in the test particle simulation ions were collected on the 2.8 R_M sphere and the upstream conditions were different from the present study), in both studies, the escaping ions formed localised groups or clusters in the tail (c.f. Fig. 4a, 4d, 4e, Fig. 7 and Fig. 8 and *Kallio and Koskinen*, 1999, and Fig. 4 in this paper) and about ~ 1 keV escaping planetary ions at the cross tail current sheet.

4.1.4 Temporal variations

The ASPERA-3 Electron Spectrometer (ELS) has observed electron oscillations with frequency peaks which are typically in the range 0.01 – 0.02 Hz [*Winningham et al.*, 2006]. In addition, plasma and magnetic field fluctuations have been observed by the MGS spacecraft (see *Espley et al.*, 2004). It is therefore interesting, that as seen in Fig. 5 and as noted in our previous study [*Kallio et al.*, 2006], fluctuations with about 10 – 20s periods can be found in the properties of the escaping planetary ions in the tail which were produced by the QNH model simulations. These fluctuations might result from statistical fluctuations caused by the finite number of ions in the simulation box, but they may also be a manifestation of instabilities generated near the ionosphere where the flow of the solar wind meets the planetary ions. In fact, an instability has been found to take place in 2-D QNH model simulations made for Venus which resulted in density fluctuations in the $+E_{sw}$ hemisphere [*Terada et al.*, 2002].

4.2. Miscellaneous remarks

An interesting issue is the question: "Are the escaping planetary ions organised in the tail with respect to the direction of the magnetic field"? That question is also related to the question of the magnetisation of the escaping ions. We have studied this question by calculating the value $T(\Theta_i, \varphi_i) = \text{sum}\{[w_i (\mathbf{v}_i - \mathbf{U}) \bullet \mathbf{n}(\Theta_i, \varphi_i)]^2\}$, which was developed in this study to provide a rough measure for the spreading of the distribution at different directions. Here **n** is the unit vectors whose direction is determined by the polar angles (Θ, φ), **U** is the bulk velocity, w_i takes into account the weight of an ion and the sum is over all velocities $\mathbf{v}_i$ that hit the x = const. planes in a given grid (dy, dz). For example, ions gyrating around the magnetic field would result to min(T) in the directions where n is along ±B and to max(T) in the direction where n is perpendicular to B. We studied whether a correlation exists between the direction of $\mathbf{n}_{max}$ (that gives max(T) value) or $\mathbf{n}_{min}$ (that corresponds min(T) value) and the direction of **B** at the analysed position. In the case shown in Figure 8, no clear correlation between $\mathbf{n}_{max}$ nor $\mathbf{n}_{min}$ with the direction of **B** could be found. One reason may be that the point [-2.0, 0, 0] R_M used in Fig. 8 is at the centre of the cross tail current sheet where the magnetic field is weak. At other locations, where the magnetic field is stronger than in the case shown in Fig. 8, $\mathbf{n}_{max}$ was found to occasionally be close to the direction of **B** (figures not shown). However, determination of the direction of **B** from the shape of the 3-D velocity distribution function of the escaping planetary ions was not found to be an accurate method, at least, in the relatively weak IMF case used for this study. From the observational point of view, such a correlation would have been useful in order to determine the direction of IMF for the case where there is no magnetometer available, as is the case for the Mars Express spacecraft.

Finally, it is worth noting that the QNH model version used in this work does not contain a Martian crustal magnetic field. It has been proposed that the acceleration of the planetary ions near the Martian magnetic anomalies may have many similarities with the acceleration processes associated with auroras in the terrestrial magnetosphere [*Lundin et al.*, 2006a, 2006b]. In this work the acceleration related to the magnetic anomalies are therefore not included and the presented properties of the escaping planetary ions result purely from acceleration caused by the convective electric field.

Summary

We have studied the properties of escaping O^+ and O_2^+ ions in the Martian tail with a self-consistent 3-D quasi-neutral hybrid model that does not contain crustal magnetic field. Our analysis shows that the model can reproduce qualitatively, and in many cases also quantitatively, many properties of ions observed by ASPERA/Phobos-2 in 1989 and ASPERA-3/Mars Express in 2004-2006, especially, [1] the acceleration of the planetary ions with an electric field $E_\rho \sim |\mathbf{E}_{sw}|$ in the magnetosheath, [2] keV-class planetary ions within the optical shadow at x ~ -3 R_M, [3] an "inverted U" shape type of energy spectra within the optical shadow, [4] $+E_{sw}/-E_{sw}$ hemisphere asymmetry, [5] different ion outflow along a line that goes through the magnetic tail lobes than along a line that goes near the cross tail current sheet and [6] that the highest particle flux comes from the same direction than the undisturbed solar wind.

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Figure caption

Figure 1. The structure of the grid on the XY and XZ planes used in the simulation in this paper. The velocity and position of O^+ and O_2^+ ions were recorded when they hit the x = -1.1 R_M, -2.1 R_M and 3.1 R_M planes, labelled in Figure 1 as plane 1, 2 and 3, respectively. The recorded ions were divided in four direction groups depending on the angle Θ between the direction of the velocity of the ion($\mathbf{v}_i/|\mathbf{v}_i|$) and the direction of the undisturbed solar wind ($\mathbf{U}_{sw}/|\mathbf{U}_{sw}|$): 0° < Θ < 22.5° (direction. No. 1), 22.5° < Θ < 45° (direction No. 2), 45° < Θ < 67.5° (direction. No. 3) and 67.5° < Θ < 90° (direction. No. 4).

Figure 2. The density of O^+ and O_2^+ ions on the XY and XZ planes in the analysed run. Notice that the IMF is in the XY plane (see $\mathbf{B}_{sw}$ vector in a and b) and that the convective electric field $\mathbf{E}_{sw}$ (= – $\mathbf{U}_{sw}$ x $\mathbf{B}_{sw}$) is in the XZ-plane. The XY plane is, therefore, a cut through the magnetic tail lobes while the XZ-plane is near the cross tail current sheet. The white dashed vertical lines at x = 3.1 R_M show the lines along which the properties of the escaping planetary ions are analyzed later in this paper in Figures 10 – 12.

Figure 3. The direction of the magnetic field vectors (red arrows) on the XZ and XY planes. The density of the O^+ ions is shown on these planes by a grey scale for comparison. The direction of the magnetic field and the density of O^+ ions are calculated by interpolating their values from the original grid (see Fig. 1) to the dx = dy = dz = 0.2 R_M grid. The three-dimensional isometric view is shown in (a) and detailed two-dimension presentations of the XY and YZ planes are shown in (b) and (c), respectively.

Figure 4. The position of 5000 O^+ ions that had $v_x < 0$ and that hit (column a) the x = -1.1 R_M, x = -2.1 R_M, and x = -3.1 R_M planes, and 5000 O_2^+ ions that hit (column b) the x = -1.1 R_M, x = -2.1 R_M, and x = -3.1 R_M planes.

Figure 5. The average outflow rate of O^+ ions through the x = -3.1 R_M plane 3 during 400 s < t < 505 s. The count rates (s^{-1}) at a given time are derived by calculating 150 point running mean of the instantaneous (dt = 0.02 s) outflow rate.

Figure 6. The particle flux of escaping (i.e. $v_x < 0$) along the x-axis, j_x[s^{-1} cm^{-2}], of O^+ ions (column a) and O_2^+ ions (column b) at the three x = const. planes (x = -1.1 R_M, -2.1 R_M and -3.1 R_M). The highest fluxes are situated near the cross tail current sheet on the +E_{sw} hemisphere (z < 0). The red vectors in the top panels show the direction of the convective electric field in the solar wind, $\mathbf{E}_{sw}$, and the direction of the IMF on the YZ plane, $\mathbf{B}_{y\,sw}$.

Figure 7. The angle between the O^+ and O_2^+ ions and the $\mathbf{U}_{sw}$ at the three planes for $v_x < 0$ ions. The red points are (y, z, Θ) values where y and z are the values of the y-axis and the z-axis, and Θ , and $\Theta = \arccos[(\mathbf{v}_i/|\mathbf{v}_i|) \bullet (\mathbf{U}sw/|\mathbf{U}sw|)]$ when an ion passes through the plane. The black dots show the points [y, z, 0], i.e. the position of the hits on the YZ-plane. Column a shows plots for the three planes with O^+ and (b) shows plots for the three planes with O_2^+. In all six plots the horizontal axis are Z and Y and the vertical axis is Θ. Note that ions near the horizontal Θ = 0° plane are moving almost to the same direction than the undisturbed solar wind. Furthermore, the optical shadow is the region within $(y^2 + z^2)^{-1/2} < 1$ R_M and the x axis crosses the three planes at [Y,Z] = [0,0].

Figure 8. The velocity $\mathbf{v} = [v_x, v_y, v_z]$ km s^{-1} of escaping (i.e. $v_x < 0$) O^+ ions around the point [x, y, z] = [-2.1, 0, 0] R_M is viewed from four directions. The black solid line shows the direction of the magnetic field, $\mathbf{B}^o$ (= $\mathbf{B}_{sw}/|\mathbf{B}_{sw}|$). This O^+ velocity is shown in three dimensions(a) and the dimensional projections in the Vy-Vz plane(b), Vx-Vz plane(c), and in the Vx-Vy plane(d).

Figure 9. The energy of escaping $v_x < 0$ (a) O^+ ions and (b) O_2^+ ions at the three planes versus the distance from the x-axis. Every black dot corresponds to an ion passing through the plane. The red(blue) line is the average energy $<+E_{sw}>$ ($<-E_{sw}>$) of ions based on ions collected in the $+E_{sw}$ ($-E_{sw}$) hemisphere. Note the linear increase of the energy of O_2^+ ions in the $+E_{sw}$ hemisphere shown at all three planes.

Figure 10. Simulated plasma and field parameters along the y-axis at x = -3.1 R_M plane, i.e., values through the magnetic tail lobes and through the cross tail current sheet. The parameters are: The density of O^+ ions (Fig. 10a, top panel), the density of O_2^+ ions (Fig. 10c, top panel), the magnetic field (Fig. 10a and 10c, bottom panels; the red solid line: B_x, the green dashed line: B_y, the blue dotted line: B_z, black solid line: |B|) and energy spectrograms for O^+ ions (Fig. 10b) and O_2^+ ions (Fig. 10d) calculated for four directions dir. No. 1 (No. 4) looking ions move predominantly parallel (perpendicular) to the direction of the undisturbed solar wind. The optical shadow is the region between the vertical dashed lines. The units of the particle density, the magnetic field, and the energy spectra are cm^{-3}, nT, and (s^{-1} cm^{-2} sr^{-1}). Note the different scales in $n(O^+)$ and $n(O_2^+)$. The horizontal red dotted lines in b) and d) at dir. No. 1 show the energy of H^+ ions in the undisturbed solar wind, 1060 eV (U = 450 km s^{-1}).

Figure 11. Simulated plasma and field parameters along the z-axis at x = -3.1 R_M, i.e. when the tail is crossed near the cross tail current sheet. See Fig. 10 for the description of the parameters. The $+E_{sw}$ ($-E_{sw}$) text labels are added to show the hemisphere where the direction of the convective electric field in the undisturbed solar wind points away from (toward) Mars. Note the different

scales in n(O^+) and n(O_2^+). The horizontal red dotted lines in b) and d) at dir. No. 1 show the energy of H^+ ions in the undisturbed solar wind, 1060 eV (U = 450 km s^{-1}).

Figure 12. Comparison of the simulated energy spectrograms at the three planes calculated along the z-axis (Fig. 12a, b, c) and along the y-axis (Fig. 12d, e, f). In all figures the energy is in $\log_{10}$ scale from 10 eV to 30 keV. Fig. 12c is the same as Figs. 11b and 11d. Fig. 12f is the same as Figs. 10b and 10d. The vertical dashed lines indicate the region of the optical shadow. Note that moving along the z-axis corresponds to the crossing the tail near the cross-tail current sheet while moving along the y-axis corresponds to crossing through the magnetic tail lobes. The counts that can be seen in dir. No. 1 (dir. No. 4) are planetary ions moving predominantly parallel (perpendicular) to the direction of the undisturbed solar wind.