On the possibility of identifying heavy ion acceleration processes in the magnetotail of Mars

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The dependence of the energy of ions on their mass could be a useful tool for the identification of possible acceleration processes in the Martian plasma sheet. The study is based on a few cases when heavier ions and protons were registered simultaneously in the plasma sheet by the TAUS energy spectrometer, and on published data of the ASPERA instrument. The analysis of mass dependence of the ion energy in the plasma sheet suggests that frictional preacceleration of ions probably in the pole regions of the Martian magnetosphere can be responsible for not more than 40% of the energy gain of heavy ions in the plasma sheet, the cross-tail current sheet acceleration yields up to 70%, and from 30 to 70% of the heavy ion energy is provided by the acceleration due to magnetic field line stresses (and/or electric field aligned acceleration).

1. Introduction

Plasma experiments TAUS (Rosenbauer *et al.*, 1989) and ASPERA (Lundin *et al.*, 1989) on board the Phobos 2 orbiter revealed that the Martian magnetosphere is dominated by ions of planetary origin, primarily by oxygen ions. The most intense fluxes of tailward streaming heavy ions (ions with mass/charge ratio $M_i/q_i > 3$) were observed in the magnetotail plasma sheet (Rosenbauer *et al.*, 1989; Verigin *et al.*, 1991). Velocity and intensity of heavy ion fluxes reach their peak values in the vicinity of the magnetic neutral line. The energy of these ions varies from ~100 eV up to > 6 keV. 2D ion spectra measured by the TAUS spectrometer in the Phobos 2 elliptical orbits revealed a supersonic, highly anisotropic distribution function of heavy ions (Rosenbauer *et al.*, 1989). Analysis of these 2D spectra at times when the spacecraft was spinning, suggests that the 3D distribution function of heavy ions has a "mushroom cap" shape similar to the shape of proton distributions in the plasma sheet boundary layer of the terrestrial magnetotail (Kotova *et al.*, 1997).

Several acceleration mechanisms were invoked for explanation of such ion distributions in the Earth's magnetotail (Eastman *et al.*, 1986). Simple field aligned acceleration with adiabatic deformation of distribution function was examined by Kotova *et al.* (1997) and it was demonstrated that this mechanism can account for the Martian magnetotail observations only in a case of initial preacceleration of ions

to velocities of several tens of km/s. This preacceleration might occur by the direct interaction of ionospheric ions with magnetosheath plasma in the 'pole' regions of the Martian magnetosphere (Verigin *et al.*, 1991). Ip (1992) considered ion acceleration due to the formation of neutral lines in the near-tail region of the Martian magnetosphere. Dubinin *et al.* (1993) showed that acceleration due to the magnetic field stress could explain an increase of ion energy toward the center of the tail. The effect of the magnetic field line stress can be expressed via the effect of the electric field raised by the charge separation (Haerendel, 1987).

On the basis of the TAUS ion spectrometer and MAGMA magnetometer data correlations between several plasma sheet and solar wind parameters were found which indicate importance of the magnetic field line stress acceleration and the central current sheet acceleration of heavy ions (Kotova *et al.*, 1997, 2000). Meanwhile none of the proposed acceleration processes can explain all the features of the Martian plasma sheet.

In this paper the dependence of heavy ion energy on the ion mass will be examined on the basis of Phobos 2 plasma experiments. This dependence provides an additional useful tool for the identification of possible acceleration processes.

2. Observations

The TAUS ion spectrometer on board the Phobos 2 Mars orbiter measured fluxes of protons and heavy ions (mass/charge ratio $M_i/q_i > 3$) separately in the energy range of 0.03–6 keV. It provided data from 5 elliptical and ~60 circular orbits. In circular orbits a 1D heavy ion spectrum was measured during 8 s in every 2 min. Published data of the
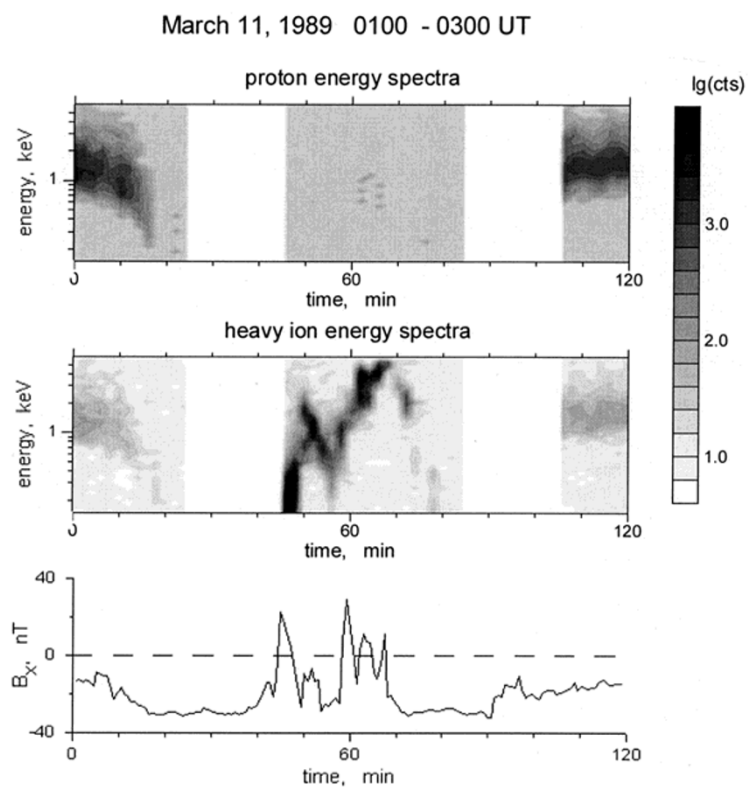
Fig. 1. Energy vs. time plot of proton and heavy ion spectra (in counts) and the magnetic field component parallel to Sun-Mars line, measured on March 11, 1989 inside the Martian magnetosphere.
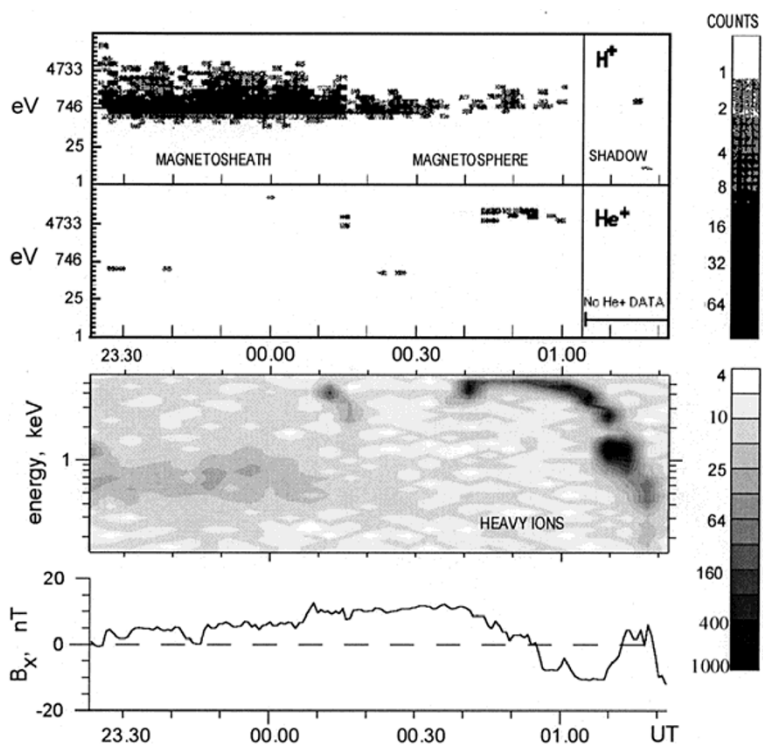
Fig. 2. Energy vs. time plot of proton and helium ion spectra obtained by the ASPERA instrument (top two panels) in the Martian plasma sheet on March 1–2, 1989 (Barabash *et al.*,1995) and corresponding heavy ion spectra measured by TAUS. Bottom panel presents the magnetic field B_x component as observed by the MAGMA magnetometer.

ASPERA ion mass-spectrometer (Lundin *et al.*, 1989) will be also considered. This instrument included 10 moment sensors with a field of view of $5°$–$36°$ and measured positive ions in the range of 1–23 keV/q. The ASPERA instrument also included mass-sensors which provided more detailed ion composition measurements but with lower sensitivity and time resolution compared to the moment sensors (Barabash *et al.*, 1995).

Figure 1 presents example of proton and heavy ion measurements by TAUS when Phobos 2 passed through the Martian magnetotail on March 11, 1989. The bottom panel shows the magnetic field component parallel to the Mars–Sun line measured by the MAGMA magnetometer to visualize the magnetic neutral sheet traversals inside the magnetotail where this component changes sign. Rather high fluxes of protons (and 'ghosts' in the heavy ion channel) in the beginning and in the end of the presented time interval refer to the magnetosheath. Martian plasma sheet crossings are well seen in Fig. 1: close to multiple crossings of the magnetic neutral sheet the TAUS instrument recorded heavy ions and their energy varies through the entire instrumental energy range. In this case also protons were observed in the plasma sheet, while most of the time the sensitivity of TAUS was not enough for proton observations inside the tail. On March 11, 1989 the energy of protons in the plasma sheet was ~4 times less than the energy of simultaneously observed heavy ions.

More data on ion composition of the Martian plasma sheet were obtained by the ASPERA instrument due to its better mass resolution. Norberg *et al.* (1993) and Barabash and Norberg (1994) mentioned observations of helium ions He$^+$ whose energy seems to be ~1.5 times less than the energy of oxygen ions. Figure 2 shows the results of hydrogen and helium ion observations by ASPERA (Barabash *et al.*, 1995) and the data obtained by the heavy ion channel of TAUS. At the time close to the first current sheet crossing (0055 UT) heavy ions (supposedly oxygen) with peak energies higher than the TAUS instrument range were observed. ASPERA recorded rather high fluxes of protons and visible fluxes of helium ions at ~0050 UT. Similarly to the first example the energy of protons (~1500 eV) is ~4 times less than the energy of oxygen ions, and the energy of helium ions (5–10 keV) is close to the energy of oxygen or slightly less. Contrary to these observations Lichtenegger and Dubinin (1998) presented an example of E_i/q_i–M_i/q_i matrix measured by the mass-sensor of the ASPERA instrument in the Martian tail, which shows approximately linear dependence of the energy E_i on mass M_i for light (H$^+$, H$_2^+$/He^{++}, He$^+$) and heavy (O$^+$, O$_2^+$, CO$_2^+$) ions. However the matrix in figure 5 of Lichtenegger and Dubinin (1998) was collected during a long time interval of 35 minutes (March 16, 1021–1056 UT). In the same orbit but within shorter time interval (1029–1037 UT) enclosing the current sheet crossing ASPERA practically did not observe light ions (figure 2 in Norberg *et al.*, 1993). Hence these ions might be not of plasma sheet origin but admixed, e.g., from the magnetospheric boundary layer.

The ASPERA data (Norberg *et al.*, 1993; Dubinin *et al.*, 1993, etc.) revealed also that all heavy ions O$^+$, O$_2^+$, CO$_2^+$ have nearly the same energy. Figure 3 taken from Dubinin *et al.* (1993) presents the peak energy of protons and molecular ions observed in the plasma sheet as a function of the

peak energy of oxygen ions (solid and dashed lines will be discussed below). It is seen that the energy of protons is ~2–4 times less than the energy of oxygen ions, in agreement with TAUS observations. On the other hand the energy of molecular ions is approximately equal to the energy of O$^+$. Using the ASPERA data, Dubinin *et al.* (1993) sometimes succeeded in identifying O^{++} ions whose energy/charge ratio E_i/q_i coincide with that of O$^+$ and concluded that E_i/q_i of heavy ions does not depend on M_i/q_i.

The observations reported so far can be summarized as follows:

- energy of molecular ions (O$_2^+$, CO$_2^+$) is close to energy of O$^+$ ions;

- energy/charge ratio of O^{++} is close to energy of singly charged O$^+$ ions;

- energy of protons is usually 2–4 times less than energy of O$^+$ ions;

- the energy of singly ionized helium seems to be ~1.5 times less than the energy of O$^+$ ions.

3. Data Analysis and Discussion

The acceleration processes which have been considered to explain the observed heavy ion fluxes are as follows:

- frictional preacceleration of all ions to velocity V_0;

- field-aligned electric field acceleration or magnetic field line stress acceleration of all ions to equal energy per charge $E_i/q_i = U$;

- cross-tail electric field acceleration of all ions which results in an approximately equal velocity increase $\Delta V = 2c\varepsilon/B_\perp$, where c is the velocity of light, ε is cross-tail electric field, $B_\perp$ is magnetic field component perpendicular to the current sheet (Speiser, 1965; Shabanskiy, 1972). The energy gain of ions in this case is $\Delta E_i = M_i(\Delta V)^2/2 + M_i V(\Delta V)$, where V is the initial velocity of the ion.
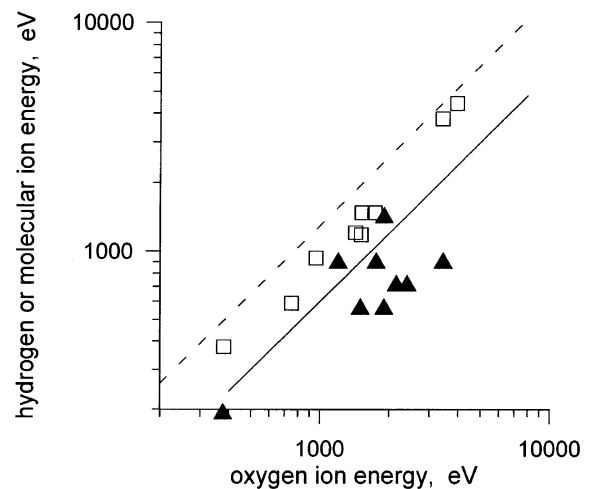

Fig. 3. Peak energy of protons (solid triangles) and molecular ions (open squares) versus peak energy of oxygen ions as measured by the ASPERA instrument (Dubinin *et al.*, 1993). Solid and dashed lines show the relations: $E_{H^+} = 0.6E_{O^+}$ and $E_{O_2^+} = 1.3E_{O^+}$, respectively.
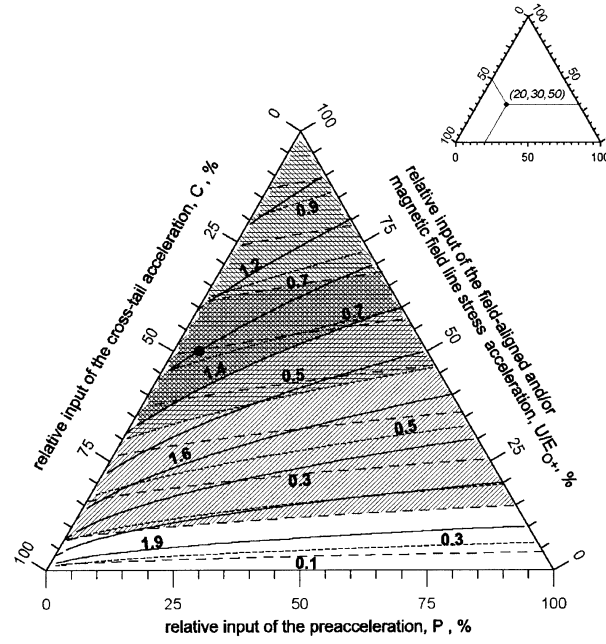
Fig. 4. Liquidus projection of isolines of E_{H^+}/E_{O^+} (dashed), E_{He^+}/E_{O^+} (dotted), and $E_{O_2^+}/E_{O^+}$ (solid) in coordinates: energy gained due to preacceleration relative to the total energy vs. energy gained due to cross-tail current sheet acceleration relative to the total energy vs. energy gained due to field-aligned acceleration relative to the total energy for oxygen ions in the plasma sheet. Left hatching marks the region of $E_{O_2^+}/E_{O^+} < 1.4$, right hatching shows the region of $0.2 < E_{H^+}/E_{O^+} < 0.7$ and horizontal hatching corresponds to the region of $0.6 < E_{He^+}/E_{O^+} < 1$.

The origin of the cross-tail electric field ε in the Martian magnetotail is quite unclear now. The radius of the Martian magnetotail is just several times larger than the Larmor radius of heavy ion in the plasma sheet and ion kinetic effects in the Martian magnetotail are more important than in the Earth's magnetotail. However, the correlation of heavy ion velocity with the inverse value of the minimum magnetic field in the tail (Kotova *et al.*, 1997, 2000), points on possible existence of the cross-tail electric field in the Martian magnetotail. Estimates done in the paper by Kotova *et al.* (2000) show that the same formulas for cross-tail electric field acceleration are appropriate for the initial consideration of both magnetotails.

The total energy acquired by a heavy ion after the action of all 3 acceleration mechanisms could be thus estimated:

$$\frac{E_i}{q_i} = U + \frac{M_i V_0^2}{2q_i} + \frac{M_i (\Delta V)^2}{2q_i} + \frac{M_i \Delta V}{q_i} \sqrt{V_0^2 + \frac{2q_i U}{M_i}}. \quad (1)$$

According to the Phobos 2 observations the Martian plasma sheet is primarily filled by oxygen ions and thus it is useful to consider the ratio of the energy per charge gain of an arbitrary ion to the energy of oxygen ion:

$$E_{O^+} = U + \frac{M_O V_0^2}{2} + \frac{M_O (\Delta V)^2}{2} + M_O \Delta V \sqrt{V_0^2 + \frac{2U}{M_O}}, \quad (2)$$

M_O is the mass of oxygen ion. It is also convenient to choose the following relative values:

$$P = \frac{M_O V_0^2}{2E_{O^+}}, \quad (3)$$

$$C = \left(\frac{M_O (\Delta V)^2}{2} + M_O \Delta V \sqrt{V_0^2 + \frac{2U}{M_O}} \right) \cdot \frac{1}{E_{O^+}}, \quad (4)$$

where P is the fraction of the energy gained by oxygen ion due to preacceleration and C is the fraction of the oxygen ion energy acquired in the central current sheet. Obviously the relative input of the field-aligned acceleration $U/E_{O^+} = 1 - P - C$. Substituting all these parameters into (1), the ratio of the energy per charge gain of an arbitrary ion to the energy of oxygen ion can be expressed as:

$$\frac{E_i/q_i}{E_{O^+}} = \left[\sqrt{1 - P - C + P \frac{M_i}{M_O q_i}} \right. \\ \left. + \left(1 - \sqrt{1 - C} \right) \sqrt{\frac{M_i}{M_O q_i}} \right]^2. \quad (5)$$

The relation (5) determines the ratios E_i/E_{O^+} for singly charged hydrogen ($M_i = 1$), helium ($M_i = 4$) and molecular oxygen ($M_i = 32$) ions as functions of parameters P and C. These parameters determine the relative input of the preacceleration and tail current sheet acceleration, respectively, to the total acceleration of plasma sheet oxygen ions and including the relative input of field-aligned acceleration U/E_{O^+} the sum of the parameters P, C, U/E_{O^+} is equal to 100%. Therefore it is convenient to use a liquidus projection to show the results of calculations. Figure 4 presents proper ternary graph of isolines of E_{H^+}/E_{O^+}, E_{He^+}/E_{O^+}, and $E_{O_2^+}/E_{O^+}$. Every point inside this graph has three coordinates, which are determined in the way shown in the top right corner of Fig. 4. The sum of these coordinates is equal to 100%. Some

overlapping regions of the parameters E_{H^+}/E_{O^+}, E_{He^+}/E_{O^+}, and $E_{O_2^+}/E_{O^+}$ were selected which agree with the observations summarized in the previous section. These regions are marked by different hatchings. Figure 4 permits to make some quantitative conclusions on the relative influence of the different acceleration processes. It is seen, for example, that when E_{H^+}/E_{O^+} is in the range of 0.45–0.7, then the ratio $E_{O_2^+}/E_{O^+}$ varies from $\sim$1.2 to $\sim$1.4, and E_{He^+}/E_{O^+} lies in the range of 0.6–0.8. In this case the relative input of the preacceleration process in the overall plasma sheet ion acceleration may not exceed 40%, the relative input of the magnetic field line stress acceleration and/or field-aligned acceleration is in the range of 30–70%, and the relative input of the cross-tail current sheet acceleration is up to 70%. It is worth to mention that magnetic field line stress acceleration and/or field-aligned electric field acceleration cannot be zero to be consistent with observations from Fig. 4.

Even more strict limitations might be possible. When the relative preacceleration input is <20%, then bigger difference is allowed between the energies of protons and molecular ions as suggested by observations. This may occur only in the case when the relative input of cross-tail current acceleration is in the interval of 25–55% and the energy gained by heavy ions due to magnetic field line stress acceleration or electric field aligned acceleration must be in the range of 45–55%. In Fig. 3 the solid and dashed lines illustrate the dependencies $E_{H^+} = 0.6E_{O^+}$ and $E_{O_2^+} = 1.3E_{O^+}$, respectively, which correspond to the dark point in Fig. 4, where $C = 45\%$ and $P = 5\%$.

It is also possible to check with Eq. (5) whether the energy/charge of O_2^+ relative to the energy of O^+ corresponds to the observations. For the dark point in Fig. 4 the value of $E_{O_2^+}/2E_{O^+}$ is about 0.82, not contradicting to the observations.

Such a relation between the acceleration processes is also approved by the analysis of the TAUS data, suggesting a preacceleration velocity of at least 45 km/s (Kotova *et al.*, 2000), while the observed average heavy ion velocity in the Martian plasma sheet was $\sim$140 km/s (varied from $\sim$45 km/s to $\sim$270 km/s). The relative influence of the cross-tail current sheet and magnetic field line stress acceleration possibly depends on the solar wind ram pressure determining the solar wind interaction with Mars (Kotova *et al.*, 2000; Verigin *et al.*, 1997).

The proposed identification method of relative contribution of possible acceleration processes assumes that the all ion species have undergone the same acceleration processes and took the similar transportation route. This assumption is reasonable for the ion species of planetary origin, while we cannot exclude the possibility that there is a case in which the observed protons came from the solar wind. Since we have rather limited amount of proper data so far this question cannot be resolved now.

4. Conclusion

It was demonstrated that the dependence of the energy of heavy ions on their mass could be a useful tool for the identification of possible acceleration processes in the Martian plasma sheet. The study was based on a few cases when heavier ions and protons were registered simultaneously in the plasma sheet by the TAUS energy spectrometer, and on

published data of the ASPERA instrument. According to the presented results frictional preacceleration of ions probably in the pole regions of the Martian magnetosphere can be responsible for less than 40% of the energy gain of heavy ions in the plasma sheet; the input of the cross-tail current sheet acceleration is likely to contribute up to 70%, and from 30 to 70% of the heavy ion energy is provided by the acceleration due to magnetic field line stresses (and/or electric field aligned acceleration). A further detailed mass analysis of the data may help to confirm this conclusion.

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