Cosmic Research, Vol. 37, No. 1, 1999, pp. 27–33. Translated from Kosmicheskie Issledovaniya, Vol. 37, No. 1, 1999, pp. 31–37.
Original Russian Text Copyright © 1999 by Kotova, Verigin, Shutte, Remizov, Rosenbauer, Riedler, Schwingenschuh, Delva, Szegö, Tatrallyay.

Acceleration of Heavy Ions in the Martian Magnetosphere Tail by the Data of the TAUS and MAGMA Experiments on the *Phobos-2* Spacecraft

G. A. Kotova*, M. I. Verigin*, N. M. Shutte*, A. P. Remizov*, H. Rosenbauer, W. Riedler***, K. Schwingenschuh***, M. Delva***, K. Szegö****, and M. Tatrallyay******

** Space Research Institute, Russian Academy of Sciences, ul. Profsoyuznaya 84/32, Moscow, 117810 Russia*
*** Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany*
**** Institut für Weltraumforschung, Graz, Austria*
***** Central Research Institute for Physics, Budapest, Hungary*

Received February 4, 1997

Abstract—The data obtained in the TAUS experiment carried out on board the *Phobos-2* spacecraft showed that in a plasma sheet in the vicinity of Mars, the three-dimensional distribution functions of heavy ions of the planetary origin have the form of a “mushroom cap”. To analyze the distribution of ions in the Martian magnetic tail both kinetic and magnetohydrodynamic approaches are used. A number of relationships between the properties of plasma and magnetic field in the magnetosphere tail and in the solar wind are considered. They bear witness to the following acceleration mechanisms taking part in the formation of the observed distribution of ions in the plasma sheet in the vicinity of Mars: acceleration due to the tension of magnetic field lines, acceleration in longitudinal and transverse electric fields of the tail, and acceleration through direct interaction of circumplanetary plasma with the plasma of a magnetosheath in polar regions of the magnetosphere.

INTRODUCTION

One of the most interesting results of measurements with the plasma TAUS experiment in the vicinity of Mars was the discovery of a plasma sheet in the Martian magnetosphere tail [1, 2]. The measurements showed that significant ion flows, streaming away from the planet, are often observed in the Martian magnetic tail. These flows were always recorded in the vicinity of that area, where the component of magnetic field B_x parallel to the Sun–Mars line changes its sign [3]. The data of the TAUS experiment showed that in contrast to the plasma sheet of the Earth's magnetosphere, which is, in the main, formed by protons, the Martian plasma sheet basically consists of heavy ions with the ratio of mass/charge $m/q > 3$. The simultaneous measurements with the ASPERA experiment, also carried out onboard *Phobos-2*, showed that the plasma sheet in the Martian magnetosphere is mainly formed by ions of oxygen O^+, though ions with other masses were also recorded [4, 5].

In several first orbits of the *Phobos-2* spacecraft about Mars, two-dimensional spectra of heavy ions were measured by the TAUS instrument. Rosenbauer *et al.* [1, 2] demonstrated examples of two-dimensional spectra (in terms of count rate), from which it is seen that the distribution of heavy ions in the Martian magnetosphere tail is very anisotropic: a spread in energies in the direction of motion of the flow (from the planet) is essentially less, than in the transverse direction. These distributions of ions are very similar to the proton distribution functions observed in the plasma sheet boundary layer near the Earth [6]. To explain the specific distributions of heavy ions in the Martian magnetosphere tail a few mechanisms of accelerating the circumplanetary ions were proposed: acceleration as a result of direct interaction of the solar wind plasma and circumplanetary ionospheric plasma [3]; acceleration under the action of tension of magnetic field lines [5]; acceleration in the current sheet of the magnetic tail [7], etc.

Below, the experimental data obtained in the plasma sheet near Mars will be considered in detail for the purpose of further more detailed analysis of possible mechanisms of the ion acceleration.

THE ANALYSIS OF MEASUREMENT RESULTS

On board the *Phobos-2* spacecraft, the TAUS energy-mass-spectrometer was installed, and with its help the measurements of energy (in the range ~50 eV to ~6 keV) and angular (within the limits of solid angle ±20° from the sunward direction) distributions of protons and heavy ions ($m/q > 3$) in the vicinity of Mars were performed [8]. The data obtained from ~60 identical circular orbits in February–March, 1986 (the radius of an orbit is ~9600 km) represent rather rich material for the statistical analysis. In these orbits, the one-dimensional energy (150 eV–6 keV) spectra of ions were measured for 8 s every 2 min.

0010-9525/99/3701-0027$22.00 © 1999 МАИК “Наука/Interperiodica”

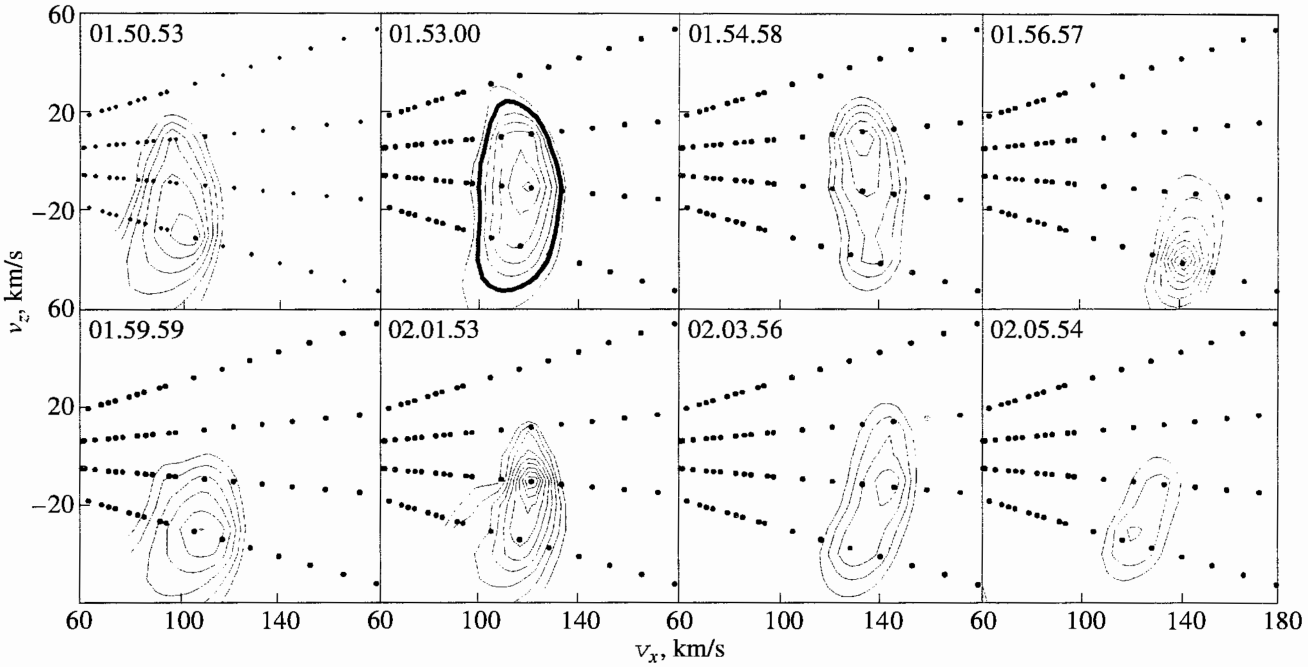

Fig. 1. Two-dimensional distribution functions of heavy ions (on the assumption that $m = 16$) recorded on the second elliptic orbit of *Phobos-2* near Mars on February 5, 1989. Positions in the phase space, in which the measurements were carried out by the TAUS instrument, are marked by points. Most external isoline of distribution functions corresponds to the value $f = 10^{-21}$ s^3 cm^{-6}, every next isoline corresponds to an increase of f by a factor of $10^{0.2}$.

In the first five elliptical orbits near the planet (pericenter is ~800 km), the two-dimensional spectra of heavy ions were also measured for some time (one spectrum per minute). The two-dimensional spectra result from integrated observations over the azimuth angle. In the mode of three-axis stabilization (3rd, 4th, and 5th orbits), the spectra were recorded approximately in the *XZ* plane of the Martian solar-ecliptic coordinate system. However, reliable two-dimensional measurements of the spectra of the plasma sheet ions in the mode of three-axis stabilization of the spacecraft were carried out only in the 4th orbit, because in the 3rd and 5th orbits the measurements of two-dimensional spectra of heavy ions fell on an area near the magnetopause.

In the first and second elliptical orbits, the spacecraft rotated with a period of ~10 min around the axis approximately oriented to the Sun, and this allows us to reconstruct the character of three-dimensional spectra of ions by the measured two-dimensional ones.

To measure the magnetic field in the vicinity of Mars the MAGMA flux-gate magnetometer was installed onboard the *Phobos-2* spacecraft [9]. Unfortunately, because of the rotation of the spacecraft, in the majority of orbits about the planet one can use for a reliable analysis only the magnitude of magnetic field B and its components along (B_x) and across the Sun–Mars line ($B_\perp = \sqrt{B_y^2 + B_z^2}$).

Figure 1 shows examples of the two-dimensional spectra of heavy ions recorded in the Martian plasma sheet in the second elliptical orbit (every second spectrum is shown sequentially). It is seen that the spectra at all times have a characteristic extended bean-like form, only the maximum of the distribution function is shifted, obviously, because of the rotation of the spacecraft around the axis, whose true direction deviates by a ~15° angle from the sunward direction. The presented distribution functions testify that the real three-dimensional distribution of the plasma sheet ions is approximately symmetric relative to the sunward direction and has the specific form of a "mushroom cap." Similar distributions of protons were observed previously near the Earth in the plasma sheet boundary layer [6]. To explain such distribution functions, some possible mechanisms of ion acceleration in the plasma sheet were considered: acceleration in the longitudinal electrical field, deformation of spectra because of conservation of the magnetic moments of particles, acceleration in the current sheet of the magnetic tail, etc.

Assuming that the initial distribution of ions in the vicinity of Mars is close to a Maxwellian one, it is not difficult to calculate what changes in the distribution function of ions their acceleration in the longitudinal electrical field will cause, provided that the first adiabatic invariant (magnetic moment) is also conserved. Let us consider the initial ion distribution

$$f(v'_{\parallel}, v'_{\perp}) = n(m/2\pi kT)^{3/2} \times \exp[-m((v'_{\parallel} - v_0)^2 + v'^2_{\perp})/2kT], \tag{1}$$

where $v'_{\parallel}$ and $v'_{\perp}$ are the initial velocity components along and across the magnetic field, v_0 is the initial bulk velocity, m, n, and T are the mass, density, and temperature of ions, respectively, and k is the Boltzmann constant. New components of the ion velocity, $v_{\parallel}$ and $v_{\perp}$, can be expressed through their initial values, using the energy conservation law and the condition of conservation of the magnetic moment of ions:

$$v^2_{\parallel} + v^2_{\perp} = v'^2_{\parallel} + v'^2_{\perp} + \frac{2q\Phi}{m}, \qquad \frac{v^2_{\perp}}{B_2} = \frac{v'^2_{\perp}}{B_1}, \tag{2}$$

where B_1 and B_2 are the magnetic field magnitudes in the areas before and after ion acceleration, respectively, q is the electric charge, Φ is the electric potential difference. According to the Liouville's theorem, in this case the final distribution of ions is

$$f(v_{\parallel}, v_{\perp}) = n(m/2\pi kT)^{3/2} \times \exp\left[-\frac{m}{2kT}\left(\left(\sqrt{(v^2_{\parallel} + v^2_{\perp}(1 - B_1/B_2) - 2q\Phi/m)} - v_0\right)^2 + v^2_{\perp}\frac{B_1}{B_2}\right)\right]. \tag{3}$$

Now, one can define the "width" of such a distribution of ions at some level $f = f^*$, along the magnetic field $\Delta v_{\parallel}$ ($v_{\perp} = 0$):

$$\Delta v_{\parallel} = \sqrt{2\left(v^2_{\max} + \frac{2kT\eta}{m}\right) + 2\sqrt{\left(v^2_{\max} + \frac{2kT\eta}{m}\right)^2 + 4\frac{2kT\eta}{m}\frac{2q\Phi}{m}}}, \tag{4}$$

and across the magnetic field $\Delta v_{\perp}$ (between points, where $\partial f/\partial v_{\parallel} = 0$):

$$\Delta v_{\perp} = 2\sqrt{\frac{2kT\eta}{m}\frac{B_2}{B_1}}, \tag{5}$$

where $v_{\max} = \sqrt{v_0^2 + 2q\Phi/m}$ is the ion velocity at a maximum of distribution function, $f_{\max} = n(m/2\pi kT)^{3/2}$, $\eta = \ln(f_{\max}/f^*)$.

By this means, any experimentally observed ion distribution function with parameters $v_{\max}$, $\Delta v_{\parallel}$, and $\Delta v_{\perp}$ can be approximated by theoretical expression (3) at a unique combination of the values Δ, v_0, T for any known ratio B_1/B_2.

Let us consider as an example the second spectrum in the top row of Fig. 1 measured at 01:53 UT. The level of distribution function shown by a heavy line in this spectrum corresponds to the following parameters: $\Delta v_{\parallel} = 33$ km/s, $\Delta v_{\perp} = 78$ km/s, $v_{\max} = 120$ km/s, $\eta = \ln(10^{-19.8}/10^{-20.8})$. Figure 2 shows calculated distribution functions of ions (3), having the same parameters, for four various values of the ratio B_1/B_2 (see table). It is seen from this figure that at least two right spectra have too strong a condensation of contour lines at the left part in comparison with the experimental spectrum. Thus, it is possible to describe the experimental spectrum by distribution function (3) only assuming that before the considered mechanism of acceleration in the longitudinal electrical field with simultaneous conservation of the magnetic moments of ions comes into play, there is also some preliminary acceleration of particles up to velocities of ~100 km/s. Moreover, attention should be drawn to the fact that the magnetic field in the area of observation of accelerated particles should be stronger than the initial magnetic field. The polar areas of the Martian magnetosphere, which are similar to the polar areas in the induced magnetosphere of Venus considered in [10], can serve as such regions of ion preacceleration. Ionospheric ions can be accelerated in these regions due to direct interactions with the solar wind of the magnetosheath.

Another mechanism of acceleration, which can be responsible for the specific form of distribution functions of ions in the plasma sheet of the Martian magnetosphere, is the acceleration in the current sheet of the magnetic tail [11, 12]. In the thin current sheet, at the center of the magnetic tail, magnetic moments of particles are not conserved, and under the action of the transverse electric field the particles are accelerated along the tail, gaining at initial energy close to zero the velocity $v \sim 2c\varepsilon/B_{\min}$, where ε is the electric field across the tail and c is the velocity of light. Some correlation dependences (Fig. 3) revealed as a result of analysis of the data obtained in circular orbits near Mars point to possible participation of such a mechanism in acceleration of planetary ions in the Martian magnetosphere tail. Figure 3 shows at the left panels the dependences of the maximum energy E of heavy ions recorded in each spacecraft passage through the plasma sheet and of corresponding velocity v of oxygen ions on the minimum value of magnetic field $B_{\min}$ measured in the cur-

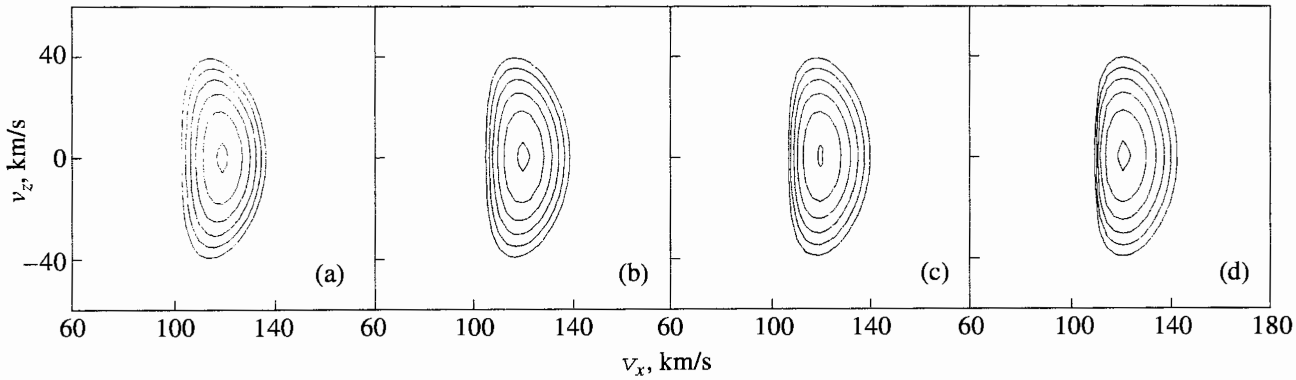

Fig. 2. Calculated distribution functions of ions, having the same parameters $v_{\max}$, $\Delta v_{\parallel}$, $\Delta v_{\perp}$ as distribution recorded on February 5, 1989 at 01:53 UT by the TAUS instrument.

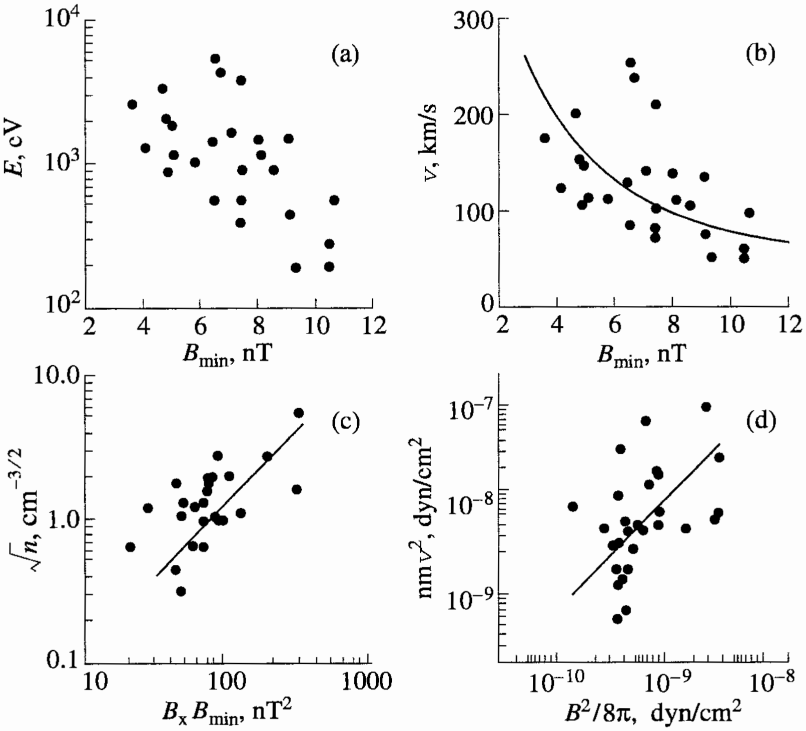

Fig. 3. Correlations of parameters of the plasma sheet heavy ions and magnetic field in the Martian tail. Lines correspond to approximation by the least squares method.

rent sheet. A clear inversely proportional dependence of these values is seen, which can be interpreted as evidence for the existence of an electric field across the Martian magnetic tail. The average magnitude of this field was ε ~ 0.4 mV/m during the operation of *Phobos-2* in orbit. The same estimation of the electric field strength can be obtained from the correlation of magnitudes $\sqrt{n}$ and $B_xB_{\min}$, also shown in Fig. 3. Such a correlation should follow from the expression for the transverse electric field:

$$\varepsilon = \frac{B_x B_{\min}}{\sqrt{4\pi n m}}, \tag{6}$$

that was obtained on the basis of the Ampere law and the law of conservation of particles [13, 14]. Substituting $\varepsilon = vB_{\min}/2c$ into expression (6) and taking into account that $B_x \approx B$, we obtain

$$nmv^2 = \frac{B^2}{\pi}. \tag{7}$$

Indeed, the linear approximation of the dependence between the quantities nmv^2 and $B^2/8\pi$ (Fig. 3d) is close to equation (7).

By this means, ions of planetary origin in the current sheet of the Martian magnetic tail, in the configuration of magnetic field in the tail similar to the Venusian magnetic tail configuration, where a determining role is played by the induced magnetic field, can be accelerated to significant energies moving in the direction away from the planet (see [15]). These ions can be observed in a rather narrow area in the vicinity of the neutral sheet, since the transverse drift component of the velocity, $\sim c\varepsilon/B_x$, does not move the ions far from this sheet at a distance of ~6200 km from the planet, corresponding to the circular orbit of the *Phobos-2* spacecraft. In this case, the distribution functions of accelerated particles have the characteristic form of a "mushroom cap" [16]. However, it should be noted that these distributions have also a rather sharp low-energy edge, while no such phenomenon is observed in the data of the TAUS experiment.

One more circumstance requires further analysis. In the current sheet of the magnetic tail the ions of various masses are accelerated to one and the same velocity and, hence, their energy should be proportional to their mass. Nevertheless, this is not supported by the data of the ASPERA experiment (Fig. 4, [5]), which show no dependence of energy of heavy ions on their mass, but the energy of protons recorded in the plasma sheet is less than the energy of oxygen ions by a factor of 2–3.

One more possible mechanism of the acceleration of planetary ions into the plasma sheet of the Martian magnetic tail, i.e., the acceleration due to a tension of magnetic field lines, was considered by Dubinin *et al.* [5]. In the approximation of the magnetic hydrodynamics:

$$\rho(\mathbf{V}, \nabla\mathbf{V}) \approx \frac{1}{c}[\mathbf{j}, \mathbf{B}], \tag{8}$$

where $\rho = nm$ is the mass density of heavy ions, $j = \frac{c}{2\pi}\frac{B_x}{\delta}$ is the current density across the magnetic tail, and δ is the characteristic thickness of the current sheet. In the direction of the X axis of the Martian solar-ecliptic coordinate system, (8) is reduced to the equation:

$$\rho v \frac{\partial v}{\partial x} \approx \frac{1}{c} j B_{\perp}, \tag{9}$$

where v is the flow velocity of heavy ions directed away from Mars. The dynamic pressure of the flow of heavy ions can be estimated as follows:

$$\rho v^2 \approx \frac{B_x B_{\perp}}{\pi} \frac{L}{\delta}, \tag{10}$$

where L is the characteristic scale of acceleration along the X axis. Figure 5a shows the dynamic pressure of the heavy ion flow versus the quantity $B_x B_{\perp}$. Indeed, a certain correlation of these quantities is seen. A correlation straight line drawn in the plot corresponds to the ratio L/δ, i.e., at $L \sim 4000$ km, $\delta \sim 1000$ km, which comprises ~10% of the characteristic value of the diameter of the Martian magnetic tail (cf. [3]).

Table

Parameter	Fig. 2a	Fig. 2b	Fig. 2c	Fig. 2d
V_0, km/s	102	73	60	53
T, 10^3 K	160	320	480	680
Φ, V	335	760	900	970

The correlation is improved (Fig. 5b), if one assumes that the δ quantity is proportional to the ion cyclotron diameter

$$\delta = \chi \frac{2v_{\text{th}}}{\omega_{ci}} = 2\chi c \frac{\sqrt{2kTm}}{qB_x} \tag{11}$$

and

$$\rho v^2 \approx \frac{qB_x^2 B_{\perp}}{2\pi c\sqrt{2kTm}\chi} \frac{L}{\chi}, \tag{12}$$

where χ is a factor of proportionality, v_{th} is the thermal velocity of the ions, and ω_{ci} is the cyclotron frequency. The correlation straight line shown in Fig. 5 corresponds to $\delta \sim 1500$ km ($\chi \sim 3.5$) for $L = 4000$ km and typical parameters $T = 2 \times 10^5$ K and $B_x = 10\gamma$. Both correlations presented in Fig. 5 confirm that the conjectures of Dubinin *et al.* [5] warrant consideration and testify that the mechanism of acceleration of planetary ions in the Martian magnetosphere tail through the tension of magnetic field lines probably plays a significant role.

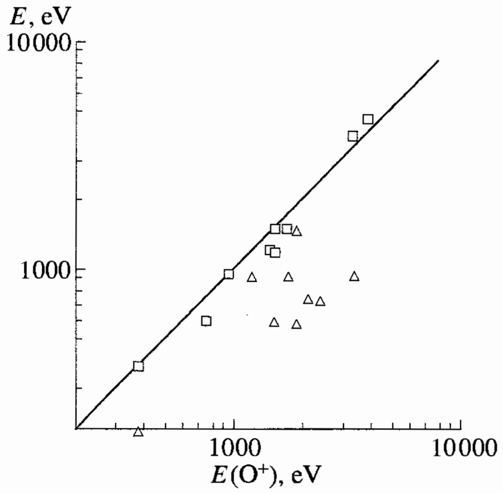

Fig. 4. Dependence of the maximum energy of the flows of molecular ions CO_2^+, O_2^+ (squares), and protons (triangles) on the maximum energy of oxygen ions for several passages of the *Phobos-2* spacecraft through the Martian magnetic tail by the data of the ASPERA experiment [5].

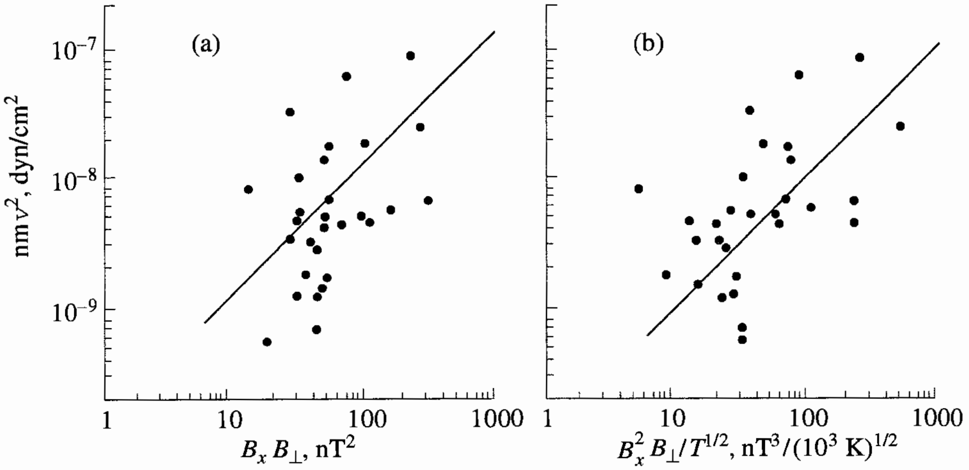

Fig. 5. Dynamic pressure of plasma sheet heavy ions versus combinations of the magnetic field components and temperature of ions in the Martian tail. Straight lines correspond to approximation by the least squares method.

CONCLUSIONS

(1) Two-dimensional measurements of ion spectra in the TAUS experiment carried out on the *Phobos-2* spacecraft showed that the distribution functions of heavy ions in the plasma sheet of the Martian magnetosphere tail have a specific form, reminding one of a mushroom cap. Similar distributions of protons were observed in the Earth's plasma sheet boundary layer, and this testifies that the mechanisms of ion acceleration in the tails of the magnetospheres of Mars and the Earth are possibly the same.

(2) The observed distribution functions cannot be a consequence of the mechanism of ion acceleration in a longitudinal electric field with simultaneous deformation of the distribution function due to conservation of the magnetic moment, because, in this case, ions should be preaccelerated to a velocity of ~100 km/s.

(3) One-dimensional measurements of ion spectra in the TAUS experiment on circular orbits of the *Phobos-2* spacecraft in February–March, 1989 gave fairly rich statistical material for the analysis of dependences of the parameters of heavy ions of the Martian plasma sheet on the magnetic field strength in the tail and on parameters of the solar wind.

(4) The correlation of the flow velocity of heavy ions and the minimum magnetic field value recorded in the area of the neutral sheet seems to point to the existence of a transverse electric field in the Martian magnetosphere tail and, hence, to a possible acceleration of the ions in the central current sheet of the tail.

(5) The correlation of the dynamic pressure of the flow of the plasma sheet heavy ions and the quantity $B_x^2 B_\perp / T^{1/2}$ (and less clearly pronounced correlation with $B_x B_\perp$) shows that the ion acceleration through the tension of magnetic field lines is also probably essential in the Martian magnetosphere tail.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 95-02-04223) and INTAS (grant no. 94-982).

REFERENCES

1. Rosenbauer, H., Shutte, N., Apathy, I., *et al.*, Ions of Martian Origin and Plasma Sheet in the Martian Magnetosphere: Initial Results of the TAUS Experiment, *Nature*, 1989, vol. 341, no. 6243, p. 612.
2. Rosenbauer, H., Shutte, N., Apathy, I., *et al.*, First Results of Measuring the Ions of Martian Origin and Discovering a Plasma Layer in the Magnetosphere of Mars according to the Data of TAUS Experiment onboard the *Phobos-2* Spacecraft, *Pis'ma Astron. Zh.*, 1990, vol. 16, p. 368.
3. Verigin, M.I., Shutte, N.M., Galeev, A.A., *et al.*, Ions of Planetary Origin in the Martian Magnetosphere (Phobos 2/TAUS Experiment), *Planet. Space Sci.*, 1991, vol. 39, p. 131.
4. Lundin, R., Zakharov, A., Pellinen, R., *et al.*, First Measurements of the Ionospheric Plasma Escape from Mars, *Nature*, 1989, vol. 341, no. 6243, p. 609.
5. Dubinin, E., Lundin, R., Norberg, O., and Pissarenko, N., Ion Acceleration in the Martian Tail: Phobos Observations, *J. Geophys. Res.*, 1993, vol. 98, p. 3991.
6. Eastman, T.E., DeCoster, R.J., and Frank, L.A., Velocity Distributions of Ion Beams in the Plasma Sheet Boundary Layer, in *Ion Acceleration in the Magnetosphere and Ionosphere*, Geophysical Monograph 38, Washington, D.C.: AGU, 1986, p. 117.
7. Ip, W.-H., Ion Acceleration at the Current Sheet of the Martian Magnetosphere, *Geophys. Res. Lett.*, 1992, vol. 19, p. 2095.
8. Rosenbauer, Kh., Shutte, N., Apathy, I., *et al.*, Investigation of 3D Distribution Functions of Basic Ions (Protons and Alpha-Particles) of the Solar Wind, in the "Phobos" Project. The TAUS Experiment (MPK Complex), in

Apparatura i metody issledovaniya kosmicheskogo prostranstva (Instrumentation and Methods for Space Research), Moscow: Nauka, 1989, p. 30.

9. Aydogar, Ö., Schwingenschuh, K., Schelch, G., *et al.*, The Phobos Fluxgate Magnetometer (MAGMA) Instrument Description, IWF-8904, Austrian Academy of Sciences, 1989.
10. Perez-de-Tejada, H., Viscous Flow Circulation of the Solar Wind behind Venus, *Science*, 1980, vol. 207, p. 981.
11. Shabanskii, V.P., *Yavleniya v okolozemnom prostranstve* (Phenomena in the Near-Earth Space), Moscow: Nauka, 1972, pp. 167–190.
12. Speicer, T.W., Particle Trajectories in Model Current Sheets. 1. Analytical Solutions, *J. Geophys. Res.*, 1965, vol. 70, p. 4219.
13. Eastwood, J.W., Consistency of Fields and Particle Motion in the "Speicer" Model of the Current Sheet, *Planet. Space Sci.*, 1972, vol. 20, p. 1555.
14. Hill, T.W., Magnetic Merging in a Collisionless Plasma, *J. Geophys. Res.*, 1975, vol. 80, p. 4689.
15. Cowley, S.W.H., Plasma Populations in a Simple Open Model Magnetosphere, *Space Sci. Rev.*, 1980, vol. 26, p. 217.
16. Lyons, L.R. and Speicer, T.W., Evidence for Current Sheet Acceleration in the Geomagnetic Tail, *J. Geophys. Res.*, 1982, vol. 87, p. 2276.