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PLANETARY HEAVY IONS IN THE MAGNETOTAIL OF MARS: RESULTS OF THE TAUS AND MAGMA EXPERIMENTS ABOARD PHOBOS

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ABSTRACT

Both kinetic and hydrodynamic properties of specific 'mushroom-cap' distributions of heavy ions in the plasma sheet of the Martian magnetotail are analyzed to identify possible processes of planetary ion acceleration. A number of correlations of different plasma sheet and solar wind parameters are studied to find signatures of ion acceleration by magnetic field line shear stress, field aligned and cross tail electric field, as well as by direct interaction with the magnetosheath plasma in the 'pole' regions.

INTRODUCTION

One of the most interesting phenomena in the near-Martian space discovered by the TAUS experiment aboard Phobos 2 is the plasma sheet in the magnetotail of the planet (Rosenbauer *et al.*, 1989). The observations demonstrated that the plasma sheet in the Martian magnetotail surrounded the magnetic neutral sheet, similar to the plasma sheet in the geomagnetic tail. However the Martian plasma sheet mainly consists of planetary heavy ions ($m/q > 3$) in contrast to the case of the Earth (Verigin *et al.*, 1991). Simultaneous observations by the ASPERA instrument indicated the presence of ions with different masses in the Martian plasma sheet though oxygen ions were prevailing (Lundin *et al.*,1989; Dubinin *et al.*, 1993)). Few 2-D ion spectra released by Rosenbauer *et al.* (1989) demonstrated a supersonic, highly anisotropic ion distribution function in this formation. Different acceleration processes were considered to explain the existence of fast planetary ion fluxes in the magnetotail of Mars, e.g., acceleration resulting from the shear stress of the draped magnetic field lines, field aligned and cross tail current sheet acceleration, as well as acceleration by the direct interaction with the magnetosheath plasma in the 'pole' regions (Verigin *et al.*, 1991; Ip, 1992; Dubinin *et al.*, 1993). Both kinetic and hydrodynamic properties of the Martian plasma sheet will be analyzed below in order to provide additional information on possible processes of planetary ion acceleration.

OBSERVATIONAL DATA AND THEIR ANALYSIS

The TAUS ion spectrometer and the MAGMA magnetometer on board the Phobos 2 spacecraft provide a near complete set of data from ~ 60 circular orbits around Mars for statistical studies of heavy ion fluxes in the magnetotail of the planet. In these orbits the TAUS instrument measured 1-D heavy ion energy spectra once every 2 min. In addition, in several portions of elliptical orbits, 2-D ion measurements were performed. These spectra were measured once per minute in the plane nearly coincident with the XZ plane of the Martian solar ecliptic coordinates at three axial stabilized orbits (3-5); in the 1-st and 2-nd elliptical orbits the rotation of the spacecraft with a period of ~ 10 min approximately around the X-axis can be used for elucidation of the properties of 3-D velocity distribution of heavy ions.

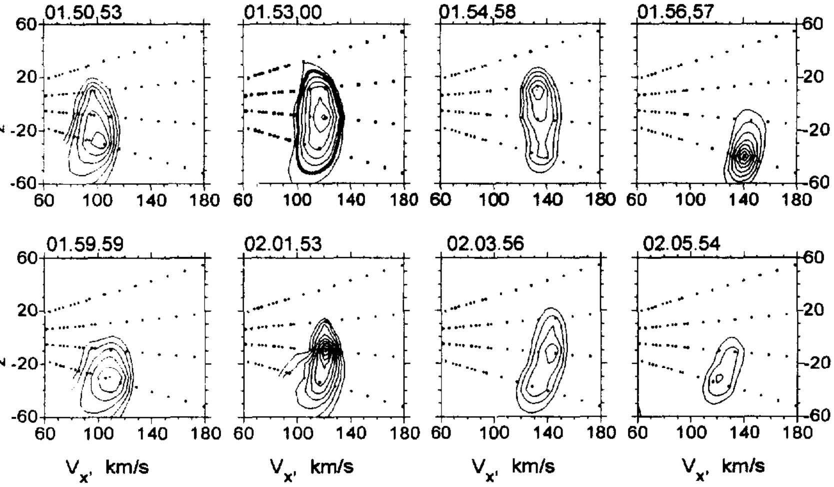


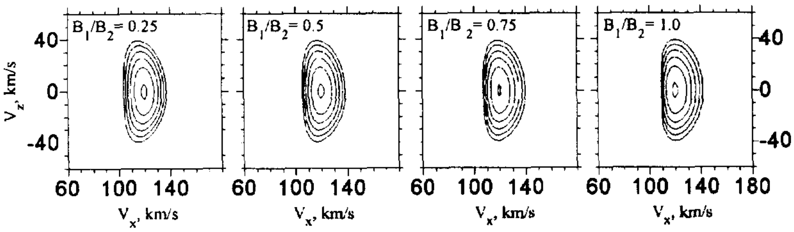
Fig. 1. 2-D heavy ion spectra (m assumed to be 16) measured in the second elliptical orbit 5 February 1989. (points mark the centers of the instrument velocity space windows where the values of distribution function f were evaluated from measurements). The outermost isoline of the distribution function corresponds to f = 10^{-21} s^3cm^{-6}; f increases by a factor of $10^{0.2}$ to every inner isoline.

Figure 1 presents examples of 2-D heavy ion spectra successively measured by TAUS in the 2-nd elliptical orbit (every second spectrum is shown). Each 2-D "cross-section" of the real 3-D distribution function f in Figure 1 has a specific "bean" shape while the maximum of f moves up and down along the instrument Z-axis with a period of the s/c rotation. It means that the 3-D distribution function is more or less symmetric around the X-axis and has specific "lima bean" or "mushroom cap" shape. In the Earth's magnetosphere similar distributions were observed in the plasma sheet boundary layer where several acceleration mechanisms were invoked for the explanation of the above mentioned shapes of ion distributions, e.g. acceleration by the field-aligned electric field, adiabatic deformation of the distributions, acceleration in the current sheet etc. (Eastman *et al.*, 1986).

To check whether the effect of field-aligned acceleration combined with adiabatic deformation can explain the observed distribution functions of ions, the following calculations were made. The initial convective maxwellian distribution $f(v'_{\parallel}, v'_{\perp}) = n(m/2\pi kT)^{3/2}\, e^{-m((v'_{\parallel}-v_0)^2+v'^2_{\perp})/2kT}$, where $v'_{\parallel}$, $v'_{\perp}$ are the initial ion velocity components parallel and perpendicular to the magnetic field, v_0 is the initial ion bulk velocity, m, n, and T are the mass, density and temperature of ions, respectively, is transformed by the action of the field-aligned electric field with potential Φ. Under the condition of conservation of magnetic moment, new ion velocity components $v_{\parallel}$, $v_{\perp}$ are expressed through the initial ones and the final distribution can be written as

$$f(v_{\parallel}, v_{\perp}) = n(m/2\pi kT)^{3/2}\, e^{-\frac{m}{2kT}\left(\left(\sqrt{\left(v_{\parallel}^2+v_{\perp}^2(1-B_1/B_2)-2e\Phi/m\right)}-v_0\right)^2+v_{\perp}^2\frac{B_1}{B_2}\right)}, \tag{1}$$

where B_1 and B_2 are the magnitudes of the initial and final magnetic fields, respectively. At some level f^*, velocity distribution widths along ($\Delta v_{\parallel}$) and perpendicular ($\Delta v_{\perp}$) to the magnetic field are the following: $\Delta v_{\parallel} = \sqrt{2(v_{max}^2 + 2kTc^*/m) - 2\sqrt{(v_{max}^2 - 2kTc^*/m)^2 + 16e\Phi kTc^*/m^2}}$, $\Delta v_{\perp} = \sqrt{8kTc^*/m \cdot B_2/B_1}$, where $v_{max} = \sqrt{v_0^2 + 2e\Phi/m}$ and $c^* = \ln(f_{max}/f^*)$, v_{max} corresponds to the maximum value of the distribution function f_{max}. So, for any value of the ratio B_1/B_2, the only values of Φ, v_0 and T can be determined which fit the observed combination of parameters v_{max}, $\Delta v_{\parallel}$, $\Delta v_{\perp}$.



V_0	102	73	60	53	km/s
T	160	320	480	640	10^3K
Φ	335	760	900	970	V

Fig. 2. Calculated distribution functions with the same parameters v_{max}, $\Delta v_{\parallel}$, $\Delta v_{\perp}$ as those of the distribution function observed by TAUS on Feb.5, 01.53 UT.

To compare measured and calculated heavy ion spectra, the spectrum from Figure 1 measured at 01.53UT was used. A level of distribution function marked by the thick curve defines the following values of: $\Delta v_{\parallel}$= 33 km/s, $\Delta v_{\perp}$= 78 km/s, v_{max}= 120 km/s, and c^* = $\ln(10^{-19.8}/10^{-20.8})$. Figure 2 shows the spectra calculated with Eq.1 for four different values of the ratio B_1/B_2. At least two spectra on the right side have too sharp low energy edge in comparison with the observed spectrum. This figure demonstrates that for the approximation of heavy ion spectra observed in the Martian plasma sheet by the model of field aligned acceleration with adiabatic deformation, it is necessary to assume that some preacceleration process exists to velocities v_0 of several tens of km/s. Possible sites of preacceleration are the 'pole' regions of the induced part of the Martian magnetosphere, similar to those introduced by Perez-de-Tejada (1980) for the induced magnetosphere of Venus, where magnetosheath plasma can directly drive planetary heavy ions.

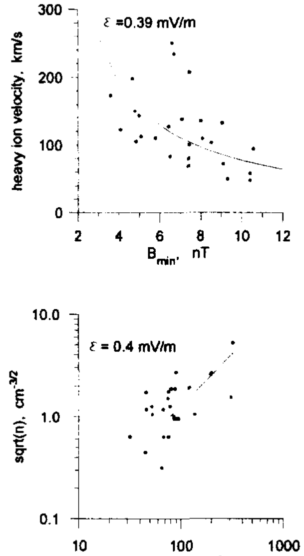


Fig. 3. Correlations of plasma sheet ion and magnetic field parameters giving evidence for the current sheet acceleration

Another acceleration mechanism that could account for the specific shape of heavy ion spectra in the plasma sheet is acceleration in the magnetotail current sheet (Speicer, 1965, Shabanskiy, 1972). Indeed, Figure 3 shows that the maximum bulk velocity of heavy ions v_{max} recorded at every spacecraft crossing of the plasma sheet is inversely proportional to the minimum value of the magnetic field measured in the current sheet. Taking into account that $v_{max} \approx 2c\varepsilon/B_{min}$, where ε is a cross tail electric field in the Martian magnetosphere, c is the velocity of light, correlation in Figure 3 provides a possibility to estimate the average electric field during the time of the Phobos 2 flight as $\varepsilon \approx 0.4$mV/m. Furthermore, the same estimation of the average electric field can be obtained from the correlation of $\sqrt{n}$ and $B \cdot B_{min}$ which is also shown in Figure 3. This correlation follows from the expression for the cross tail electric field deduced by Eastwood (1972) (see also Hill, 1975). However, in the process of current sheet acceleration, ions of different mass get the same velocity and hence, their energy is proportional to mass. This fact seems not to be completely consistent with the ASPERA instrument data (see Figure 4 in Dubinin *et al.*, 1993) which do not indicate clear dependence of the energy of heavy ions on their mass while the energy of protons observed in the plasma sheet is 2-3 times less than the energy of oxygen ions.

Dubinin *et al.*(1993) studied the possibility of acceleration of ions to the Martian plasma sheet as a result of the action of magnetic field line shear stresses. In the MHD approximation, the projection to the X-axis of the equation of ion motion can be reduced to: $\rho v \partial v/\partial x \approx jB_\perp/c$, where ρ is the ion mass density, $j \approx (c/2\pi)(B_x/\delta)$ is the cross tail current, $B_\perp = \sqrt{B_y^2 + B_z^2}$, δ is the specific width of the current sheet. So after a distance L, the ram pressure of accelerated ions is estimated as $\rho V^2 \approx (B_x B_\perp/\pi)(L/\delta)$. Figure 4 shows, that there is really some correlation between the heavy ion ram pressure and the value of $B_x B_\perp$. Assuming δ to be proportional to the ion cyclotron diameter: $\delta = \eta 2 v_{th}/\omega_{ci} = 2\eta c\sqrt{2kT/(qmB_x)}$, where η is a coefficient and v_{th} is the ion thermal speed, we should expect also the correlation between the ion ram pressure and the value of $B_x^2 B_\perp/T^{1/2}$. This latter correlation was also revealed and was better than the former one. Both correlations provide evidence that the magnetic field line stress acceleration is also an important process in the Martian magnetotail, thus supporting Dubinin et al., (1993) consideration.

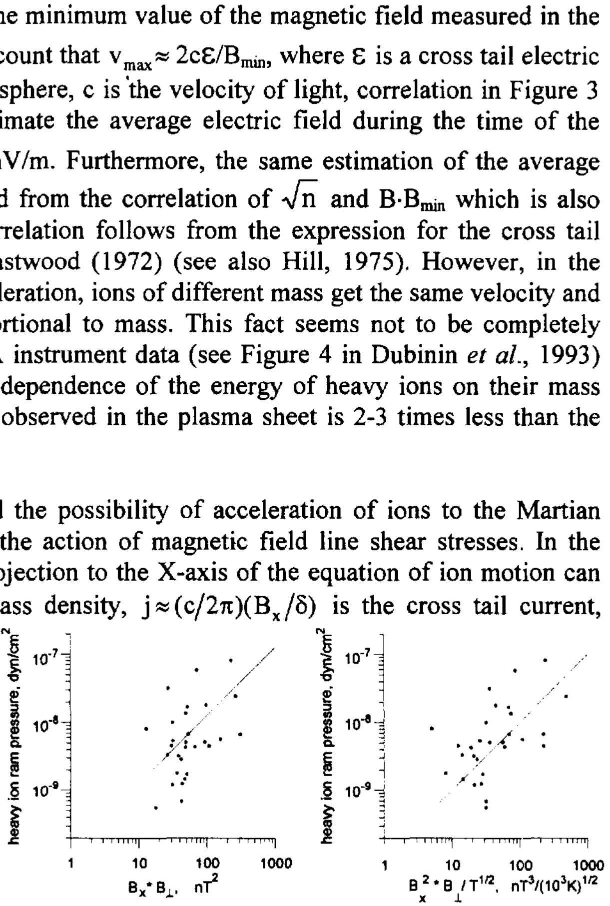


Fig. 4. Correlations of plasma sheet ion and magnetic field parameters giving evidence for the shear stress acceleration.

Finally, the TAUS spectrometer data revealed further correlations between the parameters of plasma sheet heavy ions and solar wind protons (Figure 5). Thus, heavy ion ram pressure is approximately equal to the solar wind ram pressure, that could be the consequence

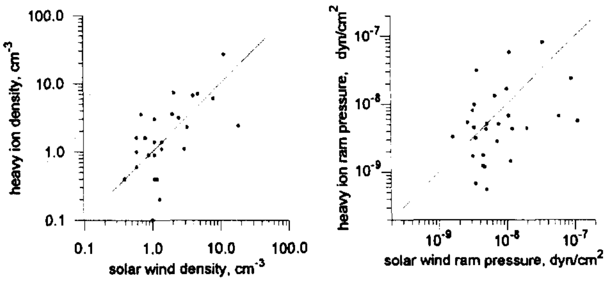


Fig. 5. Correlations of the plasma sheet parameters with solar wind characteristics.

of the direct dynamic connection of the solar wind plasma with the plasma sheet, possibly through the 'pole' holes. The data also showed that the density of heavy ions in the plasma sheet is nearly the same as the solar wind density. This striking dependence has no explanation now and should be carefully examined in future missions to Mars.

CONCLUSIONS

- The specific 'mushroom-cap' distribution function of heavy ions in the Martian plasma sheet is reminiscent of the shape of proton distributions in the magnetotail of the Earth, assuming similarity of some aspects of acceleration processes.
- The distribution functions observed can not be explained within the frames of field aligned acceleration and adiabatic deformation model only and initial preacceleration of ions to velocities of several tens of km/s is required in this case.
- 1-D heavy ion measurements by TAUS during Phobos 2 circular orbits in February - March 1989 provide reasonable statistics to analyze the dependencies of the parameters of plasma sheet heavy ions on the Martian tail lobe magnetic field and on solar wind characteristics.
- The correlation between heavy ion velocity and minimum magnetic field strength in the neutral sheet might be attributed to the current sheet acceleration, which also can produce the observed 'mushroom-cap' ion distributions.
- The correlation of heavy ion ram pressure with the value $B_x^2B_\perp/T^{1/2}$ (and a less pronounced correlation with $B_xB_\perp$) shows that the magnetic field line stress acceleration is also important in the Martian magnetotail.
- The correlation of plasma sheet ram pressure with that of the solar wind could be the consequence of the direct dynamic connection of the solar wind plasma with the plasma sheet (possibly through the 'pole' holes) while the striking 'equality' of solar wind and plasma sheet ion densities still needs explanation.

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