Pergamon

Phys. Chem. Earth (C), Vol. 25, No. 1-2, pp. 157-160, 2000

1464-1917/00/$ - see front matter

PII: S1464-1917(99)00060-4

Heavy Ions in the Magnetosphere of Mars: Phobos 2/TAUS Observations

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Received 30 September 1998; revised 11 March 1999; accepted 6 May 1999

Abstract. Data on heavy ion (mass/charge ratio $m_i/q > 3$) fluxes in the Martian plasma sheet collected by the TAUS experiment aboard the Phobos 2 orbiter and data of the MAGMA magnetometer are analyzed statistically. The analysis suggests that acceleration due to magnetic field line stresses and acceleration in the central current sheet could account for the observations, though planetary ions are likely to be preaccelerated to velocities of 40 – 50 km/s. The effectiveness of these acceleration processes of heavy ions in cases of high and low solar wind ram pressure is considered.

1 Introduction

Plasma sheet in the Martian magnetotail was revealed with the TAUS (Rosenbauer et al., 1989) and HARP (Shutte et al., 1989) plasma experiments aboard the Phobos 2 spacecraft, and so far this orbiter provided the only plasma measurements in the deep planetary tail. The Martian plasma sheet is a layer of plasma surrounding the magnetic neutral sheet, but contrary to the terrestrial plasma sheet, that is formed primarily by protons, the Martian plasma sheet mainly consists of planetary heavy ions accelerated tailward (Rosenbauer et al., 1989, Lundin et al., 1990). Different acceleration processes were considered to account for the observations: field aligned and cross tail electric field acceleration, acceleration due to shear stresses of the draped magnetic field lines, direct interaction with magnetosheath plasma in the 'pole' regions (see e.g. Verigin et al., 1991; Ip, 1992; Dubinin et al., 1993, Kotova et al., 1997). Analysis of 2D ion spectra measured by the TAUS spectrometer in several parts of Phobos 2 elliptical orbits at times when the spacecraft was spinning, suggested that 3D distribution function of heavy ions has a "mushroom cap" shape similar to the shape of proton distributions in the terrestrial plasma sheet boundary layer (Kotova et al., 1997). It was then demonstrated, that simple field aligned acceleration with adiabatic deformation of distribution function can account for the observations only in a case of initial preacceleration of ions to velocities of several tens of km/s. A number of correlations of plasma sheet and solar wind parameters were found that pointed on the importance of magnetic field line stress acceleration and magnetotail current sheet acceleration of heavy ions (Kotova et al., 1997). More detailed analysis of these mechanisms will be given below.

Plasma and magnetic measurements aboard the Phobos 2 orbiter suggested that both planetary ionosphere and magnetic field seem to be important in the solar wind interaction with Mars under different upstream plasma ram pressures (Verigin et al., 1997). Recent measurements aboard Mars Global Surveyor stressed the importance of the solar wind interaction with the Martian ionosphere but revealed numerous magnetic anomalies that could be responsible for the variability of plasma boundaries (Acuna et al., 1998). Significance of different acceleration processes of heavy ions in cases of high and low solar wind ram pressure will be considered below.

2 Observations

The TAUS plasma spectrometer was installed aboard the Phobos 2 Mars orbiter for ion measurements in the energy range 0.03 – 6 keV. It measures separately proton and heavy ion (mass/charge ratio $m_i/q > 3$) spectra and provides data from 5 elliptical and ~ 60 circular orbits. 1D heavy ion spectrum was measured during 8 s once per 2 min. It is worth to mention that in most of the orbits the spacecraft was rotating with the period ~ 10 – 12 minutes around the axis directed nearly to the Sun. Magnetic field data were obtained with the MAGMA magnetometer aboard Phobos 2.

The TAUS instrument recorded fluxes of planetary heavy ions in every magnetotail traversal except one, and the ion energy varies through the entire instrument range. Figs. 1 and 2 present examples of heavy ion measurements inside

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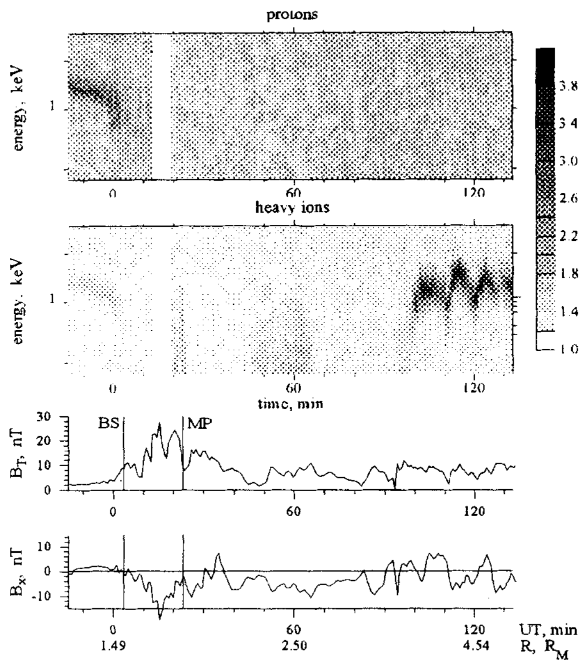

Fig. 1 Proton and heavy ion fluxes and magnetic field measured in the second elliptical orbit of Phobos 2 since 23.45 UT, February 4 till 2.13UT, February 5. Spectra of protons and heavy ions are given in counts logarithmically scaled from white to black.

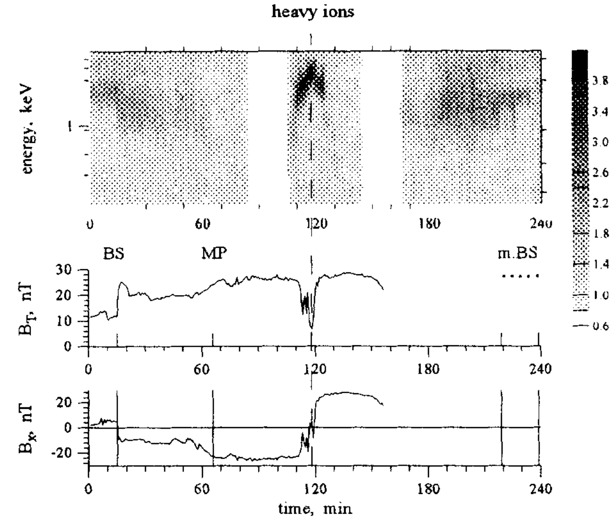

Fig. 2 Heavy ion fluxes and magnetic field measured in the circular orbit of Phobos 2 on March 11, 1989, 08.00 – 12.00 UT. Heavy ion spectra are given in counts logarithmically scaled from white to black.

the Martian magnetotail on February 5, 1989 (elliptical orbit) and on March 11, 1989 (circular orbit with the radius of ~ 2.85 planetary radius R_M), respectively. Heavy ion and proton fluxes are logarithmically coded from white to black. At the bottom magnetic field magnitude B_T and B_x component (in the Mars – Sun direction) are shown. Crossings of the magnetic neutral sheet refer to the moments when B_x changes its sign. BS and MP symbols mark the crossings of the bow shock and magnetopause, respectively. In the solar wind and magnetosheath 'ghosts' of proton fluxes are seen in the heavy ion channel. Inside the Martian magnetotail the TAUS spectrometer did not record any proton fluxes, but fluxes of heavy ions with wide descending energy spectrum were often observed, like those seen at ~ 00.22 UT and 00.50 – 01.05 UT in Fig. 1. These fluxes probably belong to the boundary layer adjacent to the magnetopause. They were also called 'side rays' by the ASPERA team. (Dubinin et al., 1991). These fluxes will not be considered below. The attention will be paid to pronounced fluxes of accelerated heavy ions such as those observed since 01.40 UT on February 5 and at 09.50 – 10.05 on March 11. These ion fluxes were observed in the Martian plasma sheet and their maximum intensity and velocity approximately corresponds to the magnetic neutral sheet crossing. According to ASPERA instrument data oxygen ions dominate in the Martian magnetotail (Lundin et al., 1989), and this also corresponds to the content of the Martian atmosphere.

3 Heavy ion acceleration processes

Since the shape of the heavy ion distribution function resembles the shape of the proton distributions in the terrestrial plasma sheet boundary layer, similar acceleration processes were considered. The classical acceleration of ions in the plasma sheet is the acceleration in the central current sheet of the tail (Speicer, 1965; Shabanskiy, 1972; Ip, 1992).

Fig. 3 shows the dependence of heavy ion velocity V_i (maximum velocity for every traversal of the Martian magnetotail) on the inverse value of the minimum magnetic field magnitude B_{min}. It was already mentioned, that minimum magnetic field apparently perpendicular to the Sun – Mars axis was recorded approximately simultaneously with the maximum velocity of ion flux. Fig. 3 is similar to Fig. 3 in Kotova et al. (1997), but now more precise approximation will be considered $V_i \approx 2\dfrac{E}{B_{min}} - V_0$ (E - is cross-tail electric field). Least square fitting gives $E \cong 0.5$ mV/m and $V_0 \cong 45$ km/s. Thus, ionosphere ions are likely to be preaccelerated to velocity V_0, possibly in the pole regions of the magnetosphere (Perez-de-Tejada,1980). The energy range of the TAUS instrument permits to measure oxygen ions with velocities from ~ 45 to ~ 270 km/s, therefore ions before the acceleration could not be clearly recorded, but it might be ions with wide descending energy spectrum seen in Fig. 1.

It is well known that in the magnetosphere of the Earth accelerated ion fluxes with mushroom-cap like shape are recorded in the plasmasheet boundary layer but not in the central plasma sheet. In case of current sheet acceleration in the Martian tail the ion velocity component perpendicular to the magnetic neutral sheet $V_\perp \sim E/B_x \sim 0.5$mV/m / (8÷35)nT ~ 15÷60 km/s; the velocity in the Sun – Mars direction $V_i \sim 2E/B_{min}$; the height of the spacecraft circular orbit ~ 6000 km and hence the distance from the point of ion

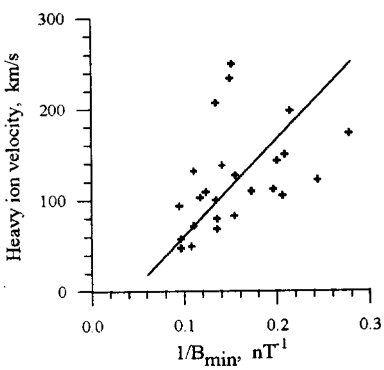

Fig. 3 Heavy ion velocity as a function of inverse value of minimum magnetic field in the Martian tail. Line represents the function V_i=1060/B_{min}-45

acceleration L < 6000 km. The time of ion travel from the acceleration point to the spacecraft ~ L/V_i and the ion can be recorded at a distance $l \sim (L/2)\cdot(B_{min}/B_x) \sim$ 600 km from the magnetic neutral line. Since the spacecraft velocity was ~ 2 km/s, this distance was crossed in ~ 5 min., that corresponds to two spectra measurements. In fact this time shift between the moment of the tail current sheet crossing and large heavy ion fluxes registration is close to the maximum because L should be less than 6000 km as the preaccelerated ion moves ~ 2 times faster along the magnetic field, than across it to the point of acceleration. Thus it is not surprising that maximum heavy ion fluxes in the Martian magnetotail are observed near the magnetic neutral sheet.

Another estimation that should be made is concerned to the ion gyroradius. In the current sheet acceleration model the distance moved by ion in the neutral sheet plane is approximately equal to the ion gyroradius $\rho_{\perp} \cong 2\frac{Em_i}{eB_{min}^2}$ (Speicer, 1965; Shabanskiy, 1972). Apparently this distance should be less than the magnetotail thickness $D \sim 5\ R_M$, where R_M is Mars radius (Verigin et al., 1993). This means that B_{min} should be less than 3 nT in order to realize the current sheet acceleration process. Indeed, Fig. 3 shows that during the observation of heavy ion fluxes B_{min} was always higher than 3 nT, and it is worth noting that in the only case of cross tail crossing when no heavy ion fluxes were observed by the TAUS instrument, the minimum magnetic field measured during the current sheet crossing was ~ 1 nT.

From the above consideration it follows, that current sheet acceleration is likely to operate in the Martian magnetotail. Previously it was shown that magnetic field line stress acceleration should also work in the Martian tail (Dubinin et al., 1993; Kotova et al., 1997). The efficiency of these processes probably depends on the 'mode' of the Martian magnetosphere. In the paper by Verigin et al. (1997) on the basis of the TAUS ion spectrometer and MAGMA magnetometer data collected aboard Phobos 2 in February-March, 1989 a model of the Martian magnetopause has been developed for the period of maximum solar activity. This model simultaneously describes the observed relation between the solar wind ram pressure ρV^2 and the magnetopause position in the magnetotail, the observed relation between ρV^2 and the flaring angle of the magnetopause, and a few magnetopause crossing observations above the day side of the planet. A specific feature of the model is the "stagnation" of the subsolar

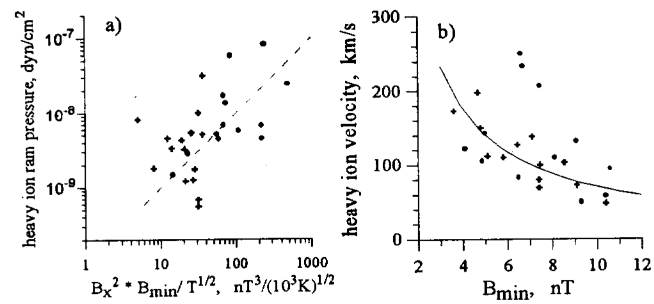

Fig. 4 Correlation of plasma sheet ion and magnetic field parameters supporting the shear stress acceleration (a) and central current sheet acceleration. Crosses correspond to the cases of low solar wind ram pressure and dots correspond to the cases of high solar wind ram pressure.

magnetopause when the ram pressure increases to values $\geq 6\times10^{-9}$ dyn cm^{-2} while the magnetotail still remains compressible up to very large ram pressures. The ram pressure value of 6×10^{-9} dyn cm^{-2} seems dividing two 'modes' of the Martian magnetosphere: when ram pressure is low intrinsic magnetic field determines the solar wind interaction with Mars, when pressure is high ionosphere plays the main role in this interaction. As it was emphasized in the original paper (Verigin et al., 1997) this model was not considered as a proof of the existence of the Martian intrinsic dipole moment. Certainly the proofs can come only from the direct measurements (Acuna et al., 1998), but independently of the nature of the Martian obstacle the developed model describes correctly the shape of the Martian magnetopause and its variations.

Fig. 4a presents the dependence of heavy ion ram pressure on the value of $B_x^2 B_{min}/T^{1/2}$ (T – is the ion temperature) supporting the process of magnetic field line stress acceleration in the Martian magnetotail (Kotova et al., 1997). In Fig. 4 crosses mark cases when the solar wind ram pressure $\rho V^2 < 6\times10^{-9}$ dyn cm^{-2}, and dots correspond to cases when $\rho V^2 > 6\times10^{-9}$ dyn cm^{-2}. The same symbols also separate two magnetosphere 'modes' in Fig. 4b, which is similar to Fig. 3. Dots show better correlation than crosses in Fig. 4a, while in Fig. 4b crosses correlate better. So, it follows that low solar wind ram pressure is likely to create better conditions for current sheet acceleration of heavy ions in the Martian tail and high solar wind ram pressure is more favorable for magnetic field line stress acceleration. Originally ion acceleration in the central current sheet was proposed for the terrestrial magnetotail. And as it was mentioned above in case of low ram pressure solar wind interaction with Mars is more 'Earth-like'. In case of high ram pressures the situation is more similar to the interaction of the solar wind with nonmagnetic Venus and then magnetic tension is stronger.

4 Conclusions

Statistical analysis of plasma and magnetic field data collected in the Martian plasma sheet evidences that acceleration due to magnetic field line stresses and acceleration in the central current sheet could account for the observations, though planetary ions are likely to be preaccelerated to velocities of 40 –50 km/s. This supports the conclusion, made in Kotova et al. (1997) on the basis of 2-D heavy ion spectra analysis.

Attempt to separate different magnetotail regimes for high and low solar wind ram pressures leads to the following conclusion: in case of low solar wind ram pressure the current sheet acceleration seems to prevail and high solar wind ram pressure is more favorable for magnetic field line stress acceleration.

Acknowledgements. The research described in this publication was made possible in part by grant 94-982 from INTAS.

References

Acuna, M.H., Connerney, J.E.P., Wasilewski, P., Lin, R.P., Anderson, K.A. et al., Magnetic field and plasma observations at Mars: Initial results of the Mars Global Surveyor mission, *Science, 279,* No. 5357, 1676, 1998.

Dubinin E., Lundin R., Riedler W., Schwingenschuh K., Luhmann J.G., Russell C.T., and Brace, L.H., Comparison of observed plasma and magnetic field structures in the wakes of Mars and Venus, *J. Geophys. Res., 96,* 11189,1991

Dubinin, E., Lundin, R., Norberg, O., Pissarenko, N., Ion acceleration in the Martian tail: Phobos observations, *J. Geoghys. Res., 98,* 3991, 1993

Ip, W.-H., Ion acceleration at the current sheet of the Martian magnetosphere, *Geophys. Res. Lett., 19,* 2095, 1992.

Kotova, G.A., Verigin, M.I., Shutte, N.M., Remizov, A.P., Rosenbauer, H., *et al.,* Planetary heavy ions in the magnetotail of Mars: Results of the TAUS and MAGMA experiments aboard Phobos, *Adv. Space Res., 20,* 173, 1997.

Lundin, R., Zakharov, A., Pellinen, R., Borg, H., Hultqvist, B. *et al.,* First measurements of the ionospheric plasma escape from Mars, *Nature, 341,* 609, 1989.

Lundin, R., Zakharov, A., Pellinen, R., Borg, H., Hultqvist, B. *et al.,* Plasma composition measurements of the Martian magnetosphere morphology, *Geophys. Res. Letters, 17,* 877, 1990.

Perez-de-Tejada, H. Viscous flow circulation of the solar wind behind Venus, *Science, 207,* 981, 1980.

Rosenbauer, H., Shutte, N., Apathy, I., Galeev, A., Gringauz, K., *et al.,* Ions of Martian origin and plasma sheet in the Martian magnetosphere: initial results of the TAUS experiment, *Nature, 341,* 612, 1989.

Shabanskiy, V.P., *Phenomena in the Near Terrestrial Space* (in Russian), Nauka, pp.167-190, Moscow, 1972.

Shutte, N.M., Kiraly. P., Cravens, T.E., Dyachkov, A.V., Gombosi, T.I., *et al.,* Observations of electron and ion fluxes in the vicinity of Mars with the HARP spectrometer, *Nature, 341,* 612, 1989.

Speicer, T.W., Particle trajectories in model current sheets, 1.Analitical solutions, *J. Geophys. Res.,70,* 4219,1965.

Verigin, M.I., Shutte, N.M., Galeev, A.A., Gringauz, K.I., Kotova, G.A. *et al.,* Ions of planetary origin in the Martian magnetosphere (Phobos 2/TAUS experiment), *Planet. Space Sci., 39,* 131, 1991.

Verigin, M.I. Gringauz, K.I., Kotova, G.A., Remizov, A.P. et al., The dependence of the Martian magnetopause and bow shock on solar wind ram pressure according to Phobos 2/TAUS ion spectrometer measurements, *J. Geophys. Res., 98,* 1303, 1993

Verigin, M., Kotova, G., Shutte, N., Remizov, A., Szego, K., *et al.,* Quantitative model of the Martian magnetopause shape and its variation with the solar wind ram pressure based on Phobos 2 observations, *J. Geophys. Res., 102,* 2147, 1997.