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THE MARTIAN ATMOSPHERE DISSIPATION PROBLEM: PHOBOS-2 TAUS EXPERIMENT EVIDENCES

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ABSTRACT

Measurements of proton and heavy ion spectra by the TAUS spectrometer onboard the Phobos-2 orbiter provided the first in-situ experimental data on the problem of martian atmosphere dissipation. They are (i) the newly revealed escape of planetary heavy ions through the plasma sheet of the martian magnetotail, and (ii) the deceleration of solar wind protons upstream of the planetary bow shock possibly due to the presence of the hot oxygen corona of Mars.

INTRODUCTION

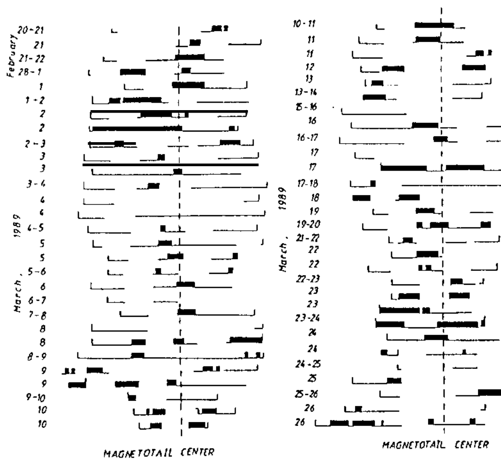
The first mass-spectrometric plasma measurements in the vicinity of Mars provided by the TAUS /1/ and ASPERA /2/ experiments onboard the Phobos-2 orbiter in February-March, 1989 permitted to estimate the loss rate of planetary oxygen through the martian magnetotail as a few times 10^{25} s^{-1}. Based on the data of a limited number of orbits the authors of /1/ found the largest ion fluxes in the plasma sheet while in /2/ was claimed that the escape of ionospheric plasma is predominantly contained in the tail boundary of Mars. The former conclusion was subsequently supported by a detailed statistical consideration of heavy ion fluxes measured by the TAUS spectrometer in the magnetotail over all available Phobos-2 orbits /3/. The existence of the magnetotail plasma sheet was confirmed by ASPERA data /4/ although the authors of these measurements still suggested that heavy ions mainly escape through the martian boundary layer /5/.

An other competing process of the martian oxygen dissipation is its nonthermal escape through the hot oxygen corona of the planet /6,7/. In the present paper the certainty of the interpretation of Phobos-2/TAUS observations is discussed. The consequences of the presence of the extent martian oxygen corona in the solar wind are also discussed.

INSTRUMENTATION AND DATA ANALYSIS

A system of two hemispherical electrostatic analysers with a magnetic deflection system of TAUS spectrometer permitted to measure separately the energy spectra of three species of ions - protons, alpha-particles and heavy ions (M/q > 3). The instrument's field of view of ~40^0 x 40^0 was centered on the nominal direction toward the sun, and it was divided into 8 azimuthal x 8 elevational channels. The energy per charge (E/q) range of ~ 30 V - 6 kV was subdivided into 32 channels. To analyse the planetary ion losses through the plasma sheet the longest uniform set of TAUS data from the circular orbits was used. For the study of solar wind deceleration TAUS data were used only from the first three elliptical orbits, during which the planetary bow shock was crossed close to the subsolar point. Additional details on the TAUS instrument and data evaluation can be found in /3,7,8/.

The locations of the plasma sheet in the areomagnetotail according to the TAUS data are presented in Fig.1 /3/. From the data for the 58 circular orbits available we can conclude that on average during these measurements the martian plasma sheet could be observed during ~ 25% of the part of Phobos-2 orbit in the magnetotail. In further estimations we assume that the angles under which the s/c could cross the plasma sheet were uniformly distributed over $(0,\pi)$ interval during the observational period. Then the characteristic width of the plasma sheet can be determined as d ~ 10% of magnetotail diameter D (Fig.2) /3/. Statistics of maximal ion fluxes with 150 V < E/q < 6 kV observed in the martian plasma sheet for the 58 Phobos-2 circular orbits was studied in /3/. According to the TAUS data the average flux of heavy ions was evaluated to be F ~ $2.5*10^7$ $cm^{-2}s^{-1}$.



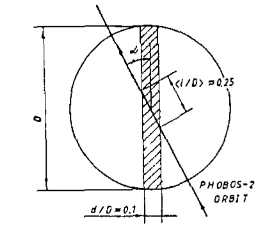


Fig.2.A cross-section of the model magnetotail of Mars. The plasma sheet is hatched. Solid line represents an orbit of Phobos-2.

Fig.1. Plasmasheet locations in the martian magnetotail on circular orbits. On the left side dates of the tail crossings are given. Heavy black lines mark the parts of Phobos-2 orbits where the heavy ion fluxes exceed 2 times the instrument background. The innermost magnetopause positions are shown by vertical bars. Gaps correspond to the absence of TAUS data.

The average magnetotail diameter was found to be approximately D ~ 15,000 km, or ~ 4.4 martian radii at the areocentric distances of 2 - 3 martian radii downstream of the planet /3/. Taking now the possible martian plasma sheet configuration with D given above into account, and the average heavy ion flux F, we can estimate the average loss rate of martian oxygen through the plasma sheet to be $\Phi \sim F*d*D \sim$ $\sim 5*10^{24} s^{-1} \sim 150$ g/s.

Figs.3a,b present the bulk velocity V and number density n_p of protons before the bow shock crossing (S) on the third elliptical orbit. The specific feature of velocity profile presented is a strong deceleration of solar wind protons upstream of the bow shock, which was also observed in the first two orbits /7/. There are two possible reasons for such a deceleration: (i) the mass-loading of the solar wind stream by ions of planetary origin and/or (ii) the solar wind loading by protons which are specularly reflected from the bow shock. The deceleration of the solar wind due to mass-loading by heavy ions was observed upstream of the bow shock of comet Halley (see e.g./9,10/). This process can be also going near Mars because of the existence of the extent nonthermal oxygen and thermal hydrogen corona of the planet.

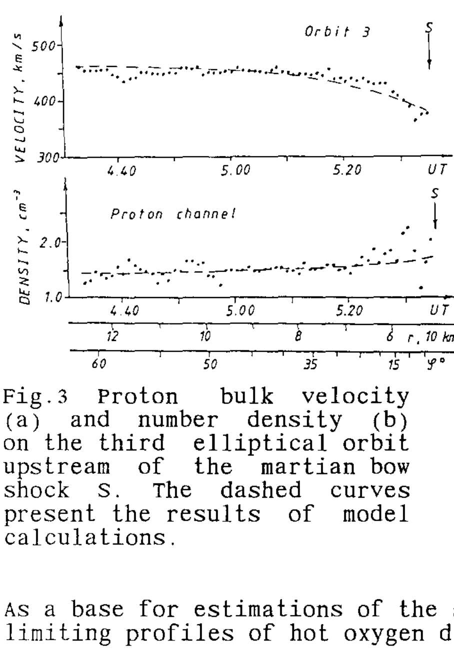


Fig.3 Proton bulk velocity (a) and number density (b) on the third elliptical orbit upstream of the martian bow shock S. The dashed curves present the results of model calculations.

The numerical estimations of the solar wind deceleration by the planetary corona are rather straightforward and will be described below while a number of reflected protons is a complicated function of upstream plasma parameters. Of course with the neglect of the shock foot (and of hydrogen corona) deceleration the results concerning the oxygen corona should be considered only as upper limits.

As a base for estimations of the solar wind deceleration the average of the two limiting profiles of hot oxygen density model /11/ was used:

$$n_h(r) \sim n_o (r_o/r)^2 + n_1 (r_o/r)^5 , \qquad (1)$$

where r is the areocentric distance, $n_o \sim 90\ cm^{-3}$, $n_o/n_1 \sim 3$, and $r_o \sim 10{,}000$ km. The solution of well known hydrodynamic flow equations /12/ for weakly loaded, highly supersonic solar wind has the form similar to the one presented in /13/. The final expressions for $V(r,\varphi)$ and $n_p(r,\varphi)$, which were applied for the analysis of TAUS data, are the following /7/:

$$V = V_0 - \frac{(\gamma+1)Mn_o r_o}{2n_{p_o}\tau_i m_p}\left(\frac{r_o}{r}\right)\frac{\varphi}{\sin\varphi}\left(1+\frac{1}{3}\left(\frac{n_1}{n_o}\right)\left(\frac{r_o}{r}\right)^3\frac{\cos^3\varphi-3\cos\varphi+2}{\varphi\sin^3\varphi}\right)$$

$$n_p = n_{p_o} + \frac{(\gamma+1)Mn_o r_o}{2V_o\tau_i m_p}\left(\frac{r_o}{r}\right)\left[\left(\frac{2\varphi}{(\gamma-1)\sin\varphi}+\frac{\varphi-\sin\varphi\cos\varphi}{2\sin^3\varphi}\right) + \left(\frac{n_1}{n_o}\right)\left(\frac{r_o}{r}\right)^3\left(\frac{4(\cos^3\varphi-3\cos\varphi+2)}{3(\gamma-1)\sin^4\varphi}+\frac{4(1-\cos\varphi)^3}{3\sin^6\varphi}\right)\right], \qquad (2)$$

where m_p, M are the masses of protons and oxygen ions, respectively, φ is the angular distance of the point of observation from the stagnation point of the flow, γ is the ratio of specific heats, and $\tau_i \sim 2*10^6\ s^{-1}$ is the ionization time scale of oxygen at ~ 1.5 AU. In Fig.3a,b the results of best fit over the variables n_o, V_o , and n_{p_o} are shown by dashed lines for the following set of parameters $n_0 \sim 500$ cm^{-3} , $V_0 \sim 505$ km/s, and $n_{p_0} \sim 1.3$ cm^{-3} . General correspondence of the observed and calculated velocities and densities is obvious.

DISCUSSION

The process of oxygen ion losses through the plasma sheet of the martian magnetotail is the first process of a mass loss by the planet measured by direct in-situ method. The average loss rate estimated above of ~ 150 g/s corresponds to a martian atmospheric dissipation rate of ~ $4*10^{-17}$ mbar/s. If this rate is permanent, the present 7-10 mbar martian atmosphere would dissipated during ~ $5-8*10^9$ years. This time is comparable to the age of the planet. The above process is therefore important for the evolution of the martian atmosphere.

Before Phobos-2 the only experimental attempt to estimate an oxygen flux through the martian tail was made in /14,15/ using the data from the RIEP spectrometer on Mars-5. The authors of these measurements detected ion fluxes escaping through what they thought was a thin (~ 1000 km) boundary layer of the magnetotail and estimated the ion loss rate to be ~ 10^{24}- $10^{25} s^{-1}$. Although they interpreted the results in terms of heavy ions they could not be sure because their spectrometer only contained an electrostatic analyser and could not discriminate masses. Later on /16/ RIEP data were interpreted by the presence of protons only (see also /17/ for response).

The conclusion of the authors of ASPERA measurements, that the main loss of oxygen ions takes place in the martian boundary layer /5/, seems to be in contradiction to the TAUS data presented above. Really, in this case, in different orbits the enhanced fluxes of heavy ions (Fig.1) would be mainly recorded near the magnetopause, that was not observed. Conversely, the plasma sheet can be observed both in the center and near the magnetotail boundary. Some difference in numerical estimates of the escaping oxygen flux between /3/ and /5/ cannot be considered as essential because the details of evaluation procedure were not presented in /5/.

Though the process of martian oxygen ion outflow through the plasma sheet is important for the evolution of the planetary atmosphere, it is not the main process of oxygen dissipation. The dissociative recombination of O_2^+ ions at the exobase leads to neutral oxygen dissipation flux of $F \sim 5*10^7$ $cm^{-2}s^{-1}$ /6/. So, the total rate of oxygen dissipation from the sunlit planetary hemisphere can be estimated as $\Phi \sim 2\pi r_c^2 F \sim 4*10^{25} s^{-1}$ ($r_c \sim 3600$ km), i.e. it could be an order of magnitude higher than the loss rate through the plasma sheet. Although the existence of the martian hot oxygen corona was predicted 18 years ago, this formation still needs observational verification /18/. The deceleration of the solar wind upstream of the martian bow shock can be considered as the first (although indirect) in-situ evidence of the existence of the martian corona.

In the above evaluations we have assumed that the density profile of the hot oxygen corona is that one of /11/ model. A slightly better agreement can be obtained between the calculated and measured velocity profiles if the ratio of n_0 to n_1 parameters in (1) is chosen to be $n_0/n_1 \sim 1$. In this case the best fit parameters for the third orbit are $n_0 \sim 200$ cm^{-3}, $V_0 \sim 480$ km/s, and $n_{p_0} \sim 1.3$ cm^{-3}. In any case the density of the oxygen corona in the periods close to solar cycle maxima can be several times higher compared to the existing coronal models /11,18/.

In (1) the first term describes the density of fast oxygen atoms, which are moving radially outward from the planet with a velocity of $v \sim 2$ km/s, while the second term represents the slower oxygen atoms basically returning to the planet /7/. The production rate of fast oxygen can be estimated as $Q \sim \pi r^2 n_0 (r_0/r)^2 v \sim 10^{26} s^{-1}$, where we used $n_0 \sim 200$ cm^{-3}. This value corresponds to the rate of oxygen dissipation from the sunlit hemisphere of the planet through the oxygen corona, which is somewhat higher than previously estimated /6/. It might be connected with the special time of Phobos-2 observations. The dissipation rate determined above corresponds to an oxygen loss of ~ 2.5 kg/s from Mars, or to a decrease in atmospheric pressure of ~ $7*10^{-16}$ mbar/s. If this rate is permanent, the present ~ 7 mbar pressure of the martian atmosphere would be dissipated in ~ $3*10^8$ years, i.e. an order of magnitude faster than in the process of martian oxygen dissipation through the plasma sheet of the martian magnetotail.

At sufficiently large planetocentric distances exceeding a few tens of thousand kilometers just like in the case of the cometary neutral gas (see e.g. /19/) the following expression can be used for the description of oxygen density in the martian corona /7/: $n_n(r) \sim Q/(4\pi r^2 v) \exp(-r/v\tau_i)$. Finally, all oxygen atoms will be ionized and picked-up by the solar wind. This process mainly takes place at a distance of $\lambda \sim v\tau_i \sim 4*10^6$ km, which gives the natural outer scale of the martian oxygen corona. If a spacecraft approaches the planet perpendicular to the Sun-Mars line, on-board mass-spectrometer should measure the net flux of oxygen ions beginning from several million kilometers: $F \sim Q / (8\ r\tau_i v) \sim 4*10^3 * (r_1/r)\ cm^{-2}s^{-1}$, where $r_1 = 10^5$ km. This way measuring the planetocentric distribution of picked-up heavy ions in a future martian mission (e.g. Mars-94), we can determine the dissipation rate of oxygen through the corona, as well as its density distribution.

CONCLUSION

Plasma measurements by the TAUS spectrometer of Phobos-2 mission revealed the existence of the plasma sheet on both sides of the magnetic neutral sheet in the martian magnetotail and the deceleration of solar wind upstream of the bow shock.

The average loss rate of oxygen ions through the plasma sheet is estimated to be $\sim 5*10^{24} s^{-1}$, or ~ 150 g/s. The process of martian heavy ion losses through the plasma sheet is the only one supported by reliable in-situ observational data.

The amplitude of the solar wind deceleration observed upstream of the martian bow shock (~ 100 km/s) implies that the hot oxygen corona of Mars at solar cycle maximum could be several times denser than it was anticipated. The loss of planetary oxygen through the corona is the main process of oxygen loss by Mars; the intensity of these losses could be determined as $< 10^{26}$ oxygen atoms, or ~ 2.5 kg of oxygen per second.

The study of planetocentric distribution of heavy ions onboard the Mars-94 spacecraft could be a useful tool for the exploration of the martian hot oxygen corona and of oxygen losses by the planet.

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