Planet. Space Sci., Vol. 39, No. 1/2, pp. 131–137, 1991
Printed in Great Britain.

0032–0633/91 \$3.00+0.00
Pergamon Press plc

IONS OF PLANETARY ORIGIN IN THE MARTIAN MAGNETOSPHERE (*PHOBOS* 2/TAUS EXPERIMENT)

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(*Received* 15 *May* 1990)

Abstract—The measurements onboard the *Phobos* 2 Martian orbiter revealed one more physical process of Martian neutral atmosphere dissipation—outflow of heavy ions of planetary origin through the magnetic tail of Mars. The distribution of heavy ions through the cross-section of the Martian magnetotail is studied based on TAUS spectrometer data. Average loss rate of heavy ions through the plasmasheet (separating magnetotail lobes) is evaluated as $\sim 5\times 10^{24}$ s^{-1}. The revealed process of Martian atmosphere dissipation is important for cosmological time and constitutes $\sim 10\%$ of non-thermal oxygen dissipation due to dissociative recombination of molecular oxygen ions near exobase.

INTRODUCTION

During February–March 1989 the first mass-spectrometric plasma measurements in the vicinity of Mars were performed by the experiments TAUS (Rosenbauer *et al.*, 1989) and ASPERA (Lundin *et al.*, 1989) onboard the *Phobos* 2 orbiter. At this time the first *in situ* plasma measurements were made deep in the Martian magnetotail as well as in the optical shadow of the planet. The data of both instruments revealed the dominance of heavy ions of planetary origin (mainly O^+) in the Martian magnetotail and permitted the estimation of the loss rate of planetary oxygen through the magnetotail as a few times 10^{25} s^{-1} (Rosenbauer *et al.*, 1989; Lundin *et al.*, 1989).

These preliminary estimations of the ion loss rate were based on measurements taken at the few orbits analysed in the first publications. Lundin *et al.* (1989) claimed that the escape of ionospheric plasma is predominantly contained in the tail boundary of Mars, while Rosenbauer *et al.* (1989) noted that the largest ion fluxes were observed in the plasma sheet of the Martian magnetotail.

Now the complete set of plasma measurements is available, and it is reasonable to analyse the distribution of heavy ion fluxes in the cross-section of the Martian magnetotail in more detail. After this and other analyses the average loss rate of oxygen ions through the magnetotail will be re-evaluated. The results obtained will be compared with the oxygen losses by other processes estimated in a number of previous publications.

OBSERVATIONS AND LOSS RATE ESTIMATION

The TAUS instrument onboard *Phobos* 2 was specially designed for the investigation of the solar wind interaction with Mars. The energetic spectra of three species of ions: protons, alpha-particles and heavy ($M/q > 3$) ions could be measured separately by a system of curved electrostatic analysers and a magnetic deflection system. The instrument field of view of $\sim 40^\circ \times 40^\circ$ was centred on the nominal direction towards the Sun, and it was divided into 8 azi-

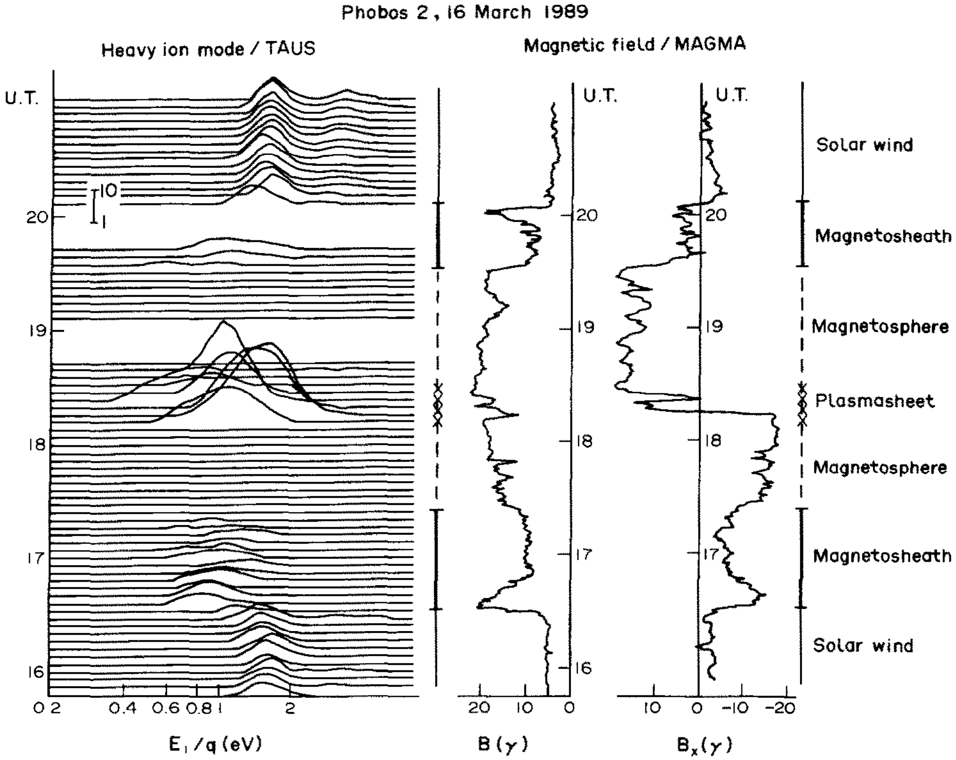

FIG. 1. FOUR-MINUTE AVERAGES OF ENERGY SPECTRA REGISTERED BY TAUS IN THE HEAVY ION MEASUREMENT MODE ON 16 MARCH 1989 (LEFT PANEL).

Intensity B (central panel) and the component of B_x of the magnetic field parallel to the Sun–Mars line (right panel). Time runs from the bottom to the top. On the right of the outer panels different space regions are marked. The solid line denotes the solar wind region, the thick full line the magnetosheath, the dashed line the magnetosphere, and the crosses mark the plasmasheet.

muthal ×8 elevational channels for obtaining the angular resolution. The energy per charge (E/q) range of ~30 V–6 kV was subdivided into 32 channels. The sensitivity of the instrument was nearly constant over its entire field of view, depending only on the ion speed. A more detailed description of the TAUS experiment is presented in Rosenbauer *et al.* (1989a).

During the active life of the *Phobos* 2 orbiter, TAUS data from four elliptical orbits with low (h ~ 850 km) pericentre, from one elliptical orbit with high (h ~ 6400 km) pericentre, and from 58 circular orbits, quasi-synchronous with the Phobos moon (h ~ 6150 km) were obtained. For the systematic studies of planetary heavy ion losses it is reasonable to use the longest uniform set of TAUS data from the circular orbits.

The sequence of 4 min averages of the TAUS counting rates in the heavy ion mode as a function of E/q is presented in the left panel of Fig. 1 for 16 March 1989. The time is progressing from bottom to top. From ~16:00 U.T. to ~21:00 *Phobos* 2 passed subsequently from the solar wind to the magnetosheath region through the bow shock at ~16:30 U.T., and then from the magnetosheath to the magnetosphere through the magnetopause at ~17:23 U.T. Approximately in the centre of the magnetospheric tail (from ~18:10 U.T. to ~18:30 U.T.) the most intense fluxes of heavy ions with $F \sim 2\text{–}4 \times 10^7$ cm^{-2} s^{-1} were observed. [Please note that the ion fluxes in Fig. 1 observed in the solar wind and in the magnetosheath are mainly ghosts of protons from the proper channel. In the magnetotail, where the protons as a rule were not observed even by the proton channel (much more sensitive to protons than the heavy ion channel), their influence on the heavy ion channel was negligible.] After the subsequent magnetopause (~19:32 U.T.) and the bow shock (~20:08 U.T.) crossings, *Phobos* 2 entered the solar wind region again. The bow shock and the magnetopause positions were defined by the specific changes of the proton spectra measured by the TAUS instrument and described in Rosenbauer *et al.* (1989).

In the central and right-hand panel of Fig. 1 the intensity (B) and the component parallel to the magnetotail axis (B_x) of the magnetic field are presented, respectively, as measured by the magnetometer MAGMA. It is clear that the most intense fluxes of heavy ions were observed in the vicinity of the B_x component reversals, i.e. in the vicinity of the magnetic neutral sheets. The region of increased plasma energy and density, in the magnetic tails of Earth and Venus (see e.g. Gringauz, 1981), which includes the neutral sheet, is commonly called plasmasheet. That is the reason why such a formation in the magnetic tail of Mars was also named plasmasheet by Rosenbauer *et al.* (1989).

The main features of the areomagnetotail plasmasheet are the ion composition and the extreme variability of the location of this formation. In the geomagnetosphere at quiet conditions the plasmasheet consists primarily of protons and only during certain substorms does the contribution of heavy ions of ionospheric origin reach ~50%. In the areomagnetosphere, however, the plasmasheet consists mainly of heavy ions.

The positions of the plasmasheet in the areomagnetotail according to the TAUS data are presented in Fig. 2. Heavy lines mark the portions of the *Phobos* 2 orbits in the magnetotail when heavy ion fluxes exceeded the background values of the instrument by a factor of two or more. The innermost magnetopause positions are marked in Fig. 2 by thin vertical bars, and gaps correspond to periods when TAUS plasma measurements were absent. From the data presented in Fig. 2 it is clearly seen that in the Martian magnetotail the plasmasheet was observed not always in the centre of the tail (cf. Fig. 1) but also near the in-bound and out-bound magnetopause as well as in other parts of the magnetotail; sometimes multiple plasmasheet crossings took place during one orbit.

From the data for the 58 orbits presented in Fig. 2 we can conclude that the Martian plasmasheet was observed by the TAUS instrument during ~15% of the time when *Phobos* 2 was located in the magnetotail. Taking into account the gaps of data we can estimate that on average during these measurements the plasmasheet could be observed during ~25% of the part of the *Phobos* 2 orbit in the magnetotail.

The statement that enhanced fluxes of heavy ions measured by TAUS are really observed near the magnetic neutral sheet was checked by comparison of simultaneous plasma and magnetic field measurements. Such a comparison could be made for the magnetotail measurements during 36 circular orbits, where proper TAUS and MAGMA data were available. Every time, when *Phobos* 2 crossed the magnetic neutral sheet and the B_x component changed its sign, increased fluxes of heavy ions were observed. We found only one exception (at ~17:50 U.T. on 4 March 1989). On the other hand, the enhanced fluxes of heavy ions were not necessarily accompanied by the proper change of magnetic field direction. This circumstance does not influence our concept as the plasmasheet scale should be essentially larger than that of the neutral sheet (e.g. in the geomagnetotail), and *Phobos* 2 could register the plasmasheet ions without neutral sheet crossing.

In case the reversal of the B_x component was observed near the in-bound (out-bound) crossing of the magnetopause, enhanced fluxes of heavy ions were measured just after (before) the magnetopause. This circumstance and the limited number of observational data considered by Lundin *et al.* (1989) in the first publication are possible reasons for their conclusion that the predominant escape of ionospheric plasma is contained in the Martian tail boundary. In fact the most intensive fluxes of heavy ions were measured in the plasmasheet, whether it was observed close to the magnetopause or in the centre of the magnetotail.

Observations of multiple plasmasheet crossing on some orbits (Fig. 2) may be caused by the motion of this formation relative to the spacecraft. There are plasmasheet motions in the geomagnetotail as well. In the areomagnetotail where the contribution of the induced magnetic field is significant (Riedler *et al.*, 1989), the plasmasheet could change its orientation and be shifted depending on the direction of the interplanetary magnetic field component perpendicular to the Sun–Mars line, and the solar wind. Thus during different *Phobos* 2 orbits the spacecraft can cross the plasmasheet region under different α-angles (Fig. 3). This angle can also vary during one crossing resulting in multiple plasmasheet observations.

Assuming that the α-angles were uniformly distributed on average over the $(0, \pi)$ interval during the observational period, we can estimate the characteristic width of the plasmasheet to be $d \sim 10\%$ of magnetotail diameter D (Fig. 3).

Prior to the evaluation of the plasmasheet ion fluxes we must be sure that the fluxes are negligible out of the field view (FOV) of the TAUS spectrometer. To verify this, 2-D high bit rate measurements in the plasmasheet during elliptical orbits were used. The position of the count rate maximum in the 2-D spectra of heavy ions (see e.g. Fig. 4 of Rosenbauer *et al.*, 1989) was shifting from the upper to the lower bound-

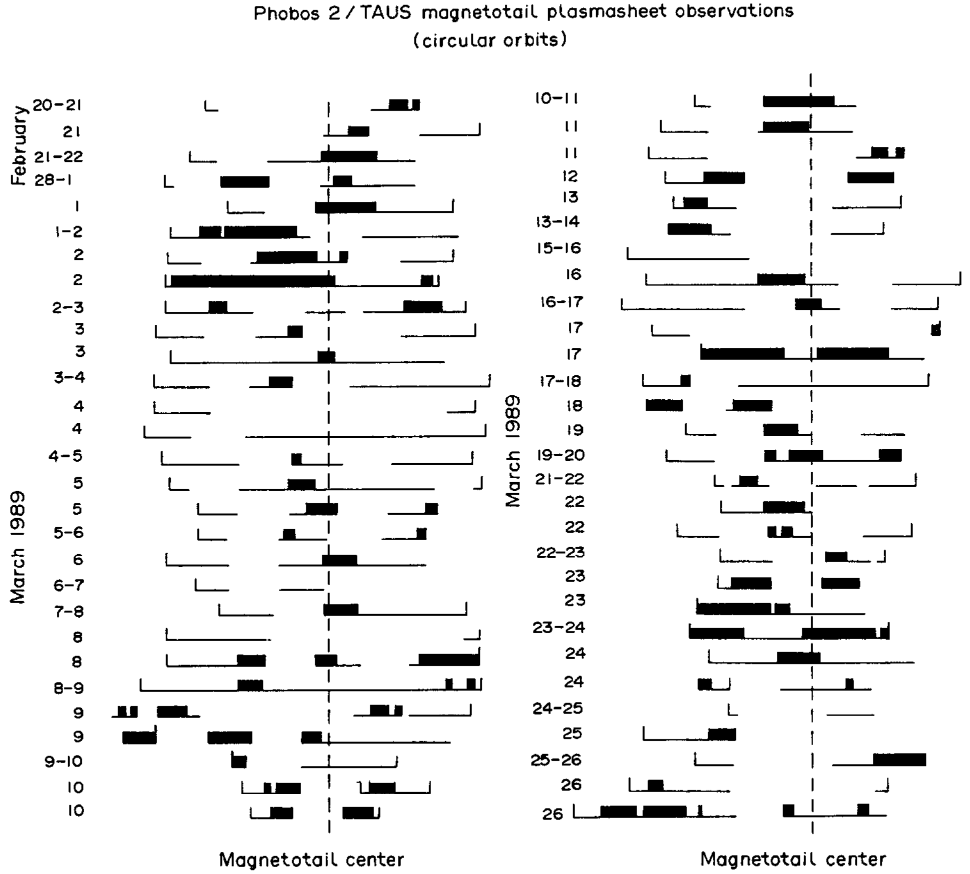

FIG. 2. PLASMASHEET LOCATIONS IN THE MARTIAN MAGNETOTAIL ON CIRCULAR ORBITS.
On the left side dates of the tail crossings are given. Heavy black lines mark the parts of the *Phobos* 2 orbits where the heavy ion fluxes exceed twice the instrument background. The innermost magnetopause positions are shown by vertical bars. Gaps correspond to the absence of TAUS data. The distance along the abscissa is proportional to the distance along the orbit from the midnight meridian crossing (dashed line).

ary of the instrument's FOV while *Phobos* 2 was rotating around its X-axis with a period of ~ 10 min; so the evaluated heavy ion fluxes were modulated by the rotation of the orbiter. It is only when the count rate maximum is close to the FOV centre and the flux evaluated reaches maximal value that we can be certain that its estimation is reliable.

On circular orbits during low bit rate measurement the heavy ion fluxes as measured by TAUS were also often modulated by the rotation of the orbiter. To be certain that the ion collection by instrument FOV is complete, 1-D angular spectra (averaged over E/q) could be used. For a single *Phobos* 2 pass through the magnetotail the maxima of heavy ion fluxes should be used for reliable estimation of the plasmasheet ion flux for this orbit. Statistics of maximal ion fluxes with $150 \text{ V} < E/q < 6$ kV observed in the Martian plasmasheet for the 58 *Phobos* 2 circular orbits are presented in Fig. 4. According to the TAUS data the average flux of heavy ions can be estimated to be $F \sim 2.5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ for the period of active operation of *Phobos* 2. This value is marked by an arrow in Fig. 4.

The last information needed to estimate the oxygen ion loss rate through the plasmasheet is the width of the areomagnetic tail. In Fig. 5 the magnetopause and the bow shock crossings (including multiple ones) during the *Phobos* 2 circular orbits are shown. The magnetopause and the bow shock crossings for elliptical orbits are also shown in this figure by heavy dots

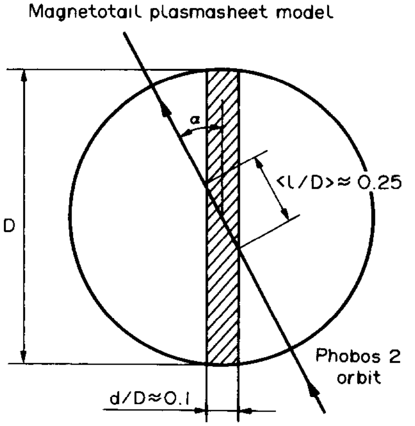

FIG. 3. A CROSS-SECTION OF THE MODEL MAGNETOTAIL OF MARS.
The plasmasheet is hatched. The solid line represents an orbit of *Phobos* 2.

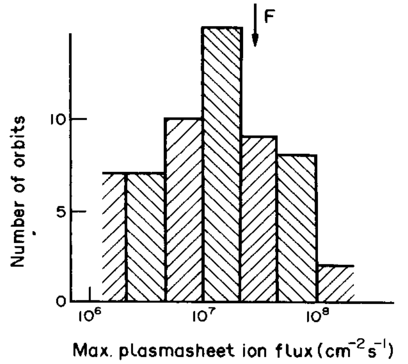

FIG. 4. THE HISTOGRAM OF THE DISTRIBUTION OF HEAVY ION FLUXES IN THE MARTIAN PLASMASHEET.
Fifty-eight circular orbits were considered. The arrow marks the average flux of the plasmasheet ions.

and triangles, respectively. Smooth solid and dashed curves in Fig. 5 represent the positions of the magnetopause and the bow shock boundaries according to the hydrodynamical model of Spreiter *et al.* (1970) with the H/r_0 parameter value of ~ 0.3 and with the subsolar height of the obstacle $h \sim 600$ km. General agreement of the observed magnetopause and bow shock positions with the theoretical curves is obvious, as well as the presence of large variations of the magnetotail width.

The data presented in Fig. 5 permit us to estimate the average magnetotail diameter to be approximately $D \sim 15{,}000$ km, or ~ 4.4 Martian radii at the areocentric distances of 2–3 Martian radii downstream of the planet. According to the *Mars*-5 orbiter measurements the characteristic magnetotail width was ~ 3.2 Martian radii on February 1974 (Gringauz, 1981). Both estimations essentially exceed the characteristic magnetotail width of the non-magnetic Venus (~ 2.2 planetary radii; Gringauz, 1981), thus indicating the influence of the Martian intrinsic magnetic field on the magnetotail formation.

Taking now the possible Martian plasmasheet configuration (Fig. 3) 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 plasmasheet to be $\Phi \sim F \times d \times D \sim 5 \times 10^{24}\ \mathrm{s}^{-1} \sim 150\ \mathrm{g\ s}^{-1}$.

The accuracy of Φ evaluation is not high. It is mainly concerned with the observed variations (by a factor of 2–3) of the magnetotail width D (Fig. 5) and of the heavy ion fluxes F (Fig. 4). The above estimations are also model-dependent to some extent.

DISCUSSION

The process of oxygen ion losses through the plasmasheet of the Martian magnetotail is the first process of a mass loss of the planet measured by a direct *in situ* method. The average loss rate estimated above of $\sim 150\ \mathrm{g\ s}^{-1}$ corresponds to a Martian atmospheric dissipation rate of $\sim 4 \times 10^{-17}\ \mathrm{mbar\ s}^{-1}$. If this rate is permanent, the present 7–10 mbar Martian atmosphere would be dissipated during $\sim 5\text{–}8 \times 10^9$ years. This time is comparable to the age of the planet. The process of Martian atmosphere dissipation revealed by the *Phobos* 2 plasma experiments is therefore important for the evolution of the Martian atmosphere.

The loss of Martian ions through the planetary magnetotail has never been considered theoretically. In the papers of Michel (1971) and Cloutier *et al.* (1974) only ion escape to the solar wind above the obstacle is considered. In both papers the total ion escape flux in this region (1–10 g s^{-1}) was drastically underestimated due to the assumption of an exponentially decreasing source of heavy ions although, as is clear now, the main source of heavy Martian ions in the solar wind is the huge hot oxygen corona of the planet (see below).

The only experimental attempt to estimate an oxygen flux through the Martian tail before *Phobos* 2, was made by Vaisberg *et al.* (1975) and Vaisberg (1976) using the data from the RIEP spectrometer on *Mars*-5. They detected ion fluxes escaping through what they thought was a thin (~ 1000 km) boundary layer of the tail of diameter $D \sim 12{,}000$ km and with

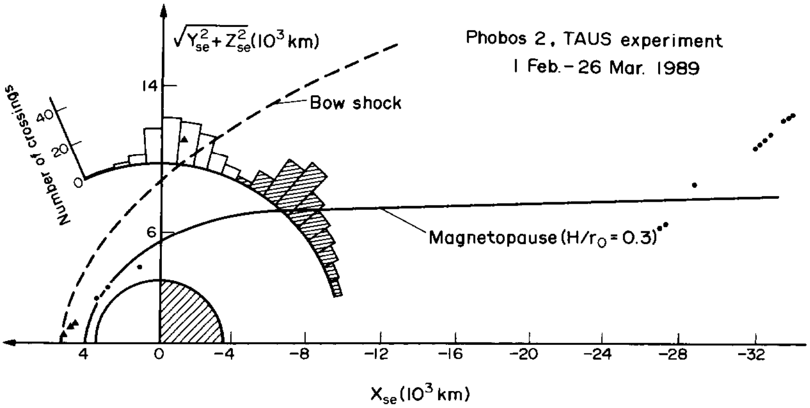

FIG. 5. STATISTICS OF MAGNETOPAUSE AND BOW SHOCK CROSSINGS (INCLUDING MULTIPLE ONES) FOR *Phobos* 2 CIRCULAR ORBITS.

Martian solar ecliptic coordinates are used. The solid and dashed curves show the positions of the magnetopause and bow shock, respectively, according to the hydrodynamical model of Spreiter *et al.* (1970), with $H/r_0 \sim 0.3$ and a subsolar height of the obstacle $h \sim 600$ km. Heavy dots and triangles mark magnetopause and bow shock crossings on the elliptical orbits, respectively.

a typical ion flux of $F \sim 2 \times 10^6$ cm^{-2} s^{-1} ($F \sim 3 \times 10^7$ cm^{-2} s^{-1} on 20 February 1974) arrived at an ion loss rate of $\Phi \sim 10^{24}$–10^{25} s^{-1} (Vaisberg, 1976; Vaisberg and Smirnov, 1986).

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 Bezrukikh *et al.* (1978) interpreted RIEP data with the presence of protons only (see also Vaisberg and Smirnov, 1978, for response). The *Mars*-5 orbit did not penetrate far into the Martian tail and was not able to determine the relationship to the plasmasheet structure as has been done here.

Though the process of Martian oxygen ion outflow through the plasmasheet is important for the evolution of the planetary atmosphere, it is not the main process of oxygen dissipation. Indeed, the dissociative recombination of the main ionospheric ion O_2^+ in the vicinity of the Martian exobase ($h_c \sim 200$ km) leads to the formation of fast oxygen atoms. The dominant energy of such atoms $E \sim 2.5$ eV exceeds the oxygen escape energy $E_{esc} \sim 2$ eV thus leading to the formation of the hot oxygen corona and providing a heavy ion dissipation flux of $F \sim \alpha n_e^2(h_c)H \sim 8 \times 10^7$ cm^{-2} s^{-1}, where $n_e \sim 10^4$ cm^{-3} is the exobase electron density, $H \sim 28$ km is the neutral scale height, and $\alpha \sim 3 \times 10^{-7}$ cm^3 s^{-1} is the dissociative recombination rate (Krasnopolsky, 1986; Ip, 1988); so, the total rate of oxygen dissipation from the sunlit planetary hemisphere can be estimated as $\Phi \sim 5 \times 10^{25}$ s^{-1}, i.e. by an order of magnitude higher than the loss rate through the plasmasheet.

Although the existence of the Martian hot oxygen corona was predicted 18 years ago (McElroy, 1972), its observational verification is still absent (Nagy and Cravens, 1988). The oxygen loss rate through the corona still needs experimental confirmation.

What is the origin of oxygen ions escaping from the planet through the magnetotail plasmasheet? It can be shown that the production rate of O^+ ions from the hot oxygen corona between exobase and magnetopause is more than an order of magnitude less than the one needed, even for the model of the hot oxygen corona of Ip (1988) with a larger oxygen density that in the case of the Nagy and Cravens (1988) model. O^+ ions originating from the thermal oxygen population, which is much more abundant below the magnetopause, need to be accelerated into the plasmasheet.

Possible regions for such a process could be the wide polar caps as part of the Martian magnetosphere produced by a feasible weak intrinsic magnetic field, or the polar holes (Perez-de-Tejada, 1980) of the induced part of the Martian magnetosphere. In the first case the polar winds and the subsequent heavy ion drifts towards the plasmasheet under the influence of cross tail electric field can provide a proper plasma population. In the second case the acceleration of heavy ions takes place under their interaction with the magnetosheath plasma, which has direct access to the magnetosphere through the polar holes.

The origin of Martian plasmasheet ions and the process of their acceleration need further detailed experimental and theoretical studies and can be considered as a matter for further publications.

CONCLUSION

The plasma measurements deep in the Martian magnetotail by the *Phobos* 2 TAUS spectrometer revealed the existence of a plasmasheet on both sides of the magnetic neutral sheet.

The plasmasheet of the Martian magnetosphere is mainly formed by heavy ions (O^+).

At areocentric distances of 2–3 Martian radii downstream from the planet:

—the average magnetotail width is ~ 4.4 Martian radii;

—the characteristic plasmasheet scale is $\sim 10\%$ of magnetotail width;

—the typical flux of heavy ions in the plasmasheet is $\sim 2.5 \times 10^7$ cm^{-2} s^{-1}.

The average loss rate of oxygen ions through the plasmasheet is estimated to be $\sim 5 \times 10^{24}$ s^{-1}, or ~ 150 g s^{-1}. The process of Martian heavy ion losses through the plasmasheet is the only one supported by reliable *in situ* observational data. The oxygen loss rate evaluated is important for the evolution of the Martian atmosphere.

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