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ON THE PROBLEM OF THE MARTIAN ATMOSPHERE DISSIPATION: PHOBOS 2 TAUS SPECTROMETER RESULTS

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Abstract. The measurements of proton spectra obtained by the TAUS spectrometer on board the Phobos 2 spacecraft in elliptical orbits near Mars are presented. A strong deceleration of the solar wind upstream of the Martian bow shock was revealed. It can be caused by the mass loading of the plasma flow by ions originating from the hot oxygen/hydrogen corona of Mars and/or by protons specularly reflected from the bow shock. In the first case the deceleration of the solar wind by about 100 km/s implies that the hot oxygen corona of Mars could be several times denser than it was anticipated to be (at least during the observation period that was close to solar cycle maximum). Furthermore, the loss of planetary oxygen through the corona appears to be the main process of oxygen loss from Mars. The upper limit of loss rate for such a process is determined to be 10^{26} oxygen atoms or 2.5 kg of oxygen per second.

Introduction

The first mass-spectrometric plasma measurements in the vicinity of Mars provided by the TAUS (proton and alpha particle spectrometer) [Rosenbauer et al., 1989a] and ASPERA (automatic space plasma experiment with a rotating analyzer) [Lundin et al., 1989] experiments on board the Phobos 2 orbiter in February-March 1989 revealed the dominance of heavy ions of planetary origin (mainly O^+) in the Martian magnetotail. These observations permitted estimations of the loss rate of planetary oxygen through this region to be a few times 10^{25} s^{-1} [Rosenbauer et al., 1989a; Lundin et al., 1989].

On the basis of the data from a limited number of orbits, Rosenbauer et al. [1989a] found that the largest ion fluxes occurred in the plasma sheet of the Martian magnetotail, while Lundin et al. [1989] 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 the heavy ion fluxes measured by the TAUS spectrometer in the magnetotail over all available Phobos 2 orbits [Verigin et al., 1991]. The average loss rate of Martian oxygen ions through the plasma sheet was estimated to be ~5×10^{24} s^{-1} with a large spread of the loss rates derived for individual orbits. Lundin et al. [1990b] confirmed the existence of the magnetotail plasma sheet, although they still suggested that the heavy ions mainly escape through the Martian boundary layer [Lundin et al., 1990a].

The process of the Martian oxygen outflow through the plasma sheet is important but not necessary to the main process of planetary oxygen dissipation [Verigin et al., 1991]. The estimated rate of oxygen dissipation from the planetary sunlit hemisphere through the hot oxygen corona [e.g., Krasnopolsky, 1986] could be an order of magnitude more than the loss rate through the plasma sheet. Even though the existence of the Martian hot oxygen corona itself was predicted more than 18 years ago [McElroy, 1972], the oxygen loss rate through the corona nevertheless needs experimental confirmation [Nagy and Cravens, 1988].

In the present paper the observational evidence of the deceleration of the solar wind upstream of the Martian bow shock is presented. Then for the first time the upper limit of the density distribution of the planetary corona is evaluated by considering this deceleration as a consequence of the solar wind mass loading by oxygen ions originating from the planetary corona. Finally, the upper limit of the loss rate of oxygen through the corona is evaluated. The results obtained are compared with previous oxygen loss rate estimations, and the consequences of the possible presence of a huge Martian oxygen corona in the solar wind are discussed.

Instrumentation and Raw Data Processing

The TAUS instrument on board Phobos 2 was specially designed for the investigation of the solar wind interaction with Mars. The energy spectra of three species of ions - protons, alpha particles, and heavy ($M/q > 3$) ions - could be measured separately by a system of two hemispherical electrostatic analyzers with a magnetic deflection system. The instrument's field of view of ~40° x 40° was centered on the nominal direction toward the Sun, and it was divided into eight azimuthal by eight elevational channels for obtaining the angular resolution. The energy per charge (E/q) range of ~30 V to 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 by Rosenbauer et al. [1989b].

During the active life of the Phobos 2 orbiter, TAUS data were obtained from four elliptical orbits with low (h ~ 850 km) pericenter, one elliptical orbit with high (h ~ 6400 km) pericenter, and 58 circular orbits, quasi-synchronous with the Phobos moon (h ~ 6150 km).

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For the study of solar wind deceleration, TAUS data will be used from the first three elliptical orbits, during which the planetary bow shock was crossed close to the subsolar point. On the fourth elliptical orbit with low pericenter there is a gap in the TAUS data in the vicinity of the bow shock, and the bow shock was intersected far from the subsolar point during the following orbits.

For a fixed energy and elevation the different charge electron multipliers (CEMs) of the TAUS instrument measured proton fluxes in all azimuthal directions simultaneously for ~24 ms. Thus taking into account the scanning over elevation and energy, three-dimensional (3-D) spectra of protons consisting of 2048 count rates were measured in ~8 s. Due to telemetry limitations this information was compressed by the TAUS microprocessor system. For the data considered here, 312 selected count rates (in the vicinity of the maximum value) were transmitted by telemetry from the complete 3-D proton spectra set every minute. Additionally, two sets of 2-D proton spectra (sums of 3-D data over the azimuth or elevation) and two sets of 1-D spectra (sums over azimuth and elevation) were transmitted with the same frequency.

Figures 1a and 1b present the bulk velocity of protons for a time interval of ~1 hour before the crossing of the Martian bow shock (indicated by S) on the first and second elliptical orbits,

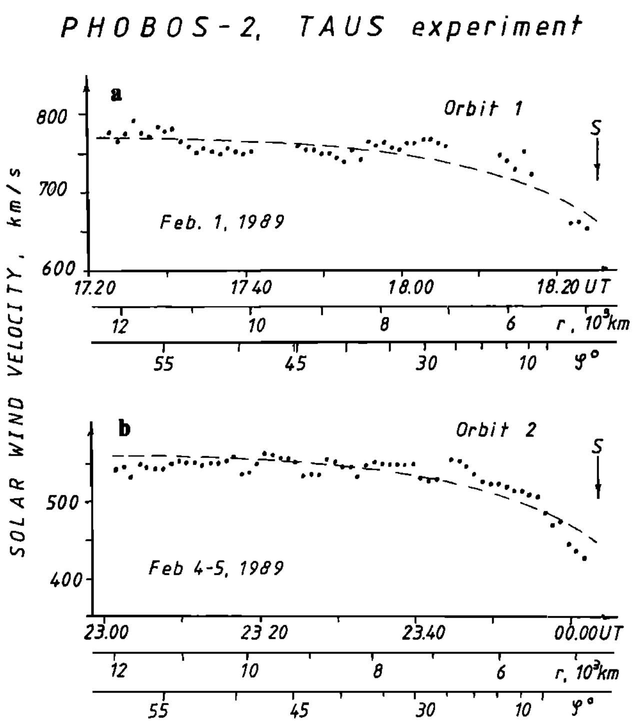

Fig. 1. Proton bulk velocity values of ~1-hour time interval upstream of the Martian bow shock on the (a) first and (b) second elliptical orbits. The bow shock positions (S) were defined by the characteristic changes of the proton spectra [Rosenbauer et al., 1989a]. The deceleration of solar wind protons upstream of the shock is evident. The dashed curves present the results of model calculations of solar wind flow decelerated due to mass loading by heavy ions originating from the hot oxygen corona of Mars.

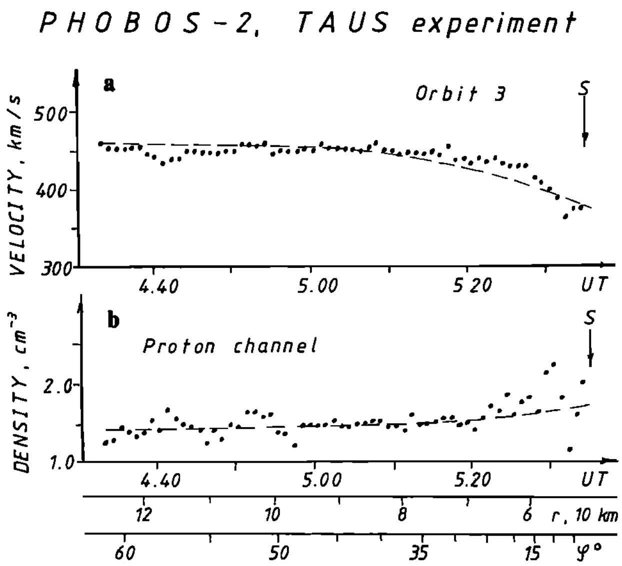

Fig. 2. (a) Proton bulk velocity and (b) number density values on the third elliptical orbit. Notations are the same as in Figure 1.

respectively. (The bow shock positions were identified by certain specific changes of the proton spectra described by Rosenbauer et al. [1989a].) In Figures 2a and 2b the proton bulk velocity $\vec{V}$ and number density n_p are shown for the similar time interval in the third elliptical orbit. At first the average values of the 3-D proton distribution function were determined for the element of velocity phase space using the results of instrument calibrations. Then density and velocity components were calculated as the zeroth and first moments of the distribution function, respectively.

We should note the following: 1. During the first two orbits the Phobos 2 spacecraft was rotating around the axis pointing approximately toward the solar direction with a period of ~10 min, and the spacecraft was three-axis stabilized during the third orbit. The number densities evaluated during the first two orbits were modulated by this rotation and thus are not presented here. On the other hand, the calculated proton velocity values are practically not influenced by the rotation of the spacecraft. 2. For very high proton velocities during the first orbit (Figure 1a) the selection of elements of 3-D raw proton spectra for telemetry transmission was not properly functioning, and the velocities presented in this figure are evaluated from the 2-D proton spectra. 3. In-flight operation of some channels of the instrument is still under detailed analysis, and the number densities presented in Figure 2b could later be changed by a factor of the order of 1.

Data Analysis

The obvious feature of the velocity profiles presented in Figures 1a, 1b, and 2a is the very pronounced deceleration of solar wind protons upstream of the planetary bow shock. This deceleration is of the order of ~100 km/s and cannot be connected with any instrumental or data processing effects. The deceleration also cannot be occasional, as it was observed in each of the three available TAUS data sets, when the Phobos 2 spacecraft was close to the subsolar part of the Martian bow shock.

There are two possible reasons for such a deceleration. First, this effect could be a consequence of the mass loading of the solar wind stream by ions of planetary origin continuously being born in the solar wind. Second, the slowdown could be the result of the solar wind loading by protons which are specularly reflected from the bow shock (shock foot).

In the second case the number of reflected protons is a complicated function of plasma beta (β) and Mach number in the upstream flow, and of the angle between the direction of the upstream magnetic field and the shock normal. Furthermore, it is strongly dependent on the magnitude of the ratio of the specific heat capacities chosen in the Rankine-Hugoniot relations [Livesey et al., 1984; Gosling and Thomsen, 1985; Wilkinson and Schwartz, 1990]. Detailed analyses of the relative importance of both processes mentioned should be based on the joint consideration of the data of different Phobos 2 plasma experiments and are a subject of future studies.

The deceleration of the solar wind due to mass loading by heavy ions continuously born in the solar wind was observed upstream of the bow shock of comet Halley [e.g., Verigin et al., 1987; Coates et al., 1987]. Why might a similar deceleration appear near Mars? A possible reason for such a process is the existence of a huge oxygen corona of Mars. Indeed, the dissociative recombination of the main ionospheric ion O_2^+ ($O_2^+ + e \rightarrow O + O$) in the vicinity of the Martian exobase (h_c ~200 km) leads to the production of fast oxygen atoms. The dominant kinetic energy of such atoms of E ~ 2.5 eV exceeds the oxygen escape energy of E_{esc} ~ 2 eV, thus leading to the formation of the hot oxygen corona.

The numerical estimations of the solar wind deceleration by the oxygen corona are rather straightforward and will be described below. Of course, with the neglect of any deceleration effect associated with the bow shock structure and hydrogen corona, our estimates of the intensity of the Martian oxygen corona should be considered only as upper limits.

There are two recent models of such a hot oxygen corona [see Nagy and Cravens, 1988; Ip, 1988]. The latter may be more appropriate for the solar cycle maximum [Nagy and Cravens, 1990]. Since the Phobos 2 mission took place during the increasing phase (close to the maximum) of solar activity, we will use the result from Ip [1988] as a working model. This model was calculated for altitudes h < 10,000 km. Down to an altitude of h ~ 1000 km the average of the two limiting profiles of the hot oxygen density presented in Figure 3 of Ip [1988] can be approximated by the following empirical relation:

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

where r is the areocentric distance, n_o ~ 90 cm^{-3}, n_o/n_1 ~ 3, and r_o ~ 10,000 km. As Ip [1988] estimated, an oxygen corona with such a density could decelerate the solar wind only 5-10 km/s.

The process of mass loading and deceleration of the solar wind by heavy ions, newly born from neutrals, is well known and was considered previously in a number of models of solar wind interaction with comets (see, for example, the review by Mendis et al. [1985]). In the case of a sufficiently large comet, the pickup ions first form a ring in velocity phase space; then the Alfvén wave turbulence, excited by the ion cyclotron instability, isotropizes the new ions in the coordinate system moving with the solar wind [Sagdeev et al., 1986]. A simple, axially symmetric, analytical solution for weakly loaded hydrodynamic solar wind flow with isotropic heavy ions, which is convenient for the description of the variation of plasma parameters along the spacecraft trajectory, can be found in the paper by Gringauz and Verigin [1990].

It is a matter of debate whether heavy ions could be isotropized near Mars or their motion should be considered with a test particle approach [Luhmann, 1990]. This is because the scale of the disturbances in the solar wind flow is comparable to the gyroradius of the freshly born O^+ ions. For qualitative estimations, a fluid model is used in which incompleteness of the pitch angle isotropization of new ions can be partially taken into account by varying the ratio of the specific heats $\gamma = (k + 2)/k$ (where k is the degree of freedom for an exchange of the kinetic energy, k = 3 for a complete isotropization). We will use here the equations of hydrodynamic flow with mass loading [e.g., Biermann et al., 1967]:

$$div(n_p\vec{V}) = 0, \qquad (2a)$$

$$div(\varrho\cdot\vec{V}) = Q(r), \qquad (2b)$$

$$\varrho(\vec{V}\cdot\nabla)\vec{V} = -p - Q(r)\cdot\vec{V}, \qquad (2c)$$

$$div\{\vec{V}[\varrho V^2/2 + p\gamma/(\gamma-1)]\} = 0, \qquad (2d)$$

where ϱ and p are the mass density and pressure in the flow, respectively, $Q(r) = M_i n_n(r)/\tau_i$ is the mass loading rate, M_i is the mass of oxygen atoms, and τ_i ~ 2 x 10^6 s is their ionization time scale at ~1.5 AU.

The solution of equations (2) for weakly loaded, highly supersonic ($M^2 = \varrho V^2/\gamma \cdot p >> 1$) solar wind is similar in form to the one presented by Gringauz and Verigin [1990]. The final expressions for V(r, φ) and n_p(r, φ), which were further applied for the analysis of TAUS data, were obtained by using (1):

$$V = V_o - \frac{(\gamma+1)M_i n_o r_o}{2\varrho_o\tau_i}\left(\frac{r_o}{r}\right) \cdot \frac{\varphi}{\sin\varphi}\left[1 + \frac{1}{3}\left(\frac{n_1}{n_o}\right)\left(\frac{r_o}{r}\right)^3 \cdot \frac{\cos^3\varphi - 3\cos\varphi + 2}{\varphi\sin^3\varphi}\right] \qquad (3a)$$

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

where φ is the angular distance of the point of observation from the stagnation point of the flow. (Below we define φ as the angle between the point of observation and the X axis of the solar ecliptic coordinate system which is rotated by an angle $\alpha \sim \tan^{-1}(V_m/V_o)$ around the Z axis to take into account the orbital motion of Mars with a velocity of $V_m \sim 24.1$ km/s.)

In order to find the best fit for expressions (3) to both the proton velocity and density observed we minimized the sum of the relative squared differences between the pertinent theoretical values and measured velocities and densities over the variables n_o, V_o, and n_{Po}. The best fits are shown in Figures 2a and 2b by dashed lines for the following set of parameters: $n_o \sim 500$ cm^{-3}, $V_o \sim 505$ km/s, and $n_{Po} \sim 1.3$ cm^{-3}. General agreements between the observed and calculated velocities and densities for the third orbit are obvious. The statistical error is rather small ($\delta n_o/n_o \sim 20\%$) and cannot be considered as an accuracy of n_o evaluation (see discussion).

For the first two orbits (Figures 1a and 1b) we used the n_o value estimated above and fitted V_o and n_{Po} parameters for the first relation of (3). Dashed lines show the best fits in Figure 1a ($V_o \sim 820$ km/s, $n_{Po} \sim 1.2$ cm^{-3}) for the first orbit and in Figure 1b ($V_o \sim 605$ km/s, $n_{Po} \sim 1.2$ cm^{-3}) for the second one. The n_{Po} values for both orbits are in reasonable agreement with the proton densities (highly modulated by spacecraft rotation) evaluated by the TAUS data for these orbits.

Discussion

The deceleration of the solar wind observed by the TAUS instrument upstream of the Martian bow shock (Figures 1 and 2) is obvious. Why was such a strong deceleration not found earlier in the previous missions to Mars? Possible reasons can be listed as follows:

1. Previously, ion spectra were measured in the vicinity of Mars on board the Mars 2 and Mars 3 (1971-1972) and Mars 5 (1974) orbiters, i.e., at the decreasing and close to minimum phases of the solar cycle, when the Martian atmosphere could be less extensive than close to solar cycle maximum phase in February-March 1989.

2. During those missions, the bow shock was observed mainly far from its subsolar point ($\varphi > 50°$) with a poor time resolution.

The amplitude of the deceleration observed (~100 km/s) implies that the hot oxygen corona of Mars at least in the periods close to solar cycle maxima could be denser than it was assumed in the existing coronal models of Nagy and Cravens [1988, 1990] and Ip [1988].

According to the above evaluations, for the agreement between calculated and observed deceleration of the solar wind to be reasonable the hot oxygen parameter n_o should be <(500/90) ~5 times greater than in the model of Ip [1988]. Taking into account (1) the absence of observations on the planetary corona, (2) the possible uncertainty of the data on which the corona models are based, and (3) the fact that the TAUS observations were performed close to the solar cycle maximum, this conclusion does not seem improbable.

Additionally, in our evaluations we have assumed that the density profile of the hot oxygen corona is the one of Ip's [1988] model (i.e., the ratio of n_o to n_1 parameters in expression (1) is fixed $n_o/n_1 \sim 3$). Figures 1 and 2 show some systematic difference between the calculated and measured velocity profiles which may be attributed to the faster increase of the corona density when approaching the planet in comparison to the assumed one. It means that the n_o coefficient of the slowly increasing ($\sim(r_o/r)^2$) term in (1) could be overestimated in our calculations. A slightly better agreement can be obtained between the calculated and measured velocity profiles if the ratio of n_o to n_1 parameters in (1) is chosen to be $n_o/n_1 \sim 1$. In this case the best fit parameters are $n_o \sim 200$ cm^{-3}, $V_o \sim 480$ km/s, and $n_{Po} \sim 1.3$ cm^{-3}. At the same time the density of the oxygen corona could again be several times higher ($n_o \sim n_1 \sim 200$ cm^{-3}) than the one according to (1). It should be noted that the agreement between the calculated and measured velocity profiles also might be improved by taking into account specularly reflected protons.

The deceleration of the solar wind was mainly observed by the TAUS instrument 10-15 min before Phobos 2 crossed the Martian bow shock (Figures 1 and 2). This region has some other peculiarities. A gradual increase of the magnetic field intensity B was observed by the MAGMA (magnetic fields near Mars) magnetometer (Figure 5 of Schwingenschuh et al. [1990]) accompanied by the growth of magnetic field fluctuations (Figure 2 of the same paper), by the appearance of the broadband noise extending from below the lower hybrid frequency to the electron plasma frequency [Grard et al., 1989], and by the appearance of a second peak of electron fluxes with energies of ~10^2 eV (Figure 2 of Shutte et al. [1991]).

Originally, these effects were interpreted as the observation of the shock foot, raised by protons reflected from the shock front [Grard et al., 1989; Schwingenschuh et al., 1990]. But these phenomena can be also connected with mass loading of the solar wind flow by heavy ions. For instance, the excited MHD turbulence should have a maximum around ~10^{-2} Hz [e.g., Tsurutani and Smith, 1986] that does not contradict the power spectra of magnetic field presented in Figures 3 and 4 of Schwingenschuh et al. [1990]. Also the appearance of electrons with energies of ~10^2 eV may be connected to the presence of oxygen ions just like what was observed during the artificial comet experiments of the AMPTE mission with the release of Li in the solar wind [Paschmann et al., 1986; Hall et al., 1986].

There is an interesting interpretation of both terms in (1): at sufficiently large planetocentric distances the first term gives the density of oxygen atoms, which are moving radially outward from the planet with a velocity of $v \sim [2(E - E_{esc})/M_i]^{½} \sim 2$ km/s, while the second term represents the slower oxygen atoms in ballistic orbits. The production rate of fast oxygen can be estimated as

$$Q \sim \pi r^2 n_o (r_o/r)^2 v \sim 10^{26}\ s^{-1}, \tag{4}$$

where we used $n_o \sim 200$ cm^{-3} and (in order to take into account the nonuniformity of the production rate of coronal oxygen above the sunlit hemisphere of the planet) the cross section as a measure of surface through which the fast atoms move originally is taken to be πr^2.

At sufficiently large planetocentric distances exceeding a few tens of thousand kilometers, as in the case of the cometary neutral gas [e.g., Haser, 1957], the following expression can be used for the description of atomic oxygen density in the Martian corona:

$$n_n(r) \sim Q/(4\pi r^2 v)\, exp(-r/v\tau_i)\,. \tag{5}$$

Finally, all oxygen atoms will be ionized and picked up by the solar wind. This process mainly takes place at a distance of $\lambda \sim v\tau_i \sim 4x10^6$ km, which gives the natural outer scale of the Martian oxygen corona. The total number of fast neutral atoms N_o in the Martian corona can be estimated as

$$N_o \sim 4\pi \int r^2 n_n(r)\, dr \sim Q\tau_i \sim 2x10^{32}. \tag{6}$$

The loss rate L of these atoms in the ionization processes mentioned above is naturally equal to their production rate:

$$L \sim N_o/\tau_i \sim Q \sim 10^{26}\ s^{-1}. \tag{7}$$

The ionization loss of slower atoms of the planetary oxygen corona (second term in equation (1)) can be neglected because the number of such atoms above r ~ 5000 km, N_1, is small compared with N_o:

$$N_1/N_o \sim \tfrac{1}{2}(n_1/n_o)\,(r_o^2/\lambda \cdot r^2) \sim 5x10^{-3}. \tag{8}$$

So the deceleration of the solar wind upstream of the detached Martian bow shock might be considered the first observed indirect indication of the hot oxygen corona of Mars. The rate of oxygen dissipation from the sunlit hemisphere of the planet through this formation of $\leq 10^{26}\ s^{-1}$ as determined above is higher than previously estimated. Actually, the nonthermal atomic oxygen dissipation flux of $F \sim 5x10^7\ cm^{-2}\ s^{-1}$ [Krasnopolsky, 1986] corresponds to an oxygen dissipation rate of $\sim 2\pi r_c^2\ F \sim 4x10^{25}\ s^{-1}$ from the sunlit exobase of the planet (r_c ~ 3600 km). This difference may be connected again with the special time of Phobos 2 observations.

The dissipation rate estimated above corresponds to an oxygen loss of ~2.5 kg/s from Mars, or to a decrease in atmospheric pressure of $\sim 7x10^{-16}$ mbar/s. If this rate is permanent, the present ~7-mbar pressure of the Martian atmosphere would be dissipated in $\sim 3x10^8$ years. This time is comparable to the age of the planet; therefore the process considered here can be important in the evolution of the Martian atmosphere.

The process of oxygen dissipation through the plasma sheet of the Martian magnetotail is also important ($L \sim 10^{25}\ s^{-1}$) [Verigin et al., 1991], but its rate is smaller by an order of magnitude.

What are the other consequences of the existence of such a huge ($\lambda \sim 4x10^6$ km) neutral oxygen corona around Mars, and how can its existence be verified by in situ measurements?

If a spacecraft approaches the planet in the direction perpendicular to the Sun-Mars line, an ion mass spectrometer on board the spacecraft should measure the net flux of oxygen ions beginning from several million kilometers:

$$F \sim Q/(8r\tau_i v) \sim 4x10^3 (r_1/r)\ cm^{-2} s^{-1}, \tag{9}$$

where $r_1 = 10^5$ km. This planetocentric distribution of the picked-up heavy ions could be measured during a future Martian mission (e.g., Mars-94); thus we can determine the dissipation rate of oxygen through the planetary corona, as well as its density distribution by in situ plasma measurements.

Far upstream of the planetary bow shock the solar wind mass loading effect near Mars could resemble that near a weak comet with a gas production rate of $Q \sim 10^{26}\ s^{-1}$. Therefore a more detailed analysis of 3-D TAUS measurements of the plasma flow near Mars could be useful in preparation for the planned CRAF (Comet Rendevous and Asteroid Flyby) mission to comet Kopff. During the apparition of this comet in 1983 its gas production rate at perihelion (~1.58 AU) reached $Q \sim 7x10^{28}\ s^{-1}$ [Devine, 1989]. At a heliocentric distance of ~3 AU the gas production rate of this comet could be comparable with that of Mars [Flammer et al., 1991].

Conclusion

The measurements of proton spectra by the TAUS spectrometer during elliptical orbits of the Phobos 2 mission revealed a strong deceleration of the solar wind upstream of the Martian bow shock, possibly due to mass loading of the plasma flow by O^+ ions originating from the hot oxygen corona of the planet. The amplitude of the deceleration observed (~100 km/s) implies that the hot oxygen corona of Mars during the observation period close to solar cycle maximum could be several times denser than anticipated.

The loss of planetary oxygen through the corona appears to be the main process of oxygen loss by Mars; the intensity of this loss could be determined as $<10^{26}$ oxygen atoms, or <2.5 kg of oxygen per second. The development of advanced models for the hot oxygen corona and for the solar wind interaction with this corona is necessary for more precise evaluations of oxygen dissipation. The study of the planetocentric distribution of heavy ions on board 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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