

## PICKED-UP PROTONS NEAR MARS: PHOBOS OBSERVATIONS

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**Abstract.** The measurements carried out by the plasma spectrometer, ASPERA, onboard the PHOBOS-2 spacecraft show that protons, originating in the extended hydrogen corona of Mars, were observed at altitudes  $\leq 7500$  km. The cyclotron instability of these pickup ions appears to generate Alfvén waves observed by the MAGMA magnetometer. Analysis of the plasma data shows that weak pitch-angle diffusion of a ring-distribution of pickup protons occurs. The altitude profiles of pickup proton fluxes and number densities of the parent hydrogen atoms are derived.

## Introduction

The Martian hydrogen corona was discovered from Lyman  $\alpha$  observations on the spacecraft Mariner-6,7,9 and Mars-2,3 [Anderson and Hord, 1971; Anderson, 1974; Dostovalov and Chuvahin, 1973]. This corona extends far beyond the bow shock. [Nagy et al., 1990]. Exospheric protons created by photoionization and charge-exchange processes should be picked up by the solar wind electric field. Similar effects were observed near the comet Halley [Neugebauer et al., 1989], whose outer coma consists of the hydrogen atoms produced by the dissociation of  $H_2O$  molecules.

The pickup process should be accompanied by the excitation of Alfvén wave turbulence. A peak at the proton Larmor frequency in magnetic field power spectra has been observed upstream of the Martian bow shock [Russell et al., 1990]. It was suggested that this peak is due to the cyclotron instability of picked-up protons. Herein we present observations of the direct measurements of these exospheric protons.

## Instrumentation

The data used herein were obtained by the PHOBOS-2 ion mass-spectrometer, ASPERA, [Lundin et al., 1989] and the magnetometer, MAGMA [Riedler et al., 1989]. The three dimensional plasma composition experiment, ASPERA, consists of two spectrometer systems with  $360^\circ \times 5^\circ$  fields of view, lying in a plane perpendicular to the plane of rotation. One system called the 'moment sensors' has a sufficient mass resolution to resolve the 'major' ion

constituents. The hydrodynamical plasma parameters are obtained from the moment sensors. The  $360^\circ$  field of view is divided into 10 sectors. Spectral information for ions is obtained in 3 directions. The data from only the two sunward sensors,  $D1 + D10$ , with an aperture of  $72^\circ \times 5^\circ$  are used in the paper. The other system, called the 'mass sensors', has a better mass resolution and it is used for more detailed ion composition measurements. The two mass sensors had fields of view of  $72^\circ \times 5^\circ$  in the sunward and antisunward directions.

## Observations

The data discussed below were obtained from two elliptical orbits on 8 and 11 February 1989 when the spacecraft, PHOBOS-2, had three-axis stabilization. During the approaches to Mars the ASPERA scanner was not operating, and the special conditions needed for viewing picked-up protons could be achieved. Pick-up ions form a ring distribution in velocity space. The ring lies along the intersection of the sphere,  $S$ ,

$$(V_x + U_{sw})^2 + V_y^2 + V_z^2 = U_{sw}^2$$

and the plane perpendicular to the magnetic field vector,  $B$ , passing through the point  $(0, 0, 0)$ . The  $V_x$ -axis points toward the Sun,  $V_z$  is northward perpendicular to the Mars orbit and  $V_y$  completes the right handed system. We have neglected the  $4^\circ$  aberration of the solar wind and assumed that the solar wind has vector coordinates  $(-U_{sw}, 0, 0)$  in this system. Figure 1 shows the locus  $R$  of picked-up protons on both orbits 3 and 4. The average orientation of the interplanetary magnetic field for the period ( $\approx 1$  hour) before the bow shock crossing is shown. The plane of the field of view of the ion spectrometer was different in the two cases. It is assumed that picked up ions move along cycloidal trajectories and the pitch-angle diffusion due to particle-wave interactions is small. The sensors,  $D1 + D10$ , will 'see' the picked-up protons if the ring  $R$  is in their field of view as sketched in Figure 1. The 'conditions of visibility' for the 2 orbits are the following:

$$\begin{aligned} 54^\circ \leq \varphi \leq 126^\circ \\ 234^\circ \leq \varphi \leq 306^\circ \\ -1/\cos 36^\circ \leq \cos \varphi / \sin \theta \leq \tan 36^\circ \end{aligned} \quad \begin{array}{l} \text{(February 8)} \\ \text{(February 11)} \end{array}$$

where  $\varphi$  and  $\theta$  are the magnetic field azimuth and inclination. The orientation of IMF was different for these orbits. On February 8 the spacecraft was in the foreshock region, but on 11 February, it was not magnetically connected to the Martian bow shock. Moreover the distance between the spacecraft and bow shock surface was more than one and up to four proton Larmor radii. So we assume that the contribution to the "picked-up" population from any

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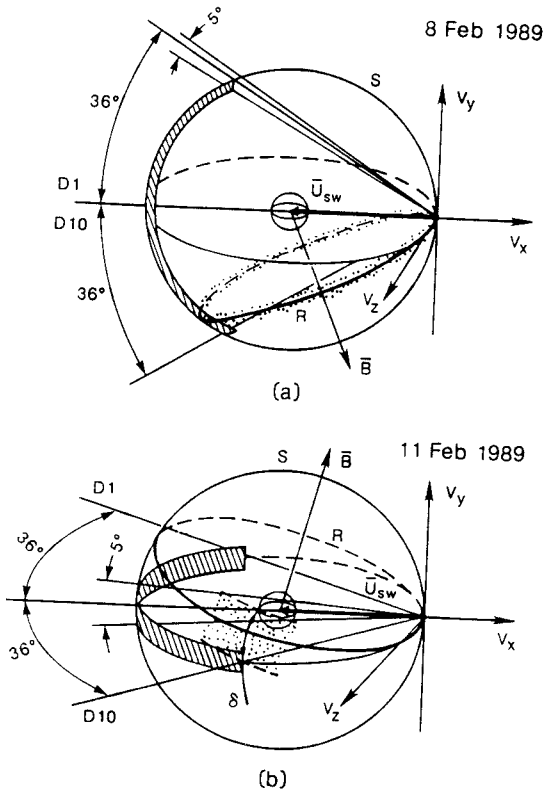


Fig. 1. Geometry of the plasma observations. The dots indicate the expected ring of pickup ions.

reflected ions is rather small on February 11 which data will be used in the detailed analysis below. As for orbit on February 8, the observation of features in the spectra of IMF fluctuations [Russell et al., 1990] gives us a basis for assuming that we observed the picked-up protons here too.

Figure 2a shows the energy-time spectrograms of proton fluxes, recorded by the D1 + D10 detectors (left panel) along the orbit 4 on February 11. The right panel gives the function  $\cos\phi/\sin\theta$  that determines the conditions of visibility (the region between the dashed lines in Figure 2a). It is seen that with the exception of a brief period near 1026 UT the spectrometer should not have seen picked-up protons in the absence of pitch angle scattering. There are no high temporal resolution data available at all until well after the bow shock is crossed. The energy of the picked-up protons in the limit of the weak pitch angle diffusion is  $E_{pi} \leq 4E_{sw} \sin^2\alpha$ , where  $E_{sw}$  is the energy of solar wind protons, and  $\alpha$  is the angle between  $U_{sw}$  and the IMF. For the period of time under study  $\sin^2\alpha = 0.6$  to  $0.85$ ,  $E_{sw} = 1.2$  keV, and  $E_{pi} \leq 2.9$  to  $4$  keV. It is seen that from 1022 UT secondary peaks in the proton energy spectra appear at energies from 1.9 to 3.8 keV whose intensity increases with decreasing distance to the planet. The energy of these ions is less than  $4E_{sw}$  (the energy of picked-up protons in the limit of strong scattering.) On the other hand the observation of particles moving strictly along the cycloidal trajectories is restricted by the narrow aperture of the spectrometer. Thus, in order to observe these particles one must assume that rather weak pitch-angle diffusion takes place. Spreading by diffusion should result in the observation of protons with higher energy (see the dots on Figure 1b). The angular width of

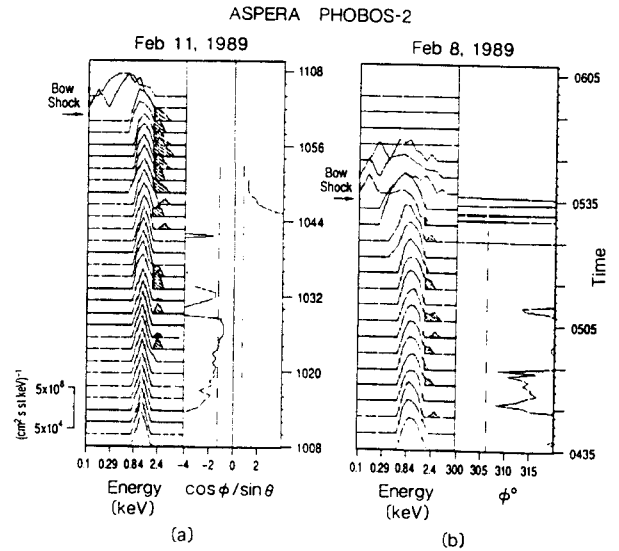


Fig. 2. Time-energy spectrograms of proton fluxes (from the 'moment sensors') upstream of the bow shock; a) orbit 4 on February 11, b) orbit 3 on February 8. The shaded peaks correspond to pickup protons. The angular conditions for 'visibility' of the pickup protons are given on the right panel.

the spreading ring can be estimated from the maximum energy of the observed pickup protons. This estimate gives a width  $\delta$  of  $\approx \pm 20^\circ$ .

Figure 2b gives the data for orbit 3 on February 8. Shown are energy-time spectrograms of proton fluxes, and the angular function of the visibility. The spectrometer would record pickup protons if  $\phi \leq 306^\circ$ . Pitch angle diffusion can also bring pickup ions into the field of view. Fortunately on this pass, high resolution magnetic field data are available [Russell et al., 1990]. These data showed a spectral peak at the proton gyro frequency from 0511 to the foot of the shock at 0527. The possibility that the ions in Figure 2b were due to  $He^{++}$  is excluded by examining the proton channel of the instrument's mass detector. A clear second peak in the proton data was seen on Feb 11 as shown in Figure 3.

## Discussion

The observation of the additional proton population confirms the existence of the extended Martian hydrogen corona. Integrating the secondary peak by energy we can get the observed picked-up ion flux  $F_{ob}(h)$  at the different altitudes  $h$ . But due to its narrow field of view the instrument was able to observe only a fraction  $k$  of the total flux  $F_t(h)$ ,  $k = F_{ob}(h)/F_t(h)$ .

Figure 4 shows the altitude dependence of the flux of picked-up protons for February 11. The stars show the experimental data with  $k = 0.2$ . The points marked by 'PH' correspond to the measurements made at an altitude  $\approx 6000$  km, i.e., in the region, where the Phobos torus may exist [Ip, 1988; Dubinin et al., 1990]. The gaseous Phobos torus could give an additional increase of the flux of picked up protons so we excluded these points. The linear fit of the flux at altitudes of 3500 to 7500 km along the orbit of

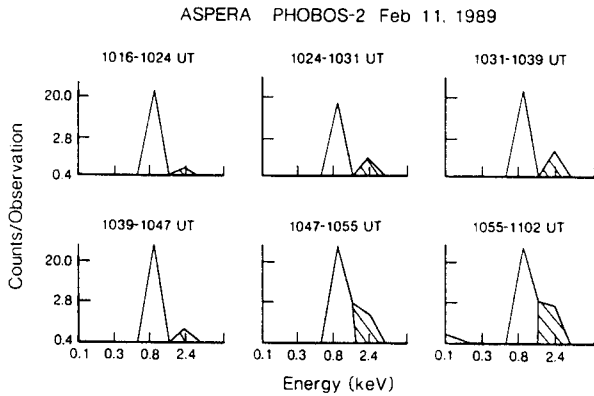


Fig. 3. Proton spectra obtained from mass sensors showing peaks related to pickup protons on Feb.11.

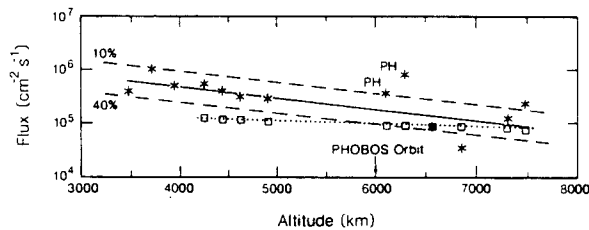


Fig. 4. The altitude profiles of the fluxes of pickup protons along the trajectory of PHOBOS-2. The dependence on factor  $k$  (the fraction of pickup proton flux that ASPERA detects) is illustrated by the three flux curves for  $k = 0.2$  (solid line);  $k = 0.1$ ; and  $0.4$  (dashed lines). The stars correspond to experimental data for  $k = 0.2$ . Open squares and dotted line correspond to fluxes that would be observed if the neutral hydrogen altitude distribution is taken from the model of Anderson and Hord [1972]. The arrow shows the location of the Phobos orbit.

PHOBOS-2 is shown by the dotted line. Dashed lines correspond to  $k = 0.1$  and  $0.4$ .

It is interesting to compare the data with the measurements of the neutral corona [Anderson and Hord, 1971]. The flux of picked-up ions is determined by

$$F_{th}(h) = \int_0^{\infty} \frac{N(s) ds}{\tau_{ion}}$$

where  $N(s)$  is the number density of neutral hydrogen,  $\tau_{ion}$  is the time of ionization and the integral is taken along the streamline of the picked-up ions that goes through the point of observation. In the limit of weak pitch angle diffusion this streamline is determined by the velocity of picked-up ions

$$V_{pi} = U_{sw} - \frac{(\sigma_{sw} \cdot B)}{B^2} B$$

The altitude dependence of the neutral hydrogen number density was taken from Anderson and Hord [1971]. The time of ionization including both time of photoionization  $\tau_{ph}$  and the time of charge exchange  $\tau_{ce}$  with solar wind protons gives

$$\tau_{ion} = \frac{\tau_{ph} + \tau_{ce}}{\tau_{ph} + \tau_{ce}} = 7 \times 10^6 \text{ s}$$

for  $\tau_{ph} = 3.1 \times 10^7 \text{ s}$  and  $\tau_{ce} = 8.5 \times 10^6 \text{ s}$ . Integrating numerically, we obtain the 'theoretical' points of the flux of picked-up ions shown in Figure 4 by the open squares. The dotted line is the linear fit for this result. The intersection of 'experimental' (solid) and 'theoretical' (dotted) curves at the point corresponding to the altitude at which pickup protons first appeared determined the choice of the factor  $k = 0.2$ . One should keep in mind that the error in the estimate of the percentage of the observed picked-up protons could be a factor of  $\approx 2$ .

The newly born ions form a beam along the magnetic field ( $-U_{\parallel}$ ) in the solar wind reference system where  $U_{\parallel}$  is the solar wind velocity along the magnetic field. Simultaneously these ions take part in cyclotron motion. Cyclotron instability of the beam generates Alfvén waves with a frequency  $\omega'$  and wave number  $k$  [Wu and Davidson, 1972]

$$\omega' - k U_{\parallel} = \Omega_{Bi}$$

where  $\Omega_{Bi}$  is the proton Larmor frequency. The frequency of waves in the spacecraft reference frame,  $\omega$ , determined by the Doppler-effect will be  $\omega = \omega' - k U_{\parallel}$  i.e., close to  $\Omega_{Bi}$ .

The wave energy comes from the beam energy. On the other hand the wave-particle interaction in the waves' reference frame occurs without a change of particle energy. Thus one can estimate the energy of excited waves  $\delta B^2/8\pi$  as

$$\frac{N \tau_{gr} m_p V_A (U_{\parallel} - V_A) - (\delta B)^2}{\tau_{ion}} = \frac{(\delta B)^2}{8\pi}$$

For  $N = 10^4 \text{ cm}^{-3}$ ,  $\tau_{ion} = 7 \times 10^6 \text{ s}$ ,  $V_A = 50 \text{ km/s}$ ,  $U_{\parallel} = 360 \text{ km/s}$ , and  $\tau_{gr} = 10/\gamma = 10/\Omega_{Bi} = 40 \text{ s}$  (growth time of the instability), we have  $(\delta B)^2/8\pi = 1.5 \times 10^{-11} \text{ erg/cm}^3$ . We perhaps overestimate the level of turbulence, because there is a lack of space near Mars for the excitation of the instability to reach saturation (in contrast to the comet case). From the power spectrum of the fluctuating magnetic field  $P_B(\nu)$  the observed value is  $P_B(\nu) \delta \nu = (0.7 \text{ nT}^2/\text{Hz})(2 \times 10^7 \text{ Hz}) = 1.4 \times 10^{-12} \text{ erg/cm}^3$ .

The maximum energy of picked-up ions is less than  $4E_{sw}$  and close to  $4E_{sw} \sin^2 \alpha$ . Thus the pitch-angle scattering is small. It is easy to understand this lack of scattering. The scale of the pitch-angle diffusion is  $L_{diff} = U_{sw} \tau_{diff}$  where  $\tau_{diff}$  is the temporal scale of scattering. From Wu et al. [1973]

$$\tau_{diff} = \frac{2 \cdot B_0^2}{\pi^2 \nu_{Bi}^2 P_B(\nu_{Bi})}$$

where  $B_0$  is the value of IMF, and  $2\pi\nu_{Bi} = \Omega_{Bi}$ . Thus  $L_{diff}$  is about  $5 \times 10^4 \text{ km}$ , compared with the much smaller distances ( $5 \times 10^3 \text{ km}$ ) of the observations. However, numerical simulation of the pitch-angle diffusion dynamics by Ziebell et al. [1990] shows that for conditions that are rather close to the conditions near Mars (picked-up ion density is about 0.5% of solar wind density), the shell of pick up protons (in velocity space) is broadened due to diffusion at angles  $\approx 20^\circ$  to  $30^\circ$  during a time about one-tenth of the diffusion time. Such weak diffusion is sufficient to explain the ASPERA observation of picked-up protons.

It is possible to try to reconstruct an altitude profile of the neutral hydrogen. The inverse problem is reduced to the minimization of the functional

$$\phi(n_c, H) = \sum_i \int \frac{N(n_c, H, h)}{\tau_{ion}} ds - F_c(h_i) |^2$$

where  $N(n_c, H, h)$  is the model altitude profile of atomic hydrogen. The total pickup ion flux,  $F_p$ , is the one observed at altitude  $h$ . The integration is along the streamline of the picked-up ions that goes through the point of observation and the sum is taken over the measurement points  $i$ . From Chamberlain [1963] the model profile was chosen in the form

$$N(n_c, H, h) = n_c \exp\left(H \cdot \left(\frac{1}{R_m + h} - \frac{1}{R_m + h_c}\right)\right) \cdot \zeta\left(\frac{H}{R_m + h}\right)$$

where  $n_c$  and  $h_c$  are the hydrogen density and altitude of the exobase,  $R_m$  is Mars radius,  $\zeta$  is the partition function for high altitudes,  $H$  is characteristic scale  $H = \gamma m_p M_m / kT$ , where  $\gamma$  is the gravitational constant,  $m_p$  is proton mass,  $M_m$  is mass of Mars,  $k$  is Boltzmann constant and  $T$  is exospheric temperature.  $h_c$  was taken as 250 km [Anderson and Hord, 1971]. The minimization gave  $n_c = 3 \cdot 10^4 \text{ cm}^{-3}$  and  $H = 16140 \text{ km}$ . Figure 5 shows the altitude profile of hydrogen in the corona of Mars. The profiles are obtained from Lyman  $\alpha$  measurements on Mariner 6, 7 [Anderson and Hord, 1972] and Mars 2, 3 [Dostovalov and Chuvalin, 1973]. The higher number density may be the effect of more solar activity during the PHOBOS mission. In spite of good agreement between plasma and optical measurements at  $h < 3000 \text{ km}$  the model only poorly describes the experimental data and the standard deviation in this case is  $1.0 \cdot 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ .

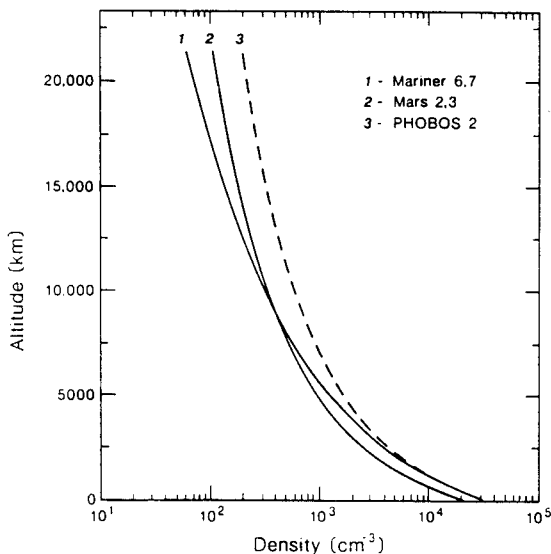


Fig. 5. Altitude profiles of the density of the hydrogen corona obtained from the altitude distribution of pickup protons (curve 3). The curves (1), (2) correspond to the Lyman  $\alpha$  measurements onboard Mariner 6, 7 and Mars 2, 3 spacecraft. The dashed lines show the range of altitudes over which ASPERA measurements of pickup protons were made.

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