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1. Gringauz, K. I., Bezrukikh, V. V., Verigin, M. I. & Rezimnov, A. P. *J. geophys. Res.* **81**, 3349-3352 (1976).
2. Vaisberg, O. L. in *Physics of Solar Planetary Environment* Vol. 2 (ed. Williams, D. J.) 8450 (American Geophysical Union, Washington, DC, 1976).
3. McElroy, M. B., Kong, T. Y. & Yung, Y. L. *J. geophys. Res.* **82**, 4379-4388 (1977).
4. Hanson, W. B., Sanatani, S. & Zuccaro, D. R. *J. geophys. Res.* **82**, 4351 (1977).
5. Chappell, C. R., Moore, T. E. & Waite, J. H. Jr *J. geophys. Res.* **92**, 5896 (1987).

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Ions of martian origin and plasma sheet in the martian magnetosphere: initial results of the TAUS experiment

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UNLIKE plasma instruments used on previous space missions to Mars, the TAUS instrument on Phobos 2 was designed so that the energy per charge and angular spectra of three species of ions could be measured separately. These species were H^+ and He^{2+} characteristic of the solar wind, and 'heavy ions' collected in one integral channel covering the mass per charge (M/q) range 3 to ∞, which we anticipated to find predominantly in the near-martian regime. In all spacecraft orbits around Mars we found a sharp boundary, separating the shocked solar wind from the martian magnetosphere which was characterized by the absence of solar-wind-like plasma. As the plasma inside the magnetosphere, and particularly in the tail, was dominated by heavy ions with number densities orders of magnitude higher than found in the solar wind, we assumed it was mainly of martian origin. Typically, heavy ions of low tailward flow velocity were seen near the boundary of the magnetotail, whereas high-speed tailward plasma flows of such ions were detected deeper inside the tail, a region not investigated before. Near the centre of the martian magnetotail a plasma regime, comparable to the terrestrial as well as the venusian[1] plasma sheet, was detected, characterized by highly supersonic tailward streams of heavy ions. The flux of planetary ions leaving Mars through its magnetotail is tentatively estimated to be of the order of a few times 10^{25} s^{-1}. Such loss rates would be significant for the dissipation of the martian atmosphere on cosmological timescales.

The instruments previously used for investigating the martian plasma environment were either plasma cups or curved electrostatic analysers by which different types of ions generally cannot be distinguished. To resolve this deficiency, the TAUS spectrometer, which uses electric and magnetic fields for separating ions according to their M/q, was specially designed for investigation of the solar wind and its interaction with Mars. The instrument features a field of view of $\sim 40° \times 40°$ centred on the nominal direction towards the Sun and divided into 8×8 channels for angular resolution. Its energy per charge (E/q) range

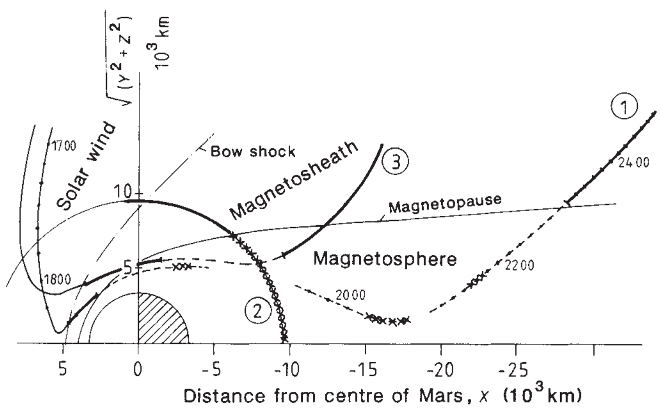

FIG. 1 The orbits of Phobos 2 on 1 February, ①; and on 2 March, ②; and of Mars-5 on 13 February 1974, ③; are given in cylindrical, Mars-centred solar-ecliptic coordinates. Approximate positions of the most important boundaries, the bow shock and the magnetopause, as derived from TAUS data, are shown, too. Along orbit ①, time tags are given for easy reference to Fig. 2. Those parts of the trajectories where the spacecraft passed through solar wind are indicated by thin full lines, shocked solar wind is marked by enhanced full lines, and the passage through the martian magnetosphere is indicated by dashed lines. Crosses on the dashed lines show the positions where supersonically tailward streaming plasma was found. Gaps in the orbital lines indicate that no data were received.

of $\sim$30 V-6 kV is subdivided into 32 channels. In the H^+ and He^{2+} channels, three-dimensional (3D) spectra, resolved in energy, azimuth and elevation can be measured whereas the spectra in the heavy-ion channel can only be resolved in E/q and elevation. The sensitivity of the instrument is nearly constant over its entire field of view but depends on the ion speed. The one-count detection limit for density, for example for a cold O^+ plasma with a speed of 100 km s^{-1}, would be $\sim 1 \times 10^{-3}$ cm^{-3}. As a data rate of only $\sim$10 bits s^{-1} was available for most of the time, the instrument's high resolution in velocity space and time could not be fully exploited; instead the information had to be compressed on board.

As the first orbit of the Phobos 2 spacecraft around Mars, on 1-2 February, provided a good survey of the martian plasma environment, we will demonstrate our initial results using mainly these data. The Phobos spacecraft trajectory for this period is shown in Fig. 1 in Mars-centred solar-ecliptic cylindrical coordinates.

In Fig. 2*a*, we present 4-min averages of proton count rates as a function of particle energy, with time progressing from bottom to top. The lower spectra show that the solar wind with a speed of $\sim$750 km s^{-1} and a temperature of $\sim 150 \times 10^3$ K was steady. The sudden decrease of mean energy and broadening of the spectra at $\sim$18:25 UT is the signature of the martian bow shock, which indicates the first major interaction of the solar wind with the 'obstacle' Mars.

Between the bow shock crossing and the transition through the magnetopause at $\sim$18:37 UT, the observed spectra were broad and fluctuating as is typical of shocked solar wind in the magnetosheath. On crossing the magnetopause, the proton fluxes fell below the sensitivity threshold of our instrument and remained at this level everywhere in the martian magnetosphere up to $\sim$23:10 UT, when broad turbulent proton spectra indicate that the spacecraft was in the magnetosheath again.

These characteristic variations of proton spectra in near-martian space have been observed before, for example by instruments on spacecraft Mars 5 (ref. 2). Bow-shock positions determined by Phobos instruments are also close to those obtained in previous martian missions.

The most interesting new result of the Phobos plasma

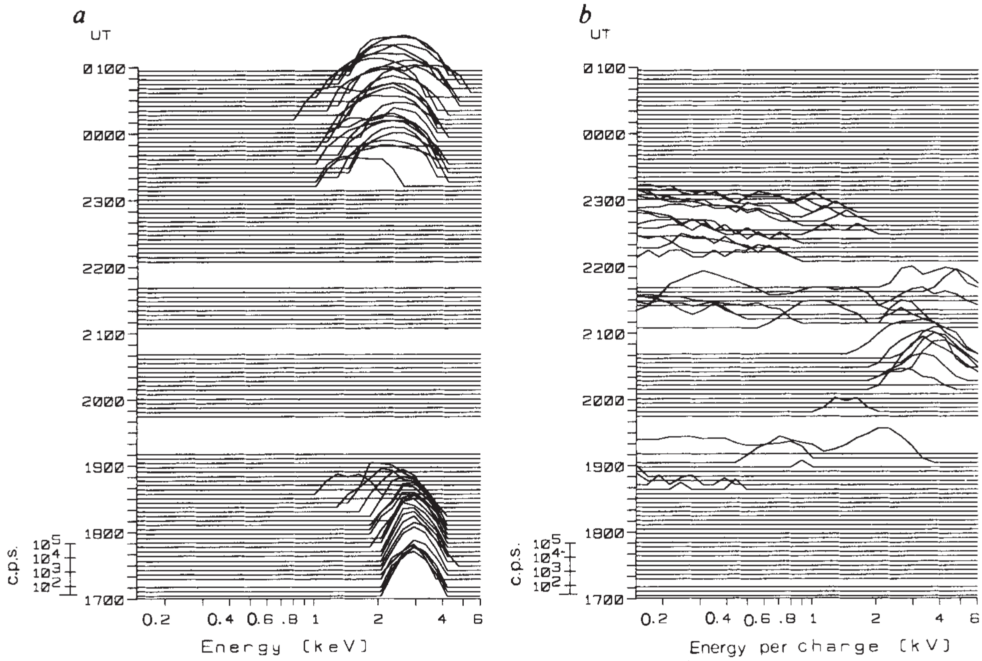

FIG. 2 Four-minute averages of energy-per-charge spectra in terms of count rates of protons (*a*) and heavy ions (*b*) as a function of time including the passage through the martian magnetosphere of the Phobos 2 spacecraft during its first martian orbit on 1–2 February are presented. The foot-lines of the spectra correspond to the one-count level or 40 counts per second. Average background count rates have been subtracted, and cross talk from the proton channel to the heavy-ion channel removed. Blanks indicate data gaps; c.p.s., counts per second.

measurements is the discovery of strong fluxes of heavy ions in the martian magnetosphere. Figures 2*b* and 3*b* show examples of E/q spectra in terms of count rates recorded by the TAUS heavy-ion channel while the spacecraft was crossing the martian magnetosphere. Figure 2*b* shows that heavy ions with energies per charge ≤ 1 kV were observed on 1 February immediately after the entry of the spacecraft into the magnetosphere. Although the maximum ion energy per charge is rather high, the plasma may be nearly stagnant because the maximum of the distribution is found in the lowest E/q channels. By comparison with the opposite side of the magnetotail (22:00–23:00 UT) and with other orbits (see Fig. 3*b*) it appears that this type of heavy-ion plasma is typical of the boundary region of the martian magnetosphere traversed by the Phobos spacecraft. However, in a few cases, supersonically tailward-streaming plasma was observed just inward of the magnetopause as well.

As the spacecraft proceeds further into the magnetotail, a high-energy peak develops in the spectra that eventually, near the centre of the tail, remains as the sole feature of the distributions. This means that the plasma has a well-defined, highly supersonic tailward flow speed in that region. As this type of fast tailward streaming plasma was also found in other orbits (see Fig. 3*b*) always near to the region where the tailward component of the magnetic field reverses sign and the total field strength is close to a minimum, we conclude that this is the region corresponding to the plasma sheet in the geomagnetic tail. However, whereas the Earth's plasma sheet is normally populated by solar-wind-type plasma, and heavy ions of ionospheric origin are only found in appreciable amounts during substorms, the martian plasma sheet seems to consist, at least in its central region, of supersonically tailward-streaming heavy-ion plasma most of the time. Protons were seen only in a few cases. Inspection of all of the tail crossings shows that the position of the martian plasma sheet is considerably more vari-

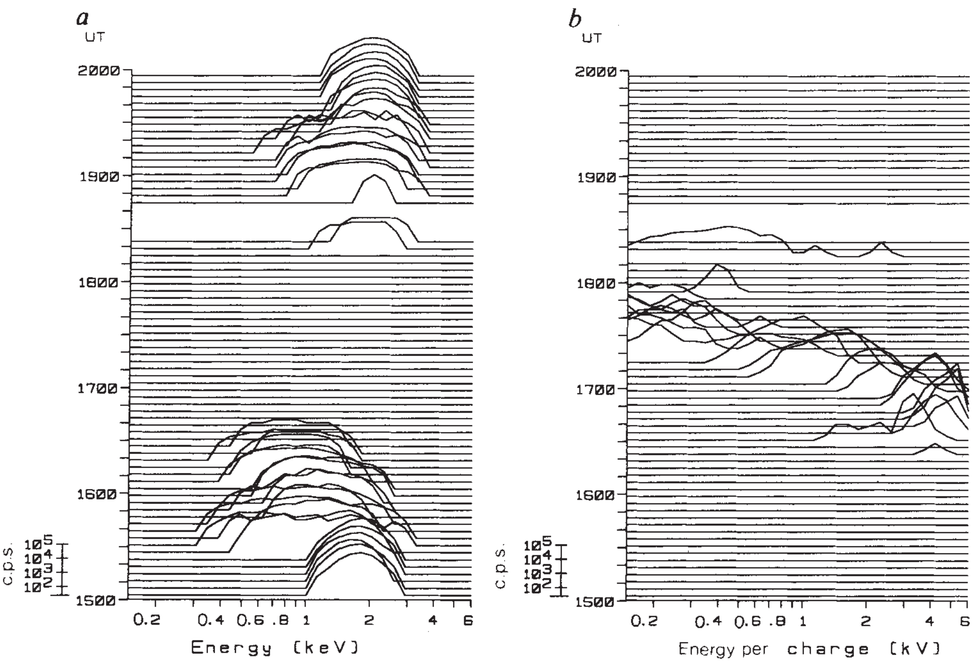

FIG. 3 Energy-per-charge spectra are shown for the circular orbit on 2 March 1989 (see curve ② in Fig. 1) in the same format as in Fig. 2. In the proton data (*a*), the inbound and outbound bow-shock crossings at 15:28 UT and 19:22 UT respectively are clearly visible. Although the maximum flow speed of heavy ions (*b*) was found close to the boundary of the magnetotail, its position again coincides with the reversal of the axial component of the magnetic field, typical of the plasma sheet, and the plasma characteristics are similar to those presented in Fig. 2 where the maximum of the flow speed was measured close to the centre of the tail.

able than the Earth's; also, the density and speed of the plasma found are different from orbit to orbit. This is probably due to the large amount of 'induced' magnetic field in the martian magnetosphere introducing most of the interplanetary magnetic field fluctuations into the tail.

The ion-velocity distributions found in the martian plasma sheet are also worthy of note. As an example, two two-dimensional spectra measured in the plasma sheet region during the second and the fourth elliptical orbit, at a distance of $\sim 1.5 \times 10^4$ km from the centre of Mars, are shown in Fig. 4. Although the mean tailward velocities of the plasma sheet ions were vastly different, the distributions are similar: the transverse (in the instrument's frame of reference) velocity spread or temperature is much higher than the longitudinal one and the resulting anisotropy of ~ 7 is probably one of the largest ever observed in a plasma anywhere. These velocity distributions are regarded as a very important diagnostic tool for the identification of the ion-acceleration processes at work.

Another interesting aspect of these E/q distributions is that they are only singly peaked. This strongly indicates that the observed plasma consists essentially of one ion species only. The high density of these heavy ions, which exceeds that of the heavy ions ($M/q \geq 3$) in the solar wind by about three orders of magnitude, leaves us no choice but to assume that they are of martian origin. The known composition of the upper martian ionosphere[3] from where they have probably been removed makes it highly probable that they are O^+.

It is of interest to estimate the total flux of heavy ions lost by the planet through its magnetotail. As the largest ion fluxes are observed in the plasma sheet, and we do not yet know much about plasma-sheet structure and variation with time, this initial evaluation must be regarded as tentative. We assume that we do not miss a major part of the ion flux as a result of the limited field of view of our instrument and take the width of the plasma sheet to be one martian diameter, $2R_M$, and to extend over the whole tail diameter of $\sim 4.5R_M$. From the data obtained during the second elliptical orbit the density and velocity of O^+ ions in the plasma sheet can be estimated to be of the order of $1.5\ cm^{-3}$, and $150\ km\ s^{-1}$, respectively. This results in a total tailward flux of O^+ ions of $\sim 2 \times 10^{25}\ s^{-1}$, meaning that Mars would be deprived of all of its presently existing atmosphere after $\sim 10^9$ years, if the mass loss rate did not change with time and no other loss or gain processes existed. □

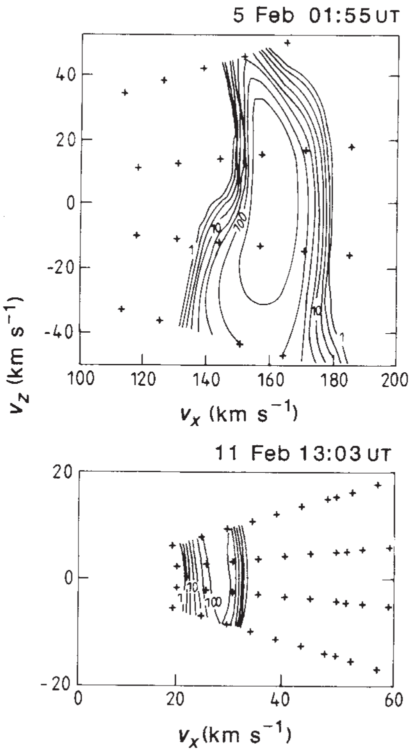

FIG. 4 Contour plots of count rates (to first order representing two-dimensional velocity distributions) obtained in the heavy-ion channel during the second (top) and fourth (bottom) orbit near the plasma sheet. Lines are spaced logarithmically by a factor of $\sqrt[3]{10}$ between adjacent contours. Crosses indicate the centres of the measurement channels. Conversion from E/q to velocity was made by assuming that the ions are O^+. V_x is the anti-sunward component of the velocity, and V_z is perpendicular to V_x. (The direction of V_z relative to the ecliptic plane cannot yet be given because of still missing information on the roll angle of the spacecraft.)

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1. Slavin, J. A. *et al. J. geophys. Res.* **94**, 2383–2398 (1989).
2. Gringauz, K. I. *Rev. Geophys. Space Phys.* **14**, 391–402 (1976).
3. Hanson, W. B. *et al. J. geophys. Res.* **82**, 4351–4363 (1977).

Observation of electron and ion fluxes in the vicinity of Mars with the HARP spectrometer

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THE highly elliptical orbits of the Phobos 2 spacecraft, early in February 1989, proved particularly useful for plasma and field investigations of the martian environment. The low-altitude (~860 km) pericentres and the deep penetration into the magnetotail provided excellent opportunities to explore new and important regions. Here we present preliminary results of electron and ion measurements in the vicinity of Mars with the hyperbolic analyser in the retarding potential mode (HARP). HARP is a differential electrostatic analyser, simultaneously covering eight directions arranged in a fan-shaped geometry, in the anti-solar hemisphere. The angular resolution is ~20°, the energy resolution ~10%. During the first two elliptical orbits, to be discussed here, electrons from 3.4 to 550 eV and ions from 0.25 to 550 eV were measured in 25 and 50 logarithmic energy steps, respectively. The energy distribution of electrons in the magnetosheath was found to be generally characterized by two distinct peaks. A fairly hot electron component was discovered in the plasma sheet of the areo-magnetic tail.

The HARP differential electrostatic analyser allowed the measurement of charged particles within an energy (or, more precisely, energy per charge) range of ~0.2–800 eV. The energy steps of the instrument were adjustable, that is, a more detailed study of some selected energy intervals was also possible by telecommand. Particles were measured simultaneously in eight sectors (20° × 10° each), symmetrically arranged relative to the anti-solar axis. The actual instrument package on the Phobos 2 spacecraft consisted of two independent and identical sensors. The sensors were mounted to point at 90° from each other. Each unit had four independent anodes. The combined directional