may result from the fact that these regions are adjacent to each other. The existence of a plasma sheet containing accelerated electron fluxes in the interior of the Martian magnetosphere was first detected in the HARP experiment.

The physical mechanisms responsible for electron acceleration behind the bow shock and the appearance of bimodal energy distributions are not yet known. We can assume, however, that future analysis of our data in conjunction with their detailed comparison with the results of other plasma and magnetic experiments on the Phobos craft, as well as with earlier observations (Gringauz, 1981), will considerably improve our understanding of the physical nature of the plasma around Mars.

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*Deceased.

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# First measurements of ions of Martian origin and observation of a plasma layer in the magnetosphere of Mars: the TAUS experiment on the spacecraft Phobos 2

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On the spacecraft Phobos 2 the TAUS instrument was used to measure detailed energy and angular spectra of ions entering a 40°×40° solid angle in the direction of the sun. These measurements, confirming previous results from the satellites Mars 2, 3, and 5 (see e.g., Gringauz *et al.* (1976), Gringauz (1976, 1981), and Dolginov *et al.* (1976)), are also the first plasma measurements deep in the optical shadow of the planet; mass spectrometry of ions in near-Martian space had not been carried out previously. As a result of these measurements, it was observed that the Martian magnetosphere is to a significant degree filled with fluxes of heavy ions, originating in the atmosphere of the planet, and that there is a plasma layer in the areomagnetic tail, also consisting mainly of heavy ions. The flux of planetary ions leaving Mars through the areomagnetic tail is tentatively estimated to be $(0.5\text{–}2)\cdot 10^{25}\,\text{sec}^{-1}$.

The analysis of ions with respect to energy $E_i$ ($i = 1, \ldots, 32$) in the TAUS experimental was carried out using a hemispherical electrostatic analyzer with energy resolution in the energy/charge range $30\ \text{eV/q} \le E_i/q \le 6\ \text{keV/q}$. Using a similar electrostatic analyzer installed behind it, which had a variable accelerating potential $U_a$, all ions passed through with fixed energy $E_i + qU_a \approx 6$ keV. Protons, α particles, and heavier ions ($m_i/q \ge 3$) were separated using a magnetic system located in the middle of this analyzer.

In the TAUS experiment, for each value of $E_i$, we simultaneously used individual scintillation detectors to measure the flux of protons (or α particles) in eight azimuthal directions $\phi_j$ ($j = 1, \ldots, 8$) for a three-axis orientation of the spacecraft, and the flux of heavy ions arriving within the range $\phi_j \approx \pm 20°$. Scanning over the angles $\vartheta_k$ ($k = 1, \ldots, 8$) was done using an electrostatic deflector located in front of the first analyzer. In most operating modes, the ion integration time was approximately 24 msec. The three-dimensional ($E_i$, $\phi_j$, $\vartheta_k$) spectrum of protons and α particles, consisting of 2048 measurements, and the two-dimensional ($E_i$, $\phi_j$) spectrum of heavy ions were measured in 8 sec.

In connection with the limited telemetry bandwidth of the spacecraft, a microprocessor in the TAUS instrument implemented a data compression scheme. Summing over (j, k), (i, k), or (i, j), the multidimensional ion spectra were reduced to one-dimensional energy ($i = 1, \ldots, 32$) and angular ($j, k, = 1, \ldots, 8$) spectra. Moreover, from the three-dimensional ion spectra we calculated their zeroth (density), first (velocity vector), and second (six components of the pressure tensor) moments. The relationship between the quantities of transmitted three-, two-, and one-dimensional spectra and their moments varied as a function of the operating mode of the spacecraft telemetry system (fast ≈200 bits/sec, slow ≈10 bits/sec for TAUS),

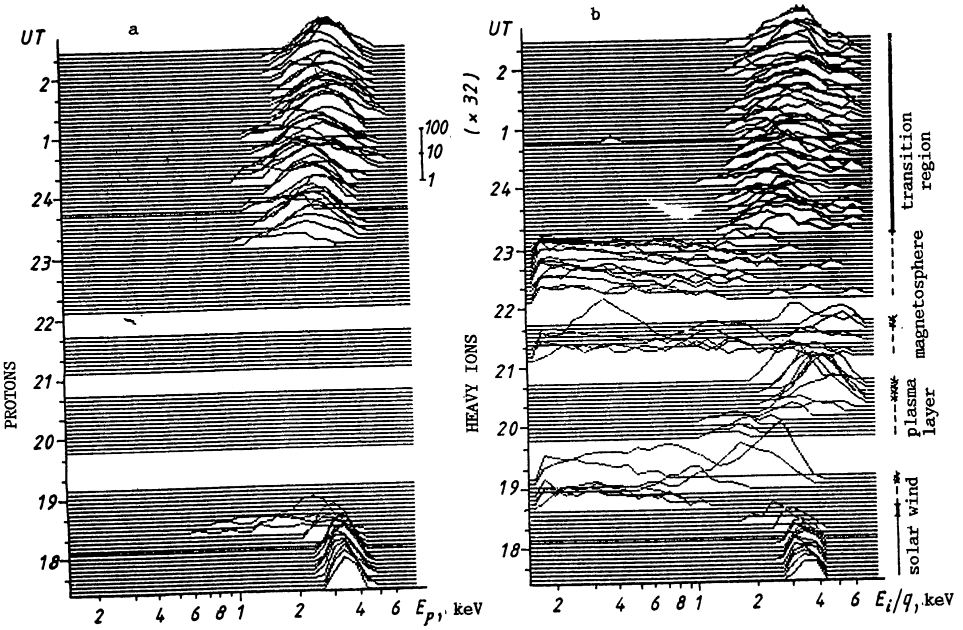

FIG. 1. Energy spectra of protons (a) and heavy ions (b), as measured on 1-2 February 1989, averaged over 4 min. The lines on the right identify those parts of the satellite trajectory that lay in the undisturbed solar wind (solid), the transition region (heavy), and the magnetosphere of Mars (dashed). The crosses mark the places where fluxes of heavy ions were observed within the magnetosphere.

and the operating mode of the instrument. The TAUS experiment is described in greater detail in the paper by Resenbauer et al., (1989).

Figure 1a shows the energy spectra of protons, averaged over 4 min, as measured by the TAUS experiment on 1-2 February 1989, during the first flyby of Phobos 2 in the vicinity of Mars on an elongated elliptical orbit. The trajectory of the spacecraft at that period is shown in Fig. 2 in an areosolar ecliptic (ASE) cylindrical coordinate system taking account of the aberration of the direction of approach of the solar wind due to the planet's orbital motion.

A distinctive feature of the spectra shown in Fig. 1a is the significant decrease of the average energy and broadening of the proton energy spectrum near 1825 UT. The latter is related to a drop in proton translational velocity and thermalization by the near-Martian shock wave. It should be noted that some decrease in the translational velocity and thermalization of the protons began ≈15 min before Phobos 2 crossed the bow shock (Fig. 1a), as the spacecraft crossed the foreshock region, which is probably formed, as in the near-Earth shock wave, by protons of the solar wind reflected from the shock front.

After crossing the blow shock, all the way to crossing the magnetopause at ≈1837 UT, the TAUS energy spectrometer recorded broad fluctuating spectra of turbulent fluxes of protons in the transition region.

The aforementioned characteristic variations in the proton spectra in different parts of near-Martian space were observed previously, for example by the spacecraft Mars 5 (Gringauz, 1976). The position of the shock wave according to the data of Phobos 2 and according to the data of previous Martian experiments on Mars 2, 3, and 5 (see, e.g., Gringauz et al., 1976; Grinzauz, 1976, 1981; Dolginov et al., 1976) are also extremely close. A preliminary comparison of the positions of the bow shock and the magnetopause, as determined by the data of the TAUS experiment, the HARP electron spectrometer (Shutte et al., 1989) and the MGMA and PhGMM magnetometers, in all cases indicated reasonable agreement.

In all, over the active lifetime of the spacecraft Phobos 2, plasma measurements near Mars using the TAUS spectrometer were made from four elliptical orbits with pericenter at ≈850 km, one transfer elliptical orbit with pericenter equal to the altitude of the moon Phobos, and ≈60 circular orbits, close to the orbit of Phobos. As an example, Fig. 3a shows the proton energy spectra, varying from one of the circular orbits of 2 March 1989. The typical variations of the proton spectra along such orbits permit an extremely reliable determination of the time intervals when Phobos 2 was located in the solar wind, in the transition region, or in the Martian magnetosphere. Just as in Fig. 1, these time intervals are marked on the right-hand side

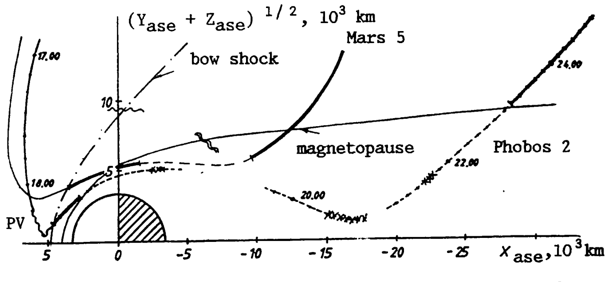

FIG. 2. First elliptical orbit of the satellite Phobos 2 in the solar-ecliptic cylindrical coordinate system of 1 February 1989.

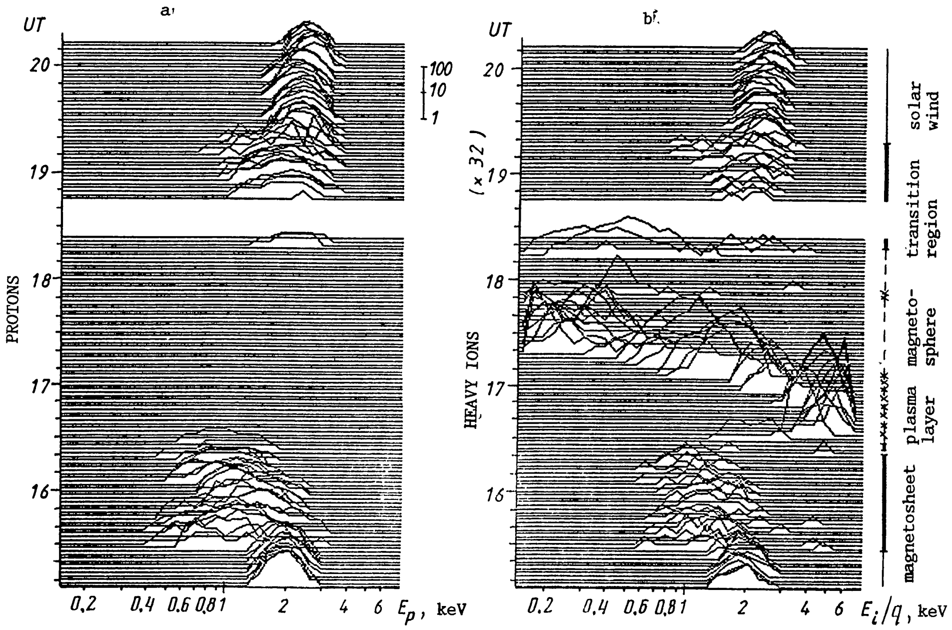

FIG. 3. Energy spectra of protons (a) and heavy ions (b), obtained from the circular orbit of 2 March 1989. The notation is the same as in Fig. 1.

of Fig. 3 by a thin, thick, or dashed line, respectivelly.

The plasma measurements from circular orbits lead us to believe that at the time of the Phobos 2 measurements, the magnetopause in the magnetotail was apparently located farther from the axis of the areomagnetic tail, and accordingly this tail was thicker than at the time of the Mars 3 measurements.

To illustrate this tentative conclusion, Fig. 2 shows one of the orbits of the satellite Mars 5. Just as for the orbit of Phobos 2 the dashed line shows the period when Mars 5 was inside the magnetosphere. The double wavy line on Fig. 2 shows the region of near-Martian space where the magnetopause was observed in approximately 30% of the circular orbits analyzed thus far. The characteristic thickness of the areomagnetic tail at $X_{ASE} \approx -7 \cdot 10^3$ km at the time of the Phobos 2 measurements was $\approx 4R_M$, while at the time of the Phobos 2 measurements was $\approx 4R_M$, while at the time of the Mars 5 measurements in 1974 the characteristic thickness of the tail at these same distances from Mars was $\approx 3.2R_M$ (Gringauz, 1981). As one moves away from the planet, the thickness of the areomagnetic tail increases even more (Fig. 2); on the second elliptic orbit, upon leaving the magnetosphere ($X_{ASE} \approx 30 \cdot 10^3$ km), the intersection of the areomagnetic tail was observed all the way to $\sqrt{Y^2_{ASE} + Z^2_{ASE}} \approx 13.6 \cdot 10^3$ km, which formally corresponds to a tail thickness $\approx 8R_M$. However, at such distances from the planet one should take into account the possible deviation of the approach direction of the solar wind.

The most interesting result of the Phobos 2 plasma measurements was the observation in the Martian magnetosphere of significant fluxes of heavy ions of planetary origin. In Fig. 1b and Fig. 3b we present energy spectra in the channel designed for detecting heavy ions. It should be noted that this channel also includes a negligible contribution from solar-wind protons, but these are easily distinguished by comparing with the simultaneously measured proton spectra (Fig. 1a and Fig. 3a). In making such a comparison, it should be taken into account that the spectra in Fig. 1b and Fig. 3b, identical in altitude to the spectra of Fig. 1a and Fig. 3a, correspond to ion fluxes 32 times lower.

As can be seen from the data presented in Fig. 1b, the fluxes of heavy ions with energies $\lesssim 1$ keV on 1 February 1989, were detected by the TAUS spectrometer immediately after Phobos 2 entered the magnetosphere of Mars. However, the largest fluxes of heavy ions with the greatest energies, $E_i \approx 4$ keV, were detected at 2020-2040 UT in the neighborhood of the deepest penetration of the spacecraft into the areomagnetic tail (Fig. 2). Before Phobos 2 left the magnetosphere, the energy of the heavy ions detected by TAUS did not again exceed $\approx 1$ keV; their fluxes decreased and fell below the detection threshold of the instrument right after crossing the magnetopause at $\approx 2310$ UT.

From the other elliptical and circular orbits, there was also observed a nonuniform distribution of the intensity and energy of the heavy-ion fluxes in the areomagnetic tail, which varied from orbit to orbit. The region with the most energetic heavy ions was not always located deep within the areomagnetic tail, and heavy-ion fluxes were not generally detected everywhere within the magnetosphere of Mars. An example of such measurements is shown in Fig. 3b. On this orbit, the spacecraft entered the region with the largest fluxes of energetic heavy ions $E_i \gtrsim 3$ keV soon after crossing the magnetopause. As it moved further along the orbit, the energy of the ions decreased, and between about 1800 and 1820 UT no heavy ions at all were detected. As in the first orbit, heavy ions were detected with energy $\lesssim 1$ keV before the spacecraft left the magnetosphere.

It seems rather obvious that the heavy ions detected by TAUS in the magnetosphere of Mars

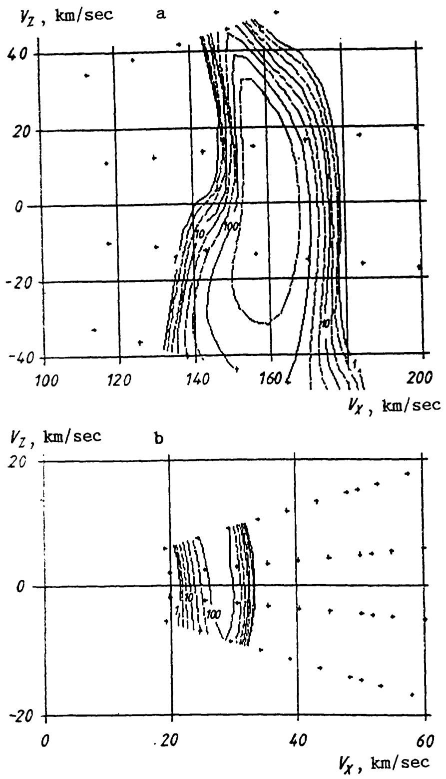

FIG. 4. Two-dimensional spectra of heavy ions detected in the Martian magnetotail on 5 February 1989 (0155 UT) (panel a) and 11 February 1989 (1303 UT) (panel b). We show the isolines of the detector readout in the heavy-ion channel in the ($V_X$, $V_Z$) plane under the assumption that the detected ions are O$^+$ ions. The crosses mark the centers of the regions in which particle fluxes were measured.

are of planetary origin. The existing information on the composition of the upper atmosphere of Mars (see, e.g., Nagy and Cravens, 1988; Ip, 1988) suggests that these are mainly O$^+$ ions, which agrees also with the mass-spectrometer measurements in the Martian magnetosphere done in the ASPERA experiment.

A preliminary comparison of the TAUS heavy-ion measurements in the Martian magnetosphere with the simultaneously measured magnetic field shows that the greatest fluxes of such ions (as a rule, having the greatest energies) are observed in the neighborhood of the change in sign of the $B_X$-component of the magnetic field — the neutral sheet. These time intervals are marked by crosses in Figs. 1-3. The region of enhanced plasma density in the geomagnetic tail on either of the neutral sheet is generally called the plasma sheet. The structure with similar properties in the areomagnetic tail may reasonably also be called the plasma sheet.

What is the difference between the geomagnetic and areomagnetic plasma sheets? In the geomagnetosphere, the plasma sheet consists mainly of protons, and only during substorms does the number of heavy ions of ionospheric origin reach 50%, whereas the areomagnetospheric plasma sheet apparently consists mainly of heavy ions. However, according to the estimates of Kennel (1989), due to the small dimensions of the Martian magnetosphere its substorms should be frequent, with typical times ≈6.5 min between them. The location of the areomagnetic plasma sheet is significantly more variable than the geomagnetic one. This is apparently related to the fact that, as the magnetic measurements by the Phobos spacecraft showed, the induced component of the magnetic field in the areomagnetic tail is extremely important. In that case, the location of the plasma layer may vary when the interplanetary magnetic field changes direction. To clarify this effect we need a further detailed comparison of plasma and magnetic measurements in the neighborhood of Mars.

Despite the obvious influence of unipolar induction on the formation of the Martian magnetosphere, one can hardly assume that it is fully "induced" like the magnetosphere of Venus. Some evidence in support of the existence of an intrinsic Martian magnetic field is the aforementioned significant thickness of the areomagnetic tail ( $\gtrsim 4R_M$). At the corresponding distances, the relative thickness of the magnetotail of Venus is significantly smaller ( $\approx 2.2R_V$) (Gringauz, 1981).

As noted above, in the TAUS experiment we measured the two-dimensional spectra of heavy ions. For example, two such spectra, obtained in the plasma layer of the magnetosphere, on the second and fourth elliptic orbits ($X_{ASE} \approx 1.5 \cdot 10^4$ km), are shown in Fig. 4. In this figure in velocity space (assuming that the detected ions are O$^+$ ions) are shown the isolines of the counting rate in the heavy-ion channel. Although the energy of the planetary ions near the plasma sheet on the second orbit ( ≈2 keV) was significantly higher than on the fourth (≈60 eV), the ion distribution function has a common feature: the transverse velocity spread of the observed distributions is much larger than the longitudinal. As in the Earth's magnetosphere, measurements of the velocity distributions of such ion beams may be used as a diagnostic for identifying ion acceleration processes (for example, adiabatic deformation of the Maxellian distribution, acceleration by a longitudinal potential difference, or acceleration in the neighborhood of the neutral sheet (Eastman et al., 1986). It is of interest to use the TAUS spectrometer data to estimate the total flux of heavy ions in the areomagnetic tail. Since the greatest ion fluxes in the areomagnetic tail are in the plasma sheet, while its shape has not yet been studied, such an estimate must be considered tentative. For definiteness we assume that the transverse cross section of the plasma sheet is 0.3 of the transverse cross section of a tail of thickness (4-5)$R_M$. On the second elliptic orbit, the density and velocity of O$^+$ ions in the plasma sheet can be estimated using the TAUS data to be $n_i \approx$ (1-2) cm$^{-3}$, V ≈ 150 km/sec (usually the ion flux in the plasma layer is somewhat lower). The total flux lost through the areomagnetic tail of planetary heavy ions can then be estimated to be $(0.5\text{-}2) \cdot 10^{25}$ sec$^{-1}$. This is comparable to the quantity of oxygen lost by Mars as a result of nonthermal dissipation. The outflow of fast oxygen atoms formed as a result of dissociative recombination is $\approx 0.5 \cdot 10^8$ cm$^{-2}$ sec$^{-1}$ (see, e.g., Krasnopol'skii (1982), i.e., $\approx 4 \cdot 10^{25}$ sec$^{-1}$ from the illuminated side of the planet.

Finally, we conclude by mentioning the possible observation of a regular perturbation of the solar wind when the spacecraft crosses the orbit of the moon Phobos. A decrease in the solar plasma flux with typical scale 400-500 km across the orbit of Phobos was observed in the TAUS data on the first and third elliptical orbits (on the second elliptical orbit, the expected decrease coincided with the periodic decrease in the ion flux due to the rotation of the spacecraft). It should be noted that during these crossings of the orbit of Phobos by the spacecraft, the Martian moon itself was located far from it. In this case, to explain the observed events it is necessary to assume the presence in the orbit of Phobos of a belt of gas, dust, or larger particles. Previously, this idea was discussed by Ip (1988) and Soter (1971). However, this interpretation should not be considered as definitive, since similar disturbances of the solar wind flux were observed by the TAUS experiment in other parts of the orbit as well.

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Translated by P. J. Moxhay

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# Television pictures of Phobos: first results

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In February-March 1989, 37 television images of the Martian satellite Phobos were obtained by the Phobos 2 spacecraft from distances of 200–1100 km. These images provide an important supplement to the TV data from the American Mariner 9 and Viking spacecraft in coverage of the surface of Phobos and in resolution in certain regions, in spectral range, and in range of phase angles. They make it possible to refine the figure and topographic and geological maps of the surface of Phobos, its spectral and angular reflective characteristics, the surface composition and texture, and characteristics of the orbital and librational motion.

## PREPARATION AND EXECUTION OF THE EXPERIMENT

The primary tasks of the TV experiment were: a) photography of Phobos from circular and quasi-synchronous orbits for global studies of its surface, as well as to refine its orbital motion with the aim of the real-time solution of the navigation of problems; b) photography of Phobos with centimeter resolution during the planned drift of the automatic interplanetary station (AIS) at an altitude of 50 m above the surface of Phobos.

To solve these problems, specialists from Bulgaria, East Germany, and the USSR have developed the Fregat videospectrometric complex (VSC), which incorporates a three-channel TV camera, a spectrometer, and a 1.5 Gbit video recorder (a limited amount of video data could also be stored in the