On Electron and Ion Components of Plasma in the Antisolar Part of Near-Martian Space

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Results of measurements of boundary positions and characteristics of the transition layer behind the Martian bow shock are presented. For the first time, measured characteristics of the plasma formation located behind the inner boundary of the transition layer on the antisolar part of near-Martian space are considered. The possible nature of this formation is discussed and some considerations in favor of its interpretation as the plasma sheet in the Martian magnetospheric tail are presented.

The spacecraft Mars 5 became a satellite of Mars on February 13, 1974 (the pericenter was ~1800 km; the apocenter, ~32,000 km; the inclination to the ecliptic plane, ~60°; and the rotation period, ~25 hr). Wide angle charged particle traps were installed for measuring ion and electron component characteristics of the low-energy plasma. By means of a solar pointing Faraday cup with angular response of ±45°, differential ion energy spectra were measured within the energy range from 0 to 4.1 keV. The electron trap, with angular response of ±40° and retarding potentials of 0–300 V, oriented in the antisolar direction provided integral spectra of electron fluxes (retardation curves).

The detailed description of devices, their performance, their location on spacecraft, the techniques of processing the data obtained, and the measurements made were presented by *Gringauz et al.* [1974*a*]. In this paper, data are presented on new measurements of the location of boundaries and characteristics of the transition layer, the Martian magnetosheath (see, for example, *Gringauz et al.* [1973*a*, *b*, 1974*b*], *Vaisberg et al.* [1973], *Vaisberg and Bogdanov* [1974], and *Dolginov et al.* [1973, 1974]), and on the first measurements of characteristics of a plasma formation located behind the inner boundary of the transition layer in the dark side region of near-Martian space. A preliminary report on that plasma formation was given by *Gringauz et al.* [1974*c*].

Figure 1*a* shows the orbit of Mars 5 on February 14, 1974, in solarareoecliptic coordinates *X*, *Y*, and *Z*. The *X* axis is directed toward the sun, the *Y* axis is in the orbital plane of Mars and makes a 180° angle with the velocity vector of the planet, and the *Z* axis completes the right-hand coordinate system. In Figure 1*b* a part of the same orbit is presented in coordinates *X* and $(Y^2 + Z^2)^{1/2}$. The analysis of ion and electron energy spectra obtained during all available communication sessions showed that near the planet the satellite crossed three zones (zones 1–3) with substantially different plasma characteristics. Typical primary ion spectra and electron retardation curves corresponding to these three zones are shown in Figure 2. In zone 1, ion and electron spectra are typical of the undisturbed solar wind (Figure 2*a*). The criterion for crossing of the bow shock front and entering the transition layer (zone 2) is the characteristic change of charged particle spectra (Figure 2*b*). Ions are thermalized, and their fluxes increase; I_{max} of electron retardation curves also increases. (I_{max} is the current corresponding to zero retarding potential and proportional to $n_e(T_e)^{1/2}$, where n_e is the electron density and T_e is the electron temperature [see *Gringauz et al.*, 1974*b*].)

In zone 2 the retarding potential, which characterizes the energy of electrons, also increases.

Characteristics of these two zones are similar to those observed during 1971–1972 aboard the Mars 2 and Mars 3. Results of electron [*Gringauz et al.*, 1973*a*, *b*] and ion [*Vaisberg et al.*, 1973; *Vaisberg and Bogdanov*, 1974] plasma measurements and magnetic measurements [*Dolginov et al.*, 1973*a*, *b*] from these two spacecraft established the existence of the bow shock. Characteristics of the plasma in zone 3 in the antisolar part of near-Martian space are measured for the first time. We divide near-Martian space into solar and antisolar parts by means of a plane which includes the terminator of the planet. An abrupt decrease of ion currents is typical in zone 3 when compared to zones 1 and 2 (Figure 2*b*). The decrease of measured ion currents is so great that along approximately 30% of parts of the orbit inside zone 3 the ion fluxes are below the limit of the sensitivity of the instrument and only along 40% are the ions measured quite reliably (the level of signal exceeds the minimum telemetry signal by a factor of 3 or more). Values of electron currents in zone 3 also decrease in comparison with those in zone 2 (Figure 2*c*). However, they are higher in zone 3 than in the undisturbed solar wind (zone 1, Figure 2*a*) and are always registered.

Let us consider in detail the results of plasma measurements. During four orbits of Mars 5 (see Table 1) the instrument was not switched on during the crossing of the bow shock front and the entrance into the transition layer. From values of areocentric distances *Z*, the sun-Mars-satellite angles ϕ at which the spacecraft crossed the bow shock front, and gasdynamic calculations [*Spreiter and Alksne*, 1969] of the flow past an obstacle having the form of the magnetosphere of the earth (at $M_\infty = 8$ and $\gamma = \frac{5}{3}$), one can estimate the altitude of the obstacle h_{obst} (at the subsolar point) deflecting the solar wind in a similar way as was done by *Gringauz et al.* [1974*b*]. In Table 1, values of the density *n*, the bulk velocity *V*, and the dynamical pressure of solar wind protons ρV^2 are also given prior to the crossing of the shock wave front; in telemetry sessions with 2-min intervals between successive electron and ion spectra the given values are averaged over 10-min intervals. Values of the density and velocity of solar wind ions were estimated from three readings close to the maximum ones under the assumption of a Maxwellian distribution in the coordinate frame moving with the velocity *V*. The proton and electron temperatures at the moments of time under consideration were within (80–200) × 10^3 °K and (70–230) × 10^3 °K, respectively. While entering the transition layer the charged particle density (estimated from the electron trap

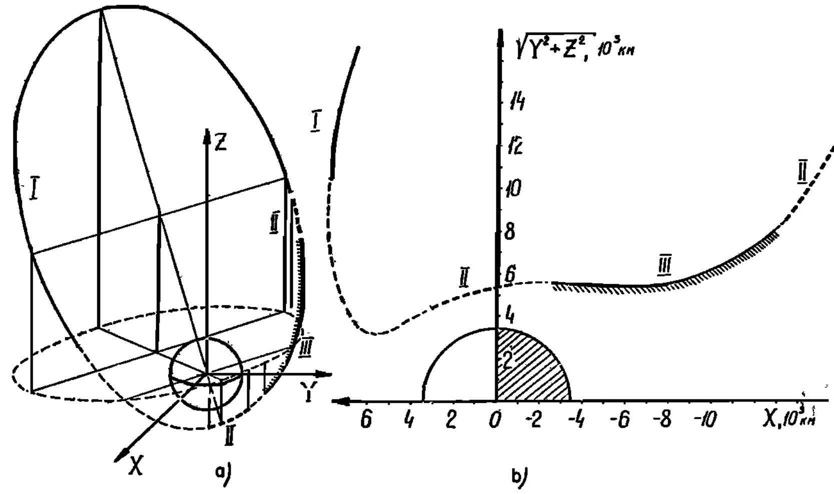

Fig. 1. The trajectory of the spacecraft Mars 5 on February 14, 1974. The zones are labeled I, II, and III. There are no measurements for dashed lines that are not labeled.

data) increased by a factor of 1.5–3, and the electron temperature reached (0.3–1) × 10^6 °K.

When comparing values of the altitude of the obstacle at the stagnation point (Table 1) with the solar wind dynamical pressure in 2-min measurement sessions on February 20 and 22, one can see that the altitude of the obstacle decreases while ρV^2 increases. On February 13 and 24 the large scatter in the estimates of h_{obst} is related to the fact that the measurements were performed rather infrequently (electron and ion spectra are measured within ~1 min at intervals of 9 min), but as the solar wind dynamical pressure in these sessions was less than it was on February 20 (see Table 1), the obstacle altitude seemed not to be less than it was in the latter session (although this altitude varied within the range mentioned in Table 1).

Therefore a minimum estimate of the obstacle altitude from the Mars 5 data is h_{obst} ~ 500 km, made from the data of the bow shock crossing on February 20, 1974. Note that according to the data from Mars 2 and Mars 3 the minimum estimate of h_{obst} was ~600 km (from the bow shock crossing by the Mars 2 satellite on May 12, 1972), and this estimate is close to the aforementioned one. It should be noted that the estimate of the obstacle altitude, h_{obst} ~ 500 km, is obtained with values of the solar wind number density n ~ 11 cm^{-3} and velocity V ~ 480 km/s^{-1}, and these values substantially exceed an average value of n and somewhat exceed an average value of V even at the orbit of the earth.

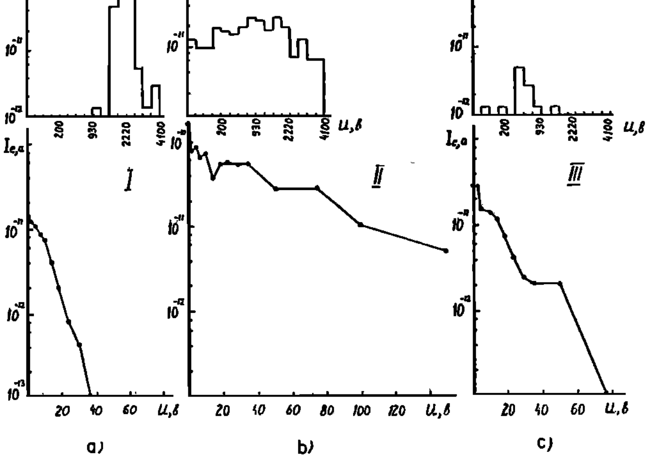

Fig. 2. The ion spectra and electron retardation curves typical of zones 1–3.

Let us estimate the obstacle dimensions from all crossings of the bow shock front by Mars 2, Mars 3, and Mars 5 satellites, as was done by *Gringauz et al.* [1974*b*]. Figure 3 shows the portions of the orbits of these satellites during which the shock front was crossed. Characteristics of the plasma measured at the near-planet points and shown in Figure 3 are typical of the magnetosheath (Figure 2*b*) and are at distant points from the undisturbed solar wind (Figure 2*a*). Areocentric distances to the subsolar point of the obstacle and bow shock front, chosen in such a way [*Gringauz et al.*, 1974*b*] that the sum of the square of the distances from both ends of the orbit segments at which the bow shock front was crossed to the bow shock front would be a minimum, are (4.6 ± 0.8) × 10^3 km and (5.7 ± 1) × 10^3 km, respectively, i.e., from all crossings of the bow shock front the estimate of an average obstacle altitude h_{obst} is ~1200 ± 800 km.

When considering these estimates, one should bear in mind the fact that the results of measurements from Mars 2, Mars 3, and Mars 5 satellites are not sufficient for unambiguous definition of the shape of the obstacle which creates the bow shock. It is possible that its shape appreciably varies in time with the ratio of the solar wind ram pressure to the planetary magnetic moment or with the reversal of the sign of the interplanetary magnetic field due to reconnection.

Let us consider in detail the physical characteristics of the zone 3 data, which are obtained for the first time. One can see from Figure 1*b* that the part of the orbit crossing zone 3 on February 14, 1974, corresponded to $(Y^2 + Z^2)^{1/2}$ from ~5800 km to ~8000 km, i.e., to the interval of distances from the sun-Mars line exceeding 2000 km. The extent of this part of the orbit along the X axis is not less than several Mars radii.

As was mentioned above, ion currents measured in zone 3 are substantially less than those in the undisturbed solar wind, and electron currents are higher. Ion energies are more changeable (as a rule they are lower but sometimes higher in zone 3 than in zone 1, see Figure 4), and one cannot exclude the possibility that in cases when ion currents are not recorded there are particles beyond the energy range of the instrument. From retardation curves obtained by means of the electron trap in zone 3, one can estimate the electron temperature and

TABLE 1. Results of Plasma Measurements During Four Orbits of Mars 5

Date	Time, LT*	r, 10^3 km	ϕ, deg	n, cm^{-3}	V, km s^{-1}	h_{obst}, km	ρV^2, 10^{-8}dyn cm^{-2}
Feb. 13	1917–1927	5.6–5.2	40–55	9	455	750–100	3.1
Feb. 20	0019–0021	5.5–5.4	44–48	11	480	650–450	4.2
Feb. 22	0153–0155	5.8–5.65	39–42	1.8	640	900–800	1.2
Feb. 24	0337–0347	5.85–5.3	35–47	2.5	620	1050–400	1.6

All dates are in 1974.
*Local time is Moscow time.

charged particle density in this zone. The typical value of electron temperatures is $T_e \sim 100 \times 10^3$ °K. However, there were observed values of $T_e \sim (70–250) \times 10^3$ °K. Note that any bulk velocity of the electrons (it is less here than that in the solar wind) slightly influences the accuracy of the determination of T_e [*Gringauz et al.*, 1974*b*]. According to *Gringauz et al.* [1974*b*], estimates of n_e are ~2–8/cm^3, i.e., approximately the same as they are in the solar wind.

Under these conditions a sharp decrease of ion currents in the modulating trap in comparison with that in the solar wind (see Figures 1*a*, 1*c*, and 4) can occur in two cases: either the bulk ion flux considerably changes its direction (the ion trap has a wide angle response [*Gringauz et al.*, 1974*b*]), or this flux becomes quasi-isotropic. Note that the change of the direction of the plasma motion or its isotropization should be revealed in the ion current but not in the electron current, as the electron flux is quasi-isotropic even in the undisturbed solar wind. The isotropization of the ion flux should decrease the ion current approximately by a factor of 20 in comparison with the cold ion flux normal to the trap aperture (see the characteristics of the instrument in the work of *Gringauz et al.* [1974*b*]). An increase of the average energy $\bar{E}$ of protons near the satellite up to values exceeding the upper energy limit of the instrument ($\bar{E} \lesssim 4000$ eV) is unlikely, as all changes of ion

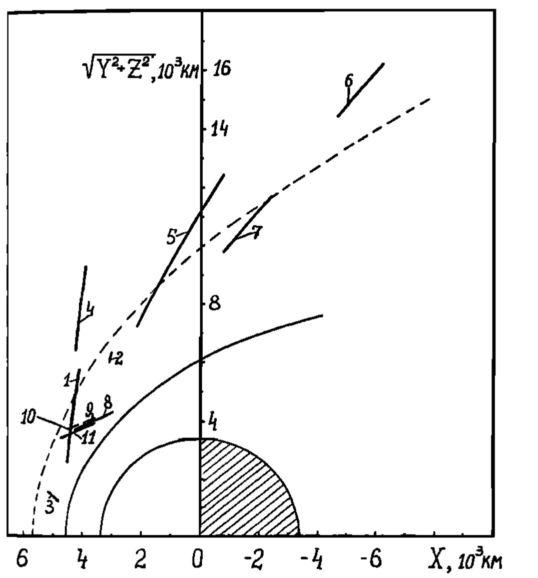

Fig. 3. The bow shock crossings of Mars satellites. The crossings are indicated by numbers. Mars 2 crossings are represented by 1 (February 17, 1971), 2 (January 8, 1972), and 3 (May 12, 1972). Mars 3 crossings are indicated by 4 (December 15, 1971), 5 (January 9, 1972), 6 (January 21, 1972), and 7 (January 21, 1972). Mars 5 crossings are indicated by 8 (February 13, 1974), 9 (February 20, 1974), 10 (February 22, 1974), and 11 (February 24, 1974). The solid lines represent the positions of the obstacles, and the dashed line represents the bow shock front.

spectra in zone 3 (when these spectra are measured) are mainly observed with the maximum currents within the energy range ~200–500 eV.

The comparison of results of the plasma measurements under consideration with the simultaneous magnetic data from Mars 5 [*Dolginov et al.*, 1975] shows the following. (1) The magnetic data also give evidence of the existence of three different zones along the near-planet part of the satellite orbit. (2) According to both types of measurements, boundaries between the zones coincide during all orbits of the satellite around the planet. (3) Zone 3 is characterized by a substantial decrease of magnetic field fluctuations (they are quite considerable in zone 2) and a considerable increase of a regular magnetic field strength. This point gives a basis for attributing zone 3 to the tail of the Martian magnetosphere [*Dolginov et al.*, 1975].

Generally speaking, either of two explanations is possible about the nature of plasma zone 3. It may be related either to the 'plasma sheet' similar to that in the central part of the magnetospheric tail of the earth (see, for example, *Gringauz* [1969] and *Hones et al.* [1972]) or to the boundary layer between the transition layer (the Martian magnetosheath) and the Martian magnetosphere similar to that observed in the magnetospheric tail of the earth [*Hones et al.*, 1972; *Akasofu et al.*, 1973].

If it is a boundary layer, the direction of the plasma motion should be primarily antisolar [*Hones et al.*, 1972; *Akasofu et al.*, 1973], although in the boundary layer of the magnetosphere of the earth, deviations were observed of the bulk ion velocity from the antisolar direction by ~±20° [*Intrilligator et al.*, 1972]. Though one can see some decrease of the average ion velocity from variable ion spectra in zone 3, it is necessary to assume, for an explanation of the observed decrease of ion

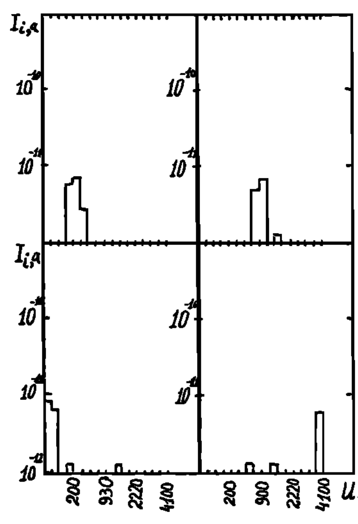

Fig. 4. Samples of ion spectra registered in zone 3.

fluxes, that either there is a considerable decrease of the plasma density in zone 3 in comparison with that in the undisturbed solar wind or there is a significant (30°–40°) deflection of the plasma bulk velocity vector at the boundary between zones 2 and 3. However, if it is the former case, it will be impossible to explain why electron currents measured in zone 3 are higher than those in zone 1. It is also extremely difficult to explain the cause of such a deflection of plasma flow.

If zone 3 is the plasma sheet of the Martian magnetospheric tail, the values of low-ion currents can be explained by the high isotropy of ion fluxes in this zone which is similar to that in the plasma sheet of the magnetospheric tail of the earth. In this case, a contradiction between the simultaneous measurement of low-ion currents and high-electron currents is removed. In the magnetosphere of the earth the energy of isotropic ions of the plasma sheet is $\bar{E} > E_0$, where E_0 is the energy of the ions in the undisturbed solar wind ($\bar{E} \sim 6$ keV, see *Akasofu et al.* [1973]). In zone 3, $\bar{E} < E_0$. This difference between the magnetosphere of the earth and that of Mars may be related to the fact that the Martian magnetic field is relatively weak and therefore is not able to cause the ion acceleration.

The totality of the plasma data pertaining to zone 3 and data of magnetic measurements in this zone gives evidence in favor of a magnetic nature of the obstacle: the increase of the regular component of the magnetic field and the decrease of magnetic field fluctuations with the simultaneous decrease of the plasma density in comparison with that in the transition layer, zone 2. The solar wind flow past this obstacle creates the near-Martian bow shock wave. However, in the absence of magnetic field data at low altitudes or on the surface of Mars the decisive proof of the existence of an intrinsic planetary magnetic field may be found in our opinion only from a joint study of simultaneous data on magnetic field variations in the interplanetary space and in the vicinity of the planet [*Dolginov et al.*, 1975].

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