ON THE NATURE OF THE SOLAR-WIND-MARS INTERACTION

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ABSTRACT

The results of plasma measurements near Mars on the USSR Mars-2, -3, and -5 spacecraft are considered. The data are compared with simultaneous magnetic measurements. Strong evidence is obtained in favor of a direct interaction and mass exchange between the solar-wind plasma and the gaseous envelope of Mars.

INTRODUCTION

The first experimental evidence on the solar-wind interaction with Mars was obtained from the flyby trajectory of Mariner-4 and was suggested by crossings of the Martian bow shock [1, 2]. Much more detailed measurements of the Martian environment were performed on the Mars-2, -3, and -5 satellites by means of a tri-axial fluxgate magnetometer [3, 4], narrow-angle plasma spectrometer RIEP* [5], and wide-angle Faraday cups (particle traps) [6]. Figure 1 shows the summary of results of RIEP for Mars-2, -3, and -5. The figure shows the parts of the orbits where the satellites crossed the ion thermalization front (open dots for Mars-2 and -3, and closed dots for Mars-5) and where the satellites passed the boundary layer (open curves for Mars-2 and -3, and closed ones for Mars-5). Boundaries were obtained as mean curves fitted to observations: I is bow shock, II is upper limit of boundary layer, III is inner edge of boundary layer, and IV is effective flank boundary of an obstacle. The triangle shows the shock crossing by Mariner-4 [1].

The results of data analysis were:

- The permanent existence of a bow shock was established [4, 7, 8, 9, 10]. Data were obtained on the shock position [11 through 17] and its physical properties [12, 13, 18].
- A region of increased magnetic field on the dayside [3, 9] and a region of a stable magnetic field on the nightside of the planet [4] were found and were interpreted in terms of an internal planetary field with magnetic moment 2.6×10^{22} G-cm^3 [3, 4].

*RIEP is an acronym from original Russian which translates as Instrument to Measure Ion and Electron Fluxes.

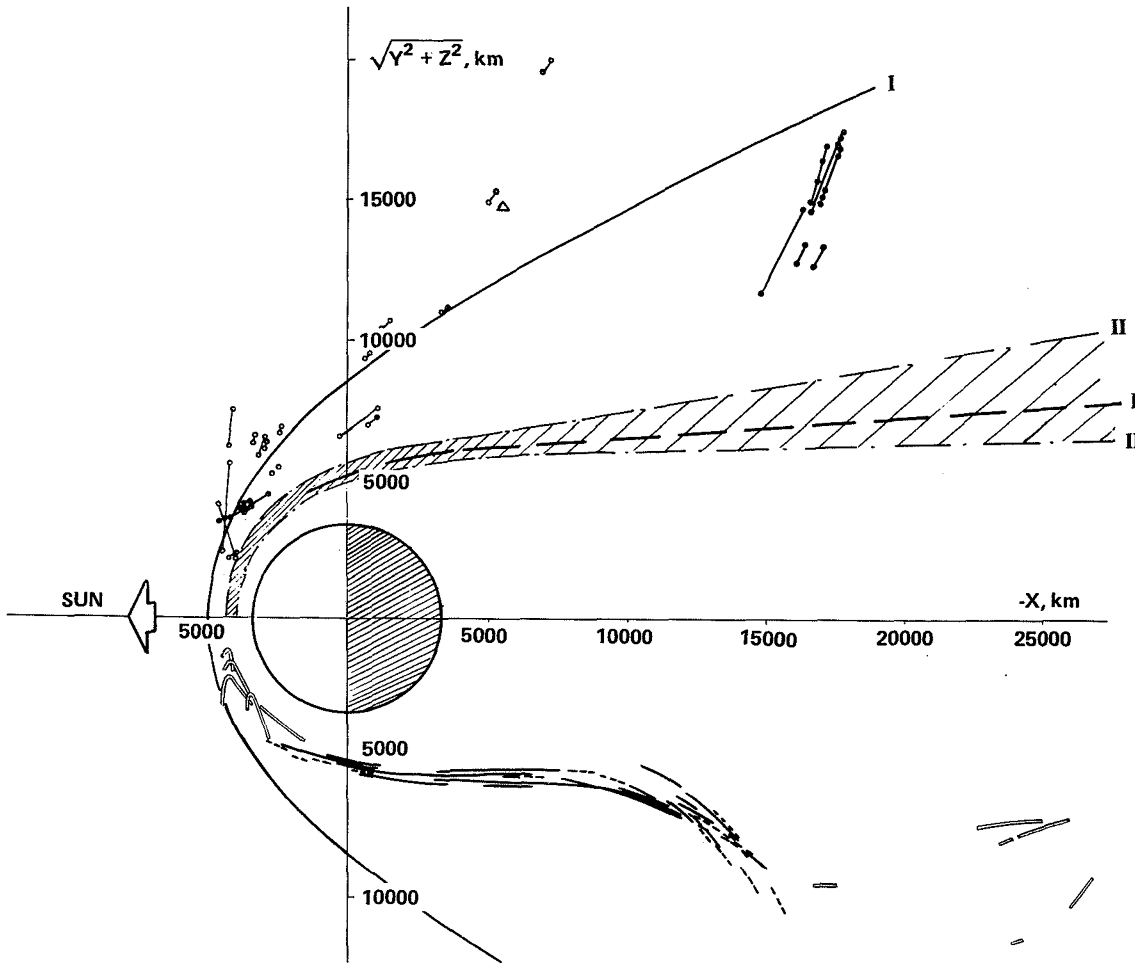

Figure 1. Summary of the results of the plasma experiment RIEP from Mars-2, -3, and -5 about the structure of the solar-wind-Mars interaction region.

The two plasma experiments have observed some structure in the solar-wind-Mars interaction region:

- Inside the interaction region, a layer was found with a colder plasma moving with a lower transport velocity called the boundary layer [12, 19]. The position of this layer and its plasma parameters were obtained [12, 13, 18, 19]. Downstream observations of the boundary layer suggested the existence of a Martian tail [19], which was later found [4, 16, 18].

- Data on the existence of an isotropic plasma, interpreted as a plasma layer in the Martian tail, were published by the authors of the experiments with particle traps [16, 17, 20, 21].

The three experiments have shown some discrepancies in (1) the determination of the bow-shock position, and (2) the determination of similarities and differences between the characteristics of the interaction of the solar wind with Mars and with Earth.

The purposes of this paper are:

1. A comparative analysis of solar-wind-Mars and solar-wind-Earth interactions with respect to bow shock and magnetosheath, and

2. Determining the nature of the obstacle from plasma measurements in the interaction region and inside the obstacle and from the structure of the interaction region.

MARTIAN BOW SHOCK

The three experiments have demonstrated the permanent existence of the bow shock [4, 13, 17, 18]. The thickness of the ion thermalization front is often $\lesssim$100 to 200 km [12, 13], in agreement with some terrestrial bow-shock observations [22].

It could be seen from Dolginov et al. [3, 4] that upstream magnetic-field fluctuations often exist (see also figures 2 and 3). In some cases heating of the electron component was found before the thermalization of ions (figure 4).

A salient feature of the terrestrial bow shock appears to be the jump of electric potential [23] with the initial growth of the potential before the ion thermalization [22, 23]. The manifestation of this phenomena, initial deceleration, was observed near Mars [13].

Theoretical consideration of solar-wind interaction with the atmosphere of a planet, without a significant, intrinsic field [24, 25, 26, 27], showed that a shock could develop due to accretion of ions from the plasma flow [25, 26]. One of the Martian bow-shock crossings, that on February 22, 1974, showed smooth velocity and temperature profiles similar to the profiles of an accretion shock. However, simultaneous measurements on Mars-4 at a distance of 3.5×10^6 km from Mars showed a significant variation of solar-wind parameters. Thus, the unusual shock profile might be connected with solar-wind variations. Smooth shock profiles were observed at large Sun-Mars-satellite angles [13] and multiple crossings of the bow shock were reported [12]. It can be concluded that the structure and physics of the Martian bow shock appear to be not unlike that observed near the Earth.

However, some contradictory data were published on the Martian bow-shock position. Shock crossings close to the planet and remote ones were noted [12, 21]. Many attempts were made to determine the mean position of the bow shock [11 through 17]. The authors of the experiment using particle traps reported a mean areocentric distance at the subsolar point of the shock, R_0, as 5400 km [14], 5900 km [15], 5700 ± 1000 km [16] and 6300 ± 1100 km [17]. In our RIEP experiment, the value of R_0 of 4600 to 4800 km was found from Mars-2 and -3 data [12] and with the addition of the 24 Mars-5 crossings, about 4800 km [13].

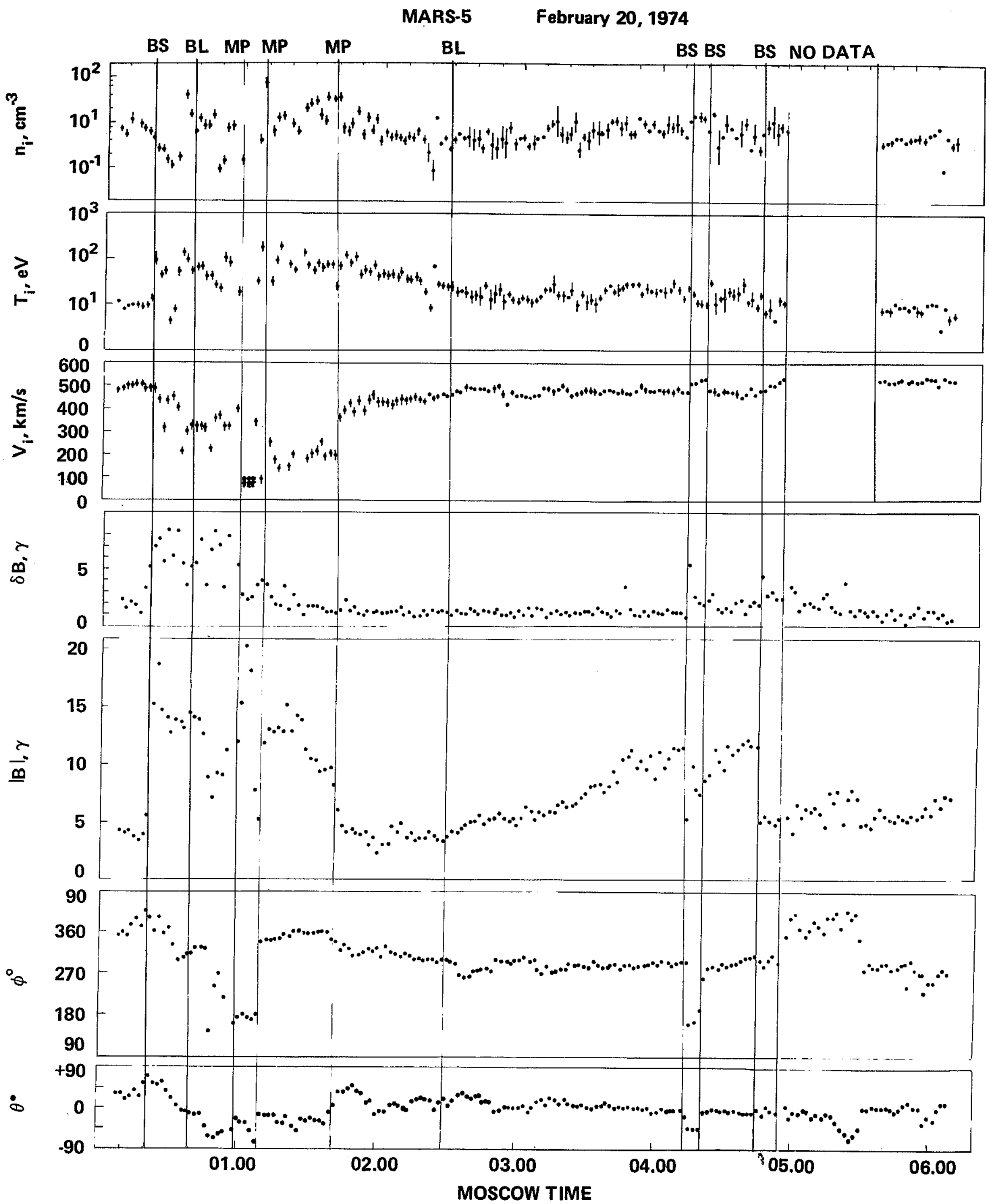

Figure 2. The parameters of the ion component of plasma and magnetic field parameters along the orbit of Mars-5 on February 20, 1974. Boundaries and regions crossed by the satellite are shown.

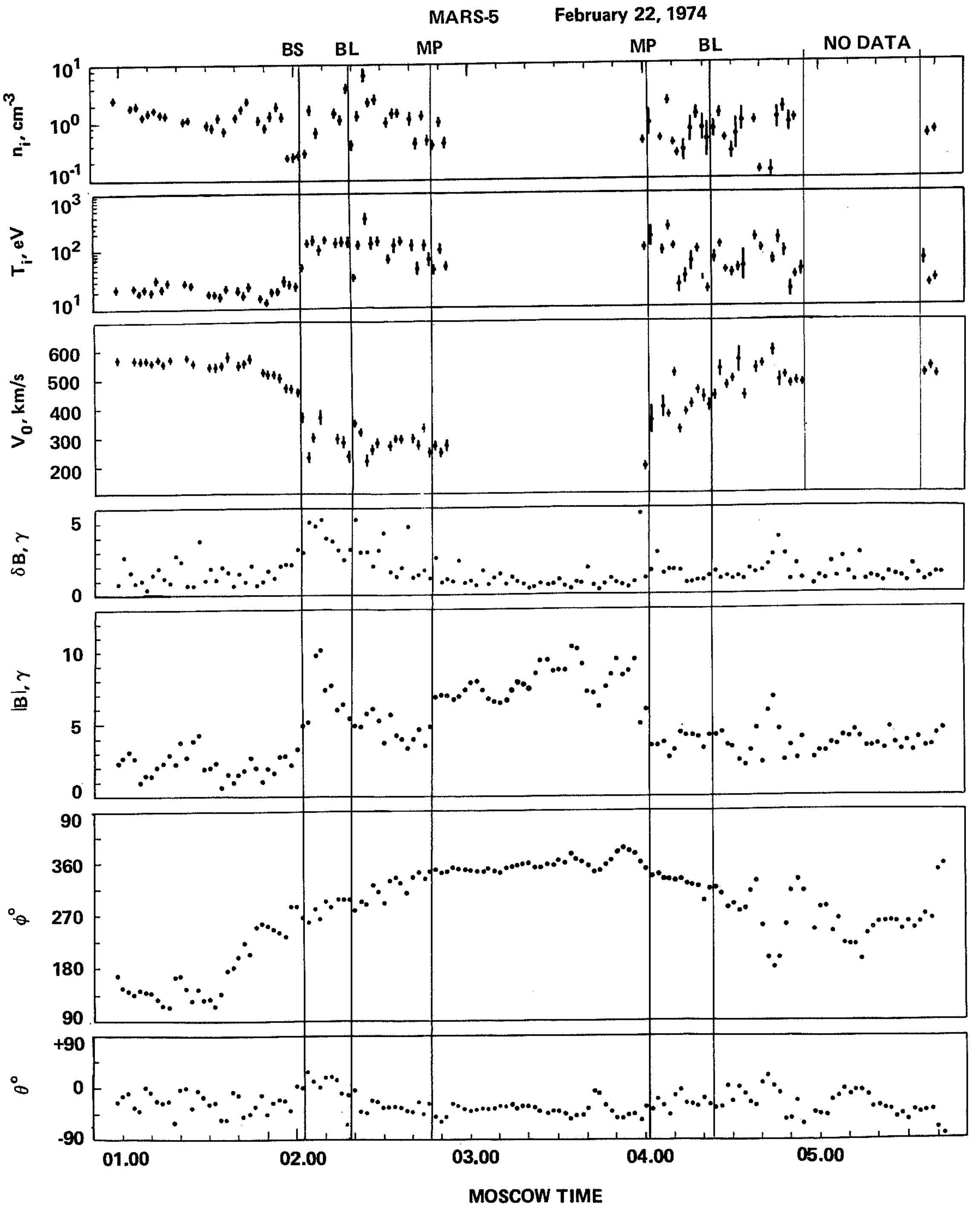

Figure 3. The parameters of the ion component of plasma and magnetic field parameters along the orbit of Mars-5 on February 22, 1974. Boundaries and regions crossed by the satellite are shown.

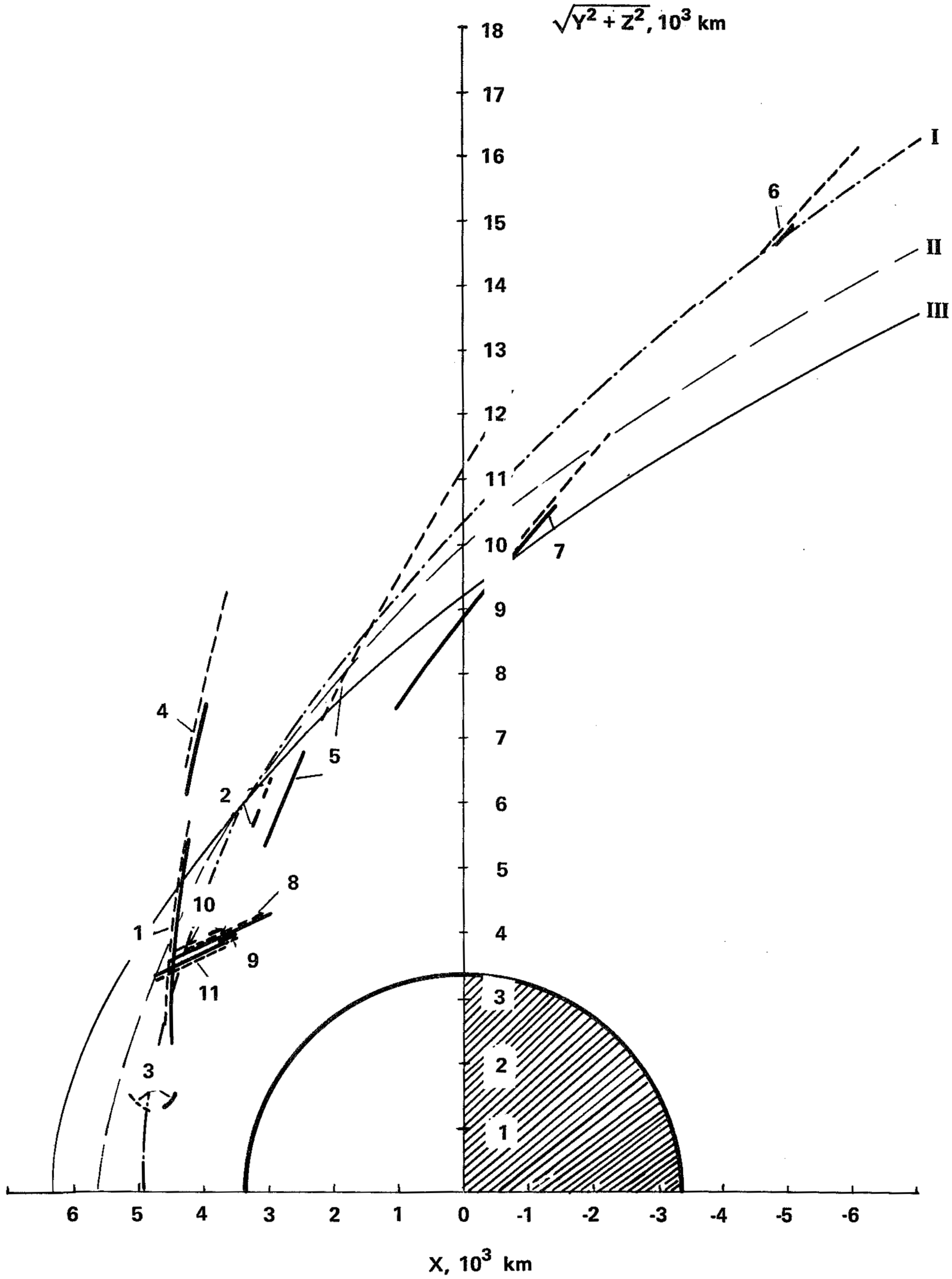

Figure 4. Intercomparison of shock crossings observed in RIEP data (solid lines) and from data of traps (dashed lines) [16, 17]. I is least square fit of conical surface to data of traps; II is mean shock from Gringauz et al. [16]; III is mean shock from Gringauz et al. [17].

Figure 4 shows the results of a comparison of reported crossings from the two plasma experiments. It follows that:

- The shock crossings from the traps' data were identified either almost simultaneously (points 1, 6, 8, 9, and 11) or slightly before (points 2, 3, 4, 5, 7, and 10) the RIEP crossings. These differences could be connected with different criteria. The RIEP crossings were determined from the thermalization of the ions while the Mars-2 and -3 crossings from the traps were determined by the rise of the collector current and the appearance of nonthermal tails in the electron spectra, which is a well-known upstream shock phenomenon [28].
- The difference in the calculated values of R_0 could not be explained only by differences in the determination of a particular crossing. It is seen from figure 4 that the majority of dayside crossings, which are essential for shock position determination, are well inside of the curves II and III drawn by the authors of the experiment with the traps.
- Curve I in figure 4 is our best conical fit to the traps' crossings and gives $R_0 \approx 4900$ km, in close agreement with the RIEP figure.

Thus, the elevated values of R_0 in Gringauz et al. [14 through 17] can be explained by poorly-based assumptions on the shape of the Martian bow shock. The available experimental data show that the mean areocentric distance to the bow-shock subsolar point, 4800 to 5000 km, has to be considered as reliable.

Two more distant dayside bow-shock crossings may be possibly explained by low Mach numbers and by the development of the structure of a quasi-parallel shock.

MAGNETOSHEATH

Measurements of the ion flow on Mars-5 were made by RIEP analyzers oriented in two directions [18]. This made it possible to determine, in certain cases, the direction of plasma flow [13] and to show that in the magnetosheath, except for the boundary layer, the plasma flow is in agreement with the gasdynamic model [2, 29] and with the near-geomagnetosphere observations [30].

The following features of the Martian magnetosheath plasma behavior were found:

- In some cases within the magnetosheath, the velocity is high and the temperature of the ions is low compared to the gasdynamic model [2, 29].
- Cases of nearly-harmonic oscillations were found (figure 2). The boundary layer was mapped by Mars-2, -3, and -5 measurements and variations of plasma parameters across the layer were measured [13, 18]. The thickness of the boundary layer on the dayside is ~350 km, near the terminator ~500 km, and at 3R♂ downstream ~1000 km (see figure 1).

Significant fluctuations are seen in the mean transport velocity and in the temperature profile of the boundary layer (figures 2, 3, and 5). The ion temperature in the deep boundary layer is sometimes ~10 to 30 eV, that is, significantly lower than in the magnetosheath (this fact was established by Mars-2 data [11, 12]). The heating of the plasma is seen at the initial deceleration in the boundary layer.

The similarity of the Martian boundary-layer profile and a gasdynamic boundary-layer profile stimulates attempts to estimate certain gasdynamic parameters of the boundary layer of Mars.

The Reynolds number is

$$R_1 = \left[4.64\left(\frac{\ell}{\zeta}\right)\right]^2$$

where

ℓ = the distance from lobe,

ζ = the boundary layer thickness.

(The expression holds for thin plates [31].)

Substituting 10,000 km for ℓ and 1,000 km for ζ, we obtain $R_1 \approx 2000$, which allows the existence of a vortex street. The kinematic viscosity is

$$\upsilon = \frac{v_0 \ell}{R_1}$$

where v_0 is the velocity external to the boundary layer flow. Substituting 500 km/s for v_0, we obtain $v \approx 2.5 \times 10^9$ m^2/s, a value somewhat higher than that obtained from studies of microfluctuations in the solar wind, 8.8×10^8 m^2/s [32].

HEAVY IONS IN THE PLASMA FLOW CLOSE TO MARS

Measurements of the ion spectra in the RIEP plasma spectrometer on Mars-5 were made with nonsaturated channel multipliers with different gains. Two Sun-directed electrostatic analyzers of RIEP measured different energy spectra in the solar-wind-Mars interaction region and the difference was most significant in the boundary layer. The analysis of data and additional laboratory tests of channel multipliers showed that the most probable explanation of the difference in measurements of the two analyzers is the change of ion composition. With this assumption, two ion components were revealed—light ions of solar origin and heavy ions apparently of ionosphere origin [13]. Figure 5 is an example of the behavior of the two ion components in the boundary layer with the heaviest ions observed at the inner edge of the boundary layer, where the energy of the net motion is low. A diminishing heavy ion flux is observed in the outer part of this layer.

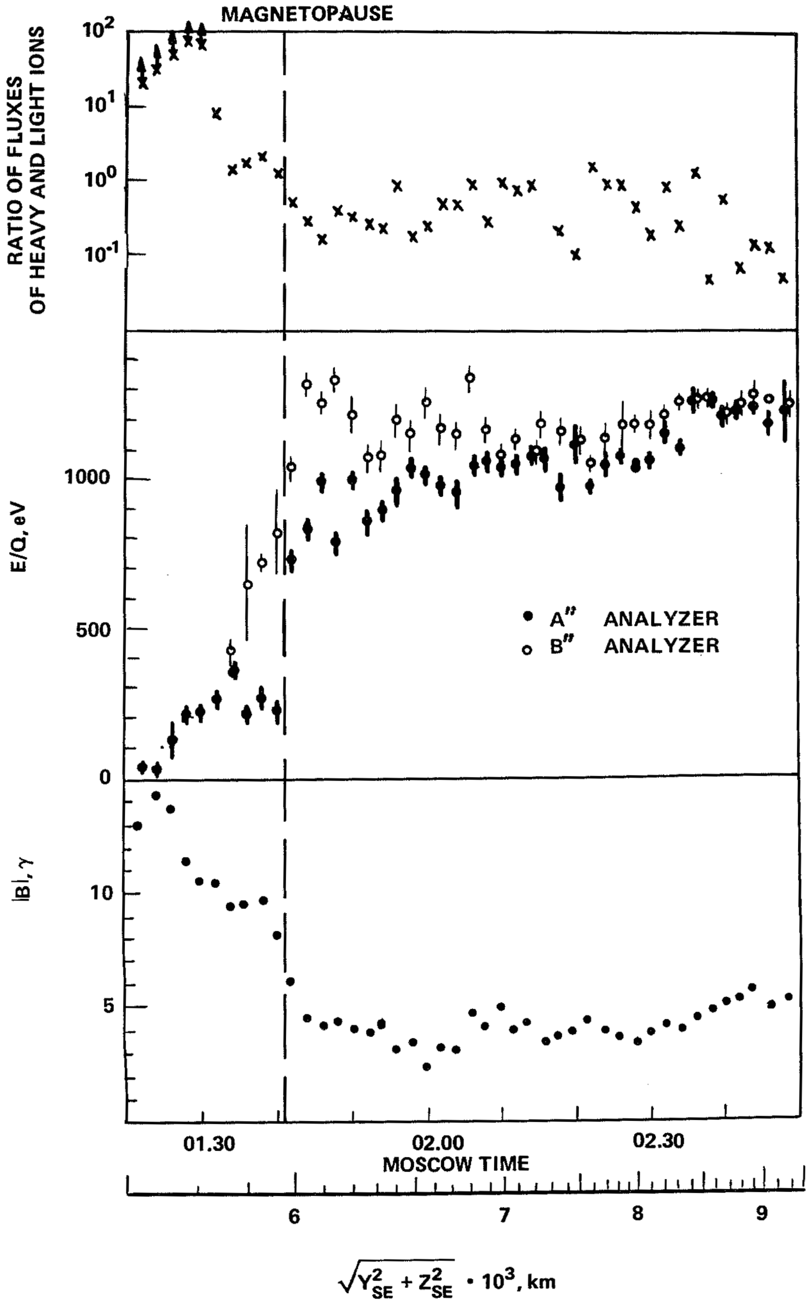

Figure 5. Boundary-layer crossings on February 20, 1974. The upper panel is ratio of heavy ion number flux to light ion number flux; the middle panel is energy of directed motion according to measurements of analyzer A, which registered total flux of ions (solid dots) and according to analyzer B, supposedly measuring only light ions (open dots); and the bottom panel shows the modulus of magnetic field. Magnetopause position is also shown.

Two estimates of M/Q of the heavy ions were made [13]: the first from a comparison of the inward gradient of heavy ion flux (~1000 km) and outward gradient of light ion flux (~100 km), and the second, from the maximum height of the heavy ion observations near the terminator (~1800 km) assuming that the ions are accelerated by an electric field (as suggested in [33] from the top of the ionosphere ~400 km). Supposing that the geometry is determined by the gyroradius of ions with energy from RIEP measurements and with the magnetic field from Dolginov et al. [4, 34], M/Q was estimated as 15, Vaisberg et al. [13] suggesting O^+ as the principal constituent, but not excluding any heavier ones.

From the measured number flux, for an axisymmetric boundary layer, the loss rate for Mars was obtained as $\sim 10^{25}$ particles/s [13]. This estimate appears to be an upper limit because it is made from the Mars-5 observations on February 20, when the heavy ion flux in the boundary layer was higher than usual, and because it is made for a convected Maxwellian distribution of heavy ions, which may not be the case [33].

The Mars satellites probe only the outer part of the obstacle; the closest approaches of Mars-2, -3, and -5 on the dayside were at 1100 km, 1100 to 2300 km, and 1760 km, respectively. In some cases, Mars-2 and -3 entered in the dayside region of the magnetic field increase and plasma deceleration while Mars-5 probed this region on the nightside.

The effective dimension of the solar-wind obstacle could be approximately estimated by the position of the bow shock with the use of the gasdynamic analogy [2, 29] or with scaled near-Earth data [35]. With $R_0 \approx 4800$ km, the effective stagnation point height is ~3800 km or ~400 km above the Martian surface [12, 13]. The reliability of this figure is not high but does suggest that the plasma flow interacts with the upper atmosphere of Mars.

There is an apparent contradiction between this mean effective dimension of the obstacle and observations of the region of increased magnetic field [3, 9] and that plasma with strongly different parameters [13, 15, 36] at heights ~1100 km on Mars-2 and -3. Considering this as possible entry of the satellite into the obstacle, it is necessary to recall that (1) at Sun-Mars-satellite angles 30° to 60°, where the measurements were made, the height of the obstacle will increase by 300 to 500 km compared to the stagnation point, and (2) the boundary of the obstacle should have a thickness on the order of an ion gyroradius, so that if the relative amount of hot heavy ions is high, the magnetopause or ionopause thickness may be several hundred kilometers.

The dimension of a gasdynamic obstacle with a boundary layer is determined approximately at a level of 1/3 of the boundary layer thickness [31]. Thus, plasma measurements on Mars-5 could be used to obtain the mean flank shape and dimension of the obstacle (figure 1). These data show that the flank shape of the Martian obstacle could be approximately described with the normalized H/R_{σ} parameter = 0.2 (according to [29]) and that the flank dimension of the obstacle does not contradict a bow-shock position at $R_0 \sim 5000$ km.

PLASMA IN THE OBSTACLE

Upon crossing the boundary layer, Mars-2 entered a region with ion temperature ~10 to 20 eV [11, 12]. Subsequent analysis of electron component measurements also showed the cooling of electrons in the obstacle [36]. It is difficult to expect cooling of ions by collisions at heights ~1100 km. Therefore, these measurements show the appearance of a planetary plasma in the boundary layer. As shown above, the Mars-5 data confirm this conclusion.

In the crossing of the nightside boundary layer by Mars-5, the energy of the ions dropped on the inner border of the layer and RIEP registered a low flux of particles, or else the signal dropped below instrumental threshold [13, 18]. Similar data were obtained with the ion trap [16]. But the electron trap measured an electron flux comparable with the solar-wind level. Consideration of the electron spectra measured by the electron trap in the tail of Mars [16] suggests that the measured signals are due not to an omnidirectional Maxwellian distribution of electrons, as suggested by the authors, but instead is due to a directed flow of electrons toward the planet with a streaming energy ~20 to 50 eV and $T_e \sim 10$ eV. This interpretation of the spectra will diminish the estimated n_e in the tail and weaken the discrepancy between ion and electron current, and have a strong influence on our present understanding of plasma and magnetic measurements in the Martian tail.

Intercomparison of electron and ion currents led Vaisberg et al. [13] and Gringauz et al. [16, 20, 21] to the conclusion that they have found a region of isotropic ion fluxes, which they consider as a plasma layer analogous to that in the geomagnetosphere.

The appearance of heavy ions in the inner boundary layer [13] may explain a significant part of the discrepancy between electron and ion currents, since the ion velocity (and flux) is proportional to $M^{-1/2}$ for heavy ions of the same measured energy. To resolve the contradiction between the interpretations of plasma measurements in the outer part of the Martian tail, either as a boundary layer [13, 18] or as a plasma layer [13, 16, 20, 21] and to clarify the nature of this plasma, an intercomparison of the data of the two plasma measurements has been made. Due to different angular acceptance of the two instruments, 3.5° for the RIEP and 50° for the ion trap, it is possible to obtain some information on the angular distribution of the ions.

This intercomparison showed that:

- The outer part of the boundary layer was not distinguished from the magnetosheath by the traps.
- The plasma layer determined by the traps coincides with the mean and inner parts of the boundary layer and with the region of "0" readings of the RIEP.
- In some cases when the measured signal is high, the RIEP data can reject the hypothesis of isotropy.

Figure 6 shows the results of the intercomparison of simultaneous maximum signals in ion spectra measured by narrow-angle plasma spectrometer RIEP and wide-angle ion trap on Mars-5. The shaded regions represent the various regimes of data points and computer-simulated ratios calculated with known instrumental characteristics for different plasma parameters. The diagonal dashed lines connect open dots for $n_i = 1\ cm^{-3}$ and crosses for $n_i = 5\ cm^{-3}$. The encircled numbers represent (1) the magnetosheath, (2) the outer part of the boundary layer (RIEP), equal to the magnetosheath (ion trap), (3) the inner part of the boundary layer (RIEP), equal to the isotropic or plasma layer (ion trap), and (4) "0" of RIEP and the isotropic or plasma layer of ion trap (small signals and "0"s). The centrum of each distribution is also shown in this figure.

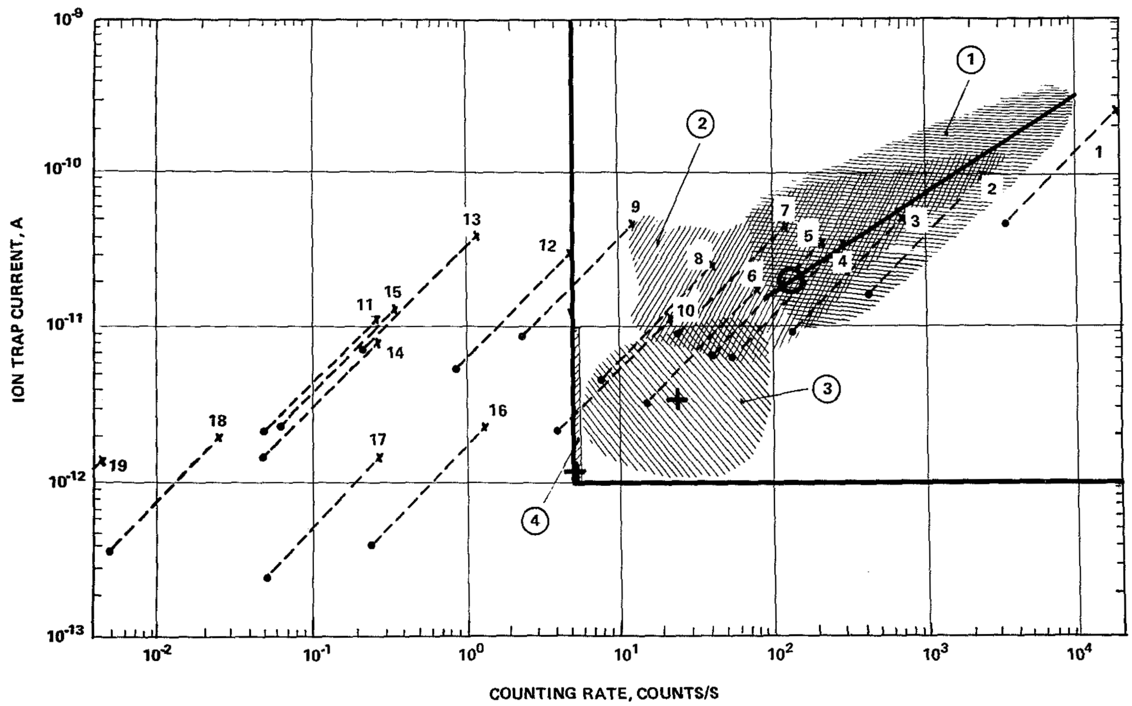

Figure 6. Results of intercomparison of simultaneous maximum signals in ion spectra measured by narrow-angle plasma spectrometer RIEP and wide-angle ion trap on Mars-5.

The simulated ratios mentioned above for figure 6 were obtained for transport velocity (if any) directed along the aperture of the instruments for the following plasma parameters:

No.	E_0, eV	V_0, km/s	T_i, eV
1	1300	500	13
2	1000	440	50
3	800	390	80
4	500	310	100
5	300	240	60
6	200	195	100
7	200	195	20
8	150	170	30
9	150	140	—
10	100	140	100
11	100	140	50
12	100	140	20
13	100	140	10
14	50	100	25
15	50	100	10
16	0	0	100
17	0	0	60
18	0	0	20
19	0	0	10

A computer experiment was performed to obtain the responses of RIEP and the ion trap, whose characteristics are known, to different convected and nonconvected Maxwellian distributions of ions. The results of these calculations are also shown in figure 6 along with the intercomparison of simultaneous maximum readings of the two instruments in the solar-wind-Mars interaction region. Thus, from measured and calculated data:

- The measurements in the magnetosheath (regime 1) and in the outer part of the boundary layer (regime 2) could be well represented by convected Maxwellian distributions.

- An isotropic plasma with T_i between 10 and 100 eV and observed number densities would not be measured by RIEP on Mars-5, so all the readings of RIEP are due to a convected flux. Isotropization can cause a drop of the ion traps readings by a factor of 10^2, not necessarily by 20 times as indicated by Vaisberg et al. [13] and Gringauz et al. [16, 20, 21].

Having this in mind, all observations of isotropic fluxes of the plasma layer [17, 21] could be divided into three groups:

1. In ~50 percent of the cases in the plasma layer, the ion trap and RIEP simultaneously measured the ion flux (regime 3 in figure 6) and isotropy can be excluded.

2. In ~25 percent of the cases, both instruments show zeros—no data and any suggestions are possible.

3. In ~25 percent of the cases, the ion trap registered low signals with zeros of RIEP; isotropy is feasible but some other explanations are possible including deviation of the plasma flow away from the axes of the angular acceptance aperture of the two instruments. There is some reason to suspect that ions can flow along magnetic field lines which are highly inclined in the Martian tail, relative to the Sun-Mars direction.

It follows from figure 6 that the plasma in the inner part of the boundary layer (regime 3), could be approximated by a convected Maxwellian distribution of heavy (and consequently slower) ions. Thus, most evidence on the plasma in the outer part of the obstacle (or inner part of the boundary layer) shows a directed motion of a lower temperature plasma compared to the magnetosheath, with a different composition. The temperature and motion of this plasma cannot be explained in terms of a plasma layer.

Comparison of the boundary-layer position, relative to the magnetopause as determined from the magnetic measurements in the Martian tail [34], shows that (see figures 2 and 3):

- There are cases of assimilated boundary layer when the magnetopause is çoincident with the layer and a significant ion flux is observed inside the tail (February 20, 1974, figure 2) and there are cases of a rejected boundary layer when ion flux was not measured below the magnetopause (February 22, 1974, figure 3). The directed energy of the ions at the magnetopause is ~0.5 of external flow energy.

- Light ions hardly penetrate inside the tail (figure 5) [13]. The flow inside the tail, if observed, appears to be essentially of heavy ions [13]. Thus, these plasma data show that the magnetic field lines of the tail are connected to the Martian ionosphere.

Thus, it can be stated that the Martian boundary layer, which in many respects is similar to the geomagnetospheric boundary layer [37, 38], differs from it in its position relative to the magnetopause and in the flow of heavy ions inside it. The internal part of the boundary layer could not be the plasma layer suggested in Vaisberg et al. [13] or Gringauz et al. [16, 20, 21] but can be considered as an analog of the geomagnetospheric mantle [38].

CONCLUSION

Consideration of experimental data shows that the gasdynamic analogy can be used for the description of the solar-wind-Mars interaction region including the boundary layer. Most of the plasma measurements do not contradict the weak internal planetary field concept. Nevertheless, part of the magnetic data and some plasma data have not yet found a satisfactory explanation in the framework of a magnetospheric model as the obstacle at Mars. Let us enumerate the reasons in favor and against the magnetospheric model.

The following arguments have been proposed in favor [4, 17, 20]:

- Increased magnetic field at heights above 1100 km on the dayside [3, 9];
- Observations of remote crossings of bow shock;
- The existence of a stable sunward-directed magnetic field region in the Martian tail [4, 34].

However, the following features have not been explained by this model:

- The mean position of the bow shock. It seems quite unexpected that the Martian magnetic field usually stops the solar-wind flow at a height which does not contradict the nonmagnetic model of an obstacle [24].
- The absence of any dependence of bow-shock position on solar-wind ram pressure, ρv^2. The Mars-5 bow-shock crossings on February 20 and 22, 1974 were used as evidence of this dependence [4, 16, 17, 21]. According to Gringauz et al. [16, 17], ρv^2 was 4.2×10^{-8} dynes/cm^2 on February 20 and 1.2×10^{-8} dynes/cm^2 on February 22. In the magnetospheric model, the dimensions of the magnetosphere and, as Gringauz et al. [16, 17, 21] consider, the position of the shock must change by a factor of

$$\sqrt[6]{\frac{4.2}{1.2}} \approx 1.23$$

  or approximately 1000 km for the stagnation point. This is four times as much as obtained by Gringauz et al. [16, 17]. A more precise determination of the shock crossing on February 22 (see figure 3) gives an even smaller change of the shock position. Thus, it appears that the factor ρv^2 does not control the size of the obstacle.
- No energetic ions were usually observed in the Martian magnetosphere. With the energy range of the RIEP up to 20 keV, only in some cases were weak bursts of 10 keV ions registered in the Martian tail.
- In two cases, on February 14 and 24, 1974, when according to RIEP (and ion trap) data, Mars-5 was inside the obstacle and the ion flux dropped considerably, the magnetometer did not measure a stable sunward-directed magnetic field [4, 34]. RIEP data show that this region corresponds to the internal part of the boundary layer [13] (see figure 2), so the assumed magnetic dipole may have reversed polarity.

The geometry of Martian bow shock and boundary layer, and the heavy ion flux within it, demonstrate that a very important feature of the solar-wind-Mars interaction is mass exchange between the solar wind and Mars. The possible existence of a weak internal field does not prevent this exchange. It is evident that the magnetic field at the heights of Mars-2, -3, and -5 is strongly disturbed by external sources and additional analyses are necessary.

The Martian magnetosphere strongly differs from the geomagnetosphere. Thus, tail structure and processes of acceleration of particles may also differ. There are evidences that the plasma tail can develop in some cases and that a directed flow of electrons toward the planet can exist.

The following conclusions can be drawn:

- A bow shock permanently exists near Mars. Its physical characteristics are similar to the terrestrial bow shock. The mean height of the bow shock at the subsolar point is ~1500 km above Mars.
- The relative positions of the bow shock and the obstacle and the plasma flow in the magnetosheath approximately correspond to a gasdynamic model.
- In the interior of the dayside and nightside magnetosheath, there is a boundary layer with a decreased flow velocity and ion and electron temperature (at least down to ~10 eV). This boundary layer is similar to a gasdynamic boundary layer at the interface of two fluids. The kinematic viscosity estimated for the thickness of the Martian boundary layer is $\sim 2.5 \times 10^9$ m^2/s.
- A flow of heavy ions, apparently of planetary origin, was found in the boundary layer. The planetary loss rate of these ions, presumably O^+, can reach 10^{25} particles/s.
- The plasma measurements confirm that there are regions near Mars where the magnetic field lines are connected to the upper atmosphere of Mars. Available plasma data do not contradict the hypothesis of a weak internal planetary field. The Martian magnetosphere is quite different from the terrestrial one.
- The boundary layer lies on or overlaps the magnetopause. The internal part of the boundary layer appears to be the analog of the terrestrial mantle, where directed plasma motion away from the planet exists [38].
- The mean shock position and the existence of a boundary layer with a flow of heavy ions in it show the important role of direct interaction and mass exchange of the shocked solar-wind plasma with the upper atmosphere of Mars.

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QUESTIONS

Vaisberg/Galperin: Strong shear in the plasma flow in the boundary layer observed by your group in the Martian experiments close to the obstacle's boundary region projects down to the ionosphere in some still undiscovered cusp-like region. This strong shear implies a very strong localized current in this region and presumably a strong local heating of the ionosphere which in turn raises the conductivity and hence the electrical current. The solar plasma-ionospheric plasma interaction will occur more effectively here than in other regions.

As a result of this local heating, the convective flow pattern near the cusp-like region, due to the ion drag, can be expected to form a specific neutral wind pattern which might be similar to that which is observed by analogy with the Earth's atmosphere. This neutral wind pattern probably influences the convection pattern and the associated magnetospheric currents by a dynamo action.

The point of all this is that this neutral wind system has a much higher inertia than the ionosphere and therefore may introduce a much higher time constant for the reversal of the induced current pattern and simple diffusion of the magnetic field. This would probably increase it several hours by comparison with the one hour quoted by P. Cloutier earlier. So if we suppose that the magnetic field is an induced one, the time constant of its reversal must be considered, taking into account the upper atmospheric wind pattern time constant.

If the ionosphere is squeezed out by the magnetosheath flow, say above the ionopause at 400 km, then no significant asymmetry in the global ionospheric density distribution is expected from the above mentioned near-cusp heating. However, modifications in the neutral atmosphere and air glow and auroral structure should be most prominent, forming a bulge at this region which interacts with the solar plasma more effectively.

Vaisberg/Gringauz: Dr. Vaisberg has spent a rather large part of his talk in criticizing our supposition on the existence of an isotropic plasma zone in the tail of the Martian magnetosphere. If one returns to the last figure in the Dolginov-Gringauz report,* one can see that there are large zones in which there are signals in the wide-angle ion trap but there are no signals for the electrostatic analyzers. Thus, these analyzers are obviously not proper devices to allow judgment on the existence or non-existence of plasma isotropy.

In these zones, we observed a large electron flux and a very low (or absent) ion flux and plasma isotropy can explain the observed results.

We never denied the existence of a zone of ion fluxes with comparatively low energies and number fluxes, but Dr. Vaisberg and his co-authors regard it like a gasdynamic boundary layer which is outside the obstacle. We think that it is inside the magnetosphere and something like a diffuse boundary of the magnetosphere as discussed by Intriligator and Wolfe and the Prognoz group, or a boundary layer near the magnetopause of Hones et al. [37] or mantle layer reported by the ESRO scientists on HEOS [38].

Some remarks now on the heavy ion fluxes. I think that they are possible but they have not been proven. The laboratory measurements were made after the flight and, consequently, not with the same channeltrons. The results of these measurements show that there is a very narrow interval in the characteristics of the channeltrons which can give the desired effect. There must be a very fortunate set of circumstances to obtain the proper time variation of channeltron characteristics during the flight in order to get into this interval. So maybe these results are real but it is necessary to prove it.

Vaisberg/Bauer: From your measured flux of heavy ions, can you make some estimates regarding the concentration of O^+ near the obstacle? How deeply did you penetrate into the obstacle when you found evidence for a directed flow rather than an isotropic flux observed by the traps?

Vaisberg: The estimated number density of heavy ions in the boundary layer is about 1 cm^{-3} on February 19 and February 20. We can relate the total estimated flux to the upward flux near the obstacle by assuming the change of the flow tube cross section or by the value of the unshielded area of the Martian atmosphere. Thus the number flux of O^+ near the obstacle could be $10^8/cm^2$-s and it is necessary to know the velocity to estimate the concentration. Really, we penetrated inside the tail (2 to 3 R♂ downstream) by 200 to 500 km. The flow is directed in at least 50 percent of the cases and we do not see reasons to believe that it is isotropic in the other 50 percent.

*See Sh. Sh. Dolginov et al.'s paper, "Magnetic Field and Plasma Inside and Outside of the Martian Magnetosphere," in this document.

Vaisberg/Galeev: Why do you consider the presence of heavy ions in the region of sunward-directed magnetic field, before Mars-5 enters the magnetosphere with an anti-sunward-directed field, as an argument against the presence of an intrinsic planetary magnetic field?

Vaisberg: It is not an argument against the intrinsic magnetic field, but argues against the suggested direction of the dipole. We consider the fact that in two passes of Mars-5 through the edge of the Martian tail, the region with a stable anti-sunward component and low-energy plasma (indicating that this region is not a part of the external flow) were seen before and to the south relative to the region with a stable sunward component. This contradicts the proposed identification of the direction of the Martian dipole and so either the Martian dipole is oppositely directed to what was shown by Dolginov or the direction of the field on the dayside disagrees with the direction of the field of the Martian tail contrary to that given in figure 6 in the Dolginov-Gringauz report. I would like somebody to draw the configuration of the Martian magnetosphere.

Dolginov: I want to make a comment on the Vaisberg/Galeev discussion. A possible interpretation of the opposite sign field peak observed by Mars-5 near the equatorial plane on the most disturbed day (February 20) was considered in *Kossmicheskiye Issledovaniya*, Volume 13, No. 1, 1975, p. 108.

Vaisberg/Ness: How do you determine a three-dimensional flow velocity from only two channeltron measurements, that is, what additional assumptions do you make to yield a unique result?

Vaisberg: The total velocity and its direction were obtained by projecting the velocity vector from the plane defined by two differently oriented analyzers to a plane containing the satellite and the X_{SE} axis. The assumption we used was that the flow velocity lies in the plane containing the Sun-Mars line, that is, there is no azimuthal velocity component in the YZ_{SE} plane.

Vaisberg/Cloutier: Comment to Bauer's question. It is difficult to extrapolate a measurement of the ion density in the flow region around Mars in order to obtain a density at the obstacle height. The ion distributions in the flow vary from equator to pole and in the opposite polar hemisphere by a factor of approximately three. A comment to Galeev's question. The question of whether heavy ions are being convected in the magnetosphere or have been picked up by the flow around the planet may be answered by looking at their energy spectra. The characteristic spectra of the ions and the flow have been calculated by Cloutier et al. [33] for opposite polar hemispheres and magnetospheric ion spectra may be estimated.

Galeev: This is in comment to Cloutier's remark. It seems to me that the heavy ion flux estimated by Vaisberg et al. in this report could be drawn out of the ionosphere through the cusp in the magnetospheric model. Therefore, I do not think that the coincidence of the theoretical estimate, for the model of the direct interaction with the ionosphere, and of the experimental estimate, to an order of magnitude can be considered as an argument in favor of the absence of an intrinsic magnetic field.