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MEASUREMENTS OF ELECTRON AND ION PLASMA COMPONENTS ALONG THE "MARS-5" SATELLITE ORBIT

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SUMMARY

On the spacecraft Mars-5, which became satellite of Mars on February I3, 1974, charged particle traps (energy mass-spectrometers) were installed for measurements of characteristics of ions with energies $E \leqslant 4.I$ kev and electrons with $E \leqslant 300$ ev. Measurements made by means of both devices have shown that during each revolution around the planet the satellite intersected three typical zones (undisturbed solar wind, transition region behind bow shock and zone, with quasiisotropic comparatively cold plasma at the antisolar part of near-Martian space). Comparison of these data with the results of simultaneous magnetic measurements have shown that bow shock positions from the magnetic and plasma data coincide and boundaries of the quasiisotropic plasma zone coincides with the boundary of the zone corresponding (to opinion of authors of magnetic measurements, Dolginov et al.) to the Martian magnetosphere created by the intrinsic magnetic field of the planet.

Variations of the solar wind dynamical pressure defined from measurements of the solar wind ion component well correlate with changes of the near-Martian bow shock position.

One can suggest that the zone of the quasiisotropic plasma at the antisolar part of the near-Martian space is some similarity of the plasma sheet in the Earth's magnetospheric tail.

I. INTRODUCTION

The spacecraft "Mars-5" was launched into the Mars satellite orbit on February I3, I974. An altitude of pericenter was ~ I800 km, of apocenter ~ 32000 km, the orbital plane inclination to ecliptic plane ~60°, period of revolution ~ 25 hours. Fig. I gives the near planet portions of "Mars-5" orbit for February I3 and February 24 in coordinates $X, \sqrt{Y^2+Z^2}$ (X -axis passes through the planetary center and is directed to the Sun).

Among the scientific instruments installed aboard the spacecraft there were charge particle traps for measurements of ion and electron components of low energy plasma. By means of oriented to the Sun ion Faraday cup with angular response ± 45° differential ion energy spectra were measured within energy range from 0 to 4.1 kev. The electron trap with angular response ± 40° and retarding potentials 0-300 v oriented in the antisolar direction, allowed to obtain integral spectra of electron fluxes (retardation curves).

The detailed description of devices, their performance, their location on spacecraft, techniques of processing the data obtained and measurements made were presented in [I] . In [2 , 3] some results of measurements were published. More detailed results of electron and ion plasma component measurements in the vicinity of the planet for the period from February I3 to 26 are given below.

2. THE EXPERIMENTAL RESULTS

Fig.2 gives ion spectra obtained from near-planet satellite passes during which plasma measurements were carried out.

Each ion spectrum was measured for ~ 50 sec, the time interval between measurements of spectra was 2 minutes or I0 min. For data presented in Fig.2 the time interval between spectra is equal to I0 min (each fifth spectrum is presented for measurements on February I9 and 2I).

Fig.2 shows that near the planet there are three intersected by satellite zones with sufficiently different plasma properties. Far from Mars ion spectra are typical for the solar wind undisturbed by the planet (see, for example, spectra 5-9 for February, I3 or I-6 for February, 2I). In this zone the magnetometer installed aboard "Mars-5" registered the interplanetary magnetic field [4] . After satellite crossing the near Martian bow shock front and an entry the transition region, ion spectra are considerably widened, maximum ion fluxes are registered with more low energies (for example, I0-I2 spectra for February, I3 and 7-I2 for February, 2I in Fig.2). This corresponds to a drop of ion bulk velocity and thermalization of ions in the transition region. A type of ion spectra is practically identical to those observing with the similar instrument in the transition zone (magnetosheath) behind the near-earth bow shock [5] . The magnetometer in this zone registered increase of magnetic field and its large fluctuations[4].

After the transition zone a sharp drop of ion fluxes is observed as compared to the solar wind and transition layer. We regard the boundary of this third zone as the boundary of the obstacle which creates the bow shock. Decrease of ion currents measured is so large that approximately in 30% of measurements carried out in this region, ion fluxes are lower than the instrument sensitivity threshold (empty squares in Fig.2) and only in 40% of cases ions are registered reliably (device output voltage level three or more times exceeds minimum level detectable by telemetry). Ion energies in this zone are much more variable, as a rule, lower, but sometimes higher than in the solar wind (for example spectra I8 for February, I4 and spectra I3 for February, 20 in Fig.2).

The magnetic field fluctuations in this zone are much lower than in previous zone, and X-component direction is stable and independent on the direction of X-component of interplanetary magnetic field [4]

In further motion of the satellite along the orbit it again enters the transition layer (for example, spectra I9-30 for February, I3 and 20-28 for February, 2I) and then leaves for the undisturbed solar wind. Bold lines in Fig.I show the trajectory portions when "Mars-5" was in the solar wind, dashed bold lines show "Mars-5" being in the transition zone, the region with the least ion fluxes is noted with the dashed bold lines.

Let us note, that the orbit of "Mars-5" intersected the "obstacle" in the antisolar part of near-martian space (if we divide space into "solar" and "antisolar" parts by means of a plane, including the terminator of the planet).

Characteristics of electron plasma component are also sufficiently different in the regions considered. Fig.3 gives the electron retardation - curves for the measurements on February, 2I in the solar wind (Fig.3a) in the transition region (with the angles φ Sun-Mars-vehicle were ~ 40÷90° (Fig.3b)), in the region with the least ion fluxes (Fig.3c) an in the transition region (with the angles $\varphi \geqslant 130^\circ$, Fig.3a). To give an idea on the characteristics type of electron retardation curves, several separate electron spectra for each region were placed in one graph. The dashed line shows the electron retardation curves that have been calculated under the assumption of Maxwellian electron velocity distribution with the bulk velicity values V, density n_e and temperature T_e, presented in Figure. One can see that in the transition region (Fig.3b) electron fluxes, their temperature and density are increased as compared to the solar wind. Fig. 3c corresponds to the region with the least ion fluxes. Here electron fluxes, T_e and n_e are less than in the transition zone, but in contrast to ions, electron fluxes are close (slightly higher) to electron fluxes in the solar wind and are always registered.

On February, 19 the plasma data show that the decrease of registered ion fluxes takes place in the depth of the transition zone behind the bow shock (see, for example, spectra 13, 16, 17), but in this day the solar wind density and pressure were maximum during the whole period of measurements (Table), that could lead to the tightening of the region with minimum ion fluxes to the planet, and to anomalous increase of ion fluxes in it.

It should be noted that a type of ion spectra and the electron retardation curves in the transition zone depends on Sun-Mars-vehicle angle φ . As φ -angle (compare Fig.3b and 3d, for example, a type of ion spectra 10-12 and 19-30 for February, 13 in Fig. 2) is increased, the charged particle temperature and concentration are decreased and the bulk velocity of ions is increased, a type of spectra of charged particles in the transition region is approached to their type in the solar wind. In the transition region with the small angles $\varphi \sim 40^\circ \div 90^\circ$ ion spectra registered from "Mars-5" are not described by Maxwellian particle velocity distribution, that can be seen from Fig.4. Two typical (compare with Fig.2) ion spectra in this region are shown by the solid lines in this Figure. The dashed lines demonstrate computated spectra based on characteristics of the trap for Maxwellian ion velocity distribution with the value of the angle between the trap axis and the bulk velocity vector $\alpha = 12^\circ$, $V = 240$ km.sec^{-1}, $T_i = 1.2\cdot 10^{6\circ}$K (Fig.4a) and $V = 320$ km sec^{-1}, $T_i = 0.4\cdot 10^{6\circ}$K (Fig.4b). Formizano et al. [6] also outlined the difference between the ion distribution function and Maxwellian distribution in the Earth's magnetosheath.

3. DISCUSSION

As in the case of measurements carried out in the near-Earth's space on the satellites with highly-eccentric orbits on the "Mars-5" satellite multuple intersection of the boundaries that divide regions with different plasma properties were observed. For example, in Fig.2 spectra I5, I7 for February 20 belong to the transition region, and spectrum I6 - to the zone with the least ion fluxes; in the same day spectra 27-29 and 32-34, are typical for solar wind, and spectra 30, 3I - for transition region. Let us note that at large φ -angles both boundaries are less sharp.

Results of measurements from "Mars-2", "Mars-3" and "Mars-5" satellites are unsufficient for unambiguous definition of the shape of the obstacle which creates the bow shock. It is possible that its shape versus the time dependent ratio of the solar wind pressure to the planetary magnetic momentum or at the reversal of the magnetic field sign appreciably varies (for example, as it was proposed by Rassbach et al. [7]). Previously from the data of electron component plasma measurements from "Mars-2" and "Mars-3" [8] , due to the absence of other possibilities, the altitude of the obstacle subsolar point was estimated (with the use of gas-dynamical calculations by Spreiter et al. [9]) under the assumption that its form was similar to that of the Earth's magnetosphere and this corresponds to the value of the parameter H/r_o =0.2 in [9] . However, due to peculiarities of the "Mars-5" orbit during a number of its revolutions around the planet the crossings of the obstacle surface at the antisolar part of the near-Martian space (see Fig.I) were twice registered during each revolution. If one consider the obstacle as a body of revolution relative to X -axis, the position of intersection points shows that in most cases the antisolar part of the obstacle surface is widened with the removing from the planet less than the boundary surface of the Earth's magnetosphere tail (see, for example, Fig.I). Therefore in evaluating altitudes of stagnation points of the obstacle forming bow shocks by the gas-dynamical method (these altitudes vary with solar wind pressure variations) seems to be advisably used the data of calculations by Spreiter at al. [9] diminishing the parameter H/r_o comparatively to the value 0.2, corresponding to the Earth's magnetosphere and using for the planet Mars in [8] . In this case at the same values of parameters M_∞ =8 and γ =5/3 the calculated altitude of the obstacle stagnation point increases.

By means of minimizing the sum of squares of distances from the ends of orbital sections, in which points of crossing by satellite of obstacle boundary and bow shock are located to the calculated locations of obstacle boundary and bow shock one can show that the experimental data in Fig.I better correspond to the obstacle with H/r_0 =0.I, i.e. more elongated one than the Earth's magnetosphere. In Fig.I the calculated position of such an obstacle is shown by the solid line. The calculated altitude of the obstacle at the subsolar point h_0 on 2.I3.74 is ~ 800 km (Fig.Ia) and on 2.24.74 h_0~ II00 km (Fig.Ib).

Fig.5 shows parts of orbits of "Mars-2", "Mars-3" and "Mars-5" satellites at which they crossed the bow shock. Characteristics of the plasma obtained at nearest to the planet points of orbital sections shown in this figure, are typical to the transition region and those at most removing points of these parts - to the solar wind. Areocentric distances to the subsolar point of the obstacle and the bow shock (choosen in such a way that a sum of squares of the distance from both ends of the part to the bow shock formed by the flow around the obstacle with H/r_0 =0.I at M_∞=8, γ =5/3 [9] was a minimum) are $(6.3 \pm 1.1) \times 10^3$km and $(5.0 \pm 0.9) \times 10^3$km respectively, i.e. from all crossings of the shock front the mean altitude was evaluated as h_0~ 1600 ± 900 km.

The calculated position of the bow shock is shown by the dashed line in Fig.5. This estimations of h are somewhat higher than those made earlier in [3] (h_0~ I200 ± 800 km) from the same experimental data. It is connected to the fact that in [3] calculations [9] were used of the flow around the obstacle having the shape of the Earth's magnetosphere ($H/r_o = 0.2$). It should be noted once more that calculated altitudes of obstacle stagnation points have to be regarded only as a rough approximations as the data are unsufficient to define the real form of the obstacle, and the value M_∞ necessary to the using of calculations [9] is not known reliably enough.

During four revolutions of the "Mars-5" satellite, the data of which are presented in Table, the device was not switched on at the crossing of the bow shock when entering the transition region (on 2.I4.74 and 2.I5.74 before the entering the transition region there was the interruption in measurements during $\sim 1^h$ which was not indicated in Fig.2). In Tabl. intervals of areocentric distances r and the angles φ are given in which the spacecraft crossed the bow shock as well as a value of the plasma density n, bulk velocity V and solar wind dynamical pressure ρV^2 before the crossing of the bow shock (in measurements with two-minutes intervals between succedingly obtained electron and ion spectra the values averaged over ten-minuts interval are presented). The density and velocity of solar wind ions were estimated from three nearest to maximum readings under the assumption of Maxwellian distribution in the coordinate system moving with the velocity V.

Comparing values of the obstacle altitude h_o at the stagnation point, given in Table (estimated as above with the using of calculations [9] of the flow around the obstacle with $H/r_o = 0.I$ at $M_\infty = 8$, $\gamma = 5/3$) to the solar wind dynamical pressure during measurements with two minutes intervals on

2.I9.74 and 2.2I.74, one can see that h_o decreases with the ρV^2 increase. Evaluations of the obstacle altitude during measurements on 2.I3.74 and 2.24.74 also coincide with this conclusion.

Let us compare in more details the data of plasma and magnetic measurements in the vicinity of Mars. Fig.6 gives the results of simultaneous measurements of plasma ion components on February, I3(continuous series of spectra) and the magnetic field's B_x component taken from the paper by Dolginov et al. [4] . From Fig.6a one can see that when the spacecraft enters the transition region at I6.27. UT the typical change of ion spectra growth of the magnetic field's X-th component's absolute value and increase of its fluctuations are observed. Simultaneously with the sharp decrease of ion fluxes at I6.57 UT magnetic field changes its sign and up to I7.57 UT it remains constant by a sign and fluctuates essentially less than in the transition region. At I7.57 UT ion fluxes are increasing again simultaneously with the magnetic field fluctuation increase (i.e. the satellite enters the transition region). For the comparison the lower part of the Figure gives ion spectra obtained simultaneously in 50 sec from "Mars-7" which was on its way to Mars on February, I3 at a distance of $\sim 5.10^6$km from the planet. These spectra as well as ion spectra obtained from this spacecraft earlier or later the time interval given in Fig.6. have no typical peculiarities, similar to those observed in plasma in the vicinity of planet.

Decrease of the magnetic field fluctuations and independence of B_x sign in the region with the least ion fluxes on the sign interplanetary magnetic field X -component allowed the authors of magnetic measurements [4] to consider this region as a tail of Martian magnetosphere which has been formed by the interaction of solar wind with intrinsic magnetic field of Mars. Note that during the measurements when the magnetic field was weak (February I4 and I5), there is no possibility to separate three characteristic regions in the near Martian space by using magnetic data while this separation is quite distinct from plasma data (see Fig.2).

Let us dwell upon plasma physical characteristics in the antisolar part (tail) of the Martian magnetosphere, data on which are obtained in the first time. When the sharp and large decrease of ion currents in the Faraday cup occures (as compared even to the undisturbed solar wind - Fig.2) the electron trap currents practically do not change (they are even slightly larger as compared to the solar wind - see Fig.3a and 3c), i.e. the plasma density is almost unchanged. This can take place in two cases: either ion flux changes its direction and rather considerably as ion trap acceptance angle is wide or ion flux becomes quasi-isotropic. Let us note that change in the direction of plasma motion or isotropization of ion flux should appreciably influence only ion currents registered, but not electron ones since electron flux is almost isotropic even in the undisturbed solar wind. Ion flux isotropization should decrease ion current registered by the trap by 20 folds as compared to cold ion flux normal to the trap aperture (see instrument performance in [I]). The probability of mean ion energy $\bar{E}$ increase up to the values beyond the energy range of instrument ($E \lesssim 4.I$ Kev) is low since with all variations of ion spectra in the Martian magnetosphere tail (in the cases when they are registered) maximum readings are mainly in the energy interval~200÷500 ev. Let us note that in the moments when there are no readings, the possibility of such an increase of energy E can not be exluded.

We can comment the nature of the plasma in the region under consideration in which least ion fluxes were recorded in the following way. If one uses similarities to the phenomena in the near Earth space, one can suppose that this region can be considered either as "plasma sheet" in the martian magnetosphere tail, similar to one, existing in the central part of the Earth magnetotail [IO, II] , or as "boundary layer" between the transition region behind the bow shock and martian magnetosphere, similar layer, revealed in the tail of the Earth's magnetosphere [II, I2] .

If it is the "boundary layer" then the plasma motion direction in it should be mainly antisolar [II, I2] though near the Earth's magnetotail boundary there was observed deviations of bulk ion velocity from antisolar direction up to angles ~ ± 20° [I3] . In spite of the fact that some decrease of ion bulk velocity is observed from variable ion spectra in the Martian magnetosphere tail, to explain the observed decrease of currents it is necessary to admit either considerable decrease of plasma density in the tail as compared to the undisturbed solar wind (however if it is available then it would be impossible to explain why electron currents in the magnetosphere tail are even higher than in the solar wind) or considerable (by ~30°÷40°) turning of the plasma bulk velocity direction on the magnetopause. It is rather difficult to explain such a phenomena. That is why it seems to us, that this version is not very probable.

If the plasma sheet exists in the Martian magnetosphere tail, then small fluxes registered may be explained by high level of ion isotropy in this zone that is similar to the Earth's magnetotail. In this case there is no contradiction between simultaneous registration of low ion and high electron currents. In Earth's magnetosphere energies of plasma - sheet isotropic ions $\bar{E} > E_o$, where E_o is the ion energy in the undisturbed solar wind ($\bar{E} \sim 6$ kev [I2]), but in the Martian magnetosphere tail $\bar{E} < E$. This difference from Earth' magnetosphere can be caused by the fact that martian magnetic field is relatively small and uncapable to provide proper acceleration of ions.

In [I4, I5] the some data are given on results of ion flux measurements by means of electrostatic analizers with narrow acceptance angle oriented to the Sun (the solid angle of device is $\sim 3 \cdot 10^{-3}$ ster) at the same "Mars-2" and "Mars-3" spacecrafts, at which measurements with wide angle electron detectors were carried out, and at "Mars-5" spacecraft, at which measurements described in present paper were made. In [I4] it is noted that at both day- and night sides of Mars inside the transition region the zone of the hot plasma was detected which is characterized by the essential decrease of the bulk velocity and which is a continuation of the plasma flow behind the bow shock. The solar wind flow around the Mars essentially differs from that at the Earth by the existence of a viscous boundary layer deep in the transition region [I4] . Further in [I4] it is written that the cause of the forming of this layer at upper boundary of the ionosphere or magnetosphere seems to be the viscous interaction with the dissipating outer envelope of Mars and it is noted that this kind of interaction of the solar wind with bodies of the solar system was not earlier observed.

In [I5] it is noted that the data from charged particle electrostatic analysers for measuring of ion fluxes on "Mars-5" confirm conclusions made from the "Mars-2" and "Mars-3" data. It is noted that when penetrating deep into the deceleration region -, the boundary layer, the simultaneous softening and decreasing of ion fluxes was observed in all energy ranges down to the value which was below the instrument threshold sensitivity.

As one can see, the experimental data given in [I4, I5] are not discrepant to results presented in this paper. However, their interpretation causes essential objections.

In contrast to [I4, I5] it is known that in the solar wind - Earth interaction the boundary layer also appears (see, for example, [II, I2] which is characterized by the gradual decreasing of the ion bulk velocity.

In [5] it is shown that during the transition of "Prognoz" satellite from the magnetosheath into the Earth's magnetosphere the decreasing of the ion bulk velocity, the softening of spectra and the decreasing of ion fluxes was very often observed (including magnetopause sections close to the subsolar point), i.e. the same effects on the ground of which authors of [I4, I5] make the conclusion about an essential difference between the character of the solar wind flow around the Mars and around the Earth. Evidently near the Earth's magnetopause the magnetosheath plasma can not experience the viscous interaction with the dissipating outer envelope of the planet. So for the explanation of the bulk velocity decreasing and spectrum softening observed near the obstacle boundary next the Mars it is not necessary to attract conceptions on "viscous interaction" as these effects fully agree with the magnetic origin of the near-Martian obstacle.

Arguments in favour of the point that the region of least ion fluxes in the Martian magnetospheric tail crossed by "Mars-5" is some similarity of the plasma sheet in the Earth's magnetosphere tail and those against its interpretation as a boundary layer were presented above. As the authors of I4,I5 did not use the data of simultaneous measurements of the electron component of the plasma and due to narrowness of angular response of their instrument they could not take into account the mentioned considerations.

4. CONCLUSION

So in addition to previously published [2, 3] data on near-Martian plasma, the data presented in this paper confirm the conclusion made earlier about the magnetic origin of the obstacle creating the near-Martian bow shock. A lack of an experimental data does not allow to define precisely the form of the Martian magnetosphere. The most part of the data from "Mars-5" are in favour of the supposition according to which in the considerable number of cases the obstacle shape corresponds to calculated one in [9] for the value of the paremeter H/r_o =0.I.

However, one must bear in mind that in the absence of the data on the magnetic field at low altitudes and at the planet surface the crucial proofs that the discussed magnetic field is the intrinsic magnetic field of Mars can, to our opinion, give only the study of the simultaneous data on magnetic field variations in the interplanetary space and near the planet (see [4]).

FIGURE CAPTIONS

Fig. I. "Mars-5" satellite orbit

a) February, I3, 74

b) February 24, 74

Fig. 2. Ion spectra registered from "Mars-5" during near-planetary measurements.

Fig. 3. Electron spectra in the regions with different plasma properties on February, 2I

a) in the solar wind

b) in the transition region ($\varphi \sim 40^\circ \div 90^\circ$)

c) in the region with least ion fluxes

d) in the transition region ($\varphi \gtrsim$ I30°)

Fig. 4. Comparison of registered and calculated ion spectra in the transition region.

Fig. 5. Mars satellite intersection of the bow shock.
"Mars-2": I-I2.I7.7I; 2-0I.08.72; 3-05.I2.72
"Mars-3": 4-I2.I5.7I; 5-0I.09.72; 6-0I.2I.72; 7-0I.2I.72
"Mars-5": 8-02.I3.74; 9-02.I9.74;I0-02.2I.74;II-02.24.74

Fig. 6. Comparison of simultaneous data of plasma and magnetic field measurements.

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TABLE

Date, I974	Time, UT	r,IO^{3}km	φ^{o}	n,cm^{-3}	V,km.sec^{-1}	h_{o},km	IO^{-8}dn,cm^{-2}
2.I3	I6.I7-I6.27	5,6-5,2	40-55	9	455	950-500	3,I
2.I9	2I.I9-2I.2I	5.5-5,4	44-48	II	480	850-700	4,2
2.2I	22.53-22.55	5,8-5,65	39-42	I,8	640	II00-950	I,2
2.24	00.37-00.47	5,85-5,3	35-47	2,5	620	II50-650	I,6

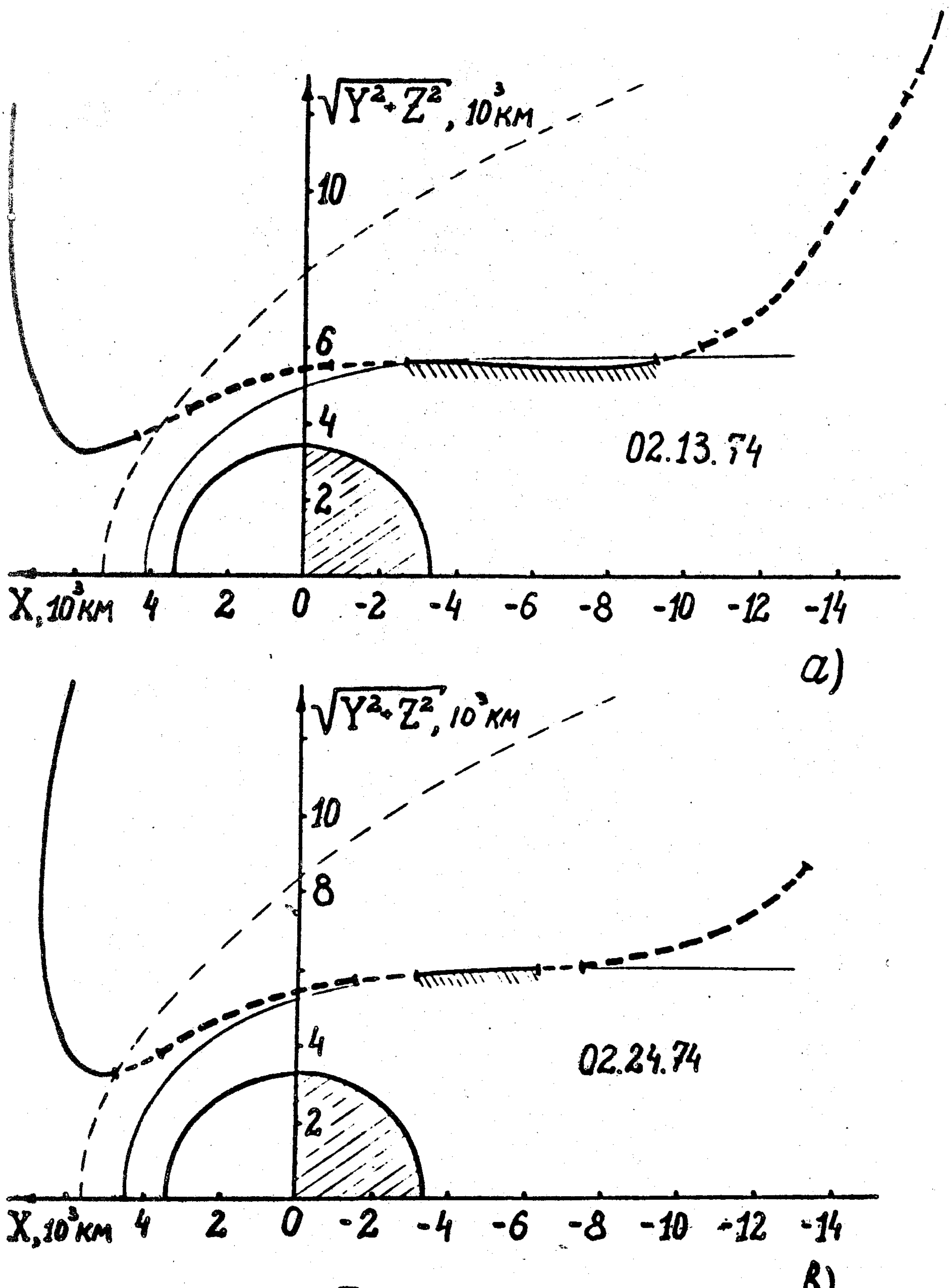

$\sqrt{Y^2+Z^2}$, 10^3 км
10
6
4
2
02.13.74
X, 10^3 км
4
2
0
-2
-4
-6
-8
-10
-12
-14
a)
$\sqrt{Y^2+Z^2}$, 10^3 км
10
8
4
2
02.24.74
X, 10^3 км
4
2
0
-2
-4
-6
-8
-10
-12
-14
в)

Fig. 1

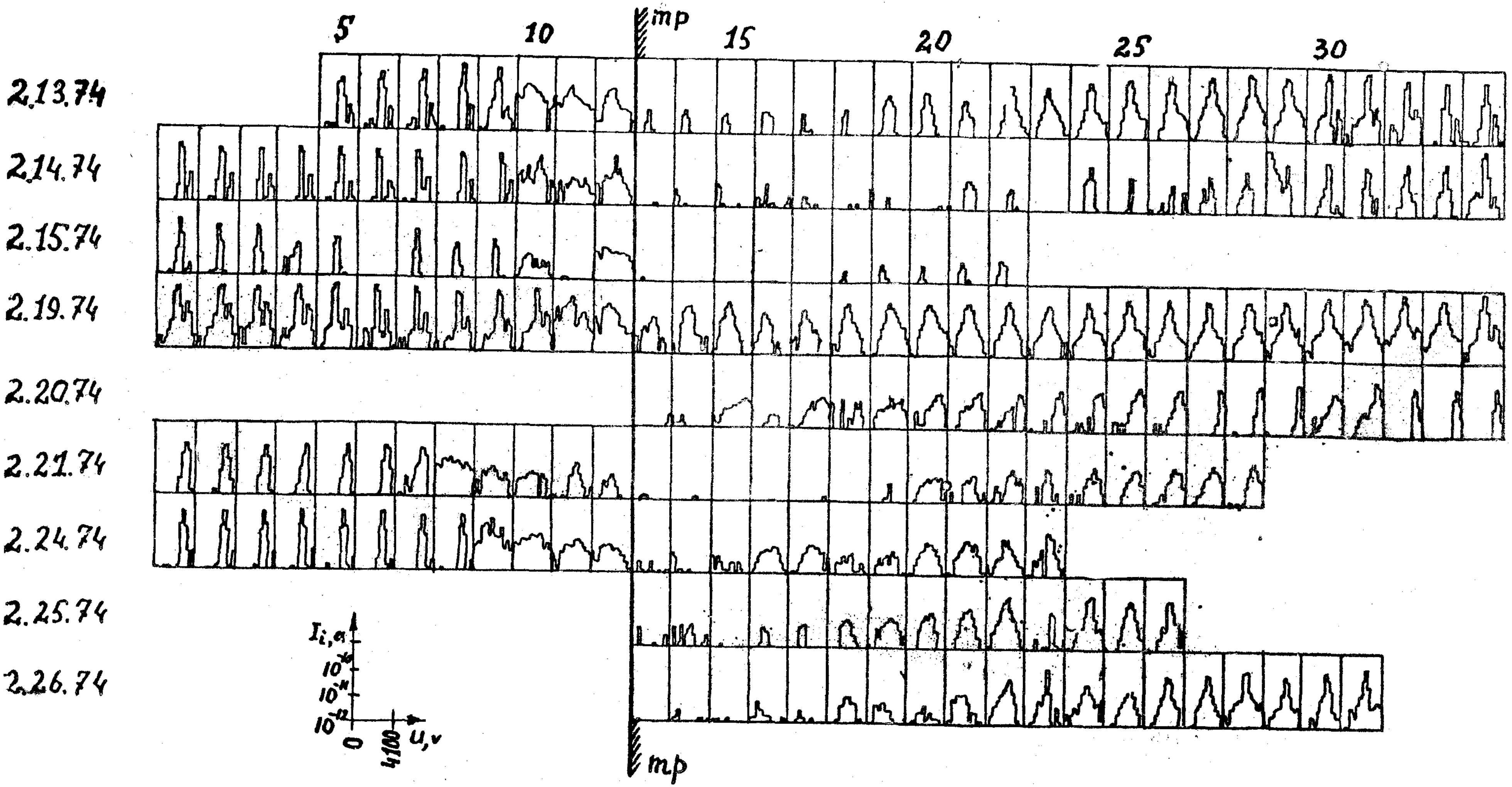
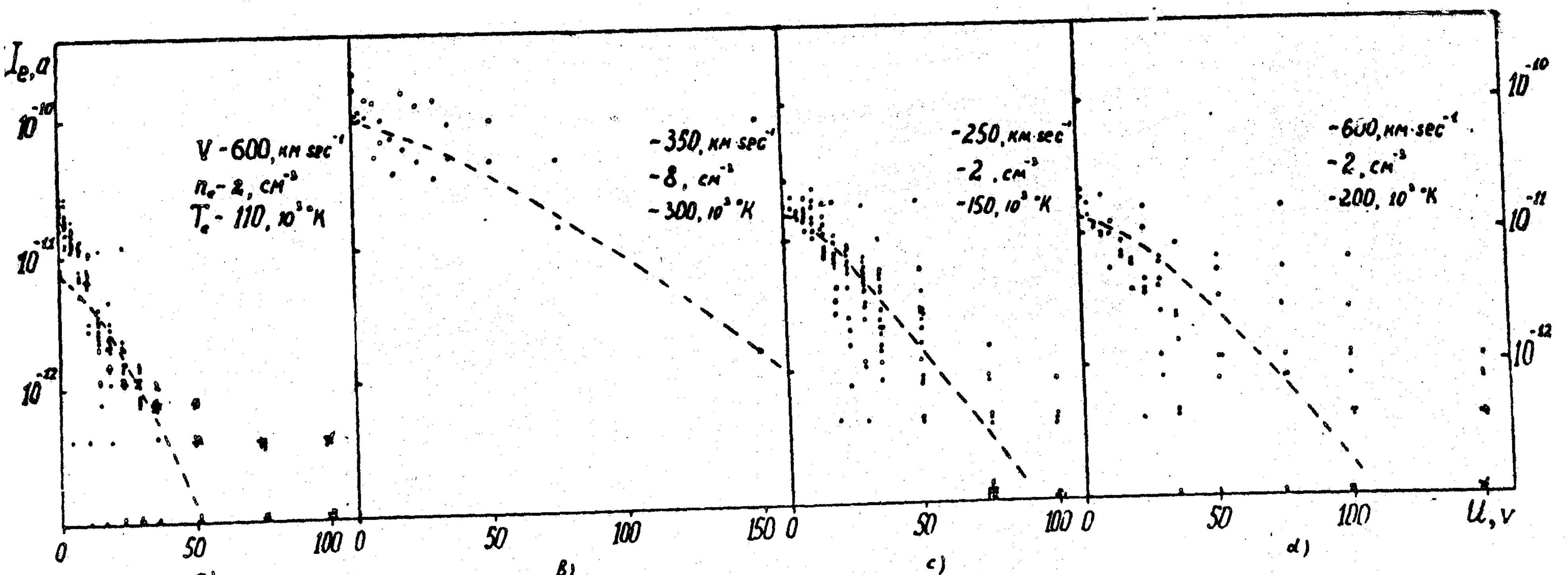

5
10
mp
15
20
25
30
2.13.74
2.14.74
2.15.74
2.19.74
2.20.74
2.21.74
2.24.74
2.25.74
2.26.74
I_i, a
10^{-10}
10^{-11}
10^{-12}
0
4100
U, v
mp

Fig. 2



I_e, a
10^-10
10^-11
10^-12
V - 600, км sec^-1
n_e - 2, см^-3
T_e - 110, 10^3 °K
-350, км sec^-1
-8, см^-3
-300, 10^3 °K
-250, км sec^-1
-2, см^-3
-150, 10^3 °K
-600, км sec^-1
-2, см^-3
-200, 10^3 °K
0
50
100
150
U, v
a)
в)
c)
d)

Fig.3

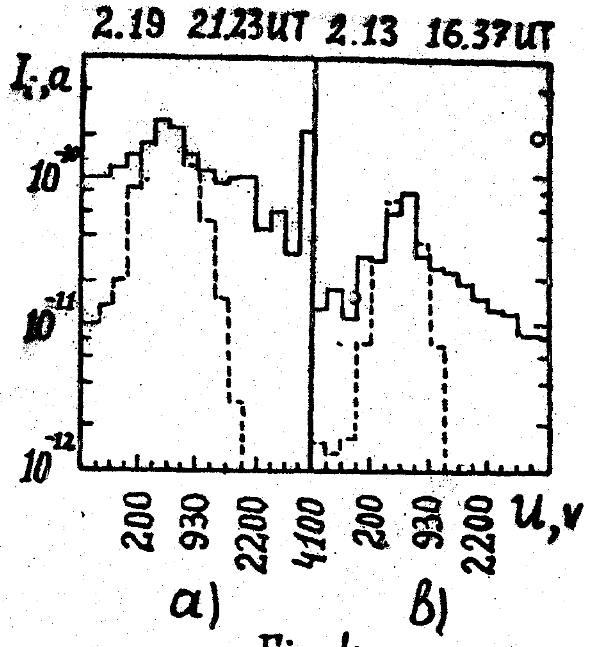

2.19 21.23UT
2.13 16.37UT
I_i,a
10^-10
10^-11
10^-12
200
930
2200
4100
200
930
2200
U,v
a)
b)

Fig. 4

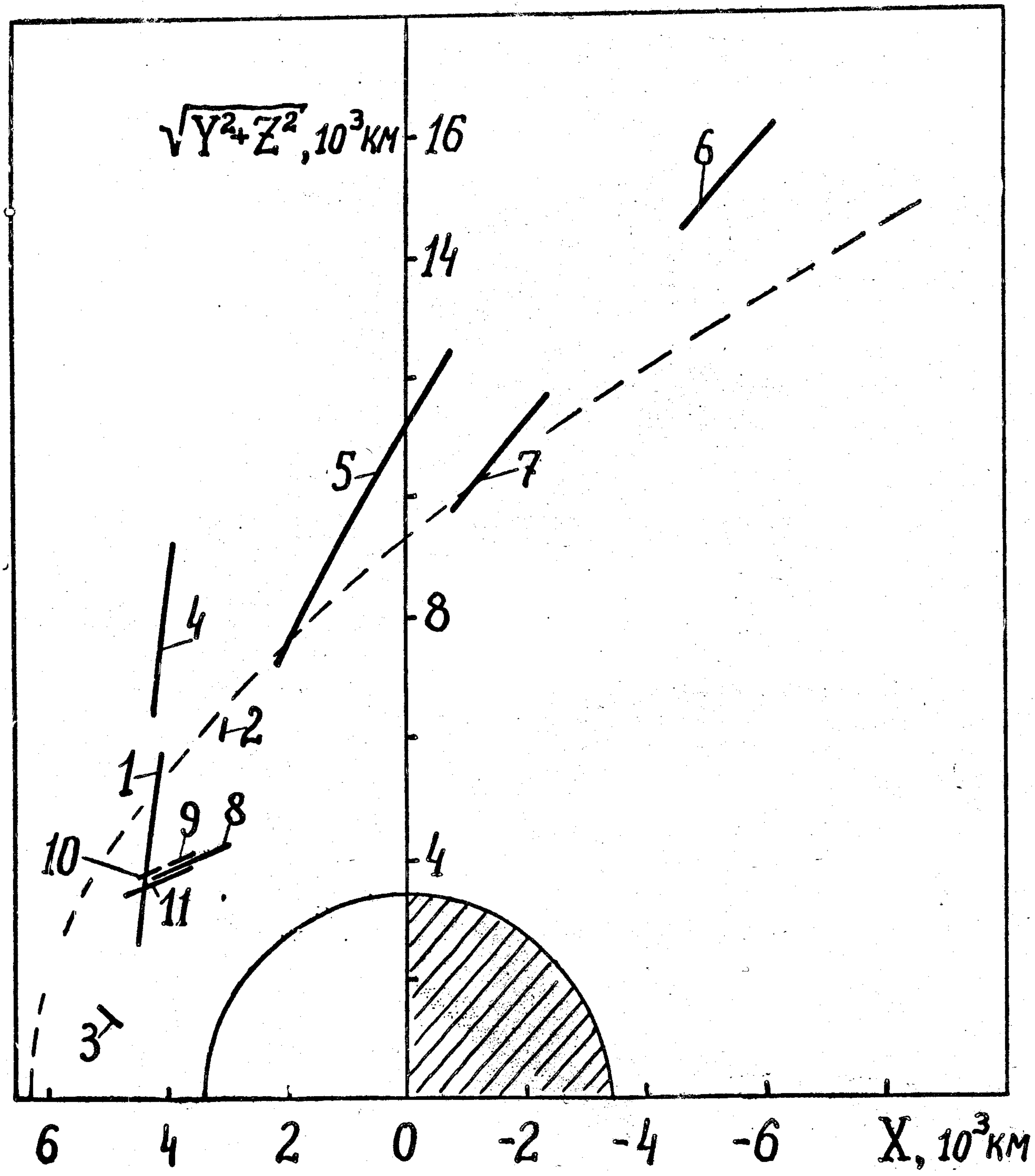


Fig. 5

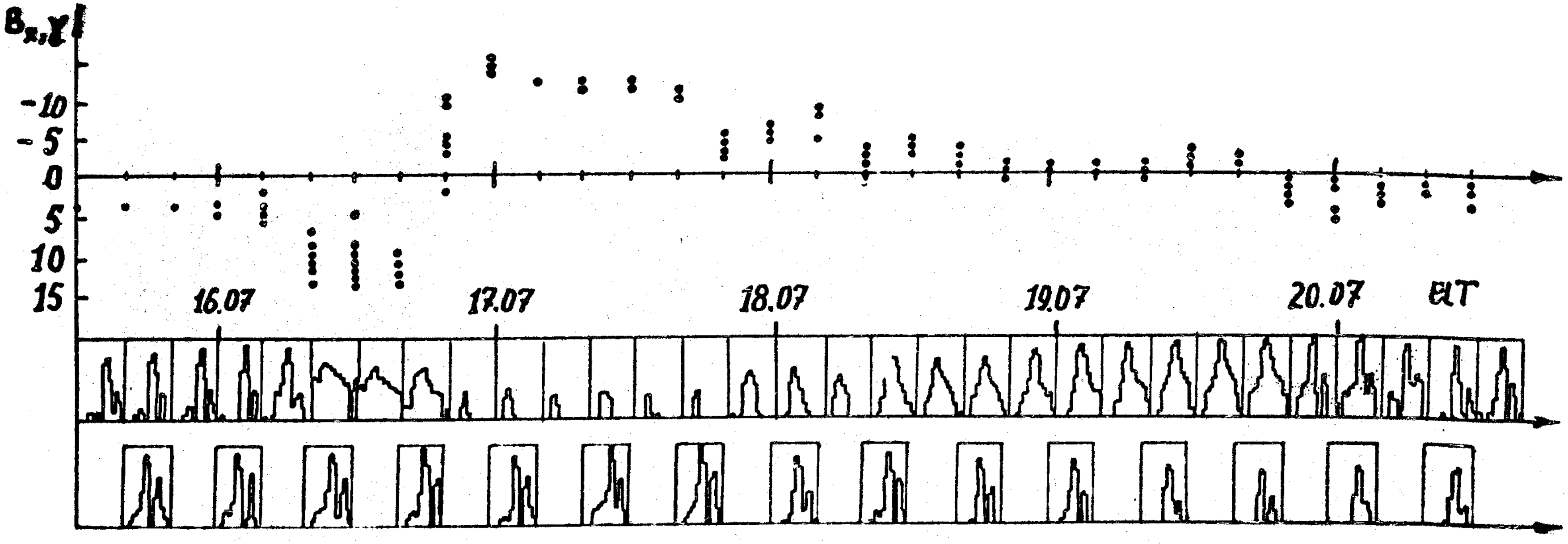


Fig. 6