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V.N.Smirnov, O.L.Vaisberg, S.A.Romanov,
J.A.Slavin, C.T.Russel, D.S.Intriligator

THREE-DIMENSIONAL SHAPE AND POSITION OF VENUS'S BOW SHOCK

1981

ABSTRACT

The results of determination of the shock front position near Venus according to the Venera-9, 10 and Pioneer-Venus data are compared. It is shown that the presence of an asymmetry of the three-dimensional form of the shock wave and its position in the ecliptic plane makes possible the explanation of the recently obtained discrepancy in determining the front position based on the data from the Venera and Pioneer-Venus data. Both the identified asymmetry of the shock wave form and the rotation of its axis of symmetry in the ecliptic plane additionally at an angle of 7.5° are probably associated with the interplanetary magnetic field influence.

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The position and the shape of bow shock near Venus have been recently considered in [1-7] using the measurements of plasma and magnetic field made on-board the Venera-9 and -10 satellites and the Pioneer-Venus Orbiter. It has been noted in [4-6] that the shock front near Venus based on the Pioneer-Venus data obtained during 1978-1979 is at a significantly larger distance from the planet than that determined from the data of the Venera-9, -10 measurements obtained during 1975-1976. According to the Venera-9, -10 data the distance at the subsolar point of the shock was estimated as equal to 1.27 radii of Venus, R_V [6], and from the Pioneer-Venus data it was estimated as 1.37 R_V [5] and 1.47 R_V [7].

Two explanations were suggested for the established discrepancy in the shock position. One of them is based on the result of [1] where an anisotropy of the shock near Venus was revealed associated with the interplanetary magnetic field orientation. The analysis of the Venera-9, 10 shock crossings, in a frame of reference with the transversal component of the interplanetary magnetic field (IMF) as one of the axes showed that in the direction perpendicular to this IMF component the Venusian shock is by 2,200 km farther from the planet near its terminator than in the direction along the transversal component of IMF [1]. This result was obtained using 17 crossings of shock for which the IMF orientation was known.

The Pioneer-Venus orbiter crosses the shock front at high planetocentric latitudes, whereas the Venera-9, -10 orbits cross the shock front at lower latitudes. Since most frequently the IMF vector lies close to the ecliptic plane the front asymmetry resulting from the IMF orientation should lead to the more distant, on an average, position of the shock at high planetocentric latitudes.

Examining a much greater amount of experimental data Slavin et al., [3,4] did not find a dependence of the shock position on the IMF orientation. It should be noted that the IMF variations increase while satellite approaches the shock wave that creates difficulties in determining the IMF orientation.

Slavin et al., [3-5] suggested an alternative explanation of the differences in the determined positions of the shock according to the Venera-9, -10 and Pioneer-Venus data, namely that they are associated with variations of the Sun's ultraviolent radiation during 11-year cycle of solar activity and its influence on the properties of the obstacle to the solar wind flow. This explanation, however, meets with certain difficulties since the observations of the ionospheric characteristics near the ionization maximum and especially of the ionopause height in the periods when the Soviet and American satellites performed measurements do not reveal any significant changes in the state of the ionosphere [8-10].

The Pioneer-Venus crossings of the shock front near Venus were analyzed within solar-zenith angles from 60° to 120° [5] and 45° to 135° [7]. 172 crossings were used in [5] and even more in [7]. 62 crossings were identified in the Venera-9, -10 data in [6] but within a wider range of solar-zenith angles

(from 25° to 150°).

Assuming that the difference in determining the position of the shock (according to the data of two satellites) is associated with its spatial position but not with the long-periodic time variations, the form of the shock front appropriate to its equatorial and polar cross-sections was obtained in [6] using combinations of the Venera-9, -10 and Pioneer-Venus crossings. The shock front form thus obtained, on the one hand, does not contradict to the presence of the asimuthal asymmetry, on an average, and on the other hand does not agree with the conclusions of [5] about the absence of the front position dependence on the IMF orientation.

In this paper we try to make a further analysis and a comparison of the Venera-9, -10 and PVO data on the shock position near Venus in order to find out the causes of the existing discrepancies and to determine more accurately the position and the shape of the shock.

Fig.1 shows the shock front crossings, 172 PVO shock crossings [5] and 54 Venera-9, -10 crossings [6]. The distance to the shock front in the terminator plane amounts to 14.4 and 12.8 thousand km based on the PVO and Venera-9,-10 data, respectively, i.e. the mean Venera-9, -10 shock location is closer to the planet by 11% compared to PVO one. The difference between Venera-9,-10 and PVO shocks reported by [4,5] is related to the fact that the comparison was made with Venera-9, -10 shock crossings from [2] where no solar wind aberration was not taken into account.

Figure 2 gives the shock front crossings (PVO and Venera-9 and -10 data) being only on the morning side of the planet that corresponds to PVO covered SZA range. It can be seen first, that compared with Fig. 1 the

difference in the position of two sets of points decreased significantly and, second, the curve describing the mean PVO shock is somewhat higher than the PVO morning crossings. In order to analyze the terminator cross-section of the shock in more details all 172 PVO crossings of the shock were projected to the terminator plane along the best fit curve given in [5] , (curve 3, Table 1), and Venera-9, -10 crossings were projected along best fit curve given by [6] (curve 2, Table 1). In the latter case only those crossings were used which are within the same range of zenith angles as PVO crossings. Fig. 3 presents the so obtained shock projections in the terminator plane. It can be seen from Fig. 3 that while the Venera-9, 10 shock crossings on the dawn ($Y_{SE} < 0$) are significantly closer to the planet' center than the PVO ones on the dusk they are located approximately at the same planetocentric distances. The distribution of points in the aberrated terminator plane in the X'Z' coordinate system suggests that the shock surface is rotated around Z'-axis at some additional angle and the center of the surface trace describing the shock front is shifted in the terminator plane along the positive direction of Y'-axis. PVO and Venera-9, -10 shock crossings projected onto the terminator plane were approximated by a least-square fit circle. The radius of this cirle is equal to R = 14.51±1.24 thousand km and its center is displaced from the origin of coordinate system by 1.98 thousand km towards $+Y'_{SE}$ - axis (this circle is shown en Fig. 4 by the dotted line). The approximation of the PVO crossings alone by a circle leads to the similar result: R = 14.52± 1.27 thousand km and the displacement is 1.40 thousand km.

As a next step the shock crossings of Venera-9, -10 and the ones of PVO were approximated separately by the conic sections

with their focuses in the planet center and symmetry axes rotated relative to the polar axis at φ_0-angles.

$$r = \frac{p}{1 + \varepsilon \cos(\varphi - \varphi_0)} \qquad (1)$$

Here, the sign of φ-angle was taken positive for the corssings at the upper side ($Y'_{se} > 0$). Three-dimensional coordinates of the shock crossings were used. Table 1 gives parameters of the obtained curves.

It is seen from this Table that the dusk-dawn asymmetry is recognized in the Pioneer-Venus data as well as in the Venera-9,-10 data, being more apparent in the latter case. This should be expected for the crossings lying near the ecliptic plane if the shock surface is rotated around Z'-axis by some angle additional to the aberration one. Thus both sets of data confirm the presence of the dawn-dusk asymmetry of the shock.

To describe the shape of the shock front more accurately, satisfying the two sets of data representing near-equatorial (Venera-9,-10) and meridional (Pioneer-Venus) cross-sections of shock, the best fit second order surface was calculated. The surface equation was taken symmetrical relative to the ecliptic plane.

$$a_{11}x^2 + a_{22}y^2 + a_{33}z^2 + a_{12}xy + a_{14}x + a_{24}y + a_{44} = 0 , \qquad (2)$$

where X, Y, Z are the coordinates of the shock front surface (R_V) in the solar-ecliptic coordinate system rotated by the solar wind aberration angle.

Approximating surface was found by the minimization of the sum of squared distances of crossings to the surface along the normals to it. The distance from a point to the surface

was calculated by the iteration method. Table 2 gives the surface coefficients (2) obtained from 226 shock crossings. The coefficient a_{22} in Eq.(2) was taken equal to 1.

Table 3 presents the crossings of the so found surface with the axes of the coordinate system as well as some parameters of this surface: ε_{xz} and ε_{yz} are the eccentricities of the cross-sections in the plane X'Z' and Y'Z' respectively; φ is the angle between the symmetry axis of the surface and X'-axis; A_z and B_y are the ellipsoid semi-axes in the Y'Z' plane.

The solid line in Fig.3 shows the cross-section of the determined surface by the Y'Z' plane. It can be seen that it describes both the Venera-9, -10 points and the PVO points projected onto the terminator plane rather well.

Fig.4 illustrates the cross-section of this surface by the X'Y' plane together with the projected onto this plane the Venera-9, -10 shock crossings for which $z \leq 5$ thousand km. Also given are the shock crossings of earlier Venera-4 and Venera-6 missions [11,12]. The subsolar point distance, X'_+, and the distance at dawn terminator, Y'_- agree well with the values obtained in [6] for a second-order symmetric 2D-curve. The distance at the dusk terminator (Y'_+), however, exceeds by about 2,000 km that at the morning terminator, being close to the value at the terminator in the X'Z' plane. It can also be seen that Venera-4 and Venera-6 shock crossings [11,12] are in reasonable agreement with both the average curve and individual shock crossings of Venera-9 and -10.

Fig.5 shows the cross-section of the shock surface in the X'Z' plane together with the PVO shock crossings projected

into the plane by rotation about the X'-axis. The distance to the shock front at the terminator in the X'Z' plane, equal to 14,380 km (2.38 R_V), is very close to the value obtained in [5] where PVO crossings were approximated by a conic section.

The histogram of deviations from observed shock crossings to the model surface along the normals to the latter is given in Fig.6. Interesting is the fact that the r.m.s. deviation, which is 0.16 R_V (960 km), in the 3-dimensional case is slightly less than the value 0.17 R_V [5] obtained for the 2-D conic section.

Thus the derived three-dimensional shock model can explain divergencies and contradictions between earlier estimations of the location and shape of the shock front, revealed from Pioneer-Venus Orbiter and Venera-9, -10 data. The explanation is the asymmetric shape of the shock front, rotated by about 7° in the ecliptic plane, in addition to the aberration angle. Relatively small number of the shock crossings on the dusk side determined from Venera-9, -10 data recorded in low temporal resolution telemetry mode may cast some doubts on the accuracy of the obtained deflection angle. Yet the analysis of dawn-dusk pairs of the shock crossings occured on the same sattelite orbit behind the planet confirms the obtained result (these pairs are marked in Fig.4). Time intervals between two crossings of the shock were about 1^h15^m. It is seen that these individual crossings agree reasonably both with all other crossings and the average curve.

Using the value of rms-deviation and geometrical considerations we evaluate an error of the rotation angle determination as ±1°. So the asymmetry of the shock and its value seem to be reliably established.

As was first shown by Walters [13] from the analysis of an oblique MHD shock the existence of the interplanetary magnetic field should lead to an additional deflection of the solar wind flow on the shock front and, as a consequence, to a rotation of its symmetry axis relative to the direction of the solar wind flow. He found that for the subsolar point of the terrestrial shock the flow deflection angle should be about 7.5°. There have been indications that this effect does exist but no unambiguous confirmation of it has been found yet [14, 15].

Following Walters' idea we may estimate this effect using the expression for the deflection angle on the perpendicular MHD shock [16]:

$$tg\,\alpha = \frac{\rho_1/\rho_0(\rho_1/\rho_0 - 1)\,tg\,\gamma_0}{M_A^2(1+tg\,\gamma_0)+\rho_1/\rho_0}, \qquad (3)$$

where ρ_1/ρ_0 is the density jump on the shock front, M_A is the Alfven Mach number, γ_0 is the angle between the normal to the shock front and the magnetic field vector.

Assuming $\rho_1/\rho_0 = 4.0$ and the conditions for Venus' orbit [5]: $M_A = 7.2$ and $\gamma_0 = -35°$ we get from (3) the angle $\alpha = -6°$ in the subsolar point which is close to the obtained value.

An attempt was made to check the relation (3) for individual pairs of shock crossings. To do this, pairs of shock crossings recorded during one Venera-10 pass near the planet (Fig.7) have been compared with calculated positions of a shock wave rotated in the ecliptic through an angle determined by the relation (3). As is seen from Fig.7, observations agree satisfactorily with the theoretical predictions.

The Venera-9 and -10 data demonstrated shock front position dependence on the angle between the normal to the front and the IMF direction [17]. This result was interpreted in [17] as a shock anisotropy, caused by different velocities of MHD wave propagation. The effect we discuss here should lead to a similar result. Fig.8 illustrates dependence of the shock distance at the terminator on the angle between the normal to the front and the IMF direction, based on the data of [17]. We must mention that the average IMF direction is determined in [17] for a 45^s interval, including a shock structure. Fig.9 distinctly shows the IMF effect on the shock front location.

The shape of the shock thus obtained is slightly asymmetric in the terminator section (see Table 3), with a ratio of semiaxes in the Z' and Y'-directions of 1.05 and their difference equal to 650 km; this asymmetry is by a factor of 3 less than the value obtained earlier [1, 17]. The key effect is the dawn-dusk asymmetry of about 2,000 km in planetocentric distances.

The results of this paper have some similarities with the recent paper of Formisano [18] who investigated the three-dimensional model of the near-Earth shock and the dependence of its position and shape on the solar-wind conditions, in particular on the IMF orientation and the Alfven Mach number, M_A. It was shown in [18] that the symmetry axis of the near-Earth shock, the position and shape of which was determined from the shock crossings normalized to the dynamic pressure of the solar wind, deviates, on the average, by 8.9° from the sunward direction. As the aberration angle due to the Earth's orbital motion is about 4°, the additional rotation angle due to IMF existence is about 5°. According to [18] this result agrees both with

the theoretical predictions (Eq.3) and with the earlier experimental results of Hundhausen et al. [14] who studied the pattern of the plasma flow in the transition region near the Earth. Comparison of the results of this paper with those obtained in [18] for the near-Earth shock emphasizes the following circumstance. Contrary to the Venusian shock, in the case of the near-Earth shock the effect associated with the dawn-dusk asymmetry is revealed only for crossings normalized to the dynamic pressure of the solar wind. This is possibly due to the different nature of obstacles near the two planets. According to [5,7] the near-Venus shock position and its variations correlate but weakly with the dynamic pressure of the solar wind and with ionopause height variations, unlike the near-Earth shock and magnetosphere [19]. It appears that the shock near Venus is automatically 'normalized' to the dynamic pressure of the solar wind.

Thus, due to the IMF effect, the near-Venus shock is non-symmetric relative to the direction of solar wind flow, and its axis is additionally rotated by about 7°, on the average, in the direction of solar wind aberration. The analysis of the position of the shock front as a function of the angle between the normal to the front and the IMF vector shows that the effect is indeed observed not only as an average one but also for individual crossings of the shock.

Since this effect follows from the conditions of flow velocity refraction at the MHD shock front we may also expect an asymmetry in a pattern of the plasma flow around the planet and possibly in the shape of the abstacle forming in the plasma flow around the ionosphere of Venus.

Table 1

Satellite	N	$p \times 10^3$ km	ε	φ_0	$r_0 \cdot 10^3$ km	$r_+ 10^3$ km	$r_- 10^3$ km
Venera-9, -10 crossings	52	13.70 (2.27R_V)	0.83	-4.6°	7.50 (1.24R_V)	14.70 (2.43R_V)	12.9 (2.13R_V)
Pioneer-Venus crossings	172	14.30 (2.37R_V)	0.69	-2.7°	8.47 (1.4R_V)	14.80 (2.45R_V)	13.8 (2.29R_V)

Table 2

a_{22}	a_{11}	a_{33}	a_{12}	a_{14}	a_{24}	a_{44}
1.0	0.190	0.912	0.214	3.82	0.329	5.156

Table 3

$X_+ \times 10^3$km	$Y_+ \times 10^3$km	$Y_- \times 10^3$	$Z_+ \times 10^3$km	$\varphi°$	ε_{xz}	ε_{xz}	$A_z \times 10^3$km	$B_y \times 10^3$km
7.68 (1.27R_V)	14.77 (2.44R_V)	-12.78 (2.11R_V)	14.38 (2.38R_V)	-74°	0.89	0.30	14.42 (2.38R_V)	13.77 (2.28R_V)

Figure Captions

Fig. 1 Crossings of the shock front according to the Pioneer-Venus (crosses) and Venera-9, -10 (circles) data in the solar ecliptic system of coordinates. The average position of the shock obtained in [5] from the PVO crossings is also shown.

Here and in the following Figures all the crossings are allowed for solar wind aberration.

Fig. 2 The same as in Fig. 1 but only the crossings are given for which $Y' < 0$: I - the curve obtained in [5] and describing the average of PVO crossings distribution; II - the curve describing the average of Venera-9,-10 crossings distribution [6] .

Fig. 3 Crossings of the shock according to the PVO and Venera- 9, -10 data projected onto the terminator plane, Y'Z', (see text). The dotted line is an approximation of the obtained points in the terminator plane by the circle with the center shifted along the positive direction of Y'-axis. The solid line is the trace of the obtained three-dimensional surface of the shock onto the terminator plane (see text).

Fig. 4 Crossing of the surface describing the shock front with the ecliptic plane, X'Y'. The Venera-9, -10 shock crossings at $Z' < 5$ thousand km were projected onto the X'Y' plane by rotation around X'-axis. Each pair of crossings with numbers 1-3 were obtained during one pass of the Venera-10 satellite. B4 and B6 show the shock crossings of the Venera-4, -6 probes.

Fig. 5 Crossing of the three-dimensional shock surface with the plane X'Z'. The PVO shock crossings (crosses) are shown projected onto the X'Z' plane by rotation around X'-axis.

Fig. 6 Histogram of the distribution of the deviations, d_n, of the shock crossings from the average shock surface, along the normals to it. The mean value of the deviation $d_n = 0.12\ R_V$: the mean-square value $d_n = 0.16.\ R_V$

Fig. 7 Dependence of the planetocentric distance of the model shock at the dawn and dusk terminator on the IMF orientation. Circles denote the distances of the shock front for one pass of the Venera-10 satellite, open circles - dawn crossings, filled circles - dusk terminator.

Fig. 8 Dependence of the planetocentric distance of the shock front (Venera-9, -10 data) on the angle between the magnetic field and the normal to the front, Ψ.

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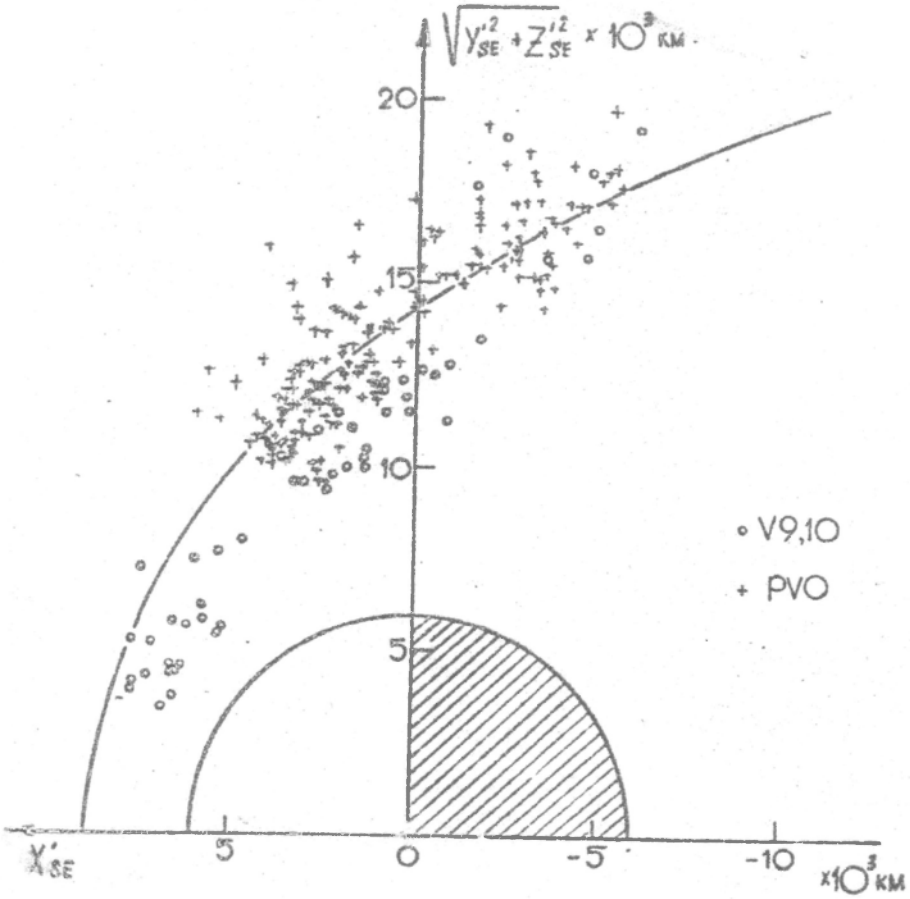
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Fig.1

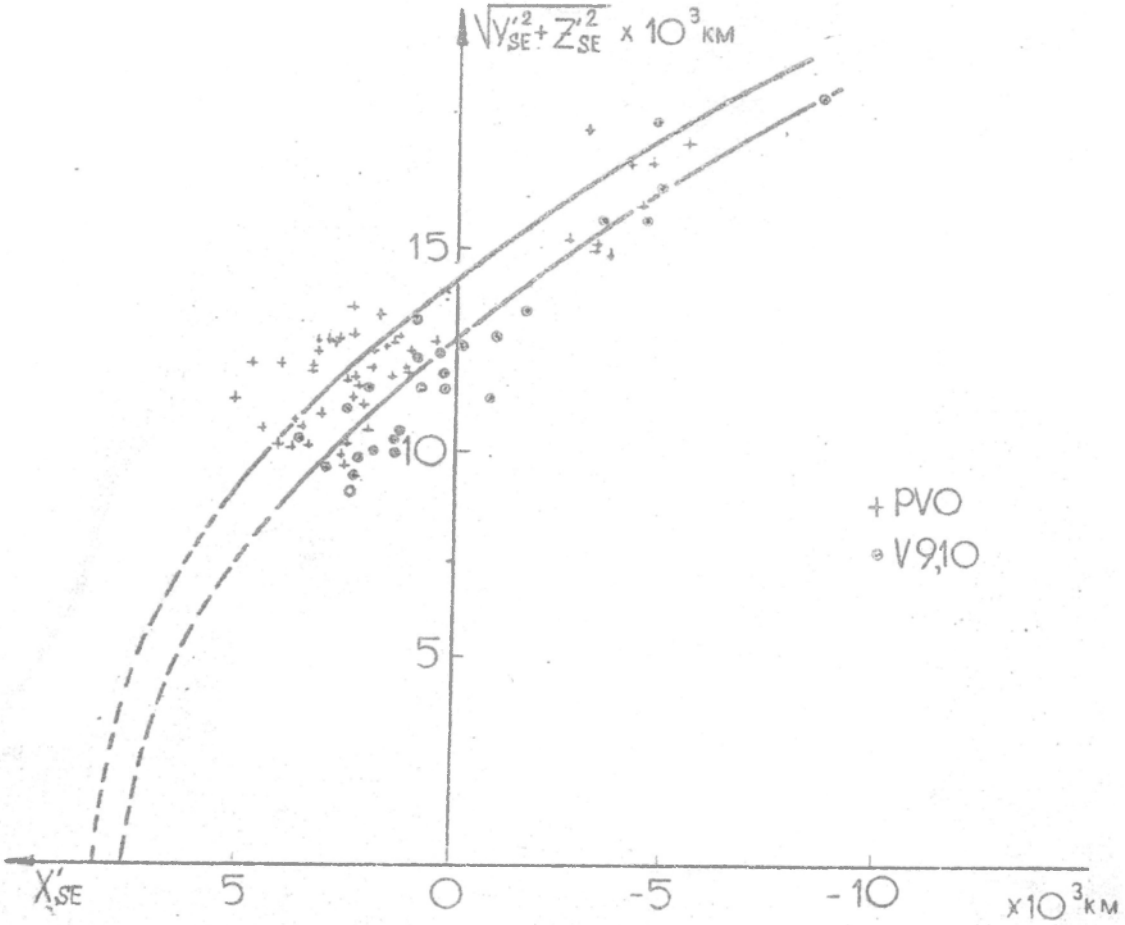
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Fig. 2

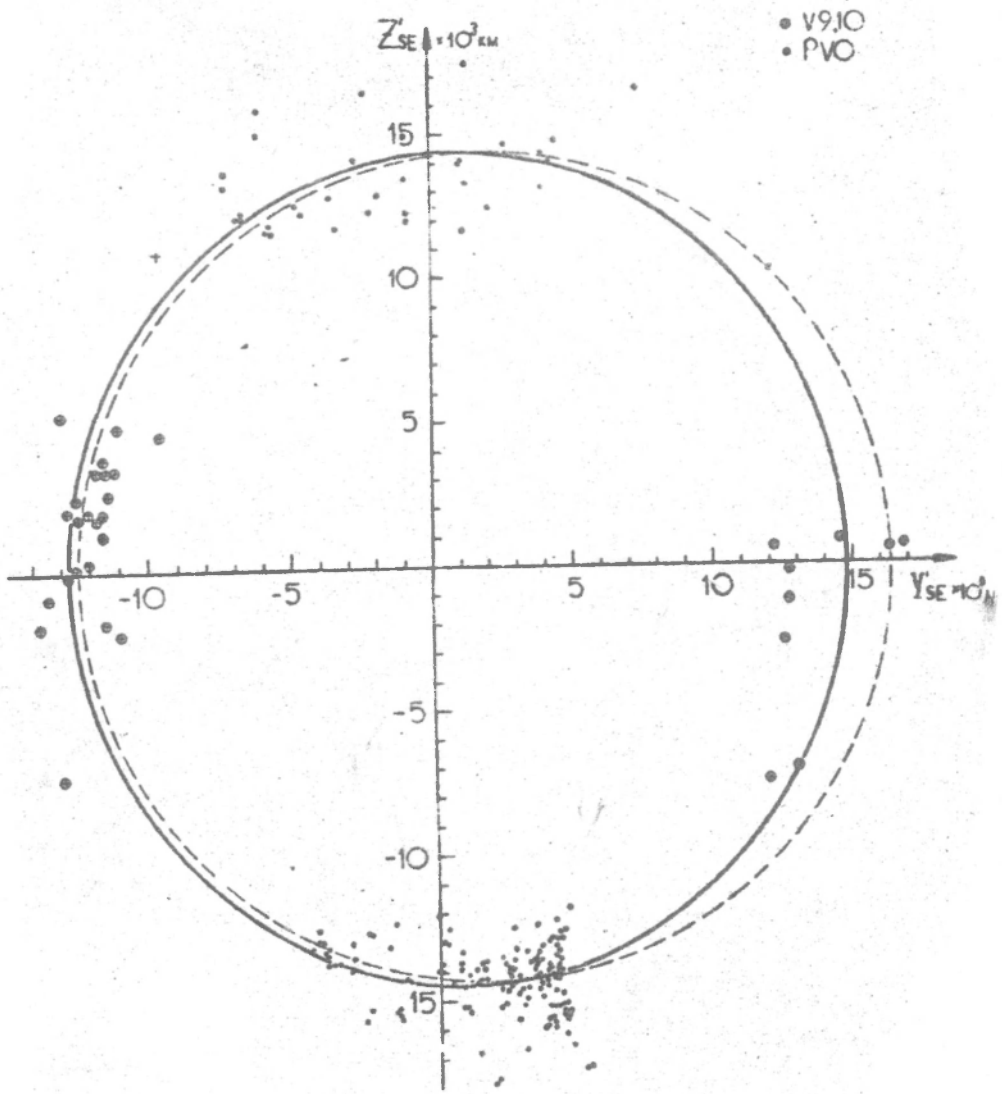


Fig. 3

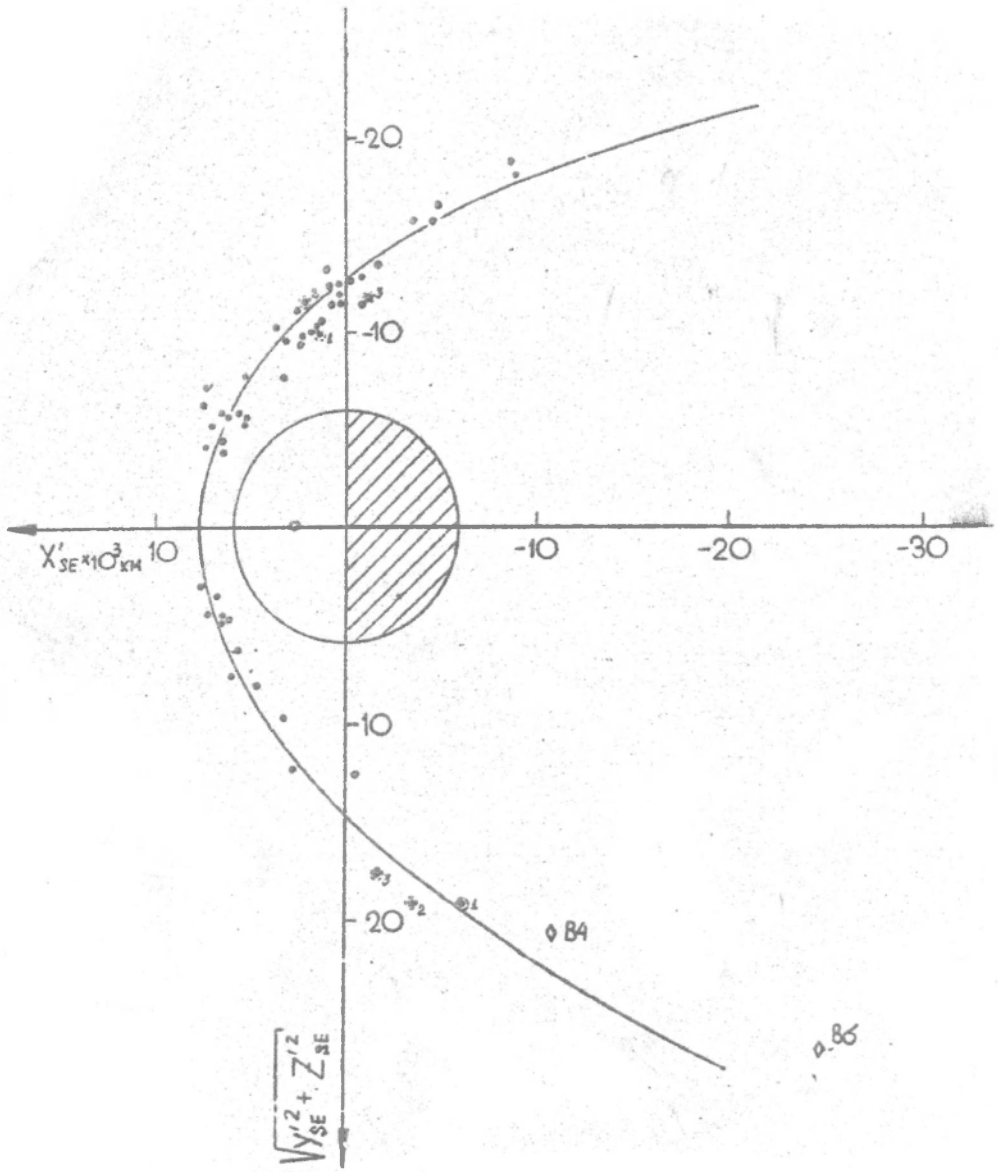
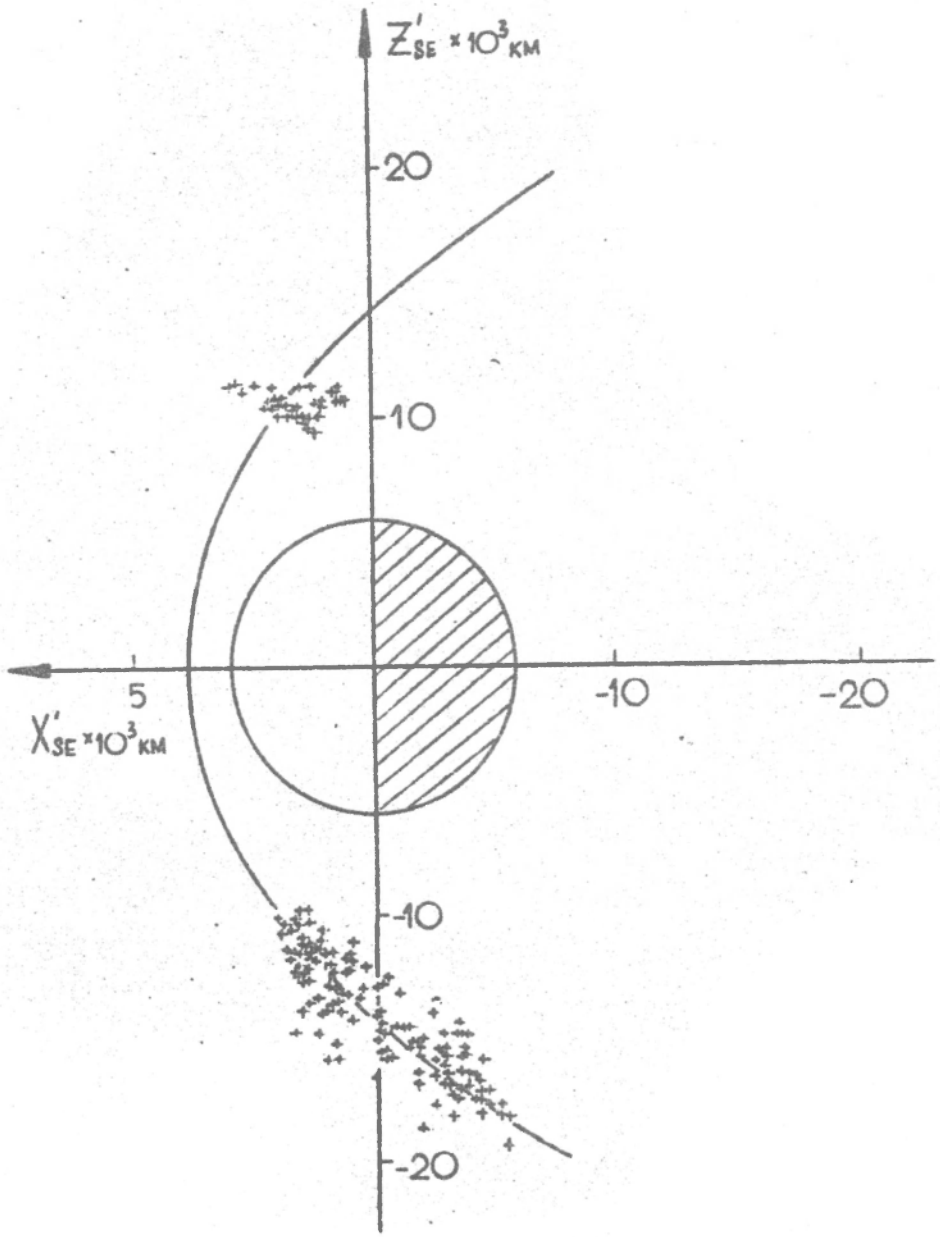


Fig. 4



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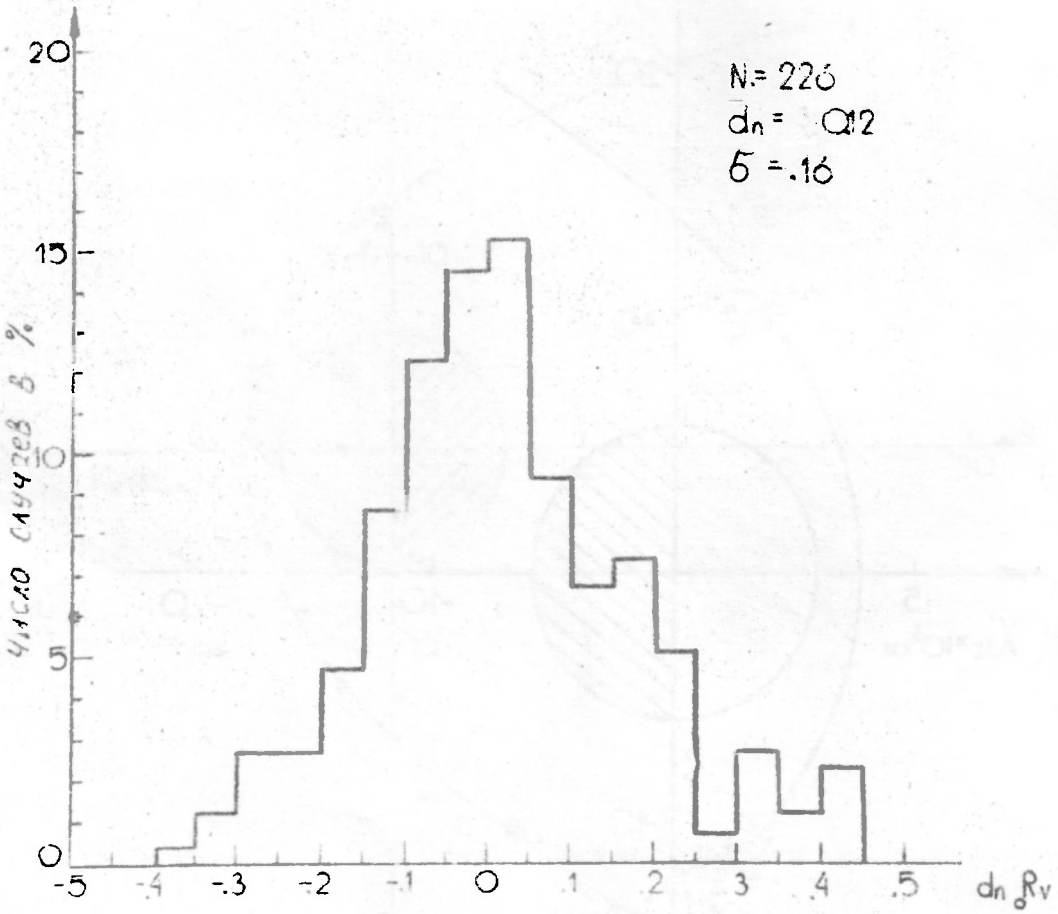

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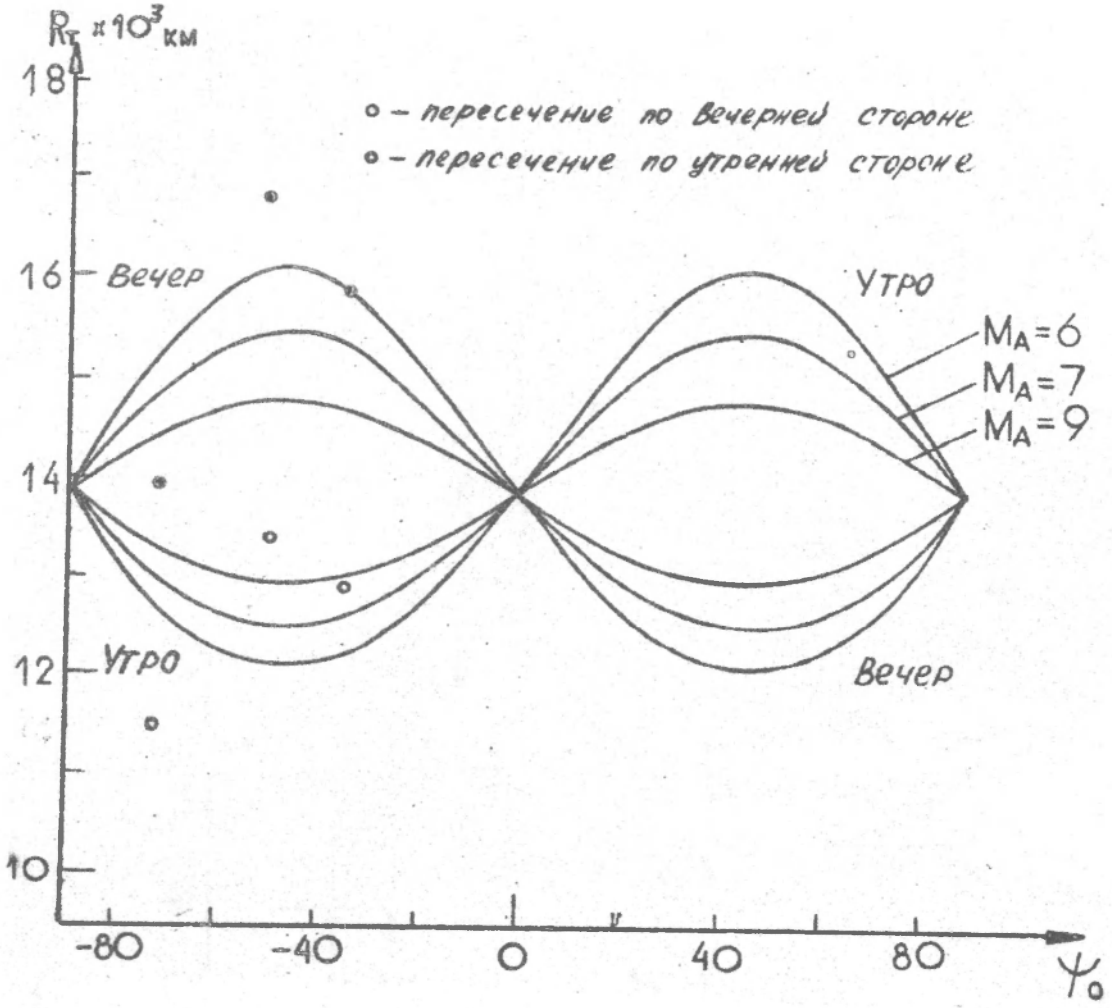
$R_T \times 10^3$ км
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16
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○ – пересечение по вечерней стороне
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Вечер
Утро
Утро
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-80
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Fig. 1

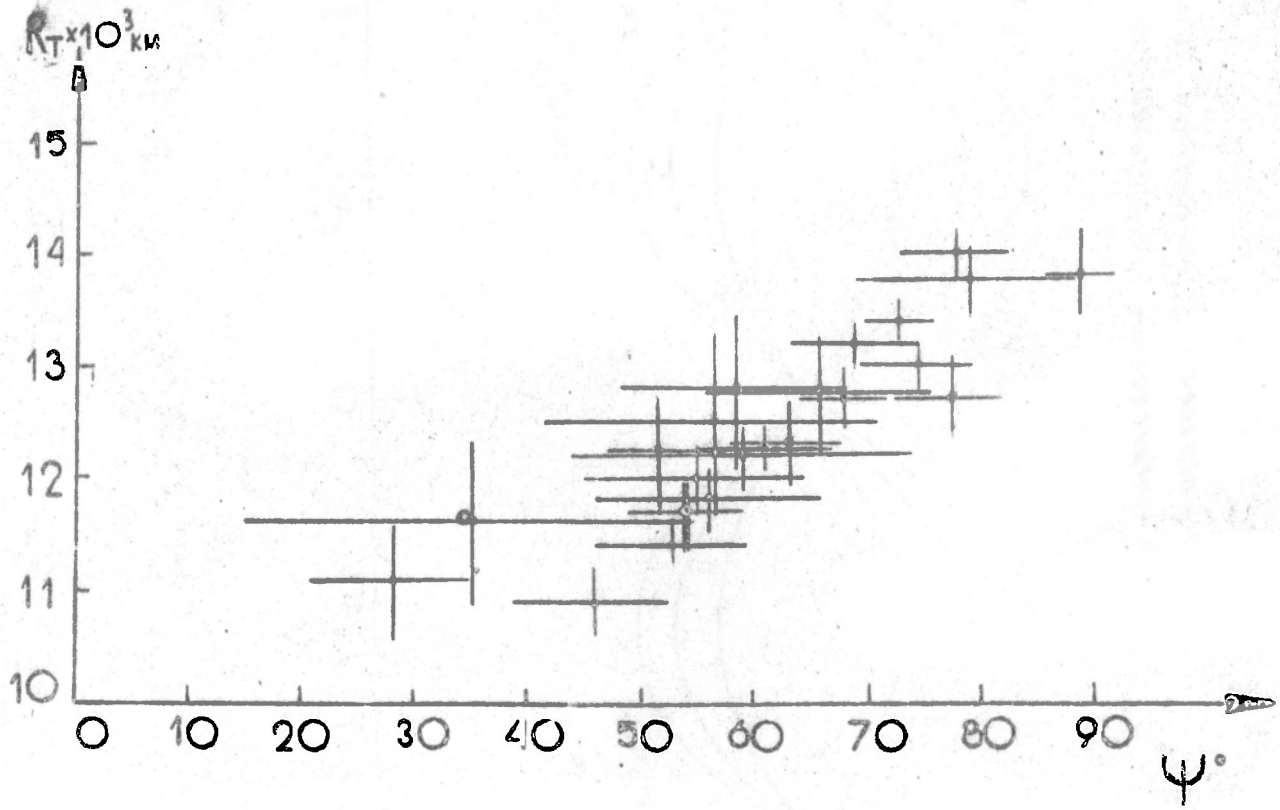

Рис. 8