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ON THE ACCELERATION MECHANISM OF PLASMA OUTFLOW FROM THE SUN

by

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ON THE ACCELERATION MECHANISM OF PLASMA OUTFLOW FROM THE SUN

Institute of Physics in the Name of P.N. Lebedev
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SUMMARY

The problem dealt with in this paper consists in finding a mechanism of plasma acceleration up to energies prevailing in the region of Earth's orbit. Its selection is based upon the results of quantitative analysis of very simple models of plasma flow from the Sun, provided they meet a series of conditions relative to relationships between solar corona and interplanetary plasma; here laminar conditions of the flux intervene, which allow the fulfilment of the gas-dynamics approximation. Several models are discussed, and within the model utilized it is assumed that the energy for the acceleration of coronal plasma is supplied by a heat source emerging as a result of dissipation of mechanical motions.

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1. The development of a more or less complete theory on plasma outflow from the Sun (solar wind theory) is virtually impossible owing to the lack of sufficient experimental data on coronal plasma properties within the 1.03-2 $R_\odot$ region and of an adequate mechanism of solar corona heating, as well as because of mathematical difficulties arising in the solution of inhomogeneous and nonstationary problems of plasma motion However, at the present time, data on coronal and, especially, interplanetary plasma, obtained by astrophysical, radiophysical and rocket methods, are apt to constitute sufficiently reliable basis for designing outflow models that would impart at least some of the properties of the plasma flowing from the Sun [1-5]. One of the most remarkable properties of the interplanetary plasma is that, within the region of the Earth's orbit, the ions attain considerable and virtually radially directed velocites when solar activity is at its lowest. If, along with this, one considers that at the maximum temperature level the hydrodynamic energy flux in the solar corona which is determined by expression $4\pi\rho v r^2\left(\frac{v^2}{2}+\frac{5}{2}\frac{\kappa T}{m}-\frac{\gamma M_\odot}{r}\right)$ is negative, while the energy transfer by molecular thermal conductivity is zero, there arises one of the most interesting problems of the theory on plasma outflow from the Sun. This problem consists in finding the mechanism of plasma acceleration

up to energies existing in the region of the Earth's orbit. The present work is dealing precisely with this problem. The selection of plasma acceleration mechanism is based on the results of a quantitative analysis of very simple models of plasma outflow from the Sun*. These models were designed on the basis of observation data and under the following assumptions:

a) The solar corona and the interplanetary plasma are parts of a dynamic formation occurring as a consequence of a certain activity of the Sun;

b) the thermal source heating the solar corona assures the emergence of energies observed in the interplanetary plasma;

c) there exists in the solar corona a level at which the entire matter participates in the laminar flow and the condition for the applicability of a gas-dynamical approximation are fulfilled within a sufficiently wide region containing this level.***

Inasmuch as direct experimental data on the corona level in which the outflow conditions may be considered laminar are inexistent, its selection was based on the data of radar observations of the Sun [3] and on the density distribution in the corona [6]. On the basis of the spread of velocities, of density distribution and of the total flux of the outflowing plasma, it is logical to place the level at which laminar conditions are formed within the 1.8 - 2.0 $R_{\odot}$ range. Naturally, within the framework of the

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* Even with the use of up-to-date computers a quantitative investigation is possible only in the case of simplest models.

** Probably, beyond the investigated level the outflow conditions are slightly turbulent; however, if one ignores the effect of Reynolds stresses on pulse and energy fluxes (which, on the basis of rocket measurements, may be done within the region of the Earth's orbit) then the mass, pulse and energy transfer equations coincide with the outflow equations under laminar conditions.

*** It should be noted that our assumptions exclude models which consider the interplanetary plasma as the manifestation at great distances of fluxed or clusters of particles with energies of several kev whose occurrence is due to solar corpuscular activity and which exist on the corona alongside a hot but virtually motionless plasma.

investigated models it is impossible to study the region of formation of laminar conditions inasmuch as the mass transfer mechanisms postulated in the model and existing in nature. It will be possible to design a solar corona-interplanetary plasma model with initial level in the region of the corona temperature maximum, only after determining the mass transfer' mechanism with the 1.05 - 1.80 $R_\odot$ corona region.

In describing plasma behavior in the region of laminar conditions, we used equations describing the stationary and spherically-symmetrical plasma outflow in a two-temperature approximation [7]. Following integration of the continuity equation and under the assumption of quasineutrality, the initial system of equations in dimensionless variables takes the following form

$$\nu w x^2 = w_0 \, ,$$

$$\frac{m_e}{m} w \frac{dw}{dx} = -\frac{1}{\nu}\frac{d}{dx}\left(\nu \tau_e\right) - \frac{m_e}{m}\frac{A}{x^2} - \left(\frac{e\tau_0}{kT_0}E + a\frac{d\tau_e}{dx}\right) + \\ + \frac{m_e+m_i}{m} R^{-1}_{eo(e)}\, w x^2 \left\{\frac{1}{x^2}\frac{d}{dx}\left[x^2 \tau_e^{5/2}\left(\frac{dw}{dx}-\frac{w}{x}\right)\right] + \frac{\tau_e^{5/2}}{x}\left(\frac{dw}{dx}-\frac{w}{x}\right)\right\}, \qquad (1)$$

$$\frac{m_i}{m} w \frac{dw}{dx} = -\frac{1}{\nu}\frac{d}{dx}\left(\nu \tau_i\right) - \frac{m_i}{m}\frac{A}{x^2} + \left(\frac{e\tau_0}{kT_0}E + a\frac{d\tau_e}{dx}\right) + \\ + \frac{m_e+m_i}{m} R^{-1}_{eo}\, w x^2 \left\{\frac{1}{x^2}\frac{d}{dx}\left[x^2 \tau_i^{5/2}\left(\frac{dw}{dx}-\frac{w}{x}\right)\right] + \frac{\tau_i^{5/2}}{x}\left(\frac{dw}{dx}-\frac{w}{x}\right)\right\},$$

$$\frac{1}{x^2}\frac{d}{dx}\left[\frac{m_e}{m_e+m_i}\left(\frac{w^2}{2}-\frac{A}{x}\right) + \frac{m}{m_e+m_i}\frac{5}{2}\tau_e - R^{-1}_{eo} x^2 \tau_e^{5/2}\frac{d\tau_e}{dx} - \right. \\ \left. - R^{-1}_{eo} x^2 \tau_i^{5/2} w\left(\frac{dw}{dx}-\frac{w}{x}\right)\right] = \frac{m}{m_e+m_i}\frac{1}{x^2}\left(\frac{e\tau_0}{kT_0}E + a\frac{d\tau_e}{dx}\right) + \\ - Q^{-1}_{eo}\frac{\nu^2}{\tau_e^{3/2}}\left(\tau_e-\tau_i\right) + q_e \Phi_e \, ,$$

$$\frac{1}{x^2}\frac{d}{dx}\left[\frac{m_i}{m_e+m_i}\left(\frac{w^2}{2}-\frac{A}{x}\right) + \frac{m}{m_e+m_i}\frac{5}{2}\tau_i - R^{-1}_{eo(i)} x^2 \tau_i^{5/2}\frac{d\tau_i}{dx} - \right. \\ \left. - R^{-1}_{eo(e)} x^2 \tau_e^{5/2} w\left(\frac{dw}{dx}-\frac{w}{x}\right)\right] = -\frac{m}{m_e+m_i}\frac{1}{x^2}\left(\frac{e\tau_0}{kT_0}E + a\frac{d\tau_e}{dx}\right) - \\ + Q^{-1}_{eo}\frac{\nu^2}{\tau_e^{3/2}}\left(\tau_e-\tau_o\right) + q_i \Phi_i \, .$$

In the system of equations (1) use was made of the dimensionless variables

$$x = \frac{r}{r_0}, \quad w = v\left(\frac{m}{\kappa T_0}\right)^{1/2}, \quad \tau_{e,i} = \frac{T_{e,i}}{T_0}, \quad \nu = \frac{\rho_e}{\rho_{eo}} = \frac{\rho_i}{\rho_{io}} \tag{2}$$

and of the dimensionless parameters

$$P_{eo}^{-1} = \frac{\varkappa_e(T_0)\, r_0}{\sqrt{m}\, I_0}, \qquad P_{eo(i)} = \left(\frac{m_e}{m_i}\right)^{1/2} a_i P_{eo}^{-1},$$

$$R_{co}^{-1} = \frac{4}{3}\frac{\mu(T_0)\, r_0}{I_0}, \qquad R_{co(i)}^{-1} = \left(\frac{m_e}{m_i}\right)^{1/2} b_i R_{co}^{-1}, \tag{3}$$

$$A = \frac{\gamma M_0 m}{r_0 \kappa T_0}, \qquad Q_{eo}^{-1} = \frac{m_e}{m_i}\,\frac{m}{m_e+m_i}\,\frac{4\sqrt{2\pi}}{\sqrt{m_e}}\,\frac{n_0 \Lambda e^4}{(\kappa T_0)^{3/2}}\,\frac{r_0}{v_0},$$

where r_0 is the position of the initial level, v_0, T_{eo}, P_{eo}, P_{io} are respectively the hydrodynamic plasma velocity, the temperature and density of electrons and ions at the initial levle, m_i is the mean ion mass, $m = \frac{m_e+m_i}{2}$ and $I_0 = (m_e+m_i) r_0^2 v_0 n_0$. The energy equations of system (1) contain volumetric heat sources with dimensionless strenghts $q_e\Phi_e$ and $q_i\Phi_i$.

At relatively small nonisothermicities in system (1) there is a small parameter $\left(\frac{m_e}{m_i}\right)^{1/2}$. The solution of system (1) may be sought in the form of an asymptotic series by powers of this parameter

$$y(x) = y_0(x) + \left(\frac{m_e}{m_i}\right)^{1/2} y_1(x) + \left(\frac{m_e}{m_i}\right) y_2(x) + \dots, \tag{4}$$

where Y is any one of the functions determined by system (1). The equations for the zero terms of series (4) can be written in the form

$$\nu w x^2 = w_0,$$

$$\frac{1}{\nu}\frac{d}{dx}(\nu\tau_e) + \left(\frac{e r_0}{\kappa T_0}E + a\frac{d\tau_e}{dx}\right) = 0,$$

$$w\frac{dw}{dx} = -\frac{1}{2}\frac{1}{\nu}\frac{d}{dx}\left[\nu(\tau_e+\tau_i)\right] - \frac{A}{x^2} + R_{eo}^{-1} w \frac{d}{dx}\left[x^2\tau_i^{5/2}\left(\frac{dw}{dx} - \frac{w}{x}\right)\right] + R_{co}^{-1} w x \tau_i^{5/2}\left(\frac{dw}{dx} - \frac{w}{x}\right), \tag{5}$$

$$\frac{d}{dx}\left[\frac{w^2}{2} + \frac{5}{4}(\tau_e+\tau_i) - \frac{A}{x} - P_{eo}^{-1} x^2 \tau_e^{5/2}\frac{d\tau_e}{dx} - R_{eo}^{-1} x^2 \tau_i^{5/2} w\left(\frac{dw}{dx} - \frac{w}{x}\right)\right] = q_e x^2 \Phi_e + q_i x^2 \Phi_i,$$

$$\frac{d}{dx}\left[\frac{w^2}{2}+\frac{5}{4}\tau_i-\frac{\Lambda}{x}-R_{co}^{-1}x^2\tau_i^{5/2}w\left(\frac{dw}{dx}-\frac{w}{x}\right)\right]=$$
$$=\frac{1}{2}\left(\frac{e\tau_0}{\pi T_0}E+a\frac{d\tau_e}{dx}\right)+Q_{co}^{-1}\frac{\nu^2x^2}{\tau_e^{3/2}}\left(\tau_e-\tau_i\right)+q_i x^2\Phi_i$$

(It should be borne in mind that ν , τ_e τ_i , contained in (5) are the zero terms of series (4); but, inasmuch as we will limit our investigation to precisely the zero-order approximation, these symbols will cause no ambiguity). In analyzing the results of the integration of system (5), it should be borne in mind that they are valid for describing the flows only if inequalities

$$d_e=\frac{\lambda_e}{r}\ll 1,\quad d_i=\frac{\lambda_i}{r}\ll 1, \tag{6a}$$

$$d_T=\left|\frac{\lambda_e}{T_e}\frac{dT_e}{dr}\right|\ll 1,\quad d_v=\left|\frac{\lambda_i}{v}\frac{dv}{dr}\right|\ll 1 \tag{6b}$$

which are the conditions under which the gas-dynamical approximation is applicable for the description, are fulfilled.* The system of Eqs. (5) contains four dimensionless parameters R_{co}^{-1} , P_{eo}^{-1} , Λ , Q_{co}^{-1} and two functions $q_e\Phi_e$ and $q_i\Phi_i$, which determine the volumetric strength of the heat source which should be set in order to achieve specific results. As regards the dimensionless parameters, the range of their possible values can be evaluated on the basis of observation data, while the experimental information on the power of heat sources is virtually inexistent.

2. Inasmuch as the hydrodynamic outflow model proposed by Parker meets virtually insurmountable difficulties [8,9] and as in an equal-temperature approximation a consistent designing of a model that would take into account the thermal conductivity and the viscosity is impossible, we have adopted (5) for the initial system which describes the plasma outflow without the assumption of equality of electron and ion temperatures,** Moreover, if one bears in mind that in the region of laminar conditions the volumetric heat sources are absent [12]

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* Relations d_e and d_i are considered to be the regional Knudsen numbers and if they considerably exceed 1, the outflow should be considered as being under collisionless conditions. The dimensionless parameters d_t and d_v determine the conditions of applicability of the expressions used in (1) for energy and impulse transfer on account of chaotic electron and ion motions.

** According to observation data, the dimensionless parameters of system (5) cannot be considered small and any contractions of the system are inadmissible.

it is possible to integrate the energy equation

$$\frac{w^2}{2}+\frac{5}{4}(\tau_e+\tau_i)-\frac{A}{x}-P_{eo}^{-1}x^2\tau_e^{5/2}\frac{d\tau_e}{dx}-R_{eo}^{-1}x^2\tau_i^{5/2}w\left(\frac{dw}{dx}-\frac{w}{x}\right)=\mathcal{E}_\infty \quad (7)$$

where E_∞ is the integration constant which is equal to the energy at the initial level.

Eliminating γ and $\frac{\varkappa}{k}\tau_e^{5/2}\varepsilon+a\frac{d\tau_e}{dx}$ and taking into consideration integral (7), system (5) is easily reduced to a form which is convenient for numerical integration

$$\frac{dw}{dx}=u\,,$$

$$\frac{d\tau_e}{dx}=\frac{\frac{w^2}{2}+\frac{5}{4}(\tau_e+\tau_i)-\frac{A}{x}-R_{eo}^{-1}x^2w\tau_i^{5/2}\left(u-\frac{w}{x}\right)-\mathcal{E}_\infty}{P_{eo}^{-1}x^2\tau_e^{5/2}}\,,$$

$$\frac{d\tau_i}{dx}=-\frac{2\tau_i}{3w}u-\frac{4}{3}\frac{\tau_i}{x}+\frac{4}{3}Q_{co}^{-1}\frac{w_2^{\,2}}{x^2w^2\tau_e^{3/2}}(\tau_e-\tau_i)+$$

$$+\frac{4}{3}R_{eo}^{-1}x^2\tau_i^{5/2}\left(u-\frac{w}{x}\right)^2, \qquad (8)$$

$$\frac{du}{dx}=-\left(\frac{2}{x}+\frac{5}{2}\frac{1}{\tau_i}\frac{d\tau_i}{dx}\right)\left(u-\frac{w}{x}\right)-\frac{u}{R_{eo}^{-1}wx^2\tau_i^{5/2}}\left(\frac{\tau_e+\tau_i}{2w}-w\right)+$$

$$+\frac{A}{R_{co}^{-1}wx^4\tau_i^{5/2}}+\frac{1}{2}\frac{\frac{d\tau_e}{dx}+\frac{d\tau_i}{dx}}{R_{eo}^{-1}wx^2\tau_i^{5/2}}-\frac{\tau_e+\tau_i}{R_{eo}^{-1}wx^3\tau_i^{5/2}}$$

In spite of a number of simplifying assumptions, the system of equations describing the outflow in a different-temperature approximation proves to be too complex for solutions by analytical means. Therefore, all the information on the properties of solutions of system (8) was determined by numerical methods. To analyze the structure of integral curves of system (8) we used the values of dimensionless parameters compiled in tables I, II, and III.

(The values of dimensionless parameters with $T_0 = 1$ were obtained with the use of the following quantities characterizing the coronal and interplanetary plasma

$$r=1{,}77R_\odot\,,\quad T_0^*=1{,}69\cdot10^{6}\,{}^\circ K\,,\ n=3\cdot10^{6}\,\text{пр/см}^3\,,\quad m=0{,}62m_n\,,$$

$$r=215R_\odot\,,\quad I_0^*=4{,}82\cdot10^{10}\,\frac{1}{\text{сек.}\,\text{см}^2}\,,\ v_A=330\,\text{км/сек}\,,\quad T_A=10^5\,{}^\circ K$$

T A B L E I

T_o	R_{eo}^{-1}	P_{eo}^{-1}	A	ε_∞	Q_{eo}^{-1}
1,50	4,19	117,21	3,17	1,53	4,83
1,25	2,65	74,17	3,80	1,84	6,33
1,20	2,40	67,07	3,96	1,92	6,74
1,10	1,93	54,06	4,32	2,09	7,67
1,00	1,52	42,53	4,75	2,30	8,86
0,90	1,17	32,66	5,28	2,62	10,38
0,80	0,87	24,33	5,94	2,88	12,39
0,75	0,74	20,70	6,34	3,07	13,65
0,70	0,62	17,42	6,79	3,29	15,14
0,667	0,55	15,48	7,12	3,45	16,28
0,625	0,47	13,14	7,60	3,63	17,93
0,588	0,40	11,27	8,08	3,91	19,64

T A B L E II

I_o	R_{eo}^{-1}	P_{eo}^{-1}	A	ε_∞	Q_{eo}^{-1}
0,30	5,00	191,15	4,75	2,30	8,86
0,75	2,00	56,73	″	″	″
1,00	1,52	42,53	″	″	″
1,50	1,00	38,33	″	″	″
3,00	0,50	14,18	″	″	″
4,00	0,38	10,63	″	″	″
6,00	0,26	7,08	″	″	″

T A B L E III

	T_{eo}/T_{io}	R_{eo}^{-1}	P_{eo}^{-1}	A	ε_∞	Q_{eo}^{-1}
$I_o = I_o^*$	0,75 0,50 0,25	1,52	42,53	4,75	2,30	8,86
$I_o = \frac{1}{3} I_o^*$	0,75 0,50 0,25	4,56	127,59	″	″	″
$I_o = \frac{1}{5} I_o^*$	0,75 0,50 0,25	7,06	212,56	″	″	″

The numerical integration of the system of equations (8) with dimensionless parameters presented in tables I, II and III is shown in Fig. 1, 2 and 3 (the integration was carried out at identical initial conditions for various groups of dimensionless parameters $w_{\bullet}=0{,}17$, $\mathcal{T}_e=\mathcal{T}_i=1$, $u_{\bullet}=0{,}44$ at $x=1$.)

Depending upon the dimensionless parameters of the problem, the solutions of system (8) belong to one of the two following types: the first type includes solutions with non zero electron temperature and with variations in the independent variable within the entire range; the second contains solutions with electron temperature becoming zero at the terminal distance from the initial level.* For a detailed analysis of each of the indicated types of solutions, integral curve families (parameter W_0) were obtained with the following sets of dimensionless parameters

I. $R_{eo}^{-1}=2{,}65,\ P_{eo}^{-1}=74{,}17,\ A=3{,}80,\ \mathcal{E}_{\infty}=1{,}84,\ Q_{eo}^{-1}=6{,}33.$

II. $R_{eo}^{-1}=0{,}26,\ P_{eo}^{-1}=7{,}08,\ A=4{,}75,\ \mathcal{E}_{\infty}=2{,}30,\ Q_{eo}^{-1}=8{,}86.$

The obtained results are shown in Fig.4 and 5.

Analysis of the results of numerical integration makes it possible to ascertain the following special features of solutions of system (8). For the set I of parameters there are three types of hydrodynamic velocity dependence on distance: 1) monotonic variation with smooth transition through sound velocity and an outlet to an almost linear growth for great x; 2) nonmonotonic variation with a maximum and minimum smooth transition through sound velocity and an outlet to an almost linear growth for great x; 3) nonmonotonic variations with one maximum and a subsonic velocity everywhere.**

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* Inasmuch as it was found to be impossible to separate analytically the regions of parameter values at which solutions of specific type take place, the problem of the nature of the solutions for each specific group of parameters was solved by numerical integration of system (8).

** Inasmuch as these conclusions were reached making use of the numerical integration of system (8), it is obvious that they are correct for the terminal distances from the initial level. The nature of individual integration curves may change with the increase of the integration range; however, their general structure is preserved (Fig. 8a and 8c). Nevertheless, we have no reasons to consider that the aforementioned special features are preserved up to any distances from the intial level.

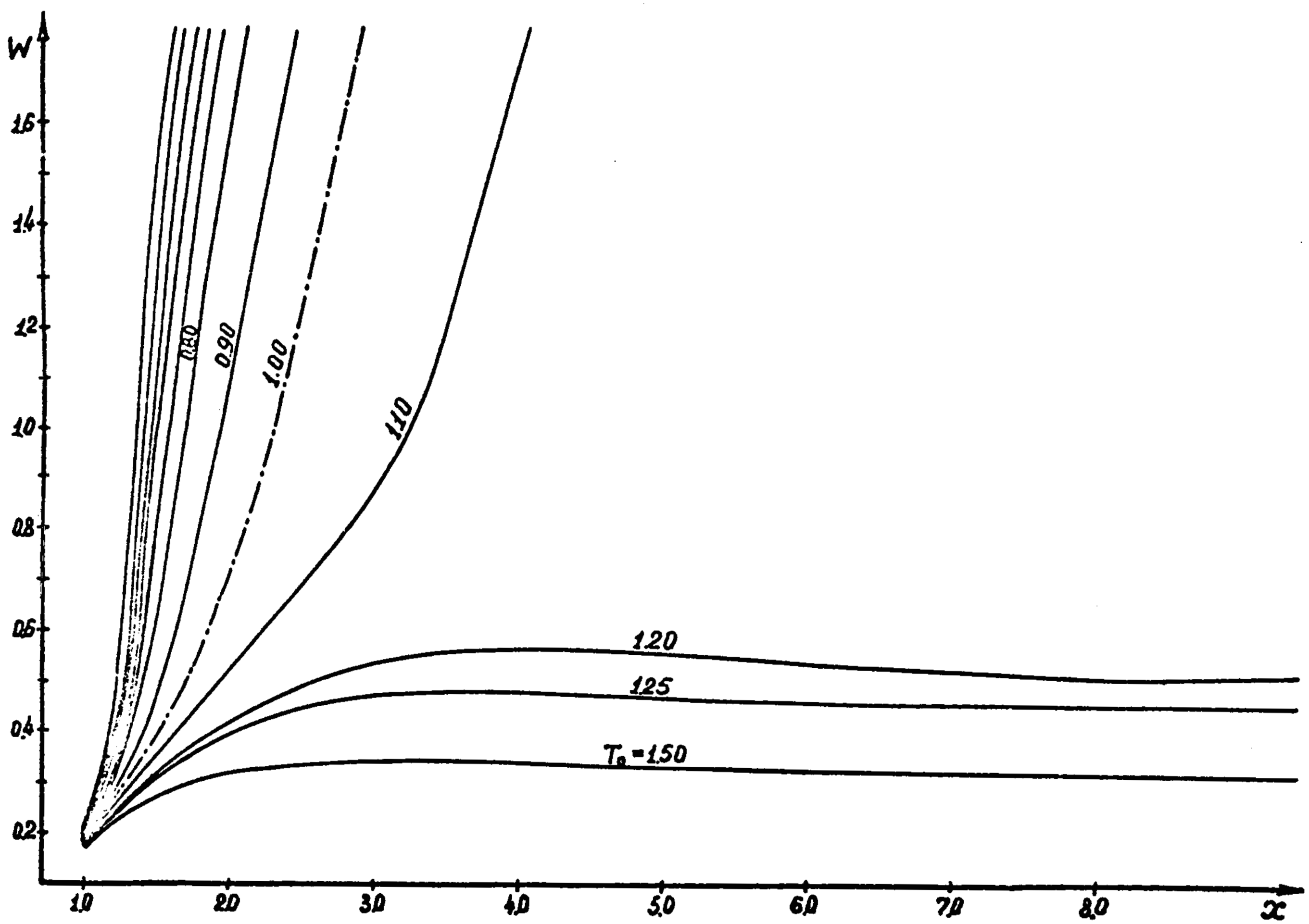
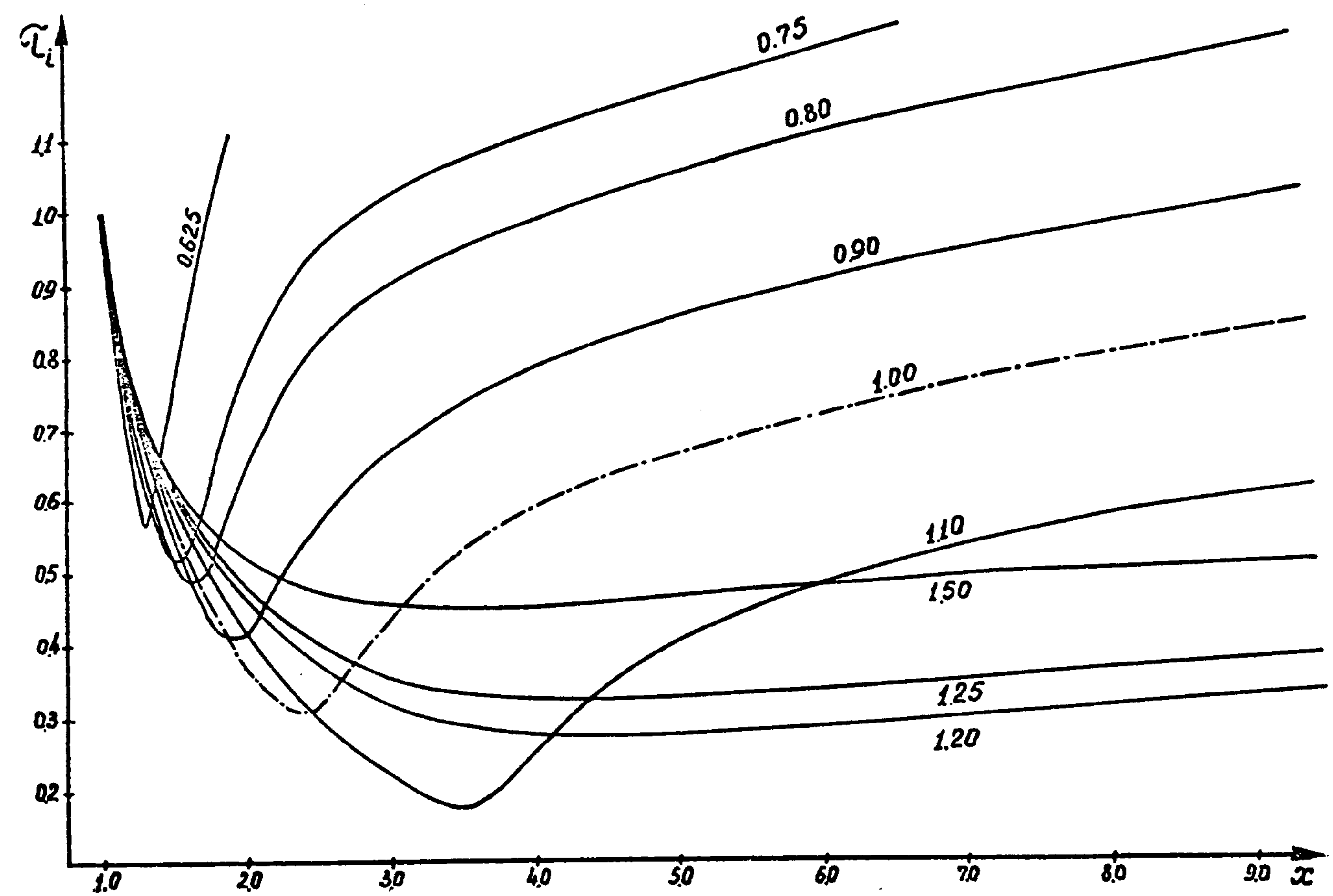


Fig. I a

Dependence of the nature of solutions on temperature at initial level.



τ_i
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
x
0.625
0.75
0.80
0.90
1.00
1.10
1.50
1.25
1.20

Fig. I b.

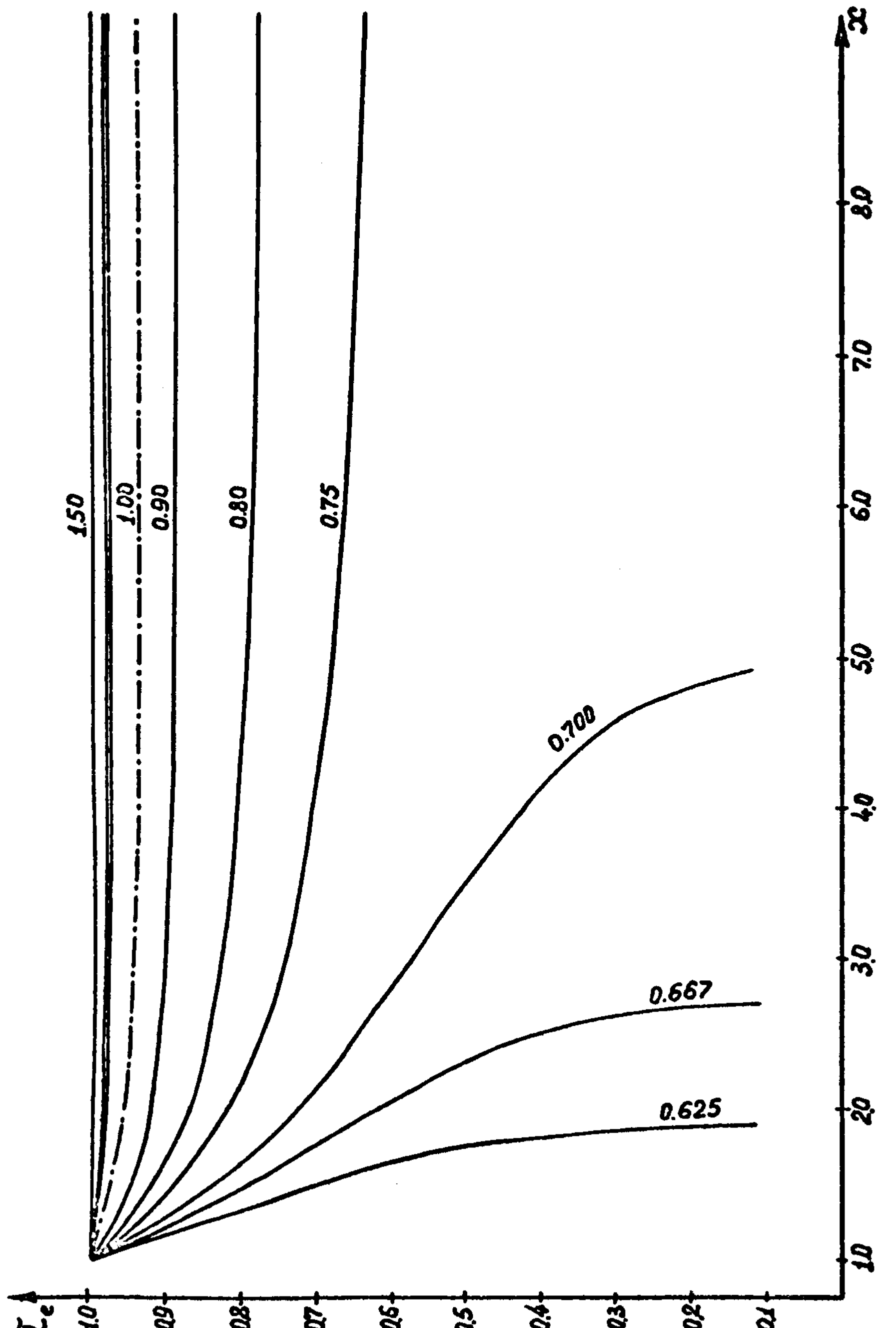

1.50
1.00
0.90
0.80
0.75
0.700
0.667
0.625
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
x

Fig. I c.

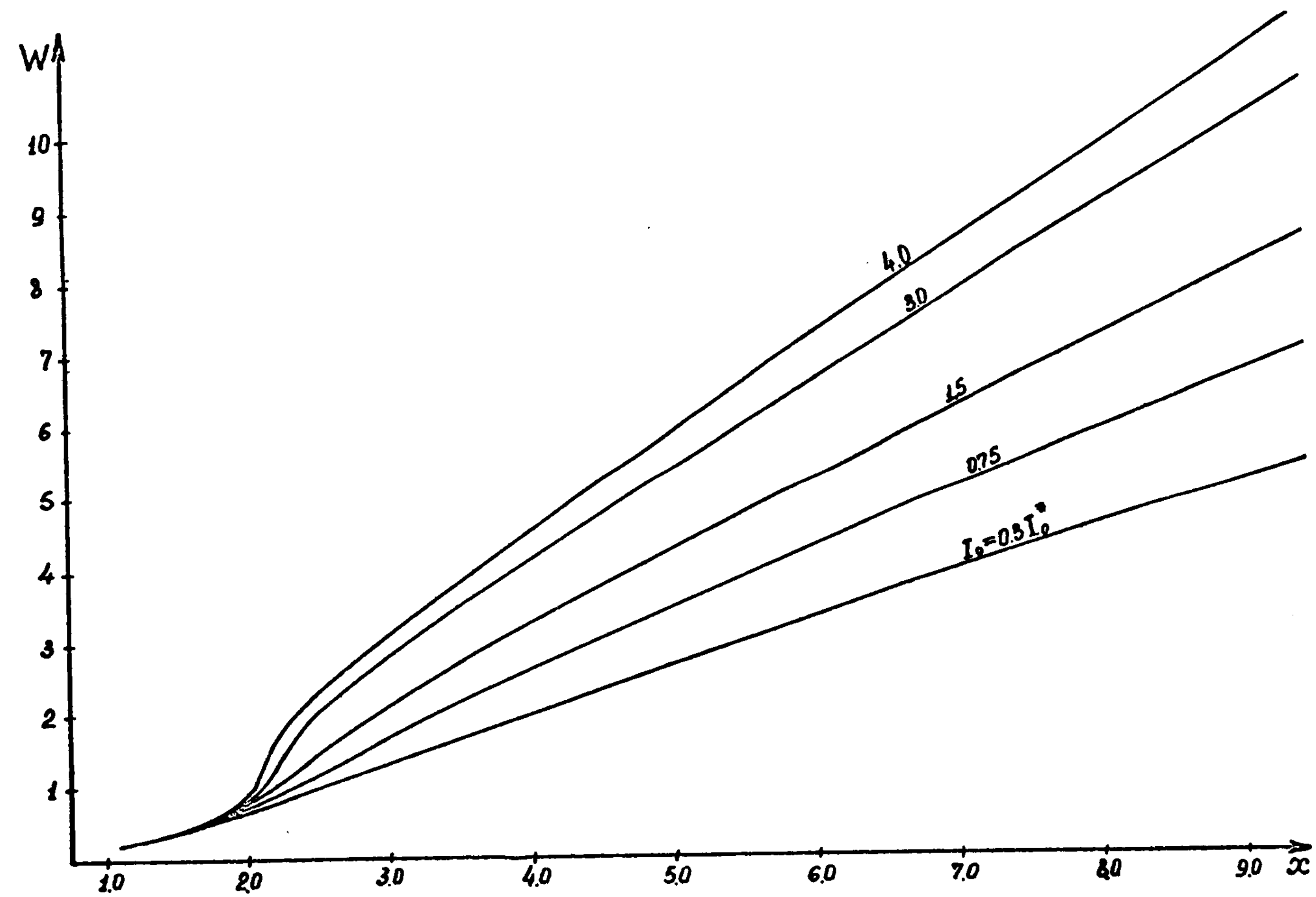


Fig. 2 a.

Dependence of the nature of solutions on the total flux of the mass.

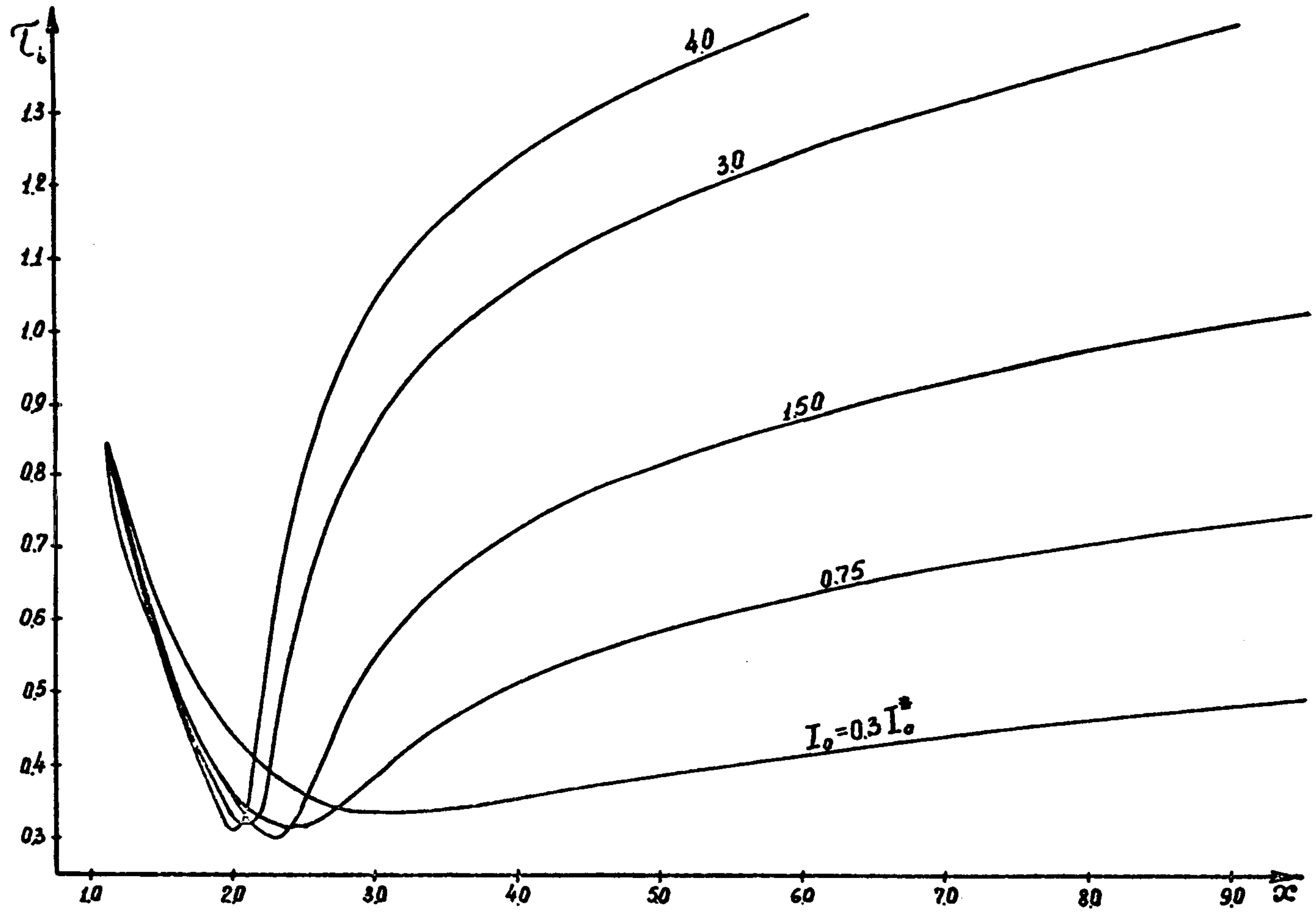

4.0
3.0
1.50
0.75
$I_o = 0.3 I_o^*$
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
x

Fig. 2 b.

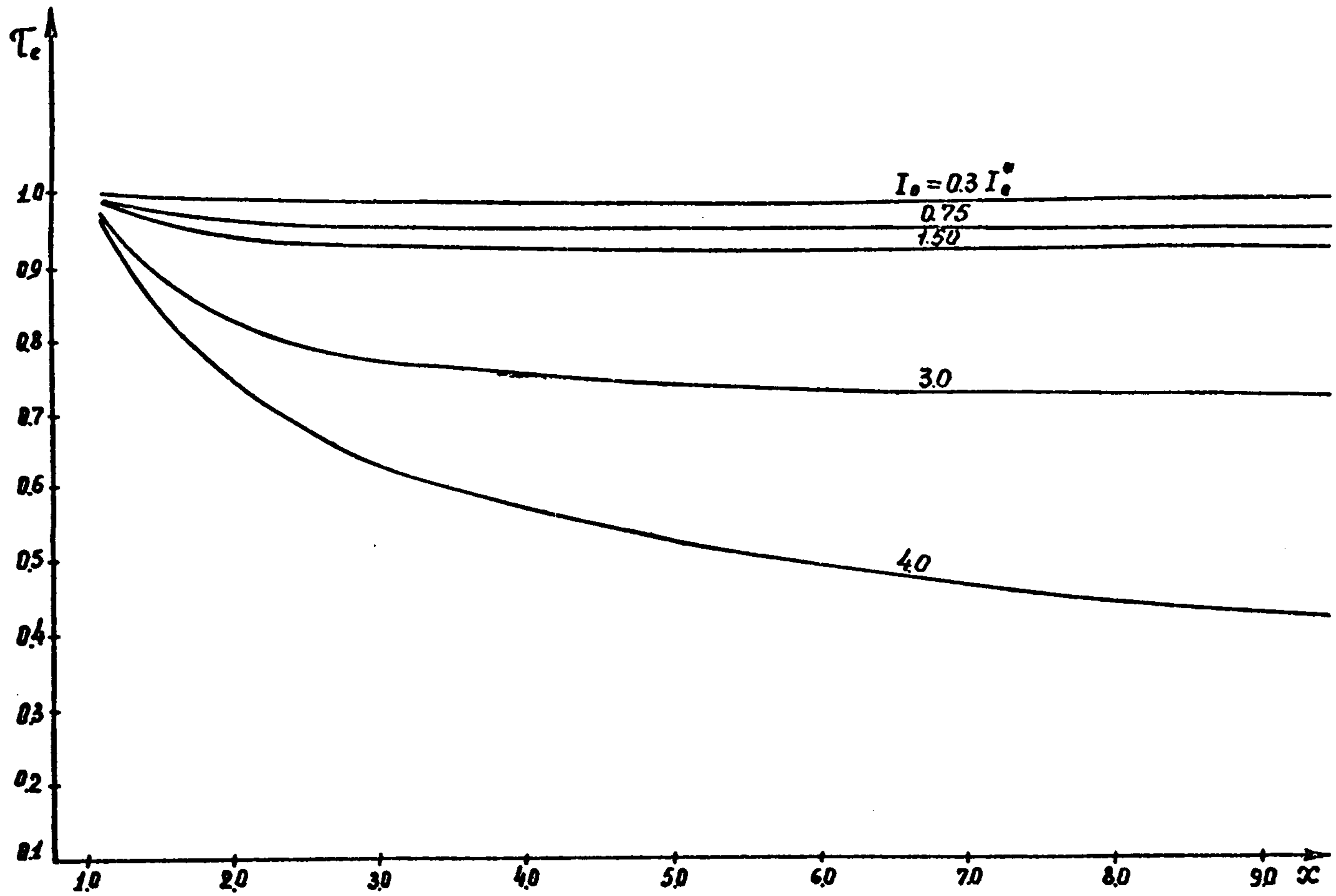

τ_e
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
x
$I_0 = 0.3\, I_0^*$
0.75
1.50
3.0
4.0

Fig. 2 c.

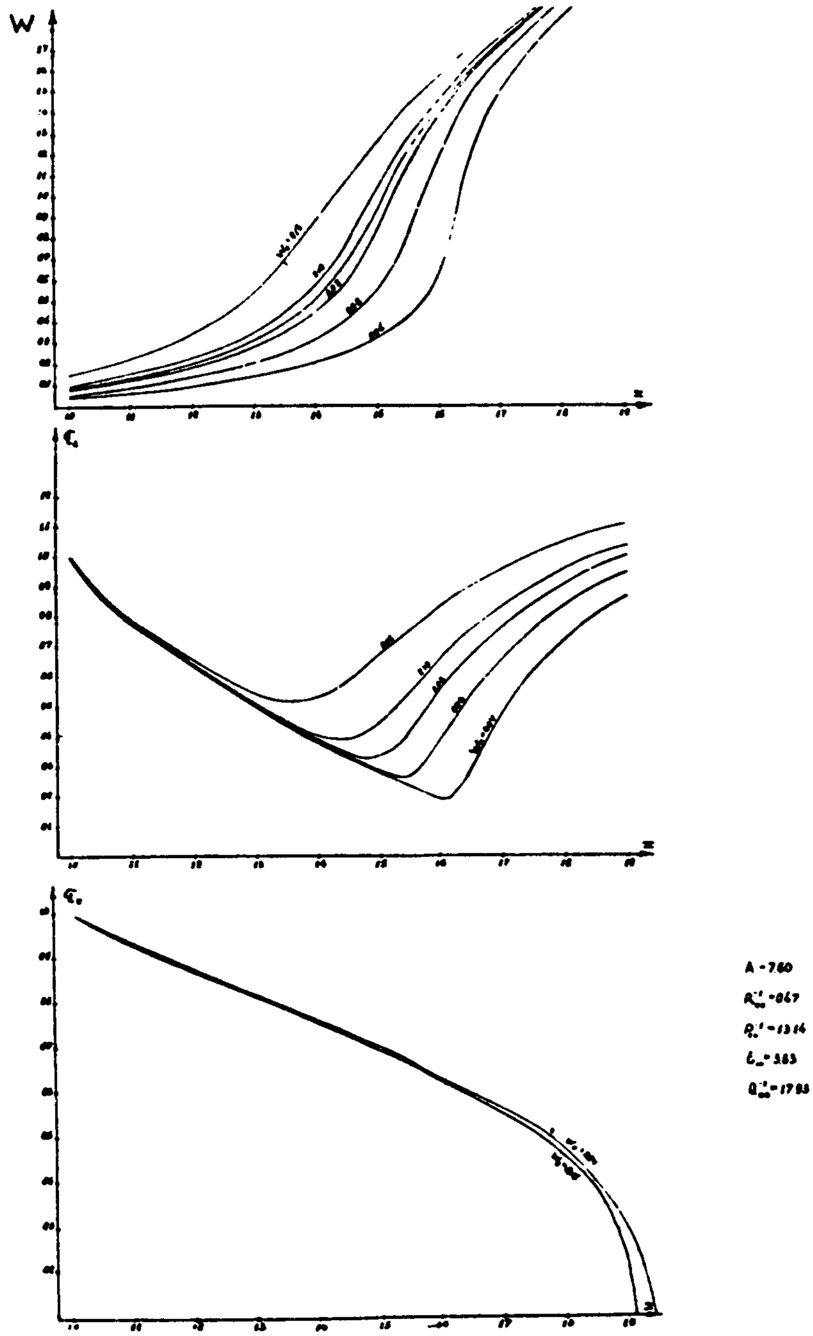


Fig. 3.

Solutions at an electron temperature becoming zero at the terminal level.

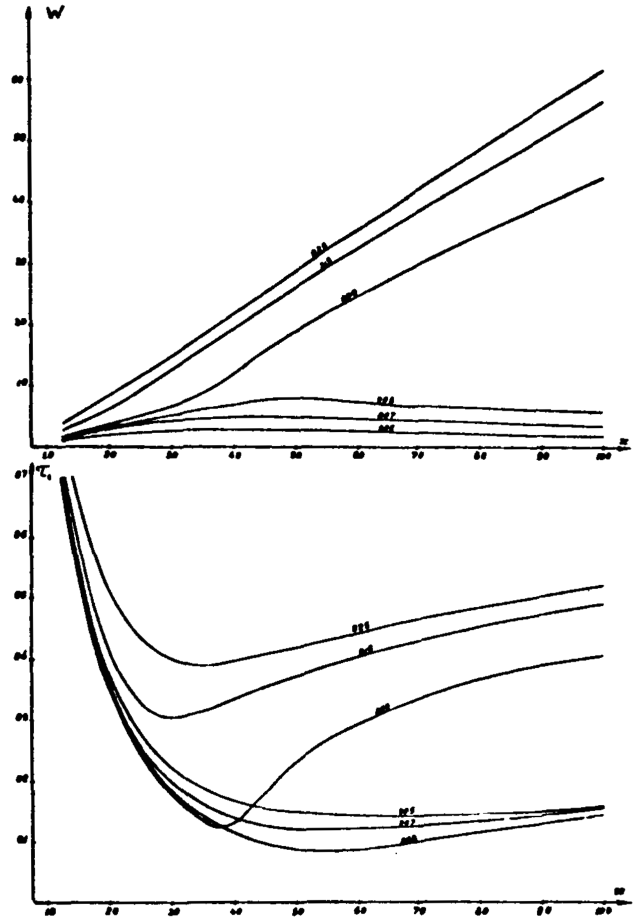


Fig. 4.

Solution at a temperature
differing from zero in the entire integration
range.

The electron temperature underwent only slight variations for any dependence W(x) whereas variations of ion temperature were substantial at least for W(x) with a smooth transition through sound velocity. One of the most important properties of solutions with nonzero electron temperature is the monotonic increment of the Knudsen number for electrons. The integration of a large number of variants admitting this type of solutions shows that, as a rule, within the region where the gas-dynamical approximation is disrupted, there takes place the inequality

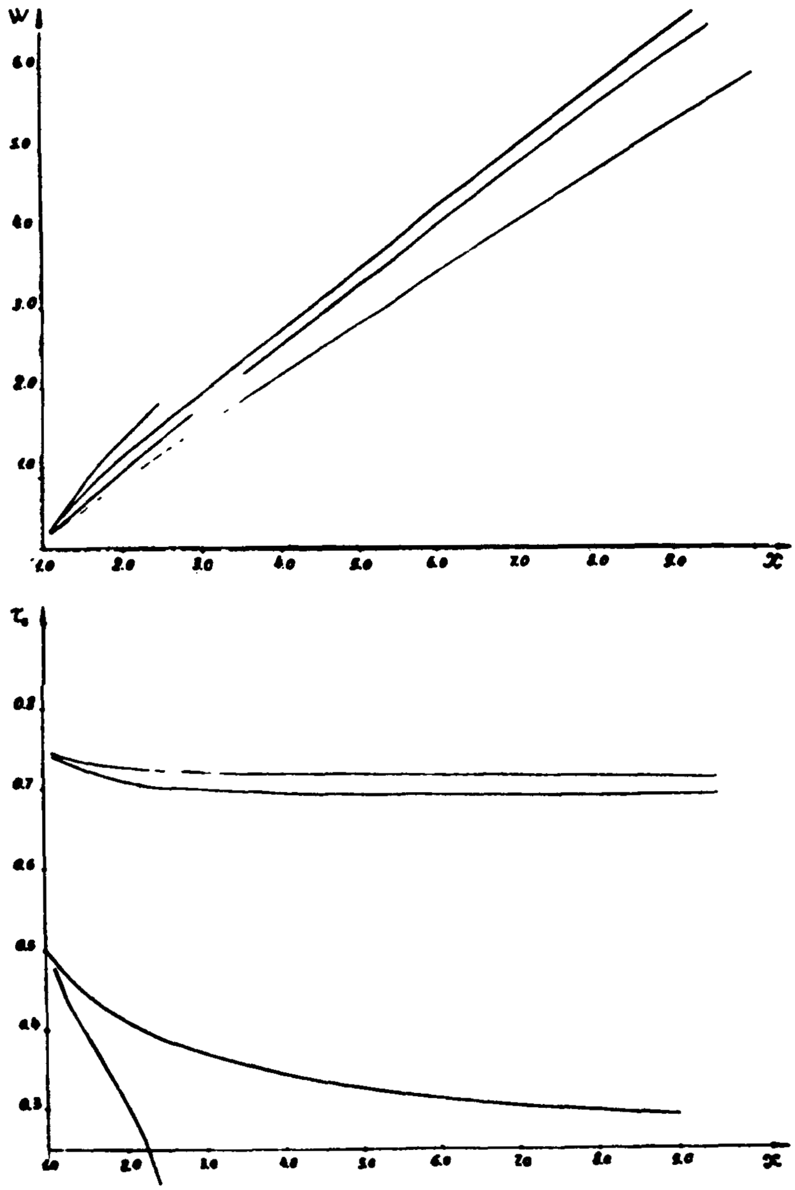


Fig. 5.

Dependence of the nature of solutions on nonisothermicity at the initial level.

$d_e > d_i$.* In case of set II of parameters, system (8) has solutions with an electron temperature becoming zero at the

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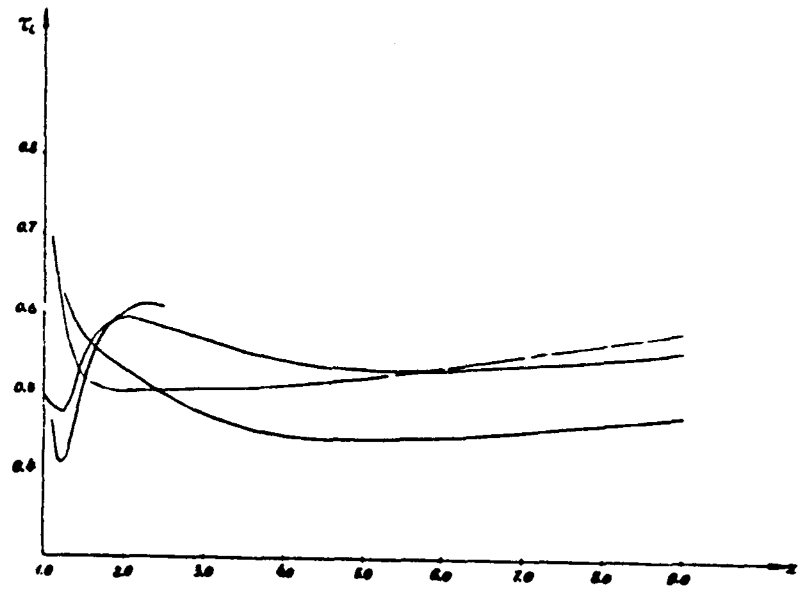
* When conditions $d_e >> 1$ is fulfilled, collisions cannot ensure the existence of locally Maxwellian distribution for electrons; this is why the results of calculations of d_t implying only slight deviations from the Maxwellian distribution are meaningless ($d_t << 1$ for the majority of the integrated variants.)



$\frac{\tau_e}{\tau_i} = 0.5; 0.75$

$\dot{u}_o = 0.44$

$A = 4.75$

$R_{e_o}^{-1} = 4.55$

$R_o^{-1} = 127.59$

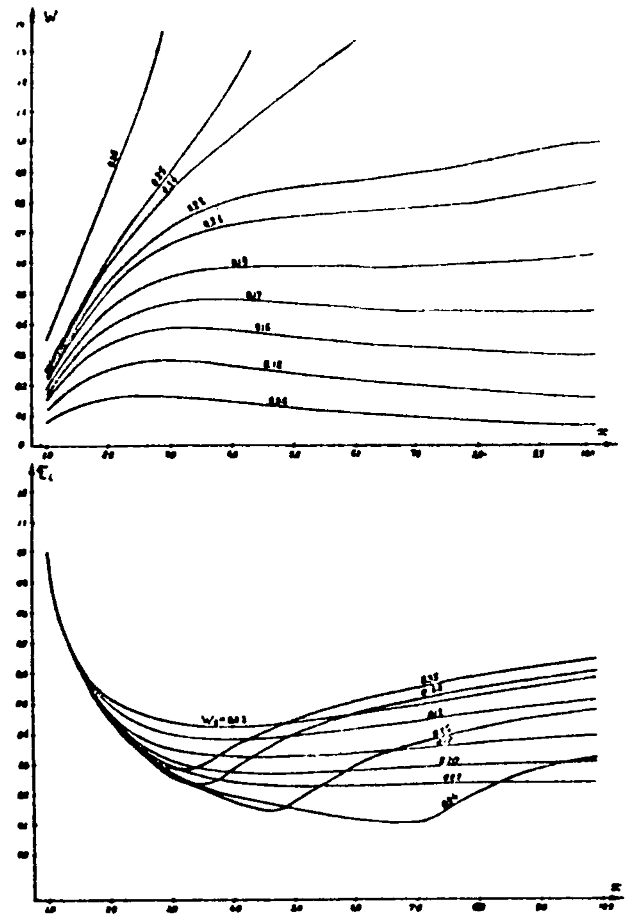
$\varepsilon_\infty = 2.3$

Fig. 5 a.

terminal distance from the initial level. The local Knudsen number for electrons varies nonmonotonically and has a maximum between the initial level and the level where electron temperature becomes zero. Investigation of various types of this variant shows that in the majority of cases, in the region where the gas-dynamical approximation is disturbed, $d_i > d_e$.

Alongside with the dimensionless parameters of the problem, the structure of the integral curve depends[*] at the initial level on the quantity U_o. Therefore, we have studied the sensitivity of the solutions to U_o variations. Fig. 8 presents the results of integration of the system of Eqs. (8) for various U_o, but, with an identical set of dimensionless parameters, ($R_{eo}^{-1} = 1{,}52$, $P_{eo}^{-1} = 42{,}53$, $A = 4{,}75$, $\varepsilon_\infty = 2{,}30$, $Q_{eo}^{-1} = 8{,}86$), wherefrom it can be concluded that the sensitivity of the solutions to U_o is slight.

[*][This sentence is obviously incomplete, in the original Russian and the verb "depends" had to be inserted to make sense.]



A = 380
R'_{∞} = 255
P'_{∞} = 7417
ε_{∞} = 184
σ'_{∞} = 633

Fig. 6.

Dependence of the nature of the solutions on the initial velocity.

3. In our opinion, the results of integration of the system of Eqs. (8) with the parameters presented in tables I, II and III, are convincing evidence of the inconsistency of the gas-dynamical approximation for the description of plasma outflow from the Sun. This means that the study of the outflow is possible only within the framework of dynamic models with a terminal radius of the region of frequent collisions. The results of the integration of system (8) suggest the possibility of designing the following dynamic models:

a) a dynamic model with terminal radius of the region of frequent collisions for electrons and uniform applicability of gas-dynamic's approximation for ions.

b) a dynamic model with a terminal radius of the region of frequent collisons for ions and a uniform applicability of gas-dyna-ical approximation for electrons.

c) a dynamic model with a terminal radius for both components. Here two variants are possible: in the first the radius of the region of frequent collisions for the electrons is larger than for ions, in the second it is the opposite.

To solve the problem of the model describing plasma outflow from the Sun, it is necessary to have accurate values for the dimensionless parameters of system (8) and the values of variables at the initial level. Inasmuch as at the present time the observation data do not yield these values with accuracy, in selecting the model we took advantage of the combination of well known data and of the singularities of the acceleration mechanism of the outflowing plasma. Thus, the first model had to be abandoned because observation data had indicated that the conditions under which the gas-dynamics approximation for the ions could be applied, were disrupted. As regards the second model and the first variant of the third model, they are in contradiction with the existence for the different ion components of directional velocities identical in magnitude [5].

Therefore, the results of plasma outflow analysis in a hydrodynamic approximation and rocket observation data on interplanetary plasma lead us to the following conclusion: in describing plasma outflow from the Sun use should be made of a dynamic model with a terminal radius of the region of frequent collisions for both components, whereupon this radius of frequent collisions must be larger for ions than for electrons. It is obvious that when investigating this model the solution of kinetic plasma equations is prerequisite under conditions when the collision frequency varies within limits in which the system of plasma equations does not contain a uniformly small parameter in the entire investigated region. Owing to the lack of effective methods for resolving kinetic equations under the required conditions, it is impossible at present to carry out a quantitative investigation of this model of plasma outflow from the Sun.

4. The foregoing analysis of the various outflow models makes it possible to provide at least a qualitative answer to the problem of the acceleration mechanism of plasma outflow from the Sun. By its very nature it is a plasma mechanism first of all*

* Contrary to Parker's hydrodynamic acceleration mechanism the essential role in the plasma mechanism is played by energy transfer of heat conductivity precisely in the light component.

and actually it is a mechanism transforming the heat conductivity flux of electron energy into a hydrodynamic flux of ions. In the region of frequent collisions this transformation takes place in two ways: by energy transfer at the expense of electron-ion collisions with power

$$Q_{ei} = Q_{eo}^{-1} \frac{\nu^2}{\mathcal{T}_e^{3/2}} \left(\mathcal{T}_e - \mathcal{T}_i\right), \tag{9}$$

which is equivalent to the volumetric heat source on the ion component and the work of the ambipolar electric field forces with strenght

$$A_{c-s} = \frac{1}{2x^2}\left(\frac{\mathcal{T}_i}{w}\frac{dw}{dx} + \frac{2\mathcal{T}_e}{x} - \frac{d\mathcal{T}_e}{dx}\right) \tag{10}$$

When the gas-dynamical approximation is violated, the role of energy transfer due to electron-ion collisions becomes negligibly small and the acceleration of the ion component proceeds mainly at the expense of the existence of the ambipolar electric field. The magnitude of this field depends on the conditions of electrons' motion. In the case when the hydrodynamic approximation can be uniformly applied to electrons, the magnitude of the strenght of ambipolar field forces is determined by formula (10). When the conditions for the applicability of gas-dynamical approximation are disrupted, the ambipolar electric field strength is determined by substantial variation of the electron distribution function in the transition layer. Prior to the transition layer it is locally Maxwellian with slight deviations ensuring the existence of energy transfer by thermal conductivity. After the transition layer, the electron distribution functionis essentially non-Maxwellian permitting only convective energy transfer. Unfortunately, the mathematical difficulties that arise in investigations of the electron distribution function in the transition layer make it impossible to formulate a strict demonstration of the existence of this acceleration mechanism and to derive an expression for the ambipolar field strenght.

5. Within the framework of the applied model, it is assumed that the energy for coronal plasma acceleration is provided by a heat source which is initiated by the dissipation of mechanical motions. For a certain angle of directions a local increase in the power of the heat source may result in the occurrence of higher velocities. However, within the framework of the investigated mechanism and in spite of the existence of a collisionless region, the occurrence of two or more interpenetrating plasma fluxes with differently oriented velocities cannot be expected. Observations of interplanetary plasma in the region of the Earth's orbit by means of rocket-borne equipment bear evidence of the existence of fluxes are velocities different in magnitudes. The solutions with these solar wind peculiarities could emerge within the framework of a model taking into account, alongside with heat

sources, the existence of plasma clusters arising as a consequence of some corpuscular activity of the Sun.*

To conclude, the author considers it his pleasant duty to thank I.M. Dagkesamanskaya and M.P. Yachina for their great help in formulating this work.

* * * THE END * * *

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* The system of equations describing the plasma outflow from the Sun in this type of model should consist of a system of equations of plasma in a hydrodynamic approximation and equations for clusters with corresponding terms for energy and impulse exchange. For a phenomenological investigation of the outflow in a hydrodynamic approximation the accounting of clusters can be materialized by defining the sources of the impulse.

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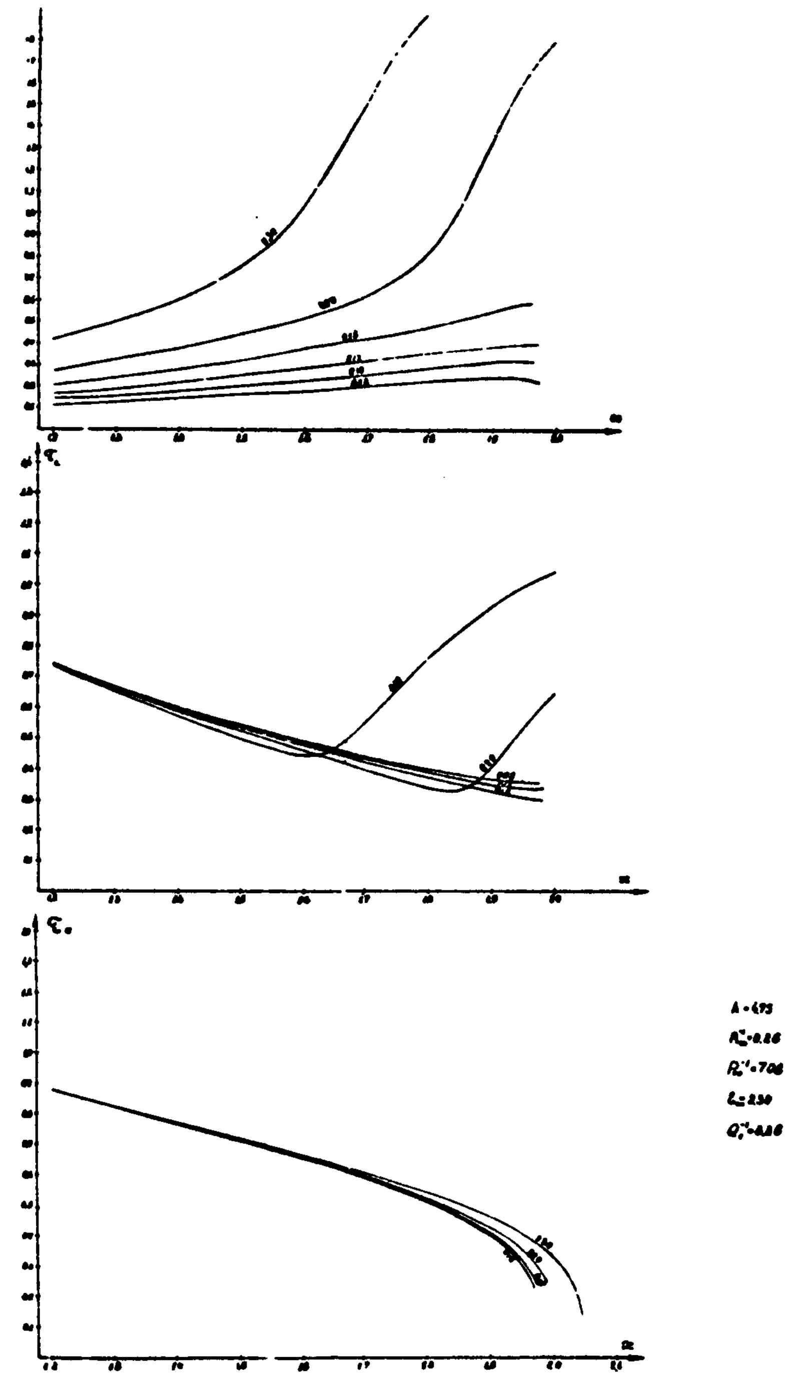

Fig. 7.

Dependence of the nature of the solutions on the initial velocity.

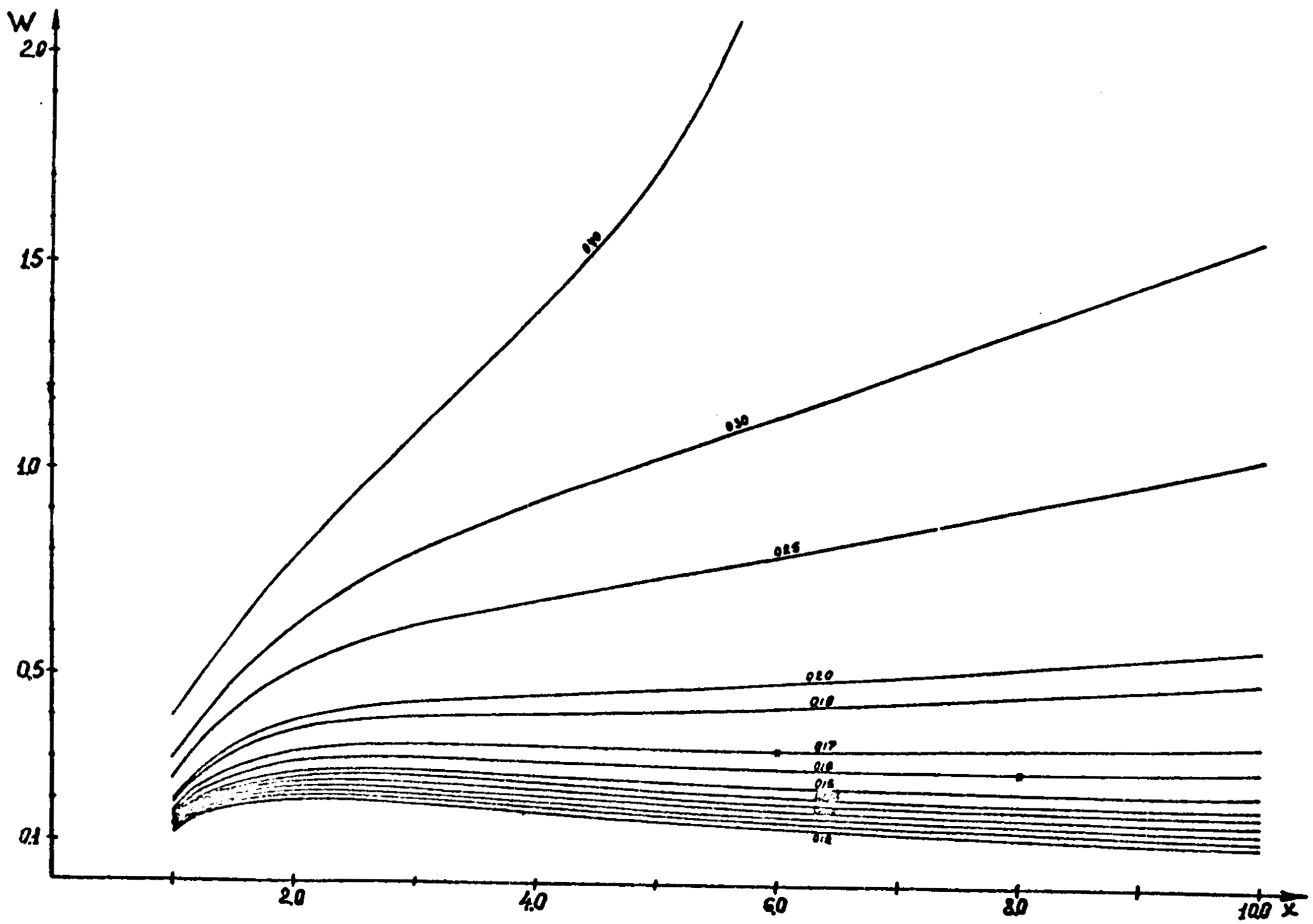

Fig. 8 a.

Dependence of the nature of the solutions on the integration region (x-position of minimum W).

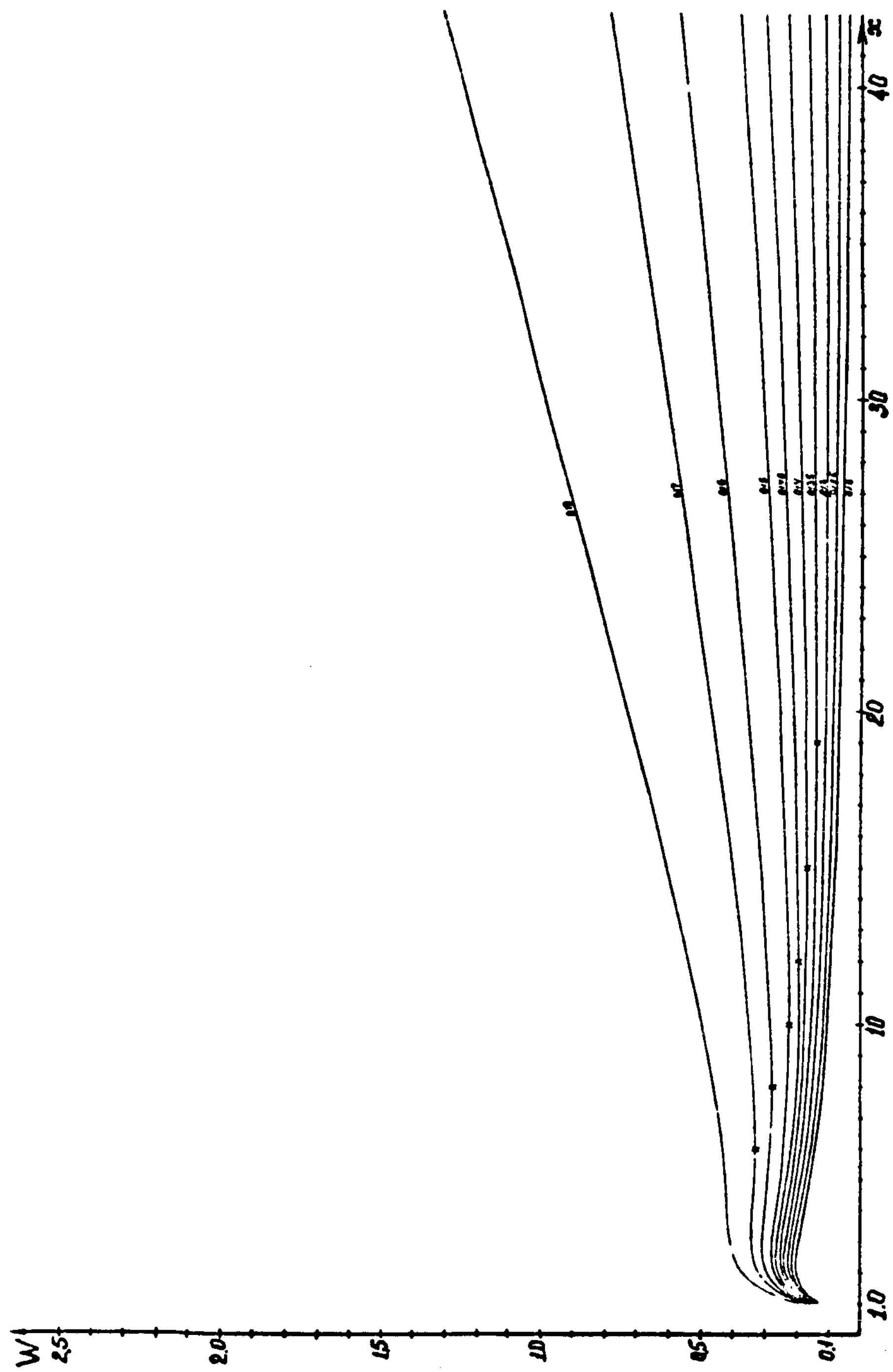

Fig. 8 c.

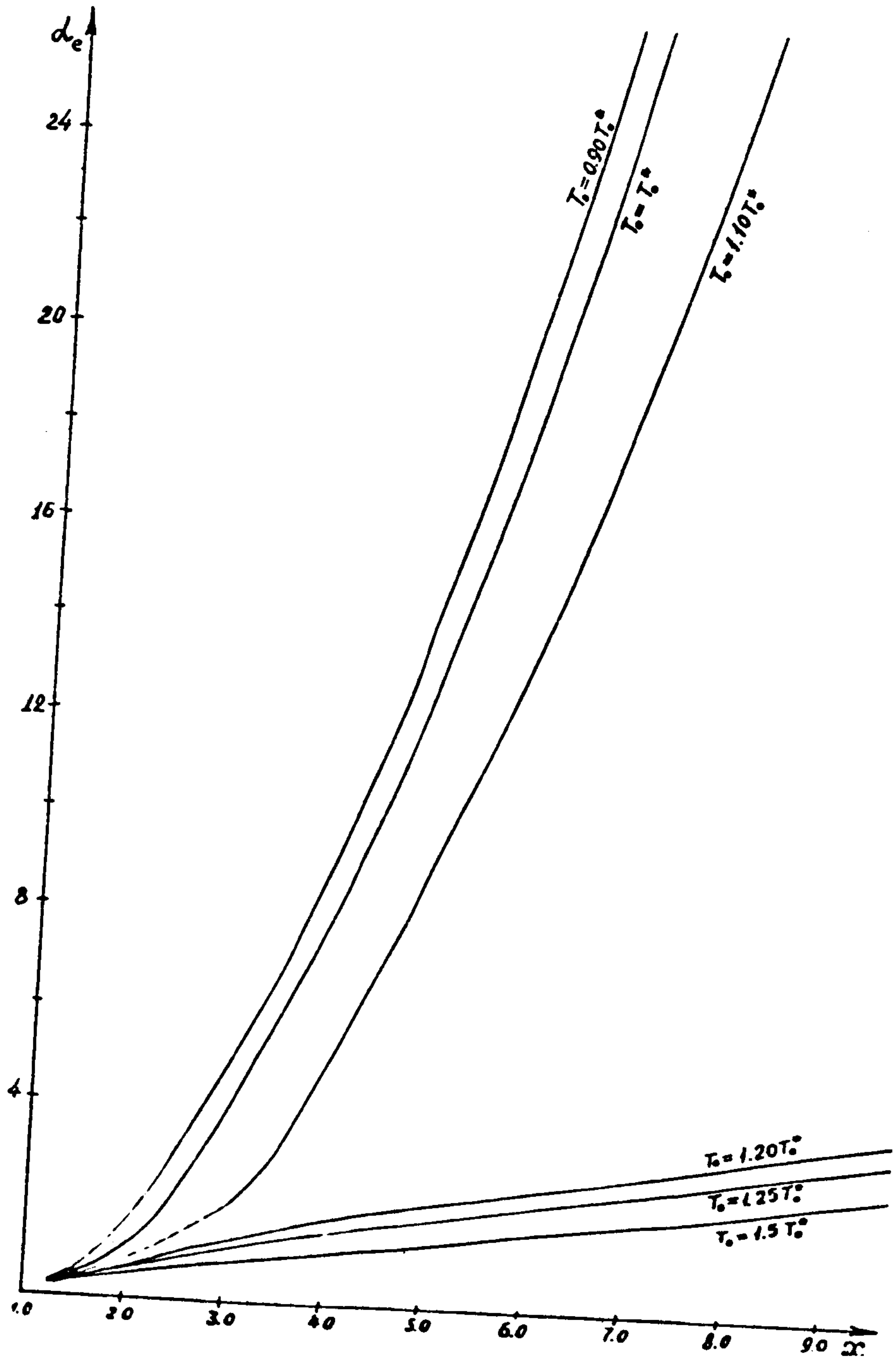
α_e
24
20
16
12
8
4
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
x
$T_o = 0.90 T_o^*$
$T_o = T_o^*$
$T_o = 1.10 T_o^*$
$T_o = 1.20 T_o^*$
$T_o = 1.25 T_o^*$
$T_o = 1.5 T_o^*$

Fig. 9 a.

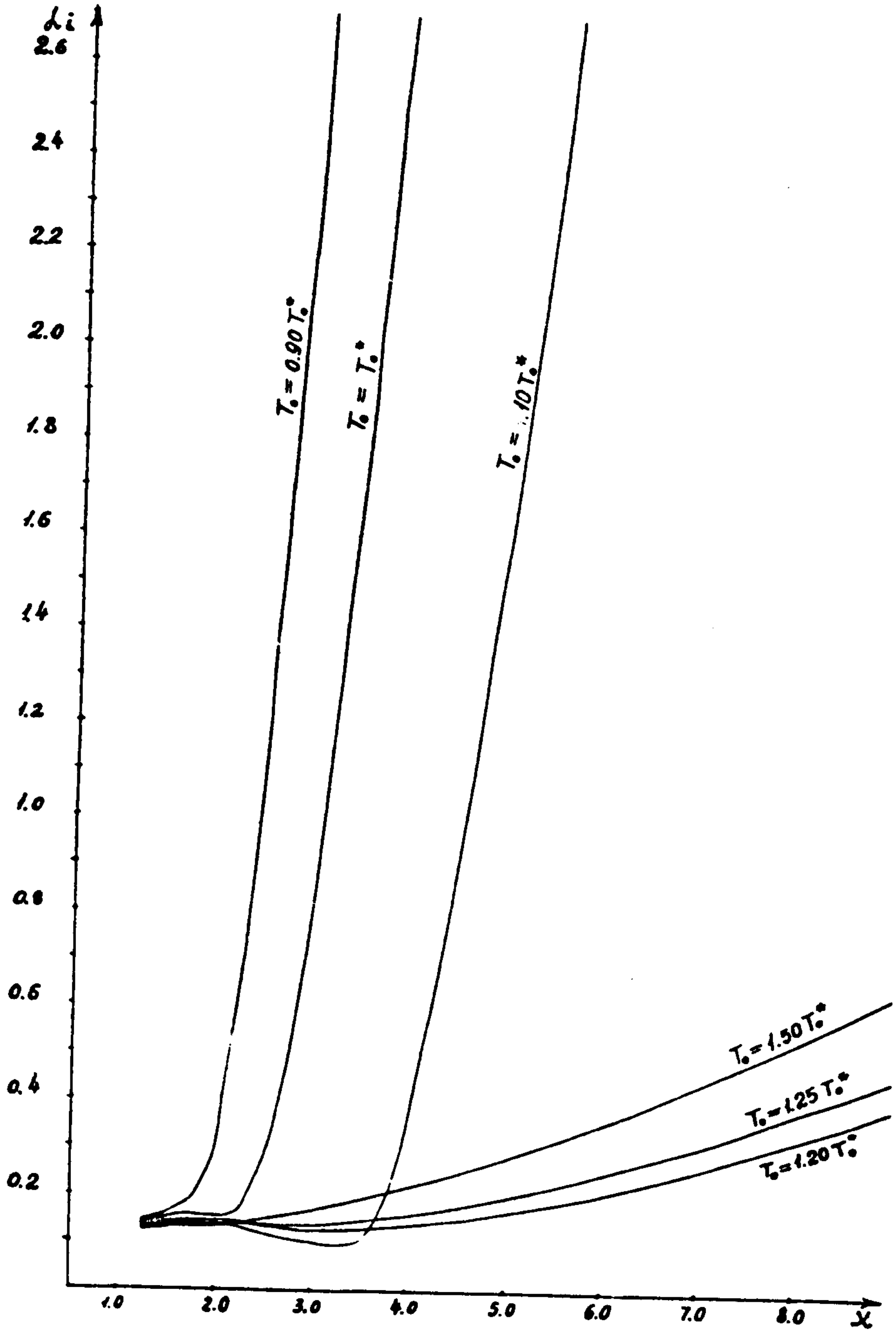

Fig. 9 c

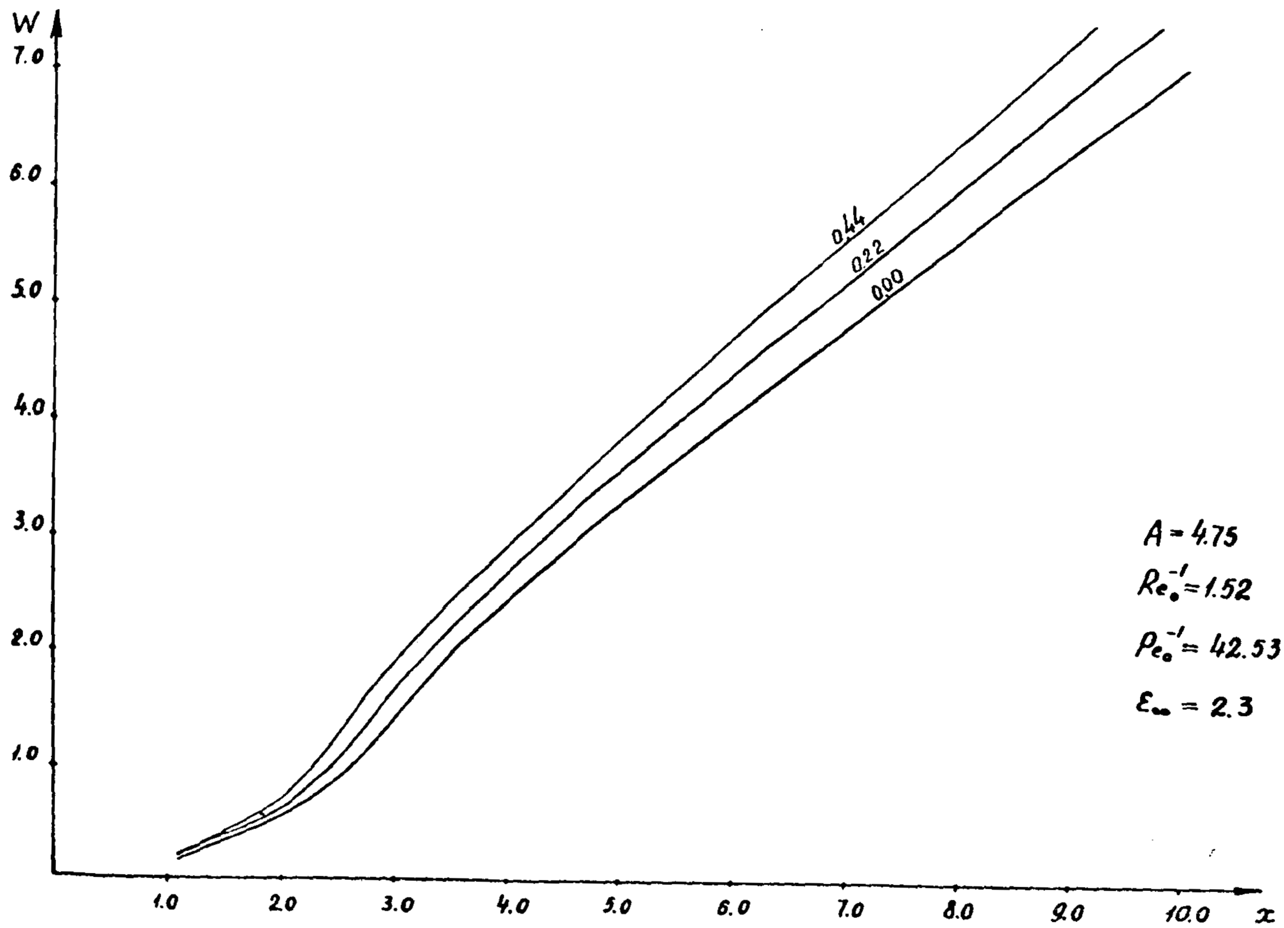

Fig. 10.

Sensitivity of solutions to kUo

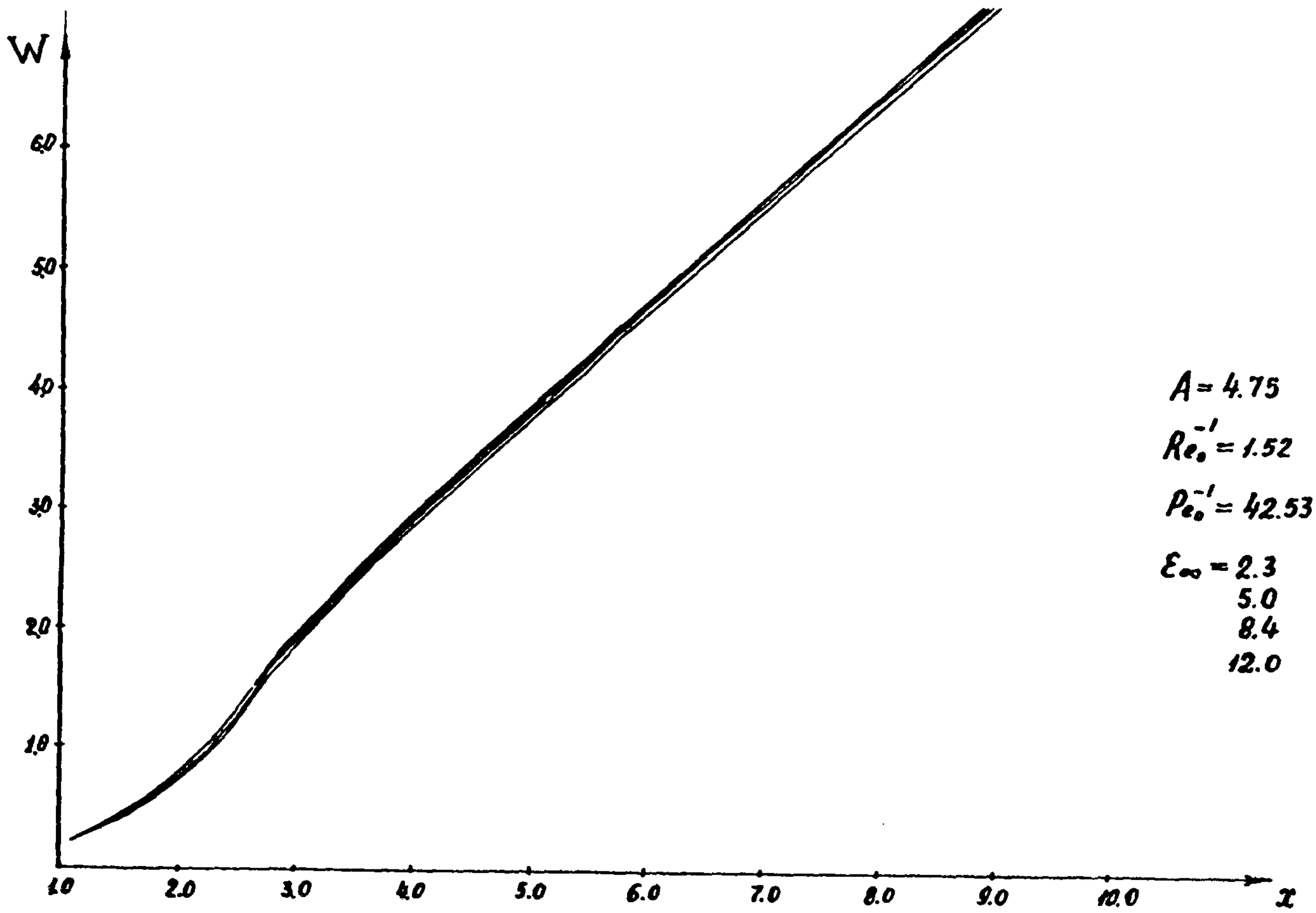

Fig. 11.

Sensitivity of solutions to kE_∞.