ON THE MODEL OF THE SOLAR WIND - INTERSTELLAR MEDIUM INTERACTION WITH TWO SHOCK WAVES

V. B. BARANOV, K. V. KRASNOBAEV, and M. S. RUDERMAN
Academy of Sciences of the U.S.S.R. Space Research Institute, Moscow, U.S.S.R.

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Abstract. The model of the solar wind interaction with interstellar medium suggested by Baranov *et al.* (1970) is developed. In this model (TSM) the presence of two shock waves is assumed, through which the solar wind and interstellar gas pass, the latter moving relative to the Sun at supersonic speed (20 km s^{-1}).

The distance between shocks was considered earlier (Baranov *et al.*, 1970; Baranov and Krasnobaev, 1971) to be small compared with their distance from the Sun, due to the hypersonic character of the flow. The structure of the subsonic flow portion may not be taken into account.

In the present paper the distribution of the gas parameters in the region between shocks is calculated which, in particular, allows us to estimate the possibility of its experimental detection, observing radio-scintillation on interstellar irregularities (Baranov *et al.*, 1975).

The possible influence on the model of galactic hydrogen neutral atoms penetrating into interplanetary medium is estimated.

1. Introduction

According to the concepts of the solar wind, the solar corona plasma – as a result of its thermal expansion – acquires supersonic speed even at the distance of the order of some solar radii and thereafter this speed remains almost constant. With spherical symmetry of this flow this means that the density increases inversely with the square of the distance from the Sun.

The density decrease results because, at some heliocentric distance, the solar wind pressure may turn out to be insufficient to push it into interstellar medium. In fact, in most of the theoretical models of the solar wind, the detailed review of which is contained, e.g., in Baranov and Krasnobaev (1973), dynamic and static pressures vanish with increasing heliocentric distance while pressure in the interstellar medium with which the solar wind eventually merges, is finite (10^{-12}–10^{-14} dyn cm^{-2}). Thus, there is a region of the strong interaction of the solar wind with the interstellar medium.

This interaction character defines the physical conditions in the interplanetary medium, and so plays an important part in studying such questions as the propagation of cosmic rays in the near-solar space, the solar L_α-radiation scattering on neutral hydrogen, the particles' distribution and the magnetic field formation in the vicinity of planets (Axford, 1972; Baranov and Krasnobaev, 1973).

The position and the form of the region of strong deceleration of the solar wind are defined by conditions in both the interplanetary plasma and the interstellar medium (e.g., by the sum of static, dynamic and magnetic pressures in the interstellar medium as well as by pressure of cosmic rays).

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Hence, in order to choose the basic mechanism of the solar wind deceleration it is important to know density, temperature, degree of the interstellar gas ionization, the value of its directed velocity relative to the Sun, the interstellar magnetic field value, and the cosmic ray flux characteristics.

Since the nearest star is removed from the Sun by more than one parsec, it is reasonable to assume that the solar wind interacts directly with the interstellar medium but not with the stellar wind as the region containing the solar wind does not exceed 10^2 to 10^3 a.u. $\sim 10^{-2}$ ps.

At present the interstellar gas is accepted to be sufficiently inhomogeneous and to consist of the dense cold clouds and the hot rarefied intercloud matter (Field, 1972). The predominant chemical element in the interstellar gas is hydrogen. The observation data analysis shows (Pottash, 1972 a, b) that the average particle concentration in clouds is $\sim 6\ \mathrm{cm}^{-3}$. At 10^2 K gas is slightly ionized (electron concentration is 10^{-2} to 10^{-1} cm^{-3}). It also follows from the observations that there are clouds of fully ionized hydrogen with high temperature $T \sim 10^4$ K, and concentration of the order of the average value given above.

In the intercloud medium the neutral hydrogen atoms concentration is $n_H \sim 0.1$ cm^{-3} when the electron concentration is $n_e \sim 0.03\ \mathrm{cm}^{-3}$ and the temperature is $T \sim 8000$ K (Dalgarno and McGray, 1972).

It should be noted that the available estimates of the neutral hydrogen concentration in the solar neighbourhood which are based on the recorded L_α-quanta background interpretation lead to the values $n_H \sim 0.05$–$0.25\ \mathrm{cm}^{-3}$ depending on the taken assumptions (Wallis, 1974; Fahr, 1974).

The peculiarites of the L_α-quanta intensity distribution are consistent with the fact that the Sun's velocity relative to the interstellar gas may be assumed equal to 20 $\mathrm{km\ s}^{-1}$ – coinciding with the estimated velocity of the Sun's motion relative to the nearest stars (Brandt, 1972). So the solar wind plasma interacts with the supersonic flow (supersonic interstellar wind) of interstellar gas if the temperature of the latter does not exceed 10^4 K. The magnetic field in the neighbourhood of the solar system is $\sim 10^{-6}$ (see, e.g., Axford, 1972).

It follows from the above considerations that the absence of precise information about physical conditions in the interstellar medium makes the study of the question of the solar-wind deceleration quite difficult. Nevertheless, at present there exists a series of theoretical models using one or another concrete mechanism of the solar wind interaction with the interstellar medium (see, e.g., available surveys on this question: Baranov and Krasnobaev, 1973; or Axford, 1972).

The interest in such models – in spite of simplifications of the real situation entailed in them – arises from the possibility of estimating the effect of different factors on a size of the region of supersonic flow of the solar wind, and to refine the gas distribution in the near-solar space. The urgency of such estimates especially increased because of their connection with the recent experimental evidences for the interstellar gas penetration into the internal regions of the solar system (Bertaux and Blamont, 1971; Thomas and Krassa, 1971) and in connection with possible (in the near future) flights of space vehicles to the outer planets (Axford, 1972, 1973).

2. Model with two Shocks (TSM)

Consider the solar wind interaction with the interstellar medium under the assumption that the phenomenon is governed by the equations of hydrodynamics. Moreover only the ionized component of the interstellar medium is taken into account (the effect of the neutral hydrogen atoms is discussed in the next section). The assumption on the validity of the hydrodynamic approximation is due to the fact that the solar-wind protons which are considered as test-particles moving in the charged-particles field of the interstellar medium, lose almost completely their directed impulse and transmit it to the electrons (see, e.g., Sivuhin, 1964) of the interstellar plasma at distances $L \lesssim 1$ a.u. at $n_e \sim 1\ \mathrm{cm}^{-3}$ and for $T \sim 5 \times 10^3$ K (total deceleration of a solar wind proton due to elastic collisions with neutral hydrogen atoms at the same concentration and temperature will occur at distances of 200 a.u.). The electrons decelerate in turn the protons of the interstellar medium.

At the same time, as will be shown below, the characteristic scale of the flow is of the order of tens of a.u. and more. If should be also noted that when two plasma flows penetrate each other, the beam instability can arise. Scattering of charged particles on arising fluctuations represents the effective mechanism of collisions excluding the existence of multiple-speed streams of ionized gas and interpenetration of single-speed streams into each other. The magnetic field can convert the system into a hydrodynamic one as well. It is seen from these considerations that there are reasons to describe the solar wind interaction with ionized component of the interstellar medium within the hydrodynamic model though the estimations are almost marginal.

If the interstellar medium were motionless with respect to the Sun, and the solar wind was spherically symmetrical, the deceleration of the latter would be accompanied by the occurrence of a spherically-symmetrical shock (Parker, 1961). Interstellar gas

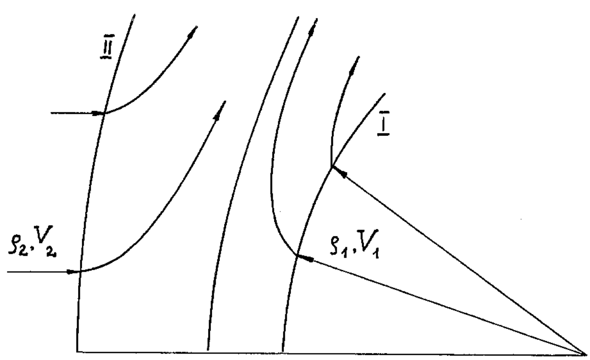

Fig. 1. The qualitative picture of the solar wind-supersonic interstellar wind interaction.

motion relative to the Sun (interstellar wind) will result in the destruction of the shock's spherical symmetry and in the commencement of axial flow. As noted in the previous section, the interstellar wind is supersonic, and a flow shown qualitatively in Figure 1 appears. Two shocks are formed; the solar wind passes through one of them (I) and the interstellar gas through the other (II). The model of such a flow (TSM) was suggested and calculated by Baranov *et al.* (1970) on the assumption that the distance between two shocks is small compared with the distance from the Sun, and so the compressed layer can be considered as a discontinuity surface across which the velocity of gas does not change. From the impulse conservation law in the gas layer in directions normal and tangent to the layer the discontinuity surface form was found (Baranov *et al.*, 1970; Baranov and Krasnobaev, 1971). This method (so-called Busemann's method) is widely used in hydro-aeromechanics for calculations of the hypersonic gas flows (Cherny, 1959).

Yet for quite a number of astrophysical applications (radio and cosmic rays propagation, L_α-radiation scattering) it is interesting to know the structure of the region between the shocks. Below this structure is calculated by the boundary layer method (Cherny, 1959).

Let the point M location be characterized by coordinates x and y (Figure 2). The distance x is measured on the symmetry axis along the tangential discontinuity $(t-t)$ up to the cross-point with the normal from M onto the tangential discontinuity. The coordinate y is equal to the length MN. The angle between the tangent to tangential discontinuity at a point N and the symmetry axis is denoted by α, and the distance from points N and M to the symmetry axis as l_t and l, respectively. If the radius of the tangential discontinuity curvature at a point N is denoted as R and $dR/dx \ll 1$, then adopting as independent variables the coordinate x and the stream function ψ,

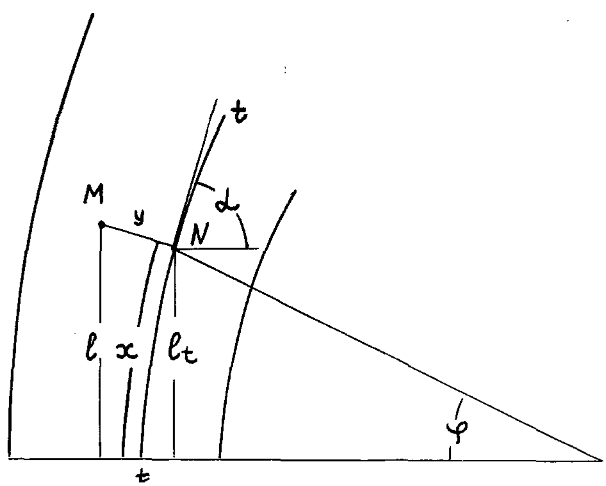

Fig. 2. The curvilinear coordinate system used.

defined by the equation

$$d\psi = \varrho u l \, dy - \varrho v l (1 + y/R) \, dx,$$

(u, v are the components of gas speed in directions x, y, and ϱ is the density) we get a set of the gas-dynamic equations for isentropic stream (Cherny, 1959) of the form

$$\varrho u \frac{\partial u}{\partial x} + \varrho v \frac{\partial v}{\partial x} + \frac{\partial P}{\partial x} = 0,$$

$$\frac{1}{1 + y/R} \frac{\partial v}{\partial x} - \frac{u}{R + y} = -l \frac{\partial P}{\partial \psi}; \qquad \frac{\partial}{\partial x}\left(\frac{P}{\varrho^{\gamma}}\right) = 0, \tag{1}$$

where P is the gas pressure and γ the adiabatic index. If the shock (I) is defined by equation $y = y_1(x)$ and the shock (II) by equation $u = y_2(x)$ (Figure 2), the relations on these shocks are written as

$$P = \frac{2}{\gamma + 1} \varrho_1 V_1^2 \sin^2(\beta_1 + \varphi) - \frac{\gamma - 1}{\gamma + 1} P_1,$$

$$\frac{\varrho_1}{\varrho} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{(\gamma + 1)} \frac{1}{M_1^2 \sin^2(\beta_1 + \varphi)} =$$

$$= \frac{-\dfrac{u y_1'}{1 + y_1/R} + v}{V_1\left[\sin(\alpha + \varphi) + \cos(\alpha + \varphi) \dfrac{y_1'}{1 + y_1/R}\right]} -$$

$$- V_1\left[\cos(\alpha + \varphi) - \sin(\alpha + \varphi) \frac{y_1'}{1 + y_1/R}\right] = u + \frac{v y_1'}{1 + y_1/R}, \tag{2}$$

for internal shock (I); and

$$P = \frac{2}{\gamma + 1} \varrho_2 V_2^2 \sin^2 \beta_2 - \frac{\gamma - 1}{\gamma + 1} P_2,$$

$$\frac{\varrho_2}{\varrho} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{(\gamma + 1)} \frac{1}{M_2^2 \sin^2 \beta_2} = \frac{\dfrac{u y_2'}{1 + y_2/R} - v}{V_2\left[\sin\alpha + \cos\alpha \dfrac{y_2'}{1 + y_2/R}\right]} \times$$

$$\times V_2\left(\cos\alpha - \sin\alpha \frac{y_2'}{1 + y_2/R}\right) = u + \frac{v y_2'}{1 + y_2/R}, \tag{3}$$

for external shock (II), where indexes '1' and '2' signify that the parameters' values are taken in the solar wind undisturbed by the shocks and the interstellar medium, respectively. M is Mach number, β is the angle between tangent to the shock and symmetry axis, and φ is the angle between the radius-vector ON and symmetry axis.

The solution of the set of Equations (1) subject to the boundary conditions (2), (3) and pressure-balance condition on the tangential discontinuity is sought as an expansion of small parameter $\varepsilon = (\gamma - 1)/(\gamma + 1)$ of the form

$$y = \varepsilon y^{(0)} + \cdots; \qquad u = u^{(0)} + \varepsilon u^{(1)} + \cdots; \qquad v = \varepsilon v^{(0)} + \cdots,$$
$$P = P^{(0)} + \varepsilon P^{(1)} + \cdots; \qquad \varrho = \frac{\varrho^{(0)}}{\varepsilon} + \varrho^{(1)} + \cdots. \tag{4}$$

In the first non-vanishing approximation the set of Equations (1) with boundary conditions (2) and (3) is integrated. In particular, for the internal and external pressures we get

$$P^{(0)} = \varrho_1 V_1^2 \sin^2 [\alpha(x) + \varphi(x)] - \frac{1}{Rl_t} \int_{\psi}^{\psi_1^*} u^{(0)} \, d\psi,$$
$$P^{(0)} = \varrho_2 V_2^2 \sin^2 \alpha(x) - \frac{1}{Rl_t} \int_{\psi}^{\psi_2^*} u^{(0)} \, d\psi, \tag{5}$$

where $\psi_{1,2}^*$ are the values of stream function in zero-order approximation for interior (I) and external (II) shocks, given by the expressions

$$\psi_1^* = -\varrho_1 V_1 \int_0^x l_t(x) \sin [\alpha(x) + \varphi(x)] \, dx,$$
$$\psi_2^* = \tfrac{1}{2} \varrho_2 V_2 l_t^2(x). \tag{6}$$

It is easy to prove that, to a zero-order approximation, the pressure-balance condition is satisfied on the discontinuity surface found by Busemann's method (Baranov

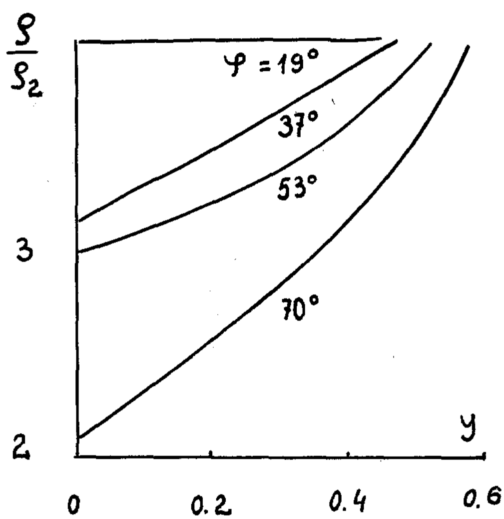

Fig. 3. Density distribution behind bow shock.

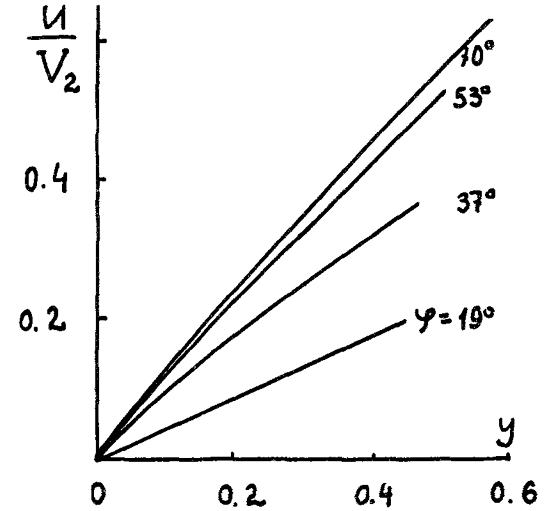

Fig. 4. Tangential component velocity distribution behind bow shock.

et al., 1970). As the form of tangential discontinuity is known from the paper just mentioned the problem is reduced to the calculation of flow over the given surface by two independent streams of plasma.

The analysis shows that the zero-order approximation does not predict well enough the position of internal shock and the flow field of the gas passing through it. However, accurate numerical computation by the 'relaxation' techniques with discontinuity separation shows that, in zero-order approximation, the form of tangential discontinuity is predicted with tolerable accuracy, as well as the character of the external flow (M. M. Gilinsky and M. G. Lebedev, private communication).

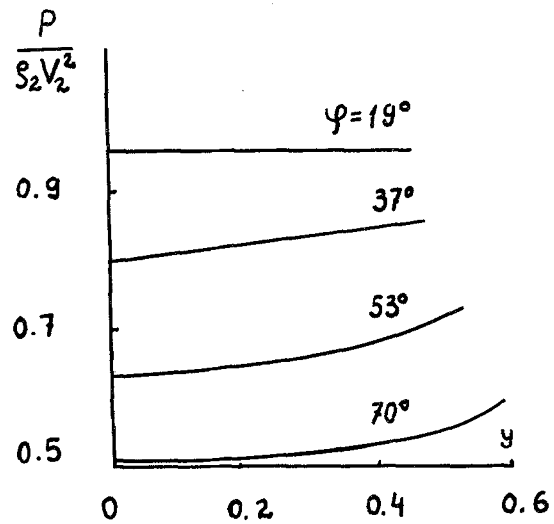

Fig. 5. Pressure distribution behind bow shock.

For an interpretation of the observations the most important characteristic is the external flow relative to the tangential discontinuity, because the gas density there is considerably higher than in the internal domain. Therefore in Figures 3 to 5 the numerical results of flow structure are represented only for the external portion relative to tangential discontinuity of the flow at $M_{1,2}=\infty(P_{1,2}=0)$ and $\gamma=5/3$. The computations give the possibility to estimate the influence of plasma compressed by the shocks on the radio-waves passing (Baranov *et al.*, 1975), on L_α- radiation scattering (Wallis, 1975), on the cosmic rays propagation.

3. The Influence of the Neutral Hydrogen Atoms of Interstellar Medium

As mentioned above, according to both the theoretical ideas and the observational data in the neighbourhood of the solar system, the presence of the neutral hydrogen atoms with concentration $n_H \sim 0.1$–$1\ \mathrm{cm}^{-3}$ can be expected. Then the interaction of solar wind with the stream of the neutral particles moving relatively to the Sun with a speed of about 20 km s^{-1} arises mainly from the charge exchange.

Wallis (1971) studied the solar wind deceleration due to this process and showed that, in this case, the continuous transition from the supersonic solar wind to the subsonic one is possible without shock formation. TSM is obviously valid (Baranov *et al.*, 1970; Baranov and Krasnobaev, 1971) if

$$r^* < r_c, \qquad r^* < r_s, \tag{8}$$

where r_c is the position of the critical point (i.e., one of transition into subsonic flow) in the case of the solar wind deceleration due to charge exchange with the neutral hydrogen atoms; r_s is the shock position if the solar wind interacts mainly with large-scaled magnetic field; and r^* is the distance up to the discontinuity along the symmetry axis towards the apex in the TSM model. In this case

$$\frac{r^*}{r_E} = \sqrt{\frac{\varrho_E}{\varrho_2}\frac{V_1}{V_2}}, \qquad \frac{r_c}{r_E} = \frac{4\gamma}{(\gamma-1)(\gamma+2)}\frac{R_{ex}}{r_E}, \qquad \frac{r_S}{r_E} = \sqrt{\frac{\varrho_E V_1^2}{B^2/8\pi}},$$

where, as before, index '1' refers to the parameters in the solar wind and index '2', in interstellar medium, $r_E=1$ a.u.; ϱ_E is the solar wind density at the Earth's orbit; and $R_{ex}=1/n_H\sigma_{ex}$ ($\sigma_{ex}=2.5\times10^{-15}$ cm^2 is the cross-section of charge exchange). From (8) it is easy to obtain (for $n_E \sim 4$ cm^{-3}, $V_1 \sim 4\times10^7$ cm s^{-1}, $V_2 \sim 2\times10^6$ cm s^{-1}, $\gamma=5/3$) that

$$\sqrt{n_2} > 0.5 n_H, \qquad \sqrt{n_2} > 10^5 B, \tag{9}$$

where the coefficients are dimensional.

If Equation (8) (or (9)) is violated, then TSM should be changed. In particular, if the first inequality (8) (or (9)) is not valid, the second shock continues to exist, but the flow of the solar wind should be calculated taking account of the charge exchange processes. Besides, even if the inequalities (8) and (9) are satisfied, the charge exchange results in the solar wind velocity will not be constant but will decrease with the helio-

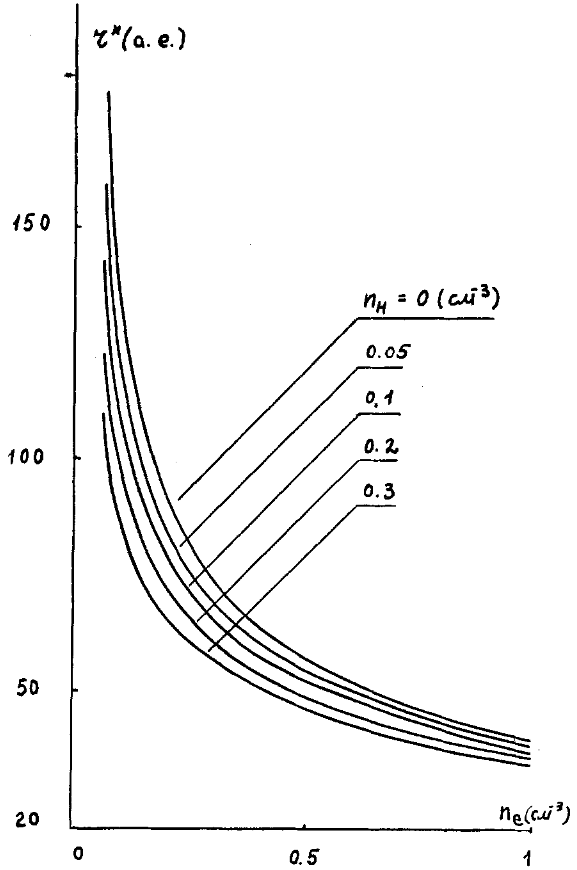

Fig. 6. The stagnation point for different n_H

centric distance r. Therefore, TSM is necessary to change in order to take into account the V_1 dependence on r.

In Figure 6 the numerical calculations of the distance to discontinuity at frontal point (in the direction of the apex) depended on the electron concentration n_e in the interstellar medium and the different concentrations of the neutral particles in the TSM model. In calculations, the equations of TSM (Baranov *et al.*, 1970) are used as well as the expression

$$V(r) = V_E \exp(-r/R_{ex})$$

for solar-wind velocity by taking into account the charge exchange under some simplified assumptions (McDonough and Brice, 1971). The calculations were carried out for the domain of parameters in which the inequalities (8) or (9) are valid. The main conclusion that follows from the analysis of curves represented in Figure 6 consists of the fact that, for a wide range of the electron concentration and of the hydrogen neutral atoms in the interstellar medium, the charge exchange results in decreasing of the value r^* found in TSM only by some dozens of percent.

4. Conclusions

On the basis of the calculations carried out so far the following conclusions can be drawn:

(1) The interaction region between two shocks is sufficiently wide. Despite this result, TSM properly predicts the position of tangential discontinuity separating the solar wind and the interstellar medium, as it was mentioned in Section 2.

(2) In the presence of neutral hydrogen atoms, the tangential discontinuity and the internal shock are displaced to somewhat smaller heliocentric distances than those predicted by TSM. Nevertheless, even if the first one of inequalities (9) breaks down, the external shock continues to exist; but in calculations of the solar wind flow, the charge exchange processes turn out to be essential.

(3) The calculations carried out so far allow us to estimate the influence of the plasma compressed by the shocks on the radio waves passing from the sources at small angles (Baranov *et al.*, 1975), the scattering of the L_α-radiation (Wallis, 1975), and the dispersion of cosmic rays. A comparison of future relevant experimental data with the results of theoretical studies will allow us to single out more precisely a model among the existing ones which corresponds best to the reality.

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