A MODEL OF THE INTERACTION OF THE SOLAR WIND WITH THE INTERSTELLAR MEDIUM

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Abstract

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A MODEL OF THE INTERACTION OF THE SOLAR WIND WITH THE INTERSTELLAR MEDIUM

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Experimental investigations of interplanetary plasma by means of spacecraft have established the fact that supersonic plasma streams from the Sun exist. The results of these investigations do not contradict the existing theories of the solar wind (see, for example, (^1, ^2)). According to the currently accepted theory of the solar wind, the plasma of the solar corona, as a result of thermal expansion, acquires a supersonic velocity already at a small distance from the Sun (on the order of several solar radii), and then the velocity rapidly approaches an asymptote. From a distance approximately equal to one astronomical unit, this velocity may be regarded as constant, which, for a spherically symmetric flow, leads to a decrease of density as $1/r^2$ (r is the distance from the Sun). According to E. Parker (^1), the magnetic pressure of the general magnetic field of the Sun at large heliocentric distances also falls as $1/r^2$, and, because of its smallness in comparison with the dynamic pressure of the solar wind, the latter cannot be braked by the magnetic field of the Sun.

The decrease in mass density ρ leads to the fact that at certain distances from the Sun the pressure of the solar wind may prove insufficient to push it into the interstellar medium.

According to the hypotheses currently in existence, the braking of the solar wind occurs as a result of its interaction either with the interstellar magnetic field, or with the interstellar gas, or with cosmic rays. From the estimates given in reviews (^3, ^4), and also in the work (^5), it follows that the region of strong braking of the solar wind begins at a heliocentric distance $r \sim$ 10–100 AU, depending on the nature of the hypothesis adopted. In this case the character of the interaction depends substantially on the degree of ionization of the interstellar medium.

The degree of ionization of the interstellar gas in the vicinity of the solar system is at present practically unknown. However, estimates from the scattering of solar L_α-radiation by galactic hydrogen (^6), as well as a theoretical calculation of the H II zone for the Sun (^7), using rocket measurements of the far-ultraviolet solar spectrum, show that the zone of almost complete ionization of hydrogen extends to a distance of not less than 10^3 AU. In addition, the interstellar gas in the vicinity of the solar system may be ionized by the radiation of the nearest hot stars (for example, γ Vel and ξ Pup).

The model proposed and calculated below is based on the assumption that Coulomb collisions predominate in the interstellar gas.

We shall regard the solar wind as spherically symmetric in the vicinity of the Sun and consider its interaction with interstellar gas moving relative to the Sun. Then the problem will possess cylindrical symmetry.

We shall assume that the flow can be described by hydrodynamic equations. This assumption is justified by the fact that the ions of the solar wind, considered as test ions moving in the field of charges-

charged particles of the interstellar medium almost completely lose their directed momentum and transfer it to the electrons ([8]) of the interstellar plasma at distances $L \lesssim 1$ AU (in the calculation the density and temperature of the interstellar medium were taken equal to $\rho_1 = 10^{-24}$ g/cm^3, $T_1 = 5 \cdot 10^3$ °K, and the velocity of the solar wind $v_2 = 3 \cdot 10^7$ cm/sec). The electrons, in turn, brake the ions of the interstellar medium. In addition, when two plasma streams penetrate into one another, beam instability may arise, which can also determine the scattering of charged particles. These processes may be regarded as effective

Fig. 1
Fig. 1

Fig. 2
Fig. 2

Fig. 3
Fig. 3

collision mechanisms excluding the possibility of the existence of multivelocity streams of ionized gas and allowing the possibility of mutual penetration of single-velocity streams into one another. At the same time, as will be shown below, the characteristic scale of the phenomenon is of the order of tens of astronomical units.

Both the solar wind and the stream of interstellar gas move with supersonic velocities. For the solar wind one may, to a good approximation, take the Mach number $M_2 = \infty$, while for the interstellar gas, assuming that its temperature $T_1 \lesssim 5 \cdot 10^3$ °K and its velocity $v_1 \sim 20$ km/sec, we obtain $M_1 \gtrsim 2$. In the interaction of supersonic streams a flow arises, qualitatively shown in Fig. 1. Two shock waves are formed: the interstellar gas passes through one of them, and the solar wind through the other.

In the layer between the shock waves the gas is in a compressed state, and its density substantially exceeds the density of the surrounding medium. For a rough estimate of the shape of this compressed layer we shall use the Busemann method ([9]). Considering the gas layer between the shock waves to be thin (a surface) and the gas velocity not to change across the layer, we write the law of conservation of momentum in the gas layer, in projections on the normal and tangent to the layer in a heliocentric coordinate system,

$$\rho_1 v_{1n}^2 = \rho_2 v_{2n}^2 + \frac{m v_l}{2\pi r \sin\varphi\, R};$$

$$\frac{d}{dl}(m v_l) = 2\pi r \sin\varphi\,(\rho_1 v_{1n} v_{1\tau} + \rho_2 v_{2n} v_{2\tau})\,. \qquad (1)$$

Here ρ_1, v_1 are the density and velocity of the interstellar gas; ρ_2 and v_2 are the same quantities in the solar wind; m is the mass of gas entering the layer per unit time from the solar wind and from the interstellar medium; R is the radius of curvature of this surface (the second term on the right in the first equation represents the centrifugal force acting on the gas inside the interaction region); v_l is the mean velocity of the gas along the discontinuity surface; the indices n and τ refer to the projections of the corresponding velocities on the normal and tangent, respectively; r and φ are polar

the coordinates of the surface replacing the layer of gas between the shock waves (Fig. 2). The quantities m and R are determined by the formulas (a prime denotes differentiation with respect to φ)

$$m = \pi r^2 \rho_1 v_1 \sin^2\varphi + 2\pi r^2 \rho_2 v_2 (1 - \cos\varphi);$$

$$R = \frac{(r^2 + {r'}^2)^{3/2}}{(r^2 + 2{r'}^2 - r r'')}; \qquad r = r(\varphi). \qquad (2)$$

Introducing the angle x between the direction of the velocity v_1 and the tangent to the surface, as well as the angle y between the direction of the normal to the surface and the direction of the radius vector (Fig. 2), and eliminating v_l, m, and R from (1) and (2), we obtain the equation

$$2\pi r' \sin\varphi\,(\rho_1 v_1^2 \sin x \cos x + \rho_2 v_2^2 \sin y \cos y) =$$

$$= \frac{1}{(r^2 + {r'}^2)^{1/2}} \left[\frac{2\pi r \sin\varphi\,(r^2 + {r'}^2)^{3/2}}{(r^2 + 2{r'}^2 - r r'')} \times \left(\rho_1 v_1^2 \sin^2 x - \rho_2 v_2^2 \cos^2 y\right) \right]', \qquad (3)$$

which, after taking into account the relations

$$\operatorname{tg} x = \operatorname{tg}\left[\pi/2 - \varphi + \operatorname{arc\,tg}(r'/r)\right];$$

$$\operatorname{tg} y = r'/r;$$

$$v_{1n} = v_1 \sin x; \qquad v_{1\tau} = v_1 \cos x; \qquad v_{2n} = v_2 \cos y;$$

$$v_{2\tau} = v_2 \sin y, \tag{4}$$

can be reduced to a complicated nonlinear differential equation of third order for the function $r = r(\varphi)$, which determines the shape of the surface separating two plasma flows. In dimensionless form this equation has the form (because of the cumbersomeness of the resulting equation, only its general form is written)

$$\xi''' = \psi_1(\varphi, \xi, \xi', \xi'')/\psi_2(\varphi, \xi, \xi', \xi'') \qquad (r = r_0 \xi). \tag{5}$$

Here ψ_1, ψ_2 are known functions of their arguments; r_0 is the heliocentric distance to the discontinuity surface at $\varphi = 0$; the value r_0 is determined from the relation $\rho_1 v_1^2 = \rho_2 v_2^2$ (which follows from the first equation (1) at $\varphi = 0$) using the continuity equation for a spherically symmetric solar wind, $\rho v r^2 = \text{const}$ ($v = \text{const}$).

The equation (5) was solved numerically under the boundary conditions

$$\xi = 1, \qquad \xi' = 0, \qquad \xi'' = {}^2/_5 \quad \text{at } \varphi = 0 \quad (\xi = r/r_0). \tag{6}$$

The second condition (6) is the condition of symmetry of the problem, while the third condition makes it possible to leave the singular point $\varphi = 0$, $r = r_0$ (as $\varphi \to 0$, the ratio ψ_1/ψ_2 is an indeterminacy of the form 0/0) along the integral curve passing through this point and to integrate equation (5) numerically. It should be noted that the right-hand side of equation (5), obtained from (3), (4), contains no dimensionless parameters, and all the curves $r = r_0 \xi(\varphi)$ determined by the solution of equation (5) under the boundary conditions (6) are similar to one another (r_0 depends on the ratio $\rho_1 v_1^2$ and $\rho_2 v_2^2$).

In Fig. 3 the results of a numerical calculation of the function $\xi = \xi(\varphi)$ are presented. In this figure, φ_0 denotes the angle between the plane of the ecliptic and the direction of motion of the Sun relative to the interstellar medium. The distance to the discontinuity surface along the ray $\varphi = \varphi_0$ is the distance to the discontinuity surface in the plane of the ecliptic.

Measurements show that $\varphi_0 \approx 53^\circ$. Then it follows from the calculations that $\xi(\varphi_0)/\xi(0) = r(\varphi_0)/r_0 \approx 1.2$.

Fig. 4

Figure 1: Fig. 4

In Fig. 4 the results are given of calculating the dependence of r_0 on the solar-wind velocity v_2 for various concentrations of particles n_2 in the Earth' s orbit and for $\rho_1 \sim 10^{-24}$ g/cm^3, $v_1 \sim 20$ km/sec.

Fig. 4

In particular, for $v_2 \sim 3 \cdot 10^7$ cm/sec and $\rho_2 \sim 5 \cdot 10^{-24}$ g/cm^3 ($n_2 \sim 5$ cm^{-3}) we have $r_0 \sim 35$ AU. The distance to the discontinuity surface in the plane of the ecliptic in this case is $r \sim 35 \cdot 1.2 = 42$ AU, i.e., the discontinuity surface is located somewhere in the region of Pluto' s orbit. At lower velocities or at lower densities of the solar wind, this distance, naturally, decreases.

It should be noted that at large angles φ the assumption that the layer between the shock waves is narrow is, obviously, violated. The external shock wave goes off to infinity and degenerates into a characteristic, while the internal one closes.

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Note: Figure translations are in progress. See original paper for figures.