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INTERSTELLAR MATTER AND THE LOCATION OF THE SHOCK FRONT

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Abstract—The initially supersonic flow of the solar wind passes through a magnetic shock front where its velocity is supposed to be reduced to subsonic values. The location of this shock front is primarily determined by the energy density of the external interstellar magnetic field and the momentum density of the solar wind plasma. Interstellar hydrogen penetrating into the heliosphere undergoes charge exchange processes with the solar wind protons and ionization processes by the solar EUV radiation. This results in an extraction of momentum from the solar wind plasma. Changes of the geometry and the location of the shock front due to this interaction are studied in detail and it is shown that the distance of the magnetic shock front from the Sun decreases from 200 to 80 AU for an increase of the interstellar hydrogen density from 0·1 to 1·0 cm^{-3}. The geometry of the shock front is essentially spherical with a pronounced embayment in the direction opposite to the approach of interstellar matter which depends very much on the temperature of the interstellar gas. Due to the energy loss by the interaction with neutral matter the solar wind plasma reduces its velocity with increasing distance from the Sun. This modifies Parker's solution of a constant solar wind velocity.

1. INTRODUCTION

The solar wind is presumed to drop to subsonic velocities at a specific distance $r = r_s$ from the Sun. This distance is reached, if the energy density of the solar wind plasma has decreased to the value of the energy density $B_i^2/8\pi$ of the external interstellar field. In that case both energies compete with each other and the undisturbed radial flow of the heliospheric solar wind can no longer be maintained. The plasma flow becomes controlled by the interstellar field B_i. Generally it is believed that the solar wind passes through a shock front at this region. The location r_s of the shock front can therefore easily be estimated with

$$r_s = 2v_h/B_i(n_E m_p \pi)^{1/2} \tag{1}$$

where n_E is the proton density at $r_E = 1$ AU, m_p is the mass of the proton and v_h is the constant heliospheric speed of the solar wind plasma.

Using plausible values for B_i, n_E and v_h Axford *et al.* (1963), Parker (1963) and Patterson *et al.* (1963) have found values for r_s between 60 and 100 AU.

It has been pointed out by Axford *et al.* (1963) that neutral interstellar hydrogen which enters the solar system should interact with the solar wind through the mechanism of charge exchange reactions with the solar wind protons. This mechanism must contribute significantly to the deceleration of the solar wind in the outer regions of the heliosphere and thereby to the location r_s of the shock front which depends strongly on the energy density of the solar wind plasma.

The neutrals which penetrate the shock front without undergoing charge exchange collisions enter the heliosphere with definite chances to suffer charge exchange collisions with solar protons here inside of r_s. The charge exchange collision between a proton and a hydrogen atom can be regarded as a simple cross-over of the electron from the neutral atom to the proton with negligible transfer of momentum. Therefore the charge exchange collision of a fast solar wind proton flying radially outwards from the Sun with the velocity v_h (400 km/sec) with a slow interstellar hydrogen atom which crosses the heliosphere with a velocity v (20–50 km/sec) results in a fast neutral moving outwards and a slow proton with the velocity v.

The same sort of slow protons are produced by the ionization of interstellar hydrogen atoms. Therefore this sort of slow proton originates both from charge exchange processes and EUV-ionizations. The solar wind now sweeps over these slow protons with its frozen-in magnetic field B and thus exerts a specific Lorentz force on it which causes an acceleration of the protons. This acceleration process is described by the following equation of motion:

$$m_p \frac{d\mathbf{v}}{dt} = e[(\mathbf{v}_h - \mathbf{v}) \times \mathbf{B}] \qquad (2)$$

where e is the electric charge and B is the frozen-in field which moves outward with the velocity v_h of the solar wind. The solution of Equation (2) is given by an oscillation around the velocity v_h with a period of $\tau = eB/m_p$. That means, the proton slowed down to a velocity v during the charge exchange collision is again accelerated to an average velocity v_h by the solar wind. (Blum and Fahr, 1970.)

The energy necessary for the acceleration of the slowed down proton is primarily taken from the energy of the frozen-in field B, but is indirectly taken from the kinetic energy of the plasma motion, since B is dominated by this motion. Therefore the charge exchange collisions of fast protons with slow interstellar hydrogen atoms result in an exhaustion of kinetic energy and momentum of the solar wind plasma. In their calculations of the density of fast secondary hydrogen atoms generated by charge exchange collisions within the heliosphere Blum and Fahr (1970) neglected this energy exhaustion and found an energy density for these secondary neutrals which is given in Fig. 1.

It can be seen that the density of the kinetic energy of the solar wind protons becomes equal to that of the secondary neutrals at a distance of about 90 AU. This of course is not a plausible result, because the assumptions of the authors that the energy exhaustion of the

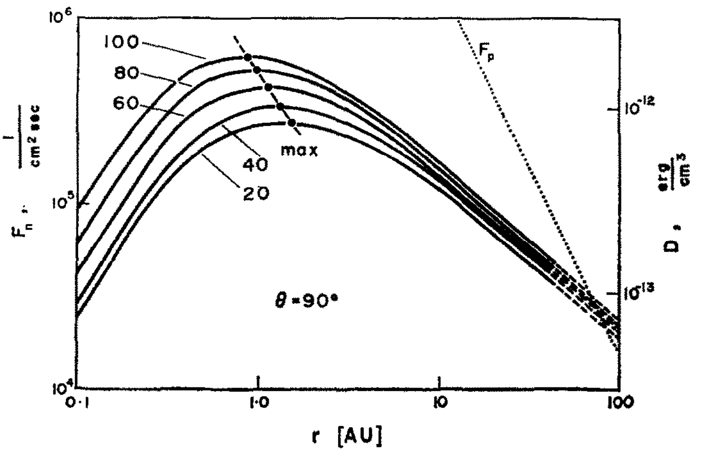

FIG. 1. THE FLUX F_n AND THE DENSITY D OF KINETIC ENERGY OF FAST SECONDARY NEUTRAL HYDROGEN ATOMS IS SHOWN VS. THE DISTANCE r FROM THE SUN FOR VARIOUS RELATIVE VELOCITIES v_0(20–100 km/sec) OF THE INTERSTELLAR MATTER WITH RESPECT TO THE SOLAR SYSTEM.

The direction in which the distance r is plotted is inclined by an angle $\theta = 90°$ against $\mathbf{v}_0$. The flux and the velocity v_h of the solar wind protons at 1 AU has been assumed to be $1{\cdot}5 \times 10^8$ protons/cm^2 sec and 4×10^7 cm/sec ($n_0 = 1$ cm^{-3}). The dotted line represents the flux F_p (the energy density D_p) of solar wind protons.

solar wind need not be taken into consideration is no longer fulfilled at distances about 90 AU. This means that in the outermost regions of the heliosphere the exhaustion of kinetic energy and momentum by charge exchange reactions of the solar wind plasma with interstellar hydrogen has to be taken into account. Especially the problem of the location of the shock front requires the exact calculation of this exhaustion. In the following we shall determine this exhaustion, in order to calculate the influence of neutral interstellar matter on the location and geometry of the magnetic shock-front.

2. EXHAUSTION OF THE SOLAR WIND ENERGY

Blum and Fahr (1970) have given a model of the density distribution of interstellar hydrogen in interplanetary space. They assume that neutral interstellar hydrogen approaches the Sun with a peculiar velocity v_0. It can be shown that more than 90 per cent of the incoming hydrogen atoms can penetrate the magnetic shock front and enter the heliosphere before suffering charge exchange collisions with the solar wind protons. Within the heliosphere interstellar hydrogen undergoes loss processes by charge exchange and EUV-ionization reactions, so that its density decreases with decreasing distances r from the Sun, in spite of the fact that gravitational focusing tends to enhance the particle density in the direction to the center of gravity.

The macroscopic motion of the interstellar hydrogen with a velocity v_0 relative to the Sun results in an anisotropic density distribution within the heliosphere with maximum densities in the direction ($\theta = 0°$) and antidirection ($\theta = 180°$) of $\mathbf{v}_0$ and minimum densities at a direction inclined by an angle $\theta = 160°$ with respect to $\mathbf{v}_0$. The numerical calculations of these densities $n(r, \theta)$ are given in the above mentioned paper of Blum and Fahr.

A solar wind proton starting at a distance r_0 from the centre of the Sun has a definite chance $W(r, \theta)$ of reaching the distance r in a radial flight without a charge exchange collision. This chance is given by

$$W(r, \theta) = \exp\left[-\frac{q_{ex}}{v_h}\int_{r_0}^{r} v_{rel} n(r', \theta)\, dr'\right] \tag{3}$$

where q_{ex} is the charge exchange cross section and v_{rel} means the relative velocity of solar wind protons with respect to neutrals at the space point (r', θ). Regarding the velocity v of the slow interstellar hydrogen atoms (20–50 km/sec) to be small in comparison to the velocity v_h (400 km/sec) of the solar wind protons, the relative velocity v_{rel} can be identified with v_h. This leads to:

$$W(r, \theta) = \exp\left[-q_{ex}\int_{r_0}^{r} n(r', \theta)\, dr'\right]. \tag{4}$$

That part of solar wind protons which have already undergone a charge exchange collision with an interstellar hydrogen atom is given by $[1 - W(r, \theta)]$. Though being reintegrated into the solar wind plasma of the velocity v_h the slowed-down and reaccelerated protons (formula 2) represent an energy loss for this plasma, because their initial energy has been transfered to neutral hydrogen atoms. A further energy loss of the solar wind plasma is due to new-born protons of nearly vanishing initial velocities which originate from EUV-ionizations of incoming neutral interstellar hydrogen atoms. The EUV-photons which leave the solar surface at a point $\{r_0, \theta\}$ become rarefied by the ionizations of these atoms on their way from the solar surface to the space point $\{r, \theta\}$. The number of EUV-photons lost per unit time along the ray from $\{r_0, \theta\}$ to $\{r, \theta\}$ is equal to the number of slow protons which have been produced by these photons and are reaccelerated to the speed of the solar wind. The remaining energy flux J at $\{r, \theta\}$ can therefore be given in the form;

$$J(r, \theta) = \tfrac{1}{2} m_p v_h^2 \left(\frac{r_E}{r}\right)^2 [F_E - F_E(1 - W(r, \theta)) - f_E(1 - U(r, \theta))] \tag{5}$$

where F_E and f_E are the fluxes of solar wind protons and EUV-photons at $r = r_E$, and the probability function $U(r, \theta)$ for the extinction of solar EUV-photons is given by:

$$U(r, \theta) = \exp\left[-q_{\text{euv}} \int_{r_0}^{r} n(r', \theta)\, \mathrm{d}r'\right] \tag{6}$$

with the EUV-ionization cross section q_{euv}. Both probability functions $W(r, \theta)$ and $U(r, \theta)$ can be represented by the first terms of their Taylor-series expansions, at least in the inner part of the heliosphere. Therefore we find from (5):

$$J(r, \theta) = \tfrac{1}{2} m_p v_h^2 (r_E/r)^2 \left[F_E - F_E q_{\text{ex}} \int_{r_0}^{r} n(r', \theta)\, \mathrm{d}r' - f_E q_{\text{euv}} \int_{r_0}^{r} n(r', \theta)\, \mathrm{d}r\right] \tag{7}$$

For low solar activity, i.e. low solar EUV-fluxes, the contribution of new-born protons to the energy exhaustion is small in comparison to that of protons which have exchanged their charge with hydrogen atoms. In any case the effect of the energy exhaustion of the solar wind by neutral matter can be studied taking account only of those protons which have exchanged charge, because the two contributions to J in (7) can for simplification formally be taken together, since both are given by the same integral. The kinetic energy density $D(r, \theta)$ which is still contained in the radially expanding plasma when it reaches a space point (r, θ) is therefore obtained from.

$$D(r, \theta) = \tfrac{1}{2} n_E \left(\frac{r_E^2}{r^2}\right) m_p v_h^2 \times W(r, \theta) \tag{8}$$

where n_E is the density of solar wind protons at $r_E = 1$ AU.

If we assume that the whole energy which is transfered to the interstellar neutrals is taken from the kinetic energy of the solar wind plasma, we have to expect that due to this energy loss the solar wind speed v_h decreases according to the equation

$$v_h'(r, \theta) = v_h W(r, \theta)$$

with a proton density

$$n_p(r, \theta) = n_E \left(\frac{r_E}{r}\right)^2 \frac{1}{W(r, \theta)}. \tag{9}$$

This means Parker's solution of a constant solar wind speed v_h cannot be fulfilled for the whole region of the heliosphere. Taking into account the charge exchange interaction between the solar wind plasma and the neutral interstellar gas we have to expect appreciably reduced solar wind velocities $v_h'(r, \theta)$ at distances r from the Sun where the neutral interstellar gas becomes dense with respect to the free motion of solar protons, that means where the so called charge exchange depth

$$d_{\text{ex}} = q_{\text{ex}}/v_h \int_{r_0}^{r} v_{\text{rel}} n\, \mathrm{d}r$$

attains the value of 1. Furthermore the location of the magnetic shock front is influenced by the energy loss due to charge exchange reactions of solar wind protons with interstellar hydrogen atoms. In a direction inclined by an angle θ against the velocity $\mathbf{v}_0$ of interstellar matter relative to the Sun the distance $r_s(\theta)$ of the shock front has, deviating from (1), to be found from the following equation

$$B_i^2/8\pi = \tfrac{1}{2}n_E\left(\frac{r_E}{r_s(\theta)}\right)^2 m_p v_h^2 W(r_s(\theta), \theta) = D(r_s(\theta), \theta). \tag{10}$$

The probability function W can be numerically calculated by the use of the densities $n(r, \theta)$ of interstellar hydrogen in interplanetary space which have been calculated in the paper of Blum and Fahr (1970). The determination of the corrected shock front distances $r_s(\theta)$ can then be carried out by the calculation of the intersection of $D(r, \theta)$ with $D = B_i^2/8\pi$.

3. NUMERICAL RESULTS AND DISCUSSION

The calculation of the probability function $W(r, \theta)$ has been carried out by the use of the interplanetary hydrogen densities $n(r, \theta)$ which had been obtained in the calculations of Blum and Fahr (1970) that had been based on a solar EUV flux of $2 \cdot 8 \times 10^{10}$ photons/cm^2 sec^1 (low solar activity) and a solar wind flux of $2 \cdot 0 \times 10^8$ protons/cm^2 sec. The relative velocity v_0 between the interstellar medium and the solar system was assumed to be 20 km/sec. The cross section q_{ex} for the charge exchange reaction between protons and hydrogen atoms has been taken to be 1×10^{-15} cm^2 (Rapp and Francis, 1962). Recent measurements of H–H$^+$ cross-sections (Belyaev *et al.*, 1967) seem to support a value of $q_{ex} = 2 \times 10^{-15}$ cm^2. This would tend to reduce the values of the shock front distance r_s and the heliospheric solar wind velocity v_h even more. The constant solar wind velocity v_h and the proton density n_E were supposed to be 4×10^7 cm/sec and 5 cm^{-3}, respectively. Parker (1963) and several other authors (Verschuur, 1968; Davies *et al.*, 1968) recommend a value $B_0 = 3 \times 10^{-6}$ G for the interstellar field B_i, though larger values also cannot be excluded. The computations of this paper have been carried out for magnetic energy densities $D_i = B_0^2/8\pi$ and small multiples of this value.

In Fig. 2 we have shown the distance r_s of the shock front versus the energy density D_i

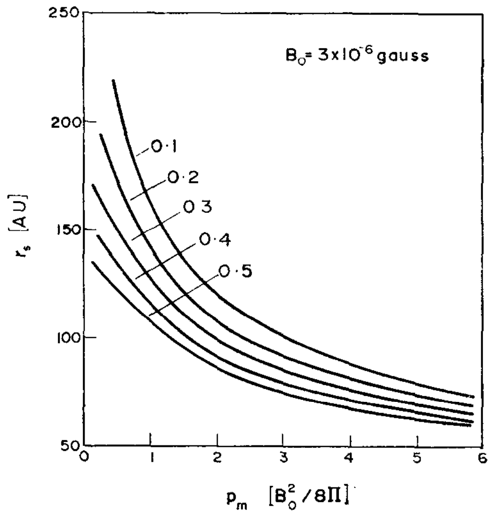

FIG. 2. THE LOCATION r_s OF THE SHOCK FRONT IS SHOWN VERSUS THE MAGNETIC PRESSURE P_m OF THE INTERSTELLAR FIELD IN UNITS OF $B_0^2/8\pi$ ($B_0 = 3 \cdot 10^{-6}$ G) FOR VARIOUS DENSITIES n_0 OF THE INTERSTELLAR MATTER NEAR THE SOLAR SYSTEM.

The density n_0 and the velocity v_{hs} of the solar wind protons at 1 AU have been taken to be 5 cm^{-3} and $4 \cdot 10^7$ cm/sec.

of the interstellar field. It can be seen that r_s decreases slowly with increasing values of D_i. The rather strong influence of neutral interstellar matter on the location r_s of the shock front can be seen in Fig. 3, where n_0 is given versus the corresponding value of r_s.

In spite of the fact that the radial density profile $n(r)$ of interplanetary hydrogen characterized by the e-folding distance r_{ex} from the Sun varies appreciably with varying inclination θ, the location $r_s(\theta)$ of the shock front shows nearly no variation ($\Delta r_s < 2$ AU)

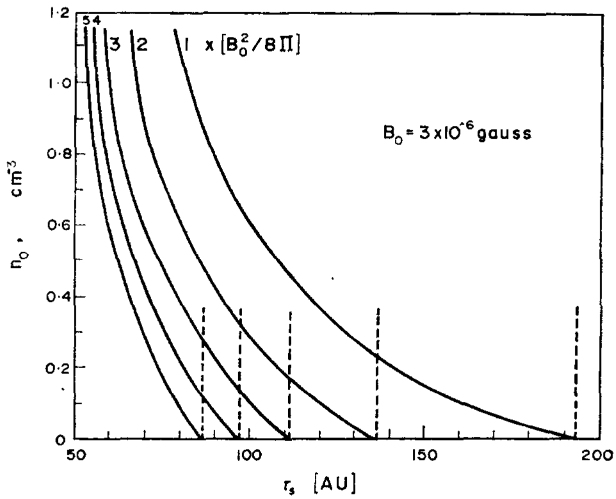

FIG. 3. THE LOCATION $\hat{rs}$ OF THE SHOCK FRONT IS SHOWN AS A FUNCTION OF THE DENSITY n_0 OF INTERSTELLAR MATTER IN THE VICINITY OF THE SOLAR SYSTEM FOR VARIOUS PRESSURES OF THE INTERSTELLAR MAGNETIC FIELD.

Density and velocity of the solar wind protons at 1 AU have been assumed to be 5 cm^{-3} and 4×10^7 cm/sec.

within the range $0° \leq \theta \leq 170°$ as can be seen in Fig. 4. This is due to the fact that the radial density profiles $n(r, \theta)$ differ only in the region inside $r = 5$ AU from each other, whereas the location of the shock front is mainly determined by the densities outside of $r = 5$ AU, where differences between the radial profiles of different angles θ vanish. Therefore the geometrical configuration of the shock front is spherical in nearly the whole range of θ.

Solely the region $170° \leq \theta \leq 190°$ shows a strong deviation from this spherical geometry. Due to the enhanced densities $n(r)$ in the antidirection ($\theta = 180°$) of $\mathbf{v}_0$ which are caused by gravitational focusing the location r_s of the shock front comes very close to the Sun in this region, so that a pronounced embayment of the essentially spherical shock front may result. The exact location of the shock front in this region cannot be determined by the use of the density values $n(r, \theta)$ of Blum and Fahr (1970), because those densities which correspond to interstellar temperatures of $T = 0$ K are not realistic for $170° \leq \theta \leq 190°$. In order to determine realistic values of the interplanetary hydrogen density in the region near and along the axis $\mathbf{v}_0$ one has to consider the termal motions of the interstellar particles, which causes an appreciable defocusing and abolishes the density singularity found by Blum and Fahr. In Fig. 5 the exact geometry of the shock front for interstellar gases of temperatures $T = 150$; 300; 450; 600 K can be seen. The density calculations for thermal interstellar gases have been carried out by Fahr (1971).

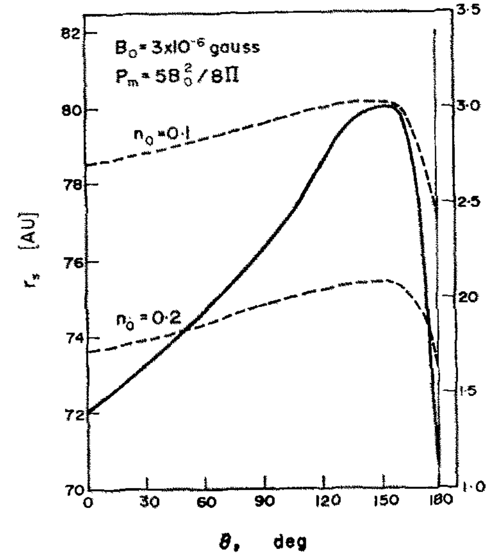

FIG. 4. THE BEHAVIOUR OF THE DISTANCE $r_s(\theta)$ OF THE SHOCK-FRONT VS. THE INCLINATION θ AGAINST THE VELOCITY v_0 OF APPROACH OF INTERSTELLAR MATTER IS SHOWN BY THE DASHED LINES FOR THE DENSITIES 0·1 AND 0·2 cm^{-3} OF INTERSTELLAR MATTER NEAR THE SOLAR SYSTEM. The magnetic pressure of the interstellar field has been taken to be $5(B_0^2/8\Pi)$ with $B_0 = 3 \times 10^{-6}$ G. The full line shows the distance $r_{ex}(\theta)$ from the Sun up to which the density $n(r, \theta)$ of slow interplanetary hydrogen atoms has reached $1/e$-th of its value n_0 at infinity.

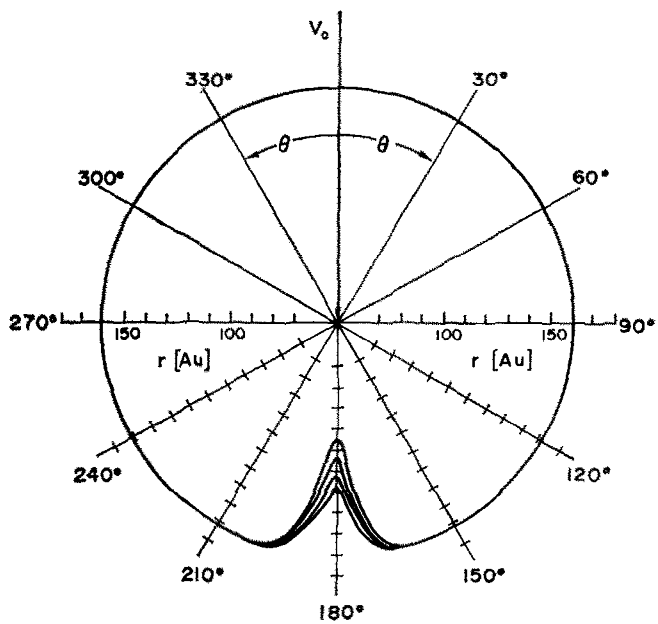

FIG. 5. THE GEOMETRICAL CONFIGURATION OF THE SHOCK FRONT.
The shock front distance r_s is given versus the inclination θ against the velocity v_0 of approach of interstellar matter. n_0 has been taken to be 0·1 cm^{-3}. The calculations of r_s in the region $160° \leq \theta \leq 100°$ have been carried out for the densities of interstellar gases with temperatures $T = 150$ K (innermost curve); $T = 300$ K; T = 450 K and $T = 600$ K (outermost curve) which have been given by Fahr (1971).

The deceleration of the solar wind due to protons which have exchanged their charge (Equation (9)) can be studied in Fig. 6. This figure shows the reduction of the initially constant solar wind velocity v_h versus the distance r from the Sun. This means that Parker's hydrodynamical solution of the solar wind motion (Parker, 1963) which yields a constant solar wind velocity within the supersonic region of the solar wind experiences considerable modifications, if the interaction of neutral interstellar matter with the solar wind plasma

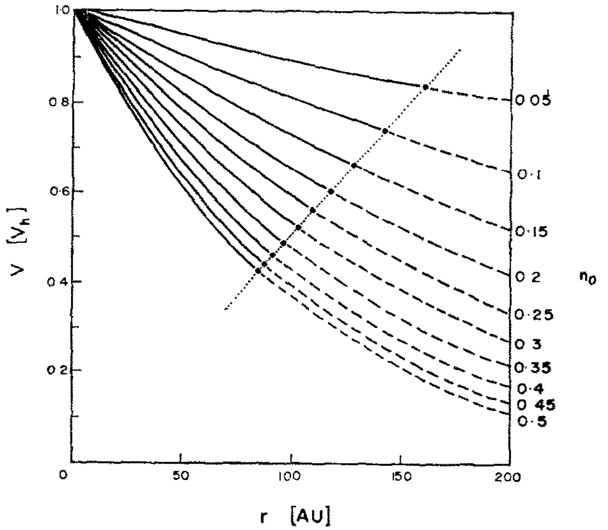

FIG. 6. THE DECREASE OF THE SOLAR WIND SPEED v DUE TO THE ENERGY EXHAUSTION BY CHARGE EXCHANGE INTERACTION WITH NEUTRAL INTERPLANETARY HYDROGEN IS SHOWN VS. THE DISTANCE r FROM THE SUN FOR VARIOUS DENSITIES n_0 OF THE INTERSTELLAR MEDIUM NEAR THE SOLAR SYSTEM.

The dotted line characterizes the distances where the shock front is located. The dashed part of the full lines is therefore only theoretical in its nature, because it would mean the heliospheric solar wind speed beyond the shock front. Density and velocity of the solar wind protons at 1 AU have been assumed to be 5 cm^{-3} and 4×10^7 cm/sec.

is taken into account. Axford *et al.* (1963) and Dessler (1967) argued that the solar wind should be influenced by the bulk motion of the interstellar hydrogen approaching the solar system and that hence its heliospheric cavity should not be spherically symmetric. This aspherical shape of the shock front has not been confirmed by the calculations of this paper. On the contrary we find the geometry of the shock front to be spherical as far as inclinations θ against $\mathbf{v}_0$ are concerned which are not too close to 180°, where a pronounced embayment of the essentially spherical shock front is produced. On the other hand the prediction of Axford *et al.*, that the interstellar neutral medium could have a considerable influence on the location r_s of the shock front could fully be confirmed. According to our results (Figs. 2 and 3) r_s is very sensitive with respect to the density n_0 of interstellar hydrogen near the solar system and changes by more than 100 AU, if n_0 increases from vanishing values to $n_0 = 1{\cdot}0\ cm^{-3}$. The results of Fig. 3 coincide very well with those of Semar (1970), who has carried out similar calculations concerning the energy exhaustion of the solar wind, but only in one direction, namely that of $\mathbf{v}_0$. In this direction of approach of interstellar matter he obtains the shock front to be located at $r_s = 50$ AU for $n_0 = 1\ cm^{-3}$ and $B_i = 1$

Gamma $\approx 3B_0$. For these values which are probably too high we obtain exactly the same location r_s of 50 AU.

Due to the enhanced densities near and along the backward axis of $\mathbf{v}_0$ which are caused by gravitational focusing the energy exhaustion of the solar wind is much more effective in this region. The resulting shock front embayment could probably cause a sidereally anisotropic background of the cosmic ray intensity which is observed. The influence of an anisotropic heliospheric cavity on the cosmic ray intensity distribution had already been suggested by Kovar and Dessler (1967). Cosmic ray particles approaching the Earth from the direction of the shock front embayment probably reach the Earth more easily than from other directions, where they are subjected to magnetic deflections of a much more extended heliosphere. The amplitude and the direction of the observed anisotropies are not well established. However, it is interesting to note that a tentative maximum of the ray intensity is found by all authors (Comforto and Simpson, 1957; Kane, 1966; Baker *et al.*, 1966 and Swinson 1969) to be located at a right ascension of RA $= 90° \pm 30°$. This coincides well with the location of the embayment, if a velocity $\mathbf{v}_0$ of approach of interstellar matter is assumed which is equal to the motion of the solar apex (RA $= 270°$; Decl $= +27°$).

REFERENCES

Axford, W. I., Dessler, A. J. and Gottlieb, B. (1963). Termination of solar wind and solar magnetic fields. *Astrophys. J.* **137**, 1963.

Baker, P., Chasson, R. L. and Kisselbach, V. J. (1966). Cosmic ray measurements by muon telescopes. *Nuovo Cim.* **6**, 1052.

Belyaev, Brezhmev and Erastov (1967). Measurements of charge exchange cross sections. *Soviet Phys. JETP.* **25**, 777.

Bertaux, J. L. and Blamont, J. E. (1970). Distribution of atomic hydrogen in the upper atmosphere and in the solar system. Preprint f. 16, May 1970, Service d'Aeronomie du C.N.R.S.

Blum, P. W. and Fahr, H. J. (1970). Interaction between interstellar hydrogen and the solar wind. *Astronomy and Astrophysics*, **4**, 280.

Blum, P. W. and Fahr, H. J. (1970a). Distribution of interplanetary hydrogen. *Astrophys. Lett.* **5**, 127.

Comforto, A. M. and Simpson, J. A. (1957). Cosmic ray measurements by neutron monitoring *Nuovo Cim.* **6**, 1052.

Davies, R. D., Booth, R. S. and Wilson, A. J. (1968). Interstellar magnetic fields from Zeeman effect measurements. *Nature* **220**, 1207.

Dessler, A. J. (1967). Solar wind and interplanetary magnetic field. *Rev. Geophys.* **5**, 1.

Fahr, H. J. (1970). Interstellar hydrogen densities in the surroundings of the solar system. *Nature* **226**, 435.

Fahr, H. J. (1971). Der interplanetare Wasserstoffkegel und seine Auswirkung auf die Schock-Front. Preprint.

Kovar, R. P. and Dessler, H. J. (1967). On the anisotropy of galactic cosmic rays. *Astrophys. Lett.* **1**, 15.

Kane, R. P. (1966). Cosmic ray, measurements by neutron monitoring for the period 1952–1969. *Nuovo Cim.* **41**, 90.

Mange, P. and Meier, R. R. (1970). Lyman-α intensity and the hydrogen concentration beyond 5 Earth radii *J. geophys. Res.* **75**, 1837.

Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic field. *Astrophys. J.* **128**, 664.

Parker, E. N. (1962). Kinetic properties of interplanetary matter *Planet. Space Sci.* **9**, 461.

Parker, E. N. (1963). Interplanetary dynamical processes New York. Interscience.

Patterson, T. N. L., Johnson, F. S. and Hanson, W. B. (1963). The distribution of interstellar hydrogen. *Planet. Space Sci.* **11**, 767.

Rapp, D. and Francis, W. E. (1962). Measurement of charge exchange cross sections. *J. Chem. Phys.* **37**, 2631.

Verschuur, G. L. (1968). Positive determination of an interstellar magnetic field by measurement of the Zeeman-splitting of the 21-cm line. *Phys. Rev. Lett.* **21**, 775.

Semar, C. L. (1970). The effect of interstellar neutral hydrogen on the termination of the solar wind. *J. Geophys. Res.* **75**, 6892.

Swinson, D. B. (1969). Sidereal cosmic ray diurnal variations. *J. geophys. Res.* **74**, 5591.