Shock-drift acceleration of pick-up protons at the solar wind termination shock

Sergei V. Chalov*

* *Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia*

***Abstract*. Shock-drift acceleration of pick-up protons at the solar wind termination shock is considered taking into account multiple reflections and shock crossings due to pitch-angle scattering in the upstream and downstream regions. The model includes large-scale variations of the magnetic field direction near the shock front connected with passages of magnetic sector structures over the termination shock. The shock-drift acceleration can explain the fluxes of energetic protons measured at the Voyager 1 spacecraft after the termination shock crossing in 2004.**

***Keywords*: anomalous cosmic rays, solar wind, termination shock**

I. Introduction

The crossing of the solar wind termination shock (TS) by Voyager 1 on December 16, 2004 revealed several interesting features in the properties on charged energetic particles. One of them is unexpected spatial behavior of the anomalous cosmic ray (ACR) fluxes. Namely, the intensity of the fluxes continued to increase, as Voyager 1 moved further downstream from the TS [16]. One of the reasons of such behaviour, proposed in [10], is that, possibly, a source of the ACRs lies somewhere in the inner heliosheath. In the paper [7] was shown that charged particles indeed can experience very efficient stochastic acceleration in the nose part of the inner heliosheath due to large exposure times during which the particles suffer this acceleration while slowly being convected towards the heliotail. It was emphasized, however, that acceleration in this region is not an alternative to acceleration of ACRs at the TS, but rather it can be considered as an additional energization mechanism in the outer heliosphere.

Other exciting data, obtained during the TS crossing, are the observed shapes of power-low differential fluxes of charged particles in the energy range from 40 keV up to 10 MeV [9]. The spectral indexes of these distributions are very close to so-called common spectral shapes observed in many different circumstances [11]. As regards to protons, in the present paper we show that the observed fluxes can be explained by shock-drift acceleration of pick-up protons at the TS, taking into account its specific shape arising from the interaction of the solar wind with the local interstellar medium (LISM).

II. Termination shock geometry and governing equation for the velocity distribution function of pick-up protons

Pick-up protons originating in the solar wind through ionization of interstellar hydrogen atoms suffer acceleration due to the interaction with solar wind Alfvénic and magnetosonic fluctuations and with interplanetary shock waves [5]. Thus, on arrival at the TS pick-up protons from the tails of their velocity distributions can experience multiple reflections at the shock front due to abrupt change of the magnetic field and gain energy from the shock-drift acceleration process. To describe the interaction of a particle with the shock front we apply here the adiabatic theory ignoring scattering of the particle during its encounter with the front which is considered as a discontinuity. The theory is based on conservation of magnetic moment of particles during their interaction with the shock. If the parameters of the shock and the initial velocity of a particle are known, this condition allows to determine the type of the interaction (reflection or transmission) and to find the final velocity of the particle (absolute value and pitch-angle) [8]. The assumption of magnetic moment conservation at the shock is valid in the case of weak scattering. However, upstream and downstream of the shock wave pick-up protons can experience pitch-angle scattering, which provides a way for reflected and transmitted particles to return to the shock front [4].

In order to describe this process mathematically we use a one-dimensional planar approximation for the plasma flow close to the TS. If the x-axis is directed perpendicular to the shock front from the upstream to the downstream part of the flow, the relevant transport equation for the evolution of the gyrotropic velocity distribution function $f = f(t, x, v, \mu)$ of pick-up protons in the solar wind plasma moving with the velocity $\mathbf{V}_{\rm SW}$ can be written in the form:

$$\frac{\partial f}{\partial t} + (V_{{\rm SW},x} + v\mu\chi)\frac{\partial f}{\partial x} = \hat{S}f\,, \qquad (1)$$

where v and $\mu = \cos\xi$ are the velocity and cosine of the particle pitch angle, ξ, in the solar wind rest frame; $\chi = \cos\psi$; ψ is the angle between the shock front and large-scale magnetic field; and $\hat{S}f$ is the scattering operator applied to the function f. This operator describes effects of pitch-angle scattering and energy diffusion [14].

The reflection conditions of energetic particles depend essentially on geometry of the interplanetary magnetic field near the TS. If the TS had a spherically symmetric

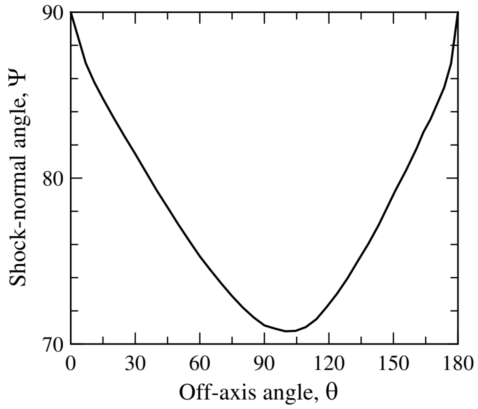

Fig. 1: The shock normal angle, Ψ, as a function of the off-axis angle, θ.

shape and the center of the sphere was at the Sun position, then the interplanetary magnetic field would be nearly perpendicular to the shock-normal for the largest part of the shock surface as is usually assumed in the literature. However, the real TS has an upwind-downwind asymmetry due to the interaction of the solar wind with the moving LISM. Figure 1 shows the shock-normal angle Ψ as a function of the angle Θ counted from the direction of the Sun's motion relative to the LISM. This dependence was obtained from numerical calculations in the frame of the self-consistent two-dimensional model of interaction between the solar wind and LISM [1] for the typical plasma and neutral hydrogen parameters. It is evident that the shock-normal angle depends significantly on the off-axis angle. At the nose and tail parts of the TS it is almost perpendicular, but the shock-normal angle can be as small as 70° at the flanks of the shock. Therefore, the efficiency of the shock-drift acceleration can essentially depend on Θ. Note, that for the first time this effect was studied in [3].

We should emphasize, however, that while the interplanetary magnetic field has the Parker structure in the average in the outer heliosphere, measurements from spacecraft show that the distributions of the angle between the magnetic field and the solar wind flow direction are rather broad with the half width of about 25° [15]. It means that even at the nose part of the TS the shock-normal angle can be smaller than 90° for some time periods. This effect is connected with passages of magnetic sector structures and it will be taken into account in the present study.

In order to solve Eq. (1) numerically it is replaced by an equivalent system of stochastic differential equations describing stochastic trajectories of particles in phase space. To obtain the differential number density of particles, we must simulate a statistically relevant set of stochastic trajectories and determine the density associated with these trajectories in phase space (see in more detail [6]).

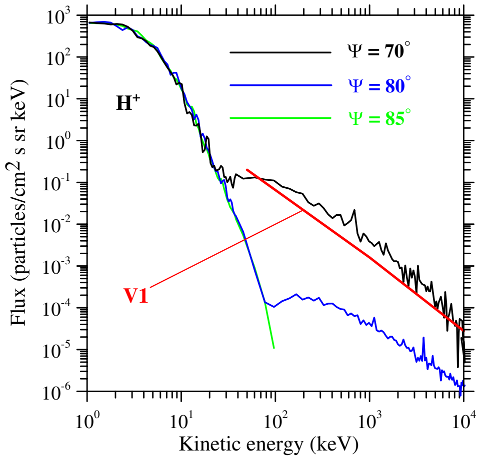

Fig. 2: Downstream fluxes of pick-up protons in the solar wind rest frame for different values of the shock-normal angle: $\Psi = 70°$, 80°, 85°. The flux of energetic protons observed at Voyager 1 after the TS crossing is shown [9].

III. Numerical fluxes of pick-up protons downstream of the termination shock

Numerical results presented in this section were obtained for those values of the solar wind and TS parameters which are close to measured by Voyager 1 during the TS crossing ($V_{\rm SW} = 386$ km s^{-1} and the shock compression $\sigma = 3$). Figure 2 shows downstream fluxes of pick-up protons in the solar wind rest frame for different values of the shock-normal angle: $\Psi = 70°$, 80°, 85°. The differential fluxes of energetic protons averaged over 160-day period of the Voyager 1 motion in the inner heliosheath is also shown in the figure [9].

It is seen from Fig. 2 that the downstream fluxes consist of two parts. The low energy parts are formed by protons which were directly transmitted through the shock front and did not suffer multiple reflections. The high energy parts of the fluxes are formed by protons which suffered multiple reflections at the shock. The second important feature which can be seen in Fig. 2 is the strong dependence of the downstream fluxes on the shock-normal angle. In the case of small Ψ the TS produces much higher fluxes of accelerated particles in the energy range from several tens of keV to about 10 MeV than in the case of large Ψ. This fact can be explained by increasing the reflection efficiency when the shock-normal angle decreases. Obviously that this dependence of the fluxes on the shock-normal angle will result in their dependence on the off-axis angle counted from the direction to the inflowing LISM (see Fig. 1).

The observed fluxes of energetic protons (shape and absolute values) are close to the theoretical at $\Psi \approx 70°$. However, according to Fig. 1 this value of the shock-normal angle corresponds to the flunks of the TS, while the angular distance of Voyager 1 relative to the direction of the interstellar medium flow during this time was about 30°. Besides, estimations of the shock-normal

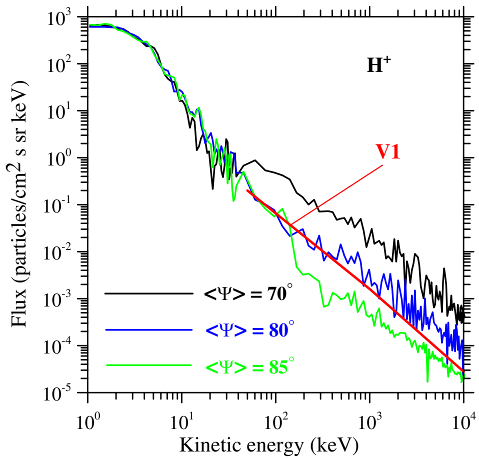

Fig. 3: Same as Fig. 2, but for the averaged values of the shock-normal angle, $\langle\Psi\rangle = 70°$, $80°$, $85°$, taking into account large-scale variations of the angle.

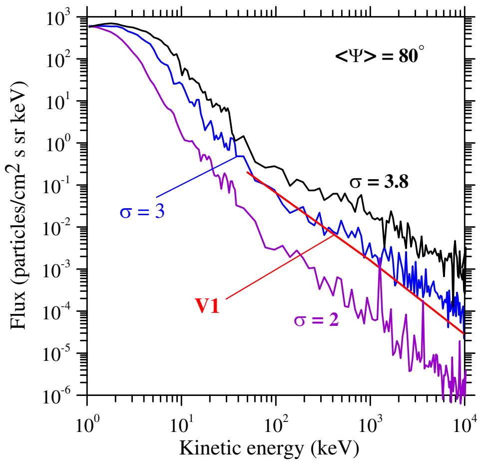

Fig. 4: Downstream fluxes of pick-up protons in the solar wind rest frame for different values of the shock compression: σ =2, 3 and 3.8. The value of the averaged shock-normal angle $\langle\Psi = 80°\rangle$.

angle during the crossing show that it lay in the range $80° \leq \Psi \leq 85°$ [2]. We show in the present paper that both the power-low slope of the observed flux and its absolute value can be explained if we take into account large-scale variations of the magnetic field direction near the shock front connected with passages of magnetic sector structures over the TS. It is known that at large heliocentric distances the magnetic field vector, according to the Parker's model, is almost perpendicular to the radial direction (with the exception of the near-polar regions). At passages of sector structures, the polarity of the field changes abruptly approximately during one day. It means that the magnetic field vector rotates by 180°. During this events, there are rather short periods of time in which the TS is almost quasi-parallel.

In the following we will take into account this large-scale variations of the shock-normal angle. As we have mentioned in Section II, to find the differential number density of energetic protons we used a system of stochastic differential equations describing stochastic trajectories of the particles in phase space. This method is applied in the upstream and downstream regions of the TS. When a particle approaches to the shock front, it interacts with the front according to the adiabatic theory ignoring pitch-angle scattering during this interaction. But now, in contrast to the case presented in Fig. 2, the shock-normal angle at given part of the TS (or at given value of the off-axis angle) is no longer fixed. We consider this angle as a random value with the probability distribution corresponding to the histogram of the magnetic field azimuth angle obtained by Pioneer 11 in 1991 [15]. It is assumed that the shock-normal angle retains its value during the interaction of the given particle with the shock front. This assumption is well-founded since the interaction time is no more than several hours. When an another particle approaches the front, we choose a new value for the shock-normal angle according to above-mentioned procedure.

Thus, returning to Fig. 1 again, we should note that now it shows the shock-normal angles $\langle\Psi\rangle$ averaged over sufficiently large time intervals (much larger than the time of a magnetic sector passage through the shock). Figure 3 shows the calculated downstream fluxes of pick-up protons accelerated at the TS at different values of the averaged shock-normal angle: $\langle\Psi\rangle = 70°$, $80°$, $85°$. It is obvious from the figure that theoretical fluxes, in the case when large-scale variations of the interplanetary magnetic field are taken into account, are significantly higher than in the case when they are absent. It is very interesting that the slope of the distributions (at different values of $\langle\Psi\rangle$) is very close to the universal spectral shapes [11]. Remarkably that the flux of energetic protons measured by Voyager 1 lies between the curves $\langle\Psi\rangle = 80°$ and $\langle\Psi\rangle = 85°$ as revealed in the magnetic field measurements [2]. We should emphasize, however, that the observed distribution is slightly more steep than the universal theoretical distributions.

It is of interest to consider how the parameters of the TS influence the fluxes of accelerated particles. Figure 4 shows downstream fluxes of pick-up protons in the solar wind rest frame for different values of the shock compression: σ =2, 3 and 3.8. The value of the averaged shock-normal angle $\langle\Psi = 80°\rangle$. The absolute values of the fluxes significantly depend on the compression, while the spectral slopes at large energies are almost identical

IV. Conclusions

We show in this paper that the differential fluxes of protons in the energy range from 40 keV up to 10 MeV averaged over 160-day period of the Voyager 1 motion in the inner heliosheath can be explained by shock-drift acceleration of pick-up protons at the solar wind termination shock. It is essential for our study that the TS has a specific shape arising from the interaction of the solar wind with the LISM and resulting in the dependence of the shock-normal angle on the off-axis angle counted from the direction of the Sun's motion relative to the LISM. It is also important that we take into account large-scale variations of the magnetic field direction near the shock front connected with passages of magnetic sector structures over the TS.

We emphasize, however, that the observed distribution is slightly more steep than the theoretical distributions. This disagreement can be connected with different factors, which were not taken into account. For instance, we do not consider essential nonstationarity of the TS during this time period. There are observational evidences and theoretical calculations showing that the TS, at the moment of the spacecraft crossing, was moving towards the Sun with relatively high velocity [9], [12], [13]. Besides, we ignore here perpendicular diffusion of protons, which can be important for high energies.

This work was supported by the RFBR in the frames of the projects 07-01-00291, 08-02-91968-DFG and the Program for Basic Researches of OEMMPU RAS.

REFERENCES

[1] Baranov V. B., Malama Y. G. 1993, J. Geophys. Res., 98, 15157
[2] Burlaga L. F., Ness N. F., Acuña M. H., Lepping R. P., Connerney J. E. P., Stone E. C., McDonald F. B. 2005, Science 309, 2027
[3] Chalov S. V. 1993, Planet. Space Sci. 41, 133
[4] Chalov S. V. 2005, Adv. Space Res. 35, 2106
[5] Chalov S. V. 2006, *Interstellar Pickup Ions and Injection Problem for Anomalous Cosmic Rays: Theoretical Aspect*, in The Physics of the Heliospheric Boundaries, V.V. Izmodenov & R. Kallenbach (Eds.), p. 245
[6] Chalov S. V., Fahr H. J. 2000, A&A, 360, 381
[7] Chalov S. V., Fahr H. J., Malama Y. G. 2007, Ann. Geophys. 25, 575
[8] Decker R. B. 1988, Space Sci. Rev. 48, 195
[9] Decker R. B., Krimigis S. M., Roelof E. C., Hill M. E., Armstrong T. P., Gloeckler G., Hamilton D. C., and Lanzerotti L. J. 2005, Science, 309, 2020
[10] Fisk L. A. 2005, Science, 309, 2016
[11] Fisk L. A., Gloeckler G. 2008, ApJ, 686, 1466
[12] Florinski V., Zank G. P. 2006, Geophys. Res. Lett., 33, L15110, doi:10.1029/2006GL026371
[13] Izmodenov V. V., Malama Y. G., Ruderman M. S. 2008, Adv. Space Res., 41, 318
[14] Schlickeiser R. 1989, ApJ, 336, 243
[15] Smith E. J. 1993, Adv. Space Res., 13, 5
[16] Stone E. C., Cummingth A. C., McDonald F. B., Heikkila B. C., Lal N., and Webber W. R. 2005, Science 309, 2017