Shock-drift acceleration of interstellar pickup protons at the solar wind termination shock

S V Chalov¹, D B Alexashov¹,², Y G Malama¹,² and V V Izmodenov¹,²,³

Institute for Problems in Mechanics, Pr. Vernadskogo 101-1, Moscow 119526, Russia
Space Research Institute, Profsoyuznaya 84/32, Moscow 117997, Russia
Lomonosov Moscow State University, Faculty of Mechanics and Mathematics, Moscow 119899, Russia

E-mail: chalov@ipmnet.ru

Abstract.

The numerical model of the shock-drift acceleration of interstellar pick-up protons at the solar wind termination shock is presented taking into account multiple reflections of the particles at and passing through the shock. The processes of the multiple interactions with the shock are possible due to pitch-angle scattering in the upstream and downstream parts of the solar wind flow. The model takes into account variations of the magnetic field direction near the shock front connected with its three-dimensional shape. The main advantage of the model is the self-consistent treatment of protons and interstellar hydrogen atoms, which interact with each other through the resonant charge exchange process. The model gives very simple and natural resolution of so-called injection problem for anomalous cosmic rays. The shock-drift acceleration can explain the fluxes of the anomalous cosmic rays measured at the Voyager 1/2 spacecraft after the termination shock crossings.

1. Introduction

The crossing of the solar wind termination shock (TS) by Voyager 1/2 spacecraft on December 2004 and August 2007, respectively, revealed several interesting features in the properties of charged energetic particles. One of them is the observed shape of power-low differential fluxes of protons in the energy range from 30 keV up to 10 MeV [1], [2]. The spectral index of these distributions is close to so-called common spectral shapes observed in many different circumstances [3]. In the present paper we show that the observed fluxes can be explained by shock-drift acceleration of interstellar pick-up protons at the TS, taking into account its specific shape arising from the interaction of the solar wind (SW) with the local interstellar medium (LISM).

The LISM surrounding the solar system is a partly ionized medium consisting mainly of hydrogen atoms. The interstellar atoms have a pronounced effect on the global structure of the extensive region separating the supersonic SW and LISM and on the physical processes in the heliosphere (e.g., [4], [5]). Apart from the fact that the position and shape of the heliospheric TS and heliopause are significantly determined by the action of the atoms, they give rise to a peculiar hot population of pick-up ions in the SW [6], [7].
Due to large mean free pathes, which are comparable with the size of the heliosphere, interstellar atoms can penetrate close to the Sun [8]. In the heliosphere some portion of the atoms is ionized through charge exchange with protons or through the processes photoionization and electron impact ionization. According to current knowledge, the speed of the interstellar wind relative to the Sun is about 26 km/s. This speed is much smaller as compared with the SW speed ranging from 350 km/s up to 750 km/s depending on the heliolatitude and solar activity phase. Therefore, the speed of newly created ions in the SW frame equals approximately the local SW speed. In other words, thermal velocities of pick-up ions are much larger than thermal velocities of solar charged particles. This is the reason why just the pick-up ions are considered as the main candidates for acceleration at the TS.

We present here results obtained in the framework of two models of the shock-drift acceleration of pick-up protons at the TS: a) one-dimensional model taking into account stochastic pre-acceleration in the supersonic SW, b) three-dimensional (3D) magneto-hydrodynamical model of the SW-LISM interaction which treat pick-up proton and interstellar hydrogen atom populations self-consistently [9].

2. Shock-drift acceleration at the plane-parallel geometry with pre-acceleration in the supersonic solar wind

On arrival at the TS some portion of pick-up protons can experience multiple reflections at the shock front due to abrupt change of the magnetic field and pitch-angle scattering in the upstream and downstream parts of the SW flow. This process results in increase of the energy of the particles due to their drift motion along the shock front in the direction of the induced electric field. The reflection condition can be written as [10]

\[ v > V_{sh} \sec \Psi / \sqrt{b}, \]

where \( v \) is the proton speed in the upstream plasma frame, \( V_{sh} \) is the upstream plasma speed relative to the shock, \( b \) is the jump in magnetic field strength across the shock and \( \Psi \) is the upstream shock-normal angle. Thus the reflection process operates for high speed particles different from a simple reflection by the electric cross-shock potential.

One can see from relation (1) that the reflection conditions depend essentially on geometry of the magnetic field near the TS. If the TS had a spherically symmetric 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 SW with the moving LISM. Thus the value of the shock-normal angle varies significantly along the TS front. 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. For the first time this important effect was studied in [11].

Pick-up protons originating in the SW can suffer acceleration due to the interaction with solar wind Alfvénic and magnetosonic fluctuations and with interplanetary shock waves [12]. 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.

In order to describe the process of multiple reflections 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
relev

Figure 1. Downstream fluxes of pick-up protons in the SW rest frame for different values of the shock-normal angle: Ψ = 70°, 80°, 85° (planar geometry). The fluxes of energetic protons observed at Voyager 1/2 after the TS crossing are shown.

Figure 2. Spatially averaged fluxes of pick-up protons in the region between the TS and heliopause at the flanks of the heliosphere (3D model). The fluxes of energetic protons observed at Voyager 1/2 after the TS crossing are shown.

3. Shock-drift acceleration in the framework of a 3D model: no pre-acceleration in the supersonic solar wind

The results presented in Fig. 1 are essentially based on the assumption that pick-up protons experience stochastic acceleration in the supersonic SW. This is needed for the pick-up protons to be able to enter the regime of drift acceleration at the TS. The efficiency of this acceleration has an influence on the downstream spectra of shock-drift accelerated particles (for more details see [13]). However, high-energy tails in the energy distribution of pick-up protons in the supersonic SW can form without the stochastic pre-acceleration through ionization of energetic atoms from the heliospheric interface [14]. This process is closed. On the one hand, energetic atoms are produced in the post-shock region by the charge exchange between protons, accelerated at the TS, and interstellar atoms. On the other hand, the energetic atoms penetrating into the
supersonic SW turn into energetic protons there through ionization. This idea gives very simple and natural resolution of injection problem for anomalous cosmic rays.

The shape of the TS is very complex due to heliolatitudinal dependence of the SW speed and number density and effect of interstellar magnetic field. Fig. 2 shows averaged fluxes of pick-up protons in the region between the TS and the heliopause at flanks of the heliosphere (at 90° from the direction of the LISM plasma flow). The averaging is over the rotary angle around the LISM plasma flow. The fluxes were calculated in the framework of our new three-dimensional model of the SW interaction with the LISM, which considers charged particles, H atoms and magnetic fields self-consistently (preliminary basic versions of the model see, e.g., in [5], [9]). It is important that H atoms are described at the kinetic level. For transport of pick-up protons near the TS we use 3D version of Eq. 2.

4. Conclusion
The drift acceleration of pick-up protons at the TS can explain the fluxes of the anomalous cosmic rays (hydrogen) measured at the Voyager 1/2 spacecraft after the TS crossings. The efficiency of the acceleration depends essentially on the configuration of the magnetic field, namely, on the shock-normal angle. For the first time we demonstrate that self-consistent consideration of protons and H atoms in the heliosphere which interact with each other through charge exchange process can give a natural explanation of injection problem for anomalous cosmic rays.

Acknowledgments
The work was supported by the RFBR (Nos. 10-01-00258, 10-02-01316, 11-02-92605), the Presidium Program of RAS (No. 22) and the Goskontract No. 14.740.11.0874 (FCP "Kadry").

References
[1] 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 2020–24
[2] Stone E C, Cummings A C, McDonald F B, Heikkila B C, Lal N and Webber W R 2008 Nature 454 71–74
[3] Fisk L A and Gloeckler G 2008 Astrophys. J. 686 1466–73
[4] Baranov V B and Malama Y G, 1993 J. Geophys. Res. 98 15157–163
[5] Izmodenov V V, Malama Y G, Ruderman M S, Chalov S V, Alexashov D B, Katushkina O A, Provornikova E A 2009 Space Sci. Rev. 146 329–351
[6] Möbius E, Hovestadt D, Kleeber B, Scholer M, Gloeckler G, Ipavich F M 1985 Nature 318 426–429
[7] Gloeckler G, Geiss J, Balsiger H, Fisk L A, Galvin A B, Ipavich F M, Ogilvie K W, von Steiger R, Wilken B 1993 Science 261 70–73
[8] Izmodenov V V 2006 Early Concepts of the Heliospheric Interface: H Atoms, in The Physics of the Heliospheric Boundaries Ed V V Izmodenov and R Kallenbach (Noordwijk: ESA Publication Division) p 45
[9] Malama Y G, Izmodenov V V, Chalov S V 2006 Astron. Astrophys. 445 693–701
[10] Decker R B 1988 Space Sci. Rev. 48 195–262
[11] Chalov S V 1993 Planet. Space Sci. 41 133–136
[12] Chalov S V 2006 Interstellar Pickup Ions and Injection Problem for Anomalous Cosmic Rays: Theoretical Aspect, in The Physics of the Heliospheric Boundaries Ed V V Izmodenov and R Kallenbach (Noordwijk: ESA Publication Division) p 245
[13] Chalov S V 2012 Astron. Lett. 38 191–200
[14] Chalov S V and Fahr H J 2003 Astron. Astrophys. 401 L1–4