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To cite this article: V S Ptuskin *et al* 2015 *J. Phys.: Conf. Ser.* **632** 012022

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Interpretation of Voyager 1 data on low energy cosmic rays in galactic wind model

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Abstract. The local interstellar energy spectra of galactic cosmic rays down to a few MeV/nucleon were directly measured in the experiment on the board of the Voyager 1 spacecraft. We suggest interpretation of these data based on our models of cosmic ray acceleration in supernova remnants and the diffusion in galactic wind where diffusion coefficient is determined by the cosmic ray streaming instability. The dependence of wind velocity on distance above the Galactic disk is determined.

1. Introduction

Launched in 1977 and expected to operate till 2020-2025, Voyager 1 is 130 AU from the Sun and Voyager 2 is at 107 AU. Voyager 1 is currently in "interstellar space" and Voyager 2 is in the "heliosheath" – the outermost layer of the heliosphere where the solar wind is slowed by the pressure of interstellar gas. This experiment extends our knowledge of the local interstellar cosmic ray spectrum and composition down to MeV energies [1]. It is assumed that the Voyager 1 spacecraft is measuring cosmic ray intensity not affected by the solar wind modulation. The spectra of protons, nuclei and electrons look as a natural continuation of spectra at energies above a few hundred MeV and no any additional low energy component was revealed. The intensity of the so called Anomalous Cosmic Rays (ACR) is diminished to zero and it confirms that these particles are accelerated somewhere in the inner part of the heliosheath (probably, at the hot spots of the solar wind termination shock). The flat shape of proton and nuclei spectra at energies less than 100 MeV/nucleon is likely explained by the combined effect of the leakage of these particles from the Galaxy and the heavy ionisation energy losses. The corresponding calculations were made in [2] based on the Voyager data in the outer heliosphere shortly before the spacecraft entered the interstellar medium. The interpretation of the final data [1] in the frameworks of the diffusion Galactic model with the cosmic ray diffusion coefficient which has minimum at about 1 GeV/nucleon and increases to smaller energies was given in [3]. Qualitatively, such energy dependence of diffusion is expected in a model with damping of the interstellar turbulence on cosmic rays [4]. The data on cosmic ray electrons and Galactic synchrotron radioemission were analysed in the same model in [5]. Other versions of the diffusion model for this problem were considered in [6] (the model with distributed cosmic ray reacceleration) and [7] (the model with diffusion and adiabatic energy losses in galactic wind).

In the present work, we analyse the Voyager data [1] by developing the model of cosmic ray transport in the Galaxy with galactic wind proposed in [8] for the interpretation of available at



that time data on the ratio of fluxes of Boron-to-Carbon nuclei at low energies. The specific feature of this model is the deceleration of the Galactic wind flow at distances up to about 1 kpc above the galactic disk.

2. Transport of low energy cosmic rays in galactic wind model

The steady-state one-dimensional (perpendicular to the galactic plane) transport equation used in the present paper for protons and stable cosmic ray nuclei in the interstellar medium reads as follows (see [9] for detail):

$$-\frac{\partial}{\partial z} D \frac{\partial f}{\partial z} + u \frac{\partial f}{\partial z} - \frac{p}{3} \frac{du}{dz} \frac{\partial f}{\partial p} - \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 b_{ion} \frac{\partial f}{\partial p} \right) + nv\sigma f = q, \quad (1)$$

where $f(p, z)$ is the isotropic part of cosmic ray density in momentum space; p is the particle momentum; z -axis is directed perpendicular to the galactic midplane, which has the coordinate $z = 0$. $D(p) = vF(p/Z)$ is the spatial diffusion coefficient, v is the particle velocity, the function F is determined by the spectrum of interstellar MHD turbulence, Z is the particle charge. $u(z)$ is the convection velocity, the velocity of galactic wind, directed symmetrically outward of galactic plane, $u(z) = -u(-z)$. The term with $\frac{du}{dz}$ represents the adiabatic momentum gain or loss in the nonuniform gas flow with a frozen-in magnetic field whose inhomogeneities scatter cosmic rays. The term $q(p, z)$ is the source term including primary and spallation contributions (the primaries are produced by cosmic ray sources). n is the interstellar gas density, σ is the total spallation cross section. The ionization energy loss rate is $(\frac{dp}{dt})_{ion} = -b_{ion}$.

We assume in the following that the cosmic ray sources and the interstellar gas, where nuclear spallation and ionization energy losses occur, are confined in a thin galactic disk and the following approximations by the delta functions in eq. (1) are applied:

$$q = s\delta(z), \quad n = \eta\delta(z), \quad b_{ion} = b\delta(z). \quad (2)$$

The source spectrum is assumed in the form

$$s = Qs_0, \quad s_0 = R^{-2.28}[1 + 0.07\log(R/0.7)\log(R/100)], \quad Q = const, \quad (3)$$

where $R = pc/Z$ is the particle magnetic rigidity in GV, c is the speed of light. Eqs. (3) are based on our results of modelling of cosmic ray shock acceleration in supernova remnants [10].

It is assumed that the diffusion coefficient D is selfconsistently determined by the streaming MHD instability of cosmic rays leaving the Galaxy [11, 12]. The corresponding equations for the diffusion coefficient are the following:

$$D = \kappa D_0, \quad D_0 = \beta(R \times s_0(R))^{-1}, \quad \kappa = const. \quad (4)$$

Here $\beta = v/c$. The expression for D_0 is replaced by $D_0 = \beta(R^2 \times s_0(R))^{-1}$ at the smallest energies where the ionization energy loss dominates over the leakage from the Galaxy.

We continue to find the approximate analytical solution of eq. (1), see also [12].

The distinctive feature of the diffusion-convection transport is the existence of a boundary layer of the size $z_c(p)$ adjacent to the galactic plane and defined by the approximate equation

$$z_c(p) = D(p)/u(z_c). \quad (5)$$

Here and below we omit the numerical coefficients of the order of 1 in the approximate equations.

The diffusive propagation with the diffusion coefficient $D(p)$ dominates in the cosmic ray transport at distances $0 < z < z_c$ (the diffusion region) whereas the convective transport with velocity $u(z)$ dominates at $z > z_c$ (the advection region). This propagation pattern is valid if the

wind velocity increases with distance, remains constant, or decreases not faster than $u \sim 1/z$. Accelerated in the sources (the supernova remnants) located in a relatively thin galactic disk, the relativistic particles fill an extensive cosmic ray halo and have low probability to return back to galactic disk if they enter the advection region where cosmic rays are carried out to the intergalactic space. Thus, for an observer in the galactic disk, the surface $z = z_c$ can be considered as an absorbing boundary.

We solve eq. (1) separately in the region $0 < |z| < z_c$, where the terms with the wind velocity $u(z)$ are neglected, and in the region $z_c < |z| \leq H$, where the diffusion term is neglected (H is the height of cosmic ray halo). The conditions of continuity for the function f and for the diffusion - convection flux $j = -D \frac{\partial f}{\partial z} - \frac{u}{3} p \frac{f}{p}$ are used to sew solutions together at $|z| = z_c$. Finally, the following equation for the cosmic ray intensity in the Galactic disk $J_0(E)$, where E is the energy per nucleon, can be derived:

$$\frac{J_0}{X} + \frac{d}{dE} \left[\left(\frac{dE}{dx} \right)_{ion} J_0 \right] + \frac{\sigma}{m_{ism}} J_0 = \frac{S(E)}{\mu}, \quad (6)$$

where

$$X = X_e \varphi_{nl}, \quad X_e = \frac{\mu v}{2u(z_c)}, \quad \varphi_{nl} = \left[1 - 3 \int_p^{dp_1} \frac{p}{p_1} \left(\frac{p}{p_1} \right)^5 \frac{J_0(E(p_1))}{J_0(E(p))} \right]^{-1}. \quad (7)$$

Here the source term is $S(E) = \frac{Ap^2}{v} s(p)$, m_{ism} is the average mass of interstellar atom, $\mu = m_{ism} \eta$ is the surface mass density of interstellar gas in the Galactic disk ($\mu \approx 10^{-3} \text{ g/cm}^{-2}$).

Eq. (6) generalizes the well known "leaky-box" approximation [9] to the case of diffusion-convection transport equation with the dependent on distance convection velocity $u(z)$. Eq. (6) for J_0 is nonlinear since the escape length X depends on J_0 through function φ_{nl} because of the adiabatic energy loss of cosmic ray particles in the galactic wind with a nonconstant velocity.

3. Results of calculations

The determination of the model parameters that fit the observational data is performed by selecting the proper escape length X and the coefficient κ . The results of our calculations of $J_0(E)$ and the wind velocity $u(z)$ are shown in Figures 1 and 2 for

$$X_e = \frac{34\beta}{D_0(R)^{0.5} + (D_0(R)^{0.5}/1.3)^{-0.71}} \text{ g/cm}^2, \quad \kappa = 2 \times 10^{27} \text{ cm}^2/\text{s}, \quad u(z_c) = \mu v / 2X. \quad (8)$$

The calculated spectra of protons and Helium are shown by solid lines. The Voyager 1 observations [1] at low energies are labeled by symbols (circles and squares). The high energy PAMELA data [13] are approximated by dotted lines. The calculations are in reasonably good agreement with the Voyager 1 data at low energies and the PAMELA data at high energies. The break in the helium spectrum at energies where transition from the calculated to the measured by PAMELA spectrum occurs in Figure 1 can reflect the difference in the source spectra of protons and Helium that was not taken into consideration in the present calculations.

The delta-function approximation (2) for the interstellar gas and the cosmic-ray source distributions in the galactic disc may affect the calculated energy spectra at the lowest energies. The account for the realistic distributions of gas and sources are beyond the scope of the analytical approach used in the present calculations. The 1D approximation used in our calculations is justified because the cosmic ray density in the galactic disk is determined by the transport coefficients in the vicinity z_c of the point of observation and the value of z_c is less than about 2 kpc at energies below 1 GeV/nucleon.

The derived galactic wind velocity is minimal at the distance about 2 kpc above the galactic disk and is rising linearly at larger distances where it merges with the galactic wind solution [11]

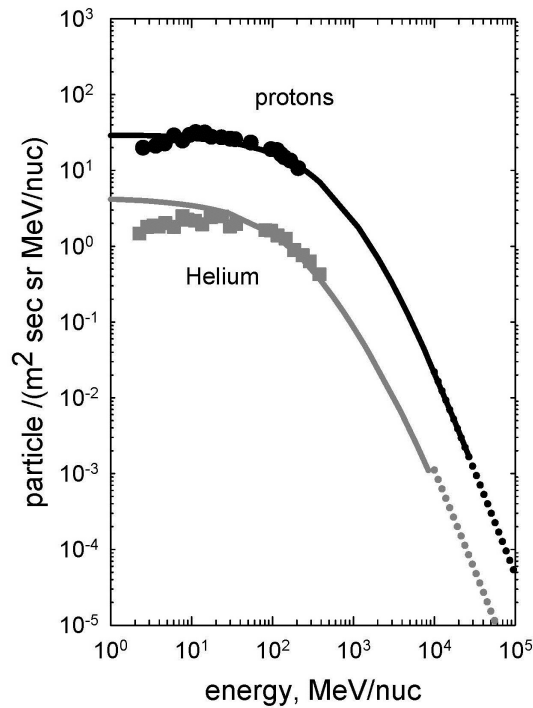


Figure 1. Calculated fluxes of protons and Helium as function of energy are shown by solid lines. Voyager 1 observations [1] at low energies are labeled by symbols (circles and squares). High energy PAMELA data [13] are approximated by dotted lines.

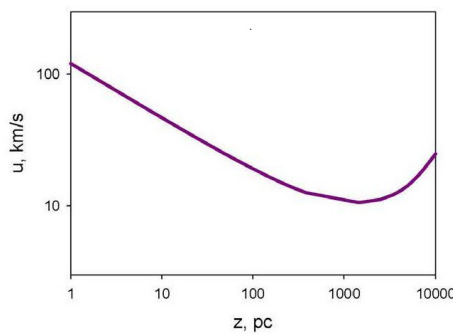


Figure 2. Calculated dependence of galactic wind velocity on distance from galactic disk.

obtained in the model of galactic wind driven by cosmic ray pressure. The decrease of velocity u with distance at $|z| < 2$ kpc may reflect the pattern of the gas flow produced by the supernova explosions in the Galactic disk.

Acknowledgments

The work was supported by the Russian Foundation for Basic Research grant 13-02-00056 and by the Russian Federation Ministry of Science and Education contract 14.518.11.7046. Part of this work was fulfilled during VSP visit to the University of Maryland, USA, where it was

supported by the NASA grant NNX13AC46G.

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