ON THE CONSEQUENCES OF FISK'S TYPE MAGNETIC FIELD CONFIGURATION FOR GALACTIC COSMIC RAY MODULATION

Z. Kobylinski[1], A. Ajabshirizadeh[2], A. Wysokinski[1]

[1] *University of Podlasie, Dept. of Renewable Energies, Siedlce, Poland*
e-mail: `zbigniewkobylinski@yahoo.com`

[2] *Dept. of Theoretical Physics and Astrophysics, Tabriz University, Iran*
e-mail: `ali_ajabshir@yahoo.com`

Three-dimensional steady state transport equation of galactic cosmic rays with drift included is solved by means of newly achieved Fortran code in two cases: 1) Fisk's type of heliospheric magnetic field dominates in the heliosphere; 2) standard Parker field fills the interplanetary space. The spherically symmetric heliosphere bounded at a distance of 100 AU is assumed. In the calculations the parallel and perpendicular diffusion coefficients are proportional to 1/B, anti-symmetric element of the diffusion tensor has the form derived under the assumption of week-scattering. The computed modulated spectra are presented and compared with experimental data (IMP3, IMP8, balloons, and CAPRICE) for the minimum period of solar activity. The best fit is obtained when the index of the power of rigidity in diffusion coefficient formula is less than 0.8.

INTRODUCTION

The heliospheric magnetic field (HMF) is formed by a macroscopic field on which the irregularities of the field are to be superimposed. The solar wind dynamics and the solar rotation determine the direction of the HMF. In the classic spiral Parker geometry [20] the HMF vector in the spherical coordinate system, with polar angle or colatitude θ and azimuthal angle φ, has the following components:

$$B_r^{(P)} = B_0(r_0/r)^2, \qquad B_\theta^{(P)} = 0, \qquad B_\varphi^{(P)} = -B_0\Omega r_0^2(r-r_0)\sin\theta/(V_r r^2), \tag{1}$$

where B_0 is the radial magnetic field strength at the source surface of the solar wind at $r = r_0$, Ω is the angular frequency of rotation of the Sun, and V_r denotes the radial solar wind velocity. According to the newer results Eq. (1) should be modified to include the dependence of V_r and Ω on polar angle θ. As Snodgrass [24] showed, $\Omega(\theta) = \Omega_{eq} - \omega$, where $\Omega_{eq} = 0.25$ rd/day is the equatorial rotation rate and $\omega(\theta) = 0.04\ \cos^2\theta + 0.03\ \cos^4\theta$ rd/day is the angular rate of differential rotation.

The Ulysses spacecraft measurements showed the evidences for the latitudinal transport of cosmic rays which implies that the high latitude regions of the heliosphere are magnetically connected with near-equatorial parts [19]. In the classic Parker geometry it would not seem possible because $B_\theta^{(P)} = 0$. The latitudinal transport could be explained in two ways. Due to turbulence the random walking of the magnetic field lines of force in the heliosphere would provide a significant contribution to perpendicular diffusion in the θ direction which would enhance the transport [12]. In the modification of standard Parker field proposed by Fisk [7] a regular $B_\theta^{(F)}$ component may play the potential role in the latitudinal transport. It would be the result of the differential rotation of the footpoints of magnetic field lines on the photosphere and subsequent non-radial expansion of the field in solar wind plasma which is described by angle β (specified in Fig. 1 of Zurbuchen *et al.* paper [26]). If the coronal hole is tilted to the solar rotation axis, then differential rotation of the bases of field lines in the photosphere, compared to the rigid rotation of the coronal hole, moves the field lines around the coronal hole and causes the large excursions of HMF lines over the wide range of latitudes. This theory applies only in the years of quiet or moderate solar activity, when there are well-developed, long lived polar coronal holes. Fisk & Jokipii [8] pointed out that *"it does not seem possible at present to objectively decide which of the two views dominate"*. We are of opinion that both mechanisms could play an important part.

In a simplified version of the model given in [26] $\omega = const$, $V_r = const$ in the whole heliosphere; and the footpoints are assumed to move around in circles, then the $B_\theta^{(F)}$ and $B_\varphi^{(F)}$ HMF components can be expressed in the corotating frame as:

$$
\begin{aligned}
B_\theta^{(F)} &= \left(B_0 r_0^2/V_r r\right)\omega\sin\beta\sin\left(\varphi+\Omega_{eq}r/V_r-\varphi_M\right), \\
B_\varphi^{(F)} &= B_0 r_0^2\left[-\Omega_{eq}\sin\theta+\omega\cos\beta\sin\theta+\omega\sin\beta\cos\theta\cos\left(\varphi+\Omega_{eq}r/V_r-\varphi_M\right)\right]/\left(V_r r\right),
\end{aligned}
\tag{2}
$$

where φ_M is a coordinate φ of the plane defined by the solar rotation axis O and the magnetic axis M. When $\omega = 0$, Fisk pattern passes into Parker field.

The galactic cosmic ray (GCR) are modulated by HMF. The principal mechanisms of modulation are the following: outward convection by solar wind, inward anisotropic diffusion through HMF irregularities governed by the diffusion tensor K, *i.e.*, unrestricted diffusion in the field's direction $K_\parallel$, and reduced rate of diffusion perpendicular to the field $K_\perp$, adiabatic deceleration from divergence of the spherically expanding solar wind, gradient and curvature drifts in HMF which are described by anti-symmetric term $K_\top$ in diffusion tensor [3]:

$$
K = \begin{pmatrix} K_\parallel & 0 & 0 \\ 0 & K_\perp & K_\top \\ 0 & -K_\top & K_\perp \end{pmatrix}. \tag{3}
$$

These mechanisms are described by consecutive terms in transport equation (TPE) of GCR formulated by Parker [21]

$$
\partial U/\partial t = \nabla\left(\mathbf{K}\cdot\nabla U\right) - \mathbf{V}\cdot\nabla U + \left(1/3P^2\right)\left(\nabla\cdot\mathbf{V}\right)\partial\left(P^3 U\right)/\partial P \tag{4}
$$

for the omnidirectional distribution function or differential number of cosmic rays density $U(\mathbf{r}, P, t)$ with respect to position $\mathbf{r}$, particle rigidity P, and time t, in units: particles/(cm^3 MeV s). $P = p\,c/q$, where $p\,c$ is the kinetic energy and $q = Ze$ is the charge of the particle. The reason for using this value is that different particles with the same rigidity follow identical paths in magnetic fields. This equation is also often solved with respect to particle kinetic energy E or momentum. It is usually assumed that V has only a radial component V_r. In early studies of modulation the role of drifts was neglected. After the Jokipii *et al.* paper [13] the drifts were incorporated into the modulation models by Kota & Jokipii [17] in 3D model and by Potgieter & Moraal [23] in 2D model with the wavy heliospheric current sheet (HCS) included. The HCS tilt angle to the Sun's rotational equator is changeable as solar activity varied. They numerically solved the following steady state TPE modified for the pitch-angle averaged drift velocity of the near-isotropic particle distribution by $\mathbf{V}_d = \nabla\cdot K_\top\mathbf{e}_B$, with the unit vector in the direction of the HMF $\mathbf{e}_B$, where $\mathbf{K}^{(\mathbf{s})}$ is the symmetric part of the tensor:

$$
\nabla(\mathbf{K}^{(\mathbf{s})}\cdot\nabla U) - \mathbf{V}_d\cdot\nabla U - \mathbf{V}\cdot\nabla U + (1/3P^2)(\nabla\cdot\mathbf{V})\,\partial(P^3U)/\partial P = 0\,. \tag{5}
$$

Drift effects result in GCR propagation. When the large-scale HMF in the northern hemisphere is directed toward the Sun (so-called negative or $A < 0$ polarity during 1980–1990, 1959–1969, and possibly 1939–1946) the positively charged particles displace inward along the neutral sheet near the equatorial plane and outward over the polar regions. With the polarity reversed ($A > 0$, 1970–1979 and possibly 1947–1956), the drift pattern also reverses.

Depending on the solved problem, one may solve TPE in terms of either the drift velocity itself (5) or the anti-symmetric diffusion tensor (3) and (4). In the following we have chosen the second way. As pointed out by Kota & Jokipii [18] and Burger & Hattingh [6] the presence of complex B_θ HMF component introduces additional mixed derivatives in 3D TPE and calculations in a numerical scheme can become unstable for some values of parameters. It is remarkably observed in smaller rigidities. It seems from our numerical experiments that the solving of TPE in the (4) form would generate less difficulties.

In spherical coordinate system equations in the steady state TPE we obtain from Eq. (4):

$$
\begin{aligned}
&\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa_{rr}\frac{\partial U}{\partial r} + r\kappa_{r\theta}\frac{\partial U}{\partial\theta} + \frac{r}{\sin\theta}\kappa_{r\varphi}\frac{\partial U}{\partial\varphi}\right) - V_r\frac{\partial U}{\partial r} \\
&+\frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\kappa_{\theta r}\frac{\partial U}{\partial r} + \frac{1}{r}\sin\theta\kappa_{\theta\theta}\frac{\partial U}{\partial\theta} + \frac{1}{r}\kappa_{\theta\varphi}\frac{\partial U}{\partial\varphi}\right) \\
&+\frac{1}{r\sin\theta}\frac{\partial}{\partial\varphi}\left(\kappa_{\varphi r}\frac{\partial U}{\partial r} + \frac{1}{r}\kappa_{\varphi\theta}\frac{\partial U}{\partial\theta} + \frac{1}{r\sin\theta}\kappa_{\varphi\varphi}\frac{\partial U}{\partial\varphi}\right) + \frac{2V_r}{3rP^2}\frac{\partial(P^3U)}{\partial P} = 0.
\end{aligned}
\tag{6}
$$

The elements of diffusion tensor with respect to the heliocentric spherical coordinate system, when HMF has meridional component B_θ, are taken from [14, 15]:

$$
\begin{aligned}
\kappa_{rr} &= (\kappa_\parallel \cos^2\psi + \kappa_\perp \sin^2\psi)\cos^2\zeta + \kappa_\perp \sin^2\zeta,\\
\kappa_{r\theta} &= (\kappa_\parallel \cos^2\psi + \kappa_\perp \sin^2\psi - \kappa_\perp)\sin\zeta\cos\zeta - \kappa_\top \sin\psi,\\
\kappa_{r\varphi} &= (-\kappa_\parallel + \kappa_\perp)\sin\psi\cos\psi\cos\zeta - \kappa_\top\cos\psi\sin\zeta,\\
\kappa_{\theta r} &= (\kappa_\parallel \cos^2\psi + \kappa_\perp \sin^2\psi - \kappa_\perp)\sin\zeta\cos\zeta + \kappa_\top \sin\psi,\\
\kappa_{\theta\theta} &= (\kappa_\parallel \cos^2\psi + \kappa_\perp \sin^2\psi)\sin^2\zeta + \kappa_\perp \cos^2\zeta,\\
\kappa_{\theta\varphi} &= (-\kappa_\parallel + \kappa_\perp)\sin\psi\cos\psi\sin\zeta + \kappa_\top\cos\psi\cos\zeta,\\
\kappa_{\varphi r} &= (-\kappa_\parallel + \kappa_\perp)\sin\psi\cos\psi\cos\zeta + \kappa_\top\cos\psi\sin\zeta,\\
\kappa_{\varphi\theta} &= (-\kappa_\parallel + \kappa_\perp)\sin\psi\cos\psi\sin\zeta - \kappa_\top\cos\psi\cos\zeta,\\
\kappa_{\varphi\varphi} &= (\kappa_\parallel \sin^2\psi + \kappa_\perp \cos^2\psi)
\end{aligned} \tag{7}
$$

with two angles which describe the direction of HMF at every point: the winding angle $\psi = \arctan(-B_\phi/B_r)$ and the deviation angle in the meridional plane $\zeta = \arctan(B_\theta/B_r)$. Their functional forms can be obtained from (1) and (2). When the field is directed from the Sun for the Parker model

$$
\psi^{(P)} = \arctan[(r - r_0)\Omega(\theta)\sin\theta/V_r], \qquad \zeta^{(P)} = 0, \tag{8}
$$

and for the Fisk field

$$
\begin{aligned}
\psi^{(F)} &= \arctan\{(\Omega_{eq} r/V_r)\sin\theta - (\omega r/V_r)[\cos\beta\sin\theta + \sin\beta\cos\theta\cos(\varphi + \Omega_{eq} r/V_r - \varphi_M)]\},\\
\zeta^{(F)} &= \arctan[(\omega r/V_r)\sin\beta\sin(\varphi + \Omega_{eq} r/V_r - \varphi_M)].
\end{aligned} \tag{9}
$$

The observed mean values of ψ at the Earth's orbit are 45° in the sector where the magnetic field is directed from the Sun and 225° in the sector with the field to the Sun. Here we quote the full tensor (7) because in the bibliography one can find another form of that tensor erroneously derived by Alania [1] and Alania & Dzhapiashvili [2], which caused the series of wrong papers directed to GCR modulation published after 1978 by Tbilisi group. Kobylinski [14, 15] in 1999 and 2001 has firstly presented the correct derivation of the tensor.

BASIC ASSUMPTIONS AND METHOD OF CALCULATION

We assume the following functional form for components of diffusion tensor (3): $\kappa_\parallel = \kappa_0 \cdot f_1(r) \cdot f_2(P)$, where $f_1(r) = B_E/B^{(I)}$, where $B^{(I)}$ is a magnitude of background HMF different in Parker ($B^{(P)}$) or Fisk ($B^{(F)}$) models and B_E is the value of the HMF at the Earth. The next function $f_2(P)$ is assumed to be $P^\alpha v/c$ if $P > 0.4$ GeV; with the particle velocity v and velocity of light c, and $P = 0.4\, v/c$ GeV if $P \leq 0.4$ GeV; $\kappa_\perp/\kappa_\parallel = 0.05$. For the anti-symmetric element of the tensor $\kappa_\top = \kappa_{\top_0} Pv/(3cB^{(I)})$, with dimensionless constant $\kappa_{\top_0} = \pm 1$. The solar wind velocity is assumed to be equal to 750 km/s everywhere for both magnetic patterns.

In our model the magnetic axis M perpendicular to the HCS plane offsets from the solar rotation axis by angle 10°. There are two coronal holes symmetrically localized around the magnetic poles and the HCS would be the plane titled to the equator also by angle 10°. However, we assume here that the HCS coincides with plane of equator, which additionally is confirmed by the choice of the point where we should compare the results for both fields. As the Fisk field is valid at high latitudes only, bounded by a cone with half-angle 50°–60°, and accordingly to above-mentioned assumptions, we take and show in Fig. 1 the results of calculation for the point above the ecliptic in the northern hemisphere determined by the coordinates $r = 1$ AU, $\theta = 50°$ and averaged over one solar rotation, *i.e.*, over the range of φ between 0° and 360°. The results of Ulysses observations have shown that this region could be representative also for GCR modulation near the Earth's orbit. The ratio of protons (> 100 MeV) between the Ulysses spacecraft and IMP satellite of the Earth during the period of the fast latitude scan that Ulysses executed in the positive epoch ($A > 0$) in the solar minimum conditions (1995–1996) was only of about 1.2 at the polar angle $\theta = 50°$ [22]. The next simplification is based on the assumption that Fisk HMF is valid at all latitudes. For this field $\beta = 16°$, $\omega = 0.05$. The inner boundary condition is that the radial density gradient is zero at the Sun (at $r° = 0.01$ AU) $\partial U/\partial r = 0$, *i.e.*, the Sun ideally reflects the cosmic particles. The modulation boundary of spherically symmetric heliosphere was at $R_b = 100$ AU. At the outer boundary a local interstellar differential intensity (LIS) of protons was specified accordingly to [25], with a small modification of coefficient (6.2 instead of 6.7), as

$$
j_{o(E)} = 6.2\, E^{0.7}/(E + 0.25)^3, \tag{10}
$$

where E is the kinetic energy of cosmic ray particles.

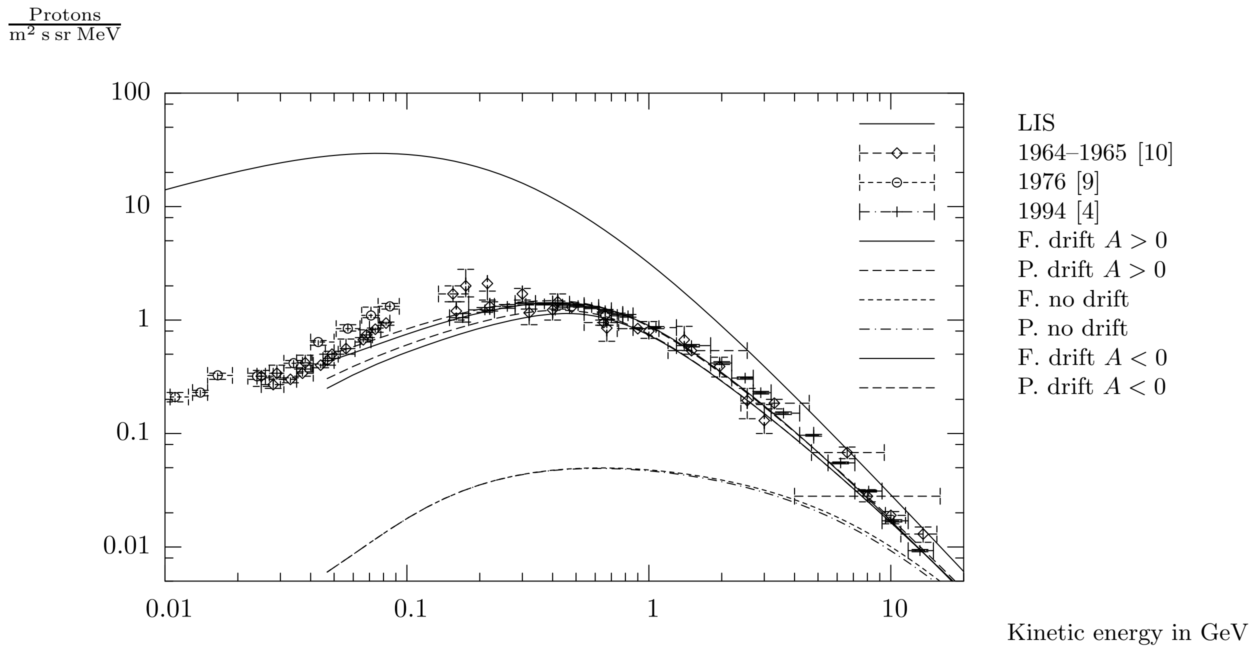

Figure 1. Comparison of drift solutions of TPE with observed proton differential intensities in the solar minimum activity for HMF models. Parameters are specified in the text

After transformation by means of $u = U/U_0$ and $\rho = r/R_b$ to dimensionless form, we derive from (6) the following equation:

$$a\frac{\partial^2 u}{\partial \rho^2} + b\frac{\partial^2 u}{\partial \theta^2} + c\frac{\partial^2 u}{\partial \varphi^2} + d\frac{\partial^2 u}{\partial \rho \partial \theta} + e\frac{\partial^2 u}{\partial \rho \partial \varphi} + f\frac{\partial^2 u}{\partial \varphi \partial \theta} + g\frac{\partial u}{\partial \rho} + h\frac{\partial u}{\partial \theta} + n\frac{\partial u}{\partial \varphi} + pu + q\frac{\partial u}{\partial P} = 0 \tag{11}$$

with outer boundary condition $u|_{\rho=1} = 1$ and initial (in rigidity) condition $u|_{P=450\,\mathrm{GeV}} = 1$.

The derivatives with respect to space coordinates and rigidity were approximated by finite difference rations using the implicit method corresponding to the points on the three-dimensional spatial grid and additionally the one dimensional grid in the rigidity direction. We have chosen the Crank–Nicholson difference scheme. Values for $u(\rho, \theta, \varphi, P)$ are obtained at series of discrete grid points $u(i, j, k, l)$. There were 150 grid points in radial direction unevenly spaced in order to obtain better spatial resolution near the Sun's and Earth's orbit, 93 points in polar angle and 359 points in azimuthal angle equally spaced. The calculation has followed from a high value of rigidity at the initial condition downward through 60 unevenly steps to minimal values which were 0.1 GeV. The integration was carried out by means of a system of linear algebraic equations. We used the method of over-relaxation. We use our new Fortran code obtained from earlier code for 2D problem. At the beginning of the 2000s only two groups, the first at the Arizona University in USA since 1983 [17] and the second at the Potchefstroom University in South Africa [11], had achieved own computational codes that allowing three-dimensional spatial simulation of the steady state GCR modulation with respect to energy or rigidity. At the University of Podlasie, Poland, two 3D Fortran codes for solving TPR have been prepared from earlier existing 2D codes, the first one by T. B. Botchorishvili presented at 1st ICP at Tehran [16], the second by Z. Kobylinski (3DTPERIG). The Botchorishvili's code has worked properly in drift modelling only for one polarity epoch ($A > 0$ or $A < 0$). Here we show preliminary results of 3D simulation of GCR transport during both epochs, which was done by the second code.

RESULTS

Figure 1 presents the results of our calculations. As the Fisk field is valid at high latitudes only, and according to above-mentioned assumptions, here we present the obtained spectra at point above ecliptic plane in the northern hemisphere determined by the coordinates $r = 1$ AU, $\theta = 50°$. We selected both constants in diffusion coefficient κ_0 and α in order to obtain the best fit of the calculated spectrum for Fisk model with drift to the observational spectra [4, 9, 10]. The values are the following: $\alpha = 0.8$ and $\kappa_0 = 4.4 \cdot 10^{22}\,\mathrm{cm}^2\ \mathrm{s}^{-1}$. Our result concerning the slope of diffusion coefficient dependence on rigidity confirms the former result derived by Bobik *et al.* [5] on the basis of 2D stochastic model ($\alpha = 0.75$).

For the Parker HMF model the values used were the same. Parker model gives a slightly bigger intensity in the range of smaller energies. It is the result of a little easier access of particles from the poles of the heliosphere to the Earth's region in Parker HMF than in Fisk field. In general, features the modulated spectra for both HMF models during positive and negative epochs are similar. During positive periods protons have an easier access to the inner heliosphere due to direction of drift velocity from the poles and due to the configuration of the filed lines in the polar regions: in the Fisk pattern a regular component of the field is weak, in Parker field the winding of magnetic spirals is much smaller than in equatorial region. Simultaneously, Figure 1 points out that our computational code works correctly. It is clear that both drift models could be successful at explaining modulation of the spectrum after a some corrections of the value of parameters particularly in a range of low energies. Due to a slow convergence of the solution of TPE in the range of low rigidities in the case of Fisk model we performed the calculation only for a rigidity of 0.1 GeV. In both HMF models the densities and intensities (Figs. 6 and 7) in the no-drift cases are smaller than in the cases when the drift is included to the calculations. Thus, this manifests that the drift transport from the pole to equator is very effective. It was also shown in earlier calculations. Fisk pattern gives a pronounced 27-day variation, but this result is not presented in the paper.

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