Reentrant heliospheric particles in 2D drift model

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**Abstract:** We developed 2D time dependent heliospheric model where particles trajectory are reconstructed back in time. The model is time dependent due to drifts in the heliosphere. We followed particles also after escaping the heliosphere in the interstellar space to found the fraction of them that reenter back again into the heliosphere. We show how this effect can change the modulation of particles in the heliosphere for different solar periods and for different orientation and strength of interstellar magnetic field. The dependence of modulation process in the heliosphere from reentrant particles is discussed in connection to particles mean free path in the interstellar space. This work is supported by the Slovak Research and Development Agency under the contract No. APVV51053805.

**Introduction**

The problem of transport and distribution of Galactic Cosmic Rays in the heliosphere and interstellar space is described by the Fokker-Planck equation (FPE hereafter) [1][2]. Many methods to solve the FPE were introduced in the last decades [3][4]. One of the commonly used is the solutions of the FPE by the Monte Carlo method based on Ito's proof that a set of stochastic differential equations is equivalent to the FPE [5]. The time reversal process is also possible [6][7]. Particles of GCR from interstellar space penetrating the heliosphere are affected by outgoing solar wind and lose energy adiabatically. Particles outside the heliosphere diffuse in the interstellar space without any energetic losses. It may happen that a particle escaping the heliosphere reenter later back again. Almost in all present models of GCR modulation in the heliosphere, particles escaping the heliosphere are no longer considered. This do not take into account the possibility of reentrant particles. Using a back-tracing model we can evaluate the effect of possible reentrant particles to the modulated spectrum inside the heliosphere.

**Diffusion in heliosphere**

Model consist from two parts. First is a particles diffusion in heliosphere, second is description of particles diffusion in the interstellar space. 2D model of particle diffusion in the heliosphere including drift effects we described in [8]. Actually used model is same, but working with a time reversal process. Particles are injected uniformly with energy at 1AU. Particle with injection energy $T_0$ during its way back in time in the heliosphere can gain energy (reversal process to adiabatic losses). After injection the particle is followed back in time inside the heliosphere to the moment when it crosses the heliosphere border at 100AU. Kinetic energy $T_1$ of the particle at the moment of first heliopause crossing is recorded.
Main parameters of model inside heliosphere are diffusion coefficient, tilt angle and solar wind velocity. The radial diffusion coefficient is \( K_R = K_R \cos^2 \psi + K_L \sin^2 \psi \), where \( \psi \) is the angle between radial and magnetic field directions. The latitudinal coefficient is \( K_\theta = K_\perp \). The parallel and the perpendicular diffusion coefficients are

\[
K_\parallel = K_0 \beta K_p (\mathcal{R}) \frac{B_0}{3B}, \quad K_\perp = (K_\perp)_0 K_\parallel
\]

\( K_0 = 2 \cdot 5 \times 10^{22} \text{ cm}^2 \text{ s}^{-1} \), \( \beta \) is the particle velocity in units of light velocity, \( K_p (\mathcal{R}) = \mathcal{R} \) take into accounts the dependence on rigidity (\( \mathcal{R} \) in GV), \( (K_\perp)_0 = 0.025 \) is the ratio between parallel and perpendicular diffusion coefficient, \( B_0 = 5 \text{ nT} \) is the value of heliospheric magnetic field at the Earth orbit, and \( B \) is the Parker field.

**Diffusion in the interstellar space**

Because the probability that a particle reenter back to the heliosphere should depend on the particle mean free path in interstellar space, we use a parallel diffusion coefficient \( K_{\parallel IS} \) in interstellar space constructed in following way [9].

\[
K_{\parallel IS} = \eta K_\parallel \sim K_0^IS \eta Z^{-1} \left( \frac{E}{\text{GeV}} \right) (\frac{B}{1 \mu G})^{-1} \text{ cm}^2 \text{ s}^{-1}
\]

where diffusion coefficient in the interstellar space \( K_0^IS = 3.3 \times 10^{22} \text{ cm}^2 \text{ s}^{-1} \). \( \eta \) is the ratio of the mean free path of the particle to the Larmor radius, \( K_\parallel \) is the Bohm diffusion coefficient \( K_\parallel = Ec/(3ZeB) \) where \( E \) is total energy, \( Z \) is the atomic number and \( B \) is the magnetic field intensity in the interstellar space. \( \eta \) is a parameter of simulation in interstellar space. We used a set of values \( \eta \) from 10 to 1000. Perpendicular diffusion coefficient \( K_{\perp IS} = (K_\perp)_0 K_{\parallel IS} \) where \( (K_\perp)_0 \) is a parameter which influence to model result was test in range from 0.01 to 1. Magnetic field in the interstellar space is the second parameter of the simulation outside the heliosphere. We assume locally a constant value of the interstellar magnetic field in the test domain (sphere with radius to one parsec from the Sun). For model calculations we choosed a locally constant homogenous magnetic field oriented wit angle \( \delta \) to ecliptic plane of the heliosphere described as \( B_r = B_0 \sin(\theta + \delta) \) and \( B_\theta = B_0 \cos(\theta + \delta) \) where value \( B_0 = 1 \mu G \).

Particle diffuse in the interstellar space. Finally when particle crosses the border 1 parsec we record its kinetic energy \( T_2 \). In this moment we evaluate two flux values. First for modulated spectrum at 1AU not affected by reentrant particles, and second affected by reentrant particles. The number of particles from local interstellar spectrum [10] for energy \( T_1 \) is added to the energy bin belonging to initial energy \( T_0 \) for the spectrum not affected by reentrant particles. Same process for energy \( T_2 \) is done to evaluate a spectrum taking into account reentrant particles. Then, next particle is injected and the process is repeated for a time long enough to obtained stable statistics. All calculations presented in this paper are made for protons.

**Results**

Influence of reentrant particles to different energies of modulated spectra is presented on figures.
1. and 2. Situation for positive solar period $A > 0$ with $\eta = 100$, $\delta = 0^\circ$, $\alpha = 30^\circ$ and $(K_{\perp}^{IS})_0 = 0.25$ is showed at Figure 1. At upper panel is the spectrum containing reentrant particles ($S_1$) evaluated for mentioned parameters compared with the spectrum without reentrant particles ($S_2$) both calculated for same parameters in the heliosphere.

![Graph 1](image1.png)

**Figure 1:** Upper panel show a modulated spectra at 1AU for $\eta = 100$ together with a local interstellar spectrum (LIS). Line with triangles denote a spectrum without reentrant particles, solid line with diamonds denote spectrum with a reentrant particles. Bottom panel of figure show a ratio between both spectra ($S_1/S_2$) for $A > 0$ and $A < 0$.

![Graph 2](image2.png)

**Figure 2:** Upper panel show $I_2/I_1$ ratio dependence on $\eta$ for a positive solar period ($A > 0$). Bottom panel show $I_2/I_1$ ratio dependence on $(K_{\perp}^{IS})_0$ for $A > 0$ and $A < 0$.

Bottom panel of Figure 1. shows ratios between both spectra ($S_1/S_2$) for positive solar period $A > 0$ and negative solar periods $A < 0$.

We made calculation for a set of $\eta$ values for particles registered at 1AU with energy 0.1 and 2 GeV. Dependence of ratio between intensity of particles without taking into account a reentrant particles ($I_1$) and with a reentrant particles ($I_2$) for a different values of $\eta$ is showed at upper panel of Figure 2. Effect of reentrant particles to registered intensity inside heliosphere also depend on a ratio
between parallel and perpendicular coefficient in
the interstellar space. To show the effect we made
a calculation for a particles registered at 1AU in a
ecliptic plane with kinetic energy 2GeV. Depen-
dence of ratio between intensity of 2GeV particles
without taking into account a reentrant particles ($I_1$) and with a reentrant particles ($I_2$) for a
different values of $(K_{\perp IS})_0$ is presented at the
bottom panel of Figure 2.

Conclusions

We estimated the influence of reentrant heliospheric influence to proton energy spectra modu-
lation at 1AU. This effect depends on many fac-
tors: particles mean free path in the interstellar
space, the interstellar magnetic field, the ratio be-
tween parallel and perpendicular diffusion coeffi-
cients in the interstellar space, the solar period
and solar period parameters as polarity and tilt
angle. Reentrant particles have stronger influence
during negative solar periods. Decreasing the ra-
tio between parallel and perpendicular diffusion
coefficient in the interstellar space, we increase
the effect of reentrant particles to spectra modula-
tion. Moreover, the effect of reentrant particles in-
creases with decreasing the particles mean free
path in the interstellar space.

References

[1] Parker, E. N., The passage of energetic
charged particles through interplanetary space,
1943.
observed charge states of low-energy solar cosmic
rays, Journal of Geophysical Research, 80, 1209-
1212., 1975.
of cosmic-ray acceleration by Ito’s stochastic dif-
ferential equations, Astron. Astrophys. 286, 314-
[6] Kóta, J., Energy loss in the solar system and
modulation of cosmic radiation, Proc. of 15
stochastic view of the solar modulation phenome-
a of cosmic rays, Geophysical Research Letters,
[8] Bobik, P., Gervasi M., Grandi, D., Rancoita,
P.G., Usoskin I.G., 2D stochastic simulation mod-
el of cosmic ray modulation: Comparison with
experimental data, Proceedings of ICSC 2003,
modulation of extragalactic cosmic rays: Possible
origin of the knee in the cosmic ray spectrum,
Progress of Theoretical Physics, Vol. 113, No. 4,
Rigidity dependence of cosmic ray proton latitu-
dinal gradients measured by the Ulysses space-
craft: Implications for the diffusion tensor, Jour-
nal of Geophysical Research, 105, A12, 27447-