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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 $K_{rr} = K_{II} \cos^2\psi + K_{\perp}\sin^2\psi$, where ψ is the angle between radial and magnetic field directions. The latitudinal coefficient is $K_{\theta\theta} = K_{\perp}$. The parallel and the perpendicular diffusion coefficients are

$$K = K_0\beta K_P(\Re)\frac{B_0}{3B}, K_{\perp} = (K_{\perp})_0 K$$

$K_0 = 2$ - 5 10^{22} cm^2 s^{-1}, β is the particle velocity in units of light velocity, K_P (ℜ) = ℜtake into accounts the dependence on rigidity (ℜin GV), $(K_\perp)_0$ = 0.025 is the ratio between parallel and perpendicular diffusion coefficient, $B_0 = 5$ 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^{IS} in interstellar space constructed in following way [9].

$$K^{IS} = \eta K_B \quad K_0^{IS} \eta Z^{-1} \left(\frac{E}{GeV}\right)\left(\frac{B}{1\mu G}\right)^{-1} cm^2 s^{-1}$$

where diffusion coefficient in the interstellar space K_0^{IS} = 3.3 10^{22} $cm^2 s^{-1}$. η is the ratio of the mean free path of the particle to the Larmor radius, K_B is the Bohm diffusion coefficient $K_B = Ec/(3ZeB)$ where E is total energy, Z is the atomic number and B is the magnetic field intensity in the interstellar space. η is a parameter of simulation in interstellar space. We used a set of values η from 10 to 1000. Perpendicular diffusion coefficient $K_\perp^{IS} = \left(K_\perp^{IS}\right)_0 K^{IS}$ where $\left(K_\perp^{IS}\right)_0$ 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 chose a locally constant homogenous magnetic field oriented wit angle δ 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 μG. 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 negative solar period A < 0 with η = 100, δ = 0°, α = 30° and $\left(K_\perp^{IS}\right)_0$ = 0.25 is showed at Figure 1. At upper panel is the spectrum containing reentrant particles (S_W) evaluated for mentioned parameters compared with the spectrum without reentrant particles (S_{WO}) both calculated for same parameters in the heliosphere. Bottom panel of Figure 1. shows ratios between both spectra (S_{WO}/S_W) for negative solar period A < 0 and η = 100.

We made calculation for a set of η values for particles registered at 1AU with energy 2 GeV. Dependence of ratio between intensity of particles without taking into account a reentrant particles (I_{WO}) and with a reentrant particles (I_W) for a different values of η 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. Dependence of ratio between intensity of 2GeV particles without taking into account a reentrant particles (I_{WO}) and with a reentrant particles (I_W) for a different values of $\left(K_\perp^{IS}\right)_0$ is presented at the bottom panel of Figure 2.

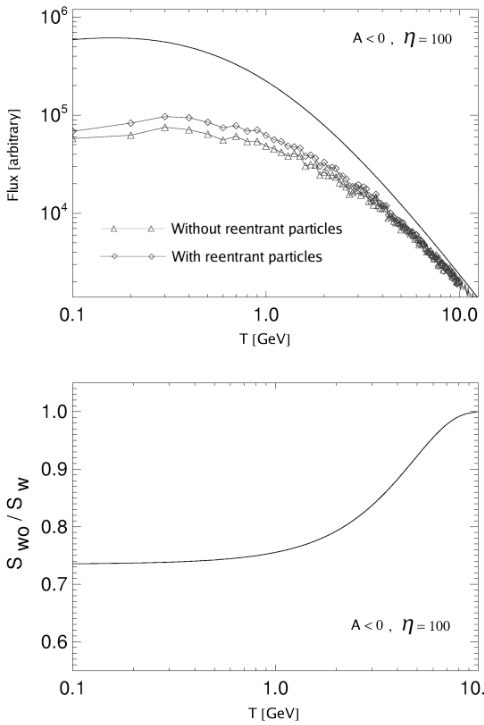

Figure 1: Upper panel show a modulated spectra at 1AU for η = 100 together with a local interstellar spectrum (LIS). Line with triangles denote a spectrum without reentrant particles, solid line with diamonds denote spectrum with a reentrant particles. Bottom panel of figure show a ratio between both spectra (S_{WO}/S_W) for $A < 0$.

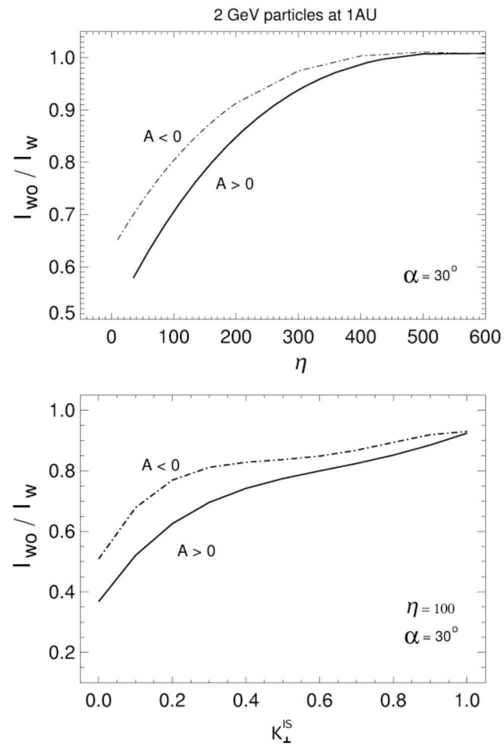

Figure 2: Upper panel show I_{WO} /I_W ratio dependence on η for $A > 0$ and $A < 0$. Bottom panel show I_{WO}/I_W ratio dependence on $\left(K_{\perp}^{IS}\right)_0$ for $A > 0$ and $A < 0$.

Conclusions

We estimated the influence of reentrant heliospheric particles to energy spectra modulation at 1AU. This effect depends on many factors: particles mean free path in the interstellar space, the interstellar magnetic field, the ratio between parallel and perpendicular diffusion coefficients in the interstellar space, the solar period and solar period parameters as polarity and tilt angle. Reentrant particles have stronger influence during positive solar periods. Decreasing the ratio between parallel and perpendicular diffusion coefficient in the interstellar space, we increase the effect of reentrant particles to spectra modulation. Moreover, the effect of reentrant particles increases with decreasing the particles mean free path in the interstellar space.

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