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Effects of solar modulation on the cosmic ray positron fraction

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Abstract

We implemented a 2D Monte Carlo model to simulate the solar modulation of galactic cosmic rays. The model is based on the Parker's transport equation which contains diffusion, convection, particle drift and energy loss. Following the evolution in time of the solar activity, we are able to modulate a local interstellar spectrum (LIS), that we assumed isotropic beyond the termination shock, down to the Earth position inside the heliosphere. In this work we focused our attention to the cosmic ray positron fraction at energy below ~10 GeV, showing how the particle drift processes could explain different results for AMS-01 and PAMELA. We compare our modulated spectra with observations at Earth, and then make a prediction of the cosmic ray positron fraction for the AMS-02 experiment.

Keywords: Heliosphere; Cosmic ray; Solar modulation; Leptons

1. Introduction

Galactic cosmic rays (GCRs) are protons, ions and leptons, produced and accelerated mainly by supernova remnants (see Blasi, 2011). GCRs remains confined in the galactic magnetic field to form a nearly isotropic flux inside the galaxy. Before reaching the Earth's orbit they enter the heliosphere, the region where the interplanetary magnetic field is carried out by the solar wind (SW). In this environment they undergo diffusion, convection, particle drift and adiabatic energy loss, resulting in a reduction of the particle's flux up to ~20 GeV, depending on the solar activity and field polarity.

The recent accurate measurements of cosmic positrons and electrons, performed by PAMELA (Adriani et al., 2009), show an anomalous positron excess at energies >10 GeV in comparison with the models of secondary production (see Zhang and Cheng, 2001 and Moskalenko and Strong, 1998). In the last years many papers discussing the nature of this excess have been published. Some of them suggest a dark matter signature (Yin et al., 2009); other authors invoke a primary production of electron/positron pairs by local astrophysical sources like Pulsars (Grasso et al., 2009). In this paper we do not discuss this cosmic ray positron fraction excess, since we focused on the energy interval ⩽10 GeV where the same observations of CR positron fraction made by PAMELA experiment are systematically below previous measurements, like e.g. AMS-01 observations (Aguilar et al., 2007), as well as below the models of galactic secondary production.

Using our 2D Monte Carlo model (Bobik et al., 2011) we argue the reasons for this discrepancy is a solar modulation effect, that is caused by gradient and curvature drifts following changes in the magnetic field polarity. In this

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paper we first describe our modulation model, then we discuss the different behaviours of particles with opposite charge sign comparing periods with reversed polarity. Finally we compare simulation results with observations and provide also a prediction for the AMS-02 experiment.

2. 2D Monte Carlo model

2.1. Transport equations

The GCRs transport in the heliosphere is described by a Fokker–Planck equation, the so-called Parker equation (Parker, 1965):

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x_i}\left(K^S_{ij}\frac{\partial U}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_{sw_i}U) + \frac{1}{3}\frac{\partial v_{sw_i}}{\partial x_i}\frac{\partial}{\partial T}(\rho T U) - \frac{\partial}{\partial x_i}(v_{D_i}U) \quad (1)$$

where U is the cosmic ray number density per unit interval of particle kinetic energy, t is the time, T is the kinetic energy (per nucleon), v_{sw_i} the solar wind speed along the axis x_i, v_{D_i} is the particle drift velocity related to the antisymmetric part of diffusion tensor (Jokipii and Levy, 1977; Jokipii et al., 1977), K^S_{ij} is the symmetric part of the diffusion tensor and $\rho = (T + 2T_0)/(T + T_0)$ (Gleeson and Axford, 1967), where T_0 is particle's rest energy. This partial differential equation is equivalent to a set of ordinary stochastic differential equations (SDEs, see e.g. Gardiner, 1989) that can be integrated with Monte Carlo (MC) techniques (see e.g. Yamada et al., 1998; Gervasi et al., 1999; Zhang, 1999; Alanko-Huotari et al., 2007; Pei et al., 2010; Strauss et al., 2011). The integration time step (Δt), is taken to be proportional to r^2 (r is the distance from the Sun) avoiding oversampling in the outer heliopshere and therefore saving CPU time (Alanko-Huotari et al., 2007). We considered the 2D (radius and polar angle) approximation of Eq. (1) (Potgieter et al., 1993), and from this we calculate the equivalent set of SDEs (Bobik et al., 2011):

$$\Delta r = \frac{1}{r^2}\frac{\partial(r^2 K_{rr})}{\partial r}\Delta t + (v_{sw} + v_{D_r} + v_{D_{NS}})\cdot\Delta t + R_g\sqrt{2K_{rr}\Delta t}$$

$$\Delta\mu = \frac{1}{r^2}\frac{\partial[(1-\mu^2)K_{\theta\theta}]}{\partial\mu}\Delta t - \frac{\sqrt{1-\mu^2}}{r}v_{D_\theta}\Delta t + R_g\sqrt{\frac{2K_{\theta\theta}(1-\mu^2)\Delta t}{r^2}}$$

$$\Delta T = -\left(\frac{2}{3}\frac{\rho V_{sw}T}{r}\right)\Delta t \quad (2\text{-}4)$$

where $\mu = \cos\theta$, with θ polar angle, and R_g is a gaussian distributed random number with unitary variance. Here the particle drift velocity is splitted in regular drift (radial drift v_{D_r}, latitudinal drift v_{D_θ}) and neutral sheet drift (v_{D_NS}) as described by Potgieter and Moraal (1985) and Hatting and Burger (1995). The diffusion tensor is taken to be $K_{rr} = K_{||}cos^2\psi + K_{\perp r}.sin^2\psi$ and $K_{\theta\theta} = K_{\perp\theta}$ (Potgieter et al., 1993; Potgieter and Le Roux, 1994), where ψ is the angle between radial and magnetic field directions; labels $\perp$ and $||$ are respectively the perpendicular and parallel components of the diffusion process with respect to the background magnetic field lines. In heliocentric spherical coordinates, the perpendicular diffusion coefficient has two components, one along the radial direction, $K_{\perp r}$, the other one along the polar direction $K_{\perp\theta}$. ρ_k is the ratio between $K_{\perp r}$ and the parallel diffusion coefficient $K_{||}$:

$$K_{\perp r} = \rho_k K_{\|} \quad (5)$$

In the present model, we use $\rho_k = 0.05$: this value is in the mid of the range suggested by Palmer (1982) – see also Giacalone (1998) and Section 6.3 of Burger et al. (2000). The value of the perpendicular diffusion coefficient in the polar direction ($K_{\perp\theta}$) can be assumed to be equal to the perpendicular diffusion coefficient in the radial direction, but we also consider an enhancement factor of ~10 in the polar regions (see Potgieter, 2000), as described in Bobik et al. (2011, 2012). The parallel diffusion coefficient is $K_{||} = k_0\beta K_P(P)(B_\oplus/3B)$ (Potgieter and Le Roux, 1994): here $k_0 \approx 0.05–0.3\times10^{-3}$ AU^{2}GV^{-1}s^{-1}, is a diffusion parameter depending on solar activity (see Section 2.3), β is the particle velocity in unit of light speed c. We are interested to an interval of energy above 1 GeV where $K_P = P$ (Potgieter and Le Roux, 1994), with $P = pc/Ze$ is the CR particle's rigidity, p is the particle's momentum and Ze is the particle's charge. $B_\oplus$ is the value of heliospheric magnetic field measured at the Earth orbit, and B is the magnitude of the heliospheric magnetic field (HMF) (Hatting and Burger, 1995):

$$B = \frac{A}{r^2}(e_r - \Gamma e_\phi)\cdot[1 - 2H(\theta - \theta')] \quad (6)$$

where A is a coefficient that allows $|\mathbf{B}|$ to be equal to $B_\oplus$, i.e., the value of HMF at the Earth orbit, and determines the field polarity, i.e., $A > 0$ for positive periods (e.g. AMS-01 observations) and $A < 0$ for negative periods (e.g. PAMELA observations); θ' is the polar angle determining the position of the heliospheric current sheet (HCS) (Jokipii and Thomas, 1981); H is the Heaviside function, thus $[1 - 2H(\theta - \theta')]$ accounts for the change of sign between the two regions - above and below the HCS - of the heliosphere; finally $\Gamma = \tan\Psi \cong \frac{\omega r \sin\Theta}{v_{sw}}$, with ψ the spiral angle. We modify the HMF according to Jokipii and Kóta (1989), increasing the magnitude of the HMF in the polar regions (see Bobik et al., 2011 for details). We use a SW broad smoothed profile according to Ulysses observation for periods of low solar activity (McComas et al., 2000, 2008), described by the relation $V_{sw}(\theta) = V_{max}$ if $\theta \leqslant 30°$ or $\theta \geqslant 150°$ and $V_{sw}(\theta) = V_0\cdot(1 + |\cos\theta|)$ if $30° < \theta < 150°$ where V_0 is approximately 400 km/s and V_{max} is 760 km/s.

2.2. Particle drift

We emphasize the importance to include particle drift in the model, since this is the only part of Eq. (1) that is sensitive to particle charge sign (or, equivalently, to the polarity of HMF). The particle drift is described by the relation (Jokipii and Levy, 1977):