PROTON AND ANTIPROTON MODULATION IN THE HELIOSPHERE FOR DIFFERENT SOLAR CONDITIONS AND AMS-02 MEASUREMENTS PREDICTION.

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Galactic Cosmic Rays (GCRs) are mainly protons confined in the galactic magnetic field to form an isotropic flux inside the galaxy. Before reaching the Earth orbit they enter the Heliosphere and undergo diffusion, convection, magnetic drift and adiabatic energy loss. The result is a reduction of particles flux at low energy (below 10 GeV), called solar modulation. We realized a quasi time-dependent 2D Stochastic Simulation of Solar Modulation that is able to reproduce CR spectra once known the Local Interstellar Spectrum (LIS). We were able to estimate the different behaviors associated to the polarity dependence of the Heliospheric modulation for particles as well as for antiparticles. We show a good agreement with the antiproton/proton ratio measured by AMS-01, Pamela, BESS, Heat and Caprice and we performed a prediction for the AMS-02 Experiment.

Keywords: Heliosphere, Cosmic Rays, Solar Magnetic Field

1. Introduction

The effect of the heliospheric structure on GCRs propagation can be reproduced by a two dimensional (radius and helio-colatitude) Stochastic model solving numerically the Parkers's equation[1]. If we do not take into account the effects of the Earth magnetosphere[2] modulated fluxes depends not only on the level of solar activity but also on particles charge sign and solar magnetic field polarity[3]. The study of the modulation of $\bar{p}/p$ ratios is particularly important, because it includes explicitly the combination of charge sign and polarity dependence. The Local Interstellar Spectra (LIS)

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used as input of the code, both for protons and antiprotons, are taken by the Galprop model[4].

2. Stochastic Model, Parameters and Data Sets

2.1. *Main parameters of the Model*

The present code simulates the interactions of a GCR entering the heliosphere which extends up to a fixed distance of about 100 AU from the Sun.

One of the main parameters of the model is the diffusion tensor. The parallel diffusion coefficient is: $K_{||}=k_1\beta K_P(P)(B_\oplus/3B)$, where P is the particle rigidity (usually expressed in GV), k_1 is the diffusion parameter discussed in the next section and $K_P \approx P$. The perpendicular diffusion coefficient has two components, radial $K_{\perp r}$, and polar $K_{\perp\theta}$. We used the relation: $K_{\perp r} = (K_\perp)_0 K_{||}$, where $(K_\perp)_0 = 0.05$. We also considered $K_{\perp\theta} = K_{\perp r}$ in the equatorial region, while we enhanced its value in the polar regions of the heliosphere[5]: $K_{\perp\theta} = 10K_{\perp r}$.

We used the tilt angle α of the heliospheric current sheet (HCS) as a parameter for the level of the solar activity[6]: the higher the value of α the lower the expected GCR flux, for both solar field polarities. Values of the tilt angle are computed using two different models: the usual model uses a line-of-sight boundary condition at the photosphere and includes a significant polar field correction; an alternative model uses a radial boundary condition at the photosphere, and requires no polar field correction. As suggested by Ferreira and Potgieter[7], the classical model is used for periods of increasing solar activity (for example 2007–2012, AMS-01 data, AMS-02 data), while the new model fits better for periods of decreasing solar activity (for example 2000–2007, BESS data).

The three drift components do not depend on external parameters, except the solar polarity[8] (A>0 for positive periods and A<0 for negative periods[6]). The general drift expression is locally unlimited for a quasi-isotropic distribution[9,10], therefore we limit all the drift components below $(\pi/4)v$, which is the spatially averaged maximum value.

2.2. *Data Sets*

We selected GCR proton and antiproton data from 5 different experiments in order to compare and tune model results: AMS-01[11], Caprice[12], BESS[13–15], HEAT and Pamela[16]. The first two experiments took data in a period of positive solar polarity, BESS in both solar polarities, and the

last two in A<0 period. The corresponding periods of measurements are: June 1998 (AMS); May 1998 (Caprice); from July 1997 to December 2004 (BESS); June 2000 (HEAT); and from 2007 to 2008 (Pamela). Solar wind values for these periods have been obtained from omniweb[17] by 27 daily averages, while tilt angle values from the Wilcox Solar Laboratory[18]. We can estimate the diffusion coefficient from a long term study[19,20] of neutron monitor measurements and the *Force Field model*[21] (FFM) approach to the treatment of Heliosphere transport of GCRs, using ~ 40 years of data ending in 2004.
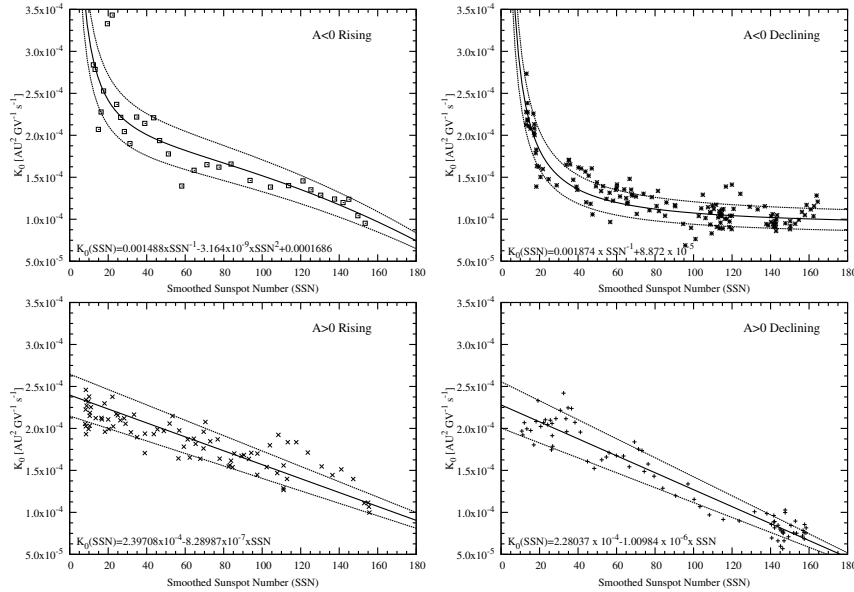

Fig. 1.   Diffusion parameter K_0 - rising and declining phases for both negative and positive solar magnetic-field polarities - as a function of the SSN value; the continuous lines are obtained from a fit of K_0 with respect to SSN values.

In FFM[21] [e.g., see also Section 4.1.2.3 of Leroy and Rancoita (2009)], Gleeson and Axford (1968) assumed that i) modulation effects can be expressed with a spherically symmetric modulated number density U of GCRs - the so-called differential density - with kinetic energy between T and $T + dT$, ii) the diffusion coefficient at the time t is given by a separable function of r (the radial distance from the Sun) and P (the particle rigidity

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in GV):

$$\mathcal{K}(r,t) = \beta k_1(r,t) K_P(P,t),$$

with $\beta = v/c$, v the particle velocity, c the speed of light, $K_P(P,t) \approx P$ for particle rigidities above $\approx 1\,\text{GV}$ and iii) the modulation occurs in a steady-state condition, i.e., the relaxation time of the distribution is short with respect to the solar cycle duration so that

$$\frac{\partial U}{\partial t} = 0.$$

They derived that the differential intensity at a radial distance r is given by the expression

$$J(r, E_\text{t}, t) = J(r_\text{tm}, E_\text{t} + \Phi_\text{p}) \left[\frac{E_\text{t}^2 - m_\text{r}^2 c^4}{(E_\text{t} + \Phi_\text{p})^2 - m_\text{r}^2 c^4} \right], \qquad (1)$$

where $J(r_\text{tm}, E_\text{t} + \Phi_\text{p})$ is the undisturbed intensity beyond the solar wind termination located at a radial distance r_tm from the Sun; E_t is the total energy of the particle with rest mass m_r and, finally, Φ_p is the so-called force-field energy loss[21,23]. When modulation is small[21,23] - i.e., $\Phi_\text{p} \ll m_\text{r}c^2, T$ -, they determined that

$$\Phi_\text{p} = \frac{ZeP}{K_P(P,t)}\, \phi_\text{s}(r,t) \approx Ze\, \phi_\text{s}(r,t),$$

where Ze is the particle charge and $\phi_\text{s}(r,t)$ is the so-called modulation strength (or modulation parameter). Assuming that v_w (the solar wind speed) and k_1 are almost constant, $\phi_\text{s}(r,t)$ - usually expressed in units of GV (or MV) - reduces to

$$\phi_\text{s}(r,t) \approx \frac{v_\text{w}(t)\,(r_\text{tm} - r)}{3k_1(t)}, \qquad (2)$$

from which one gets

$$k_1(t) \approx \frac{v_\text{w}(t)\,(r_\text{tm} - r)}{3\phi_\text{s}(r,t)}, \qquad (3)$$

i.e., k_1 is linearly dependent on $(r_\text{tm} - r)$. In the FFM, the diffusion coefficient $\mathcal{K}(r,t)$ is scalar quantity and, as a consequence, does not account for effects related to the charge sign of the transported particles. $\phi_\text{s}(r,t)$ is independent of the species of GCR particles [e.g., see discussion at page 1014 of Gleeson and Axford (1968) or Equation (1) of Usoskin and collaborators (2005)]. The values of the modulation strengths [$\phi_\text{s}(r_\text{Earth})$] were monthly determined for the time period[20] from 1951 up to 2004 using measurements of neutron monitors (i.e., located at $r_\text{Earth} = 1\,\text{AU}$); while those for the

solar wind speeds are available on the web[24]. It has to be remarked that k_1 depends on the value of the solar wind termination located at a radial distance $r_{\rm tm}$ related, in turn, also to the solar wind speed [e.g., see Chapter 7 of Meyer-Vernet(2007) and Section 4.1.2.2 of Leroy and Rancoita (2009)]. However, because the present simulation code assumes a fixed solar wind termination at 100 AU to calculate the modulated differential intensities at $r_{\rm Earth}$, one has to derive from the diffusion parameter k_1 that (K_0) for an effective heliosphere with a radial extension of 100 AU (see Sect. 2.1). Thus, using Eq. (3) one can obtain

$$K_0 \approx k_1 \frac{99\,{\rm AU}}{(r_{\rm tm} - r_{\rm Earth})} = 99\,{\rm AU}\left[\frac{v_{\rm w}}{3\,\phi_{\rm s}(r_{\rm Earth})}\right], \qquad (4)$$

where 99 AU is the distance of the Earth from the border of the effective heliosphere as defined in the current simulation code. In Fig. 1, the diffusion parameter K_0 - obtained from Eq. (4) - is shown as a function of the corresponding Smooted Sunspot Number (SSN) value.
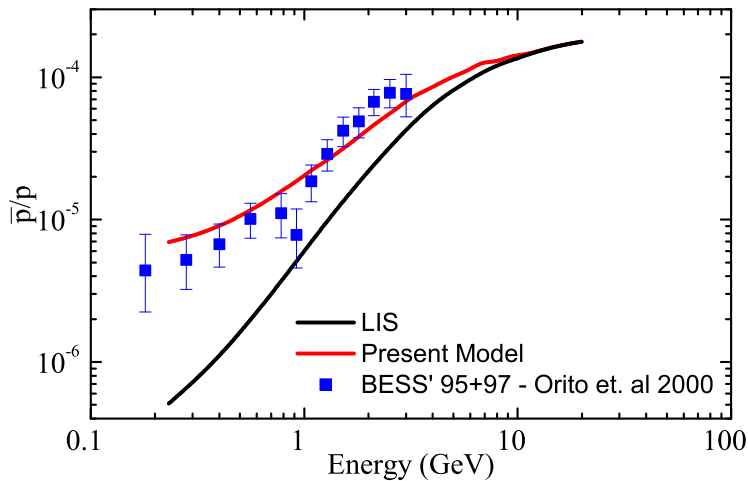

Fig. 2.   Simulated $\bar{p}/p$ ratio as a function of the kinetic energy in GeV at 1 AU in comparison with experimental data: BESS (1995-1997).

The K_0 data had to be subdivided in four sets, i.e., rising and declining phases for both negative and positive solar magnetic-field polarities. For each set, the data i) could be fitted with a relationship - indicated in in Fi. 1 - between K_0 and Smoothed Sunspot Numbers SSN[26] values and ii)
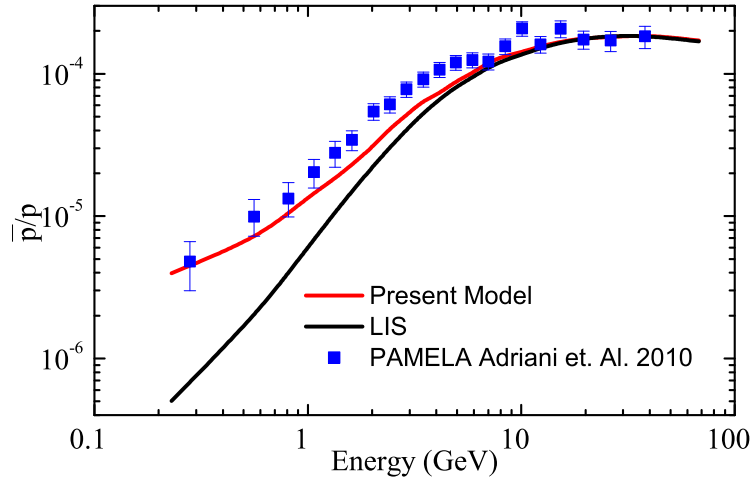
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Fig. 3.   Simulated $\bar{p}/p$ ratio as a function of the kinetic energy in GeV at 1 AU in comparison with experimental data: Pamela (2007-2008).

exhibited a Gaussian distribution of difference of K_0 values from the corresponding fitted values. The RMSs of the Gaussian distributions were found to be $\approx 0.1339, 0.1254, 0.1040, 0.1213$ for the phases rising with $A < 0$, declining with $A < 0$, rising with $A > 0$, declining with $A > 0$, respectively. In this way - i.e., from the relationships found -, we can use the estimated SSN values to obtain the diffusion parameter K_0 at times beyond 2004. In practice, this procedure allows one to extend the ≈ 40 years period by exploiting the linear relationship between the fitted K_0 values and the SSN values (one of the main parameters related to the solar activity). Thus, we introduced in our code a Gaussian random variation of K_0 with RMSs corresponding to those found for each subset of data. Results of the simulation with and without the Gaussian variation are consistent inside the uncertainties of the code[1].

2.3. *Dynamic Parameters*

Our code simulates the interactions of a GCR entering the heliosphere from its outer limit, the helio-pause, located - as already mentioned - approximately at 100 AU[27], and moving inwards to the Earth located at 1 AU. We evaluated the time t_{sw} needed to SW to expand from the outer corona up to the helio-pause. Considering an average speed of 400 km/s it takes nearly 14 months. While the time interval τ_{ev} of the stochastic evolution of a quasi

particle inside the heliosphere from 100 AU down to 1 AU is ~ 1 month at 200 MeV and few days at 10 GeV. This scenario, where $\tau_{ev} < t_{sw}$ and $t_{sw} >> 1$ month, indicates that we can not use fixed parameters (monthly averages) to describe the conditions of heliosphere in the modulation process. In fact at 100 AU, where particles are injected, the conditions of the solar activity are similar to the conditions present at the Earth roughly 14 months before. Therefore we consider τ_{ev} negligible with respect to t_{sw} and divide the heliosphere in 14 regions, as a function of the radius. For each region we evaluated[28] K_0, α and V_{sw}, in relation to the expansion velocity, in a dynamic way. In the future the time spent by a GCR particle inside the heliosphere, as a function of the stochastic path and of the particle energy, will be also taken into account.
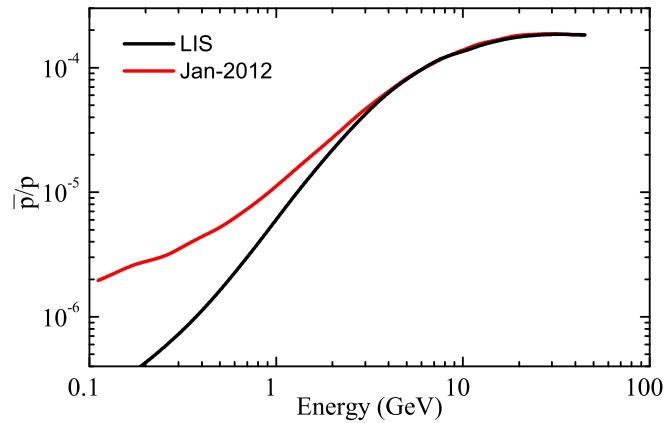

Fig. 4.   Prediction of modulated $\bar{p}/p$ ratio as a function of the kinetic energy in GeV at 1 AU for AMS-02 experiment (January 2011).

2.4. *Antiproton/Proton: Comparison with Data and Prediction for AMS-02*

We performed the simulations using dynamic values of K_0, α and V_{sw}. Results are shown in Fig. 2 and 3. Simulated fluxes with dynamic values show a very good agreement with measured data, within the quoted error bars. This happens both in periods with A>0, in comparison with BESS, and in periods with A<0, in comparison with Pamela. This means that our dynamic description of the Heliosphere improves the understanding of the complex processes occurring inside the Solar Cavity.

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The periodic behavior of the heliosphere allows us to predict, with a certain level of precision, the parameters needed for a simulation related to a time in the near future. In order to get these data we considered the prediction of SSN from IPS (Ionospheric Prediction Service) of the Australian Bureau of Meteorology[29].

We concentrate our simulations on the AMS-02 mission[30,31] that will be installed on the ISS in February 2011, and, in particular, at a time approaching the solar maximum: January 2012. We show in Fig. 4 the predictions of GCR modulation for the antiproton/proton ratio.

3. Conclusions

We built a 2D stochastic Monte Carlo code for particles propagation across the heliosphere. Present model takes into account drift effects and shows quantitatively a good agreement with measured values, both for positive and negative periods and for different particles and charge sign. This is relevant because particles with opposite charge sign undergo a different solar modulation[3]. We compared our simulations with antiproton/proton ratios measured by BESS and PAMELA. We used *dynamic* parameters values (K_0, α and V_{sw}) for the related periods, in order to reproduce the propagation of incoming GCR through magnetic disturbances carried by the outgoing solar wind. The *dynamic* description of the heliosphere and the forward approach seem to reproduce better the real physical propagation of GCR in the solar cavity. In order to have a more sophysticated model we need to introduce a dependence on the particle time spent in the heliosphere and a larger statistics of measured data during negative solar field periods, as AMS-02 will provide in the next years. Recent measurements[16] have pointed out the needs to reach a high level of accuracy in the modulation of the fluxes, in relation to the charge sign of the particles and the solar field polarity[32]. This aspect will be even more crucial in the next generation of experiments[30,31].

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