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Modelling the modulation of galactic protons in two successive very quiet solar minima

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In this study, a state-of-the-art three-dimensional (3D) drift model is used to distinguish the significant role played by particle drift in modulating galactic protons in the past two successive unusually quiet solar minima. This is done by comparing the model computations to available observations from both PAMELA and HEPD01, respectively taken in the A < 0 and A > 0 magnetic field cycles. For this abridged report, it is illustrated to what extent particle drifts occurred during the two minima. Because of these drift effects, the proton flux at lower energy is found as predicted to be even higher during the $A > 0$ solar minimum period of 2020 than during the $A < 0$ solar minimum of 2009. As such, the record of the highest ever recorded GCRs at Earth set by PAMELA has now been surpassed.

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1. Introduction

The manifestation of particle drift effects was confirmed by the observational evidence of long term galactic cosmic ray (GCRs) modulation from neutron monitor counts which always indicated consecutive flat and sharp solar minimum intensity peaks during different polarity epochs of the heliospheric magnetic field (HMF), see http://cr0.izmiran.ru/hrms/main.htm. Alongside this observational evidence, sophisticated numerical simulations that take into account the effects of particle drifts also indicate differences between the $A > 0$ and $A < 0$ spectra of GCR protons when the same modulation conditions are assumed. In particular, these models predict that the spectra of GCR protons in the $A > 0$ cycle is expected to cross that in the $A < 0$ cycle at energies between ~ 0.4 GeV and ~1.0 GeV [1, 2] depending on the prevailing modulation conditions. The surprise from the 2009 $A < 0$ observed spectra [3, 4] was that they were significantly higher than the previous $A > 0$ minimum spectra, in an apparent contrast to drift model predictions. The weaker HMF that characterized this epoch led some authors, e.g., [5] to debate the significance of particle drifts over a solar cycle, raising an important issue that needed to be resolved. However, it turned out that this was because of the extraordinary quiet modulation conditions in 2009, and not because drift models were wrong [see also 6, 7, 8].

The Payload for Antimatter Matter Exploration and Lightnuclei Astrophysics (PAMELA) on board the International Space Station [3] and High-Energy Particle Detector (HEPD01) onboard the CSES-01 satellite [9] made measurements of GCR protons below ~ 0.25 GeV during similar periods of solar activity but different HMF epochs in 2009 and 2020, respectively. Considering drift motions, GCR protons observed by PAMELA in 2009 in the $A < 0$ reached the inner heliosphere mostly along the equatorial region and thus encountered the changing tilt angle (α) of the heliospheric current sheet (HCS) [1, 2]. So to a large extent their intensity time-profile is sensitive to changes in α, whereas in 2020 GCR protons observed by HEPD01 in the $A > 0$ cycle reached the inner heliosphere mainly through the heliospheric polar regions and as such less likely influenced by the changing HCS (see also [10, 11]). Therefore, PAMELA and HEPD-01 observations provide a relevant and appropriate observational context to confirm and test the significance of particle drift theory at energies below ~ 1 GV for two successive unusually quiet solar minima. From an observation and modelling point of view, the availability of these observations at lower energies is considered as fortunate. At these low energies the heliospheric modulational effects are significant and display as such a large time dependence related to solar activity in contrast to what happen above ~ 1 GV [see, 1].

In this study a comprehensive three-dimensional (3D) numerical model which simulates the effects of particle drift is applied to gain insight into the role of particle drift in modulating GCRs during the past two successive solar minima. We emphasize that this kind of study cannot be adequately done using simplified approaches susch as the Force-Field and Diffusion-Convection approach due to their severe limitations in adhering to the main features of CR modulation as observed by previous space missions such as Ulysses [12], and even at worst, describing global modulation processes in the global heliosphere as illustrated by [13]. The continuous use of these simplified models to interpret GCR observations remains puzzling.

2. The 3D-drift modulation model

The 3D model is based on solving the transport equation derived by [14]:

$$\frac{\partial f}{\partial t} = -(\mathbf{V} + \langle \boldsymbol{v}_D \rangle).\nabla f + \nabla.(\boldsymbol{K}_s.\nabla f) + \frac{1}{3}(\nabla.\mathbf{V})\frac{\partial f}{\partial lnp}, \quad (1)$$

where $f(\boldsymbol{r}, p, t)$ is the omnidirectional GCR distribution function, p is particle momentum, t is time, and $\boldsymbol{r}$ is the heliocentric 3D position vector with three coordinates r, θ and ϕ specified in a heliocentric spherical coordinate system where the equatorial plane is at a polar angle of $\theta = 90°$, and with $\mathbf{V}(r, \theta) = V(r, \theta)\, \boldsymbol{e}_r$ the radial SW velocity. The terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, and adiabatic energy changes experienced by CRs when they enter and travel through the heliosphere up to the Earth. The symmetric diffusion tensor $\boldsymbol{K}_S$ consists of a diffusion coefficient parallel to the average HMF ($K_{||}$), and two perpendicular diffusion coefficients ($K_{\perp r}$ and $K_{\perp\theta}$). The averaged guiding centre drift velocity for a near isotropic cosmic ray distribution is given by $\langle \boldsymbol{v}_D \rangle = \nabla \times (K_A \boldsymbol{e}_B)$, with $\boldsymbol{e}_B = \boldsymbol{B}/B_m$, where B_m is the magnitude of the modified background Parker-type HMF; here K_A is the coefficient specified by the off-diagonal elements of the generalized tensor $\boldsymbol{K}$, which describes gradient and curvature drifts in the large scale HMF.

Equation (1) clearly indicates that the drift term, $\langle \boldsymbol{v}_D \rangle.\nabla f$, is the product of the drift velocities and the gradient of the distribution function ∇f; and does not depend on the drift velocities alone. This means that the drift velocity by itself does not modulate GCR particles but that the process also depends on the intensity gradients of the GCR particles in the heliosphere. Therefore, increased latitudinal diffusion, for example, results in smaller values of the intensity gradients which consequently inherently suppresses drift effects even for very large drift velocities (for the same reason, drift effects are much smaller at neutron monitor energies; see [2]). The opposite is also true; reducing for example the latitudinal enhancement of $K_{\perp\theta}$ [15, 16] causes larger drift effects. This important and significant insight into the role of particle drift has been known for a long time, but it is not always easy to recognize this from only observational studies, let alone the crossover energy between the A > 0 and A < 0 spectra. This is so because conclusions are ussually based on using only the main modulation proxies e.g., $\boldsymbol{B}$, α and $\boldsymbol{V}$ observed to be different for consecutive minima.

The details and essentials of the 3D numerical model together with the expressions of the elements of the diffusion tensor are published by [15]. The parameters that are changed with time in the model, as proxies for solar activity to obtain the GCR results simulated in this study, are the observed magnitude B of the HMF at the Earth [http://omniweb.gsfc.nasa.gov] and its polarity change during solar maximum, and the changing HCS using α [http://wso.stanford.edu]. Additionally, the values and rigidity dependence of the three elements of the diffusion tensor and the value of K_A together with the position of the solar wind termination shock can be changed with time. For a similar approach and additional information, see also [17, 18].

2.1. Selected modulation parameters

The modulation parameter values required to reproduce the PAMELA and HEPD01 proton spectra, as discussed next, for the period 2006 December to 2020 July are summarized in Table 1. The diffusion coefficients (K) are related to the corresponding mean free paths (MFPs) (λ) by $\lambda = 3K/(c\beta)$, where β is the ratio of the particle speed to the speed of light, c. The parallel mean free path for 1 GV proton is represented by $\lambda_{||}$; whereas the dimensionless quantities $c_{2||}$, $c_{2\perp}$ and c_1 respectively give the time dependence of the rigidity slopes of the DCs above and below 4 GV, with the smoothness of the transition in these slopes kept constant. In this context see Equations (4) to (8) given by [18]. The latitudinal enhancement of $K_{\perp\theta}$ is represented by $d_{\perp\theta}$. The level of drifts in the heliosphere is adjusted by P_{A0} and a dimensionless quantity K_{A0}.

Table 1: The averaged values of α and B and other modulation entities that change with time as used in the model to compute proton spectra between 2006 and 2020 at the Earth for four selected periods: 2006 December; 2009 December; 2013 December and 2020 July, that agree with PAMELA and HEPD01 proton observations as shown in Fig. 2.

Parameters	**2006 Dec**	**2009 Dec**	**2013 Dec**	**2020 Jul**
B (nT)	4.95	3.91	5.24	4.21
α (°)	16.58	9.11	65.96	5.45
$\lambda_{\|\|}$ (AU)	0.737	1.109	0.341	1.030
K_{A0}	0.90	0.90	0.0	0.90
P_{A0} (GV)	0.75	0.75	0.75	0.75
c_1	0.85	0.78	1.14	0.78
$c_{2\|\|}$	1.20	1.20	1.52	1.20
$c_{2\perp}$	0.84	0.84	1.22	0.84
$d_{\perp\theta}$	6.00	6.00	6.0	3.00

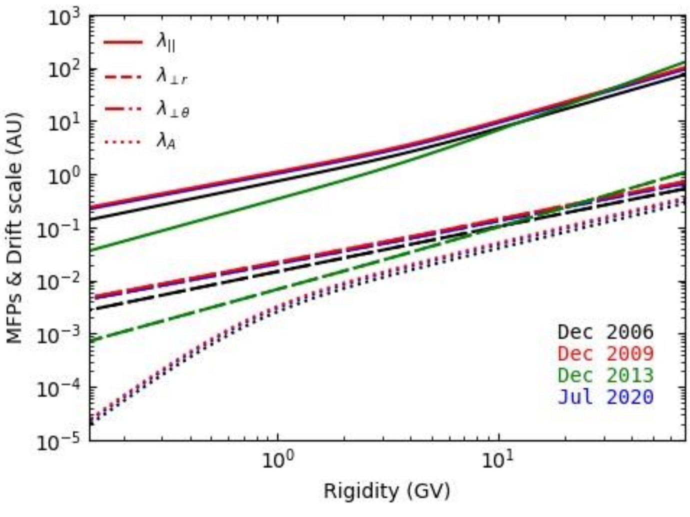

Figure 1: The three mean free paths (MFPs) and drift scale shown as a function of rigidity at Earth for the four periods as indicated and used in the model to reproduce the four modulated spectra shown in Fig. 2; parallel MFPs ($\lambda_{||}$) as solid lines; perpendicular MFPs in the radial ($\lambda_{\perp r}$) and polar ($\lambda_{\perp\theta}$) directions as dashed and dashed-dotted lines, respectively, and the drift scale (λ_A) as dotted lines.

The rigidity dependence of the MFPs and drift scale at the Earth are illustrated together in Fig. 1 for selected periods between 2006 and 2020. Although solar activity in 2020 was similar to that in 2009 (being very quiet), the solar activity proxies that we used in the model are found not to be identical as indicated in Table 1, e.g., B = 3.91 nT in 2009, while in 2020 it was 4.21 nT. However, in order to keep changes to a minimum, we hold the magnitude and the rigidity slopes of the MFPs the same in the model for the modulation in 2009 and 2020. The only differences applied is the enhancement of $K_{\perp\theta}$ as determined by the value of $d_{\perp\theta}$, and then the sign and value of B as well as α between these consecutive solar minima periods. Because of the mentioned larger B, the MFPs and drift scale are lower by ~ 8% in 2020 than in 2009 at all rigidities.

Emphasis on the numerical simulated proton spectra resulting from such slightly different modulation conditions in 2020 than in 2009 is illustrated and compared with observations from both HEPD01 and PAMELA in the next section. It follows from Table 1 that for the years 2006 and 2013 the mentioned modulation entities are being changed in order to obtain the modulation results shown next.

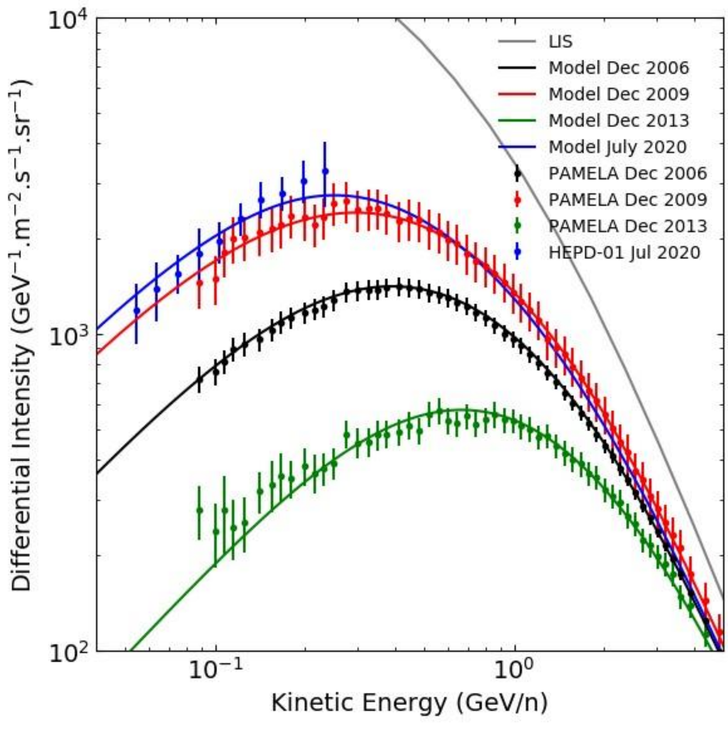

Figure 2: The VLIS for GCR protons (upper grey line) specified at the HP (122 AU) together with modulated differential intensity computed as a function of kinetic energy/nucleon at the Earth for the solar minimum period of Jul 2020 (blue line) in the A > 0 cycle together with that of Dec 2006 (black line) and Dec 2009 (red line) minimum period in the A < 0 cycle and Dec 2013 (green line) maximum solar activity period. These computed spectra are compared to the corresponding PAMELA [3] and HEPD-01 [9] and data as indicated by coloured circles and error bars.

3. Comparison of simulated spectra with PAMELA and HEPD01 observations

Figure 2 shows the observed proton spectra from PAMELA (red, black and green circles) and HEPD01 (blues circles) overlaid by the corresponding computed spectra (colored solid lines) at the Earth with respect to the very local intterstellar spectra (VLIS) specified at the heliopause

(HP) position at 122 AU. Clearly these modulated proton spectra exhibit a characteristic peak (highest intensity) in each spectrum with the kinetic energy where the peaks occur gradually shifting to lower values with decreasing modulation (less solar activity; higher fluxes); more low-energy protons reach the Earth, depending on the prevailing modulation conditions. Unfortunately, a particle detector with an energy thresh-hold of > ~ 0.3 GeV/n cannot measure the time dependence of the shifting of these peaks with changing solar activity. In this context, the availability of GCR observations extending to lower energy shown in this figure is considered as fortunate because they provide a meaningful context to gain insight into the role played by the diagonal and the off-diagonal elements of the generalized tensor [4, 15]. For example, to reproduce the December 2013 PAMELA spectrum in Fig. 2 particle drift effects were completely neglected in the model, whereas maximum drift effects were required in 2006, 2009 and 2020 modulation; see also [17, 18]. Evidently, the model with its assumptions as shown in Fig. 1 gives reasonable compatibility to the observed spectra at the Earth for the indicated periods.

Figure 2 illustrates additionally what happens to the modulated proton spectra at the Earth in two successive very quiet solar minima (cf. blue and red lines). It shows that the proton spectrum from HEPD01 in July 2020 (A > 0 cycle) is higher than the one in December 2009 from PAMELA (A < 0 cycle). Our modelling indicates that because of particle drift effects the 2020 HEPD01 spectrum is softer and its peak shifted to lower energies than the 2009 PAMELA spectrum. This is the case despite the fact that both MFPs and drift scales shown in Fig.1 are ~8% higher in 2009 than 2020; see also Table 1. We emphasize that particle drift effects do not depend on the drift scale alone but also on the gradient of the distribution function of GCRs which was increased in 2020 when the latitudinal enhancement of perpendicular MFP in the polar direction ($\lambda_{\perp\theta}$) was reduced by a factor of 2 as a required step in reproducing the observed spectra as shown in Fig. 2. These aspects will be discussed at length in a full journal paper in preparation.

The next phase of this study is to apply the model to protons observed by HEPD01 for different Carrington rotations but focussing more on illustrating the cause(s) of the similarities and differences in modulation trends for the A > 0 period after November 2018, which also includes the solar minimum modulation period around 2020. In particular, to illustrate what is predicted and observed for this period in relation to what happened between 2008 and 2011 in the A < 0 cycle, including the quiet minimum modulation period at the end of 2009.

4. Summary and conclusions

In this study, the same 3D drift model assumptions about the MFPs and drift scale as for the reproduction of the 2009 PAMELA spectrum in the A < 0 cycle were used for the 2020 HEPD-01 spectrum in the A > 0 cycle. The only modelling differences between the two successive minima are the corresponding tilt angles of the HCS together with the sign and magnitude of the HMF. We found that apart from changes in the mentioned modulation proxies, it was necessary to additionally reduce the latitudinal enhancement of $K_{\perp\theta}$ by a factor of 2 in order to reproduce the HEPD01 proton spectrum in 2020. Consequently, the gradient of the distribution function, was calculated to be smaller in 2009 than in 2020 and because of this drift effects were different in 2020 than in 2009. Therefore, the proton spectrum at the indicated lower kinetic energy range from HEPD-01 in July 2020 is higher than in December 2009 from PAMELA. As such, the record of the highest ever reccorded GCRs at Earth set by PAMELA [3, 7] has now been surpassed. Both the MFPs and drift scales were ~8% higher in 2009 than 2020.

The modelling results presented in this study confirm model predictions [1, 2, 7] that the interpretation of drift effects using GCR intensities should be understood in the context of the adjustments of the GCR intensity gradients combined with the changing drift scale, and not on the drift scale (or drift coefficient) alone.

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