Modulation mechanisms for galactic protons during the unusual solar minimum of 2009

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Abstract: The recent solar minimum of 2009 has been studied in depth due to the unusual quiet activity that governed the heliosphere throughout this $A < 0$ cycle (where the solar magnetic field points inward and outward in the northern and southern hemispheres respectively). As a result of these quiet conditions, the highest ever proton spectrum was observed by PAMELA in December 2009. By using an advanced steady state 3D model of the heliosphere, combined with accurate PAMELA observations, the modulation of galactic protons is studied over a period of four years leading up to the end of 2009. In successfully reproducing a set of four PAMELA monthly averaged proton spectra, it was found that proton mean free paths had to increase at low rigidities in order to account for the significant softening in the lower proton spectrum. Moreover, the effects of individual modulation processes, such as diffusion and drifts, are also studied. Consequently, the relative contributions that these processes delivered to the total increase in proton intensities are identified, from which we conclude that all modulation processes indeed played varying but important roles in the observed proton intensities during the 2009 minimum.

Keywords: cosmic rays, solar modulation, solar minimum, galactic protons.

1 Introduction

The minimum of cycle 23/24 has been widely recognized as being atypical when compared to previous minima, due to the unexpected prolonged solar minimum conditions that persisted throughout 2009. Characterizing this solar minimum was a weaker than usual heliospheric magnetic field (HMF) and record setting cosmic ray (CR) intensities which reached its climax in December 2009 (see e.g. [5]). Fortunately enough, this event has been thoroughly observed by the PAMELA experiment in an extended energy range, reaching lower energies where heliospheric modulation plays a dominant role ([1]).

It has been widely accepted that four primary modulation mechanisms exist, of which particle (gradient and curvature) drifts are the primary cause of the familiar 11-year and 22-year cycles observed in neutron monitor counts. The objective of this work is to investigate the various modulation mechanisms that contributed to the observed proton spectra measured by PAMELA, from 2006 to 2009, by means of a numerical modulation model that lends itself to separately adjusting the individual modulation mechanisms. As such, it is possible to identify the relative modulating contributions from each of these mechanisms (see also [10]).

2 Modulation model

Our full three-dimensional (3D) model, in which all modulation effects over periods shorter than one solar rotation are neglected, as well as any possible CR sources within the heliosphere, numerically solves the transport equation (TPE) derived by [9]. Within a coordinate system that rotates with the Sun, the TPE is given by

$$-\left(\mathbf{V}+\langle\mathbf{v}_D\rangle\right)\cdot\nabla f+\nabla\cdot\left(\mathbf{K}_s\cdot\nabla f\right)+\frac{1}{3}\left(\nabla\cdot\mathbf{V}\right)\frac{\partial f}{\partial \ln p}=0. \tag{1}$$

Here $\mathbf{V}=\mathbf{V}_{sw}-\Omega\times\mathbf{r}$, with $\mathbf{V}_{sw}$ the solar wind (SW) velocity, Ω the solar rotational velocity and $\mathbf{r}$ the position. Furthermore, $\mathbf{v}_d$ represents the drift velocity, $\mathbf{K}_s$ the symmetric diffusion tensor, p the momentum of CRs and f the omnidirectional CR distribution function which is related to the differential intensity with respect to kinetic energy by $j_T = p^2 f$. The first two terms in Equation 1 respectively represent outward convection and gradient and curvature drift motions in the global HMF, while the last two terms represent spatial diffusion and adiabatic energy changes.

In accordance with Voyager 1 findings ([12]) it is assumed that the heliopause (HP), acting as the modulation boundary, is situated at a heliocentric distance of 120 AU. Adopting a simplified approach, the diffusion coefficient (DC) parallel to the averaged background HMF is given by

$$\kappa_{\parallel}=\kappa_{\parallel,0}\beta\frac{B_0}{B}\left[\frac{\left(\frac{P}{P_0}\right)^c+\left(\frac{P_k}{P_0}\right)^c}{1+\left(\frac{P_k}{P_0}\right)^c}\right]^{\frac{b-a}{c}}\left(\frac{P}{P_0}\right)^a, \tag{2}$$

where $\beta = v/c$, the ratio of the particle's speed to the speed of light, $\kappa_{\parallel,0}$ is a constant in units of 10^{22} cm^2.s^{-1}, B the HMF magnitude with $B_0 = 1$ nT. The rest of the equation is dimensionless, with $P_0 = 1$ GV, and is written in the functional form of a double power-law in order to facilitate a key finding discussed in the following section.

For diffusion perpendicular to the average HMF in the radial and polar directions, it is assumed that

$$\kappa_{\perp,r}=0.02\kappa_{\parallel} \tag{3}$$

and

$$\kappa_{\perp,r} = 0.02 f(\theta)\kappa_{\parallel}, \quad (4)$$

where $f(\theta)$ makes provision for an $\kappa_{\perp,\theta} > \kappa_{\perp,r}$ anisotropy in the off-equatorial regions (see e.g. [7] and [10]).

Taking into account the small latitudinal gradients observed by Ulysses at low rigidities ([3]), the drift coefficient is given by

$$\kappa_A = \frac{\beta P}{3B}\left(\frac{\left(\frac{P}{P_{A,0}}\right)^2}{1+\left(\frac{P}{P_{A,0}}\right)^2}\right), \quad (5)$$

so that κ_A deviates from the weak scattering scenario in that it is progressively reduced below $P_{A,0}$ (in GV).

A shocked SW (with compression ratio of 2.5) is also included in the model, although the effects of re-acceleration are neglected for the purpose of this study. Since we assume $\nabla \cdot \mathbf{V} = 0$ beyond the termination shock, no adiabatic changes occur for protons in the heliosheat (e.g. [11]). See e.g. [8] for a discussion on the numerical procedure used to solve Equation 1.

The local interstellar spectrum (LIS), which serves as a modelling input spectrum, is taken from [4] and normalized to PAMELA proton observations at rigidities above ~ 30 GV. The LIS differential intensity is given by

$$j_{LIS} = \begin{cases} 0.707\, e^{\xi_1} & \text{if } E < 1.4 \text{ GeV} \\ 0.685\, e^{\xi_2} & \text{if } E \geq 1.4 \text{ GeV} \end{cases} \quad (6)$$

in units of m^{-2}.s^{-1}.sr^{-1}.MeV^{-1}, with

$$\xi_1 = 4.64 - 0.08\left(\ln\frac{E}{E_0}\right)^2 - 2.91\sqrt{\frac{E}{E_0}} \quad \text{and}$$
$$\xi_2 = 3.22 - 2.78\ln E - 1.5/E,$$

where E is the kinetic energy in GeV, and $E_0 = 1$ GeV.

3 Results and discussion

Using the model discussed in the previous section, the aim of this work was to investigate the modulation that protons experienced throughout the recent unique solar minimum as an attempt to uncover the relative contributions from the different modulation mechanisms to the total increase in flux intensities. This is achieved by reproducing a sample selection of year-end monthly averaged PAMELA proton spectra for the years 2006 to 2009 - a set which is representative of the time evolution of the energy spectrum (ES) of galactic protons. The sample selection consists of energy spectra from November 2006, December 2007, December 2008 and December 2009, from hereon referred to simply as the 2006, 2007, 2008 and 2009 spectra.

Since solar conditions take approximately one year to reach the outer edges of the heliosphere, preceding yearly averaged values for the HCS tilt angle (α) and the HMF magnitude at Earth (B_e) are calculated for each of the four

	2006	2007	2008	2009
α (°)	15.7	14.0	14.3	10.0
B_e (nT)	5.05	4.50	4.25	3.94

Table 1: Preceding yearly averaged values for the HCS tilt angle and HMF magnitude at Earth from 2006 to 2009.

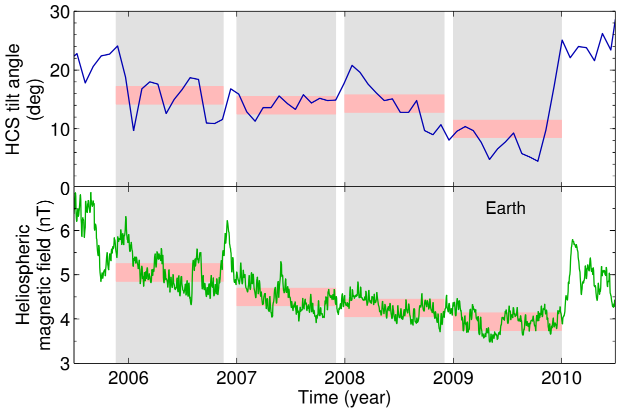

Fig. 1: Yearly averaged values calculated for the HCS tilt angle (top panel) and HMF magnitude (bottom panel) as estimated heliospheric modulation conditions during the preceding year. Shaded regions correspond to the time frames over which averages (shown by colour bands) are calculated.

PAMELA proton spectra, which are to be used as modelling input values. This is illustrated in Figure 1, showing α and B_e over time, along with the approximate yearly time frames over which the averages are calculated (shaded regions). Table 1 gives the average values for α and B_e.

In essence, a uniquely set-up model is used to reproduce each of the four sample spectra, where the different models contain the appropriate modulation parameters for their corresponding time frames. This approach is necessary in order to investigate time-dependent phenomena in the heliosphere using a steady state model.

Shown in Figure 2 are the four PAMELA proton spectra from 2006 (blue symbols) to 2009 (red symbols), overlaid by the corresponding computed spectra (solid lines). As α and B_e steadily decreased, the proton spectrum became increasingly softer below ~ 500 MeV. The spectrum at the end of December 2009 was the highest ever recorded in space. Figure 2 illustrates that the model is capable of reproducing the observed proton spectra for the selected periods while adhering to the assumptions discussed in Section 2.

Apart from changes in α and B_e, rather significant time-dependent changes in the DCs were also required to reproduce the consecutive PAMELA proton spectra. These changes are shown in Figure 3, which gives the rigidity (P) dependence of the parallel and perpendicular mean free paths (MFPs) used in calculating each of the modelled spectra. Most evident in this figure is the increase over time in the MFPs at rigidities below 3 GV. At high rigidities (above ~ 5 GV) the MFPs had a steady $P^{2.1}$ dependence, while at lower rigidities (below ~ 3 GV) it changed from a $P^{0.56}$ dependence in 2006, to a $P^{0.30}$ dependence in 2009. Adjustments in the ratio between the parallel and perpendicular DCs were not necessary, apart from the previously mentioned enhancement in the polar dependence of $\kappa_{\perp,\theta}$.

Figure 4 shows the intensity ratios observed by PAMELA with respect to July 2006. As α decreased, on average, from $\sim 16°$ to $\sim 10°$, and B_e from ~ 5 nT to ~ 4 nT, proton intensities increased by almost a factor of 3 at at lower energies - an observation that likely requires a considerable increase in proton MFPs at these energies. At higher

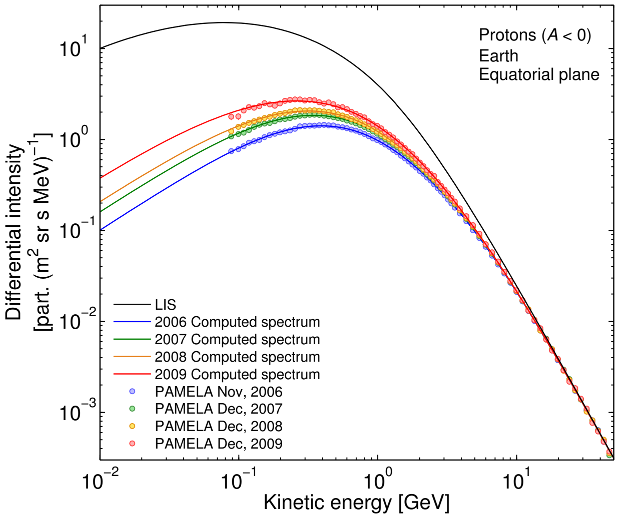

Fig. 2: PAMELA proton spectra from 2006 (blue symbols) to 2009 (red symbols) as indicated in the figure. The corresponding computed spectra are given by the solid lines.

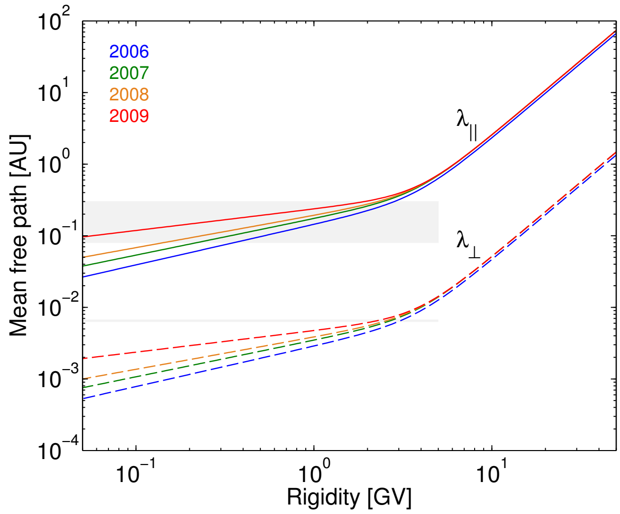

Fig. 3: Rigidity dependence for the parallel ($\lambda_{||}$) and perpendicular ($\lambda_{\perp}$) mean free paths for protons at Earth as they changed from 2006 to 2009. Here $\lambda_{\perp}$ represents the perpendicular mean free path in both the radial and polar directions.

energies, however, noticeable modulation only occurs below $\sim$ 30 GeV, while for energies above $\sim$ 30 GeV intensities seem to vary within a range. It is therefore assumed that no solar modulation occurs above 50 GeV, whereas marginal modulation occurs between 30 GeV and 50 GeV.

Making use of the advantage of a numerical model, the effects of changes in individual modulation parameters (and processes) are studied relative to the 2006 proton spectrum. This is achieved through different modulation scenarios, where changes in α, B_e and the DCs are considered separately and mutually. Figure 5 shows the computed differential intensities (left vertical scale) of the various modulation scenarios (dots), along with PAMELA proton observations (crosses), as function of time at 1.0 GeV. Intensities normalized to 2006 are presented by the vertical scale on the right. From November 2006 to December 2009, changes in only α ($\sim 16^\circ$ to $\sim 10^\circ$) result in a $\sim$ 10% intensity increase (dotted line). By changing only the DCs (as discussed in Figure 3), intensities are increased by $\sim$ 21% (dashed line). In combining the changes in these variables (that determine drifts along the HCS and diffusion), a $\sim$ 30% intensity increase is observed (dashed-dotted line). Ultimately, when including global drifts in the latter scenario, a $\sim$ 44% increase is achieved. This scenario, in which the full range of modulation processes are considered, matches the PAMELA proton observations, not only in December 2009, but throughout most of the time range, with the exception of the transient intensity decrease in 2008 caused by a sudden increase in α.

By comparing the different scenarios, we were able to identify that diffusion alone contributed $\sim$ 50% to the total modulation experienced by protons over this time, while gradient, curvature and current sheet drifts contributed the remaining $\sim$ 50%.

4 Summary and Conclusions

The recent solar minimum, due to its exceptional quiet activity, provided a unique opportunity to study solar modulation of galactic protons. PAMELA observations have shown that proton intensities became significantly softer as increasingly more low energy protons reached earth. In order to reach such high intensities as observed in December 2009, proton MFPs had to increase over time at rigidities below $\sim$ 3 GV, since changes in α and B_e alone were not sufficient to reproduce PAMELA observations. This can possibly be interpreted as an occuring decrease in turbulence. Supporting results were also found by [2] and by [6].

Following a study of the extent to which changes in the DCs, α and global drifts contributed to the total proton intensity increase over the period from November 2006 to December 2009, we are able to conclude that both diffusion and drifts were equally responsible for the observed intensity increase at 1 GeV. It should be mentioned that this effect is in fact energy dependent, such that a more "diffusion dominated" situation is prevalent at lower energies where the large DC changes contributed comparatively more to the total intensity increase. However, it is hereby shown that both diffusion and drifts, together with adiabatic cooling and convection, exhibit a complicated and interesting interplay which effectively highlights the importance of all

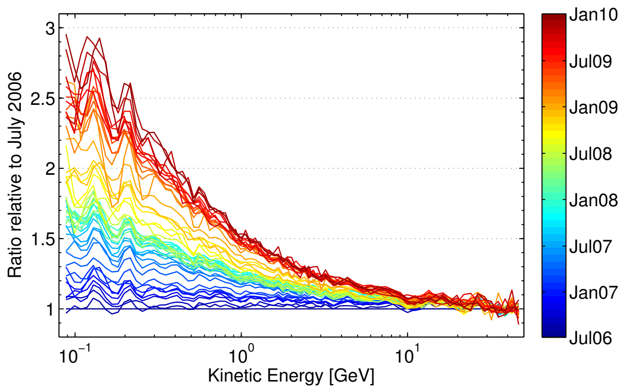

Fig. 4: Proton intensity ratios relative to July 2006 as a function of energy.

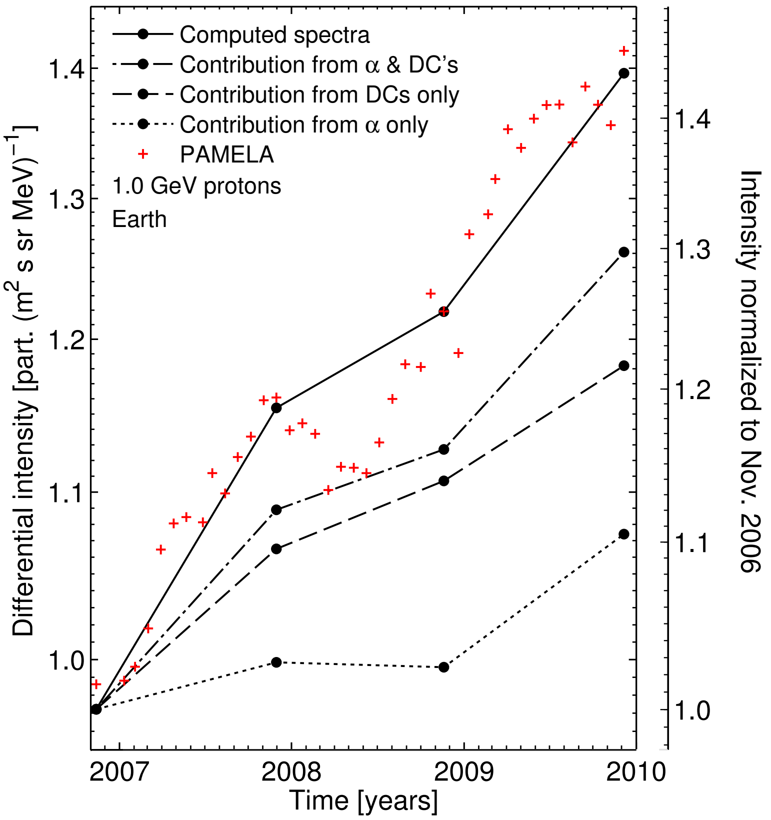

Fig. 5: Computed differential intensities for 1.0 GeV protons (dots) as a function of time for different modulation scenarios (dotted line, dashed line, dotted-dashed line and solid line; see text for detailed discussion), along with monthly-averaged PAMELA proton observations at the same energy (crosses).

these modulation processes.

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