The Time-dependent Modulation of Cosmic Ray Protons in the Inner Heliosphere from 2006 to 2009

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Abstract: Proton observations from the PAMELA mission and a comprehensive time-dependent modulation model are used to study the details of the time-dependent modulation of cosmic rays in the inner heliosphere. Recent theoretical advances in determining the diffusion coefficients are used to compute cosmic ray intensities over the unusual last solar minimum activity period. We present galactic proton spectra observed between 2006 and 2009 in comparison with the mentioned numerical model. The model utilizes the time-dependence of the solar magnetic field and the corresponding wavy current sheet and relates their time-dependence to that of the relevant diffusion coefficients. The approach is further enhanced by introducing a time-dependence in the rigidity dependence of the transport coefficients as required to reproduce the observations. It is illustrated that the model can reproduce the monthly spectra observed during the mentioned period. This makes it possible to identify the dominant modulation mechanisms for the unusual solar minimum up to 2009 and to establish why drift effects appear to be of lesser importance than during previous solar minimum cycles.

Keywords: Cosmic rays, heliosphere, solar minimum, time-dependent modulation.

1 Introduction

Observations show that the cosmic ray (CR) differential intensity is dependent on solar activity. Records obtained by experiments on Earth show that their intensity is anti-correlated with the 11-year solar activity cycle, with high CR intensities at solar minimum and low intensities at solar maximum. This phenomenon is referred to as the solar modulation of cosmic rays. The behaviour of galactic CRs in the last solar minimum of 2009 attracted the attention of many researchers because of its uniqueness as compared to the other preceding minima.

The highest levels of galactic protons were recorded at Earth in late 2009. This period was characterised by a much weaker heliospheric magnetic field (HMF) and by tilt angles of the heliospheric current sheet (HCS) not decreasing as rapidly as the magnitude of HMF at Earth, reaching a minimum value at the end of 2009. This led to the insight that modulation conditions in the heliosphere had reached unprecedented quiet levels.

This unique minimum had been observed at Earth by the orbiting PAMELA mission, launched in June 2006 [1]. This provides an excellent opportunity to study the main features of this unusual solar minimum event as it had evolved with time. In addition, by studying this time-dependence with a numerical model provides the opportunity to establish how the different modulation processes had interplayed over the four years until the end of 2009.

In utilizing this opportunity [10] used a three dimensional (3D), steady-state model with full drifts and simplified diffusion coefficients, to simulate and reproduce the proton spectra observed between 2006 and 2009. The global approach was used to determine the mechanisms mainly responsible for the modulation of protons during this period, consequently determining the cause of the highest ever recorded spectrum observed in 2009.

The comparison of the observed spectra and the numerical modelling solutions established the relative contributions of the different modulation processes that contributed to the observed increases in the proton spectra from 2006 to 2009. The 2009 modulation minimum period was described as being more “diffusion dominated” instead of “drift dominated” as previous cycles appeared to be. However, they illustrated it was actually a complex interplay of all major mechanisms, including global drifts and current sheet drifts, that was responsible for the previous unusual solar minimum.

This work follows on what [10] reported but instead uses a time-dependent, two-dimensional (2D) model to study the details of proton modulation over this peculiar solar minimum period. This model assumes azimuthal symmetry eliminating cross-terms in the numerical solution of the transport equation (TPE) thus reducing its applicability to time-scales of longer than one solar rotation (see [6], and the review by [13]).

This time-dependent model successfully simulated CR intensities observed by Ulysses [9] and Voyager 1 and 2 [8, 7]. Ndiitwani et al. [9] used the compound approach of [12, 4] to study CR modulation observed in the inner heliosphere. This approach combines the effects of the global changes in the HMF magnitude with drifts to establish a realistic time dependence in the diffusion coefficients and in the drift coefficient that describes global drifts. This approach was modified and improved by Manuel et al. [8, 7] by introducing recent progress in turbulence theory [16, 14] to determine the spatial and especially rigidity dependence of the diffusion coefficients to be used in the model. This improved compound model gave realistic modulation in the outer heliosphere comparable to both Voyager 1 and 2 observations. In this study this approach is enhanced further by introducing an additional time-dependence in the rigidity dependence of the transport coefficients.

The purpose of this work is to use the precise proton spectra for every month as provided by PAMELA [2] and the enhanced modulation model to study the details of the time-dependent modulation of CR protons at Earth.

Our analysis differs from [10] and the preliminary study of [17] in two important respects. Firstly, we use a time-dependent model instead of a steady-state model. Subsequently, we could simulate proton spectra for every solar rotation since mid-2006. Secondly, as an input to the time-dependent model, we use monthly averaged HCS tilt angles and HMF values as observed at Earth. These values were updated with every simulated solar rotation and propagated throughout the heliosphere so that modulation conditions throughout the simulated heliosphere are a better representation of what may actually have happened than the steady-state approach of [17].

2 Transport Model and Parameters

The 2D time-dependent modulation model, originally described by [6] but improved by [4] and recently by [8], is used to calculate monthly proton spectra. The model is based on the numerical solution of Parker's [11] time-dependent TPE:

$$\frac{\partial f}{\partial t} = -(\mathbf{V} + \langle \mathbf{v}_D \rangle)\cdot \nabla f + \nabla \cdot (\mathbf{K}_s \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P} + J_{source}$$

where $f(\mathbf{r}, p, t)$ is the cosmic ray distribution function; P is rigidity, $\mathbf{r}$ is position, $\mathbf{V}$ is the solar wind velocity and t is time. The terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, adiabatic energy changes and a source function, respectively. The tensor $\mathbf{K_s}$ consists of a parallel diffusion coefficient ($K_\parallel$) and the two perpendicular diffusion coefficients in the radial direction $K_{\perp r}$ and in the polar direction $K_{\perp\theta}$. See also [8].

The outer modulation boundary was assumed at 120 AU where the local interstellar spectrum (LIS) was specified for protons based on the galactic spectrum by [5] but modified to follow the PAMELA observations at rigidities higher than 30 GV [17]. The modified LIS in terms of kinetic energy E is given by:

$$J_{LIS} = \begin{cases} 0.707 \exp(4.64 - 0.08(\ln E)^2 - 2.91\sqrt{E}), \\ \text{if } E < 1.4 \text{ GeV}. \\ 0.685 \exp(3.22 - 2.78(\ln E) - 1.5/E), \\ \text{if } E \geq 1.4 \text{ GeV}. \end{cases}$$

In calculating spectra and CR intensities throughout the heliosphere, we assume for the parallel mean free path

$$\lambda_\parallel = C_1 \left(\frac{(\frac{P}{P_o})^c + (\frac{P_k}{P_o})^c}{1 + (\frac{P_k}{P_o})^c} \right)^{\frac{(b-a)}{c}} \left(\frac{r}{r_0} \right)^{c_2} f_2(t), \qquad (1)$$

where C_1 is a constant (in AU) determining the value of the mean free path, with P_o = 1 GV and r_o = 1 AU. The next term describes the rigidity dependence and is a combination of two power laws similar to what was used by [10]. This approach deviates from the relatively simple linear rigidity dependence of [8, 7] which was adequate to study modulation at a given energy but not for a complete spectrum as the focus is with this work. The next term determines the radial dependence adopted from [8, 7], where C_2 is a dimensionless constant. This constant is set to unity resulting in a similar radial dependence assumed by e.g. [17, 15]. Here, a is a power index that changes with time over the considered period (2006 to 2009); $b = 2.1$ and together with a determine the slope of the rigidity dependence respectively above and below a rigidity with the value P_k, whereas $c = 3.95$ determines the smoothness of the transition. The values for a and P_k are shown in Table 1 for the years 2006 to 2009.

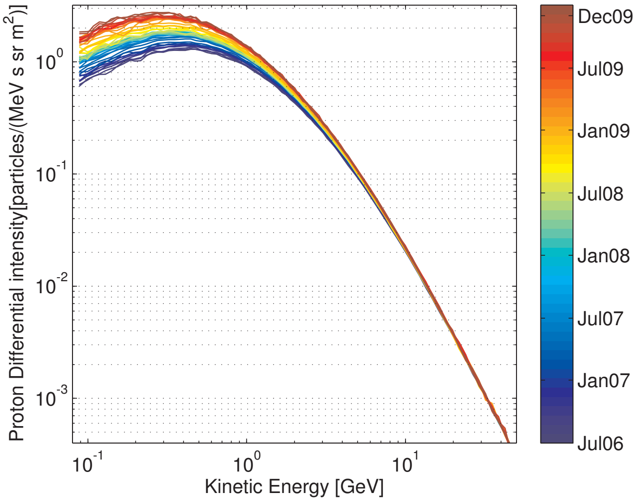


Figure 1: Proton spectra observed from July 2006 to the beginning of 2010 by the PAMELA detector. Spectra are averaged over one Carrington rotation [1, 2].

Parameter	2006	2007	2008	2009
a	0.564	0.510	0.450	0.420
P_k	3.85	3.90	3.95	3.95

Table 1: Power indices as used in Eq. 1.

Furthermore, $f_2(t)$ is a dimensionless time varying function, describing the time dependence of parallel diffusion. This function is updated in the model with every simulated solar rotation and so that the modulation effects are transported from Earth into the simulated heliosphere and outwards into heliosheath similar to what was done by [8, 7].

3 Observations and Modelling Parameters

3.1 Observations

The galactic proton spectra were studied as observed by the space-borne experiment PAMELA on board the Russian Resurs-DK1 satellite which executes a quasi-polar orbit. This instrument has been observing proton spectra since July 2006 [1, 2].

The observed spectra presented in Figure 1 are based on the data set collected between 2006 and early 2010. [See also Di Felice et al., this conference]. It illustrates how proton intensities evolved from July 2006 (blue curve) to the very beginning of 2010 (dark red curve). A closer inspection reveals that the highest spectrum was recorded at the end of 2009. In this context, see also Potgieter et al. [this conference].

Solar activity has picked up since the beginning of 2010 so that the proton intensity has consequently began to decrease which is not addressed in this work but reserved for future studies.

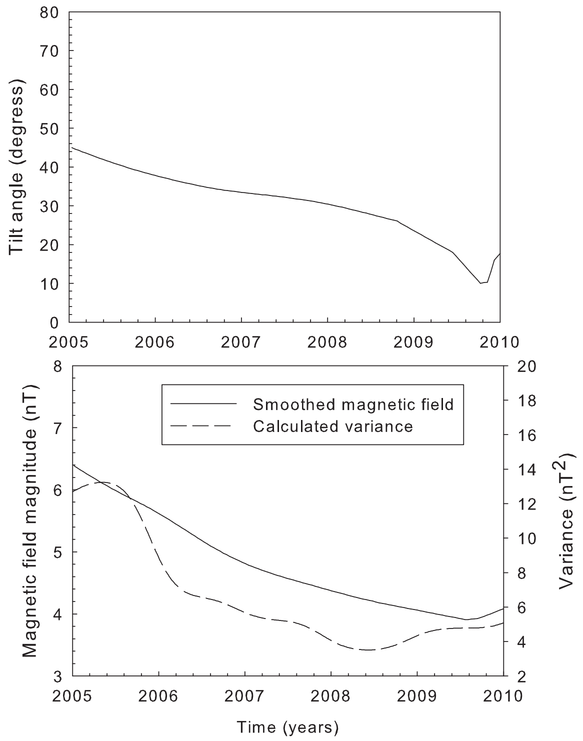
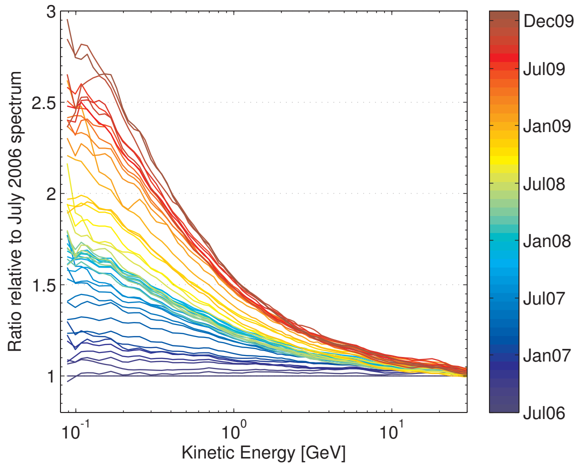


Figure 2: The top panel shows smoothed values of the classical modelling approach to the HCS tilt angle as a function of time (Wilcox observatory: http://wso.stanford.edu). The bottom panel shows the observed smoothed HMF magnitude at Earth (from NSSDC COHWeb:http ://nssdc.gfc.nasa.gov/cohoweb) and the corresponding calculated variance.

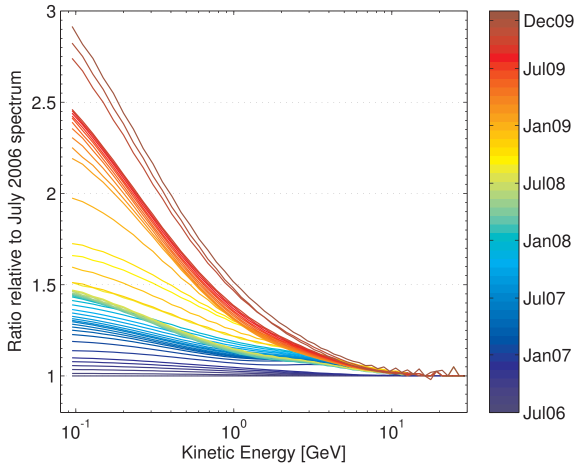
3.2 Modelling parameters

To compute corresponding spectra, the TPE is solved time-dependently for an A $<$ 0 polarity cycle using the time varying HCS tilt angles (Wilcox observatory: http://wso.stanford.edu) and the measured HMF values at Earth (from NSSDC COHWeb:http ://nssdc.gfc.nasa.gov/cohoweb) as time-dependent input parameters as shown in Figure 2. These parameters establish realistic heliospheric conditions that are propagated into the heliosphere with the solar wind. The tilt angle as shown is based on the HCS classic model preferred for studies such as this where CR modulation is explored over decreasing solar activity period.

Shown together with the HMF in the lower panel is the variance calculated using the OMNI data that was used to produce the function $f_2(t)$. The observed hourly averages of the total field magnitude were binned in 1 year intervals, and the statistical variance in each interval was calculated similarly to [8, 7]. See also Manuel et al. [this conference] for a more elaborate discussion of the finer details of the approach.



(a)



(b)

Figure 3: Ratios of consecutive monthly proton spectra with respect to July 2006. Shown in panel (a) are the observed (smoothed data) and in panel (b) the computed ratios. The color bar indicates the corresponding times.

4 Results and Discussion

Potgieter et al. [10] reproduced a selection of four monthly-averaged proton spectra between the end of 2006 and the end of 2009, each selection separated by a year. In order to do this with the 3D steady-state approach for the respective periods, the averaged values of the HCS tilt angles and the HMF magnitude of the preceding months were calculated and used as input parameters to the model. This is required in a stead-state approach because the CR flux at Earth is determined by the modulation conditions between the Earth and the outer modulation boundary. These conditions were created, of course, by solar activity several months before they reach the modulation boundary.

In contrast, in this work, the modelling focuses on using time-dependent modulation parameters as input to reproduce spectra for every solar rotation between mid-2006 and the beginning of 2010. The model reproduces the spec-

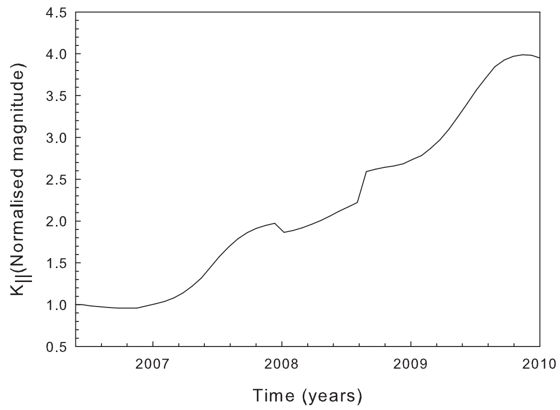


Figure 4: The normalised parallel diffusion coefficient at 1 GeV as a function of time, as related to Eq. 1.

tral features as observed although not shown here for solar rotation because of limited space. The results are summarized and illustrated in Figure 3, showing the ratio of consecutive monthly averaged spectra relative to July 2006 for both the observed (upper panel) and computed spectra (lower panel).

It follows from the observations that these spectra had progressively become softer over the 3.5 years. Comparing these model solutions with the observations demonstrates that the model reproduces the observed spectra on a monthly basis as well as the softening of the spectra as solar activity had decreased. To obtained the latter, a different rigidity dependence below 2 GV had to be assumed by changing the value of a in Eq. 1 with time as shown in Table 1. The changes of the rigidity dependence of the diffusion coefficients over this period is illustrated graphically by Vos et al. [this conference].

For the perpendicular diffusion coefficients we assumed functions similar to [8, 7] where also perpendicular diffusion in the polar direction is spatially enhanced toward the poles by a factor of 6. Their time-dependence is determined by the ratio of the changes in the magnitude of the HMF and the value of the HMF variance. In addition to these changes, the value of the parallel diffusion coefficient had to be increased with time at Earth as shown in Figure 4 in order to obtain the results shown in Figure 3(b). Evidently, it increases by a factor of $\sim$4.0 from 2006 to the end of 2009.

The result in Figure 4 indicates that the diffusion coefficients had to be increased significantly more with time than what changes in only the HMF magnitude and corresponding variance allowed. This is also significantly larger than the time-dependence of particle drifts which is determined by the time-varying tilt angle and time-varying magnetic field values that [8, 7] used. See Manuel et al. [this conference] for a full description of these parameters.

Qualitatively, this confirms the assessment that the 2009 modulation minimum was more diffusion “dominated” than previous solar minima as discussed by [10, 3].

5 Summary and Conclusion

This work presents a preliminary study of solar modulation using an enhanced time-dependent model to reproduce the precise proton observations from the PAMELA mission for every Carrington rotation from mid-2006 to the end of 2009.

In order to obtain this result, the compound modelling approach of [8, 7] was improved by introducing an additional time-dependence in the values of the diffusion coefficients over this period as well as in the rigidity dependence of these coefficients.

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