PROCEEDINGS OF SCIENCE

The 3D numerical modelling of the temporal modulation of galactic protons as per PAMELA and AMS02 observations with changing solar activity.

D.C. Ndiitwani,[a,b,*] **O.P.M. Aslam, M.D. Ngobeni,**[a,b] **M.S. Potgieter**[c] **and I.I. Ramokgaba**[a,b]

[a] *Centre for Space Research, North-West University, Potchefstroom, South Africa*
[b] *School of Physical and Chemical Sciences, North-West University, Mmabatho Campus, South Africa*
[c] *Institute for Experimental and Applied Physics (IEAP), Christian-Albrechts-University in Kiel, Germany*

E-mail: `Dzivhuluwani.Ndiitwani@nwu.ac.za`

The interest in the study of the global features of the modulation of galactic cosmic rays has increased since the observation of the 2009 solar minimum when the Sun and consequently the heliosphere was very quiet. Since then, the changing of solar activity through the period of maximum activity has kept it a subject of interest. Encouraging this interest is the high precision observations by the PAMELA and AMS02 space missions. These exceptional measurements provide an opportunity for enhanced numerical modelling of the modulation of protons over a wide range of rigidity at the Earth. A well-established three-dimensional drift model is used to compute proton spectra from 2009 until 2019 that are compatible with the mentioned observations. The main objective is to study how proton spectra quantitatively changes over time as solar activity changes for one minimum to the next. Simulated spectra are shown together with the required modulation parameters, and as such indicative of how the different modulation processes influence the time evolution of cosmic ray protons over time.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

---

[*] Speaker

PoS(ICRC2023)1318

1. Introduction

The unusual solar minimum observed between solar cycles 23 and 24 have stimulated remarkable interest on the study of the influence of solar activity on the modulation of the galactic cosmic rays (GCRs). In late 2009, PAMELA observed the lowest levels of solar activity and consequently the highest levels of GCRs since the beginning of the space exploration at the Earth [1–3]. 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. Necessary adjustment to the mathematical and numerical modelling were reported initially by [4] with respect to reproducing the proton observations during the unprecedented minimum.

A series of modulation modelling studies established quantitatively diffusion and drift coefficients for the tensor needed in the transport equation to reproduce spectral features for protons, electrons and positrons [5] as well as helium [6,10] observed by PAMELA, also including protons and antiprotons [7-9] observed by AMS02 after 2011. This work extends this approach and studies the modulation of galactic protons from 2006 until 2019, a period when solar activity had changed from one solar minimum to the next minimum. This study takes advantage of simultaneous and continuous observations of galactic protons from the PAMELA [11] and AMS02 [12] space experiments to achieve the objective of the study.

A 3D numerical model including all four major modulation processes is applied to compute galactic protons as observed by PAMELA from 2006 to 2009 and by AMS02 for the period from 2011 up to 2017. The set of modelling parameters which successfully reproduces proton spectra for the previous solar minimum period is adapted for the current study to establish modulation parameters that reproduce proton spectra observed by AMS02 for the period 2011 up to 2017. The main objective of this study is to demonstrate how proton spectra change with time (changing solar activity).

2. Numerical Model

The three-dimensional (3D) steady-state modulation model as described by [4], and recently improved by [8], is used to calculate proton spectra for monthly (and 27-day averages) up to six-month averages depending on the GCRs being studied and the particular application. The model is based on the numerical solution of Parker's [13] transport equation (TPE):

$$-(\mathbf{V}+\langle\mathbf{v}_D\rangle)\cdot\nabla f+\nabla\cdot(\mathbf{K}_s\cdot\nabla f)+\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial lnP}+J_{source}=0, \qquad (1)$$

where $f(\mathbf{r},P)$ is the cosmic ray distribution function; P is rigidity, $\mathbf{r}$ is the vector position, and $\mathbf{V}$ is the solar wind velocity. The terms from left to right represent convection caused by the expanding solar wind, gradient, curvature and HCS drifts, diffusion, adiabatic energy changes as determined by the divergence of $\mathbf{V}$, and any type of source function (in our case equal to zero), respectively. The diffusion tensor $\mathbf{K_s}$ consists of a parallel diffusion coefficient, $K_{\|}$, and two perpendicular diffusion coefficients in the radial direction $K_{\perp r}$ and in the polar direction $K_{\perp\theta}$. The modulation boundary

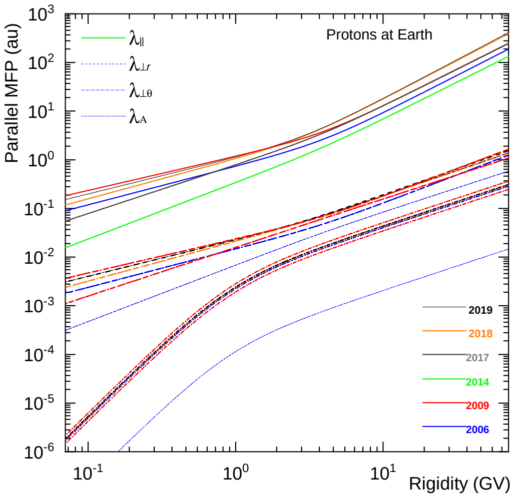

Figure 1: Rigidity dependence of the indicated three mean free paths (MFP) and drift scale, in units of au at Earth for six indicated periods as required to reproduce the representative proton spectra as shown in Figure 2. The mean free path (λ) relates to a diffusion coefficient as $K = \lambda(v/3)$ where v is the particle speed and $\beta = v/c$, with c the speed of light.

is assumed to be the heliopause (HP) specified in the model at 122 AU where the proton very LIS is used as initial spectrum which is then modulated from the HP up to the Earth. The study adopts the proton very LIS originally from [4] which was later updated by [14].

For our modelling to calculate proton spectra (differential intensities), the general expression for $K_{\parallel}$ is given by:

$$K_{\parallel} = \left(K_{\parallel}\right)_0 \beta \left(\frac{B_0}{B}\right) \left(\frac{P}{P_0}\right)^{c_1} \left[\frac{(\frac{P}{P_o})^{c_3} + (\frac{P_k}{P_o})^{c_3}}{1 + (\frac{P_k}{P_o})^{c_3}}\right]^{\frac{c_{2\parallel} - c_1}{c_3}}, \tag{2}$$

where the magnitude of the HMF is B and $B_0 = 1.0$ nT; $\left(K_{\parallel}\right)_0$ is a scaling parameter in units of 10^{22} cm^2 s^{-1}, with $P_0 = 1.0$ GV and . The constants c_i as power indices provide for two power laws with P_k specifying the rigidity at which the transition between the two power laws occurs. In this case, c_1 is a power index that changes with time and $c_{2\parallel}$, together with c_1, determine the rigidity dependent slope above and below a rigidity with value P_k, whereas c_3 determines the smoothness of the transition. The perpendicular diffusion in the radial direction is assumed to scale spatially similar to Eq. (2) using $K_{\perp r} = 0.02 K_{\parallel}$ (see [18]) with a different rigidity dependence at higher rigidity [8]. The polar perpendicular diffusion assumed for the study is as illustrated and discussed by [19]. Functional forms and details of the three diffusion coefficients and the drift coefficient used in model were discussed in detail by [8].

The input parameters to the model that simulate realistic heliospheric conditions and consequently introducing a time (solar activity) dependence is introduced in the model by using the observed magnitude B of the HMF at Earth[http://omniweb.gsfc.nasa.gov] and the changing HCS using the tilt angle α [http://wso.stanford.edu]. The averages values are introduced in the model similar to [8, 9], implementing differential running averages of B in the model depending on the extent of solar activity.

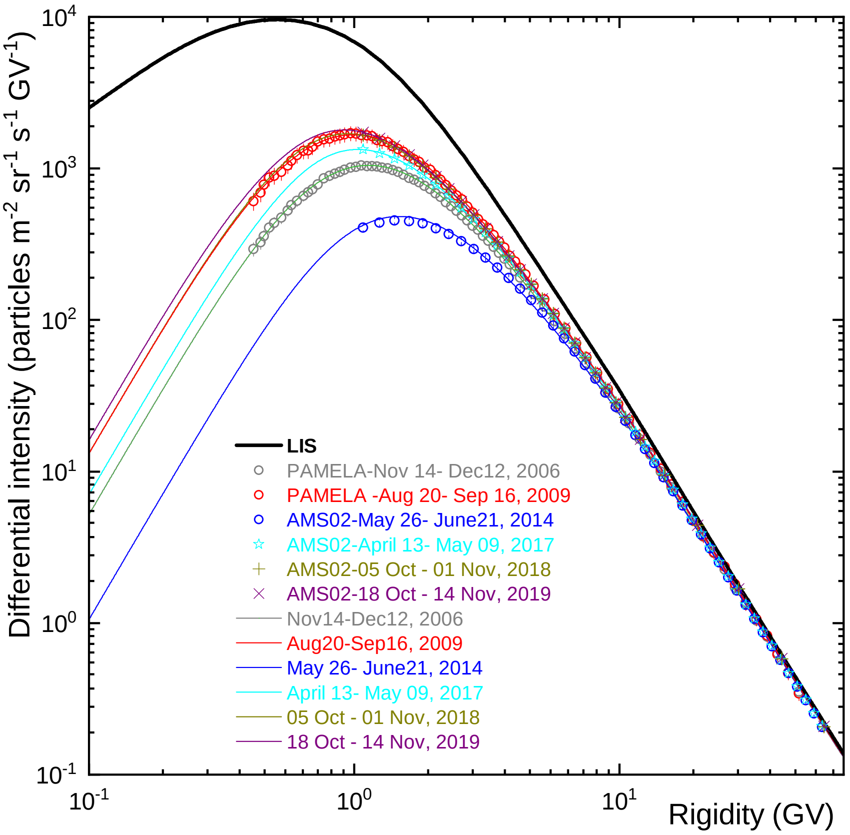

Figure 2: Modulated proton spectra (coloured lines) computed with respect to the very LIS [14] at 122 au for protons (upper black solid line) during periods of different solar activity for selected times as indicated, and compared to PAMELA and AMS02 observations [e.g., 11,12] at Earth as indicated by open coloured circles.

Figure 1 illustrates how the MFPs and drift scale varied from 2006 up to 2019 (indicated by the different colours), illustrating two power law slopes as required to simulate proton spectra at Earth as observed by PAMELA and AMS02 shown in Figure 2.

3. Simulated Galactic Proton Spectra

Figure 2 shows computed proton spectra for selected periods and overlaid by the observed spectra at Earth with respect to the corresponding very LIS. The spectra shown are not the only ones calculated but done for every six month period (meaning the first and last six months of every year mainly because of experimental constraints) using the calculated average values of α and B; see e.g., Figure 3 by [8]. For this report only six representative spectra are the selected and shown for distinguishable periods of solar activity. Comparing these solutions with observations demonstrates that the model can indeed reproduce both PAMELA and AMS02 proton spectra very well across all rigidities and from minimum to maximum solar activity and descending to next solar minimum. The model also simulates observed spectral features such as softening and hardening of the spectra as solar activity decreases or increases.

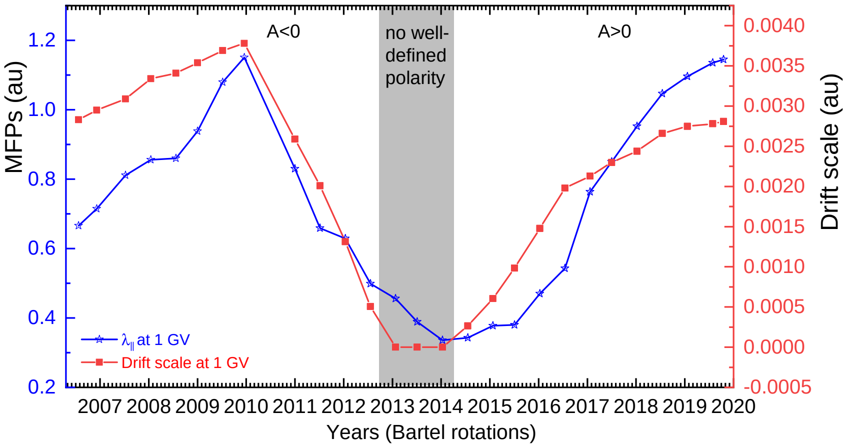

Figure 3: Time variation of the indicated MFP and drift scale over time at Earth for 1 GV protons (selected as the lowest rigidity observed by AMS). The shaded region indicates the period with no well-defined HMF polarity as happens during the period of maximum solar activity; see also [8].

It is important to note that in order to successfully reproduce both PAMELA and AMS02 observations, a time (solar activity) dependence in the rigidity dependence of the diffusion and drift coefficients had to be assumed as illustrated in Figure 1. This was possible by assuming different values of constants in Eq. (2), changing them explicitly in our calculations (see also [16]).

Figure 3 illustrates these mentioned changes to the parallel MFP and drift scale as indications of how the physics of solar modulation needs to change over time. This is done from the solar minimum of 2006-2009 to the period of increasing solar activity from and after 2010 reaching solar maximum in 2015, including the HMF polarity reversal phase from November 2012 to March 2014 and decreasing to solar minimum 2020. It is noteworthy that the drift scale was larger in late 2009 than in late 2019, and that it becomes essentially zero during the solar maximum activity period with no well-defined HMF polarity.

Complimentary studies using a similar 3D code were done by e.g. [17] who focused their studies on modulation at the peak of solar minimum period. See also the discussions by [5] to [10].

4. Summary and Conclusion

This work presents a preliminary study and abridged report of simulating proton spectra from solar minimum to maximum conditions and as well solar activity decreases, including a reversal of the HMF polarity. The modelled proton spectra reproduce the overall spectral features of PAMELA and AMS02 proton observations.

It follows from this comparison of simulated spectra with precise observations how the rigidity dependence of the diffusion and drift coefficients for protons change with solar activity in order to reproduce observations from 2006 to 2019. This illustrates the interplay between diffusion and drift as dominated factors over a solar cycles in the modulation of 1 GV protons at Earth.

References

[1] O.P.M. Aslam and Badruddin, *Solar Phys.* 269, 279, 2012.

[2] M.S. Potgieter et al., *ApJ.* 141, 810, 2015.

[3] M.S. Potgieter, *Adv. Space Res.* 60, 848, 2017.

[4] E.E. Vos and M.S. Potgieter, *ApJ.* 119, 815, 2015.

[5] O.P.M. Aslam et al., *ApJ.* 70, 873, 2019.

[6] M.D. Ngobeni et al., *Astrophy. Space Sci.* 182, 365, 2020.

[7] O.P.M. Aslam et al., *PoS* (ICRC2019), 358, 1053, 2019.

[8] O.P.M. Aslam et al., *ApJ.* 215, 909, 2021.

[9] O.P.M. Aslam et al., *ApJ.* in press, 2023.

[10] M.D. Ngobeni et al., *PoS* (ICRC2021), 264, 2021.

[11] O. Adriani, et al., *PhR* 323, 544, 2014.

[12] M. Aguilar et al., *PhRVL* 141102, 110, 2013.

[13] E.N. Parker, *Planet. Space Sci.* 13, 9.,1965.

[14] D. Bisschoff et al., *ApJ.* 878, 59 2019.

[15] E.E. Vos and M.S. Potgieter, *Solar Phys.* 2181, 291, 2016.

[16] D.C. Ndiitwani et al., *PoS* (ICRC2021), 2021.

[17] M.D. Ngobeni et al., *PoS* (ICRC2023), 2023.

[18] J. Giacalone and J.R. Jokipii, *ApJ.* 520, 204, 1999.

[19] M.S. Potgieter et al, *Solar Phys.* 289, 391, 2014.