A global view of the modulation of cosmic ray protons in the heliosphere for the solar minimum period up to 2009

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Abstract. The heliosphere was in a state of ideal solar minimum conditions for at least three years up to the end of 2009. During this period the highest ever recorded cosmic ray spectra were observed at the Earth. Fortunately, the PAMELA and Ulysses KET instruments simultaneously observed proton intensities for most of the period between July 2006 and June 2009, while Voyager 1 made observations in the outer heliosphere. This provides a good opportunity to compare the basic features of a comprehensive numerical model for the global modulation of cosmic rays in the heliosphere with these observations. Global gradients for protons are computed with the model for this prolonged solar minimum of cycle 23/24. This is done for both radial and latitudinal gradients, with the latter possible because Ulysses changed its position significantly in the heliocentric meridional plane during this period. The modulation model is set up for the conditions that prevailed during this unusual solar minimum period so that insight is gained on what role particle drifts played in establishing the observed gradients for this period. Good agreement is found between computed and observed gradients so that we conclude that the model gives a most reasonable representation of modulation conditions from the Earth to the heliopause for the mentioned period. These results can be used to refine the theory for diffusion, particle drifts and turbulence in the heliosphere.

1. Introduction

The solar minimum modulation period from 2006 to the end of 2009 had been unusual. It was expected that a new activity cycle would begin early in 2008, assuming a 10.5 year periodicity, but instead minimum modulation conditions had prevailed until the end of 2009. This was characterized by a much weaker heliospheric magnetic field (HMF) magnitude compared to previous cycles. The tilt angle of the wavy heliospheric current sheet (HCS) stayed below 15° for four consecutive years (except for a brief period in 2008). It was reported that cosmic rays (CRs) with a high rigidity reached record setting intensities during this time, e.g. [1, 2]. When the PAMELA proton spectra became available it turned out that record setting intensities were observed at the Earth at all reported energies (down to 80 MeV for PAMELA's range); see [3].

The mentioned observations were found quite puzzling from a drift theory point of view for CR modulation according to which CRs drift inwards or outwards along the HCS depending on the solar magnetic polarity cycle and the charge-sign of these particles. A higher flux of positively charged CRs should arrive at Earth during solar minimum periods with an A > 0 magnetic polarity because they then drift inwards primarily through the polar regions of the heliosphere. During A < 0 cycles, such as in 2006 to 2009, positively charged particles drift in towards the Earth mostly along the HCS, so that its waviness as represented by the tilt angle plays a more direct modulation role than during A > 0 cycles, e.g. [4,5]. It is therefore expected that proton spectra for these A < 0 cycles should be lower

than spectra during A > 0 cycles at kinetic energy $E <$ ~1 GeV. This is indeed the case, as was clearly illustrated by [6] who show that all previously observed proton spectra during solar minimum periods can be grouped together and categorized according to A > 0 and A < 0 polarity cycles without any exceptions. However, instead of grouping together with previous A < 0 cycles, the PAMELA proton spectrum for 2009 was even higher than the previously observed A > 0 spectra, as such quite a remarkable phenomenon. Of course, according to drift theory the upcoming A > 0 solar minimum period (perhaps in 2018-2019) should produce even higher CR spectra if solar activity would be again as low as in 2006 to 2009. This is expected because the Sun had been much quieter than before, even during the recent solar maximum activity period.

Particle drifts in the heliosphere are also recognized as the pre-eminent process behind the 22-year solar cycle observed in the CR latitudinal gradients; characteristically, drifts cause negative latitudinal gradients during A < 0 polarity epochs [7, 20, 27]. The model is used to compute such gradients for each year from 2006 to 2009 to be compared with values obtained by using corresponding PAMELA and Ulysses proton observations (Gieseler, private communication).

Changes in the HCS tilt angle, as for all other proxies of solar activity related to CR modulation, propagate outwards through the heliosphere at the solar wind speed so that when the Sun became quite already in 2006, these ideal solar minimum conditions settled throughout the heliosphere and lasted about three years. The heliosphere was therefore in a state of perfect solar minimum conditions for at least three years. This fact is used to simulate with a numerical model the CR proton intensities, and the corresponding radial and latitudinal gradients, throughout the heliosphere for the period 2006 to 2009. The modelling results are shown in comparison with CR observations, where available, made during this unusual and unprecedented solar minimum period.

2. The numerical model

A full three-dimensional (3D) model is used to compute the differential intensity of 10 MeV to 30 GeV protons in the equatorial plane of the heliosphere, at various radial distances along the trajectory of Voyager 1 and along the trajectory of the Ulysses spacecraft. It is based on the numerical solution of the well-known heliospheric transport equation (TPE; [8]):

$$\frac{\partial f}{\partial t} = -\left(\mathbf{V} + \langle \mathbf{v}_D \rangle\right).\nabla f + \nabla.\left(\mathbf{K}_S .\nabla f\right) + \frac{1}{3}\left(\nabla.\mathbf{V}\right)\frac{\partial f}{\partial \ln P}, \tag{2}$$

where $f(\mathbf{r},P,t)$ is the CR distribution function, P is rigidity, t is time, $\mathbf{r}$ is the position vector in three dimensions (3D), with the usual three coordinates r, θ, and φ specified in a heliocentric spherical coordinate system where the equatorial plane is at a polar angle of $\theta = 90°$ (heliolatitude of 0°). It is assumed that $\partial f / \partial t = 0$, which means that all short-term modulation effects (periods shorter than one solar rotation) are neglected, which is considered as a most reasonable assumption for the quiet solar minimum conditions during the mentioned period. Terms on the right hand side respectively represent convection, where $\mathbf{V}$ is the solar wind velocity; $\langle\mathbf{v}_D\rangle$ is the averaged particle drift velocity caused by gradients and curvatures in the global HMF, including the wavy HCS; with $\mathbf{K}_S$ the symmetry diffusion tensor; lastly, the term describing adiabatic energy changes which are treated the same everywhere in the heliosphere.

The numerical approach, the expressions for the solar wind speed and the HMF, the three diffusion coefficients (DCs) and the drift coefficient in terms of their spatial and rigidity dependence are described in great detail by [9] as well as the approach to simulate the modulation conditions throughout the heliosphere for the mentioned period. This approach produces the averaged modulation conditions in terms of the solar wind speed, the tilt angle and the HMF magnitude in the heliosphere up to about a year before the proton spectrum for a given time was observed at the Earth. The heliopause (HP) is positioned at 122 AU in the model to make it consistent with the reported Voyager 1 observations [10]. The position of the solar wind termination shock (TS) was shifted inwards from

~90 AU (2006) to ~80 AU (2009) from the Sun with deceasing solar activity; see also [11] and references therein from a cosmic ray modulation point of view, and [29] from an MHD point of view.

3. Results

3.1. The PAMELA proton spectra and modelled spectra up to the heliopause

Four PAMELA proton spectra are selected to be reproduced by the model, respectively averaged over 27 days for November 2006, December 2007, December 2008 and December 2009 and referred to as the 2006e, 2007e, 2008e and 2009e spectra, extending on the modelling reported by [9, 12]. By accounting for all of the appropriate modulation parameters in the model, and by carefully adjusting
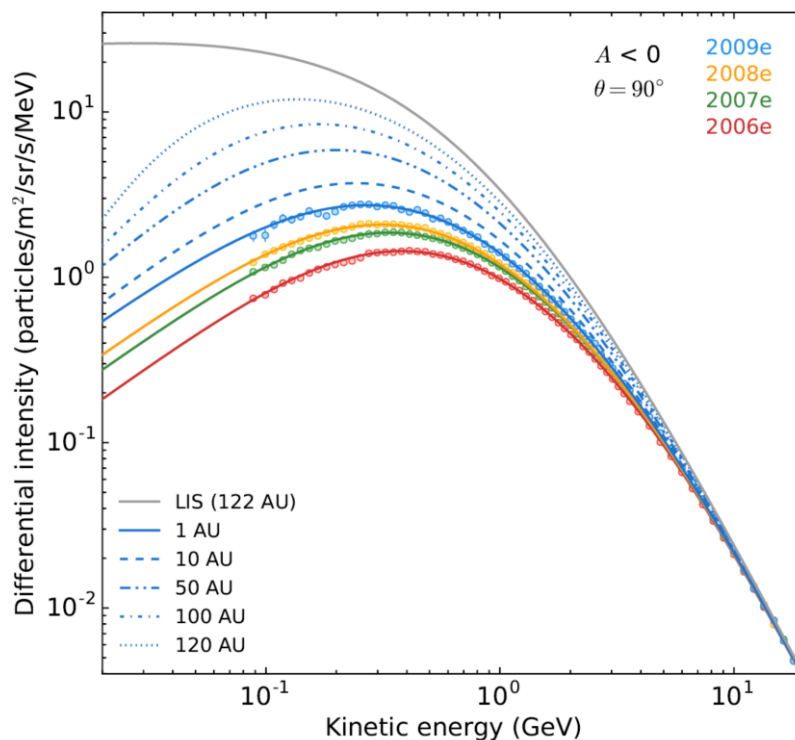

Figure 1. The observed PAMELA and computed proton spectra at the Earth (1 AU) for the periods 2006e, 2007e, 2008e and 2009e as described in the text. Corresponding computed spectra are also shown in the equatorial plane ($\theta = 90$) at 10 AU, 50AU, 100 AU and 120 AU by the blue lines. The local interstellar spectrum (LIS; grey line) from [9] is specified at 122 AU.

the values of the DCs, each consecutive year-end PAMELA proton spectrum was reproduced satisfactory as shown in Figure 1. The values of the DCs and other modulation parameters are given by [9]; see their Tables 1 and 2 and Figure 12. Additional computed spectra in the equatorial plane are shown at 10 AU, 50 AU, 100 AU and 120 AU in relation to the newly constructed very local interstellar spectrum (LIS) for protons from [9]. Concerning the new LIS's based on PAMELA and Voyager 1 observations, see also [13] and [14].

Evidently, the proton spectra at the Earth became progressively softer from 2006 to 2009, reaching a maximum intensity at the end of 2009, with an accompanying shift of the spectral peak to lower energies. Predictions of intensity levels are made with the model for kinetic energy $E < 80$ MeV, where PAMELA measurements are unavailable. Noticeably, the modulated spectra bend into the characteristic E^{+1} slope as a result of adiabatic energy losses which is the dominant process at non-

relativistic proton energies deep inside the heliosphere, e.g. [15]. The computed spectra at larger radial distances show how the maximum in the spectra progressively shifts to lower energies. Protons, with $E < 100$ MeV, evidently experience a significant amount of modulation overall but especially at large radial distances close the HP. This spatial dependent behavior is further discussed next.

3.2. The modelled radial and latitudinal profiles for CR protons
The departure point for computing the radial profiles is the PAMELA spectra as observed and reproduced by the model for the periods 2006e, 2007e, 2008e and 2009e. It is then computed how the corresponding radial profiles at a given E unfold outwards in the heliosphere. The focus is on obtaining a global view of the behaviour of CRs from 2006 up to 2009. A comparison is made with Voyager 1 observations at 182 MeV for this period as is shown in Figure 2. Concentrating on the computations first, the results illustrate how the intensity profiles change from 2006 to 2009 by increasing systematically as solar activity decreases. The radial trends of the profiles change at the TS,
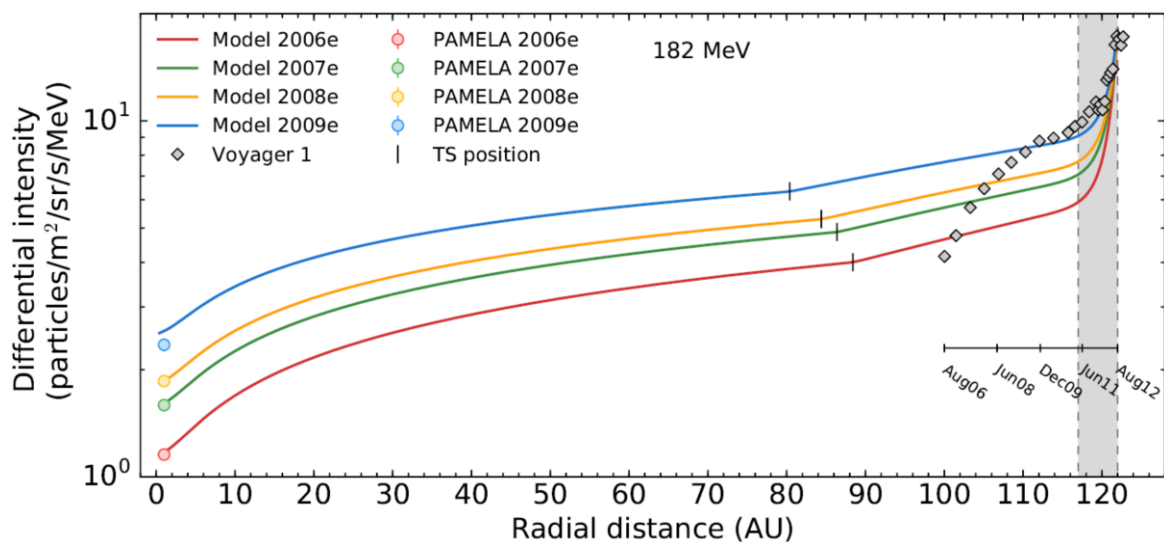

Figure 2. Computed radial intensities for 182 MeV protons at 56° colatitude based on the PAMELA measurements given by the coloured circles at 1 AU from 2006 (red line) and 2009 (blue line). The HP is fixed at 122 AU while the TS shifted its position as indicated by the short vertical black line. These profiles are compared to Voyager 1 measurements [16, 17] with time inset August 2006 to August 2012. The significance of the shaded region beyond ~116 AU is discussed in the text.

resuming inside the heliosheath with a different slope (larger radial gradients) towards the HP. Before discussing what happens beyond 117 AU inside the shaded region, first note that the way in which the Voyager 1 observed protons increased from 2006 to 2009 (see time inset), as it moved from ~100 AU to ~116 AU, corresponds very well with what the model predicts for this time period. In 2010, the observed proton intensity levels off at the position of Voyager 1 as solar minimum conditions as observed earlier at the Earth settled also in the outer heliosphere. But then, from ~ May 2011 onwards, the observed protons started to increase significantly and progressively more as the spacecraft approached the HP in August 2012 to eventually reached the observed value of the LIS at 182 MeV. From a modelling point of view, the straight forward approach of predicting the intensity globally up to 2009 based on the PAMELA spectra did not work any longer. To reproduce this increase, which is highly dependent on the energy of the CRs, the DCs in the model had to be reduced exponentially across this relatively narrow region. Although this has to be further investigated, it is evident that Voyager 1 experienced a region which may be called a HP modulation barrier for cosmic rays where

the 182 MeV galactic protons increased by a factor of ~2, over just a few AU, to reach the corresponding LIS value; see also the discussion by [18, 32]. This is indicative of a very turbulent region associated with the HP, where instabilities as predicted with MHD models [29, 30], together with large magnetic field fluctuations [31] dominate.

As mentioned above, particle drifts in the heliosphere cause the 22-year solar cycle observed in the CR latitudinal gradients with negative latitudinal gradients during A < 0 polarity epochs. A negative latitudinal gradients means the CR intensity is higher in the equatorial plane than away from it; see [20] for illustrative examples.

De Simone et al. [19] used measurements from PAMELA and Ulysses to investigate the radial and latitudinal gradients of protons in the inner heliosphere during the A < 0 solar minimum leading up to 2009. Using an empirical approach to separate the radial and latitudinal gradients, they reported for the
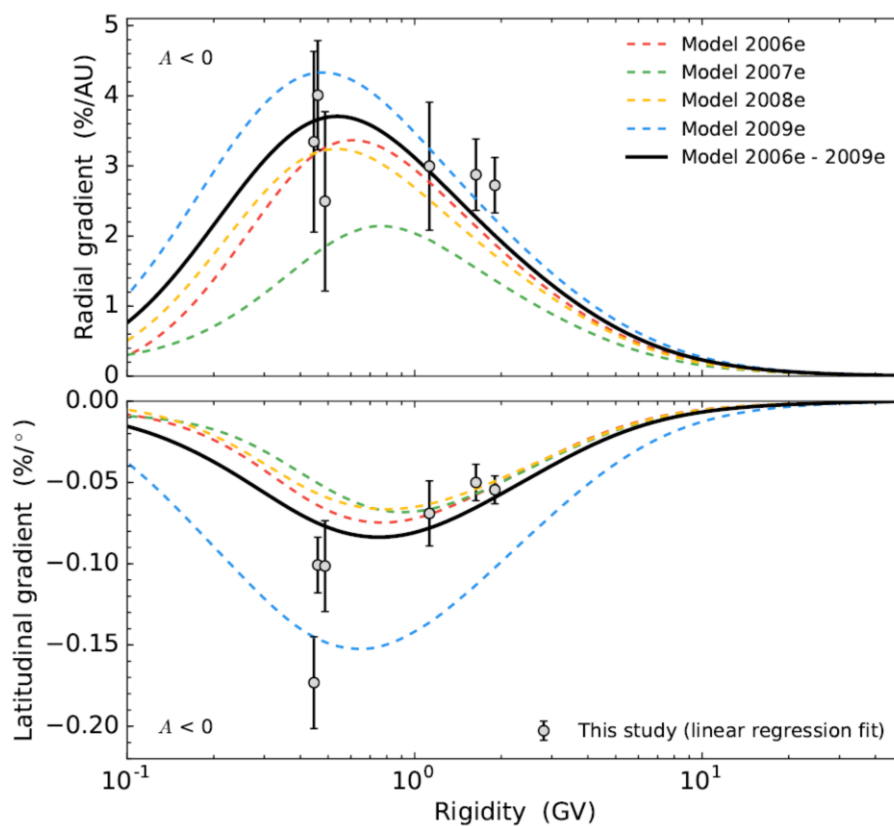

Figure 4. Top panel: Computed global radial gradients (G_r) between the positions of PAMELA (at the Earth) and along Ulysses' orbit, from July 2006 to June 2009, an A < 0 polarity cycle. Bottom panel: Similar but for the global latitudinal gradients (G_θ). In both panels the modelling gradients are given by the coloured dashed lines, with the solid black lines for the combined time period. These computed (modelled) gradients are compared to the corresponding gradients (grey symbols) calculated for this study from Ulysses KET and PAMELA proton observations.

rigidity interval 1.6 - 1.7 GV, a radial gradient $G_r = (2.7 \pm 0.2)$ %/AU and a latitudinal gradient of $G_\theta = (-0.024 \pm 0.005)$ %/degree, with the latter less negative than latitudinal gradients predicted by earlier drift models [5]. In hindsight, as discussed by [12], this was an indication that the modulation conditions during the minimum of cycle 23/24 were different and not indicative of drifts being overall less important in heliospheric modulation.

Numerical models can be used to compute local radial and latitudinal gradients for a given exact position anywhere in the heliosphere which elegantly illustrate the unique modulation characteristics of drifts, e.g. [20]. However, these local gradients are not useful if a comparison wants to be made with gradients calculated from observed CR intensities, mostly made far apart in space and at different times. For a meaningful comparison with PAMELA and Ulysses KET observations, a pragmatic, empirical method of analysis is used to calculate these global gradients, similar to the approach by [19], where details can be found; see also the PhD-thesis of Vos [21].

After applying the above mentioned procedure to every rigidity step of the model solutions, as well as to the available Ulysses KET and PAMELA observations, a comprehensive picture of the gradients G_r and G_θ emerges. This is shown in Figure 4, with G_r and G_θ given in the top and bottom panels,
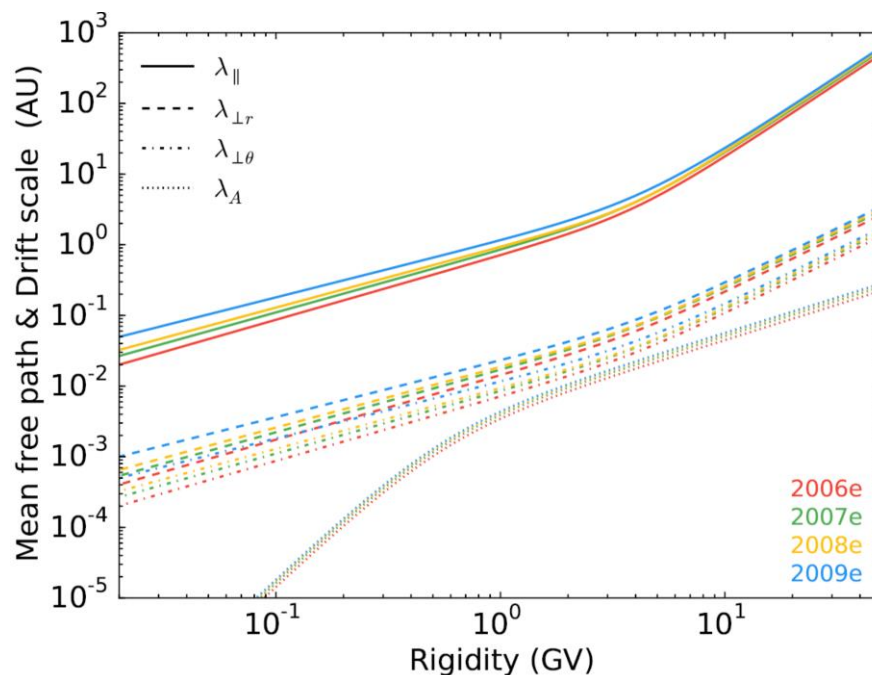

Figure 5. The time development of the rigidity dependence over the period 2006 to 2009 for the proton mean free paths (MFP) in AU; the parallel MFPs ($\lambda_\parallel$) are given by the four solid lines, the perpendicular MFPs in the radial ($\lambda_{\perp r}$) and polar ($\lambda_{\perp \theta}$) directions are given by the dashed and dashed-dotted lines, respectively. The drift scale (λ_A) is given by the four lowest dotted lines.

respectively. The model evidently produces positive G_r at all rigidities and negative G_θ for all four years, as expected for an $A < 0$ cycle but with G_θ less negative than previously predicted although still distinctively negative. According to this analysis, the model predicts that the largest G_r between the Earth and the position of Ulysses occurred during 2009, with a maximum of 4.25%/AU around 500 MV while the smallest is found for 2007, as a result of the fact that the latitudinal difference between the two spacecraft varied significantly during 2007 when Ulysses performed its fast latitude scan. Importantly, a consistency exists between the few observational values (symbols) and modelled values (lines). For G_θ, the most negative value is found for 2009, with − 0.15 %/degree around 600 MV, while the least negative G_θ is found for 2007. A characteristic of the model is that these gradients decrease significantly below ~400 MV because drifts decrease significantly with decreasing rigidity (see Figure 5). This serves to illustrate that when drifts are reduced, the negative latitudinal gradients will dissipate. The observational G_r of [19] is consistent with what we found, but G_θ is less negative

than the − 0.065 %/degree combined modelling value. Otherwise, the observational and modelling values are in a satisfactory agreement.

3.3. The rigidity-time dependent mean free paths and drift scale for the period 2006 to 2009
It was shown above that the numerical model can reproduce the proton spectra observed between 2006 and 2009. In Figure 5 the development in time of the rigidity dependence of the proton mean free paths (MFP) is shown as required in the numerical approach to reproduce the mentioned spectra (as in Figure 1). The MFPs are presented in AU for diffusion parallel and perpendicular to the magnetic field lines at Earth and for the drift scale; the parallel MFPs ($\lambda_{\parallel}$) are given by the solid lines, perpendicular MFPs in the radial ($\lambda_{\perp r}$) and polar ($\lambda_{\perp \theta}$) directions by the dashed and dashed-dotted lines, respectively, and the drift scale (λ_A) by the dotted lines. The details of the approach are given by [9, 21]. The rigidity dependence of λ_A is similar to what [22] found when studying the global modulation of galactic Carbon with an independent numerical model.

The results shown in Figure 5 can be used to refine diffusion theory for the solar modulation of protons because it can be interpreted as empirical evidence of what represents very quiet solar modulation conditions in terms of: (1) How the three main DCs should scale with rigidity over a wide range. (2) Importantly, how this rigidity dependence changes over time for the perfect solar minimum period of 2006 to 2009.

4. Discussion and conclusions
The reported PAMELA proton spectra observed between mid-2006 and the end of 2009 enabled us to do a comprehensive numerical study of modulation conditions during this unusual solar minimum period as reported by [12] and extended by [9]. A newly constructed very LIS was used as an input spectrum that takes into account recent Voyager 1 observations at low energies [9]. See also the assessment of solar minimum proton spectra by [6] and the conclusion that the 2009 PAMELA proton spectrum was the highest recorded during the space era.

Based on these studies, the conclusion was made that the modulation minimum period of 2009 can be described as unusual; being relatively more diffusion dominated instead of being drift dominated as previous A < 0 polarity cycles seem to have been. However, our studies illustrate that drifts nevertheless played a notable role [27], especially because the HMF had decreased significantly until the end of 2009, in contrast to the moderate decreases observed during previous minimum periods.

For this report, we set out using the model of [9] with the parameters tuned to reproduce four year-end PAMELA proton spectra, and then applied the model to compute the radial dependence of the proton spectrum throughout the heliosphere from 2006 to 2009. Corresponding radial profiles were computed for each year along the Voyager 1 trajectory and compared to available relevant observations. It is found that the computed intensity levels are in agreement with solar minimum observations from Voyager 1 at multiple energies. In addition, the model, after some adjustments, could also reproduce the steep intensity increases observed when Voyager 1 crossed the HP region and comprehensively simulated with independent models by [23, 24]. In this context, we conclude that our model gives a most reasonable presentation of the cosmic ray radial profiles, from the Earth to the HP, for the years 2006 to 2009.

Fortunately, simultaneous observations from Ulysses KET and PAMELA are available between July 2006 and June 2009, so that we could study the global radial and latitudinal gradients in the inner heliosphere as well. To assure a meaningful comparison between our modelling results and observations, we applied an empirical method similar to that of [19] based on our simulations at the Earth and along Ulysses' orbit for this period. We found good agreement between the computed values and those calculated from observations for both the radial and latitudinal gradients. We conclude that the model also gives a most reasonable representation of the spatial gradients in the inner heliosphere for 2006 to 2009.

Our computations reflect that drifts indeed influence CR modulation during this unusual solar minimum. The notion that drifts were unimportant during the recent solar minimum [25] is not

supported. Even though the observable effects of drifts were somewhat suppressed by the excess diffusion (larger DCs), drifts still maintain a strong presence as explained by [12]. We emphasize that the drift effects shown here, with a model tuned to the special conditions during the 2009 solar minimum, are indeed less than what drift models predicted previously for A < 0 cycles [26, 28]. Evidently, nobody had foreseen that the minimum modulation conditions for the A < 0 cycle of 2009 would be so different and unusual. The next solar minimum cycle may produce even more ideal minimum modulation conditions [6] since the Sun seems to be much quieter over the past decade than before.

Acknowledgments

References

[1]   Heber B, Kopp A, Gieseler J, et al. 2009 *Astrophys. J.* **699** 1956
[2]   Mewaldt R A, Davis A J, Lave K A, et al. 2010 *Astrophys. J. Lett.* **723** L1
[3]   Adriani O, Barbarino G C, Bazilevskaya G A, et al. 2013 *Astrophys. J.* **765** 91
[4]   Webber W R, Potgieter M S and Burger R A 1990, *Astrophys. J.* **349** 634.
[5]   Potgieter M S 2014a *Adv. Space Res.* **53** 1415
[6]   Strauss R D and Potgieter M S 2014 *Solar Phys.* **289** 3197
[7]   Potgieter M S, le Roux J A and Burger R A 1989 *J. Geophys. Res.* **94** 2323
[8]   Parker E N 1965 *Planet. Space Sci.* **13** 9
[9]   Vos E E and Potgieter M S 2015 *Astrophys. J.* **815** 119
[10] Stone E C, Cummings A C, McDonald F B, et al. 2013 *Science* **341** 150
[11] Manuel R, Ferriera S E S and Potgieter M S 2015 *Astrophys. J.* **799** 223
[12] Potgieter M S, Vos E E, Boezio M, et al. 2014 *Solar Phys.* **289** 391
[13] Potgieter M S 2014b *Braz. J. Phys.* **44** 581
[14] Bisschoff D and Potgieter M S 2016 *Astrophys. Space Sci.* **361** 48
[15] Caballero-Lopez R A and Moraal H 2004 *J. Geophys. Res.* **109** A01101
[16] Webber W R, McDonald F B, Higbie P R and Heikkila B 2011 *arXiv* 1111.2377
[17] Webber W R, Higbie P R and McDonald F B 2013 *arXiv* 1308.1895
[18] Webber W R and Quenby J J 2015 *Astrophys. J.* **806** 138
[19] De Simone N, Di Felice V, Gieseler J, et al. 2011 *Astrophys. Space Sci. Trans.* **7** 425
[20] Ngobeni M D and Potgieter M S 2010 *Adv. Space Res.* **46** 391
[21] Vos E E, 2016 PhD thesis, North-West University, South Africa
[22] Ngobeni M D and Potgieter M S 2015 *Adv. Space Res.* **56** 1525
[23] Luo X, Zhang M, Potgieter M S, et al. 2015 *Astrophys. J.* **808** 82
[24] Strauss R D, Potgieter M S, Ferreira S E S, et al. 2013 *Astrophys. J. Lett.* **765** L18
[25] Cliver E W, Richardson I G and Ling A G 2013 *Space Sci. Rev.* **176** 3
[26] Potgieter M S 2013 *Living Rev. Solar Phys.* **10** 3
[27] Kóta, J 2013 *Space Sci. Rev.* **176** 391
[28] Heber B, Dröge W, Ferrando P, et al. 1996 *Astron. Astrophys.* **316** 538
[29] Washimi H, Zank G P, Hu Q, et al. 2011, *MNRAS* **416** 1475
[30] Avinash K, Zank G P, Dasgupta B and Bhadoria S 2014 *Astrophys. J.* **791** 102
[31] Burlaga L F, Ness N F, Florinski V and Heerikhuisen J, 2014 *Astrophys. J.* **792** 134
[32] Luo X, Potgieter M S, Zhang M, et al. 2016 *Astrophys. J.* in press