

New insight from modelling galactic deuterons over changing solar activity

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Received 4 December 2025; received in revised form 10 March 2026; accepted 14 March 2026

Available online 19 March 2026

Abstract

The interest in the origin and modulation of cosmic ray deuterons is expected to increase significantly now that observations from AMS-02 and PAMELA detectors have become available. These observations provide a useful tool with which a comprehensive description of the differences in the modulation of deuterons (D) and protons (p) can be made. Observations made by AMS-02 reveal the spectral shape and features of galactic D over the rigidity range 1.92–21.1 GV, whereas those from PAMELA are at a lower rigidity, from 0.75–2.5 GV. These observations provide interesting surprises leading to subsequent challenges to the established paradigm of the secondary origin of galactic D. In this study a comprehensive 3D numerical model and a set of diffusion and drift coefficients, previously applied to a number of cosmic ray nuclei, together with a newly estimated local interstellar spectrum (LIS) for D based on AMS-02 observations, are used to simulate the modulation of D from 2006 to 2014. These modelling results are compared to published D spectra and the corresponding D/p ratios made by PAMELA over the same period, thereby focussing on modulation during a so-called A < 0 solar magnetic field polarity cycle. A particular objective is to uncover how the D/p ratio evolves at different rigidities over changing solar activity. We find that from July 2006 until December 2009 the p spectra became softer than D spectra indicating that relatively more low rigidity p had reached Earth than D. As solar activity began to pick up after 2009, the contribution of adiabatic energy losses became increasingly evident at lower rigidities, with the modulated p spectra hardening more in comparison with D spectra based on the shapes of their respective LISs. Consequently, the time dependence of the D/p ratio is found to be significant at rigidities below 1 GV, and with a different time-trend than at higher rigidities. The numerical model computations display both qualitative and quantitative compatibility with the observed features of D spectra and D/p ratios from the PAMELA detector.

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Keywords: Cosmic rays; Heliosphere; Solar modulation; Solar activity; Galactic hydrogen

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1. Introduction

The Alpha Magnetic Spectrometer (AMS-02) detector measured galactic cosmic-ray (GCR) deuteron (D) spectra averaged over four Bartels rotation (BRs) for the period extending from 2011 May to 2021 April, covering rigidity ranges between 1.92–21.1 GV (Aguilar et al., 2024). These observations provided several interesting surprises with subsequent challenges to the established paradigm of their secondary origin. In particular, the observed galactic D exhibited rigidity dependence that differed considerably from that of helium-3 (^3He) but was similar to that of protons (p), suggesting a primary-like source of D. Consequently, all the observed AMS-02 D spectra at higher rigidities are higher than could be accounted for by our current state of understanding of their secondary production in the interstellar medium. This is indeed an unexpected observation that can have far-reaching implications for the general understanding of the physical processes in the Galaxy, or perhaps even indicate the limited theoretical understanding caused by the lack of precise D observations in the past. Before this observation was made, the established paradigm was that D is destroyed rather than created during the stellar nucleosynthesis such that no significant amounts of primary D can be ejected by astrophysical sources in the Galaxy. In this regard, the spallation of helium-4 (^4He) on a proton and proton fusion processes remained the predominant mechanisms to produce D in the interstellar medium (see a detailed discussion by Gomez-Coral et al., 2023; Lenzi et al., 2025 and references therein).

The work by Aguilar et al. (2024) interpreted the new AMS-02 galactic D observations to reveal the primary component of D, which taken at face value, challenges the current understanding of the physical processes occurring in the Galaxy. Interestingly, at the time of finalizing this paper, Voyager 1 observations taken beyond the heliopause (HP) were updated and confirm the presence of the primary component of D (Cummings et al., 2025). However, Yuan and Fan (2024) demonstrated, using improved cross sections of D production processes as inputs in the GALPROP model (see also Moskalenko et al., 2002; Boschini et al., 2017), that the fragmentation of heavy nuclei up to nickel plays a crucial role in enhancing the spectrum of the cosmic D. These authors suggest a complex production of secondary CR due to heavy elements, which has been overlooked thus far owing to their low abundance. In general, accurate knowledge of the contribution of heavy nuclei in the production of D can provide important constraints, which in turn may improve our understanding of the physical processes at play in the interstellar medium. But the uncertainties (see also Coste et al., 2012; Weinrich et al., 2020) around the fragmentation cross section of various heavy nuclei to produce D makes it difficult to completely rule out the concept of the primary component of D. At the present time, there is no satisfactory GALPROP calculated D LIS capable

of reproducing AMS-02 measurements at high rigidities because either additional physical processes are required in the galactic space for these secondaries or there is indeed a primary component of cosmic D. But progress is being made in this regard (e.g. Yuan and Fan, 2024; Zhu and Wang, 2025; Cummings et al., 2025). Hopefully a deuteron LIS obtained from improved GALPROP computations and free of ambiguities will be made available in the near future.

The recent publication of galactic D rigidity spectra from PAMELA taken between July 2006 and September 2014 over the lower rigidity range of 0.75–2.6 GV (Lenzi et al., 2025) provides a privileged study sample that extend to rigidities below 1 GV where solar modulation is more pronounced. Combining PAMELA and AMS-02 cosmic D observations provide a basis to illustrate to what extent the deuteron LIS can be established from the modification of currently available GALPROP LISs (Bischoff et al., 2021; Gomez-Coral et al., 2023) using numerical modulation models by applying the knowledge obtained from studying GCR Hydrogen (H), ^4He and ^3He in the heliosphere to the modulation of D.

In this paper, a well-established comprehensive three-dimensional (3D) numerical model that has been previously applied successfully to study the modulation of galactic H and helium isotopes (Ngobeni et al., 2020, 2022; Aslam et al., 2023) is extended to include the heliospheric modulation of galactic D. The main purpose is to reproduce the published PAMELA spectra of D and the corresponding D/p ratios using the same set of diffusion and drift coefficients previously applied to H and helium modulation. This approach to D modelling and its comparison with observations around the Earth further confirms how the diffusion and drift coefficients change over a solar cycle, insight which even the latest turbulence theory is not yet able to provide (Els et al., 2024). First, the D LIS is estimated based on available GALPROP calculated LISs and observational data from PAMELA and AMS-02. The newly established LIS is used to simulate the solar modulation of D for a wide rigidity range and for periods beginning from the prolonged solar minimum activity of 2006–2009 in the $A < 0$ cycle till the end of the solar maximum activity around 2014. For each year studied the computed spectra are used to calculate the D/p ratios and compared with the recently published PAMELA observations.

In our next modelling phase, the newly reported observation of galactic D from Voyager 1 by Cumming et al. (2025), which is not included in constraining the current phenomenological LIS, will be used to refine this LIS when evaluated against the physics in GALPROP models. Therefore, this work will be extended in future to reproduce and compare the main features of the observed D/p, D/ ^4He , D/ ^3He and $^3\text{He}/^4\text{He}$ ratios observed between 2006 and 2021 by PAMELA and AMS-02. Also included will be a detailed comparison of galactic D observations from AMS-02 with our model simulations, considering all the

published BRs averages and also at rigidities above 3 GV and beyond 2013–2014 solar maximum. This will show how deuteron modulation evolves over a 22-year drift cycle in comparison with that for p and two helium isotopes.

2. The 3D cosmic ray numerical model

The comprehensive 3D numerical model and simulation approach used in this work has been described in detail recently by Ngobeni et al. (2024) and previously by several authors (e.g., Potgieter et al. 2014, 2015; Vos and Potgieter 2015; Potgieter and Vos 2017; Corti et al. 2019; Aslam et al. 2019, 2021, 2023; Ngobeni et al. 2020, 2022). Therefore, it is not our intention to repeat all the previously published features and parameters of this model but only the essentials that concern the aim and purpose of this work.

The numerical model is based on the transport equation (TPE) derived by Parker (1965) given as,

$$\frac{\partial f}{\partial t} = -(\mathbf{V}_{sw} + \langle \mathbf{v}_D \rangle) \cdot \nabla f + \nabla \cdot (\mathbf{K}_s \cdot \nabla f) + \frac{1}{3} (\nabla \cdot \mathbf{V}_{sw}) \frac{\partial f}{\partial \ln p}, \quad (1)$$

where $f(\mathbf{r}, p, t)$ is the omnidirectional GCR distribution function, p is particle momentum, $\mathbf{r}$ is the heliocentric position vector, and t is time, with $\mathbf{V}_{sw}$ and $\mathbf{K}_s$ the radial solar wind (SW) velocity and the symmetric diffusion tensor respectively. The terms on the right-hand side represent convection, particle drifts, diffusion, and adiabatic energy changes in the form of energy losses ($\nabla \cdot \mathbf{V}_{sw} > 0$) or gains ($\nabla \cdot \mathbf{V}_{sw} < 0$), respectively. The averaged guiding center drift velocity for a near isotropic CR distribution is given by:

$$\langle \mathbf{v}_D \rangle = \nabla \times (K_A \mathbf{e}_B), \quad (2)$$

with $\mathbf{e}_B = \mathbf{B} / B$, where B is the magnitude of the background heliospheric magnetic field (HMF) assumed to have a basic Parkerian geometry in the equatorial plane but modified in the polar regions similar to the approach of Smith and Bieber (1991). In Eq. (2), K_A is the coefficient that describes gradient and curvature drifts in the large-scale HMF.

The symmetric diffusion tensor $\mathbf{K}_s$ in the HMF aligned coordinates consists of a diffusion coefficient $K_{\parallel}$ that is parallel to the average HMF, a radial perpendicular diffusion coefficient $K_{\perp r}$ and a polar perpendicular diffusion coefficient $K_{\perp \theta}$. In this study this tensor is given by

$$\mathbf{K}_s = \begin{pmatrix} K_{\parallel} & 0 & 0 \\ 0 & K_{\perp \theta} & 0 \\ 0 & 0 & K_{\perp r} \end{pmatrix} = K_{\parallel} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.02 f_{\perp \theta} \frac{D_{\perp}}{D_{\parallel}} & 0 \\ 0 & 0 & 0.02 \frac{D_{\perp}}{D_{\parallel}} \end{pmatrix}, \quad (3)$$

with

$$K_{\parallel} = (K_{\parallel})_0 \beta \left(\frac{B_0}{B} \right) \left(\frac{P}{P_0} \right)^{c_1} D^{\parallel}(P), \quad (4)$$

where

$$D^{\parallel}(P) = \left[\frac{\left(\frac{P}{P_0} \right)^{c_3} + \left(\frac{P_k}{P_0} \right)^{c_3}}{1 + \left(\frac{P_k}{P_0} \right)^{c_3}} \right]^{\frac{c_2 \parallel - c_1}{c_3}}, \text{ and} \\ D^{\perp}(P) = \left[\frac{\left(\frac{P}{P_0} \right)^{c_3} + \left(\frac{P_k}{P_0} \right)^{c_3}}{1 + \left(\frac{P_k}{P_0} \right)^{c_3}} \right]^{\frac{c_2 \perp - c_1}{c_3}} \quad (5)$$

with P the rigidity, $(K_{\parallel})_0$ a scaling constant in units of $10^{22} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 1 \text{ GV}$, $B_0 = 1 \text{ nT}$; P_k is the rigidity at which the transition between the two power laws occurs that sometimes change with time if required and β is the ratio of the particle speed v to the speed of light c . The dimensionless quantities $c_2 \parallel$ (or $c_2 \perp$) and c_1 respectively give the time dependence of the rigidity slopes of the diffusion coefficients above and below P_k , while $c_3 = 2.5$ is kept constant and gives the smoothness of the transition in these slopes. The ratio $D^{\perp} / D^{\parallel}$ is the quantity that changes the rigidity dependence of $K_{\perp \theta}$ and $K_{\perp r}$ with respect to that of $K_{\parallel}$, and the function $f_{\perp \theta}(\theta)$ enhances $K_{\perp \theta}$ by a factor 6.0 towards the polar regions with respect to its value in the equatorial plane (e.g., Potgieter, 2000; Ferreira et al., 2000; Moeketsi et al., 2005).

The drift coefficient in this study, expressed as a function of a simple drift reduction factor that depends on rigidity, is given by

$$K_A = k_{A0} \frac{\beta P}{3B} \frac{(P/P_{A0})^2}{1 + (P/P_{A0})^2}, \quad (6)$$

with $P_{A0} = 0.75 \text{ GV}$ the rigidity below which the drift coefficient is suppressed with respect to the weak scattering approach and k_{A0} a dimensionless quantity that adjusts the level of particle drift in the heliosphere depending on solar activity and vary between 0 and 1.0 over a solar cycle. See the detailed discussion by Ngobeni and Potgieter (2015). The time variation in K_A in Eq. (6) depends only on k_{A0} and B , with its rigidity slope kept the same.

In the assumed modelling approach of this work, the modulation parameters that are changed with time in the model to obtain the GCR D and p results are the observed magnitude of the HMF, B , at the Earth and its polarity change during solar maximum and the tilt angle (α) of heliospheric current sheet. The B and α serve as proxies for solar activity and their ~ 27 day observed averages are shown in Fig. 1 as solid lines from 2006 to 2015. The calculated values of their corresponding running average used in the model are adapted from Aslam et al. (2023) and are indicated as dashed lines. As we showed in our previous studies, the simple $1/B$ approach to scale the three diffusion coefficients in Eq. (3) is not sufficient to reproduce the precise observations from PAMELA and AMS-02 as solar activity changes. So that additionally, the values and the

rigidity slopes of the three elements of the diffusion tensor in Eqs. (4) and (5) and the magnitude of k_{A0} in Eq. (6) are also changed with time in the model. This is shown from December 2006 to December 2014 on the left panel of Fig. 2 as the mean free paths (MFP, λ) Eqs. (3)–(5) and drift scale (λ_A) Eq. (6) as a function of rigidity, with the general relationship given as $\lambda = 3K/v = 3(K/\beta c)$. The effects of β , caused by the mass-to-charge ratio (A/Z), on both λ and K , have been shown to become increasingly significant the lower the rigidity below 5 GV (Ngobeni et al., 2020). As particles become relativistic, β approaches 1.0 above 5 GV (see Figs. 2 and 3 in Ngobeni et al., 2020) and as a result the dependence of K on A/Z is smeared out meaning all nuclei with different A/Z will have the same K values above 5 GV. However, below 5 GV p with $A/Z = 1$ has higher K values than D with $A/Z = 2$, whereas their λ values are the same. Therefore, changing the values of the diffusion and drift coefficients with time, as illustrated in Fig. 2, affects the D and p spectra differently at $P < 5$ GV. Also shown on the right panel of Fig. 2 are the ratios $\lambda_{\perp r}/\lambda_{\parallel}$ and $\lambda_A/\lambda_{\parallel}$ as a function of rigidity over the same period. It can be noted that adjusting k_{A0} in Eq. (6) influences the spread in $\lambda_A/\lambda_{\parallel}$ largely between 2010 and 2014 than 2006 and 2009 at all rigidities. While over the same period, $\lambda_{\perp r}/\lambda_{\parallel}$ shows no time dependence at $P < 5$ GV.

The changes in MFPs and drift scale are now illustrated in Fig. 3 as a function of time for 1.05 GV. This figure shows how the physics of solar modulation needs to change from the solar minimum of 2006–2009 to the period of increasing solar activity from and after 2010. What is highlighted in this figure is that even though $\lambda_{\parallel}$ is 50 times more than $\lambda_{\perp r}$ at 1.05 GV, these MFPs developed in the same

manner as solar activity changed from mid-2006 reaching solar maximum period between the end of 2012 and mid-2014. Whereas $\lambda_{\parallel}$ increased faster than λ_A from 2006 to 2009 and decreased slower than it from 2010 till the end of 2014. So as the MFPs and drift scale decreased, the adiabatic energy loss process became increasingly important at $P \leq 1.05$ GV. Therefore, the significance of the time dependence of the diffusion and drift coefficients depicted in Fig. 3 becomes pivotal in the context of understanding the physics behind the time dependence of D/p ratio at rigidities above and below 1 GV observed by PAMELA detector.

3. Computations of the solar modulation of galactic hydrogen isotopes

3.1. The D LIS

As mentioned before, to date there is no theoretically motivated D LIS capable of consistently matching AMS-02 observations recently published by Aguilar et al. (2024) when modulated. Therefore, to make progress in studying the solar modulation of D with numerical models, knowledge obtained from studying galactic H modulation in the heliosphere from Aslam et al. (2023) is used to manually adjust the available GALPROP D LISs to first compute the modulated spectra at the Earth that provide reasonable match to AMS-02 observations. The established D LIS is then used as an input in the numerical model described in Section 2 to simulate the solar modulation of D related to PAMELA observations for the period July 2006 to September 2014 published by Adriani et al. (2016) and Lenni et al. (2025). This is a continuation of numerical modelling that we did before on protons, electrons, positrons and He isotopes as observed by PAMELA. A second phase of the modelling will also involve also the observed AMS-02 modulated spectra after the 2014 solar maximum when a new solar activity and magnetic polarity cycle has started.

The top panel of Fig. 4 shows two published D LISs in units of $\text{GV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ as a function of rigidity taken from Bisschoff et al. (2021) and Gomez-Coral et al. (2023), respectively indicated as solid purple and blue lines. These two LISs are calculated using the well-known GALPROP online code, but to obtain the LIS of Bisschoff et al. (2021) the galactic propagation parameters were adjusted to reproduce the preliminary Voyager 1 observations at the HP (Webber et al., 2018). For a review on LISs, see Potgieter et al. (2021). Also shown in the top panel of this figure as solid fuchsia line is the estimated D LIS used in this paper. This LIS is based on what Gomez-Coral et al. (2023) reported at lower energies but manually adjusted at higher energies based on AMS-02 observations. Table 1 shows the tabulated data for the adjusted LIS as a function of kinetic energy/nucleon. The corresponding mathematical expression approximating this LIS to within 5% accuracy is given by

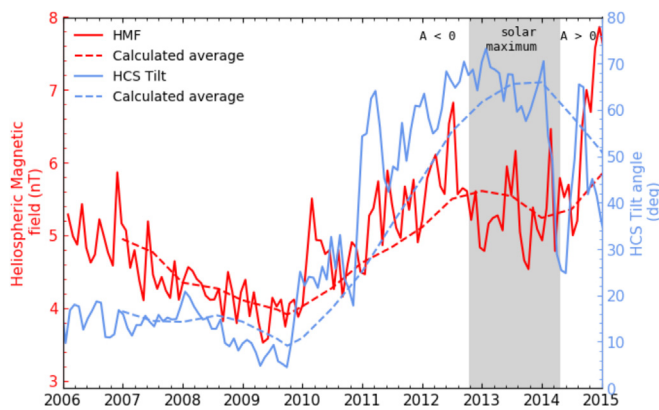


Fig. 1. The magnitude of the HMF (red solid line) observed at the Earth averaged over ~ 27 days from 2006 to 2015 taken from <http://omniweb.gsfc.nasa.gov>. The blue solid line is the ~ 27 days averages of the tilt angle of the HCS at the Earth, taken over the same period, from <http://wso.stanford.edu>. The corresponding running average values of the HMF and tilt used in the model are adapted from Aslam et al. (2023) and indicated as dashed red and cornflower blue lines, respectively. Also indicated is the $A < 0$ and $A > 0$ HMF polarity epochs before and after the period of maximum solar activity and when no well-defined HMF polarity was present (grey shaded band).

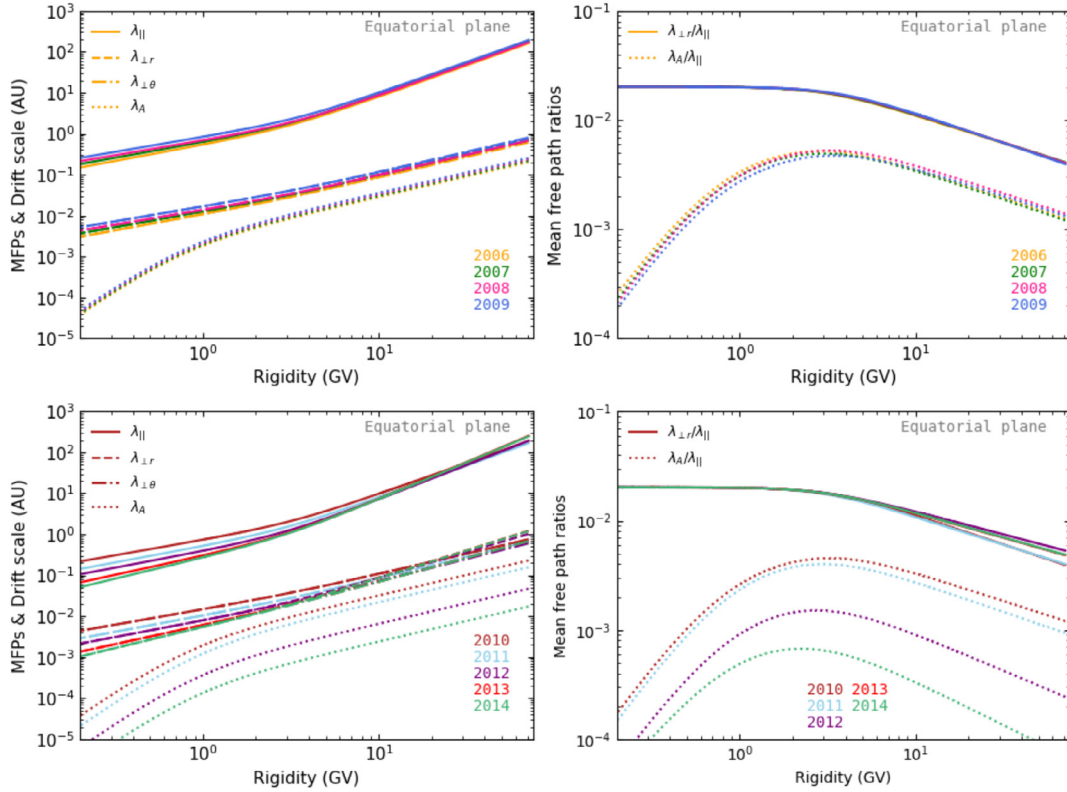


Fig. 2. Left panel shows the computed MFPs at the Earth as a function of rigidity between December 2006 and December 2014 focusing only on Carrington Rotations at the end of each year. The solid lines represent the parallel MFPs $\lambda_{\parallel}$, while the dashed and dashed-dotted lines represent the perpendicular MFPs in the radial ($\lambda_{\perp,r}$) and polar ($\lambda_{\perp,\theta}$) directions respectively and the drifts scale (λ_A) is depicted by the dotted lines. The right panel shows the corresponding ratios of the MFPs $\lambda_{\perp,r}/\lambda_{\parallel}$ (solid lines) and $\lambda_A/\lambda_{\parallel}$ (dotted lines) as a function of rigidity.

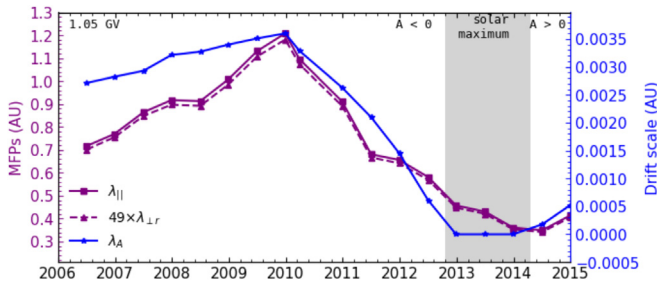


Fig. 3. Time variation of the indicated MFPs and drift scale over time at Earth for 1.05 GV protons. The shaded region indicates the period with no well-defined HMF polarity as happens during the period of maximum solar activity.

$$J_{LIS} = 29.3 \frac{E^{1.14}}{\beta^{0.46}} \left(\frac{E + 0.375}{1.4} \right)^{-3.95} - \left(\frac{E}{E_0} \right)^3 \left[\frac{\left(\frac{E}{E_0} \right) + 1}{2} \right]^{-10} \quad \text{for } 0.061 \text{ GeV/n} \leq E < 1.70 \text{ GeV/n};$$

and

$$J_{LIS} = 5.35 \exp(3.22 - 2.8(\ln E) - 1.5E^{-1}) \quad \text{for } 1.70 \text{ GeV/n} \leq E \leq 34.5 \text{ GeV/n} \quad (7)$$

where E is the kinetic energy/nucleon in GeV/n, $E_0 = 0.938$ GeV and J_{LIS} in units of $\text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The computed modulated intensities resulting from these three D LIS scenarios are shown at the Earth as dashed lines of the same colour and are compared to the corresponding AMS-02 observations published by Aguilar et al. (2024) for the period BR2426 – BR2429.

It is noted in Fig. 4 that the two GALPROP scenarios of D LISs differ the most at lower rigidity below ~ 0.8 GV. However, the computed modulated spectra obtained from these GALPROP LISs fall progressively faster than AMS-02 observations at rigidities > 5 GV. In fact, AMS-02 observations are higher than the two presented GALPROP LISs above 10 GV, indicating that these discrepancies emanate from the shape of these LISs and not from parameters related to diffusion or drift inside the heliosphere. Consequently, the latest of the two GALPROP LISs is manually adjusted at higher rigidities to obtain the LIS that can be used to quantitatively study the solar modulation of D in the heliosphere. It can be seen in Fig. 4 that the modulated spectra, depicted as a dashed fuchsia line, obtained from this adjusted LIS produces the best compatibility with AMS-02 observations at the given rigidity range.

To validate the preferred LIS in this work, the bottom panel of Fig. 4 illustrates the deviation with rigidity

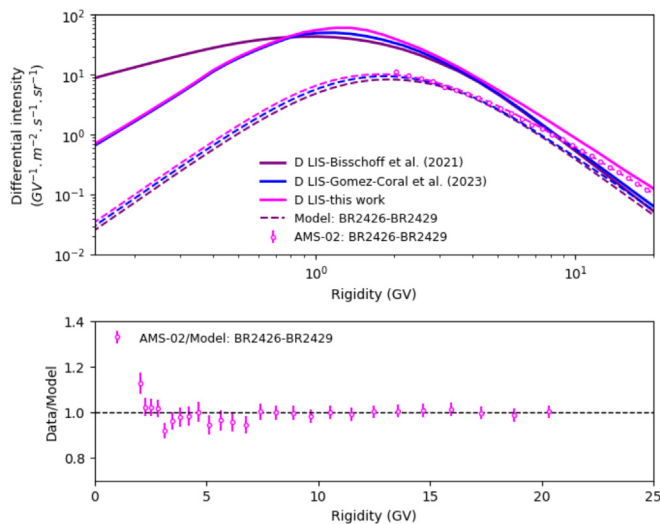


Fig. 4. Top panel: GALPROP calculated LISs for deuterons (D) obtained from Bisschoff et al. (2021) (purple solid line) and Gomez-Coral et. al (2023) (blue solid line) as a function of rigidity. Also shown as solid fuchsia line is the D LIS used in this work based on knowledge obtained from studying CR galactic H modulation in the heliosphere. The modulated spectra obtained using the three LISs are shown as dashed lines of the same colour at the Earth (1 AU); averaged for all BRs for the period BR2426 – BR2429. These modulated spectra are compared to the corresponding AMS-02 observations taken from Aguillar et al. (2024) (fuchsia open circles). Bottom panel: The ratio between the modulated spectra and AMS-02 observations (fuchsia open circles) for the preferred LIS used in this work. The parameters for the period BR2426 – BR2429 are given by Aslam et al. (2023).

between the modulated spectra obtained from the adjusted LIS and AMS-02 observations as a ratio. Clearly, the ratio is consistent with unity but with slight variations at the lower observed rigidities. The good reproduction of the observations at rigidities >6 GV indicates that the numerical modulation of D and its comparison with PAMELA and AMS-02 observations can be done using this LIS with improved confidence. This will further test the generality of

the set of modulation parameters, diffusion and drift coefficients previously used to study CR hydrogen and helium isotopes.

Fig. 5 shows the D LIS used in this work and the corresponding computed spectra as a function of both kinetic energy/nucleon (left panel) and rigidity (right panel) at the Earth. These computed spectra are compared to the corresponding PAMELA observations averaged over the period July 2006 to December 2007 (Adriani et al., 2016) and yearly averages over 2006 and 2007 (Lenni et al., 2025), thus focussing first on solar minimum modulation.

The modulated spectra depicted in Fig. 5 are in reasonably good agreement with the depicted set of observations at lower rigidities (energies) using the same set of modulation parameters validated by the galactic H observations over the period 2006 to 2007 (see Potgieter and Vos, 2017; Ngobeni et al., 2020). The overall good agreement between the numerical model and the PAMELA data is further highlighted in the bottom row of this figure by showing here the ratio of the data over the model. It is noted that the calculated ratios and their errors are consistent with unity both as a function of rigidity and kinetic energy/nucleon.

It is worth pointing out that the observation of galactic H made by both PAMELA and AMS02 was previously simply referred to as p (see Adriani et al., 2013; Martucci et al., 2018; Aguilar et al., 2018, 2021), with D completely overlooked. Prior to the recent publication of D observations from PAMELA and AMS02 detectors, Adriani et al. (2016) published simultaneously the isotopic separation between p and D at energy range from 0.1 to 1.1 GeV/nucleon for the period July 2006–Dec 2007. This presents an opportunity to use the available knowledge gained from studying the solar modulation of galactic H, and now also D, over the same period to simulate the solar modulation effects also on p separately. This is important to achieve the end result of this paper, which is the detailed

Table 1
The adjusted LIS as a function of kinetic energy/nucleon.

Kinetic energy ^a	Differential Intensity ^b	Kinetic energy ^a	Differential Intensity ^b
0.0610	195.0000	1.8350	10.5000
0.0788	215.0000	2.3850	6.0527
0.1024	226.4000	3.1010	3.3460
0.1331	224.2000	4.0310	1.8091
0.1730	215.7000	5.2400	0.9714
0.2249	195.3000	6.8120	0.4955
0.2924	166.1000	8.8560	0.2527
0.3801	127.7000	11.5100	0.1267
0.4941	93.3000	14.9700	0.0630
0.6424	66.5000	19.4600	0.0303
0.8351	43.1000	25.2900	0.0150
1.0860	27.9000	32.8800	7.2766e-3
1.4110	17.2000	34.5403	6.2564e-3

^a Kinetic energy Units: GeV/n.

^b Differential Intensity Units: $\text{GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

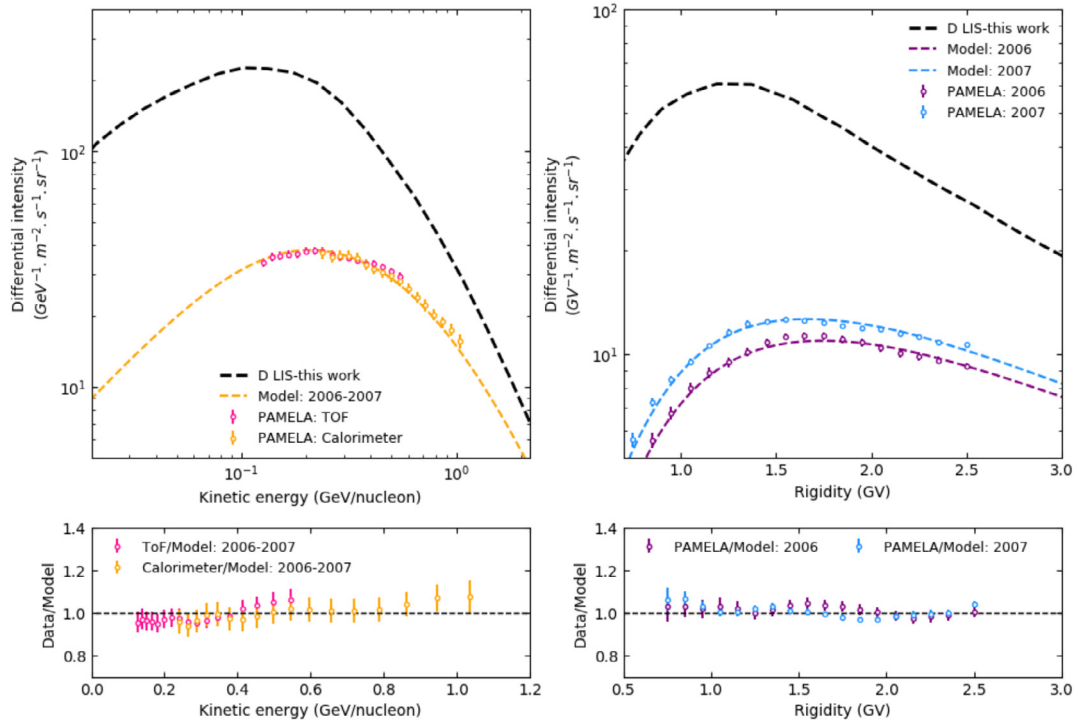


Fig. 5. Top row: The LIS for D used in this work (black dashed line) specified at the HP (122 AU) is shown together with the corresponding modulated differential intensities computed as a function of kinetic energy/nucleon (orange dashed line) and rigidity (dashed purple and blue lines) at the Earth (1 AU); averaged for all Carrington rotations for period July 2006–December 2007 (left) and yearly for 2006 and 2007 (right). The computed intensities are compared to the corresponding D observations from PAMELA with their errors taken from [Adriani et al. \(2016\)](#) using ToF (pink open circles) and calorimeter (orange open circles) detector systems and yearly D averages for 2006 (purple open circles) and 2007 (blue open circles) taken from [Lenni et al. \(2025\)](#). The bottom row shows the corresponding ratios between the modulated spectra and PAMELA observations as a function of both kinetic energy/nucleon and rigidity. The parameters for the period July 2006–December 2007 are given by [Ngobeni et al. \(2020\)](#).

reproduction of D/p ratios from 2006 to 2014 as a function of rigidity and time, displaying both qualitative and quantitative compatibility with the observed features from PAMELA. This requires that the LIS of p, as a specific input for numerical modelling, be known beforehand. In the next section the LIS of p is determined and related to the available PAMELA p observations as a function of kinetic energy at the Earth.

3.2. The p LIS

Voyager 1 & 2 observed *in situ* the spectrum of total galactic H in the interstellar medium ([Stone et al., 2013, 2019; Cummings et al., 2016](#)) in the kinetic energy range 3 MeV/nucleon to 346 MeV/nucleon, which is a combination of its two isotopes p and D. The LIS of galactic H is determined using the physics contained in galactic propagation models such as GALPROP (e.g., [Moskalenko et al., 2002; Boschini et al., 2017; Bisschoff et al., 2019](#)) and then tested and validated by reasonable compatibility with comprehensive 3D modulation models and observational constraints from Voyager 1&2, PAMELA and AMS-02 detectors (see [Bisschoff et al., 2019, 2021; Potgieter et al. 2021](#)).

The existing ideal scenario where PAMELA detector measured the intensities of p and D simultaneously over the same period provides an observational base crucial to studying modulation of cosmic H isotopes using available numerical models. The p LIS is shown in the left panel of [Fig. 6](#). For a self-consistent approach, the p LIS is derived by subtracting the D LIS depicted in [Fig. 5](#) from the GALPROP calculated galactic H LIS published by [Bisschoff et al. \(2019\)](#). The subsequent corresponding computed modulation averaged for all Carrington rotations for period July 2006 – December 2007 is compared to the corresponding PAMELA observations as a function of kinetic energy/nucleon, similarly to the left panel of [Fig. 5](#). In the right panel of [Fig. 6](#) the ratio of the modulated spectra D/p as a function of kinetic energy/nucleon is overlaid along with the corresponding PAMELA observations from the two detector systems taken from [Adriani et al. \(2016\)](#).

[Fig. 6](#) shows that D become much less abundant in galactic H the higher the kinetic energy and account for less than $\sim 1.7\%$ above 1 GeV/n for the period under consideration. The simulations in this figure reveal that the maximum value of D/p is about $\sim 4\%$ and occurs below 100 MeV/n corresponding to the kinetic energy where the adiabatic energy losses dominate the shape of the modu-

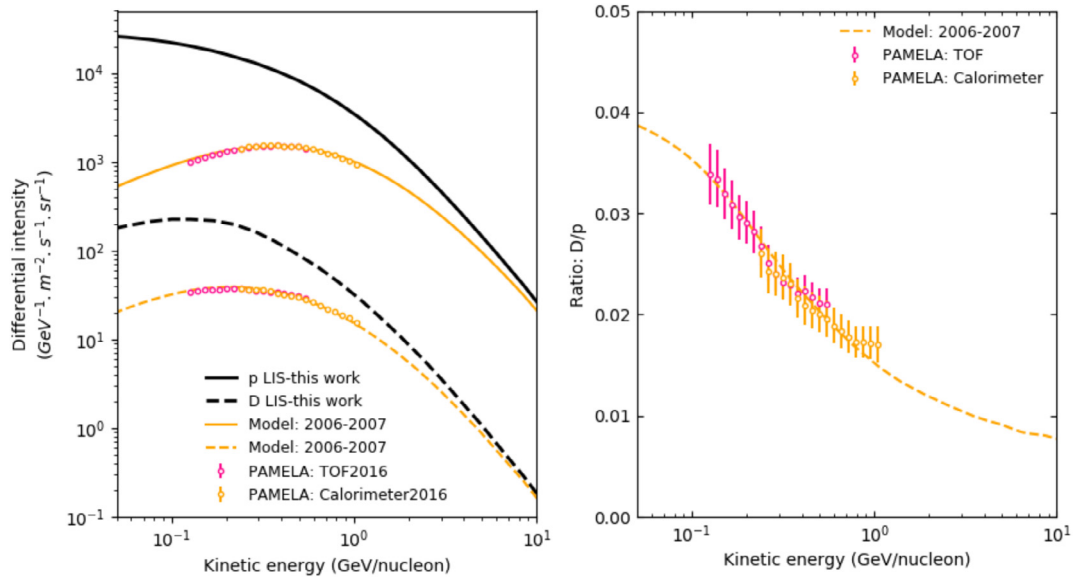


Fig. 6. Left panel: The LIS for p and D (solid and dashed black lines, respectively) specified at the HP are shown together with the corresponding modulated differential intensity (orange solid and dashed lines for p and D, respectively) computed as a function of kinetic energy per nucleon at the Earth; averaged for all Carrington rotations for periods July 2006–December 2007. Right panel: Corresponding ratios of the modulated spectra (orange dashed line). Computed spectra and ratios are compared to the corresponding p and D PAMELA observations with their error bars taken from [Adriani et al. \(2016\)](#) using ToF (pink open circles) and calorimeter (orange open circles) detector systems.

lated spectra. It is worth noting that at the same kinetic energy per nucleon, D has a rigidity that is twice that of p and experience somewhat less modulation. In this regard the modulation effects of the adiabatic energy loss process become evident at a higher energy per nucleon for p than D and the values of D/p presented in [Fig. 6](#) are expected to exhibit solar cycle related changes.

The agreement between the simulated p and D and PAMELA observations over kinetic energy range ~ 0.1 – 1 GeV/nucleon depicted in [Figs. 5 and 6](#) indicates that the solar modulation of these isotopes can be studied simultaneously over the same period. Furthermore, these results confirm our earlier conclusion ([Corti et al., 2019; Ngobeni et al., 2020, 2024](#)) that the modulation of H isotopes in the heliosphere differs from that of helium isotopes only in their LIS values and A/Z. The D and p LISs presented in [Figs. 5 and 6](#) are considered suitable for simulating solar modulation effects related to the observed D spectra and the corresponding D/p ratios as a function of rigidity and time by PAMELA from July 2006 to September 2014.

3.3. Solar modulation of D for 2006–2014

3.3.1. Observed and computed rigidity spectra

Together with high precision PAMELA and AMS-02 observations at the Earth, we previously reported on the simulation of the solar modulation of galactic H for a wide rigidity (energy) range and for every BR for the period extending from July 2006 to November 2019 (see [Aslam et al., 2023](#) and references therein). This period of study

spanned time frames that included solar maximum activity and the magnetic field reversal from the $A < 0$ to $A > 0$ cycle. Our main focus then was on finding model parameters, particularly the diffusion and drift tensors, that are consistent with existing theory and result in realistic galactic H modulation when compared to available observations. We now follow this up to report on the rigidity spectra for D by comparing our 3D modulation model computations and the PAMELA observations taken between July 2006 to September 2014, covering the transition from the 23rd solar minimum to the maximum activity of the 24th solar cycle as reported by [Lenni et al. \(2025\)](#). These measurements were taken at rigidities 0.75 GV to 2.5 GV and reveal distinct features in the solar modulation of D at lower rigidities.

As underscored in our previous studies ([Corti et al., 2019; Ngobeni et al., 2020; Potgieter et al., 2021](#)), the modulation processes between the HP and the Earth for galactic H and its isotopes are essentially similar, except for differences because of their LISs and A/Z. See also [Tomassetti et al. \(2019\)](#). To improve our understanding of the modulation of D, the TPE was solved for each Carrington rotation and averaged for each corresponding year for comparison with the PAMELA yearly spectra. The simulations were performed using the calculated average values of the HCS tilt and the HMF magnitude at the Earth shown in [Fig. 1](#), together with appropriate adjustments to the diffusion and drift coefficients exactly as done before ([Aslam et al., 2023](#)).

[Fig. 7](#) depicts the yearly averaged computed modulated spectra for D as a function of rigidity for the period from

2006 to 2014 in comparison with the corresponding PAMELA and selected AMS-02 spectra at the Earth. The modulated spectra were obtained with the newly constructed LIS shown in Figs. 4 and 5 as the input spectra at the HP. This figure illustrates the main features and characteristics of the effects of solar modulation on D spectra for an extended rigidity range, including also rigidities where observational data in not available. Evidently, these features are reproduced reasonably well by the numerical model.

Notable in Fig. 7 is the characteristic peak value in the rigidity spectra for each year depicted, and that these modulated peak values gradually decrease with increasing solar activity while shifting to higher rigidity values. For example, during the period 2006 – 2009 the whole heliosphere was in a state of almost perfect solar minimum conditions and the peak value for D intensities shifted downwards

from a rigidity of ~ 1.6 GV in 2006 to ~ 1.3 GV in 2009. Thereafter solar activity started increasing and this peak value shifted upwards to ~ 1.8 GV around 2013–2014 during solar maximum conditions. The rigidities where these peak values occur in the modulated spectra are important because they give insight into the changing interplay between drifts and diffusion with rigidity. For example, as drifts are phased out and the modulation process increasingly become diffusion dominated with increasing solar activity, the peak value shift to higher rigidities. We consider the shifting in the spectral peaks in the modulated intensities to be indicative of a general solar modulation pattern at least for all GCRs nuclei. See also a discussion of the spectral peaks of the two helium isotopes by Ngobeni et al. (2022). In what follows, the modulation of p is illustrated at the Earth.

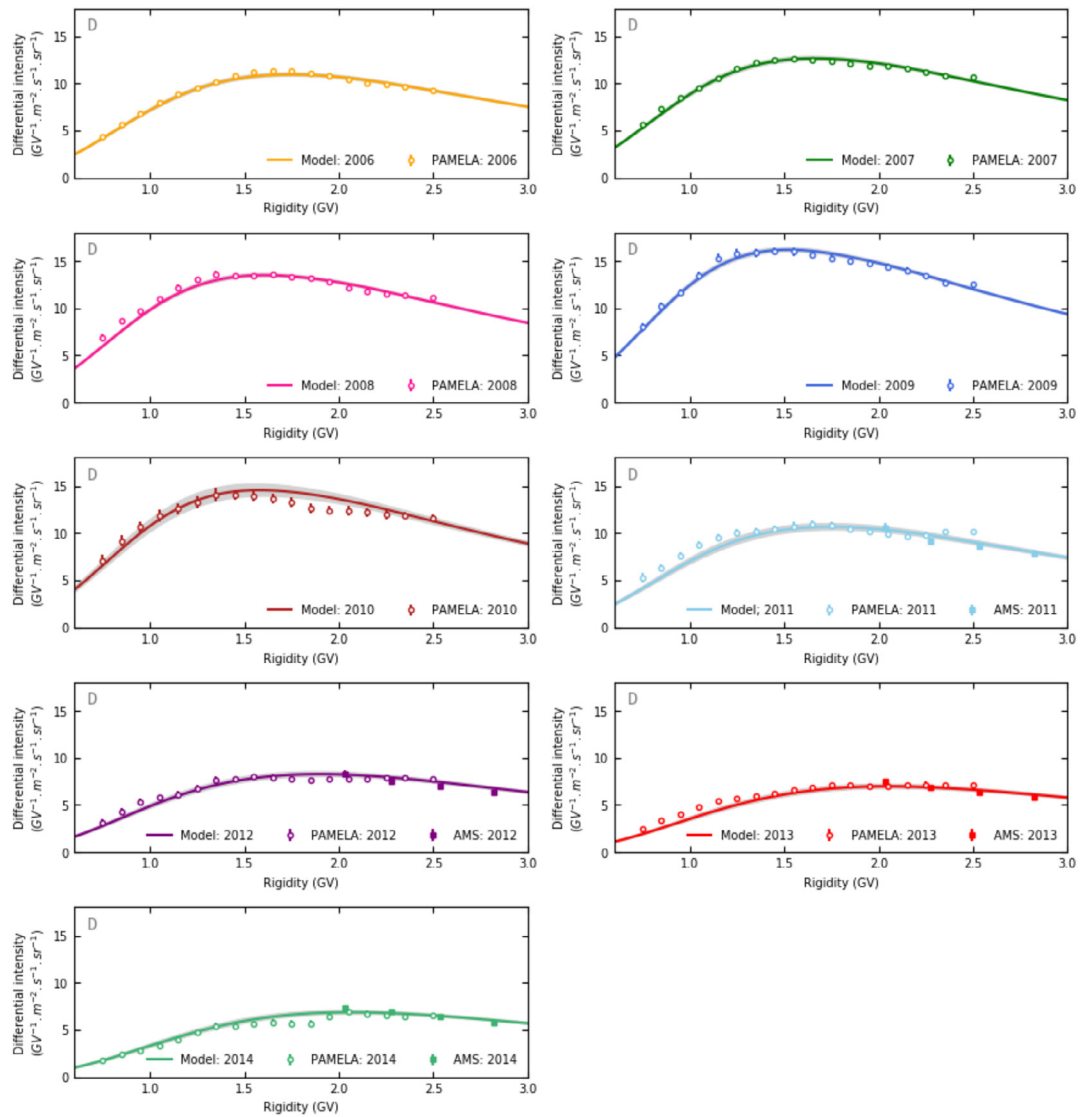


Fig. 7. Observed yearly averaged D spectra from PAMELA (coloured open circles) and AMS-02 (coloured filled squares) overlaid by the corresponding computed spectra (coloured solid lines) as a function of rigidity at the Earth shown for the period 2006 to 2014. The PAMELA and AMS-02 observations with their errors are taken from Lenni et al. (2025) and Aguilar et al. (2024), respectively. The grey bend over the modulated intensities indicates the standard error of the mean (standard deviation/ $\sqrt{n}$).

The PAMELA p spectra averaged for every year from 2006 to 2014 are shown in Fig. 8 compared to the corresponding computed modulated spectra obtained with the LIS shown in Fig. 6. The modulated spectra were computed using the same modelling approach as done for D. Whereas the p data points were obtained by averaging the published PAMELA H intensities (Adriani et al., 2013; Martucci et al., 2018) and subtracting the D PAMELA observation shown in Fig. 7. The motivation for this approach in constructing p spectra is given by Lenni et al. (2025).

As would be expected, p and D respond in a similar way to the effects of the 11-year solar modulation. The two isotopes both exhibit gradual shift in the maximum intensity values from higher to lower rigidities from 2006 to 2009 and then followed by a shift to higher rigidity values towards solar maximum. Overall, the model results presented in Figs. 7 and 8 are in good agreement with the D and p PAMELA data published by Lenni et al. (2025)

for the entire data collection period between July 2006 and September 2014.

In the next section the time dependence of the solar modulation of p and D is illustrated.

3.3.2. Time dependence of D

The solid lines in Fig. 9 depict the computed Carrington rotation averaged D intensities at rigidities 0.75 GV (purple), 1.05 GV (fuchsia) and 2.5 GV (aqua) as a function of time together with the corresponding yearly averaged PAMELA data (Lenni et al., 2025) for the period July 2006 to September 2014. The PAMELA data is indicated as open circles of the corresponding colour with error bars. From July 2006, the computed D intensities increased significantly at all rigidities until the end of 2009 consistent with PAMELA observations. This was in response to the declining levels of solar activity during this period, which relatively affected D intensities differently depending on rigidity. The D intensities reached maximum values at the

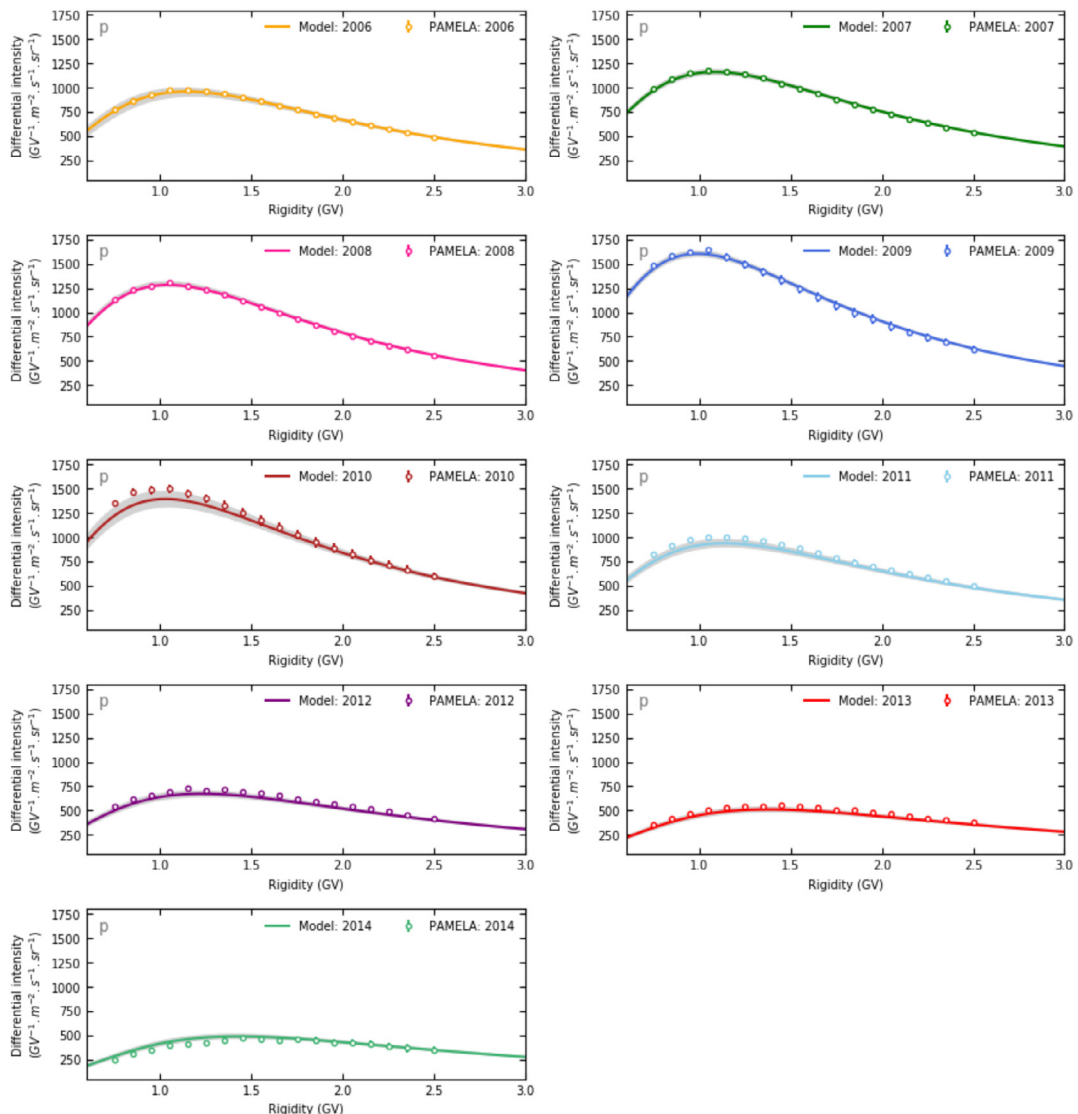


Fig. 8. Similar to Fig. 7 but shown for p modulated spectra and PAMELA observations.

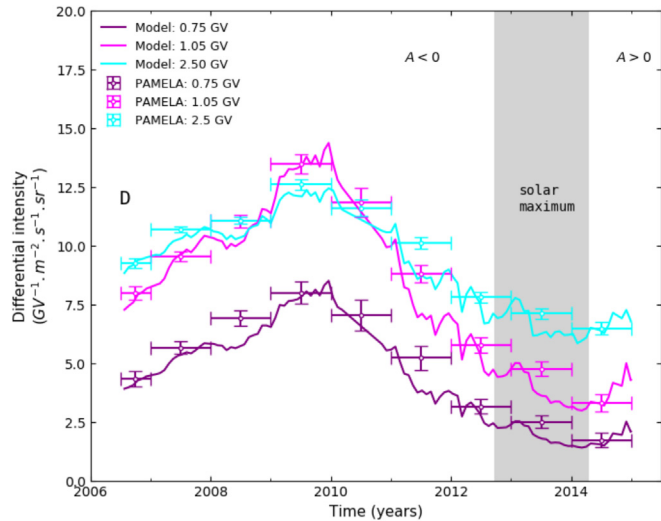


Fig. 9. The computed modulated differential intensity of D at three selected rigidities 0.75 GV (purple solid line), 1.05 GV (fuchsia solid line) and 2.5 GV (aqua solid line) as a function of time from July 2006 to September 2014, in comparison with the corresponding yearly averaged PAMELA observations (coloured open circles) obtained from [Lenni et al. \(2025\)](#). Also indicated is the $A < 0$ and $A > 0$ HMF polarity epochs before and after the period of maximum solar activity and when no well-defined HMF polarity was present (grey shaded band).

end of 2009 and thereafter decreased to their minimum values around 2013–2014 during solar maximum conditions. Comparison of the computed intensities at rigidities 1.05 GV and 2.5 GV in [Fig. 9](#) reveal that the rate of increase (decrease) towards minimum (maximum) conditions is faster at lower rigidities than higher rigidities. This is quite interesting because it implies that at rigidities of 0.75 GV and 1.05 GV the intensities will recover later than at 2.5 GV when solar activity begins to decline (see e.g. [le Roux and Potgieter, 1992](#)). Overall, the computed intensities reproduce time trends that are reasonably within the error bars of the PAMELA observations.

It is worth pointing out that compatibility between the model and observations gives an indication as to the time dependence of the diffusion and drift coefficients around the Earth. Therefore, reproducing the time dependence of the observed modulation of D, as done in this study, in addition to that of GCR p, ^4He and ^3He shown in [Ngobeni et al. \(2022\)](#) and [Aslam et al. \(2023\)](#), with the same set of model parameters becomes a handy tool for determining the eagerly pursued heliospheric diffusion tensor.

[Fig. 10](#) display the computed time-trend in the modulation of p spectra at rigidities of 0.75 GV, 1.05 GV and 2.5 GV, compared with the corresponding constructed PAMELA intensities within their errors. This figure, taken together with [Fig. 9](#), shows that the computed intensities of p and D are consistent with observations.

[Fig. 11](#) highlights how the computed intensities for both p and D evolved as a function of time relative to 2006. It follows from this figure that for the displayed time scale the computed D and p intensities show nearly identical, but not exact, time dependences and relative variations in

amplitude. At rigidities below ~ 1.0 GV, the computed intensities of p changed more than that of D relative to 2006. Whereas above this rigidity, specifically below 5 GV, D intensities changed more than p intensities. This is the consequence of differences in the slopes of their LISs and A/Z . Consequently, D/p ratios are expected to display interesting time dependences at lower rigidities that differ from those at higher rigidities. This is pursued next.

3.4. The computed D/p ratios related to PAMELA observations

The essence of [Figs. 8 and 10](#), which display computed p intensities together with the corresponding constructed

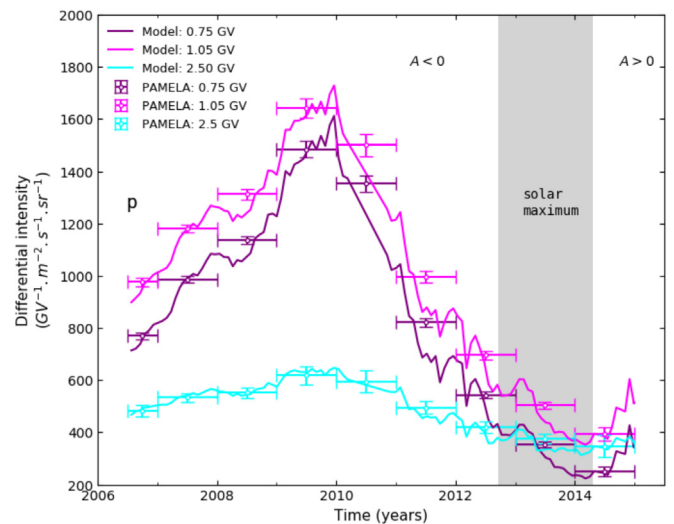


Fig. 10. Similar to [Fig. 9](#) but now shown for p compared to the yearly average constructed PAMELA data from 2006 to 2014.

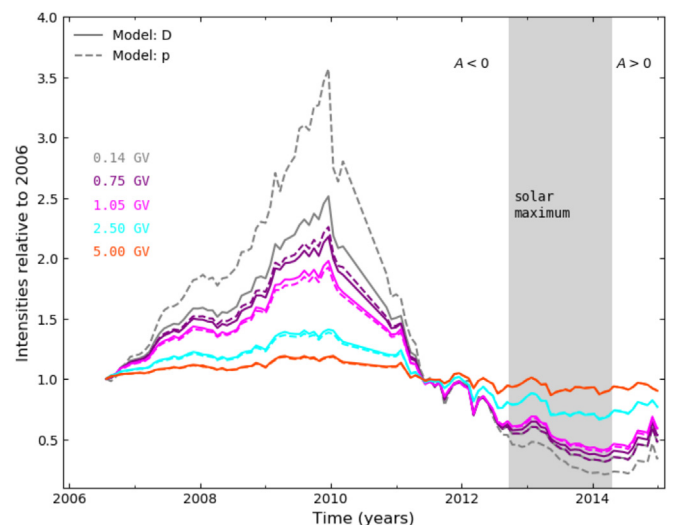


Fig. 11. Computed D and p intensities as a function of time relative to 2006 at rigidities ranging from 0.14 GV to 5.0 GV. The shaded band is similar to that in [Fig. 9](#).

spectra from PAMELA, is to show that these computed spectra can be utilized to simulate quantitatively the time trends in D/p over a wide range of rigidity values. This is important because more insight can be gained from D/p ratios related to PAMELA observations between 2006 and 2014 using numerical modelling, which could not be satisfactorily done without illustrating the solar modulation of p at matching rigidities.

Fig. 12 shows the computed D/p and those from PAMELA as a function of rigidity averaged for each year for the period between 2006 and 2014. The value and shape of D/p are reproduced quite well at the shown rigidities for the period between 2006 and 2009, but less so afterwards due to increasing systematic errors in the data also discussed in Lenni et al. (2025). It can be seen in this figure that below ~ 3 GV the D/p ratio increases with increasing

rigidity in each year shown. This is interesting because at these low rigidities the effects due to A/Z become increasingly noteworthy and the time dependence of D/p should give insight into the rigidity value where this start to be noticeable. At rigidities above ~ 13 GV, the D/p ratio has been observed by AMS-02 to flatten off with increasing rigidity (Aguilar et al., 2024). At these high rigidities the dependence of diffusion and drift coefficients on A/Z is smeared out so that the observed D/p ratio at Earth should be representative of the ratio in the interstellar medium. When the p intensities from AMS-02 are finally made public for every BR this will indeed provide new constraints in studying the solar modulation of D with a numerical model. This is so because information about the features of D/p will become available for every BR at rigidities above 3 GV.

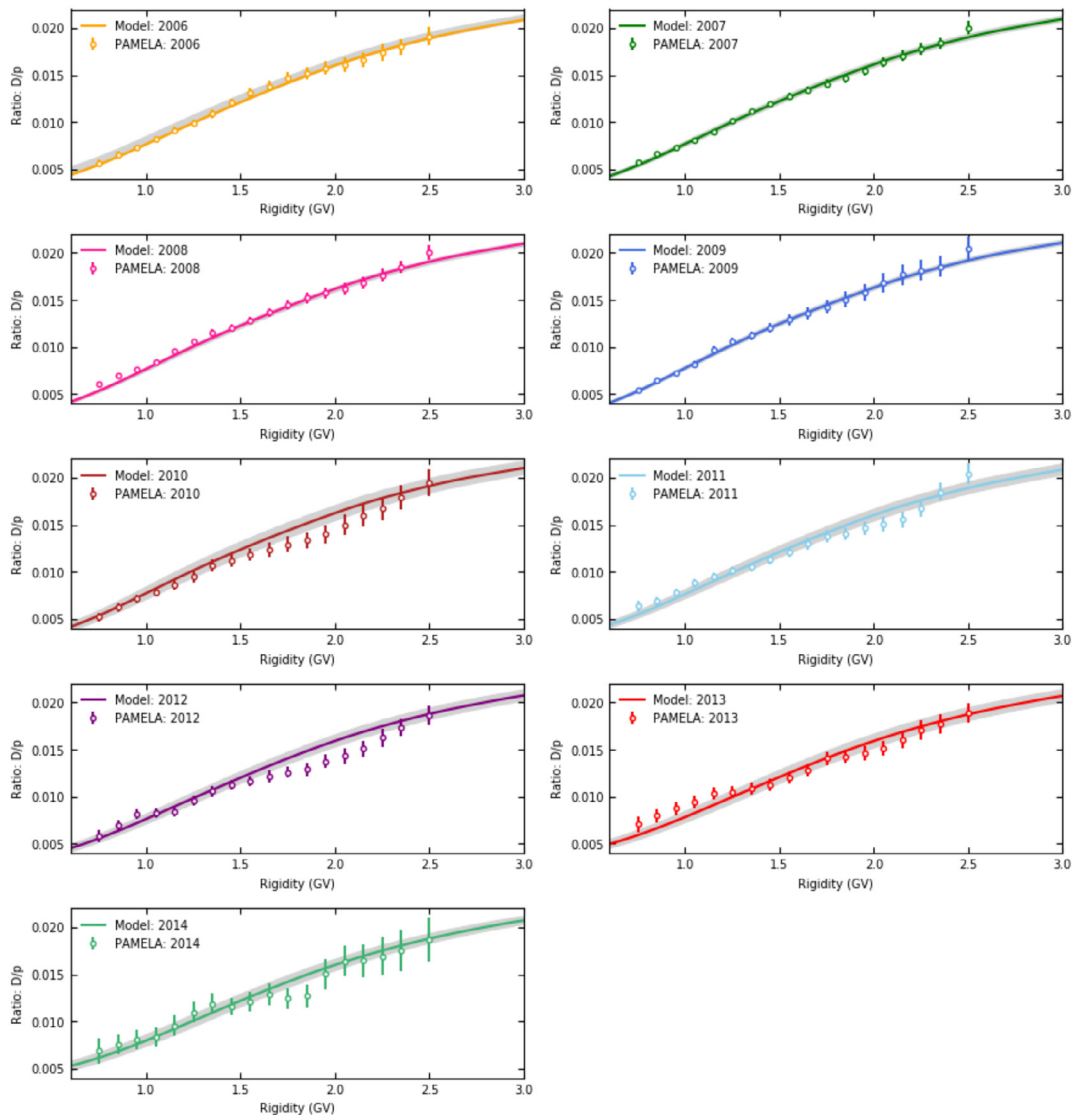


Fig. 12. The D/p ratios as a function of rigidity averaged for each year between 2006 and 2014. Computed and PAMELA observed ratios are represented by the coloured lines and open circles, respectively. The PAMELA observations with their errors are taken from Lenni et al. (2025). The grey bend over the computed ratios in each panel indicates the standard error of the mean (standard deviation/ $\sqrt{n}$).

The computed and PAMELA observed D/p are depicted together in Fig. 13 as a function of time at rigidities 0.75 GV, 1.05 GV and 2.5 GV. The computed ratio at 0.75 GV reached its minimum value at the end of 2009 when solar activity was at its lowest and then increased to its maximum value toward the end of 2013 during solar maximum conditions, consistent with PAMELA observations. In contrast, the computed and observed D/p ratios at 2.5 GV reached maximum values at the end of 2009 and thereafter decreased as solar activity increased indicating a clear different time dependence than at lower rigidities. However, at 1.05 GV the competing modulation mechanisms related to changing solar activity cause the time dependence of the D/p ratio to exhibit similarities with that at 0.75 GV (2.5 GV) for period 2012–2014 (2006–2012), indicating that the transition in rigidity occurs at ~ 1.05 GV. The computed D/p ratios reasonably follow the observed trends in the PAMELA ratios.

Another interesting aspect, which forms part of what is discussed in this paper, is to uncover the extent of the time variation of D/p ratio with a numerical model at rigidities where there are no available PAMELA observations. This is illustrated in Fig. 14 by showing the computed D/p at five selected rigidity values below 0.75 GV, whereas Fig. 15 shows the computed ratios at six rigidity values above 2.5 GV. This approach somewhat completes the general pattern of the time variation of the computed D/p ratio over a solar cycle. Below 0.75 GV, the D/p ratio shows a clear minimum value at solar minimum and a clear maximum at solar maximum modulation conditions at all five rigidity values. In contrast, above 2.5 GV the trend is

not as prominent as at lower rigidities and the maximum values are noted to occur during solar minimum conditions. However, above 4 GV, the computed temporal variation in D/p is sufficiently small to be considered observationally significant. The bottom line is that the computed time variation in D/p is more prominent at lower rigidities where solar modulation is significant.

4. Summary and conclusions

The objective of this study was to simulate and explain the observed D spectra from the PAMELA detector taken from July 2006 to September 2014, together with the corresponding D/p ratios as a function of rigidity and time. This was done by applying the 3D drift numerical model to compute the spectra of D and p over this period. However, new constraints from the recent AMS-02 observations required that the D LIS must first be revisited. For this purpose, the previously established set of modulation parameters that reproduced AMS-02 galactic H observations for the period BR2426–BR2429 taken from Aslam et al. (2023) was applied in the model to simulate modulated D spectra over the same period. The computations were repeated using two available GALPROP scenarios of D LISs, one from Bisschoff et al. (2021) as the higher option at $P < 0.8$ GV, and the latest one as the lower option from Gomez-Coral et al. (2023) and compared the modulated spectra with the corresponding AMS-02 observations. We found that AMS-02 observations are higher than the modulated spectra obtained from the two GALPROP LISs at $P > 5$ GV. In fact, AMS02 observations

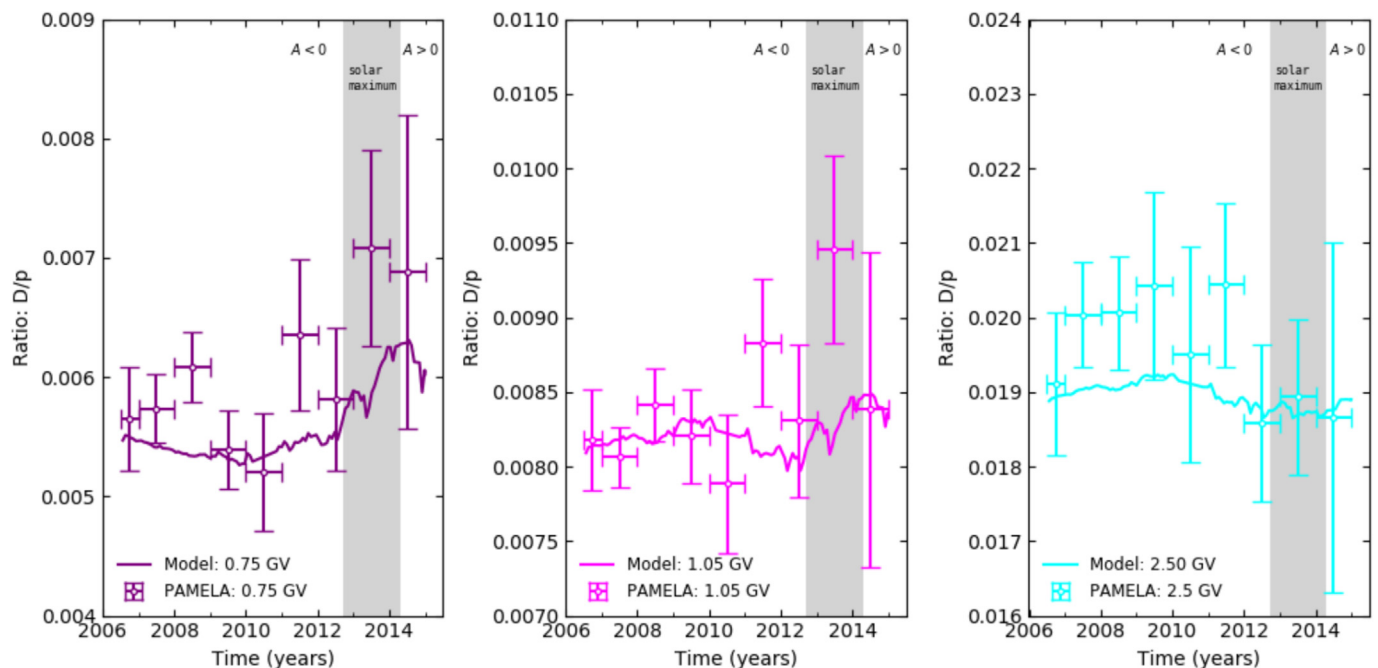


Fig. 13. The computed D/p ratios (coloured solid lines) at three selected rigidities, between 0.75 GV and 2.5 GV, in comparison with the corresponding PAMELA observation (coloured open circles with their errors) as a function of time. The PAMELA observations are taken from Lenni et al. (2025). The shaded band is similar to that in Fig. 9.

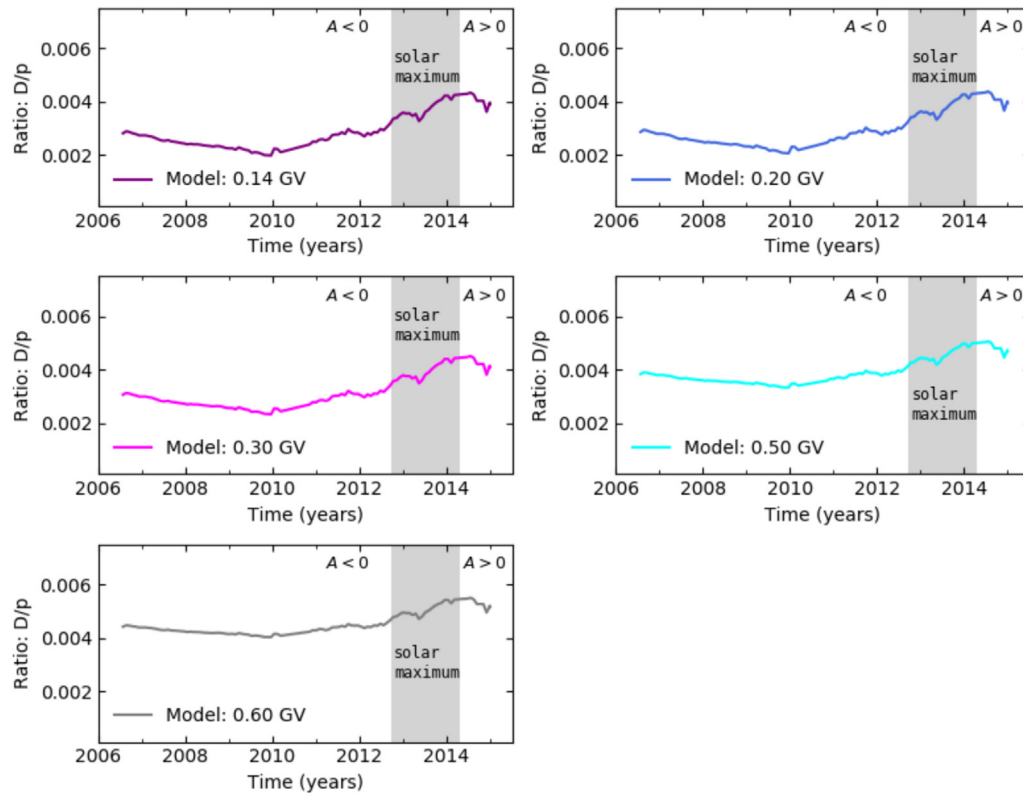


Fig. 14. The Computed D/p from the modulation model as a function of time at five selected rigidity values between 0.14 GV and 0.6 GV. The shaded band is similar to that in Fig. 9.

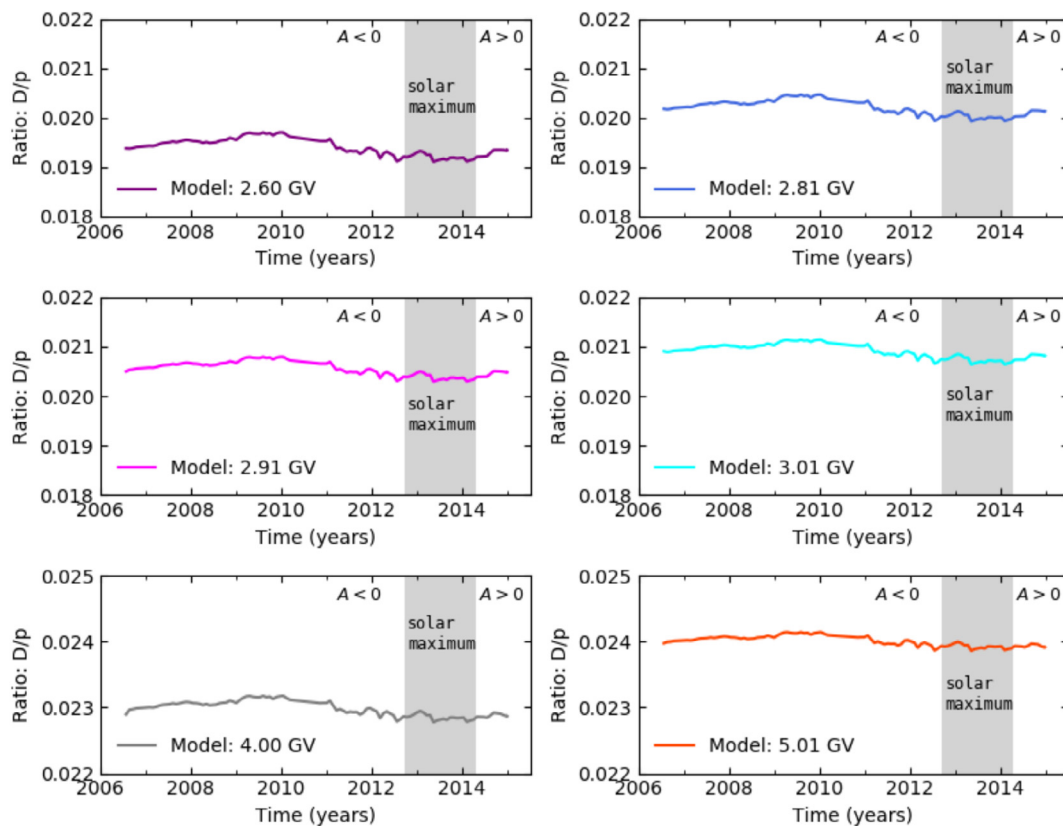


Fig. 15. Similar to Fig. 14 but shown at six rigidity values between 2.6 GV and 5 GV.

are even higher than these GALPROP LISs at $P > 10$ GV indicating that these discrepancies emanate largely from the shape of these LISs and not from parameters related to diffusion and drift inside the heliosphere. Based on these results the Gomez-Coral et al. (2023) LIS was adjusted at $P > 0.8$ GV to establish compatibility with AMS-02 observations. For a self-consistent approach, the p LIS was simply derived by subtracting the newly established D LIS from the GALPROP calculated galactic H LIS published by Bisschoff et al. (2019). At this stage these LISs result in modulated spectra for D and p that are consistent with PAMELA and AMS-02 observations (Figs. 4–8).

The established LISs of D and p were used as input spectra in the model specified at the HP (~ 122 AU) to simulate the effects of solar modulation on these isotopes from 2006 to 2014, using the same established set of modulation parameters that were previously applied for galactic H over the same period, with the only differences being their corresponding LISs and A/Z. The modulation differences between D and p over a wide rigidity range were also computed as ratios, which clearly illustrate this aspect more than what can be deduced from spectral behaviour alone. The modelling results were compared with the corresponding PAMELA observations as a function of rigidity and time. We find that the 3D drift model reproduces PAMELA measurements of D and p over kinetic energy range of 0.1–1.1 GeV/nucleon and rigidity range of 0.75–2.5 GV reasonably well both as a function of rigidity (energy) and time. This agreement between the model and the simultaneous observations of D and p, in addition to that of the two helium isotopes previously studied (Ngobeni et al., 2022) with the same model parameters, indicates that the understanding of the mechanisms responsible for the modulation of all GCR nuclei around the Earth is in good shape. The results displayed in Figs. 13–15 illustrate that the time variation in D/p is more prominent at rigidities below 1 GV where solar modulation is significant. The qualitative behaviour of the time dependence of D/p is found to be different below 1 GV than at higher rigidities. For example, the computed and observed D/p ratio shows a clear minimum value at solar minimum and a clear maximum at solar maximum modulation conditions below 1 GV. Whereas above this rigidity, but below 5 GV, the time variation is less prominent and somewhat reversed with the minimum values coinciding with solar maximum conditions and maximum values with minimum conditions. Above 4 GV the time dependence in D/p is smeared out from solar minimum to maximum conditions. Therefore, the differences between D and p modulation effects below 1 GV are found to be the consequence of the dominating interplay between diffusion and adiabatic energy losses. Increasing diffusion from July 2006 until December 2009 caused the p spectra to become softer than the D spectra, indicating that more low rigidity protons had reached Earth than deuterons. Consequently, the D/p ratio at rigidities below 1 GV decreased over this period. Scaling down diffusion with increasing solar activity caused

the effects of adiabatic energy losses to become increasingly dominant below 1 GV. This caused the p spectra to be harder than the D spectra based on the shape of their LISs. As a result, p spectra decreased more than D spectra at these rigidities from the end of 2009 till the end of the solar maximum activity. Consequently, the D/p ratio increased in line with increasing levels of solar activity at these low rigidities. It suffices to conclude that the insight gained from PAMELA observations of D and p below 1 GV combined with numerical modelling is that increasing (decreasing) diffusion at these rigidities cause p intensity to increase (decrease) more than D intensities. To simulate these effects in the numerical model the ratio $\lambda_A/\lambda_{\parallel}$ had to have significant time dependence at all rigidities, more so between 2010 and 2014. While on the other hand the ratio $\lambda_{\perp r}/\lambda_{\parallel}$ had to be independent of time over the same period for $P < 5$ GV.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

MDN thanks the SA National Research Foundation (NRF) for partial financial support under Italy and SA Joint Research Programme (Grant no: 150556). He also acknowledges that the opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the authors alone, and that the NRF accepts no liability whatsoever in this regard.

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