

Cosmic ray propagation in the galaxy and the heliosphere

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Abstract

The local interstellar spectra (LIS's) for cosmic rays (CRs) are still not fully determined over all energy ranges. Numerical modelling, such as with the GALPROP code, can be used to calculate LIS's for a wide set of CR species. At low energies the LIS's need to match the Voyager 1 (V1) observations made beyond the heliopause, while at higher energies very precise CR spectra are observed at the Earth by experiments such as PAMELA. To directly compare the observations at the Earth to the calculated LIS's below at least 20 GeV, a comprehensive 3D modulation code is required to calculate the effect of solar modulation. This study uniquely aimed to implement the above numerical models and observations to produce LIS's for electrons, positrons and protons simultaneously, while also considering CR Helium, Carbon, Boron and Oxygen. With the plain diffusion model of the GALPROP propagation code, LIS's were calculated to match the two reported V1 electron spectra. Similarly the proton and Helium observations were matched, but Carbon and B/C observations necessitated the use of the GALPROP reacceleration model. With the reacceleration model the observed spectra could be matched, while also reproducing the B/C ratio much better than the plain diffusion model. The LIS's were all tested against the corresponding observations at Earth by using the 3D modulation code. The positron LIS was investigated, but the LIS's corresponding to the electron and proton results were not promising, neither for the GALPROP plain diffusion nor reacceleration models. To improve the positron LIS and the e^+/e^- ratio, while also taking into account electron and proton LIS's, a single model was explored as positrons are secondary products related to nuclei, but propagate similarly to electrons. The initial tests did not improve the positron LIS as intended and as such a GALPROP reacceleration model that also includes convection, was tested by systematically adjusting the source and diffusion parameters. This resulted in the calculated electron LIS and the e^+/e^- ratio both matching the observations well. With this model LIS's for electrons, positrons, protons, Helium, Carbon, Boron and Oxygen could all be calculated and shown to match the relevant observations well. A GALPROP plain diffusion model was sufficient when studying electrons, protons and Helium LIS's separately, but including Carbon, the B/C ratio and positrons into the study, the constraints placed on the LIS's by observations necessitate the use of a reacceleration model and ultimately the inclusion of convection. The inclusion of positrons proved the greatest challenge, indication that GALPROP in general is not yet optimally suited to calculate positron LIS's, which may be the case for all secondary CR particles.

Keywords: Cosmic rays, local interstellar spectra, cosmic ray propagation, solar modulation, numerical modelling.

Nomenclature

Listed are the acronyms used in the text. For the purpose of clarity, the acronym is written out in full when it appears for the first time in the text.

2D	two-dimensional
3D	three-dimensional
AU	astronomical unit
CR	cosmic ray
CRs	cosmic rays
HMF	heliospheric magnetic field
ISM	interstellar stellar medium
LIS	local interstellar spectrum
LIS's	local interstellar spectra
MFP	mean free path
MFPs	mean free paths
Pldff	plain diffusion
Reacc	reacceleration
SNRs	supernova remnants
V1	Voyager 1

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Chapter 1

Introduction

The spectra of cosmic rays (CRs) from the Galaxy, entering the heliosphere and arriving at the Earth are still not fully known. While CRs can be observed at the Earth, the effect of solar modulation in the heliosphere causes the spectra to differ from the local interstellar spectra (LIS's) up to as high as 50 GeV (Strauss and Potgieter, 2014). To investigate solar modulation, heliospheric studies use the LIS's as input for numerical modelling. Conversely, in order to effectively test the output LIS's of galactic propagation models, solar modulation needs to be understood. This interplay between astrophysical and heliophysical studies has resulted in various LIS's being calculated and estimated over the years. The various LIS's have been restricted and tested by means of observational data inside the heliosphere, but with the Voyager 1 (V1) spacecraft crossing the heliopause in August 2012, observations are now available that are not limited by the effects of modulation.

These measurements made by V1 for galactic electrons, protons, Helium, Carbon and Oxygen allow the comparison of computed galactic spectra (that is to say, LIS's) with experimental data down to very low energies (a few MeV/nuc) (Stone et al., 2013; Webber and McDonald, 2013). Taking into account high energy observations made in low earth orbit by PAMELA (Adriani et al., 2011a,b, 2014; Menn et al., 2013; Boezio, 2014), improved estimations of the LIS's over a very wide range of energies can now be made.

To calculate these LIS's, a comprehensive galactic propagation model, such as the GALPROP code (Moskalenko and Strong, 1998; Strong and Moskalenko, 1998; Ptuskin et al., 2006; Strong et al., 2007; Moskalenko, 2011, 2013) can be used. The LIS's can directly be compared to the V1 spectra, but for the Earth observations, modulation still needs to be considered. For this a comprehensive three-dimensional (3D) modulation model (Potgieter and Vos, 2017) can be used. This coordinated use of the two models, a galactic propagation model and a 3D modulation model, and the CR observations, made beyond the heliopause and very precisely by PAMELA at the Earth, has not yet been done as is uniquely aimed for in this study.

Starting with the simplest GALPROP model, the plain diffusion model, LIS's will be calculated for electrons, then for CR protons and nuclei. Evaluating these LIS's against the relevant

observations will determine the viability of the plain diffusion model. Similarly the GALPROP reacceleration model can be tested. With LIS's for electrons and protons determined separately, the corresponding positron LIS's can be compared to the latest PAMELA observations at the Earth. This will help determine which modelling approach will be best suited in order to find a single model with which to calculate LIS's for all the relevant CR species simultaneously.

This study starts by giving an overview of the basic features of CRs and the processes relevant to their propagation through the Galaxy are briefly highlighted in **Chapter 2**. The numerical modelling of CR propagation, as well as its implementation via the GALPROP code, are also discussed.

In **Chapter 3**, a brief overview of the heliosphere and solar modulation is given. The relevant transport equation is shown and its implementation into a comprehensive 3D modulation model is discussed. This model includes particle drifts and is used to calculate CR spectra at the Earth in later chapters

The GALPROP plain diffusion model is used in **Chapter 4** to calculate electron LIS's. The source spectrum and diffusion parameters in the model are systematically adjusted and the resulting electron LIS's compared to the V1 observations in order to reproduce the two reported spectra, which differ due to the different analyzing procedures used.

Similarly in **Chapter 5**, LIS's for protons, Helium and Carbon are calculated with the plain diffusion model. The resulting LIS's and B/C ratio are compared to the V1 and PAMELA observations. The GALPROP reacceleration model is consequently implemented to improve on the plain diffusion results.

With LIS's for electrons, protons, Helium and Carbon calculated, the 3D modulation model is used in **Chapter 6** to further test the LIS's against the observations at the Earth. The GALPROP reacceleration model is also used to improve on the previous electron LIS's. Also shown are initial tests for positron LIS's, corresponding to the models used for electrons and protons.

To produce a viable positron LIS, a single galactic propagation model is searched for and tested in **Chapter 7** which can calculate electrons, positrons and protons simultaneously. The effect of reacceleration is tested and adjusted in the model, while convection is also tested and added to the model. Systematic adjustments to the GALPROP model parameters are made in order to converge on the desired model. The resulting LIS's for electrons, positrons and protons are shown.

In **Chapter 8** the GALPROP model found in the previous chapter is applied to all the relevant CR species. The LIS's for electrons, positrons, protons, Helium, Carbon, Boron and Oxygen are shown, as well as their corresponding modulated spectra at the Earth, using the mentioned 3D modulation model.

This study and its conclusions are summarized in **Chapter 9**.

Aspects of this study have been published by Bisschoff and Potgieter (2014), Bisschoff and Potgieter (2016) and Potgieter et al. (2017).

Chapter 2

Cosmic rays from the Galaxy

2.1 Introduction

CRs are invaluable for astrophysical studies pertaining to the Galaxy and the heliosphere. As CRs can directly be sampled, they serve as a probe for the physical processes of the Galaxy and interstellar space, supplementing other astronomical observations. The details of observed CRs, such as composition and spectral shape, can give information on the energetic particle sources and acceleration, as well as other global galactic properties (Moskalenko, 2013).

The propagation of CRs through the Galaxy can be numerically modelled. The GALPROP code is such a numerical tool, calculating the propagation of CR particles from the sources in the Galaxy, through the interstellar medium (ISM), to output CR spectra near the heliosphere (Strong et al., 2007). These spectra can then be compared to observations made by the V1 spacecraft, now situated beyond the heliosphere (Cummings et al., 2016), and high energy CR observations made at the Earth. For lower energies observations at the Earth, modulation in the heliosphere needs to be taken into account first.

This chapter gives an overview of the basic features of CRs and the relevant processes affecting their propagation through the Galaxy. The modelling of CR propagation, as well as its implementation via the GALPROP code, are also discussed. The matter of modulation of CRs in the heliosphere, and the modelling thereof will be discussed in the next chapter.

2.2 Background on cosmic rays and the Galaxy

2.2.1 Cosmic rays

CRs are energetic charged particles that are accelerated at their sources, from where they propagate through the Galaxy and the heliosphere, to arrive at the Earth. The existence of CRs were first demonstrated by Victor Hess during manned balloon flights in 1911 and 1912, in which

it was shown that an increase in altitude leads to an increase in ionizing radiation. However, the exact nature of CRs was not discovered until decades later, when it was found that CRs consist of protons, fully ionized nuclei, electrons and antiparticles. In general CRs are relativistic, having energies of between a few MeV to up to about 10^{20} eV. CRs originate mainly in the Galaxy, some in the heliosphere, but for CRs of very high energies, extragalactic origins are likely (Berezinskii et al., 1990). Those CRs accelerated in the heliosphere (anomalous CRs, Jovian electrons) or those originating from solar flares and coronal mass ejections (solar energetic particles) are not considered here. Of interest to this study are galactic CRs, so termed for their original acceleration in the Galaxy, which will be referred to here only as CRs.

2.2.2 Cosmic ray sources and abundances

The initial acceleration of CRs occurs at their sources in the Galaxy. As CRs are isotropized by the galactic magnetic field during propagation to the Earth, the arrival directions of CRs don't point back to their points of acceleration, and the corresponding CRs sources can't be observed directly. Supernova remnants (SNRs) are considered the main source of CRs in the Galaxy. Supernova explosions eject stellar matter at high velocities, giving rise to the formation of SNRs. SNRs satisfy the energy requirements for the steady power needed to sustain the observed density of CRs, they can also account for the power-law energy spectra that is observed for all CR species. Supernova blast wave shocks are formed when the expansion of SNRs interacts with the ISM. CRs traveling repeatedly across the shock waves are accelerated to high energies through the process of Fermi I acceleration, which produces power-law spectra for CRs. The size and age of SNRs are also sufficient to accelerate particles to the required high energies (Berezinskii et al., 1990).

These CRs that originate at their points of acceleration are termed primary CRs. As CRs propagate through the Galaxy, the heavier CR nuclei collide with interstellar matter and result in the expulsion of nucleons and other charged particles. These fragmentation products, produced as result of the spallation of primary CRs, continue to propagate and are termed secondary CRs. CR species such as protons are dominated by their primary component, while certain CR species, such as positrons, are assumed to consist of only of a secondary component (Schlickeiser, 2002).

The nature of the CRs sources leads to the relative abundances differing between CR species, with protons dominating at most energies. Of the total CR flux arriving at Earth, about 98% are protons and nuclei, while about 2% are electrons and positrons. For the hadronic CRs about 87% are protons, 12% are Helium nuclei and only the remaining 1% consists of heavier nuclei. In general this composition stays the same over the range of energies from a few hundred MeV to over 10^5 GeV, with the relative abundances of electrons being larger at lower energies (Schlickeiser, 2002; Potgieter, 2017).

2.2.3 Galaxy structure and features

With the Galaxy containing the CR sources and being the volume in which propagation occurs, the basic structure and relevant features of the Galaxy needs to be considered. The Milky Way Galaxy is a barred spiral galaxy with luminous matter organized in spiral arms that join in the inner Galaxy to form the galactic bulge. The matter is distributed in a disk with a height of about 100-150 pc above and below the galactic plane. The radius of the galactic disk is approximately 20 kpc, with the solar system located about 8.5 kpc from the galactic center (Berezinskii et al., 1990).

The propagation of CRs is directly affected by the galactic structure, with the gas content, interstellar radiation and magnetic fields being the most important. The gas content of the Galaxy influences the production of secondary CRs, while the radiation field and the magnetic field influence the energy loss processes affecting electrons. The turbulence properties of the magnetic field are also important as they directly influence the particle diffusion in the Galaxy. The ISM therefore contains matter, magnetic fields and radiation fields, all of which interact with CRs after they are accelerated at SNRs (Strong et al., 2007).

CRs slowly diffuse away from their sources by scattering off irregularities in the interstellar magnetic field, with CR electrons also generating synchrotron radiation due to the magnetic field. The magnetic field in the Galaxy is considered to lie in the galactic plane and is directed along the spiral arms. The magnetic field also includes a wide range of random components and the structure is not the same in different regions of the ISM. For CRs with energies below about 10^{15} GeV, the large scale structure and absolute magnitude of the galactic magnetic field are of less importance (Berezinskii et al., 1990; Strong et al., 2007).

Apart from diffusion, CR protons and nuclei interact mostly with the interstellar matter and produce secondary particles. The interstellar matter is made up of dust and gas, with the gas composed mainly of Hydrogen, Helium and a contribution from heavier elements. Most of the gas in the Galaxy is confined to the galactic plane and moves in circular orbits about the galactic center. The gas density in the Galaxy varies greatly, for example molecular clouds have densities of about $n \approx 200 \text{ cm}^{-3}$, while the atomic hydrogen density near the solar system is approximately $n \approx 0.85 \text{ cm}^{-3}$. The density distribution of atomic and molecular hydrogen also varies with radial distance in the galactic disc (Berezinskii et al., 1990). Interstellar dust is generally well mixed with the total interstellar gas and its density correlates well with the total gas density (Schlickeiser, 2002).

CR electrons interact with the magnetic and radiation fields, as well as with the interstellar matter. In addition to synchrotron radiation due to magnetic fields, electrons also produce γ -rays via inverse Compton emission when interacting with radiation fields. The interstellar radiation field extends from the far-infrared to the ultraviolet. This radiation field originates from all types of stars and is absorbed and re-emitted by the interstellar dust (Strong et al., 2007).

2.2.4 Cosmic ray propagation processes in the Galaxy

Various transport mechanisms affect the propagation of CRs through the Galaxy, influencing the movement of CRs, their spectra and composition. The relevant basic concepts are discussed here in short, for a detailed presentation on CR physics see, e.g., Berezhinskii et al. (1990); Ptuskin et al. (2006); Moskalenko (2013). For the application to numerical propagation modelling see, e.g., Strong et al. (2007), and references therein.

Diffusion

Energetic charged particles have highly isotropic distributions and are well retained in the Galaxy, having long travel times. These properties can be explained by the concept of diffusion, for which the galactic magnetic field plays a crucial role. The diffusion of CRs results from the particles scattering on random magnetohydrodynamic waves and discontinuities. The spatial diffusion that arises from this scattering is predominantly along the magnetic field lines and locally anisotropic. Strong fluctuations of the magnetic field on large scales, about 100 pc, where the strength of the random field is several times larger than the average field strength, lead to the isotropization of global CR diffusion in the Galaxy (Strong et al., 2007).

Convection

The existence of galactic winds in many galaxies suggests that the convective transport of CRs in the Milky Way may also be meaningful. The regular motion of interstellar gas, the galactic wind, is likely perpendicular to and away from the galactic disk. Direct evidence for a galactic wind in the Galaxy, inferred from X-ray images, seems to be confined to the galactic centre regions. A stationary flow can possibly be maintained by the energy of supernova explosions, stellar winds and the heat of ultraviolet intergalactic background radiation. The pressure of CRs can also help drive the galactic wind (Berezhinskii et al., 1990; Strong et al., 2007).

Reacceleration

The scattering of CR particles due to magnetohydrodynamic turbulence also leads to stochastic acceleration. This reacceleration in the entire galactic volume can't serve as the main mechanism of acceleration of CRs, specifically not for CRs of between 1-100 GeV/nuc. If this was a greater contributor to the total acceleration of CRs, the particles would spend a longer time in the galactic volume and result in an increase of the relative abundance of secondary nuclei as energy increases, which would be contrary to observation. For lower energies reacceleration may be more important and explain the existence of peaks in CR spectra and the Boron to Carbon (B/C) ratio (Strong et al., 2007).

Interactions and energy losses

Various energy loss processes affect CRs as they propagate through the ISM. As stated previously, CR electrons interact with the ISM, magnetic and radiation fields. The resulting loss processes include ionization losses, bremsstrahlung, adiabatic cooling, synchrotron radiation and inverse Compton scattering. The cross-sections for electromagnetic interactions of CR protons and nuclei are much smaller than those for CR electrons of the same Lorentz factor due to the higher mass of CR nuclei. The electromagnetic interactions thus contribute negligibly to their loss processes. The remaining important processes are ionization losses and adiabatic cooling, interactions of CR protons and nuclei with the interstellar radiation field are only relevant for CRs with very high energies of about 10^{18} eV and above (Schlickeiser, 2002).

Particle spallation

Lighter CR nuclei can be produced as spallation products via the interactions of heavier high energy CR nuclei with interstellar matter and at high energies through photodisintegration. Spallation is in effect a catastrophic particle loss, as it does not conserve the total number of particles of the considered nuclei. Estimating the yield of spallation products from the required inelastic reactions and calculating the resulting composition, spallation cross-sections are needed. To consider a complete nuclear network requires a large number of individual cross-sections, these can be obtained through direct measurements, numerical model calculations and semi-empirical formulae. Compilations of partial cross-sections for the collisions of various nuclei with Hydrogen are tabulated by e.g. Mashnik et al. (1998, 2004) and Silberberg et al. (1998).

2.2.5 Galactic propagation models

Taking the above galactic processes into account is required to accurately model the propagation of CRs through the Galaxy. Models can vary in the amount of physical processes included and how thoroughly the processes are implemented. The leaky box model is the simplest model to describe the propagation of CRs, it assumes a volume in which CRs are injected by uniformly distributed sources and propagate freely. The CRs have a certain chance to escape the volume, this chance is defined by a leakage term with a characteristic CR escape time. The escape time may be a function of particle energy, charge and mass number, but does not depend on the spatial coordinates. This model effectively assumes diffusion occurs rapidly and that the density of CRs is therefore constant in whole system and also spatially independent. Spallation and energy losses can also be included in the model, as well as uniformly distributed gas and radiation fields. The leaky box model is popular because of its mathematical simplicity and ability to describe the measured secondary to primary ratios. It is appropriate for global estimates, but not suitable for when the spatial distribution of sources or CRs are of concern (Berezinskii et al., 1990; Strong et al., 2007).

A more detailed approach to CR propagation requires solving a system of coupled transport equations for all isotopes involved in the process of nuclear fragmentation. The weighted-slab technique splits this problem into astrophysical and nuclear parts. The nuclear fragmentation problem is solved in terms of a slab model, wherein the total distance CRs traverse are divided into smaller sections, or slabs. These solutions are weighted according to a distribution function derived from an astrophysical propagation model and integrated over to calculate the total CR density. The weighted-slab method breaks down for low-energy CRs, where nuclear cross-sections have a strong energy dependence, strong energy losses and energy dependent diffusion. This weighted-slab method can also be applied to the solution of the leaky box equations (Strong et al., 2007).

A model describing CR propagation as a diffusive process within the Galaxy, which solves a more comprehensive particle transport equation, can improve on the shortcomings of the simplified models. The GALPROP model (Strong et al., 2007; Moskalenko, 2011, 2013) used in this study is based on such a diffusion model and is described in the following section as used in this study. Other galactic propagation models of varying complexity have been described by, e.g., Effenberger et al. (2012); Maccione (2013); Kopp et al. (2014); and Kissmann (2014).

2.3 The GALPROP model

The GALPROP code is a numerical tool for calculating the propagation of relativistic charged particles through the Galaxy. The code was created with the purpose of simultaneously predicting all observations relevant to CR physics via propagation calculations, this includes CR protons, nuclei, electrons, positrons, γ -rays and synchrotron radiation. GALPROP aims to incorporate current information on galactic structure, source distributions, a full nuclear reaction network and as much realistic astrophysical input as possible (Ptuskin et al., 2006).

Strong et al. (2007) and Moskalenko (2011) give overviews on the GALPROP model and the physics contained within it. Details about the code and physics implementations are presented in the GALPROP Explanatory Supplement (Strong et al., 2011a), with the GALPROP WebRun service hosted at: <https://galprop.stanford.edu>, enabling running the code via web browser (Vladimirov et al., 2011).

2.3.1 Galactic propagation equation

Describing the propagation of CRs as a diffusive process in the Galaxy, GALPROP implements the following equation for the propagation of a particular particle species:

$$\frac{\partial \psi}{\partial t} = S(\mathbf{r}, p) + \nabla \cdot (K \nabla \psi - \mathbf{V} \psi) + \frac{\partial}{\partial p} \left[p^2 K_p \frac{\partial}{\partial p} \frac{1}{p^2} \psi + \frac{p}{3} (\nabla \cdot \mathbf{V}) \psi - \dot{p} \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi, \quad (2.1)$$

where $\psi = \psi(\mathbf{r}, p, t)$ is the CR density per unit of total particle momentum p at position $\mathbf{r}$ (Strong et al., 2007). The source term $S(\mathbf{r}, p)$ includes primary, spallation and decay contributions. Spatial diffusion is represented by the coefficient K and convection velocity by $\mathbf{V}$. Reacceleration is described as diffusion in momentum space and determined by the coefficient K_p , while $\dot{p}$ is the momentum loss rate. The catastrophic particle losses are represented by timescales, with τ_f the timescale for fragmentation, which depends on the total spallation cross-section, and τ_r the timescale for radioactive decay.

GALPROP assumes a simplified approach to diffusion, with the spatial diffusion coefficient K assumed to be independent of radius r and height z . This coefficient is taken as being proportional to a power-law in rigidity P :

$$K = \beta K_0 (P/P_0)^\delta, \quad (2.2)$$

where $\delta = \delta_1$ for rigidity $P < P_0$ (the reference rigidity), while $\delta = \delta_2$ for $P > P_0$. Here $\beta = v/c$ is the speed of particles v at a given rigidity relative to the speed of light c . The magnitude of the diffusion coefficient K_0 is in effect a scaling factor for diffusion, generally with units of $10^{28} \text{ cm}^2 \text{ s}^{-1}$. When considering reacceleration, the momentum-space diffusion coefficient K_p is estimated as related to K so that $K_p K \propto p^2 V_A^2$, with V_A the Alfven wave speed, a characteristic velocity of weak disturbances propagating in a magnetic field, set to 36 km.s^{-1} .

The CR sources are assumed to be concentrated near the galactic disk and have a radial distribution similar to that of SNRs. The distribution is assumed to be the same for all CR primaries and is given by:

$$S(r, z) = S_0 \left(\frac{r}{r_\odot} \right)^{\alpha_{distr}} \exp \left(-\beta' \frac{r - r_\odot}{r_\odot} - \frac{|z|}{0.2 \text{ kpc}} \right) \quad (2.3)$$

where S_0 is a normalization constant, $r_\odot = 8.5 \text{ kpc}$, $\alpha_{distr} = 0.5$ and $\beta' = 1.0$. The primary contribution to the sources requires an injection spectrum and relative isotopic compositions to be specified. The injection spectrum for nuclei, as input to the source term, is assumed to be a power-law in rigidity so that:

$$S(P) \propto (P/P_{\alpha 0})^\alpha, \quad (2.4)$$

for the injected particle density and usually contains a break in the power-law with index $\alpha = \alpha_1$ below the source reference rigidity $P_{\alpha 0}$ and $\alpha = \alpha_2$ above. Values for α_1 and α_2 are positive and non-zero, thus giving a rigidity dependent injection spectrum. For isotopes considered wholly secondary, no input spectrum is given and they are set to zero at the sources. For the source abundance values as used in GALPROP, this study keeps the values unchanged from what is used by Ptuskin et al. (2006). The source spectrum is the same for all CR nuclei, but may differ for electrons. The injection spectrum for electrons is input similarly to that of the CR nuclei:

$$S(P) \propto (P/P_{\alpha e 0})^{\alpha_e}, \quad (2.5)$$

where $\alpha_e = \alpha_{e1}$ below the source reference rigidity $P_{\alpha e 0}$ and $\alpha_e = \alpha_{e2}$ above. For the spallation and decay contribution depends on all the progenitor species, the associated energy dependent

cross-sections and the gas density. It can be assumed that the spallation products have the same kinetic energy per nucleon as the progenitor.

The convection velocity $\mathbf{V}$ is spatially dependent and determined by the nature of the galactic wind. The $\nabla \cdot \mathbf{V}$ term represents the adiabatic momentum gain or loss in the non-uniform flow of gas with a frozen-in magnetic field whose inhomogeneities scatter the CRs. The model can be simplified to study specific cases, one such a case is the plain diffusion model. For this model reacceleration is not considered, V_A is set to zero, and similarly convection is turned off by setting the gradient (dV/dz) in the galactic wind to zero, as the velocity is already set to zero in the galactic plane. The momentum change represented by the term $\dot{p}$ can be positive or negative. This comprises all forms of energy losses, mostly by synchrotron radiation for electrons or ionization loss for protons and heavier nuclei. Momentum can also be gained in additional forms of acceleration, such as adiabatic heating (Strong et al., 2007).

2.3.2 The numerics of GALPROP

The Galaxy is usually described as a cylindrical volume for CR propagation studies. This includes a galactic halo, in which CRs have a finite chance to return to the galactic disk. Assuming symmetry in azimuth leads to a two spatial dimensional (2D) model that depends only on galactocentric radius and height, additionally, neglecting time dependence leads to a steady-state model. When implemented in the GALPROP code this gives a 2D model with radius r , the halo height z above the galactic plane and symmetry in the angular dimension in galactocentric-cylindrical coordinates. The propagation region is bounded by $r = R$ and $z = \pm H$, giving the containment volume as shown in Figure 2.1, beyond which free escape is assumed. For this study the halo height is fixed at 4 kpc, because varying its size can simply be counteracted by directly varying the diffusion coefficient.

The GALPROP code has been designed for the propagation of CRs on either a 2D or 3D spatial grid (Strong and Moskalenko, 2001). The 3D model uses a Cartesian grid and unlike the 2D case, which is a steady-state model, the 3D case is time-dependent to account for transient CR sources like supernovae. For this study only the 2D model will be considered. The CRs are propagated in three dimensions, two spatial dimensions and momentum, giving the basic coordinates (r, z, p) for the rotationally symmetric cylindrical grid, with p the magnitude of the total particle momentum on a logarithmically spaced momentum grid. Symmetry is assumed above and below the galactic plane in order to save on the computational requirements of the code. The GALPROP code solves the transport equation, for each of the CR species that are taken into account, using a Crank-Nicholson implicit second-order scheme. The processes are described by differential operators in the propagation equation and these operators are implemented as finite differences for each dimension (r, z, p) in the numerical scheme (Strong and Moskalenko, 1998; Strong et al., 2011a).

To account for all secondary, tertiary and higher reaction products, the nuclear reaction network is solved by starting at the heaviest nuclei considered. The propagation equation is solved for

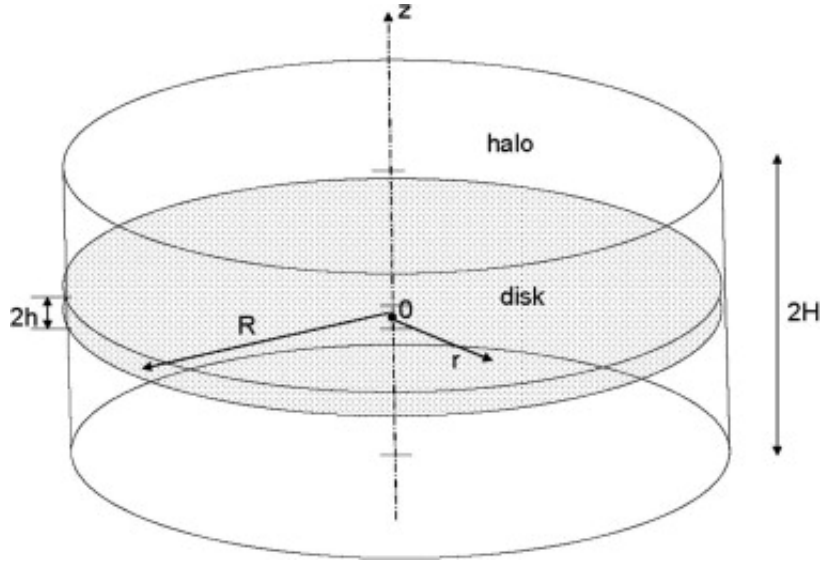


Figure 2.1: The CR containment volume for a 2D propagation model, with a rotationally symmetric cylindrical grid. The cylinder has a galactocentric radius r and height z above to galactic plane, while being bounded by the values $r = R$ and $z = \pm H$. CR sources are restricted to the galactic disk, with height $z = \pm h$ (Ptuskin, 2012).

this nucleus, computing all the resulting secondary source functions for the spallation products and proceeding to the next nucleus in the series to be propagated. The procedure is repeated down to protons, then secondary electrons, positrons and lastly antiprotons. The process is repeated at least twice to be accurate for all isotopes (Strong and Moskalenko, 2001; Strong et al., 2007). Spectra of all species on the chosen grid are output in a standard astronomical format, FITS, for presentation and comparison to data (Strong et al., 2007). For extensive details on solving the transport equation, the numerical scheme and differential operators see Strong and Moskalenko (1998); Strong et al. (2011a).

2.3.3 WebRun service

The computational runs for this study are done via the GALPROP WebRun service. While the GALPROP code can be run locally, the WebRun service offers the benefits of running the most recent version of GALPROP, with error detection, powerful computing power and user support. The service can be accessed at: <http://galprop.stanford.edu/webrun>. The details on the implementation of the WebRun service, the updated features of the code and the computer cluster specifications are presented by Vladimirov et al. (2011).

Table 2.1: List of GALPROP model parameters used for the reference models.

Model	Pldff.	Reacc.
Parameters	Reference	Reference
K_0 (10^{28} cm ² s ⁻¹)	2.20	5.75
P_0 (GV)	3	4
δ_1	0.00	0.34
δ_2	0.60	0.34
$P_{\alpha 0}$ (GV)	40	9
α_1	-2.30	-1.82
α_2	-2.15	-2.36
$P_{\alpha e 0}$ (GV)	4	4
α_{e1}	-2.4	-1.6
α_{e2}	-2.4	-2.5
V_A (km.s ⁻¹)	0	36
dV/dz (km.s ⁻¹ .kpc ⁻¹)	0	0

2.3.4 Calculated spectra and reference models

The GALPROP model is implemented for this study by referring to the models as used in the study by Ptuskin et al. (2006), in which they present a plain diffusion (Pldff) model and a reacceleration (Reacc) model. The parameter sets corresponding to the two models are shown in Table 2.1. Other parameters in the model such as source abundance values, interstellar properties, cross sections and gas densities, were adapted straightforwardly their work and are not repeated here.

The electron and proton LIS's calculated with GALPROP for the plain diffusion and reacceleration models are shown in Figures 2.2 and 2.3. The parameters and LIS's are referred to as reference models, with their respective reference LIS's, and used as starting point for the investigations in this study.

2.4 Summary

In this chapter the features of CRs and the Galaxy were presented, as well as a basic overview of the physical processes that need to be considered when studying the propagation of CRs. The GALPROP code for calculating the propagation of CRs was discussed as well as how the relevant processes are implemented in the model. The propagation equation and numerical considerations relevant to the model were summarized, together with the reference parameter values as used in this study. Reference LIS's for electrons and protons are given in Figures 2.2 and 2.3, and will serve as such in coming chapters, where they will be re-evaluated and modified. The modulation model, as used to calculate CR propagation in the heliosphere, is discussed in the following chapter.

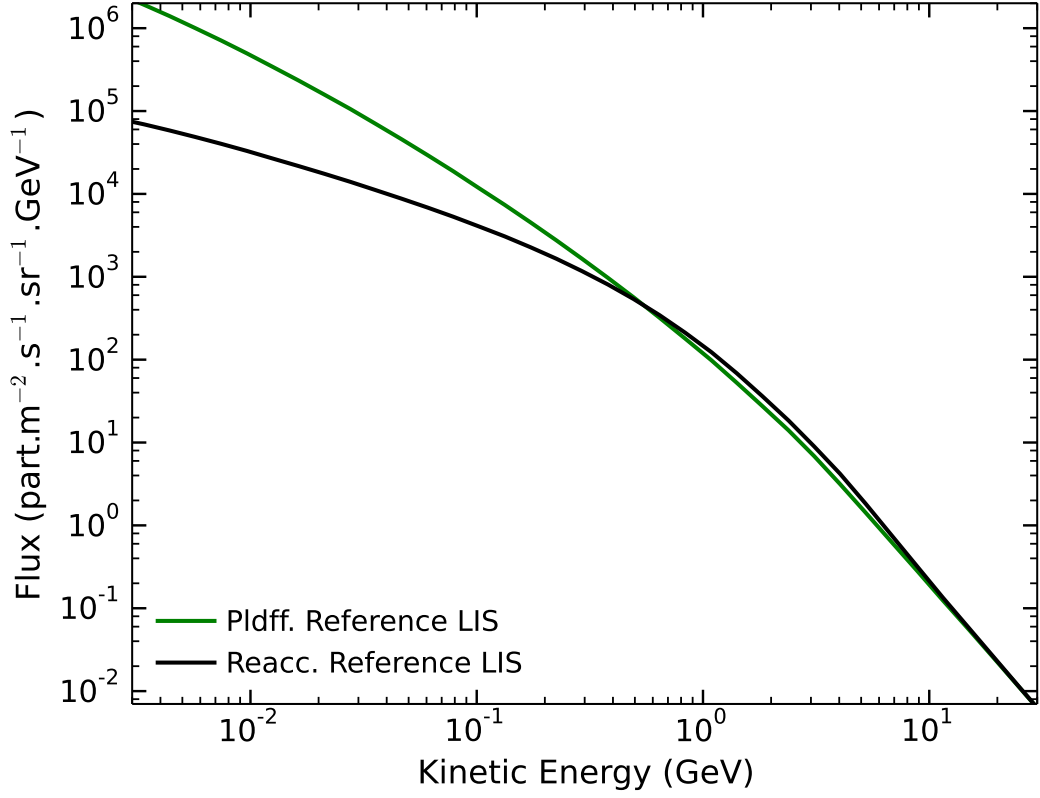


Figure 2.2: The electron LIS's, plain diffusion reference LIS (green curve) and reacceleration reference LIS (black curve), calculated with the reference model parameters of Table 2.1.

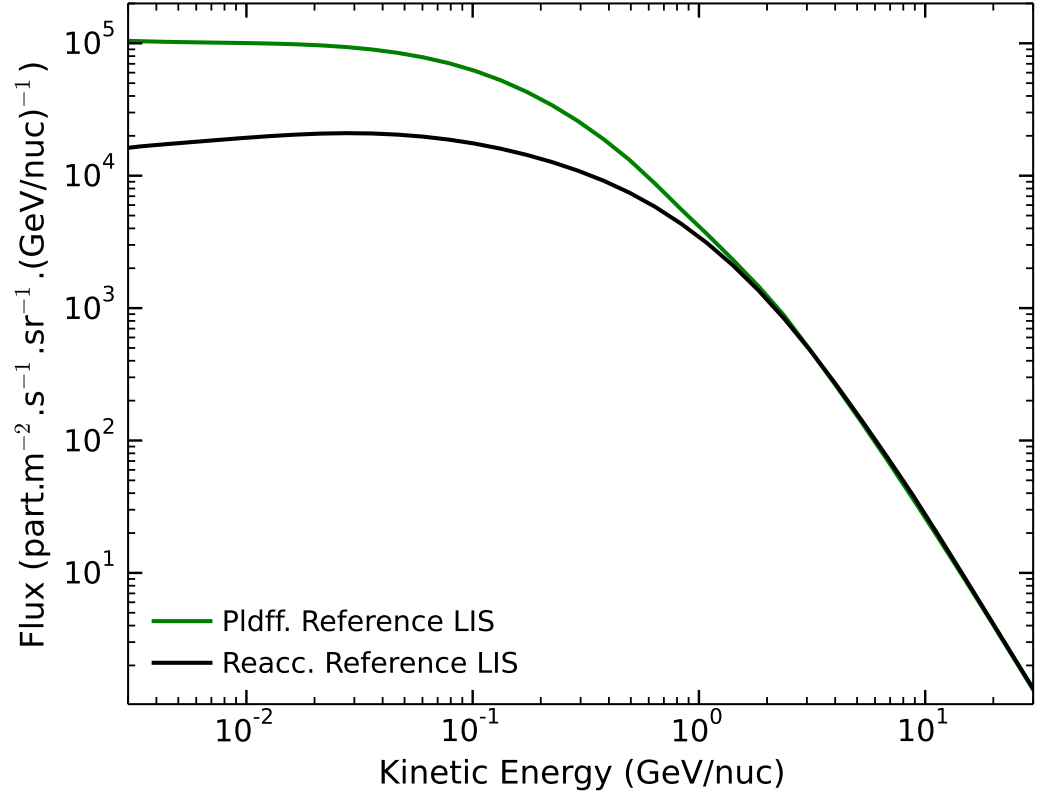


Figure 2.3: The proton LIS's, plain diffusion reference LIS (green curve) and reacceleration reference LIS (black curve), calculated with the reference model parameters of Table 2.1.

Chapter 3

Cosmic Rays in the Heliosphere

3.1 Introduction

Before arriving at the Earth, CRs need to pass through the heliosphere. This region, dominated by the Sun via the solar wind and heliospheric magnetic field (HMF), greatly affects the spectra of CRs. In order to study CRs fully and compare their observations made at the Earth with results from galactic propagation models, the effect of the heliosphere on the CRs needs to be taken into account.

CRs inside the heliosphere interact with a turbulent solar wind with an embedded HMF, leading to variations in the CR intensities and energies. These variations are dependent on position in the heliosphere and change with time, this is what is known as the solar modulation of CRs (Potgieter, 2013).

This chapter gives a brief overview of the heliosphere and the features most important to CR modulation. The relevant transport equation and its implementation into a comprehensive CR modulation model, as used in this study, is briefly discussed.

3.2 Solar modulation and the heliosphere

The Sun is a changing and active system, cycling through periodic stages of varying activity. The best known indicator of solar activity is the sunspot number, with its periodic variation helping to identify the 11-year solar cycle. Low sunspot numbers indicate a solar minimum period, whereas high sunspot numbers indicate a solar maximum period. Measurements made by various particle detectors, such as neutron monitors as illustrated in Figure 3.1, have shown that the CR intensity at Earth also varies with time and shows an inverse correlation to the level of solar activity. While the 11-year cycle is the most dominant solar activity time scale for modulation, the reversal of the HMF during each period of extreme solar activity also gives rise to a 22-year cycle. Consecutive solar cycles can thus result in marked different CR modulation profiles as shown in Figure 3.1 (Potgieter, 2013). CR transport in the heliosphere is predominantly affected by the heliospheric structure, with its solar wind and embedded magnetic field varying throughout the solar cycle.

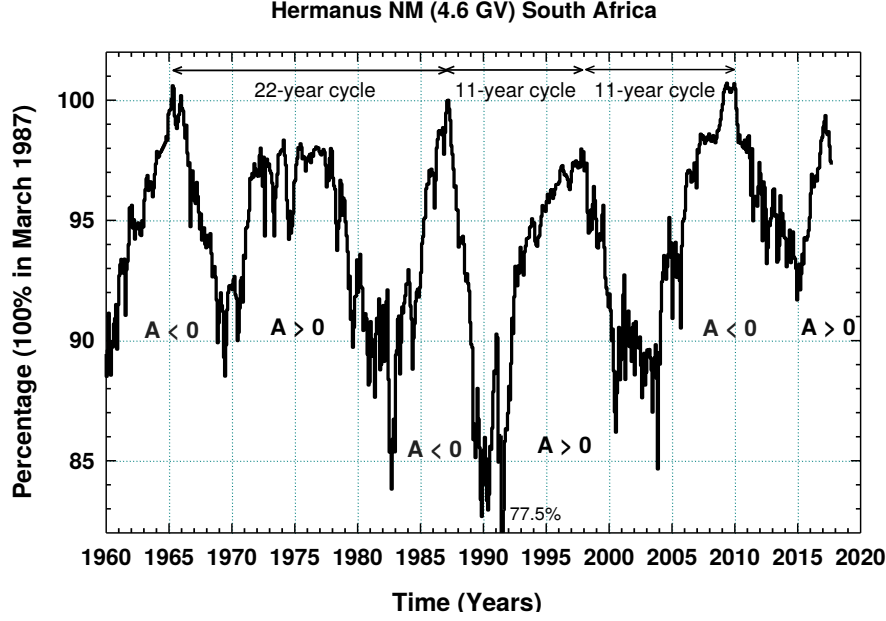


Figure 3.1: The Hermanus neutron monitor count rate (normalized to 100% in March 1987) as a function of time. This illustrates the effect that the 11 and 22-year cycles have on the CR profiles over time. The difference between consecutive cycles of opposing polarity cycles ($A > 0$ and $A < 0$). Fig. made with data from <http://natural-sciences.nwu.ac.za/neutron-monitor-data>.

3.2.1 Solar wind and the heliosphere

The solar wind is a fully ionized plasma, originating from the hot solar corona, that expands into space supersonically and radially outward. A consequence of the changing solar activity is a changing solar wind speed. Other properties of the solar wind, such as density, temperature and composition, also vary. During solar minimum conditions the solar wind is latitude dependent, with a slow solar wind of about 450 km.s^{-1} in the equatorial plane and a fast solar wind of up to about 800 km.s^{-1} in the polar regions. During solar maximum conditions the solar wind speed is on average slow at all latitudes, but it is not as clearly structured as the speed varies greatly with small changes in latitude (Heber and Potgieter, 2006; Potgieter, 2013).

As the Sun moves through space, the solar wind continuously expands into the ISM to form the heliosphere. The size and the boundaries of the heliosphere are determined by the interaction between the ISM and the solar wind. The solar wind pressure must eventually become comparable to the back pressure of the ISM, creating the heliopause which is generally considered the outer boundary of the heliosphere. The relative motion through the ISM is most likely supersonic and an upstream bow wave is expected, with the region between the bow wave and the heliopause referred to as the outer heliosheath. The expanding supersonic solar wind must decrease in velocity to a subsonic flow before reaching the heliopause; this then forms the termination shock. The region between the termination shock and the heliopause is called the inner heliosheath (Heber and Potgieter, 2006; Potgieter, 2013). The position of the termination shock has been confirmed by V1 spacecraft at 94 AU and by Voyager 2 at 84 AU, indicating that it is highly dynamic (Stone et al., 2005, 2008). The position of the heliopause was also estimated by V1 at 122 AU when it crossed into the outer heliosheath in 2012 (Stone et al., 2013).

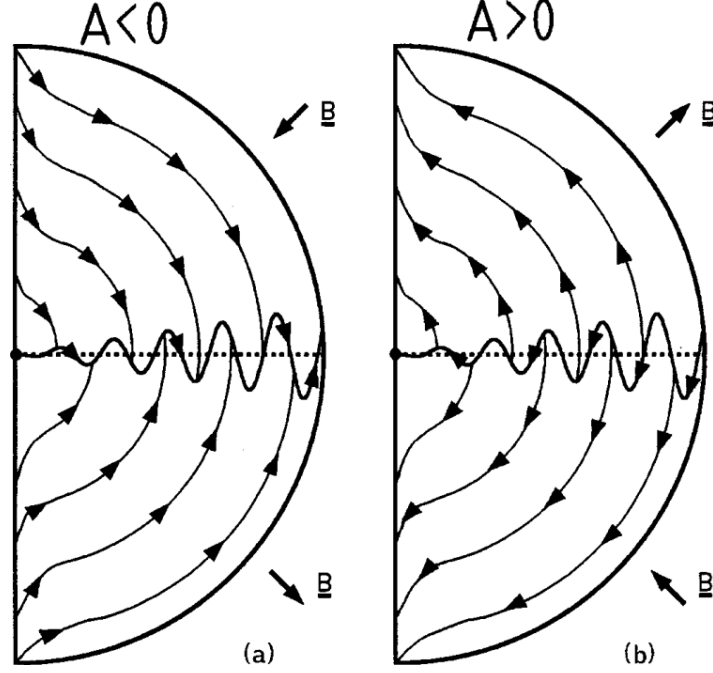


Figure 3.2: The idealistic drift directions of negatively charged CRs due to gradients and curvature in the HMF above and below the wavy current sheet, for (a) the $A < 0$ polarity cycle when the HMF is directed inward in the northern hemisphere, and (b) the $A > 0$ polarity cycle when the HMF is directed outward in the northern hemisphere. The drift directions are the opposite for positively charged particles (Fig. adapted from Heber and Potgieter, 2006).

3.2.2 Heliospheric magnetic field and current sheet

The Sun generates a complex magnetic field that extends far out into the heliosphere. The HMF can most simply be described as a dipole with an axis which is close to the Sun's rotation axis. The HMF is embedded in the perfectly conducting solar wind plasma and is carried along with the solar wind as it expands outward. The structure and orientation of the HMF changes over the 22-year cycle, with the polarity reversing about every 11 years during the solar maximum period. While the solar wind moves out mostly radially from the Sun, solar rotation give the HMF a spiral structure (Parker, 1958; Potgieter, 2013).

The opposing polarities of the HMF extend outward into the heliosphere, near the ecliptic plane the northern and southern magnetic hemispheres are separated by a neutral current sheet. This heliospheric current sheet has a wavy structure due to the tilt of the HMF axis relative to the Sun's rotational axis. This wavy structure is parameterized by its tilt angle, which strongly correlates to solar activity and can be used as a reliable index for it. During solar maximum the tilt angle continually increases, to as much as 75° , beyond which it becomes indeterminable. During solar minimum the tilt angle is much smaller, between 5° and 10° , as the magnetic and the heliographic equators are nearly aligned. The waviness becomes compressed in the inner heliosheath as the outward solar wind flow decreases over the termination shock.

CR transport is affected by the HMF through drift motions associated with the gradients in field magnitude, the curvature of the field and changes in the field direction. Particles drift along

the current sheet due to the HMF being oppositely directed on either side of the current sheet. When the HMF is directed outward in the northern hemisphere and inward in the southern hemisphere, the polarity cycle is denoted by $A > 0$. The drift direction for negatively charged particles, mainly electrons, is directed towards the inner heliosphere along the current sheet and upwards toward the polar regions of the heliosphere. For the oppositely directed HMF in the $A < 0$ polarity cycle, the drift direction is from the polar regions, down to the current sheet where the negatively charged particles drift outward along it. The $A > 0$ and $A < 0$ cycles, and their effect on negatively charged particles, are illustrated in Figure 3.2. For positively charged particles the drift directions are inverted for the same polarity cycles. The sharp and flat peaks in the CR intensity profiles during solar minimum cycles, as seen in Figure 3.1, are caused by this difference in drift directions.

For details on the effects of the HMF and the other heliospheric features on CR transport see the review by Potgieter (2013) and references therein. The values of the tilt angles, as proxy for solar activity, are reported on the website of the Wilcox Solar Observatory (<http://wso.stanford.edu/Tilts.html>).

3.3 The 3D heliospheric modulation model

In order to calculate the spectra of CRs as they arrive at the Earth, after their transport through the heliosphere, a model is required to calculate the relevant modulation. The CR transport equation, first derived by Parker (1965), is used for this purpose. The full description of the modulation problem requires the determination of the CR intensity as a function of three spatial coordinates, time and energy. Various levels of approximations can be made to simplify the numerical solution, as suited for the specific situation to be investigated.

The experimental observations relevant to this study require that only modulation during the 2009 time period (an $A < 0$ magnetic epoch), at solar minimum conditions, needs to be calculated. A full 3D modulation model, as described by Potgieter and Vos (2017) to compute modulated differential intensities throughout the heliosphere, is used for this purpose. This model takes into account the major modulation mechanisms of convection and adiabatic cooling due to the solar wind, particle diffusion and drifts due to the HMF. This steady-state model also includes a wavy current sheet and a heliosheath, but does not consider shock acceleration at the termination shock.

3.3.1 Transport equation

The modulation of CRs in the heliosphere is described by the transport equation developed by Parker (1965). The time-dependent transport equation can be written simply in the following form in terms of rigidity P :

$$\frac{\partial f}{\partial t} = -\mathbf{V}_{sw} \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}_{sw}) \frac{\partial f}{\partial \ln P}, \quad (3.1)$$

where $f(\mathbf{r}, P, t)$ the distribution function of CRs at position $\mathbf{r}$ and at time t . The numerical modulation model, as implemented by Potgieter and Vos (2017), considers a steady-state solution with $\frac{\partial f}{\partial t} = 0$, this solution is valid for solar minimum conditions or whenever the modulation parameters gradually change. The first term on the right gives the outward convection due to the solar wind with velocity $\mathbf{V}_{sw}$. Spatial diffusion and particle drift is given by the second term via the tensor $\mathbf{K}$. The third term gives the adiabatic energy losses (or sometimes gains) through the solar wind divergence. No source term is included for this study, because, as stated previously, the sources of CRs inside the heliosphere are not considered here.

The asymmetrical tensor $\mathbf{K}$ in Eq. 3.1 is given by:

$$\mathbf{K} = \begin{bmatrix} K_{\parallel} & 0 & 0 \\ 0 & K_{\perp\theta} & K_A \\ 0 & -K_A & K_{\perp r} \end{bmatrix}, \quad (3.2)$$

when aligned to the HMF. This tensor contains the diffusion and drift coefficients that determine the extent to which charged particles are transported and modulated. The coefficient $K_{\parallel}$ is the diffusion coefficient parallel to the HMF, while $K_{\perp r}$ and $K_{\perp\theta}$ are the diffusion coefficients perpendicular to the HMF, that is to say, perpendicular in the radial direction and perpendicular in the polar direction respectively. The asymmetric coefficients K_A and $-K_A$ determine the gradient, curvature and current sheet drifts. The coefficients are approximated in the model by the following equations:

$$K_{\parallel} = (K_{\parallel})_0 \beta \left(\frac{B_0}{B} \right) \left(\frac{P}{P_0} \right)^a \left(\frac{\left(\frac{P}{P_0} \right)^c + \left(\frac{P_k}{P_0} \right)^c}{1 + \left(\frac{P_k}{P_0} \right)^c} \right)^{\frac{b-a}{c}}, \quad (3.3)$$

$$K_{\perp r} = 0.02 K_{\parallel}, \quad (3.4)$$

$$K_{\perp\theta} = 0.01 K_{\parallel} f_{\perp\theta}, \quad (3.5)$$

$$K_A = (K_A)_0 \frac{\beta P}{3B} \left(\frac{\left(\frac{P}{P_{A0}} \right)^2}{1 + \left(\frac{P}{P_{A0}} \right)^2} \right), \quad (3.6)$$

where B is the magnitude of the HMF, with B_0 its value at the Earth; $f_{\perp\theta}$ in Eq. 3.5 determines the latitudinal dependence of this coefficient; the values of P_k and P_{A0} determine where a change in the slope of the assumed power-law occurs; P_0 is usually equal to 1 GV; the constants $K_{\parallel}$ and K_A are usually given in units of $6 \times 10^{20} \text{ cm}^2 \text{ s}^{-1}$. See also Vos (2016) and Potgieter (2017).

The diffusion coefficients are related to mean free paths (MFPs) by:

$$K = \frac{v}{3}\lambda, \quad (3.7)$$

with particle velocity v , giving the respective MFPs $\lambda_{\parallel}$, $\lambda_{\perp\theta}$ and $\lambda_{\perp r}$. Similarly the drift coefficient is related to a drift scale λ_A . The relevant values for the rigidity dependent MFPs (through the constants a, b and c) and drift scale used in this study are shown in the following chapters when used.

Other assumptions for the heliosphere, such as expressions for the HMF, wavy current sheet and the solar wind velocity, are used unchanged from the study by Potgieter and Vos (2017). Detailed explanations, discussions and equations for these aspects are given by Potgieter et al. (2015) and Vos and Potgieter (2015), and are not repeated here.

3.3.2 Numeric implementation

The transport equation is solved in a heliocentric spherical coordinate system with three spatial dimensions (r, θ, ϕ) and one rigidity dimension (P) , which rotates with the Sun. This system gives Eq. 3.1 as a parabolic differential equation that can be solved in three spatial dimensions and rigidity using the Alternating Direction Implicit (ADI) method, a modified Crank-Nicholson finite difference method.

The LIS is used as an initial condition for the entire heliosphere, described at the outer boundary of the heliosphere, $r_b = 122$ AU, as an input spectrum. The inner boundary of the heliosphere is specified at a distance away from the solar surface. The transport equation is solved in a 3D grid of the spherical heliosphere for each rigidity step, with rigidity incrementally decreasing from the maximum value considered. A full discussion on solving the transport equation for the 3D heliosphere is given by Hattingh (1998) and Ferreira (2002).

The numerical model has been adapted for the CUDA parallel computing platform by Vos (2016) to take advantage of the runtime performance of parallelizing the solution of the transport equation in the 3D grid. The modulation calculations required for this study use this implementation.

3.3.3 Sample solutions

Proton spectra calculated at the Earth with this 3D modulation model are shown in Figure 3.3. With a proton LIS from Vos and Potgieter (2015, 2016) the model calculates spectra to match the end-of-the-year monthly averaged PAMELA observations, as well as spectra at distances of 10 AU, 50 AU, 100 AU and 120 AU respectively. Examples of modulated electron spectra can be seen in Figure 7 of the review by Potgieter (2017) and examples of positron modulation in the results presented by Potgieter et al. (2017). For a comprehensive discussion of charge-sign dependent modulation in the heliosphere, see Potgieter (2014).

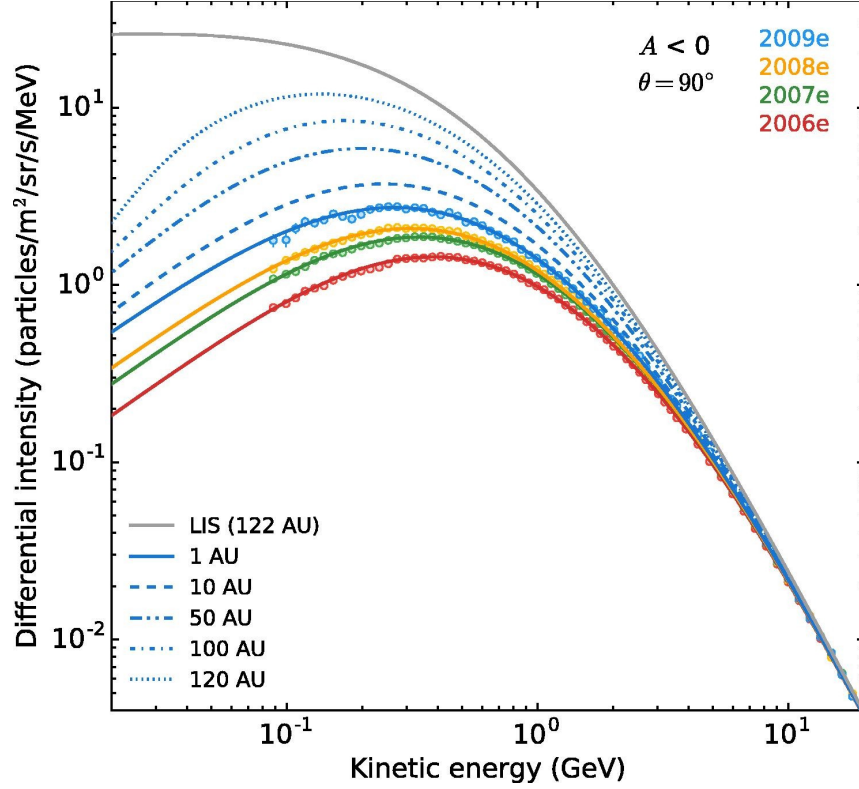


Figure 3.3: Computed proton spectra shown at the Earth (1 AU) compared to end-of-the-year monthly averaged PAMELA observations, indicated as 2006e, 2007e, 2008e and 2009e. Additional computed spectra are shown in the heliospheric equatorial plane ($\theta = 90^\circ$) at 10 AU, 50 AU, 100 AU and 120 AU (blue curves) with respect to a LIS (grey curve) from Vos and Potgieter (2015, 2016) specified at 122 AU (Fig. adapted from Potgieter, 2017).

3.4 Summary

Modulation is an important phenomena that can't be ignored for CR studies, especially when considering CRs within the energy range considered in this study. In this chapter the heliosphere and it's effect on CRs were discussed in short. The transport equation used to describe CR modulation in the heliosphere was discussed, together with its implementation in the steady-state 3D modulation model. This model is used in later chapters to calculate the respective CR spectra at the Earth for the solar minimum period of 2009, corresponding to the given LIS's, computed with GALPROP, and used as initial input condition.

With the physics and models relevant to this study being presented, the first part of this CR propagation study is discussed in the next chapter.

Chapter 4

Reproducing the Voyager 1 electron LIS's

4.1 Introduction

The first implementation of the GALPROP code will be used to calculate electron LIS's. Comparing these LIS's to observations will help establish if the electron spectra observed by V1 beyond the heliopause can be reproduced with a plain diffusion model at these low energies. The focus of this modeling approach will be on the main features of the V1 observations and not an attempt to find perfect fits to the data sets.

At high energies the electron spectrum as observed by PAMELA is used to restrain the calculated electron LIS's. This also facilitates the investigation into where the spectral break occurs in the electron LIS and if it is close to what Potgieter and Nndanganeni (2013a) found based on their solar modulation modeling.

To estimate the electron LIS the GALPROP code is used to compute various spectra based on the parameters presented by Strong et al. (2011b) without incorporating any new physics or assumptions. The LIS's that don't reproduce the reported electron spectra, with a primary focus on the V1 observations, are then eliminated. The remaining models are to have their parameters refined until satisfactory LIS's are calculated.

4.2 Electron observations

4.2.1 The Voyager 1 electron spectra

Stone et al. (2013) presented two possible LIS for electrons between 6 and 60 MeV based on their analysis of V1 observations beyond the heliopause. They calculated two different power-laws; a spectrum derived by using response functions from a pre-launch accelerator calibration,

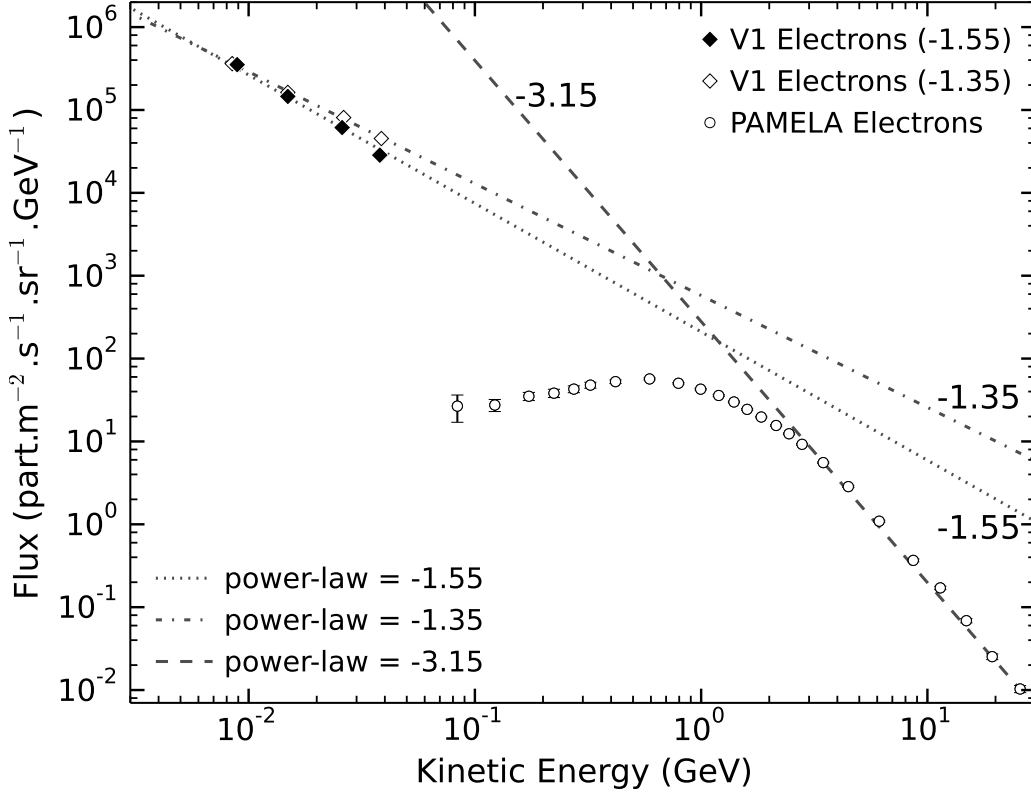


Figure 4.1: Two sets of spectra from V1 were reported by Stone et al. (2013); set 1 with a power-law index of -1.55 , based on a pre-launch calibration (filled diamonds), and set 2 with an index of -1.35 from their GEANT4 simulation (open diamonds), respectively. PAMELA observations (open circles, Adriani et al., 2011a). Data points from both V1 and PAMELA are shown together with straight lines, for illustrative purposes, with power-law indices of -3.15 , matching the PAMELA data above 3 GeV (dashed line), and -1.55 (dotted line) and -1.35 (dot-dash line) matching the two V1 data sets.

and a second spectrum based on GEANT4 simulations. The uncertainty in the power index is therefore mainly determined by the systematic uncertainties in the way the V1 electron spectra were calculated.

These two spectra reported by Stone et al. (2013) exhibit power-law indices of -1.55 (filled diamonds) based on a pre-launch calibration and a flatter -1.35 (open diamonds) from their GEANT4 simulation, respectively shown in Figure 4.1. The power-laws for the indices of -1.55 (dotted line) and -1.35 (dot-dash line) are drawn to show where the electron LIS would lie at lower energies if it remains a strict power-law with one of these indices.

The electron fluxes have almost the same value at the lowest reported energy ($\sim 6-8$ MeV), but progressively differs with increasing energy due to the two different power indices. The two spectra are considered as lower and upper limits for what a LIS possibly may be beyond the heliopause and they are to be separately reproduced in this study.

4.2.2 PAMELA electron observations

To constrain the higher energy electron LIS the observations made by the PAMELA spacecraft at the Earth (Menn et al., 2013) is used. The PAMELA electron spectrum for 2009 (Adriani

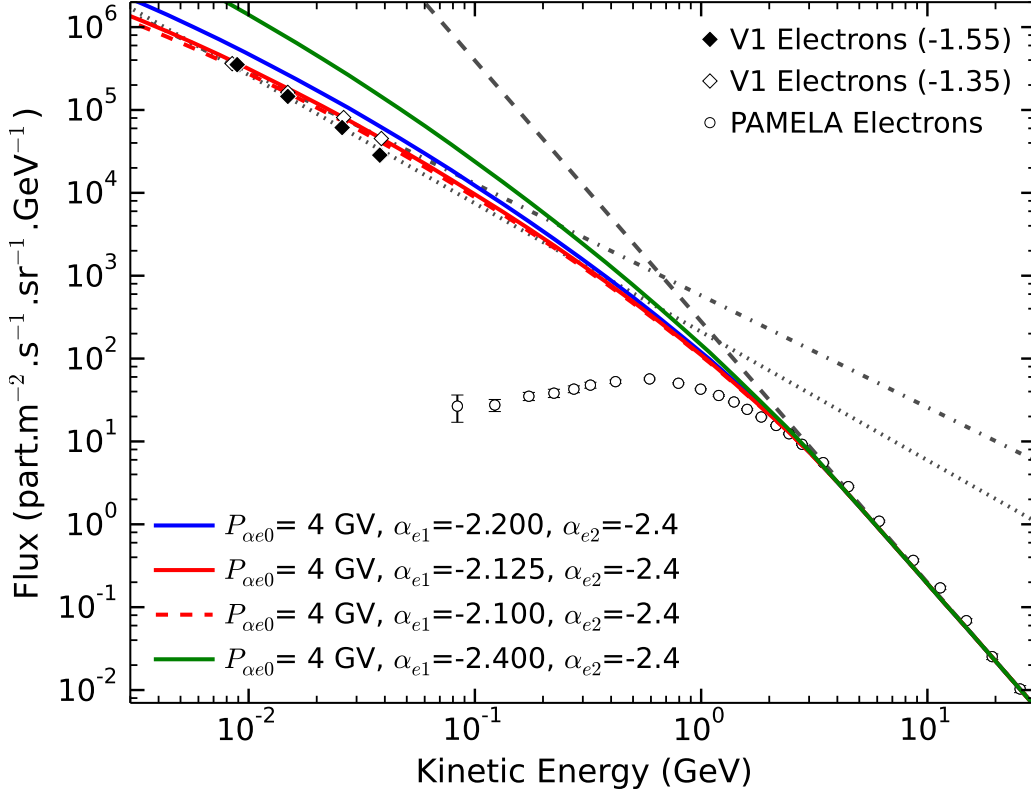


Figure 4.2: Electron local interstellar spectra (LIS's) computed with changes to the source spectrum index as in Eq. 2.5. Different values of α_{e1} and α_{e2} were investigated, with other values kept unchanged. A reference solution is shown with the solid green curve with parameters as indicated. For the modeling here α_{e2} was kept at -2.4 to reproduce the PAMELA observations at energies above 10 GeV. Three computed LIS's with α_{e1} set to -2.10 (red dashed line), -2.125 (red solid line) and -2.20 (blue solid line) are shown compared to the observations as in Fig.4.1.

et al., 2011a) is shown in Figure 4.1 (open circles) in comparison with the V1 observations. A power-law with index -3.15 (dashed line), corresponding to the PAMELA values above 4 GeV, is also drawn. This illustrates the fact that reproducing PAMELA electron observations above a kinetic energy where solar modulation is considered negligible, requires a completely different power-law than for the V1 spectra. The power-laws drawn in Figure 4.1 can be compared to the electron LIS reported by Potgieter and Nndanganeni (2013a) with $E^{-(3.15 \pm 0.05)}$ above ~ 5 GeV, with a clear spectral break occurring between ~ 800 MeV and ~ 2 GeV, but below this break the LIS has a power-law form with $E^{-(1.50 \pm 0.15)}$. This spectral break is also consistent with the computed electron spectra of Strong et al. (2011b).

4.3 Plain diffusion model

Strong et al. (2011b) studied different GALPROP based models for the electron LIS and only two aspects are re-examined here using GALPROP namely: the electron source spectrum and the galactic diffusion coefficient. The procedure described by Strong et al. (2011b) was comprehensively tested, using variations to the source spectrum index in GALPROP in order to

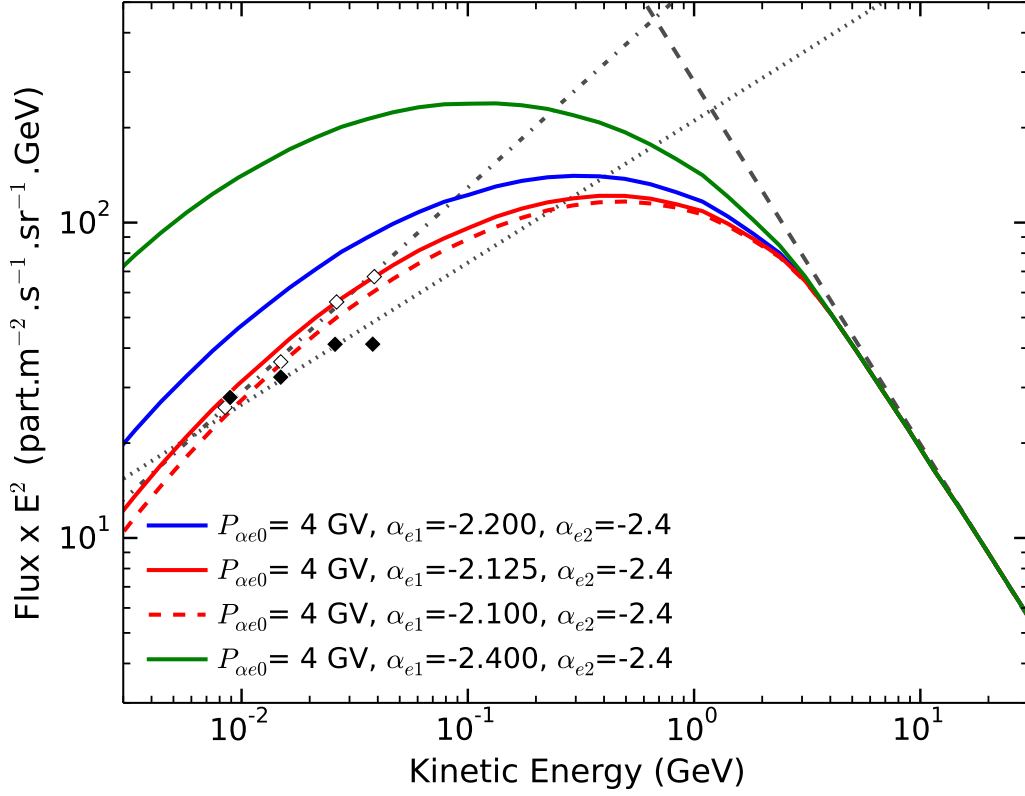


Figure 4.3: Same as Fig. 4.2 but with the intensity multiplied with $E^{2.0}$. Two new LIS's are computed that reproduce the observed -1.35 spectrum as suggested by the V1 data using α_{e1} between -2.100 (red dashed line) and -2.125 (red solid line). Adjusting only α_{e1} and α_{e2} could not reproduce the steeper -1.55 spectrum as reported by Stone et al. (2013).

reproduce electron observations at higher energies and utilizing synchrotron radiation observations to constrain the low-energy interstellar electron spectrum. The latter are replaced with V1 measurements, but otherwise a plain diffusion approach is followed, making changes to the source spectrum index and the galactic diffusion coefficient, in particular its rigidity dependence. Webber and Higbie (2013) also reported a similar study, but based on their Leaky Box Model for electron propagation in the Galaxy.

4.3.1 Source spectrum adjustment

The first step in utilizing the plain diffusion model is to establish the effects on the predicted (computed) LIS by varying only the source spectral index α_e in the assumed model while keeping all the other relevant parameters unchanged. This is done in comparison with the V1 and PAMELA electron observations mentioned earlier. A reference solution is computed first with $\alpha_{e1} = \alpha_{e2} = -2.4$, following Eq. 2.5, based on the electron modelling done by Strong et al. (2011b). Similarly to their study, α_{e1} was varied between -1.9 and -2.2 below a reference rigidity $P_{\alpha e0} = 4.0$ GV, whereas above this value $\alpha_{e2} = -2.4$ was found to reproduce the PAMELA spectrum satisfactorily.

The computed spectra are shown in Figures 4.2 and 4.3, the latter is multiplied by $E^{2.0}$, in comparison with data from both V1 (Stone et al., 2013) and PAMELA (Adriani et al., 2011a; Menn et al., 2013). For these spectra, following Eq. 2.2, $\delta_1 = 0.0$, $\delta_2 = 0.6$ and $P_0 = 3.0$ GV were kept unchanged. The PAMELA spectrum is reproduced satisfactorily above 10 GeV where solar modulation becomes progressively less. It is found that values of α_{e1} between -2.100 and -2.125 reproduce only the observed -1.35 power-law spectrum from V1, whereas for the -1.55 observed power-law spectrum changing the electron source spectrum alone is insufficient to reproduce such a steep spectrum in the required low-energy range. The reference solution (green line) is evidently far higher than the V1 data but reproduces the PAMELA data as expected.

4.3.2 Diffusion parameter adjustment

After testing adjustments to the source spectrum index, the next step is to investigate the effects of changing the diffusion coefficient similarly to the above approach, but with a greater focus on the resulting rigidity dependence.

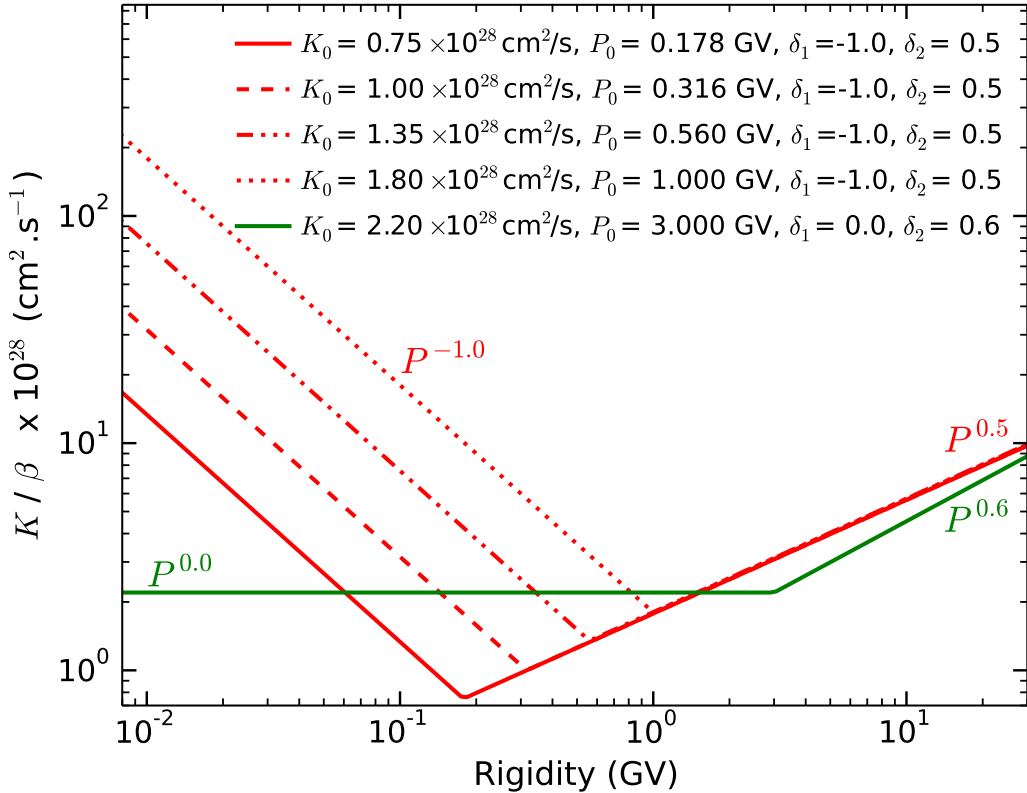


Figure 4.4: The rigidity dependence of the diffusion coefficient K , as in Eq. 2.2, resulting from changing K_0 , P_0 , δ_1 and δ_2 . Values resulting from $\delta_1 = -1.0$ for P below the respective breaks at $P_0 = 0.178, 0.316, 0.560, 1.000$ GV are shown as different red lines. For comparison values with $\delta_1 = 0.0$ below the break at 3.0 GV is shown in green, which was also used by Ptuskin et al. (2006). Above 3.0 GV the rigidity dependence is the same for all assumptions, $\delta_2 = 0.5$, with exception the green reference model which has $\delta_2 = 0.6$.

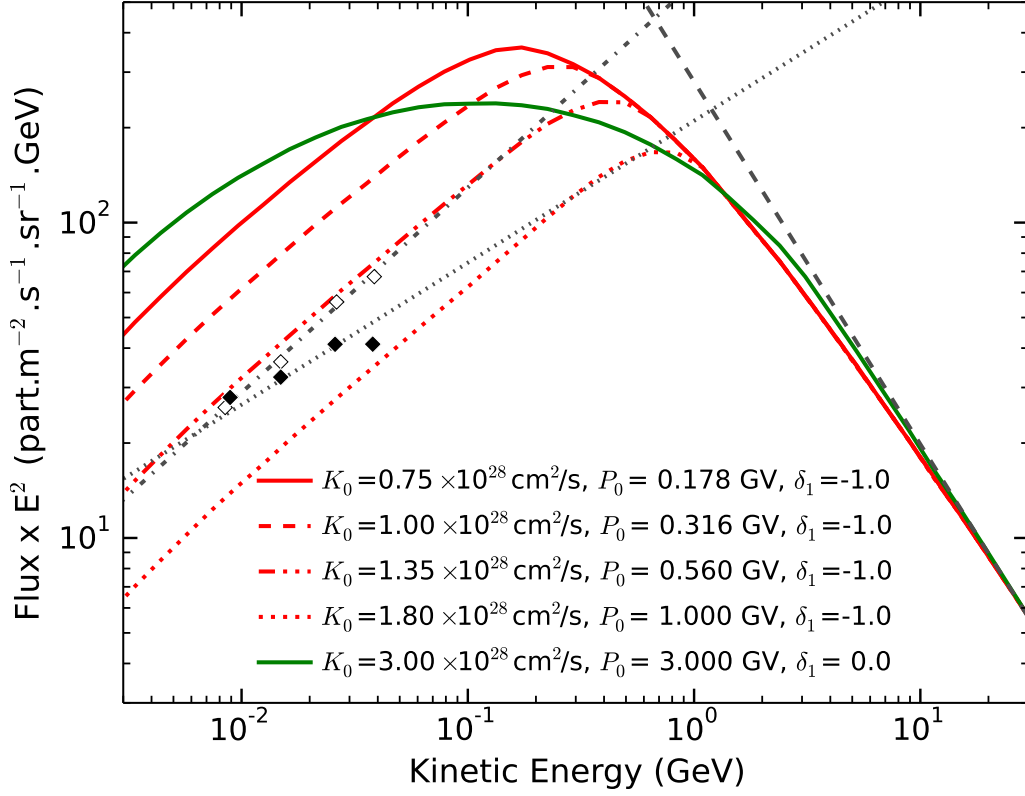


Figure 4.5: The resulting electron LIS's, multiplied with $E^{2.0}$, computed for the various rigidity dependences of K as shown in Fig. 4.4. As before, they are compared to the two V1 data sets. For the LIS's obtained with $\delta_1 = -1.0$ (four red lines), the overall intensity at low energies decreases as expected with K_0 increasing. All four exhibit power-law spectra at these lower energies similar to the observed -1.35 spectrum but don't reproduce the observed -1.55 spectrum. The reference LIS (green line) based on the green line in Fig. 4.4 is also shown.

The initial diffusion parameters

In Figure 4.4 the diffusion coefficients based on the assumptions for K_0 , P_0 , δ_1 and δ_2 are shown as function of rigidity as in Eq. 2.2. The example of Webber and Higbie (2013) is followed here, with the purpose of reproducing the power-laws observed by V1 at low energies, as are shown in Figure 4.1, more closely. In such an approach, the value of the diffusion coefficient is determined by K_0 when P_0 is changed for given values of δ_1 and δ_2 as is indicated in the figure.

The reference model (green line) has K independent of rigidity below 3.0 GV with $\delta_1 = 0.0$, but with $\delta_2 = 0.6$ above this rigidity. For the other diffusion coefficients (varying red lines), $\delta_1 = -1.0$ with δ_2 kept to a value of 0.5 above this rigidity so that the rigidity dependence here is then the same for all these assumed models. Effectively the break rigidity is shifted to lower values for each subsequent model to keep the corresponding K 's rigidity dependence the same above the break identical at the higher rigidities.

The diffusion coefficients of Figure 4.4 are implemented in the GALPROP code and the resulting spectra are shown in Figure 4.5, multiplied by $E^{2.0}$. The reference solution, based on the green line in Figure 4.4 is also shown here in green. For the LIS's obtained with $\delta_1 = -1.0$ (varying

red lines), the intensity decreases with increasing K as expected at a given low kinetic energy. The spectra (red lines) of Figure 4.5 all have maxima where the corresponding breaks in the rigidity dependence of K occur while they coincide above the corresponding and respective P_0 . They also coincide with the reference solution above 3.0 GV (green line). Importantly, all these LIS's exhibit power-laws similar to the -1.35 index suggested by the V1 data at these lower energies. The computed LIS that is the closest to the V1 spectrum with this power-law index, is the scenario with $K_0 = 1.35 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 0.56$ and $\delta_1 = -1.0$. However, the observed spectrum with the -1.55 index is not reproduced. For these results, the source spectrum indices are $\alpha_{e1} = -2.2$ and $\alpha_{e2} = -2.4$. These LIS's differ quantitatively from those produced by the Monte Carlo Diffusion Model of Webber and Higbie (2013), but qualitatively show the power-law trends at lower energies as required by the V1 observations. They found a reasonable fit to the observed -1.35 spectrum using $\alpha_{e1} = -2.2$, $P_0 = 1.76$ with $\delta_1 = -0.5$ and $\delta_2 = 0.5$ in their model.

Refining the diffusion parameters

Extending this approach, diffusion coefficients are searched for that will reproduce both the mentioned V1 observed spectra while still keeping the source spectrum indices, $\alpha_{e1} = -2.2$

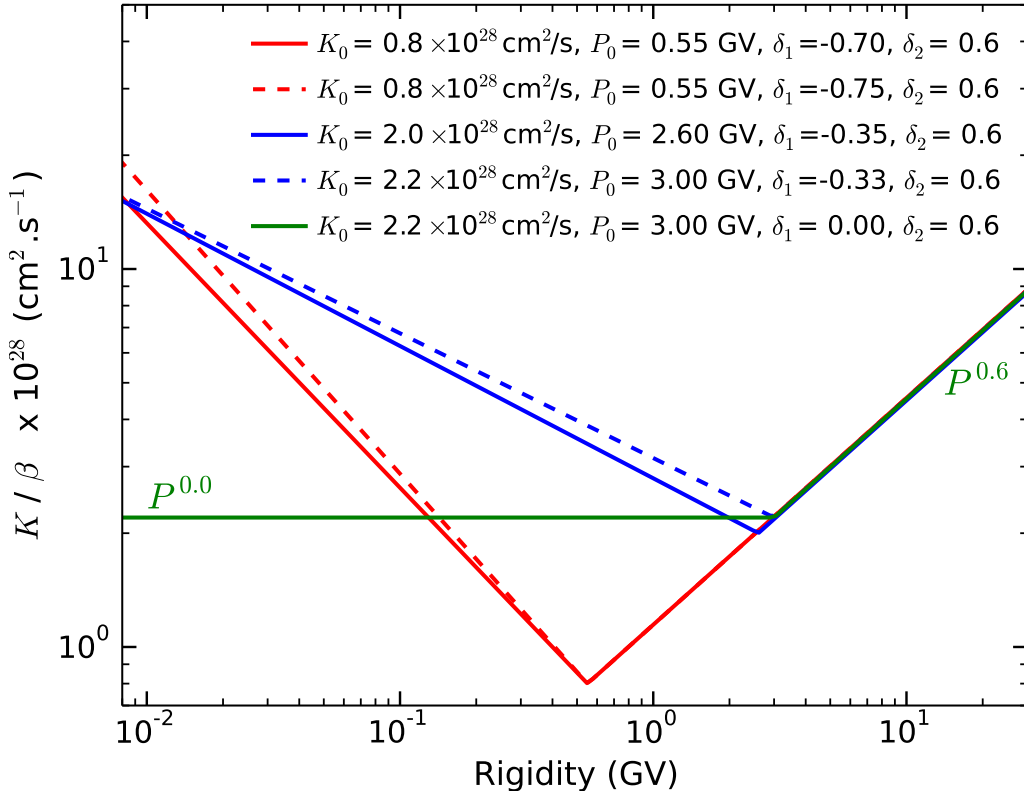


Figure 4.6: To improve on the calculated LIS of Fig. 4.5, K is refined further by changing δ_1 , δ_2 , K_0 , and P_0 from those values shown in Fig. 4.4. These changed values are indicated on the figure, and the corresponding graphs are given in blue and red, all with $\delta_2 = 0.6$. The green line serves as a reference case again, also with $\delta_2 = 0.6$, and relates to the green line in Fig. 4.4. Models found to reproduce the observed -1.35 spectrum are given in red and those found to reproduce the -1.55 spectrum are given in blue.

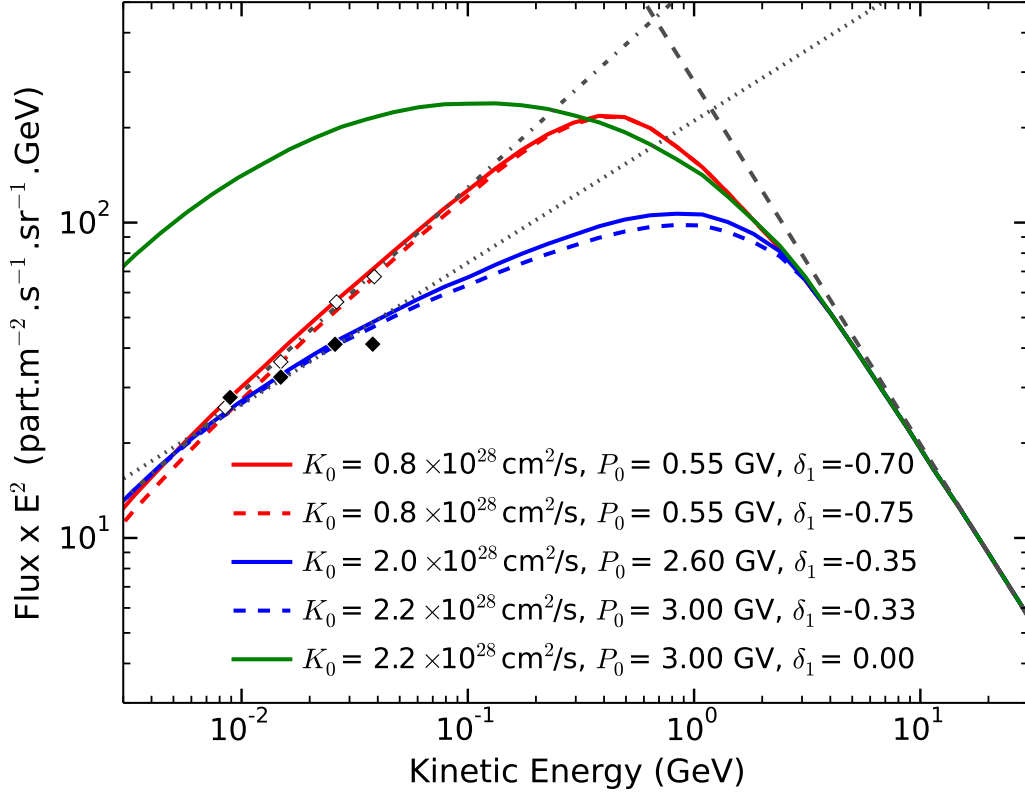


Figure 4.7: The computed LIS's, multiplied by $E^{2.0}$, computed for the diffusion coefficients as shown in Fig. 4.6. The two LIS's based on assuming $K_0 = 0.8 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 0.55 \text{ GV}$ and δ_1 between -0.70 to -0.75 are shown as red lines, reproducing the observed -1.35 spectrum rather well. The two LIS's based on $K_0 = 2.2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 3.0 \text{ GV}$ and $\delta_1 = -0.33$ are shown as blue lines, and evidently reproduce the observed -1.55 spectrum equally well. The reference LIS with $K_0 = 2.2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 3.0 \text{ GV}$ and $\delta_1 = 0.0$, is shown as the green line.

and $\alpha_{e2} = -2.4$ unchanged. This is done by varying δ_1 instead of keeping it fixed at -1.0 , as well as adjusting the break in the rigidity dependence of K through P_0 and subsequently also changing K_0 . Varying δ_1 between -0.1 and -1.0 , while adjusting K_0 and P_0 accordingly to keep the diffusion coefficient the same at the highest energies, the computed LIS's were adjusted until eventually both the observed spectra reasonably reproduced. The best corresponding set of diffusion coefficients, as a function of rigidity, is shown in Figure 4.6. The changes in the relevant parameters are also indicated in this figure. The reference case, independent of rigidity below 3.0 GV , is also shown again for illustrative purposes.

Figure 4.7 shows the corresponding computed LIS's, multiplied by $E^{2.0}$, that are based on the diffusion coefficients as shown in Figure 4.6. The two LIS's, based on assuming $\alpha_{e1} = -2.2$, $\alpha_{e2} = -2.4$, $P_{\alpha 0} = 4.0 \text{ GV}$, $K_0 = 0.8 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 0.55 \text{ GV}$, $\delta_2 = 0.6$ and δ_1 between -0.70 to -0.75 (as a margin of uncertainty in reproducing the observations), are shown as red lines, reproducing the observed -1.35 spectrum rather well. These LIS's have a maximum intensity at around 0.5 GeV indicating the break between the two power-law spectra as required to reproduce both the V1 and PAMELA observations. The next two LIS's, shown as blue lines, are based on varying $K_0 = 2.0$ to $2.2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 2.6$ to 3.0 GV and $\delta_1 = -0.35$ to

-0.33 , respectively, while keeping $\alpha_{e1} = -2.2$, $\alpha_{e2} = -2.4$, and $P_{\alpha 0} = 4.0$ GV. They evidently also reproduce the observed -1.55 spectrum equally well. These LIS's have a maximum at around 0.9 GeV. The reference LIS (green line), with $\alpha_{e1} = -2.2$, $\alpha_{e2} = -2.4$, and $P_{\alpha 0} = 4.0$ GV, $K_0 = 2.2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 3.0$ GV and $\delta_1 = 0.0$, is shown for illustrative purposes, representing the way the electron LIS was computed before the current V1 observations were made. For this reference LIS the maximum is at around 0.1 GeV, with the low energy intensities significantly too high compared to the V1 observations.

4.4 Resulting LIS's matching the two Voyager 1 spectra

4.4.1 Resulting calculated LIS's

The LIS's computed for investigation are shown together in Figures 4.8 and 4.9, multiplied by $E^{2.0}$. The relevant, corresponding parameters are summarized in Table 4.1. Firstly, the computed reference LIS as shown in Figure 4.7 is plotted again as the green line and is based on the diffusion coefficient shown in Figure 4.6. The corresponding set of parameters is given in the first row of the table. Secondly, the two spectra shown in red in Figures 4.2 and 4.3 are now replotted as an orange band with the corresponding parameter set given in the second row of the table. The orange band is thus bound by the two mentioned spectra, illustrating the difference between the solid red line in Figures 4.2 and 4.3 as the higher spectrum and the dashed-red line as the lower spectrum. This modelling approach reproduces only the observed -1.35 spectrum, and not the -1.55 observed spectrum. Thirdly, the computed LIS's shown as two red and two blue spectra in Figure 4.7 are replotted here as red and blue bands, respectively. The corresponding parameter sets are given in the third and fourth rows of Table 4.1.

Inspection of the computed LIS's in Figures 4.8 and 4.9 indicates that the modelling approach with δ_1 between -0.70 and -0.75 , gives spectra that represent the observed -1.35 spectrum reasonably, as illustrated by the red band in Figures 4.8 and 4.9 as an indication of the margin of uncertainty caused by varying δ_1 between these two values. These two LIS's can be considered as the highest possible ones based on the simplified assumptions made here. In contrast, the LIS's given as the orange band evidently reproduce the observed -1.35 spectrum less well, being too

Table 4.1: List of model parameters used to calculate the electron LIS's of Figs. 4.8 and 4.9.

Study Case	Power -law	α_{e1}	$P_{\alpha e0}$ (GV)	α_{e2}	K_0 ($10^{28} \text{ cm}^2 \text{ s}^{-1}$)	δ_1	P_0 (GV)	δ_2
Green LIS	-	-2.4	none	-2.4	2.2	0.0	3.00	0.6
Orange LIS	-1.35	-2.1 to -2.125	4.0	-2.4	2.2	0.0	3.00	0.6
Red LIS	-1.35	-2.2	4.0	-2.4	0.8	-0.70 to -0.75	0.55	0.6
Blue LIS	-1.55	-2.2	4.0	-2.4	2.0 to 2.2	-0.33 to -0.35	2.6 to 3.0	0.6
W-H LIS	-1.35	-2.2	none	-2.2	3.0	-0.5	1.76	0.5

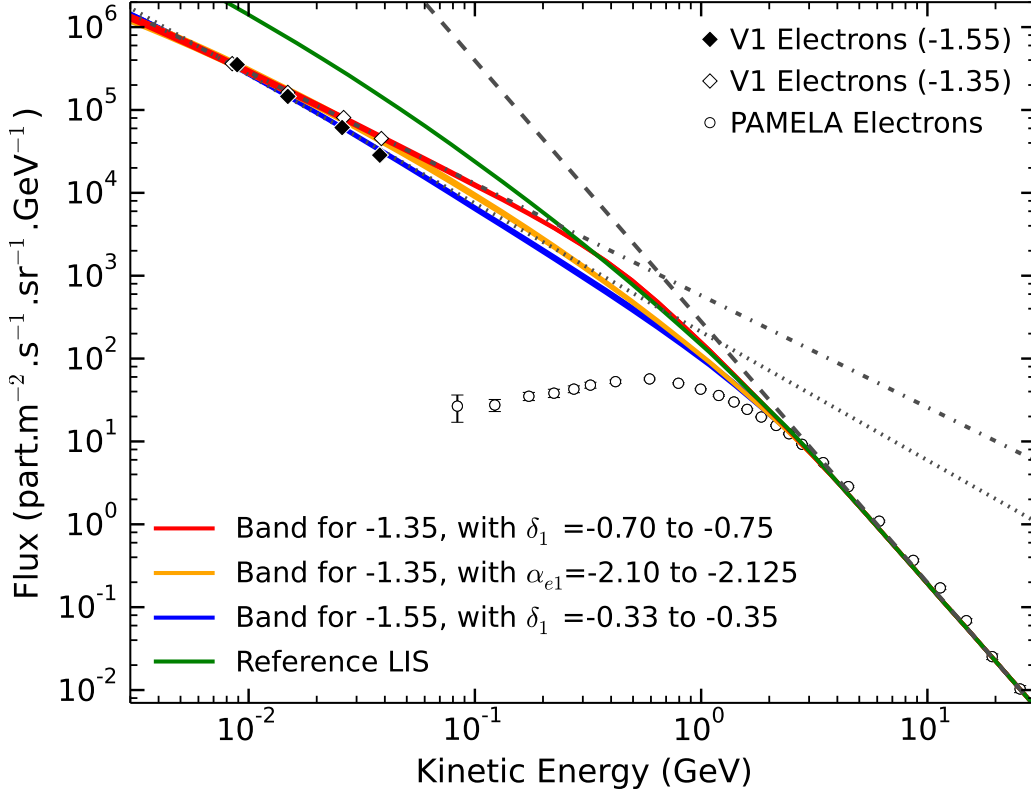


Figure 4.8: The resulting computed LIS's found in this study that reproduce the V1 and PAMELA electron spectra, as indicated in Fig.4.1, are based on the parameters as listed in Table 4.1. The LIS that reproduces the observed -1.35 spectrum, is shown as the red band as a margin of uncertainty in the input parameters, and is based on the the parameters shown in the third row of the table. The second LIS that reproduces also the observed -1.35 spectrum but less well than the previous case, is shown as the orange band and is based on the parameters given in the fourth row of the table. The LIS reproducing the observed -1.55 spectrum is given as a blue band, with parameters as given in the fourth row of the table. The reference LIS is shown as the green line, with parameters as given in the first row of the table.

low around 40 MeV. This indicates that the approach in varying only the source spectrum index seems less suitable and is perhaps too simplified. Finally, the computed LIS's reproducing the observed -1.55 spectrum, given as the blue band, are also reasonably good so that the approach as described above to establish this -1.55 spectrum seems justified. However, the LIS's for this case are evidently not reproducing the observed power-law spectra as well as the -1.35 case (red band) because they are significantly lower than the previous ones in the mid-energy range (50 to 500 MeV), which is of particular importance to solar modulation studies.

The parameters used by Webber and Higbie (2013) to reproduce the observed -1.35 spectrum with their model, are shown as the fifth row in the table. They don't seem to require a break in the rigidity dependence of the source term, whereas the results presented here indicate a break at 4.0 GV, where the index changes from as low as -2.1 to -2.4 . The diffusion coefficient is also significantly less than theirs in the energy range from 100 MeV to 1 GeV, which leads to significant higher intensity at these energies. The break in the LIS for the -1.35 spectrum is therefore more prominent.

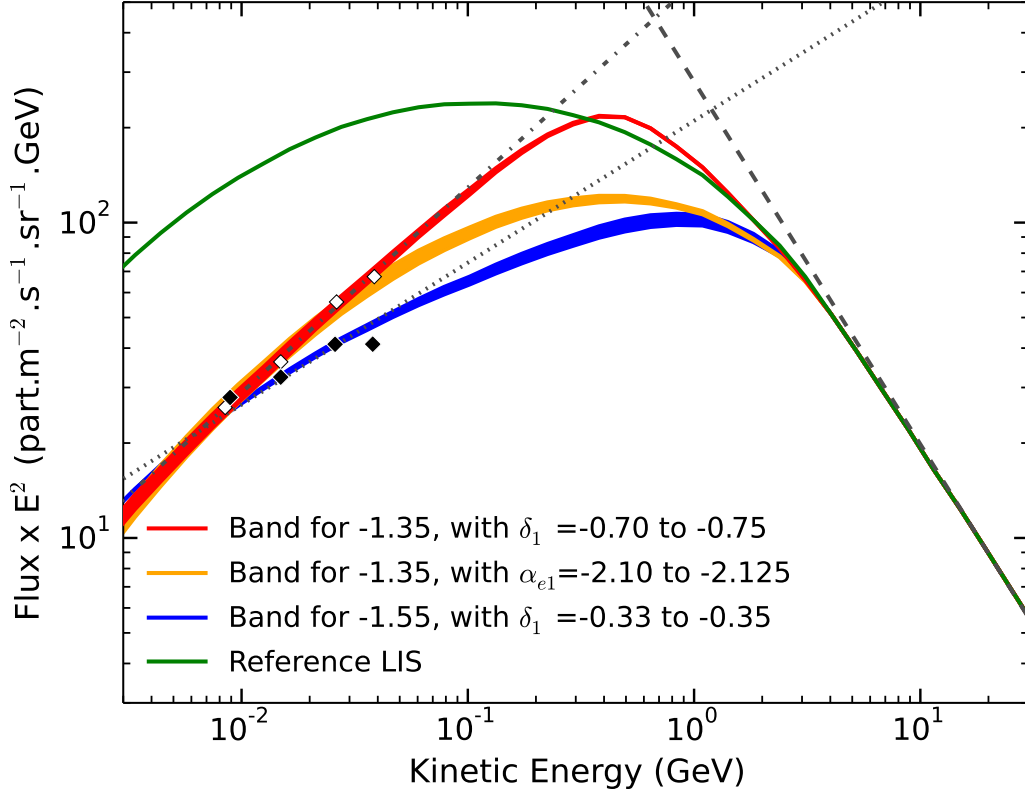


Figure 4.9: Same as Fig. 4.8 but with the intensity multiplied by $E^{2.0}$ to enhance the differences.

4.4.2 Comparison with published modelling

Reproducing the V1 data with this modelling approach results in much improved electron LIS's, which are much lower at energies below ~ 200 MeV than previous plain diffusion model estimates, such as those computed by Strong et al. (2011b). An important aspect is that the electron LIS (below 50 GeV) clearly consists of the combination of two power-laws and that the consequent break in the LIS is confirmed by the straightforward galactic propagation approach as well as by solar modulation studies. This break was also emphasized by Strong et al. (2011b). The current computations indicate that this break is at a lower energy and comes more gradually than found by Potgieter and Nndanganeni (2013a). They used V1 observations from 2010 which clearly show a power-law up to 120 MeV before the break occurs. However, Webber and Higbie (2013) also concluded that this break is gradual, starting at about 2 GeV where the spectrum is $E^{-(3.15 \pm 0.05)}$ and continuing down to about 100 MeV where the spectrum becomes $E^{-(1.45 \pm 0.15)}$. They emphasized the fact that they could reproduce the observed V1 and PAMELA electron spectra with a single power-law source spectrum with index $\alpha_{e1} = \alpha_{e2} = -2.2$, whereas somewhat better results are found here when including a break in the index with $\alpha_{e1} = -2.2$ below, and $\alpha_{e2} = -2.4$ above $P_{\alpha 0} = 4.0$ GV.

The realization that a power-law is also exhibited at very low energies came when V1 observed such a spectrum once it had gone beyond the solar wind termination shock. The solar modulation modelling and application of turbulence theory for galactic electrons in the heliosphere, lead

Potgieter and Nndanganeni (2013a,b) to predict that the electron heliopause spectrum, and subsequently the LIS, must have such a spectral shape. Making this conclusion was complicated by the fact that V1 had observed a factor of ~ 400 increase for ~ 10 MeV electrons from late 2004 (at ~ 94 AU), when it crossed the termination shock, to August 2012 (at 121.7 AU), when it crossed the heliopause. While traversing the relatively narrow heliopause region, these electrons increased by a factor of ~ 2 . Although the power-law spectral shape became quite clear, the value of the differential intensity was more difficult to determine, this was made even more complicated by the two procedures used by the Voyager team to calculate the differential flux from counting rates. At present, it is reasonable to give the intensity beyond the heliopause at 10 MeV as (350 ± 50) electrons $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$ decreasing to (50 ± 5) electrons $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$ at 100 MeV, when the -1.35 spectrum is used.

4.5 Summary

The observed LIS for electrons by V1 and PAMELA between about 1 MeV and 100 GeV indicates that it is the combination of two power-laws, with $E^{-(1.45 \pm 0.15)}$ below ~ 100 MeV but with $E^{-(3.15 \pm 0.05)}$ above energies where solar modulation is negligible.

By using the GALPROP plain diffusion model the galactic propagation modelling approach can easily reproduce the observed -1.35 spectrum. This can be done by either modestly adjusting the power index of the source spectrum or by also including reasonable adjustments of the rigidity dependence of the spatial diffusion coefficient. For the source spectrum index variations only a value for α_{e1} of between -2.1 and -2.125 is required, with all the other parameters unchanged. When changing the rigidity dependence of the diffusion coefficient, values of $\alpha_{e1} = -2.2$ and δ_1 between -0.70 to -0.75 are needed.

It was not as easy to reproduce the observed -1.55 spectrum with a plain diffusion approach. No fit was found by using this method of varying only the source spectrum index at lower rigidity. For the diffusion coefficient adjustments a value for δ_1 between -0.33 to -0.35 gives a reasonable approximation to the V1 data. This computed LIS seems less convincing (in terms of its spectral shape), with significantly lower intensity between 50 MeV and 1 GeV which will have a considerable impact, if indeed the case, on solar modulation studies where the prime objective is to reliably determine a 'standard' set of modulation parameters for electrons during at least solar minimum activity conditions.

Focusing on the observed -1.35 spectrum indicates that the LIS exhibits a gradual turn in the spectral shape, starting from (2.0 ± 0.5) GeV, and ending at (100 ± 10) MeV. According to this simplified modelling, the break is caused primarily by galactic propagation effects, as presented in Figure 4.6 and summarized in Table 4.1. For this spectrum it is found that the electron intensity beyond the heliopause at 10 MeV is (350 ± 50) electrons $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$, decreasing to (50 ± 5) electrons $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$ at 100 MeV.

Further comparisons with these results will use only the highest and lowest LIS's in Figure 4.9 as upper and lower boundaries for the results of this specific implementation for the electron LIS's calculated with a plain diffusion model.

The contents of this chapter have been published by Bisschoff and Potgieter (2014).

Chapter 5

Reproducing the Voyager 1 LIS's for cosmic ray nuclei

5.1 Introduction

The observations made by V1 also include those for galactic protons, Helium and Carbon (Stone et al., 2013). Similarly to the electron observations, this allows the comparison of computed galactic spectra with experimental data down to a few MeV/nuc.

Following the implementation of the GALPROP code in the previous chapter, LIS's for CR protons are calculated next and subsequently also for Helium ($^3\text{He}_2 + ^4\text{He}_2$) and Carbon ($^{12}\text{C}_6 + ^{13}\text{C}_6$). These LIS's are calculated using the GALPROP propagation code in its simplest form over the energy range 3 MeV/nuc to 100 GeV/nuc. The galactic diffusion parameters are adjusted in the model and then additional features are included as needed, such as adding reacceleration and adjusting the source input.

By eliminating the calculated LIS's that don't agree with the required observational restrictions, such as PAMELA observations at the Earth, a single set of parameters can possibly be found to reproduce the mentioned the V1 observed spectra simultaneously.

5.2 Cosmic ray nuclei observations

5.2.1 The Voyager 1 spectra for cosmic ray nuclei

As with the electron data, Stone et al. (2013) presented LIS's for protons, Helium, Carbon and Oxygen beyond the heliopause. Unlike the electron LIS, the nuclei don't show power-laws at the V1 energies, but instead the LIS's level out with decreasing energy for protons and Helium. The Carbon LIS not only levels out, but the intensity slowly decreases with decreasing energy. The Oxygen LIS shows even more interesting behaviour at lower energies, but in this Chapter only the LIS for protons, Helium and Carbon will be investigated. The corresponding V1 nuclei LIS's are shown in Figure 5.1 and will be discussed in more detail below.

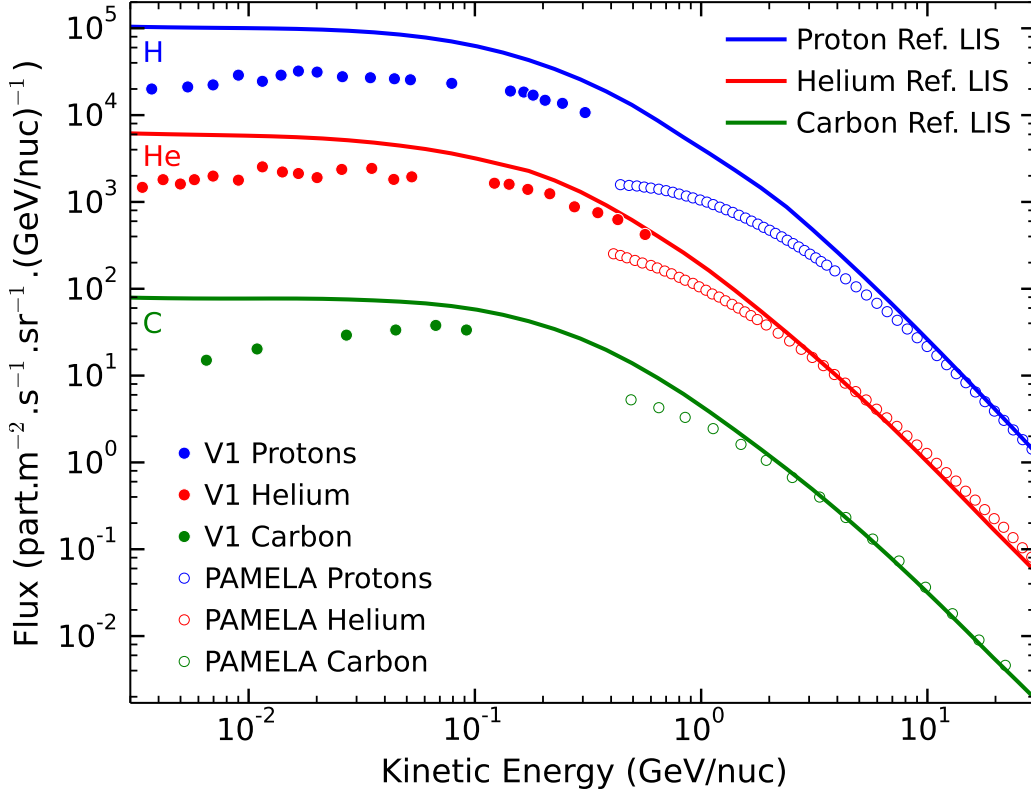


Figure 5.1: Plain diffusion reference model LIS's for protons (blue curve), Helium (red curve) and Carbon (green curve) shown alongside the observational data from V1 (Stone et al., 2013) (filled circles) and spectra from PAMELA at the Earth, averaged for 2006-2008 (Adriani et al., 2011b, 2014; Menn et al., 2013) (open circles).

5.2.2 PAMELA nuclei observations

The PAMELA experiment also made observations at the Earth for CR nuclei (Adriani et al., 2011b, 2014; Menn et al., 2013; Boezio, 2014). The PAMELA observations are used here again to constrain the higher energy LIS's and are also shown in Figure 5.1. The B/C ratio will also be used to further test the relevance of the models used to calculate the protons, Helium and Carbon LIS's.

5.3 Plain diffusion model

When comparing the V1 observations for protons, Helium and Carbon (Stone et al., 2013) to the LIS's computed by previous propagation models, it becomes clear that the models mostly overestimated the intensity of the LIS's below about 1 GeV/nuc. This is illustrated in Figure 5.1, where the V1 observations are compared to such LIS's produced with the GALPROP code. These LIS's, for protons (blue curve), Helium (red curve) and Carbon (green curve), are considered here to be reference nuclei LIS's for the GALPROP plain diffusion model. The observations show that any further estimations of the LIS's produced by numerical models would have to reduce the spectral intensity for the observed V1 energy range.

5.3.1 Diffusion parameter adjustment

As done in the previous chapter, the GALPROP plain diffusion model is implemented with the parameters K_0 , P_0 and δ_1 , determining the rigidity dependence of the diffusion coefficient in Eq. 2.2, considered as free parameters. The parameter δ_2 was initially also taken as such, but investigative tests showed that the reference value of $\delta_2 = 0.6$ was needed in order for the LIS's to reproduce the observations. The value of δ_2 is thus kept unchanged for all the plain diffusion model runs. For the source function the values are kept fixed from the reference model at $P_{\alpha 0} = 40$ GV, $\alpha_1 = -2.30$ and $\alpha_2 = -2.15$ in Eq. 2.4 .

In order to simply reproduce the observations, K_0 and P_0 are adjusted together, with separate model runs adjusting δ_1 . This manner of choosing parameter values shows that only adjusting δ_1 can't achieve the reproduction of the V1 observations, although δ_1 does affect the shape of the computed LIS's significantly in the required energy range. After finding the sets of values for K_0 and P_0 that most closely give computed LIS's that reproduce the V1 data, δ_1 is then adjusted to finely control the computed LIS shape. The resulting sets of assumed diffusion coefficients are shown in Figure 5.2, together with the parameters used for the reference spectra shown in Figure 5.1 (black line).

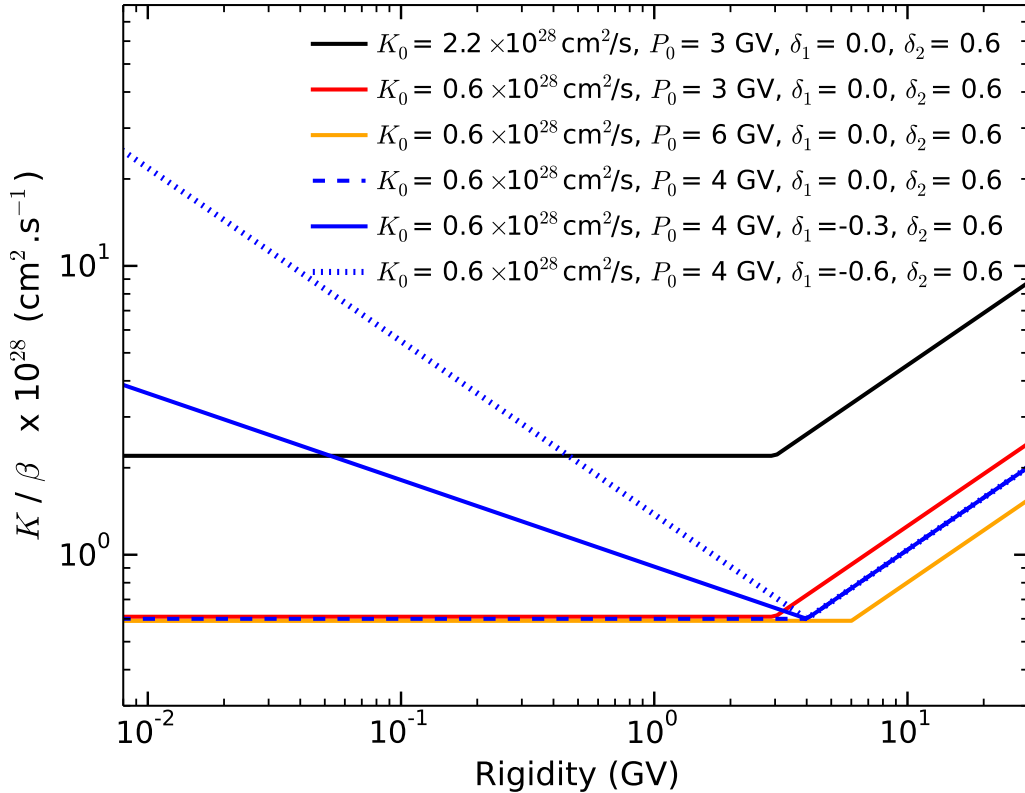


Figure 5.2: The assumed diffusion coefficient, as function of rigidity, as implemented for the reference model of Fig. 5.1 is shown in black. Adjusted model parameters are chosen as to potentially reproduce the V1 proton observations. This gives the listed values for K_0 , P_0 and δ_1 , and gives the diffusion coefficients shown with the red, yellow and three blue lines.

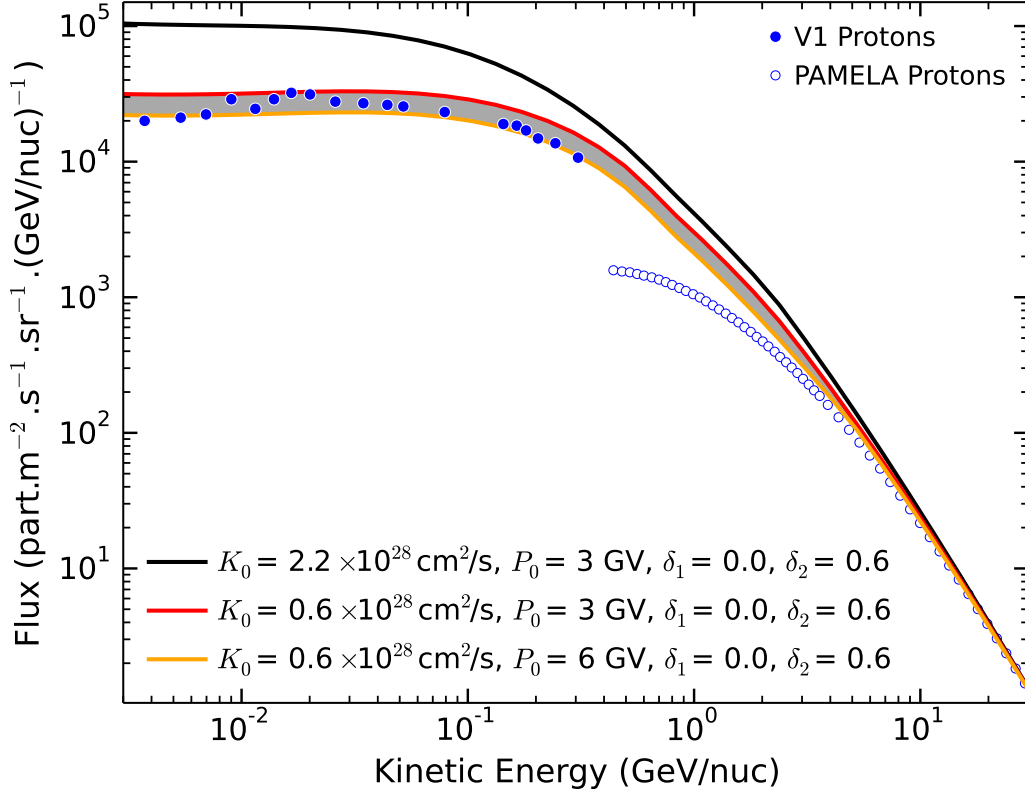


Figure 5.3: The computed proton LIS band bounded by the parameters listed in Fig. 5.2, upper value given by the red curve and lower value by the yellow curve. These two LIS's, together with the reference LIS (black curve), are compared to the V1 and PAMELA proton observations as in Fig. 5.1.

Adjusting only K_0 and P_0 gives the models with $K_0 = 6.0 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 3.0 \text{ GV}$ (red line) and $K_0 = 6.0 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 6.0 \text{ GV}$ (orange line), producing the spectrum band of Figure 5.3. These computed LIS's give lower (red curve) and upper (orange curve) bounds to the proton LIS needed to match the V1 spectrum. The higher value of P_0 (orange curve) results in a lower diffusion coefficient giving a lower intensity for the LIS at energies below 10 GeV/nuc. A computed proton LIS reproducing the V1 proton data should ideally lie within this band, given the spread in the observations. This band represents the most reasonable computed LIS when considering diffusion coefficients where the indices are the same as those of the reference model. The PAMELA observations above 20 GeV are clearly reproduced well where solar modulation becomes negligible.

Attempting to give a better representation of the observations than the LIS band of Figure 5.3, parameters are chosen to give models as shown by the three blue lines in Figure 5.2. The value of K_0 is kept the same, but P_0 is now set to 4.0 GV and for two of these models δ_1 is adjusted to -0.3 (solid blue line) and -0.6 (dotted blue line) instead of 0.0. Figure 5.4 shows the three corresponding computed LIS's. The change in δ_1 greatly increases the diffusion coefficient at the lowest rigidities and evidently lower the computed LIS's for energies below about 4 GeV/nuc. Effectively the LIS shape is changed, creating a sharper change in the LIS's at about 4 GeV/nuc and a flatter shape below this spectral change. The resulting proton LIS for $\delta_1 = 0$ (dashed

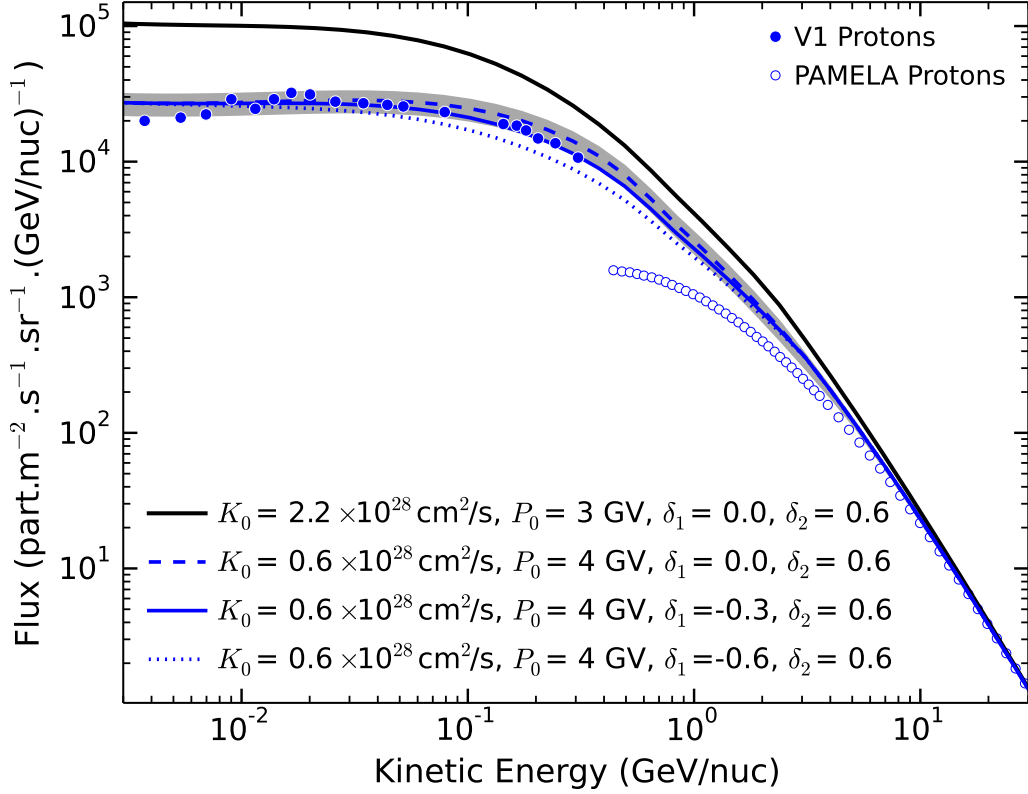


Figure 5.4: The computed proton LIS's for the remaining models in Fig. 5.2 (blue curves) compared to the band (shaded grey area) of Fig. 5.3 and the reference LIS (black curve), showing the change in slope for the LIS with a decrease in δ_1 . For $\delta_1 = -0.3$ (solid blue curve) the LIS satisfactorily matches the V1 protons, while only overestimating the values below 7 MeV/nuc. Observations as shown in Fig. 5.1.

blue curve) agrees well with the data only at lower V1 energies, while for $\delta_1 = -0.6$ the LIS only matches the highest energy observations of V1. The resulting proton LIS for $\delta_1 = -0.3$ reproduces the V1 data well above 7 MeV/nuc and is the best representation of the observations within the band.

5.3.2 Resulting LIS's for He and C

With the computed proton LIS reproducing the V1 proton observations well, the Helium and Carbon LIS's are compared next. Figure 5.5 shows the LIS's computed with $K_0 = 6.0 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 4.0 \text{ GV}$ and $\delta_1 = -0.3$, for protons (blue curve), Helium (red curve) and Carbon (green curve).

Unfortunately, this computed Helium LIS is lower than the V1 observations, as well as having a lower intensity than the PAMELA observations above 4 GeV/nuc, similarly to the reference Helium LIS in Figure 5.1. In order to correct this discrepancy, while keeping the proton LIS unchanged, the relative abundance of $^4\text{He}_2$ (the primary Helium isotope at the sources) needs to be increased. To match the PAMELA values above 50 GeV/nuc, where heliospheric modulation can be safely ignored (Strauss and Potgieter, 2014), an increase of about 30% in the $^4\text{He}_2$ abundance is sufficient, as is represented in Figure 5.5 with the dashed orange curve. As expected

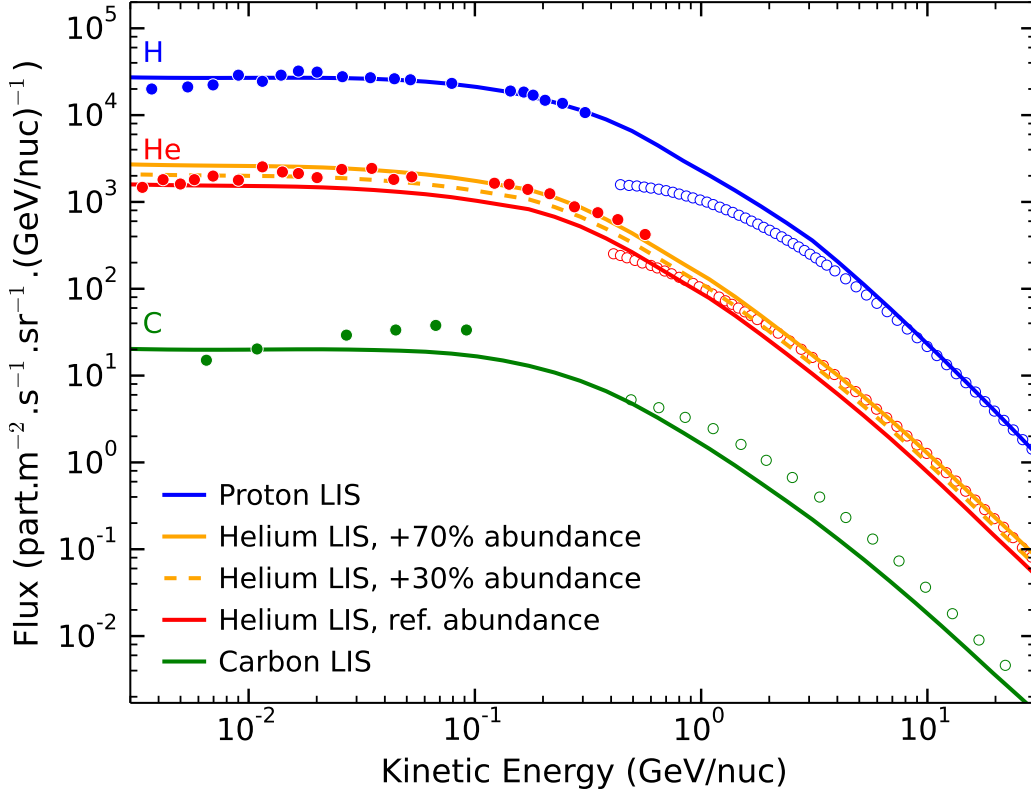


Figure 5.5: The computed proton LIS (blue curve) from Fig. 5.4, the corresponding computed Helium LIS (red curve) and computed Carbon LIS (green curve) compared to the observational data as in Fig. 5.1. The computed LIS for Helium with an increased ${}^4\text{He}_2$ source abundance is shown for an increase of 30% (dashed yellow curve) and an increase of 70% (solid yellow curve).

the proton and Carbon LIS's are unaffected, while the Helium LIS has an increased intensity over all energies and now matches the PAMELA values above 50 GeV/nuc. For the V1 data above 0.1 GeV/nuc this Helium LIS remains too low, while also undercutting the PAMELA data at energies below 50 GeV/nuc, which from a solar modulation point of view is not suitable. The effect of a 70% increase to the ${}^4\text{He}_2$ abundance is also shown in Figure 5.5 with the solid orange curve. This computed Helium LIS achieves the required effect as the LIS matches the V1 data well (above 0.01 GeV/nuc) while keeping above the PAMELA data at all energies, which is a requirement for a solar modulation; an assumed or computed LIS can't be lower than the observed spectrum at the Earth. The drawback however, is that the computed LIS is slightly higher than the PAMELA values at energies above 50 GeV/nuc where it is expected to match more closely.

The computed Carbon LIS shown in Figure 5.5 gives a relatively poor representation of the measured intensities. Increasing the Carbon abundances similarly to the Helium abundances could improve the LIS over most energies, but the slope of the LIS then results in the PAMELA observations above 10 GeV/nuc not being matched, while the reference LIS of Figure 5.1 matches the slope suggested by these observations. The corresponding computed B/C ratio, as shown in Figure 5.10, also then greatly overestimates the values over all energies, while the reference model gives a good representation of the observed ratio, but evidently fails to reproduce the V1

spectra. This then indicates that simply changing the parameters of the plain diffusion model is insufficient to compute acceptable LIS's for protons, Helium and Carbon simultaneously.

5.4 Reacceleration model

To address the above mentioned problem the reacceleration model as implemented in GALPROP. This model is less simplistic as it also includes diffusion in momentum space. The variables for the reacceleration propagation model are similar to that of the plain diffusion model in GALPROP, but now includes an Alfvén wave speed, $V_A = 36 \text{ km.s}^{-1}$, and particularly a single index δ for the diffusion coefficient, above and below the reference rigidity. Consequently, a new reference model is derived from the approach of Ptuskin et al. (2006) that includes reacceleration. The source function parameters are also changed correspondingly with $P_{\alpha 0} = 9.0 \text{ GV}$, $\alpha_1 = -1.82$ and $\alpha_2 = -2.36$ in Eq. 2.4.

5.4.1 Diffusion parameter adjustment

To reproduce the measured CRs intensities, the diffusion coefficient parameters of the new reference model are adjusted similarly to what was done for the plain diffusion model. The index

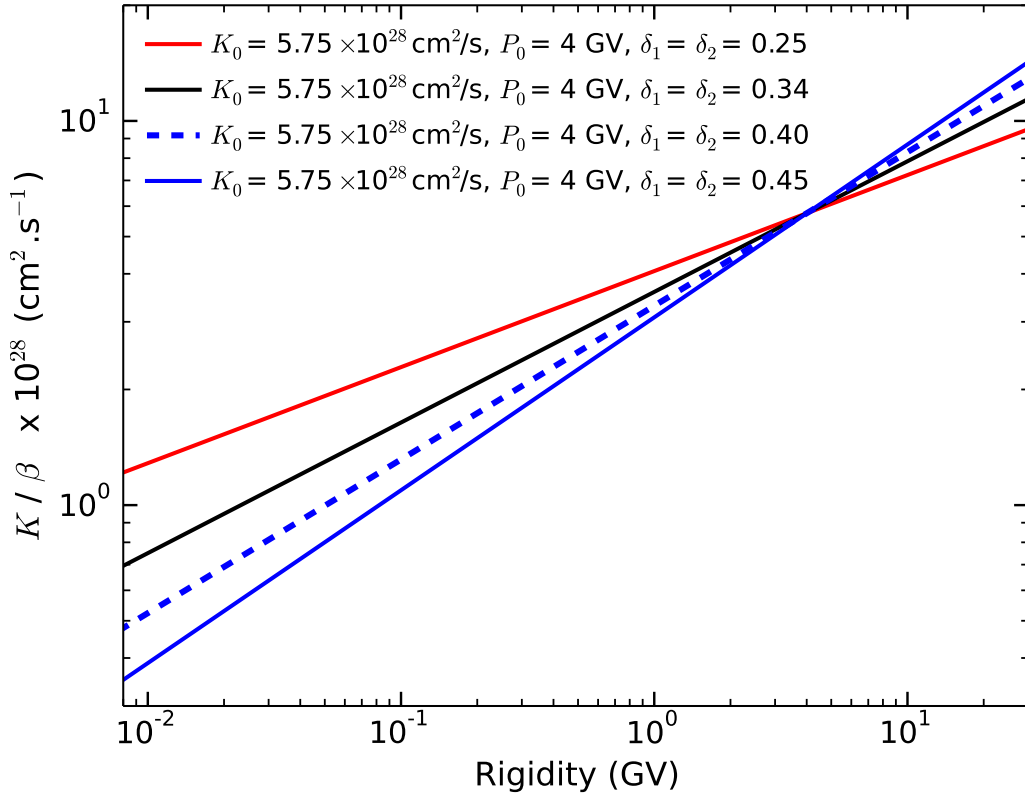


Figure 5.6: The chosen diffusion parameter values, according to Eq. 2.2, for reacceleration models with variations in δ : 0.25 (solid blue line), 0.30 (dashed blue line), 0.45 (solid red line), and the reacceleration reference model with index of 0.34 (black line). K_0 is kept at $5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and P_0 at 4.0 GV.

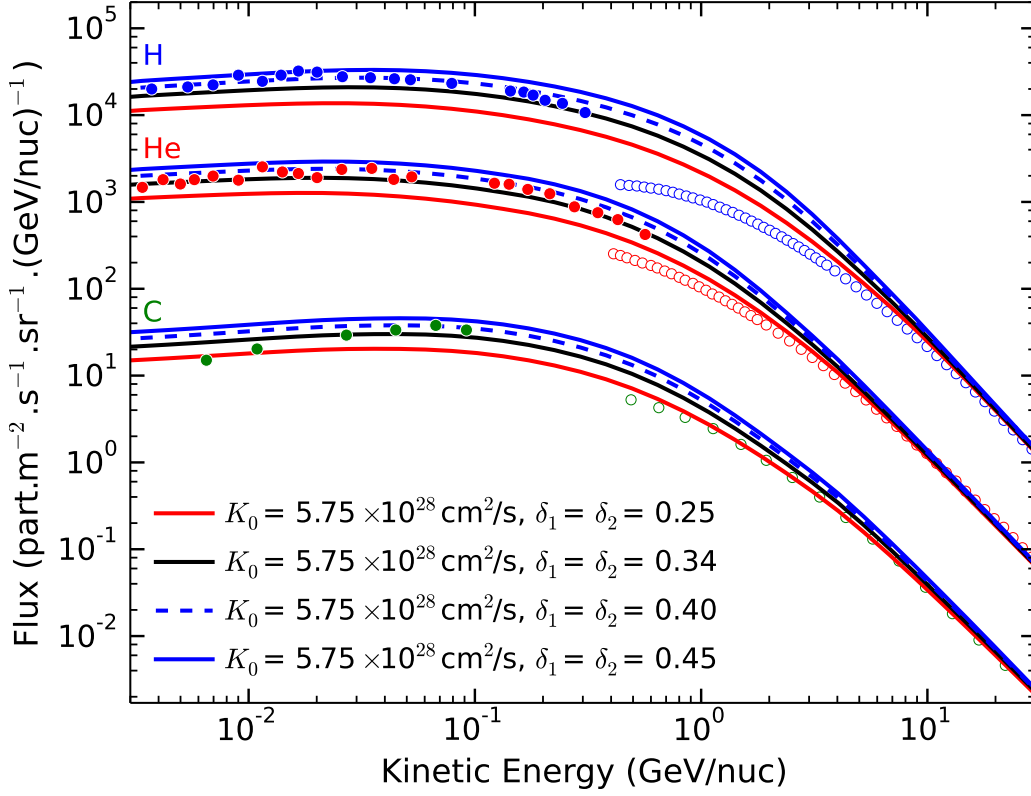


Figure 5.7: Computed LIS's for the parameters given in Fig. 5.6 with protons at the top, Helium in the middle and Carbon at the bottom. These LIS's are compared to observations as in Fig. 5.1. Models with a larger δ evidently give LIS's with increased intensity to better match the V1 data than the reference LIS.

δ is initially adjusted while keeping the values of K_0 and P_0 the same. The parameters are shown in Figure 5.6 where δ is adjusted to 0.25 (red line), 0.40 (dashed blue line) and 0.45 (solid blue line) from the reacceleration reference index of 0.34 (black line), while $K_0 = 5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and $P_0 = 4.0 \text{ GV}$ are unchanged. The corresponding LIS's computed with these parameter values are shown in Figure 5.7. Lowering the value of δ is seen to decrease the computed LIS intensity, as shown for $\delta = 0.25$ (red curve), as such an index steeper than the reference value is clearly needed. For $\delta = 0.45$ the computed LIS's (solid blue curves) for protons, Helium and Carbon give upper values to the CR spectra in the V1 energy range, while the reference value $\delta = 0.34$ LIS (black curve) gives the lower values. The computed LIS for $\delta = 0.40$ match both the V1 and PAMELA observations well, but none of the computed Carbon LIS's can reproduce the decreasing trend suggested by the lowest energy of V1 observations. These computed LIS's show higher intensities in the energy range 0.1 GeV/nuc to 10 GeV/nuc for protons when compared to the plain diffusion LIS of Figure 5.5. In this energy range solar modulation should be considered when comparing the LIS's to the PAMELA observations, the plain diffusion LIS lies too close to the observations, seemingly underestimating the amount of expected modulation when compared to the estimations of Strauss and Potgieter (2014). Including reacceleration in the model gives a LIS that more closely reproduces the expected modulation.

The next set of reacceleration models have only the K_0 values adjusted in Eq. 2.2. A break in the index δ is not included, therefore the value of P_0 could also be adjusted to achieve

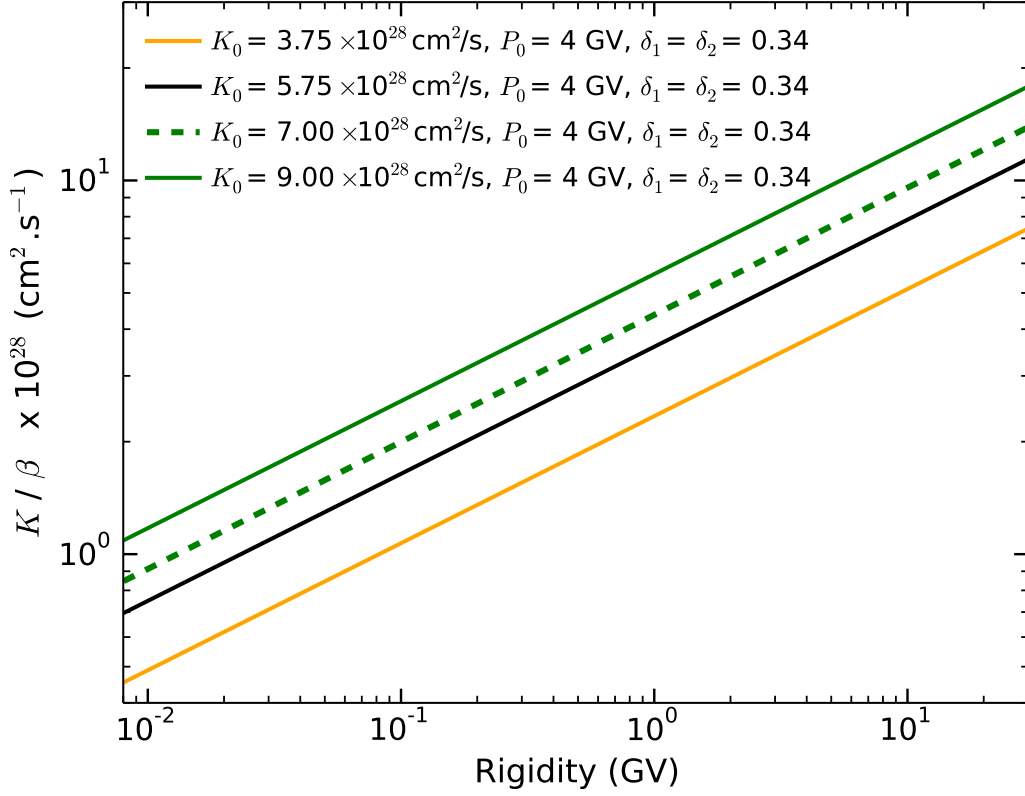


Figure 5.8: The diffusion parameter values for reacceleration models with variations, in Eq. 2.2, for K_0 : $3.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid yellow line), $7.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed green line), $9.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid green line), compared with the reference model with a value of $5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed black line). P_0 is kept at 4.0 GV and δ at 0.34.

the same effect, but is kept unchanged for these runs. The models are shown in Figure 5.8, where K_0 is adjusted to $3.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid yellow line), $7.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed green line), and $9.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid green line) from the reference value of $5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (black line), while the parameters $P_0 = 4.0 \text{ GV}$ and $\delta = 0.34$ are kept fixed. Figure 5.9 shows the corresponding computed LIS's resulting from these adjustments. For a lower value of K_0 the LIS intensities are decreased at lower energies, while increasing the intensities for energies above about 1 GeV/nuc. The inverse is true for a higher K_0 , giving increased intensity at lower energies and decreased intensity for $E > 1 \text{ GeV/nuc}$. This decrease is too large for $K_0 = 9.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid green curve) as it matches the the PAMELA values closely above 3 GeV/nuc, thus ignoring requirements of heliospheric modulation. For $K_0 = 7.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed green curve) the decrease is less, while giving a good match to the V1 observations over all energies for protons and Helium. However, once again the steeper trend of the V1 Carbon below 60 MeV/nuc can't be reproduced.

5.4.2 Resulting B/C ratios

The most suitable models are selected from the above diffusion parameter tests and the computed B/C ratios for these models are shown in Figure 5.10 in comparison with the PAMELA B/C

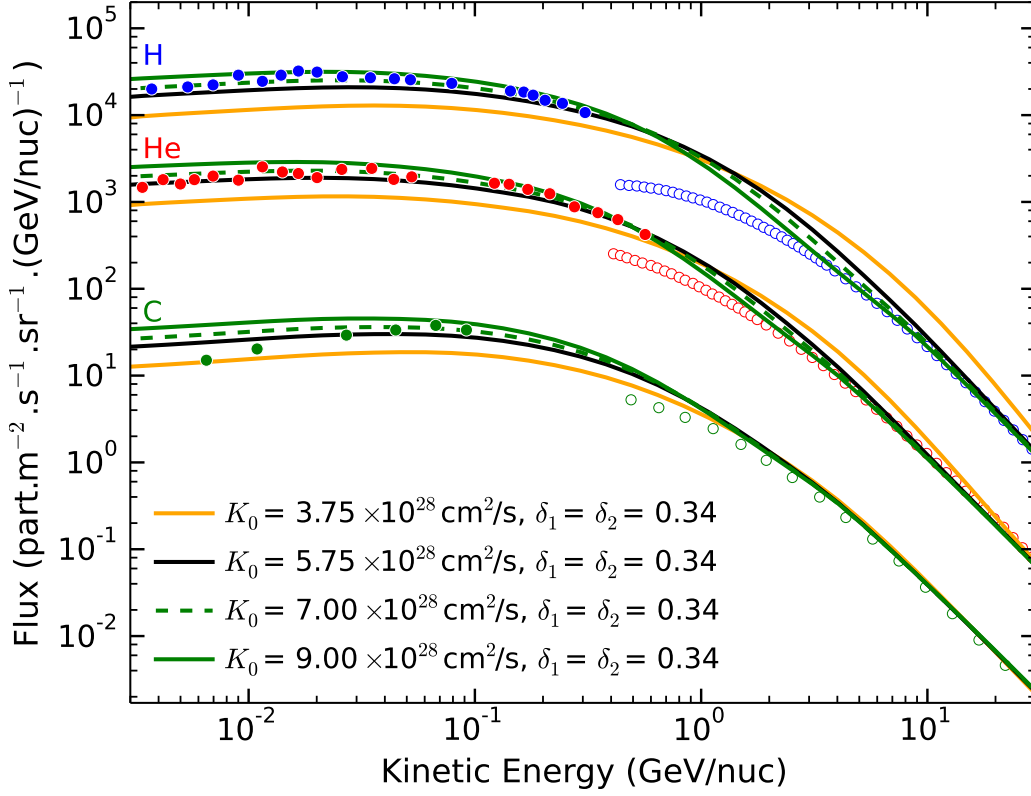


Figure 5.9: Computed LIS's for the parameters given in Fig. 5.8 with protons at the top, Helium in the middle and Carbon at the bottom compared to observations as in Fig. 5.1. The models with a lower K_0 give lower intensities below 1 GeV/nuc, but give higher intensities above this energy. Higher values of K_0 work in the opposite direction.

observations from Adriani et al. (2014). This includes the reacceleration models with $\delta = 0.40$ (dashed blue curve) and 0.45 (solid blue curve) of Figure 5.6 and the models with $K_0 = 7.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed green line) and $9.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (solid green line) of Figure 5.8. The plain diffusion model from Figure 5.2 with $\delta_1 = -0.3$, $K_0 = 6.0 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$ and $P_0 = 4.0 \text{ GV}$ is also shown (dashed grey curve). Both the reference models, for plain diffusion (grey curve) and reacceleration (black curve), match the PAMELA B/C values quite well.

As stated in the previous section, the best plain diffusion model does not reproduce the observed ratio and lies well outside the uncertainty range. In contrast the reacceleration models produce ratios that better match the PAMELA values. The two K_0 adjusted models underestimate the ratio, with $K_0 = 7.00 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (dashed green line) giving a reasonable match at high energies. The two δ adjusted models match the ratio well for energies above 1 GeV/nuc, but for $\delta = 0.45$ (solid blue curve) it is underestimated slightly at higher energies. Of the four reacceleration models $\delta = 0.40$ (dashed blue curve) gives the most satisfactory reproduction of the B/C ratio, with only the lowest energy PAMELA observations not being reproduced.

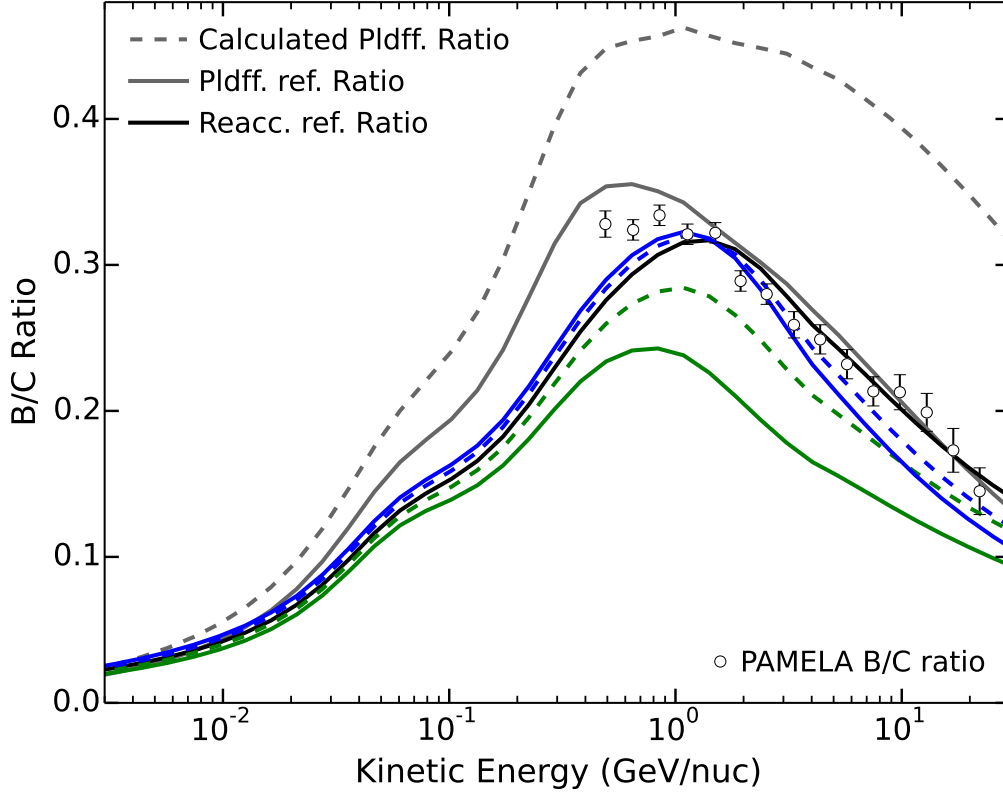


Figure 5.10: Computed B/C ratios for selected models compared to the PAMELA B/C observations (open circles, Adriani et al., 2014). The plain diffusion model (dashed grey curve), as used to calculate the LIS's of Fig. 5.5, overestimates the observed ratio over all energies, while the reacceleration models reproduce the ratio more closely. The reference models, for plain diffusion (solid grey curve) and reacceleration (black curve), match the B/C ratio well above 1 GeV/nuc. From the selected reacceleration models the models from Fig. 5.6 (blue curves) show better matches than those from Fig. 5.8 (green curves), as these underestimate the ratio significantly. The closest match is that of the dashed blue curve (with corresponding LIS's in Fig. 5.7) for $\delta = 0.40$.

5.5 Comparing the LIS results

The computed LIS's produced by the plain diffusion model reproduce the V1 data over all energies for both protons and Helium, except for the values below 0.01 GeV/nuc. This decreasing intensity trend for CR intensities at lower energies is present in both the proton and Helium observations and not seen in any LIS's produced with the plain diffusion model, but can be seen in the reacceleration model LIS's. This suggests that reacceleration is required to reproduce this feature in the observed spectra. The computed LIS's for the reacceleration models reproduce the V1 data reasonably well over all energies, as well as reproducing the Carbon observations. Only the values for protons and Helium above 0.2 GeV/nuc are better represented via the plain diffusion model. None of the considered models could reproduce the steeper decreasing trend seen in the V1 Carbon observations below 60 MeV/nuc.

For the PAMELA data, the plain diffusion proton LIS matches the observations closely above about 5 GeV/nuc, but the reacceleration model suggests an amount of modulation in this energy

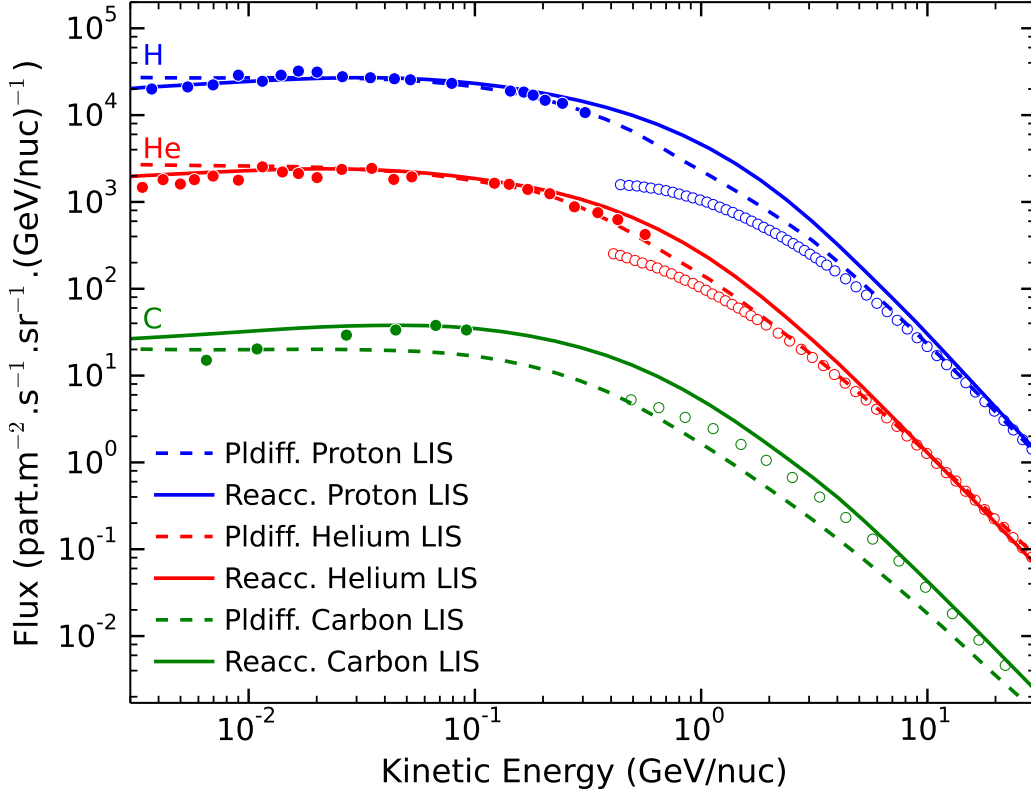


Figure 5.11: The set of self-consistent LIS's computed with $K_0 = 5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 4.0 \text{ GV}$ and $\delta = 0.40$. Protons are shown in blue, Helium in red and Carbon in green and compared to observations as in Fig. 5.1. The dashed curves were produced with the plain diffusion model and match the proton and Helium data well, but not the Carbon. The solid curves are from the reacceleration model and reproduce the data sets, especially the Carbon data, satisfactorily.

range that more closely follows the estimations of Strauss and Potgieter (2014). The plain diffusion Helium LIS, with an increased source abundance, is higher than the PAMELA values at energies above 50 GeV/nuc. While the LIS is expected to match the observed values more closely, as the heliospheric modulation is negligible in this region, it is an improvement on the plain diffusion reference model and this computed LIS still meets the other requirements. The reacceleration Helium LIS also shows an acceptable amount of modulation below 10 GeV/nuc, but above this energy slightly underestimates the PAMELA values, this is not easily rectified without influencing the lower energy data reproduction. To determine if any of these LIS's really reflect the amount of modulation in the heliosphere, the LIS's would have to be examined closer using an advanced heliospheric modulation code (e.g. Potgieter et al., 2014). The reacceleration model greatly improves on estimating the Carbon observations, specifically the high energy spectral slope and overall intensity, neither of which the plain diffusion model could reproduce satisfactorily.

With these conclusions, together with the comparison of calculated B/C ratios to observations, the best computed LIS's for both the plain diffusion model and the reacceleration model are shown together in Fig. 5.11. When compared to the results of the plain diffusion model (dashed lines), the LIS's for protons, Helium and Carbon computed with the reacceleration model (solid

lines) are preferred. This model has the parameter set: $K_0 = 5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 4.0 \text{ GV}$ and $\delta = 0.40$ in Eq. 2.2, with no breaks in the rigidity dependence of the diffusion coefficient.

5.6 Summary

In order to extend the approach of the previous chapter to CR nuclei, the effect of the diffusion parameters K_0 , P_0 and δ_1 on the computed proton, Helium and Carbon LIS's was investigated. The intensities of the computed LIS's were decreased from that of the plain diffusion reference model to those matching the V1 proton and Helium observations made outside the heliosphere. To improve on the relatively poor reproduction of the Carbon LIS and B/C ratio with the plain diffusion model, reacceleration was included in the models. When considering this reacceleration approach, no breaks in the rigidity dependence of the diffusion coefficient was required, adjusting only the index δ , to match the observational data.

The plain diffusion model overestimates the B/C ratios and does not reproduce the Carbon observations when the diffusion parameters are adjusted to decrease the proton intensity. With the reacceleration model, LIS's can be calculated that reproduce the V1 observations outside the heliosphere, while still adhering to the limits set forth by the PAMELA observations at the Earth.

The GALPROP based reacceleration model is therefore preferred to reproduce the V1 observations and the model with $P_{\alpha 0} = 9.0 \text{ GV}$, $\alpha_1 = -1.82$, $\alpha_2 = -2.36$ in Eq. 2.4, Alfvén wave speed $V_A = 36 \text{ km.s}^{-1}$ and $K_0 = 5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $P_0 = 4.0 \text{ GV}$, $\delta = 0.40$ in Eq.2.2 is found to be the best representation.

The contents of this chapter have been published by Bisschoff and Potgieter (2016).

Chapter 6

Matching the observations at Earth with a modulation model

6.1 Introduction

As previously stated, a LIS should ideally be tested via modulation in the heliosphere and comparing it to observations made at Earth. This is the next step for testing the resulting electron and nuclei LIS's shown in Chapters 4 and 5.

The inclusion of reacceleration with the GALPROP model improved on the plain diffusion LIS's for protons, Helium and Carbon and new LIS's for these were calculated in the previous chapter. These three LIS's can now be used as input to a modulation code to calculate the corresponding spectra at the Earth. With these modulated spectra, a direct comparison with Earth based satellite measurements can be made at energies where modulation has a significant effect.

Similarly the calculated electron plain diffusion LIS's can be compared to observations at the Earth. With the success of adding reacceleration to the galactic model to produce nuclei LIS's, this approach will now also be used to calculate a new electron LIS. After which the electron reacceleration LIS can also be modulated and compared to observations at the Earth.

Once evaluating the electron, proton, Helium and Carbon LIS by means of the Earth observations proves successful, this same process can be applied to positrons to estimate a possible LIS or at least a likely range of positron LIS's.

6.2 Modulating calculated LIS's

Before comparing the resulting nuclei LIS of Chapter 5 to observations at the Earth, the LIS's must first be modulated. Once this is done for the proton LIS, the Helium and Carbon LIS's can then be modulated correspondingly.

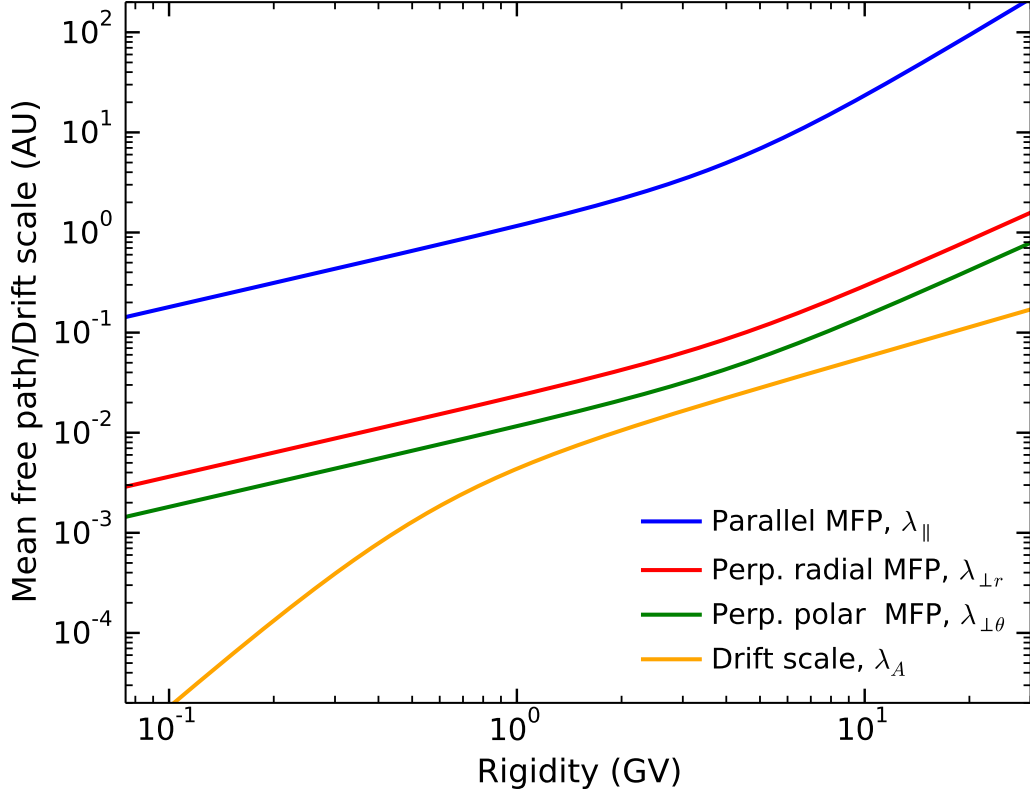


Figure 6.1: The rigidity dependent MFPs and drift scale used for modulation as implemented from Vos and Potgieter (2015) for the 2009 period. Shown is the parallel ($\lambda_{\parallel}$, blue curve), radial perpendicular ($\lambda_{\perp r}$, red curve), polar perpendicular ($\lambda_{\perp \theta}$, green curve) MFPs, and the drift scale (yellow curve). These rigidity dependent values result from the choice of parameters, $(K_{\parallel})_0 = 68.155 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$, $a = 0.8$, $b = 2.1$, $c = 2.2$, $P_k = 4.3 \text{ GV}$, for Eqs. 3.3 to 3.6, through the relation $K = \frac{v}{3} \lambda$.

6.2.1 Modulated spectra

Using the sophisticated 3D modulation code presented by Vos and Potgieter (2015), as discussed in Chapter 3, the proton LIS can be modulated to calculate the corresponding spectrum at the Earth; see also Potgieter and Vos (2017). Keeping the modulation parameters from Vos and Potgieter (2015) that correspond to the 2009 time period, the proton LIS calculated from the reacceleration model, as shown in Figure 5.11, can be modulated. In the modulation code the parameters for the diffusion equations are implemented as follows, for the 2009 time period, for Eqs. 3.3 to 3.6: $(K_{\parallel})_0 = 68.155 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$, $a = 0.8$, $b = 2.1$, $c = 2.2$, $P_k = 4.3 \text{ GV}$.

These parameter values result in the rigidity dependent MFPs: $\lambda_{\parallel}$ (blue curve), $\lambda_{\perp r}$ (red curve), $\lambda_{\perp \theta}$ (green curve), and the drift scale (yellow curve) as shown in Figure 6.1. The resulting spectrum at 1 AU is compared to the PAMELA proton measurements of Dec. 2009 (Adriani et al., 2013a). The modulated spectrum (dashed black curve) is shown in Figure 6.2 compared to the PAMELA (open blue points) and V1 (filled blue points) proton measurements (Stone et al., 2013), as well as the proton LIS (solid black curve). The spectrum at the Earth lies above the PAMELA values at all energies, showing that the amount of modulation needs to be increased in the modulation model for this particular LIS to match the measured values.

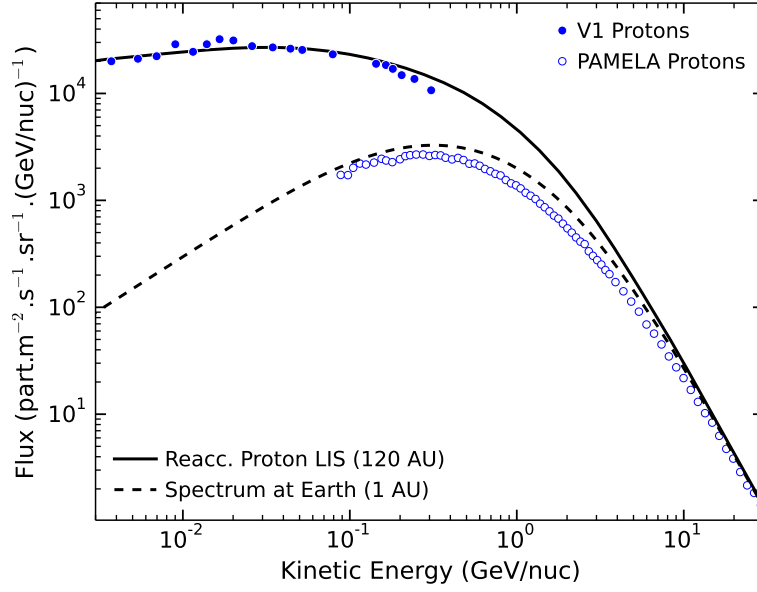


Figure 6.2: The proton LIS (solid black curve) from the galactic reac-celeration model, as shown in Fig. 5.11, is modulated for the 2009 time period at the Earth (dashed black curve), using parameters by Vos and Potgieter (2015) as shown in Fig. 6.1. These spectra are compared to the V1 proton observations (filled blue points, Stone et al., 2013) and the PAMELA proton observations for the Dec. 2009 time period (open blue points, Adriani et al., 2013a).

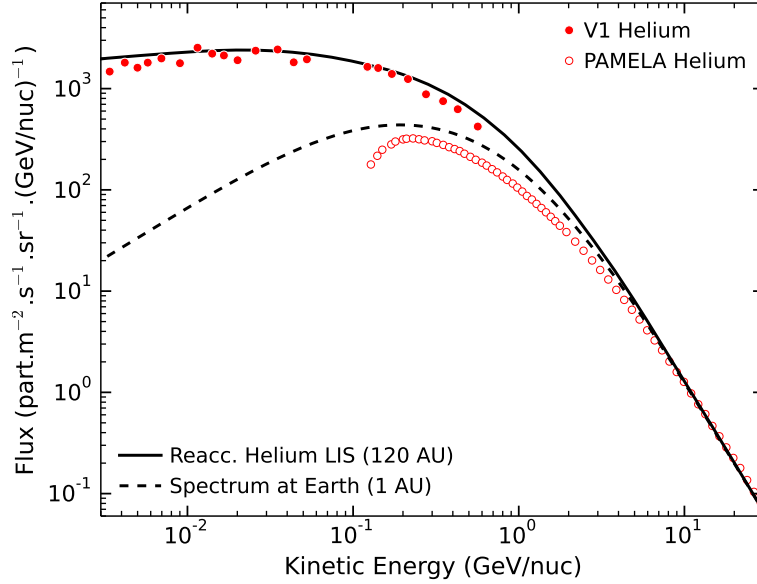


Figure 6.3: The Helium LIS (solid black curve) from the galactic reac-celeration model, as shown in Fig. 5.11, is modulated similarly to the proton LIS in Fig. 6.2, resulting in the modulated spectrum (dashed black curve).

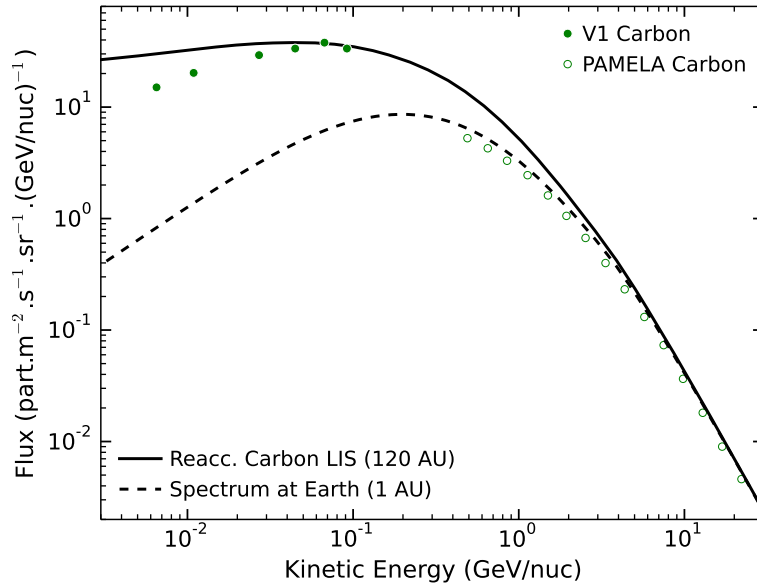


Figure 6.4: The Carbon LIS (solid black curve) from the galactic reac-celeration model, as shown in Fig. 5.11, is modulated similarly to the proton LIS in Fig. 6.2, resulting in the modulated spectrum (dashed black curve).

The Helium and Carbon LIS's in Figure 5.11, calculated with the galactic reacceleration model, are also modulated similarly to the protons. The resulting spectra at 1 AU are compared to the PAMELA measurements of 2006 to 2008, averaged monthly. The Helium spectrum at 1 AU (dashed black curve) is compared to the PAMELA Helium values (open red points), the V1 Helium values (filled red points) (Stone et al., 2013) and the Helium LIS (solid black curve) in Figure 6.3. Similarly the Carbon spectrum at 1 AU (dashed black curve) is compared to the PAMELA Carbon values (open red points), the V1 Carbon values (filled red points) (Stone et al., 2013) and the Carbon LIS (solid black curve) in Figure 6.4. As with the proton spectrum, both the modulated Helium and Carbon spectra lie above the PAMELA observations. The amount of modulation therefore needs to be increased in order to decrease the CR intensity at the Earth and have the spectra match the modulation more closely.

6.2.2 Improved proton, Helium and Carbon modulation

For the above modulated spectra the modulation parameters are used unchanged from Vos and Potgieter (2015). The parameters can now be adjusted to increase the level of modulation, decreasing the intensity of the spectra at the Earth to match the measured spectra more closely. The subset of diffusion parameters should be sufficient to achieve this goal.

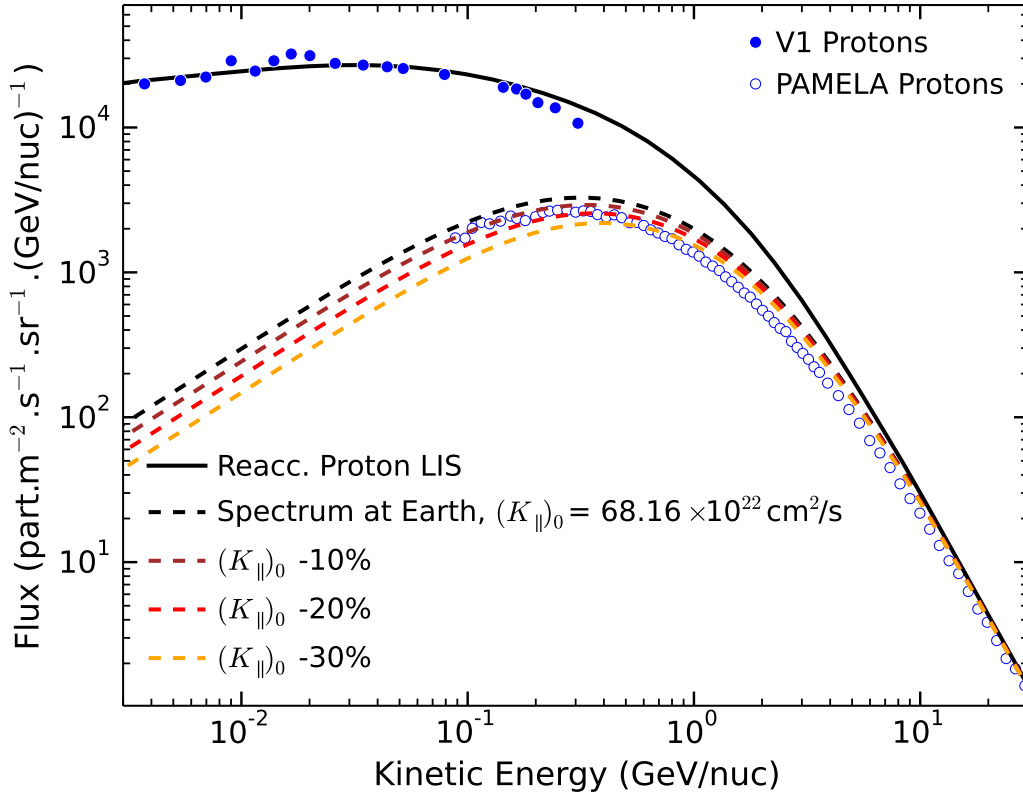


Figure 6.5: The reacceleration proton LIS is modulated as in Fig. 6.2, but with progressively lower values of $(K_{\parallel})_0$ in Eqs. 3.3 to 3.6, to give the dashed curves. For the dashed brown curve $(K_{\parallel})_0$ is lowered by 10%, for the dashed red curve it is lowered by 20% and for the dashed yellow curve it is lowered by 30%. To match the PAMELA observations (open blue points, Adriani et al., 2013a), only lowering $(K_{\parallel})_0$ is not sufficient.

The parameters from the diffusion equations, Eqs. 3.3 to 3.6: $(K_{\parallel})_0$, a and b are tested by varying the values slightly. First only the scaling factor $(K_{\parallel})_0$ is decreased to 90% (brown dashed curve), 80% (red dashed curve) and 70% (yellow dashed curve) of the previous value. This decreases the diffusion coefficients $K_{\parallel}$, $K_{\perp r}$ and $K_{\perp \theta}$ over all rigidities, effectively increasing the overall modulation. This results in the progressively lower modulated spectra (dashed lines) of Figure 6.5. These spectra are closer to the measured values, but don't yet match the suggested spectral shape.

The low rigidity index a is adjusted next, from 0.8 to 0.4 and 1.2 respectively. Figure 6.6 shows that lowering the index (flattening the diffusion coefficient below the break) decreases the modulation below the bend in the spectrum, giving a higher proton intensity at lower energies, while above the bend proton intensity is slightly decreased. This is shown by the spectrum with $a = 0.4$ (dashed blue curve). Conversely, increasing the index (steepening the diffusion coefficient below the break) increases the modulation below the bend, giving a lower proton intensity at lower energies, while also slightly increasing it above the bend. This is shown by the spectrum with $a = 1.2$ (dashed red curve). Adjusting the high rigidity index b shows no visible difference in the spectrum at any energy. This is likely because the index influences the modulation at higher energies where modulation has a very small effect on CRs. This parameter will be kept unadjusted at 2.1 in further tests.

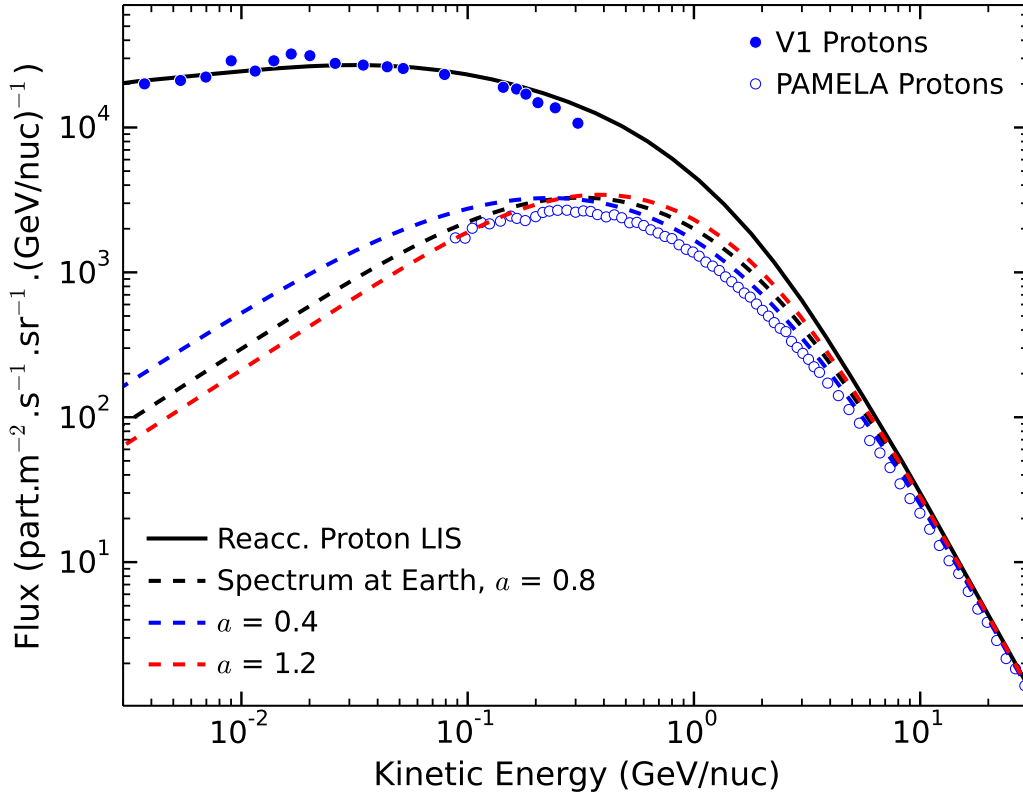


Figure 6.6: The reacceleration proton LIS is modulated as in Fig. 6.2, but with the value of the index a in Eqs. 3.3 to 3.6, adjusted to give the dashed curves. For the dashed blue curve a is adjusted to 0.4 from the value of 0.8 (dashed black curve) and for the dashed red curve $a = 1.2$. These adjustment change the shape of the spectra, while at about 0.2 GeV/nuc the intensity is unchanged. Observations as in Fig. 6.1.

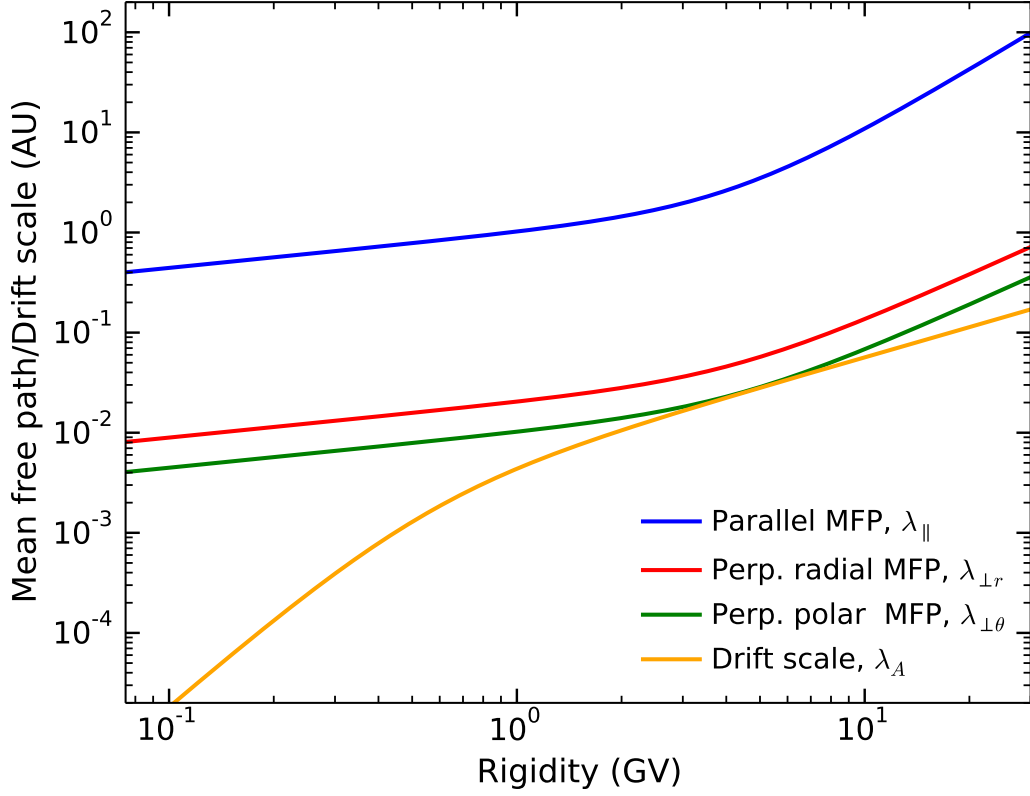


Figure 6.7: The MFPs and drift scale for the adjusted parameters used to modulate the proton, Helium and Carbon LIS's in order to better match the PAMELA observations at all energies. Shown is the parallel ($\lambda_{||}$, blue curve), radial perpendicular ($\lambda_{\perp r}$, red curve), polar perpendicular ($\lambda_{\perp \theta}$, green curve) MFPs, and the drift scale (yellow curve). These rigidity dependent values result from the adjusted values for the parameters for Eqs. 3.3 to 3.6, through the relation $K = \frac{v}{3}\lambda$.

Adjustments to $(K_{||})_0$ and a are now combined to try and match the PAMELA observations more closely in overall intensity and spectral shape. Iterative adjustments to the parameters result in improvements to the modulated spectra, particularly with the values of $(K_{||})_0 = 60.0 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$ and $a = 0.35$, with the other parameters in Eqs. 3.3 to 3.6 kept the same and the drift scale is also unchanged. The rigidity dependent diffusion coefficients are shown as MFPs (in AU) in Figure 6.7.

This combination of parameter values gives the modulated proton spectrum (solid blue curve) of Figure 6.8 which now more closely matches the PAMELA observations values across all energies. The Helium and Carbon LIS's are again also modulated similarly to the protons. The modulated Helium spectrum (solid red curve) is shown in Figure 6.9 and matches the observations similarly to the proton spectrum. The modulated Carbon (solid green curve) in Figure 6.10 also matches the observations closely, but lies slightly below the measurements for energies below about 2 GeV/nuc. As the measured values for Helium and Carbon are averaged over the time period of 2006 to 2008, the modulated spectra for 2009 are expected to lie above the measured values as seen for Helium. While this is not true for Carbon, it should be taken into account that the proton measurements are the most statistically reliable of the three sets and that any changes to the modulation model would negatively affect the proton spectrum.

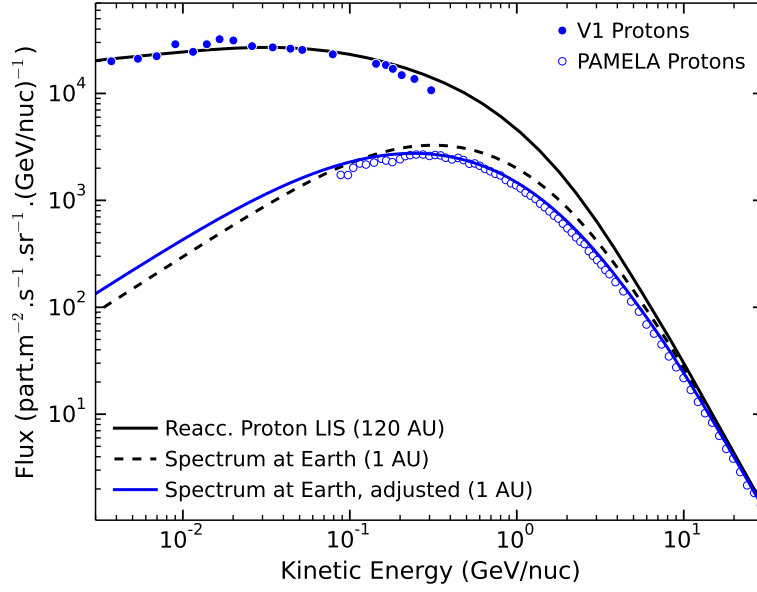


Figure 6.8: The proton reacceleration LIS (solid black curve) is modulated as in Figure 6.2 and then modulated with adjusted diffusion parameters (solid blue curve) to more closely match the observed Dec. 2009 PAMELA proton spectrum (Adriani et al., 2013a).

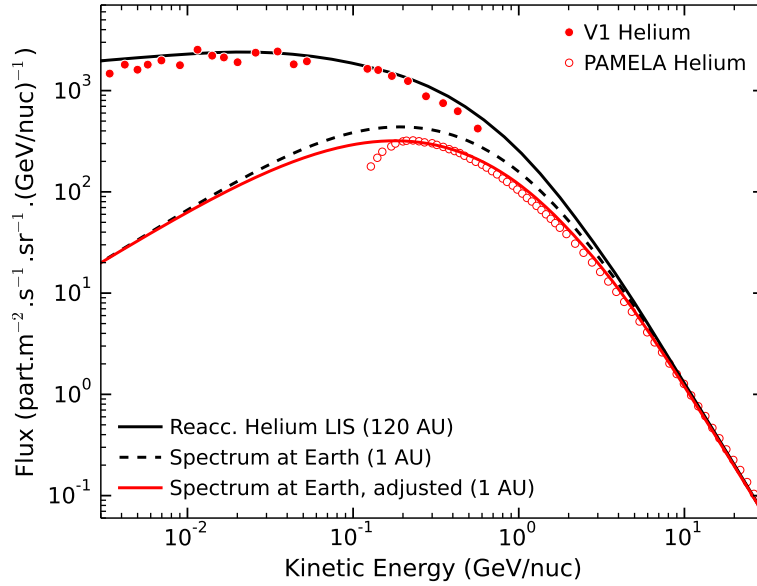


Figure 6.9: The Helium reacceleration LIS (solid black curve) is modulated similarly to the proton LIS in Fig. 6.8 using the adjusted diffusion parameters (solid red curve).

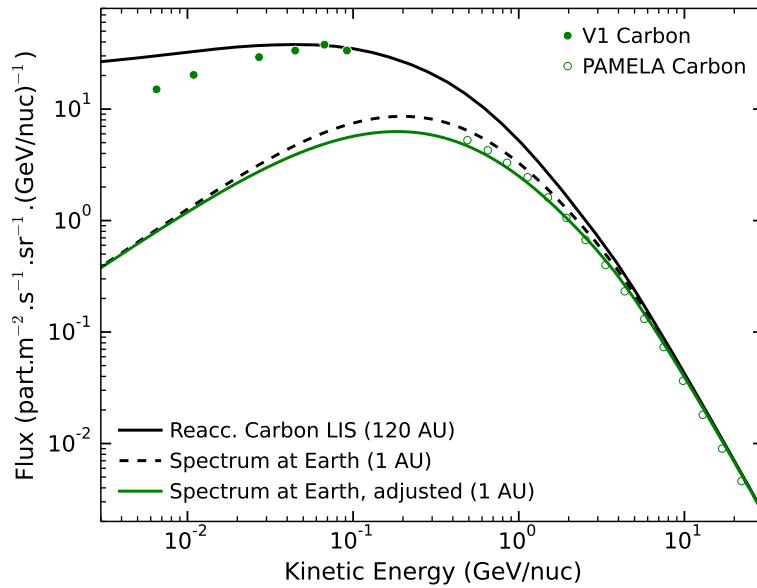


Figure 6.10: The Carbon reacceleration LIS (solid black curve) is modulated similarly to the proton LIS in Fig. 6.8 using the adjusted diffusion parameters (solid green curve).

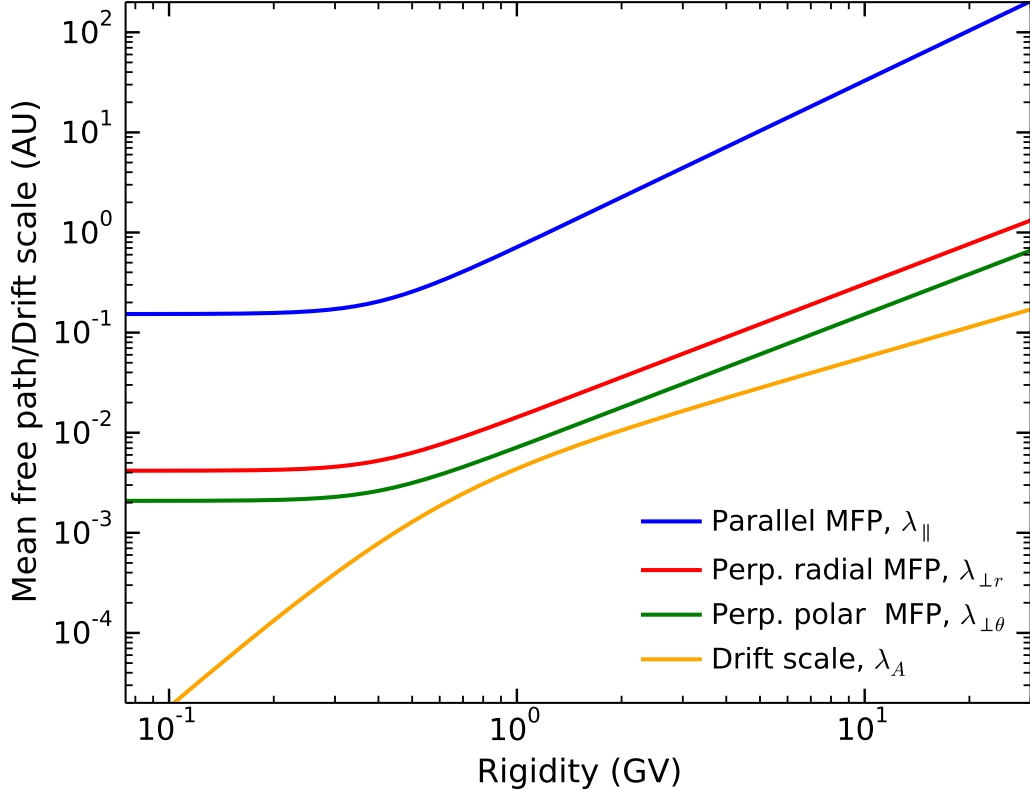


Figure 6.11: The MFPs and drift scale implemented from Potgieter et al. (2015) to modulate the electron LIS's in Fig. 4.8. Shown is the parallel ($\lambda_{\parallel}$, blue curve), radial perpendicular ($\lambda_{\perp r}$, red curve), polar perpendicular ($\lambda_{\perp \theta}$, green curve) MFPs, and the drift scale (λ_A , yellow curve). These rigidity dependent values result from the values chosen for the parameters for Eqs. 3.3 to 3.6, through the relation $K = \frac{v}{3}\lambda$.

6.2.3 Modulated electron spectra

The electron LIS's calculated in Chapter 4 were intended to reproduce the two V1 spectra, but were not primarily intended to represent the PAMELA electron observations at energies below 10 GeV. These LIS's, for the V1 power-law spectra of -1.35 and -1.55 respectively, can now be modulated and compared to the observations at the Earth. This comparison will further test the viability of the calculated electron LIS's. The diffusion parameters of the modulation code will be taken as the same as used by Potgieter et al. (2015) for electrons and discussed in Chapter 3; see Eqs. 3.3 to 3.6.

In the 3D modulation code the parameters of these equations are implemented as follows for electrons for the second semester 2009 time period: $(K_{\parallel})_0 = 41.822 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$, $a = 0.0$, $b = 1.667$, $c = 4.0$, $P_k = 0.4 \text{ GV}$. These rigidity dependent diffusion coefficients are shown as MFPs (in AU), together with the drift scale, in Figure 6.11. The two resulting modulated spectra (dashed curves) are compared to the PAMELA measurements in Figure 6.12, together with the -1.35 LIS (solid blue curve) and the -1.55 LIS (solid red curve) from Fig. 4.8.

Both these modulated spectra fall below the PAMELA observations for energies below about 10 GeV. For the -1.35 LIS the modulated spectrum (dashed blue curve) matches the observations

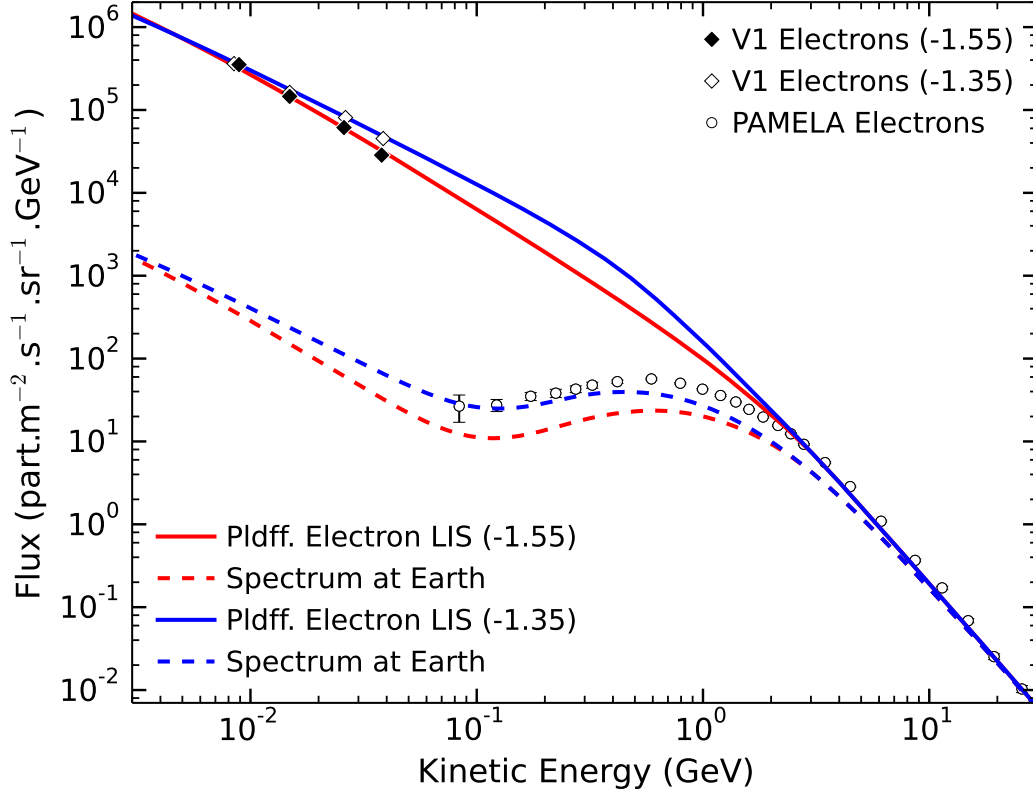


Figure 6.12: The electron LIS's, calculated with the galactic plain diffusion model, for the V1 -1.35 slope (solid blue curve) and for the V1 -1.55 slope (solid red curve) are modulated to give the respective dashed curves. These spectra are compared to the two V1 slopes (Stone et al., 2013) and the PAMELA observations for the second half (semester) of 2009, at the Earth (Adriani et al., 2015).

again at 0.1 GeV. This is explained by the fact that the two LIS's already lie directly on or below the PAMELA values for energies as low as 3 GeV. This effectively means that the two LIS's underestimate the effect of modulation in the heliosphere. Unlike for the nuclei LIS's, adjustments to the modulation parameters will not improve the spectra at the Earth as needed. To correctly account for modulation and match the PAMELA values, an electron LIS will have to be higher in at least the energy range of 1 to 10 GeV, while still matching either of the V1 spectra.

6.3 GALPROP reacceleration model for electrons

To improve on the above mentioned electron LIS's the GALPROP reacceleration model is implemented next for electrons, similarly to what was done in Chapter 5 for CR nuclei. With the galactic reacceleration model a third possibility for an electron LIS can be calculated that can possibly reproduce the V1 measurements beyond the heliopause, while also more accurately reproducing modulation at the energies observed by PAMELA.

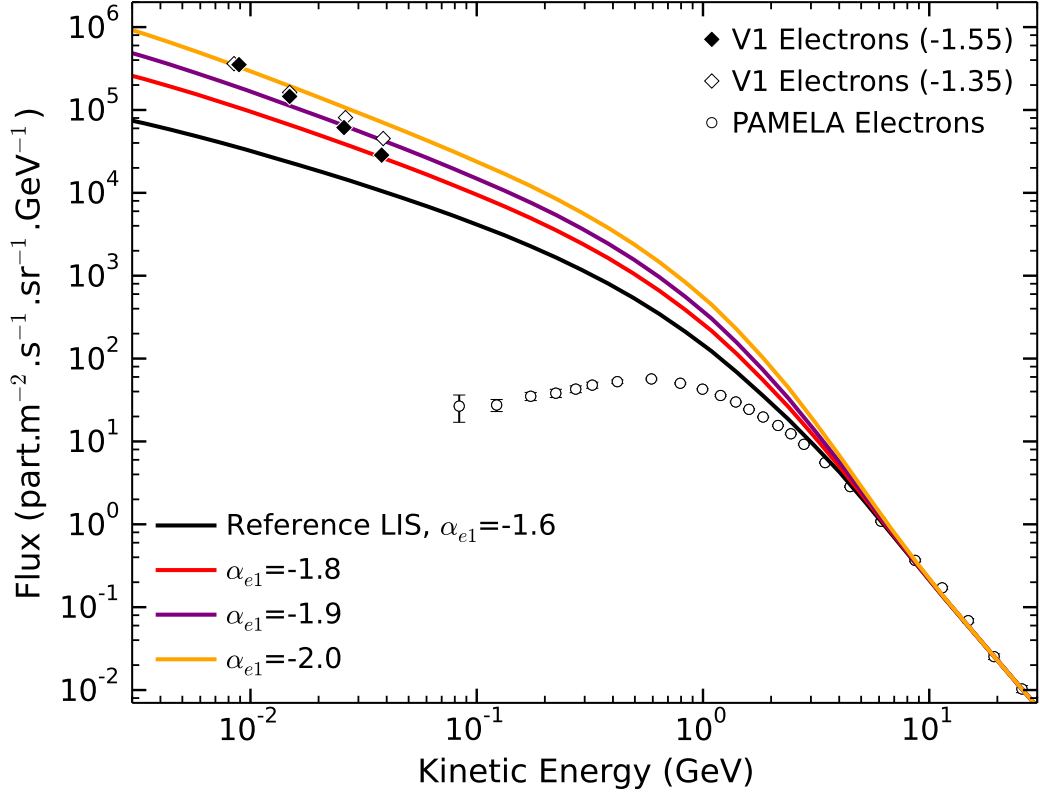


Figure 6.13: The electron LIS's resulting from adjusting the electron source spectrum in the reacceleration model is compared to the galactic reacceleration reference LIS (solid black curve), as well as the V1 and PAMELA electron observations as in Fig. 6.12. The index α_{e1} in Eq. 2.5 is adjusted from -1.6 to -1.8 (solid red curve), -1.9 (solid purple curve) and -2.0 (solid yellow curve) respectively.

6.3.1 Reacceleration LIS for electrons

As the goal is to produce a LIS that can match the PAMELA electron spectrum more closely when considering modulation, the electron LIS of Potgieter et al. (2015) is used as a guideline. As this LIS has already been modulated to match the PAMELA values, it serves as goal for the GALPROP reacceleration code to reproduce in shape and intensity. For the initial GALPROP reacceleration tests the electron LIS calculated by Ptuskin et al. (2006) serves as the basis of the reference model used here. This reference LIS is shown in Figure 6.13 (solid black curve) and matches the PAMELA values well at higher energies, but lies below the V1 measurements and has a flatter power-law in this energy range.

The galactic propagation parameters, as given in Eqs. 2.2 and 2.5, are adjusted similarly to what has been done for protons in Chapter 5 previously. The power-laws in the electron source spectrum of Eq. 2.5 are adjusted from the reference values first. The index (α_{e2}) above the reference rigidity ($P_{ae0} = 4 \text{ GV}$) can be used to change the intensity of electrons at higher energies, but this change in the electron LIS at energies above about 30 GeV is not required as the high energy PAMELA values are already well matched. The index α_{e2} will therefore be kept fixed at -2.5 .

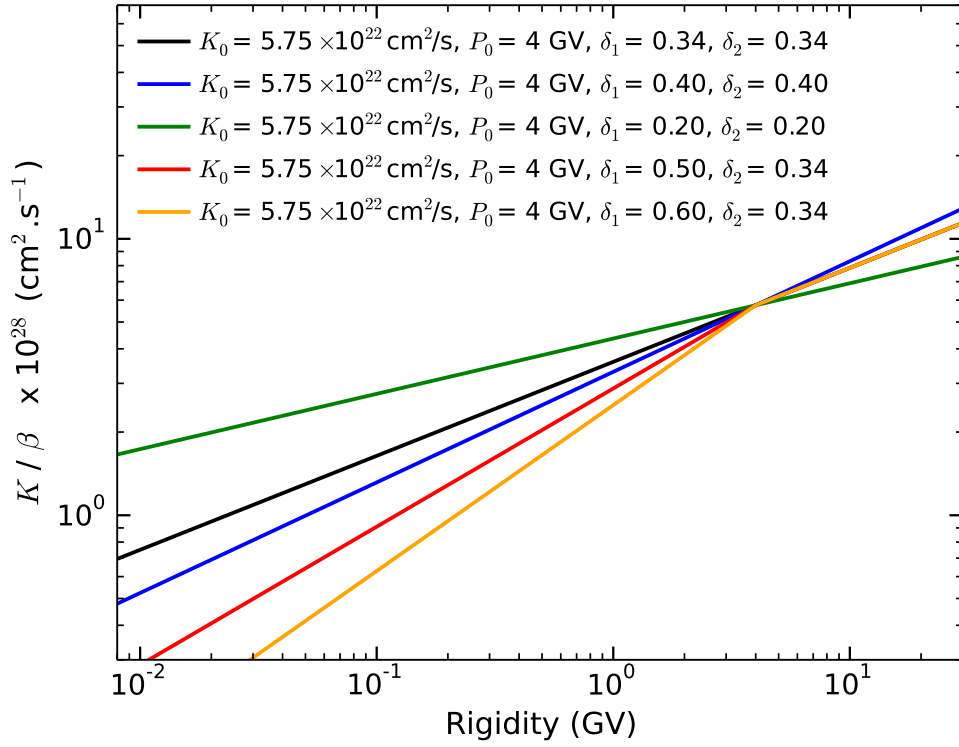


Figure 6.14: The galactic diffusion coefficient parameters are adjusted from the reference reacceleration model values (solid black line). The indices δ_1 and δ_2 are shown in various combinations, while values for K_0 and P_0 are kept unchanged in Eq. 2.2.

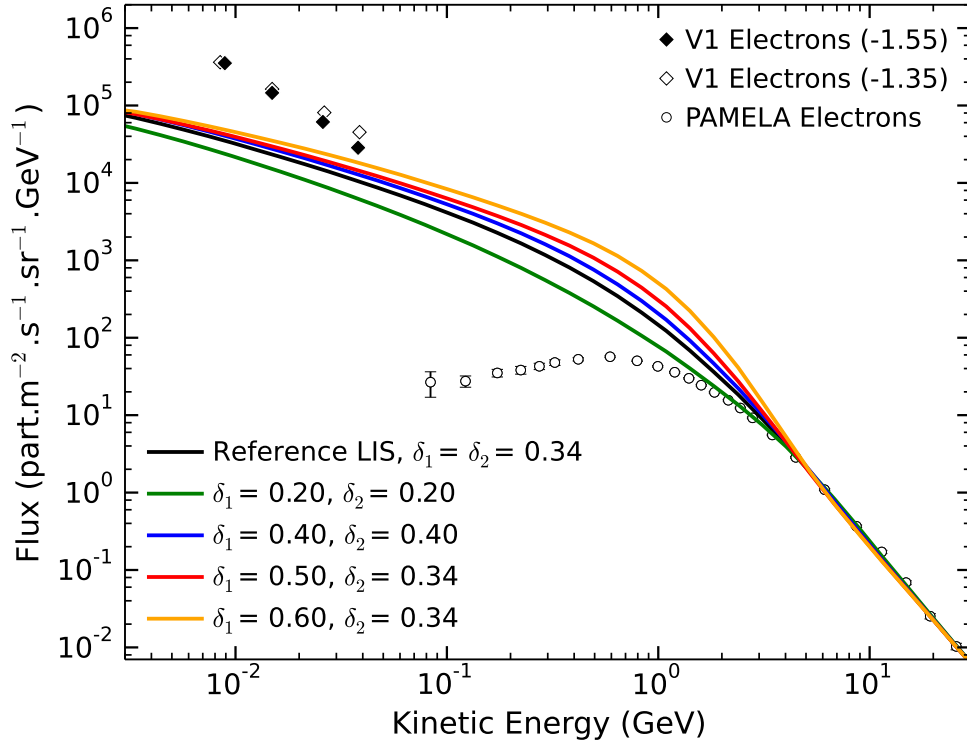


Figure 6.15: The calculated electron LIS for the adjusted galactic diffusion coefficient values of Fig. 6.14. The reacceleration reference LIS (solid black curve) is compared to the different shaped LIS's (solid coloured curves) resulting from changing the diffusion indices δ_1 and δ_2 in Eq 2.2, for illustrative purposes. Observations as in Fig. 6.12.

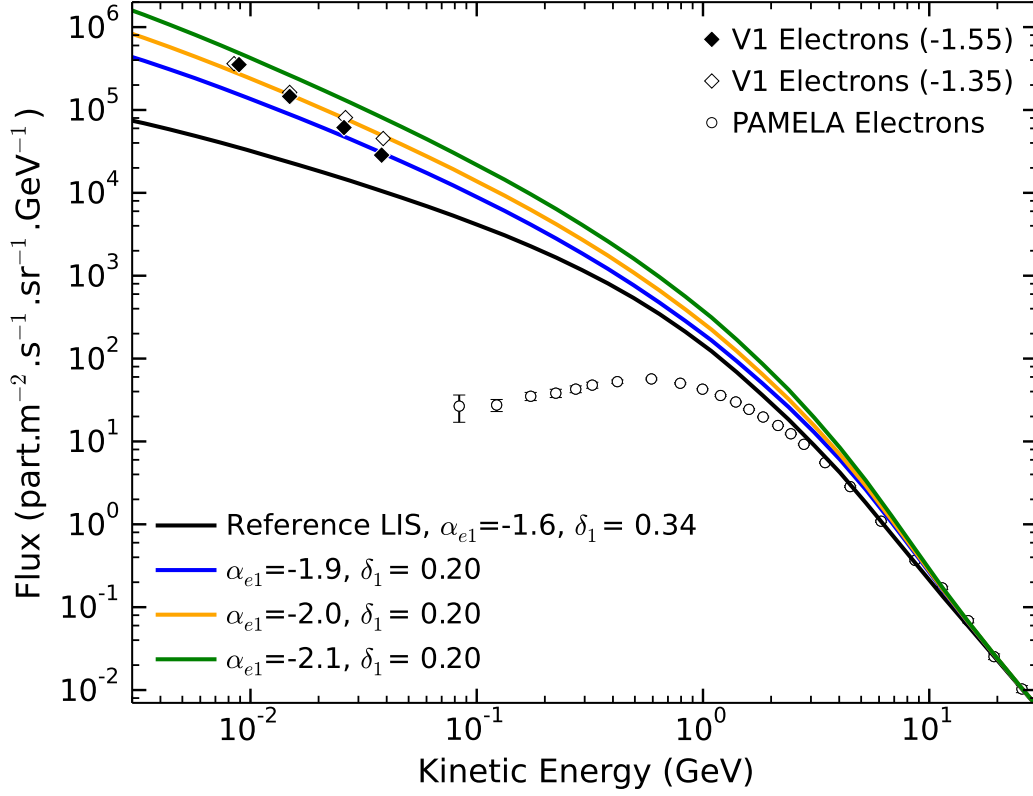


Figure 6.16: Adjusting both the source spectrum indices and the diffusion coefficients in the galactic reacceleration model, allow the LIS to match the slope and magnitude of the CR intensity of V1 observations more closely. For the parameters $\alpha_{e1} = -2.0$ and $\delta_1 = 0.20$ the orange LIS shows the best match to the V1 electron spectra. Observations as in Fig. 6.12.

The changes in the electron reacceleration LIS can be seen in Fig. 6.13 when adjusting the index α_{e1} . Decreasing α_{e1} correspondingly increases the electron intensity at energies below 10 GeV. Coupled with reacceleration this gives a LIS with a steeper slope between 1 and 10 GeV. A value for α_{e1} of between -1.8 (solid red curve) and -2.0 (solid yellow curve) gives a range in which a calculated electron LIS can match the V1 spectra intensities.

Next the diffusion parameters of Eq. 2.2 are adjusted in the galactic reacceleration model. The magnitude of the galactic diffusion coefficient is kept fixed at $K_0 = 5.75 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ initially and the reference rigidity is unchanged with $P_0 = 4 \text{ GV}$, while the indices δ_1 and δ_2 are adjusted as in Fig. 6.14. Changing the index above P_0 has little effect on the spectra below 10 GeV and as such δ_2 will be kept unchanged with $\delta_2 = 0.34$ for the rest of the tests. The corresponding calculated LIS's are shown in Figure 6.15. Adjusting δ_1 to higher values increases the electron intensity below 5 GeV, but this effect becomes smaller at lower energies and the slope of the spectrum changes little at the V1 energies.

The effect of changing K_0 was also tested. An increase in K_0 results in a less rounded spectrum between 0.1 and 10 GeV, but has little effect elsewhere. Decreasing K_0 greatly changes the shape of the spectrum, but neither of these changes improve the reproduction of the V1 spectra and K_0 will be kept fixed for further tests.

The electron LIS's resulting from combining the effects of adjusting the source index α_{e1} and the diffusion index δ_1 are shown in Figure 6.16. The high rigidity indices, above the respective reference rigidities, are still kept fixed at $\alpha_{e2} = -2.5$ and $\delta_2 = 0.34$. Increasing the amount of lower energy electrons directly via the input spectrum results in intensities closer to that of the V1 electrons. Lowering δ_1 , flattening the rigidity dependence of the diffusion coefficient at lower energies, changes the shape of the reacceleration bump and for the green curve moves it to higher energies. Iterations of combinations for values for α_{e1} and δ_1 lead to the electron LIS's of Figure 6.16, where $\alpha_{e1} = -2.0$ and $\delta_1 = 0.20$ (orange curve) give a good match to the V1 -1.35 spectrum. This LIS also has a shape similar to that of the Potgieter et al. (2015) LIS, but lies above it between 1 and 6 GeV due to the rounder curve given by the reacceleration. The other LIS's in the figure result from lower and higher values for α_{e1} respectively. The $\alpha_{e1} = -1.9$ LIS (blue curve) gives a lower bound to the -1.55 V1 spectrum, but has a less steep slope and only matches the highest energy data point. The $\alpha_{e1} = -2.1$ LIS (green curve) overestimates the V1 values.

Further adjustments to the source spectrum and diffusion parameters, of the galactic model, show no improvements to the calculated LIS's and from these tests the LIS resulting from $\alpha_{e1} = -2.0$ and $\delta_1 = 0.20$, the orange curve in Figure 6.16, reproduces the V1 spectra the best.

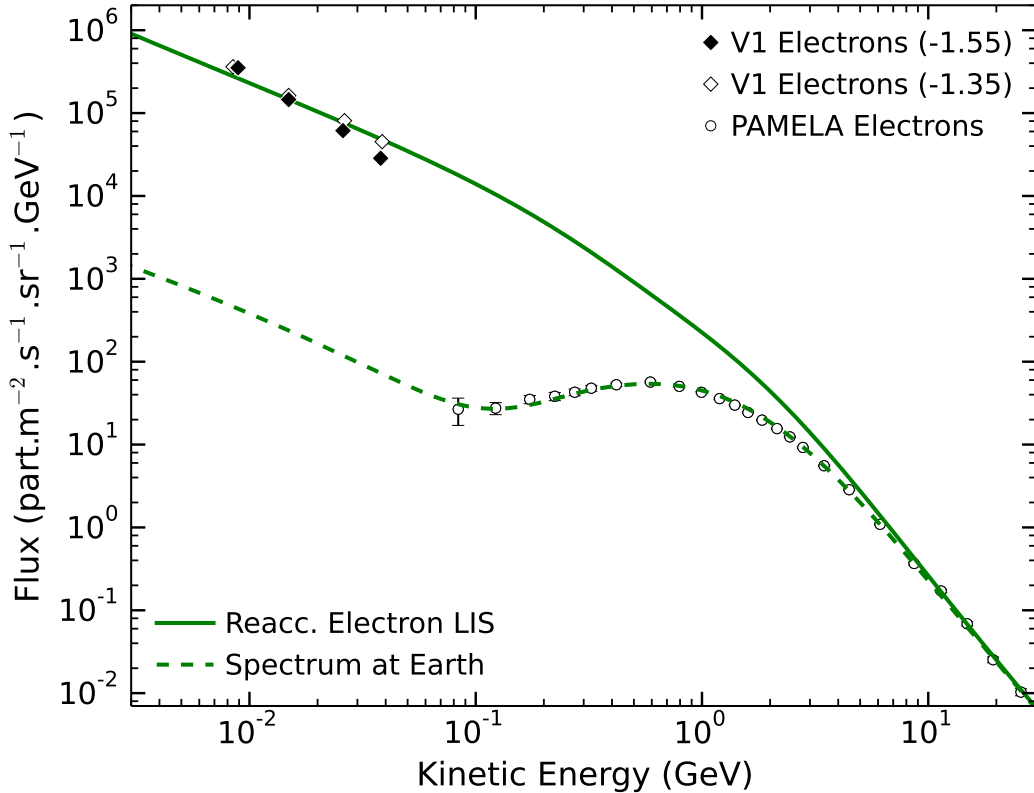


Figure 6.17: The electron LIS (solid green line) shown in Fig. 6.16 resulting from the galactic reacceleration model with $\alpha_{e1} = -2.0$ and $\delta_1 = 0.20$, is modulated (dashed green line) and compared to the PAMELA electron observations for 2009. The modulated spectrum now matches the observations much more closely than the previous electron spectra in Fig. 6.12.

6.3.2 Modulating the resulting electron LIS

The electron LIS in Figure 6.16, resulting from the reacceleration model with $\alpha_{e1} = -2.0$ and $\delta_1 = 0.20$, is now modulated and compared to the PAMELA measurements in Figure 6.17. The modulation diffusion parameters are kept unchanged from those used previously to modulate the electron LIS's in Figure 6.12. The modulated spectrum matches the PAMELA values exceptionally well at all energies. This is not surprising as this electron LIS corresponds well to that of Potgieter et al. (2015).

6.4 Positron LIS's

With the electron model updated to include reacceleration, the positron LIS can be investigated next. The calculated electron LIS's, for both plain diffusion and reacceleration models, are used as a starting point. With no measurements of positrons beyond the heliopause, coupling the positron propagation to other CRs is needed to restrict possible LIS's. After the positron LIS's are calculated, the spectra can be modulated and compared to observations at the Earth. At the time of conducting these tests for the positron LIS, the PAMELA positrons observations below 1 GeV were not yet published. The positron observations presented in the work of Munini (2016) are subsequently used in order to aid in evaluating the calculated LIS's, but should be considered as preliminary.

The positron LIS's calculated by GALPROP can be seen to produce lower intensities, at energies above about 1 GeV, than is observed at the Earth. This positron excess (see e.g. Adriani et al., 2009) can't be reproduced by GALPROP in its current form and the positron LIS's presented here all have an excess expression added to take into account this phenomenon.

6.4.1 Positron LIS's corresponding to electron and proton results

The two electron LIS's produced with the plain diffusion model, shown in Figure 4.8, are calculated with the diffusion parameters shown in Figure 6.18. These diffusion parameter sets give the electron LIS's that match the V1 -1.35 slope (blue curve) and the V1 -1.55 slope (red curve), respectively. The positron LIS's that are calculated with GALPROP with these exact parameters are shown in Figure 6.19 with the same colour scheme. All other propagation parameters are kept the same as for calculating the electron LIS's. The two electron LIS's serve as upper and lower limits to the LIS that can be calculated with the plain diffusion model to reproduce the V1 electron observations. Similarly, these two positron LIS's can be considered to give upper and lower limits to a plain diffusion positron spectrum.

The proton plain diffusion LIS, shown in Figure 5.5, is calculated with the diffusion parameters indicated by the black line in Figure 6.18. The corresponding LIS calculated with these parameters (black curve) is shown in Figure 6.19. The positron LIS is also indirectly affected

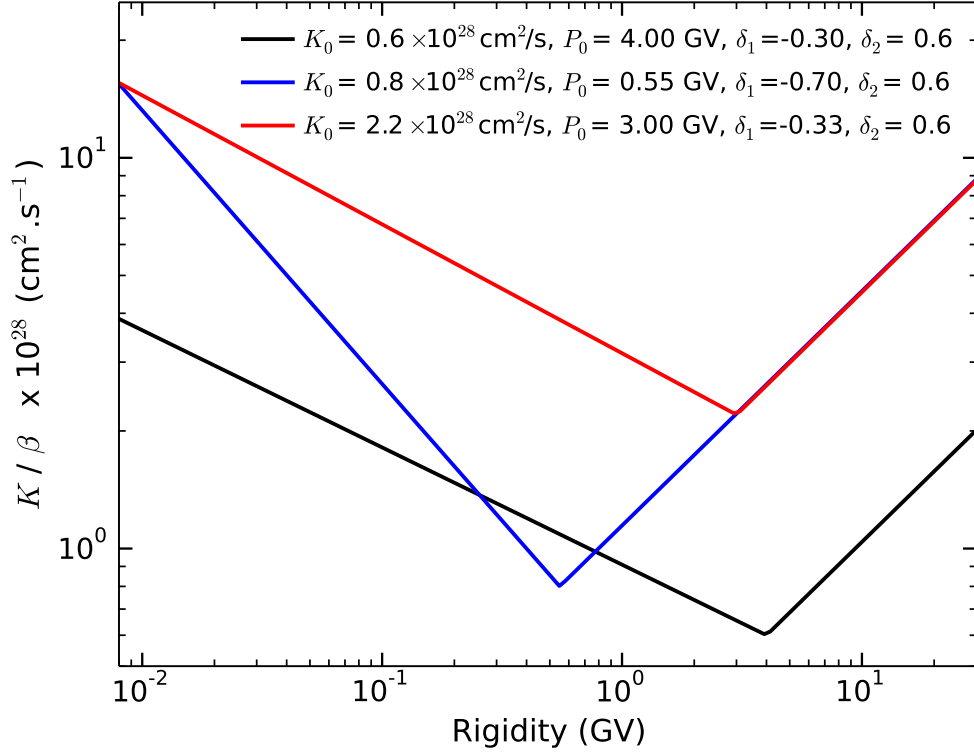


Figure 6.18: The galactic diffusion coefficient values for the proton plain diffusion model from Fig. 5.5 (black line) and the electron plain diffusion models from Fig. 4.8 (red and blues lines). With parameters values as adjusted in Eq. 2.2.

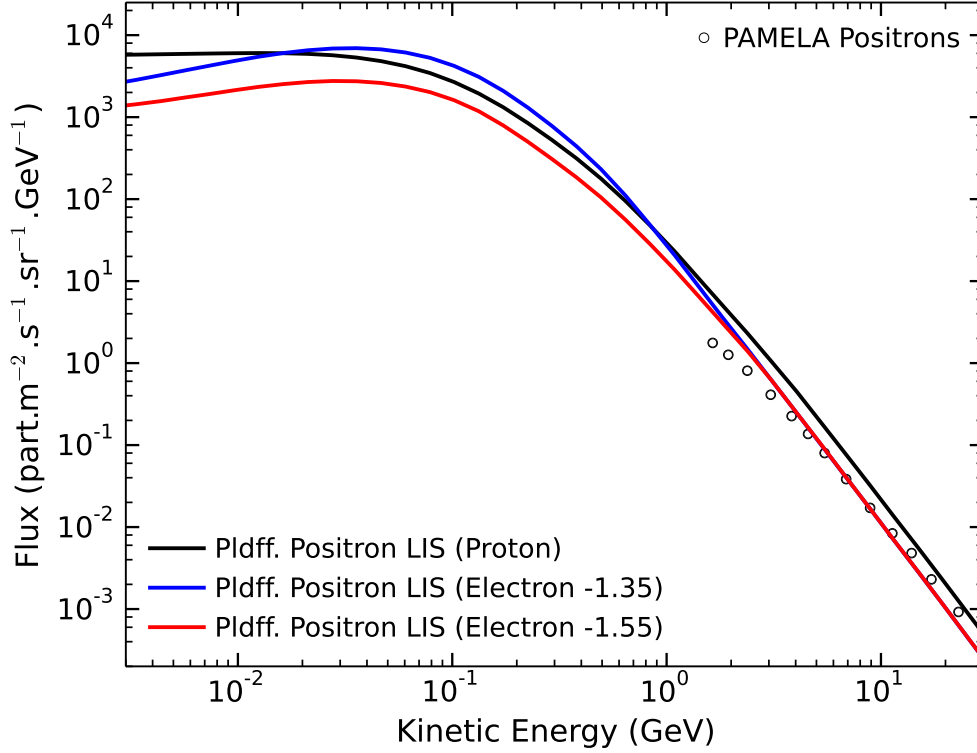


Figure 6.19: The positron LIS's corresponding to the diffusion coefficient values for the respective plain diffusion models of Fig. 6.18, proton plain diffusion model (black curve), electron plain diffusion models (red and blues curves) compared to the PAMELA positron values (open black circles) (Adriani et al., 2013b).

by the nuclei source spectrum used in the GALPROP model, as positrons are secondary CRs. All other propagation parameters are also kept the same as for calculating the proton LIS. This LIS shows an overestimation of the CR intensity at higher energies and is the only positron LIS in Figure 6.19 that does not reproduce the PAMELA values above 5 GeV.

The diffusion parameters differ greatly between what was used to calculate the electron LIS's and the proton LIS for the plain diffusion model, with the electron LIS's also having different values for diffusion at lower rigidities, as seen in Figure 6.18. These diffusion values still give similar shaped positron LIS's in Figure 6.19, but with the steeper values of δ_1 (red and blue curves) from the electron models giving steeper positive slopes for the positron LIS at energies below 0.1 GeV.

For the GALPROP reacceleration model the diffusion parameters used to calculate the electron (green line) and proton LIS (grey line) are shown in Figure 6.20, respectively. The diffusion indices for the proton LIS are the same above and below the reference rigidity ($P_0 = 4$ GV) with $\delta_1 = \delta_2 = 0.4$. While for the electron LIS the indices differ, $\delta_1 = 0.2$ and $\delta_2 = 0.34$, this flatter index for the lower rigidities is required to match the slope of the V1 electron observations. For both electrons and protons all the other parameters were kept the same, including source parameters, and the resulting positron LIS's in Figure 6.21 differ due to these values for δ_1 and δ_2 .

The positron LIS's from the above figures are summarized in Fig. 6.22. These LIS's from both the plain diffusion and reacceleration models show the possible range of a positron LIS. The difference in the LIS's are due to not only the choice of model (plain diffusion or reacceleration) but also the choice of diffusion parameters. These LIS's give a range of possible positron LIS's that can be calculated with either the plain diffusion or reacceleration models while matching either the electron or proton observations.

6.4.2 Modulating resulting positron LIS's

From Fig. 6.22 the three positron LIS's that correspond to the three electron LIS's are selected as to best represent the range of LIS's. As with the electron LIS's previously, the sophisticated 3D modulation code as used by Potgieter et al. (2015) is implemented to modulate the three positron LIS's, to obtain the spectra at the Earth. The same modulation parameters (corresponding to the second half of 2009) as used for the electron LIS's are used to modulate the positron LIS's, with only the charge sign dependence differing. The resulting spectra are compared to the PAMELA positron observations as shown in Fig. 6.23. The plain diffusion LIS's (dashed blue and red curves) both match the observations at the Earth well. While the reacceleration model (dashed green curve) overestimates the intensity at the Earth, such a LIS would require increased modulation to match the PAMELA values.

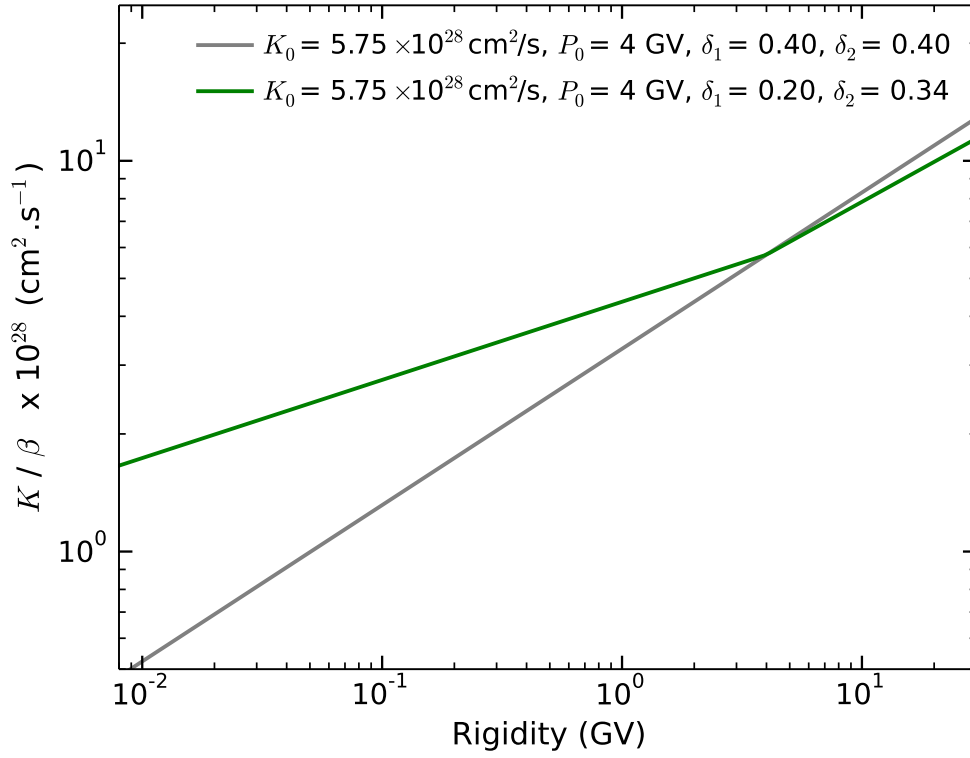


Figure 6.20: The galactic diffusion coefficient values for the proton reacceleration model from Fig. 5.11 (grey line) and the electron reacceleration model (green line) shown in Fig. 6.17. With parameters values as adjusted in Eq. 2.2.

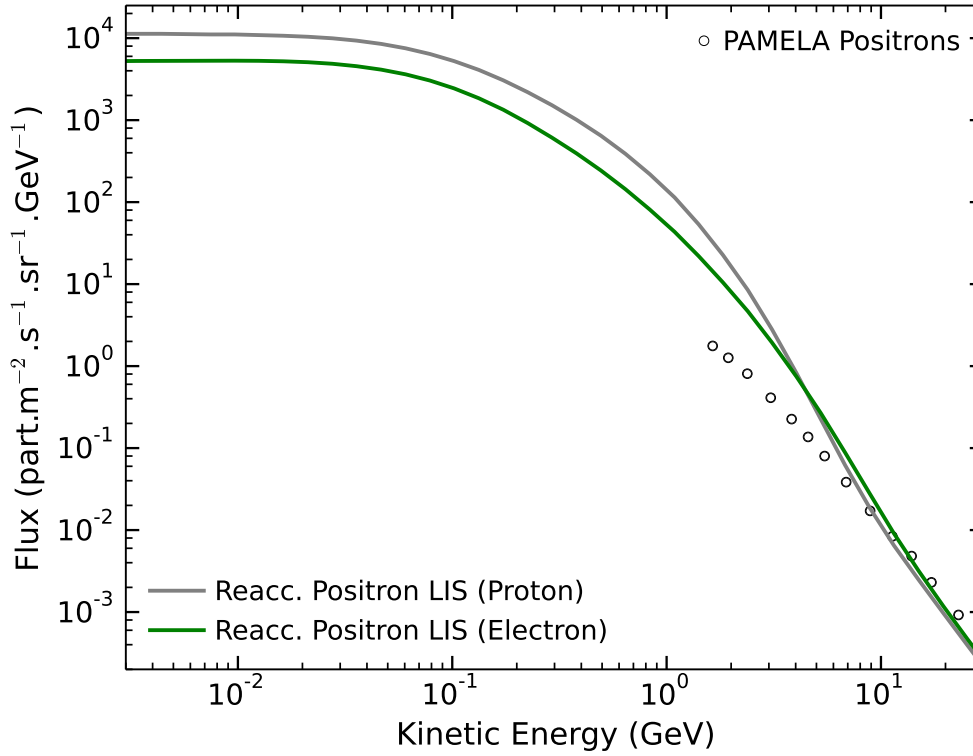


Figure 6.21: The positron LIS corresponding to the diffusion coefficient values for the two reacceleration models of Fig. 6.20, proton reacceleration model (grey curve), electron reacceleration model (green curve), compared to the PAMELA positron values (open black circles) (Adriani et al., 2013b).

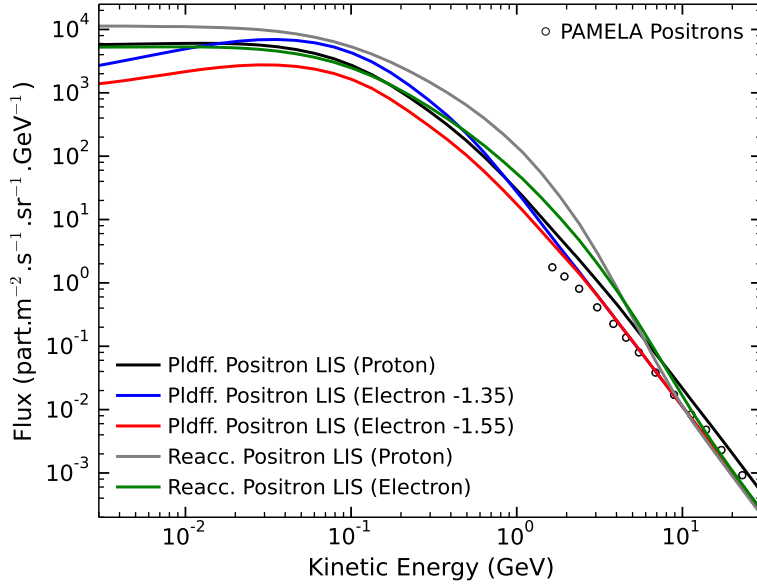


Figure 6.22: All five positron LIS's produced via the electron and proton GALPROP models as shown in Figs. 6.19 and 6.21 compared to the PAMELA positron observations (Adriani et al., 2013b). These LIS's give a band of where a possible positron LIS might lie when using the GALPROP models and matching the proton and electron observations. These LIS's don't include the positron excess above 10 GeV.

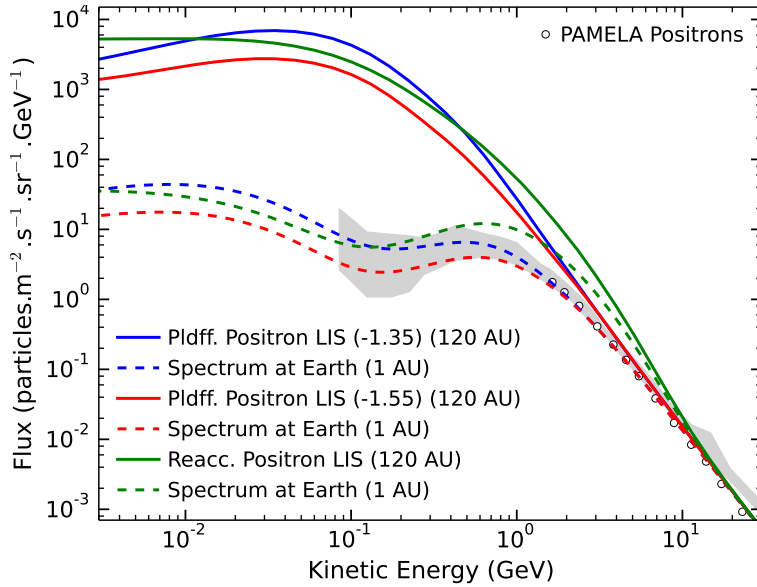


Figure 6.23: Modulated positron LIS's for the galactic plain diffusion (dashed red and blue curves) and reacceleration models (dashed green curve) compared to the PAMELA positron observations: three year average (black open circles) (Adriani et al., 2013b) and half year variations for Jul 2006 to Dec 2009 (grey band) (Munini, 2016). The LIS's and modulated spectra now include the positron excess.

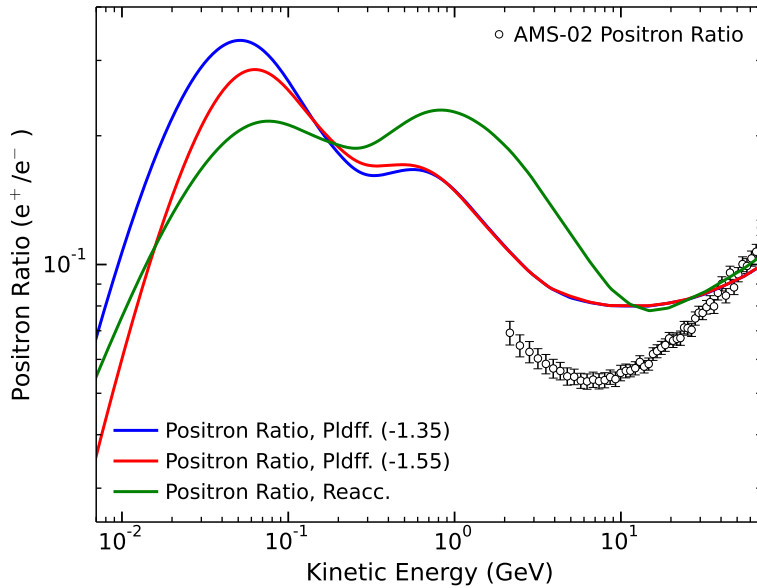


Figure 6.24: The positron ratios (e^+/e^-) corresponding to the positron spectra of Fig. 6.23. With plain diffusion model ratios (solid red and blue curves) and reacceleration model ratio (solid green curve) compared to the AMS-02 positron ratio observations (Aguilar et al., 2014).

The positron ratio (e^+/e^-) is calculated for the above modulated LIS's and compared to the AMS02 observed positron ratio at the Earth in Fig. 6.24. The GALPROP LIS's resulted in ratios that only match the observations above 20 GeV where the added excess takes effect. This is due to the modulated positron LIS for the galactic plain diffusion model matching the observations, while the modulated electron LIS underestimates the intensities. Inversely the modulated positron LIS from the galactic reacceleration model overestimates the observations, while the modulated electron LIS matches the observations well.

Neither of these two models can match the observations for electrons and positrons at the Earth at the same time. To solve this, two concepts are yet to be investigated. Firstly, combining the galactic model parameter sets for electrons and nuclei into a single model, thus calculating all CRs species simultaneously instead of leptons and hadrons separately, as was done for the above LIS's. This is an important aspect as the CR nuclei propagation produces positrons as secondary CRs. Secondly, a model that lies in between the plain diffusion model and the full reacceleration model also needs to be tested.

6.5 Summary

The electron and nuclei LIS's shown in Chapters 4 and 5 were modulated to further test the suitability of the various computed LIS's when compared to observations at the Earth. The initial modulation for the galactic reacceleration model protons, Helium and Carbon, shows that the modulation needed to be increased from what was found by Vos and Potgieter (2015) for protons. Adjusting the modulation parameters gives improved modulated spectra that match the PAMELA observations well.

The plain diffusion electron LIS's were also modulated and showed the galactic plain diffusion model to be insufficient to match both V1 and PAMELA electron observations. Similarly to what was done for the CR nuclei, reacceleration was included in the galactic electron model to calculate a LIS that reproduces the V1 spectra well and after modulation also reproduces the PAMELA spectrum closely.

Using these electron and proton galactic models, corresponding positron LIS's were calculated that give a range of possible GALPROP models that can also match either the electron or proton observations. Modulating these LIS's shows that neither the galactic plain diffusion, nor the reacceleration model can give LIS's that match both the electron and positron observations at the Earth with a single parameter set.

The next goal is to combine the electron and nuclei model parameters sets into a single model and test models that lie in between the plain diffusion model and the full reacceleration model.

Chapter 7

Finding a single GALPROP model to calculate self-consistent LIS's

7.1 Introduction

As discussed previously, the positron LIS is dependent on the source injection spectrum of CR nuclei. To find a positron LIS that matches both the observed positron intensities and the e^+/e^- ratio, while also correctly estimating the proton LIS's, a single model needs to be used in GALPROP to calculate all the LIS simultaneously.

So far the observations of both electron and positrons have not been reproduced simultaneously with either the plain diffusion model or the reacceleration models. A model with reduced reacceleration strength can possibly encompass the effects of both the above models.

Maccione (2013) shows that their galactic propagation model is able to match observations for both electrons and positrons at the Earth, while also matching nuclei observations, but no attempt was made to reproduce the V1 observations as presented in previous chapters. This model differs from the GALPROP model and will be discussed in Section 7.3. The propagation parameters presented by Maccione (2013), including convection, are adapted to the GALPROP model to investigate if the results can be obtained while reproducing also the V1 observations. With these results, and the tests in the previous chapters, the GALPROP model parameter values will be improved to match all the relevant CR observations.

7.2 Combining the electron and proton model parameters

To combine the model parameters in order to match the electron, positron and proton observations simultaneously, the electron reacceleration model is used as starting point. This reacceleration model is the same one that was used in Chapter 6 to calculate an electron LIS that matched the V1 and PAMELA electron observations closely, as shown in Figure 6.17. The parameters used are all kept unchanged and the resulting proton LIS calculated with this model, as shown in Figure 7.1 (black curve), can be seen to underestimates the V1 values at all energies.

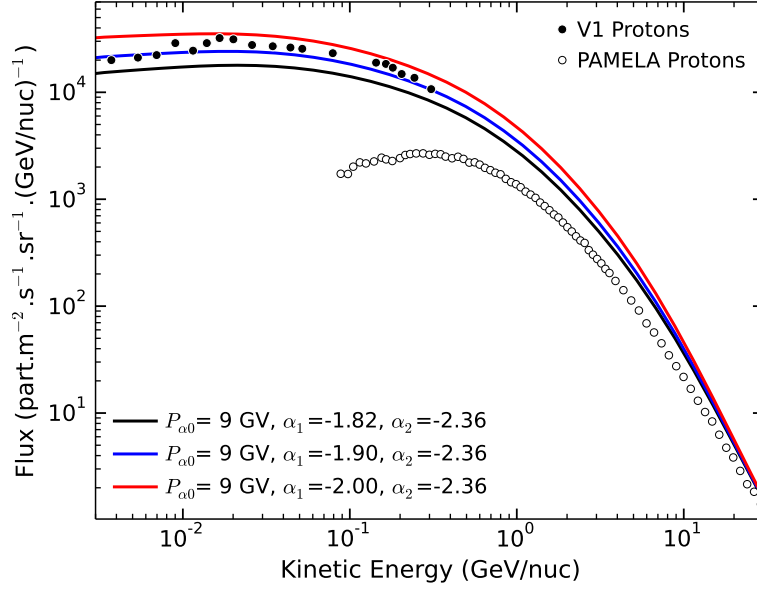


Figure 7.1: The proton LIS's, resulting from the reacceleration model from Ch. 6 used to match the electron observations in Fig. 6.17, are shown compared to the V1 (Stone et al., 2013) and PAMELA (Adriani et al., 2013a) proton observations. The reference values for the nuclei source spectrum, $\alpha_1 = -1.82$, $\alpha_2 = -2.36$, $P_{\alpha 0} = 9$ GV in Eq. 2.4, give the reference LIS (black curve). The index α_1 is adjusted to -1.90 (blue curve) and -2.00 (red curve) to give the respective LIS's.

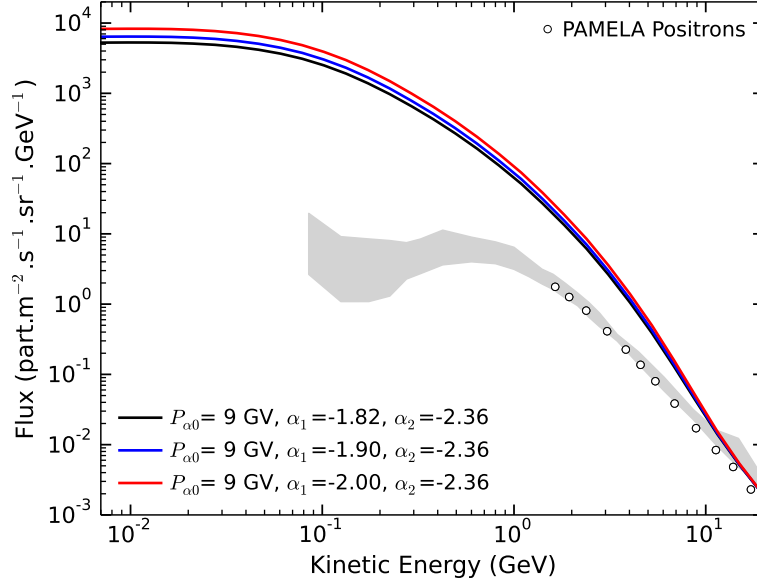


Figure 7.2: The positron LIS's corresponding to the reacceleration models used for the proton LIS's of Fig. 7.1 compared to the PAMELA positron observations: three year average (black circles) (Adriani et al., 2013b) and half year variations for Jul 2006 to Dec 2009 (grey band) (Munini, 2016).

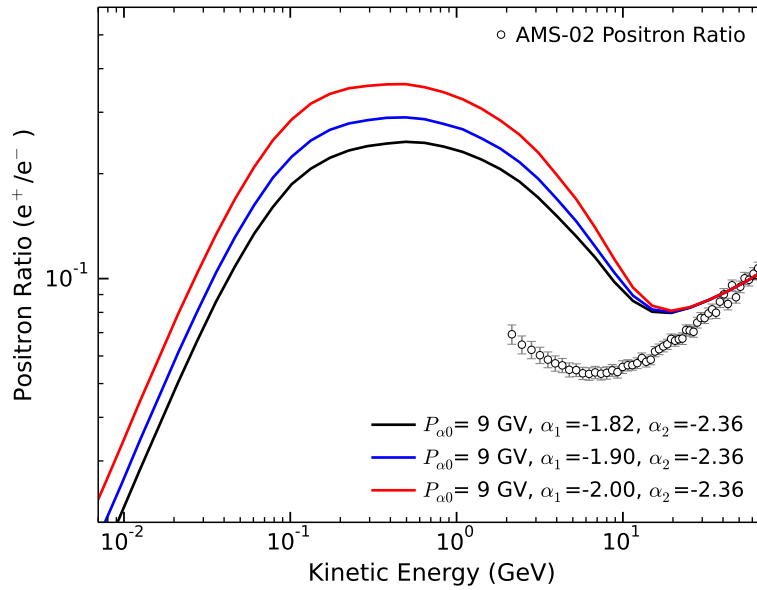


Figure 7.3: The positron ratios (e^+/e^-) corresponding to the reacceleration models used for the proton LIS's of Fig. 7.1 compared to the AMS-02 observations (Aguilar et al., 2014).

7.2.1 Adjustment of the low rigidity nuclei source index

To increase the proton LIS intensity at the V1 energies, the nuclei source spectrum is adjusted to produce more lower energy protons, without affecting the calculated electron LIS. To calculate the electron LIS, the nuclei source spectrum is kept unchanged from the reference model. The source spectrum is given by the values $\alpha_1 = -1.82$, $\alpha_2 = -2.36$ and $P_{\alpha 0} = 9$ GV in Eq. 2.4. The index α_1 is adjusted to -1.90 (blue curve) and -2.00 (red curve) to give the respective LIS's in Figure 7.1. An increase in source protons gives an overall increase to the proton LIS at energies below 10 GeV/nuc. For $\alpha_1 = -1.90$ the proton LIS represents the V1 values reasonably well.

The corresponding positron LIS's are shown Figure 7.2. As with the proton LIS's increasing the source nuclei also increases the positron LIS intensities below 10 GeV. These increases can also be seen to affect the positron ratios of Figure 7.3. With the electron LIS from Figure 6.17 remaining unaffected by the nuclei source changes, the ratios change similarly to the positron LIS's, increasing at lower energies. Evidently, changing only this parameter can't improve the ratio to match the observations.

7.2.2 Adjustment of the high rigidity nuclei source index

To further test the effect of the nuclei source parameters, the index α_2 is adjusted next, while $\alpha_1 = -1.82$ is kept unchanged. The proton LIS's resulting from adjusting α_2 to -2.20 (blue curve) and -2.05 (red curve) from -2.36 (black curve) are shown in Figure 7.4 respectively. Decreasing the index lowers the CR intensity at all energies due to the LIS's being affected at the normalization energy. For $\alpha_2 = -2.20$ the proton LIS matches the PAMELA observations better above 10 GeV/nuc and it would likely be easy to match the rest of the observations after modulation. The LIS's increasingly underestimate the V1 protons with increasing α_2 .

The corresponding positron LIS's are seen in Figure 7.5 to have lower intensity at energies below about 10 GeV, but unlike the proton LIS's, show slight increases above 10 GeV. This effect can more clearly be seen in the positron ratios of Figure 7.6. The increase in α_2 greatly changes the positron ratio, moving the ratios closer to the observations below 10 GeV, but increasing the ratio above this energy. Adjusting the positron excess that is added to the positron LIS would improve the ratio between 10 and 60 GeV, but at higher energies would no longer match the observations.

7.2.3 Adjustment of the reference rigidity nuclei source spectrum

The final part of the nuclei source spectrum is the reference rigidity $P_{\alpha 0}$. The value in Eq. 2.4 is adjusted from 9 GV (black curve) to 3 GV (blue curve) and 40 GV (red curve) to calculate the proton LIS in Figure 7.7, with α_1 and α_2 unchanged. These changes greatly affect the proton LIS's, with a higher $P_{\alpha 0}$ leading to a lower intensity proton LIS and a lower $P_{\alpha 0}$ resulting in a higher intensity proton LIS. For $P_{\alpha 0} = 3$ GV the proton LIS matches the V1 protons better,

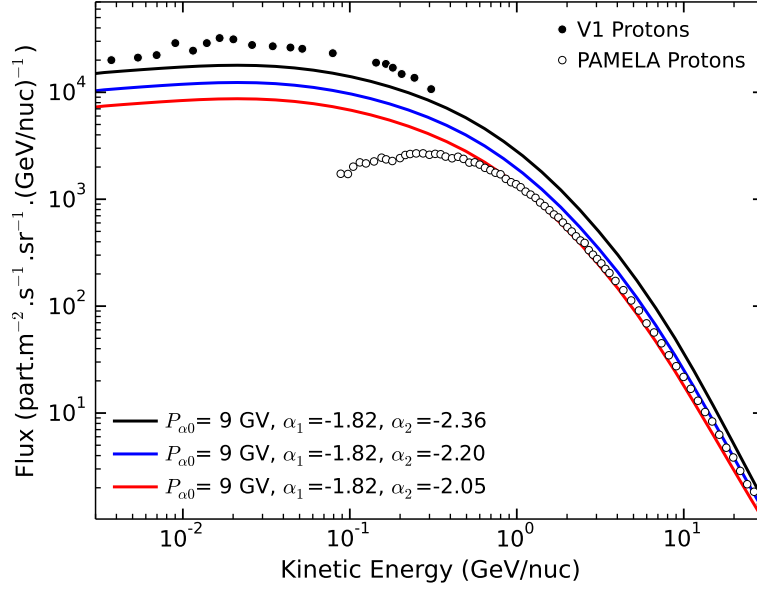


Figure 7.4: The proton reference LIS (black curve), from Fig. 7.1, has an index $\alpha_2 = -2.36$ in Eq. 2.4, with α_2 now adjusted to -2.20 (blue curve) and -2.05 (red curve) to give the respective LIS's. Observations as in Fig. 7.1.

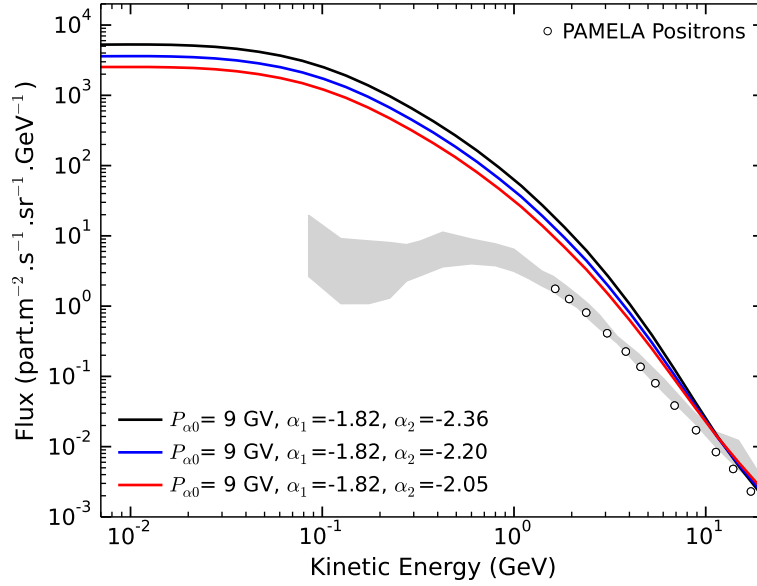


Figure 7.5: The positron LIS's corresponding to the reacceleration models used for the proton LIS's of Fig. 7.4. Observations as in Fig. 7.2.

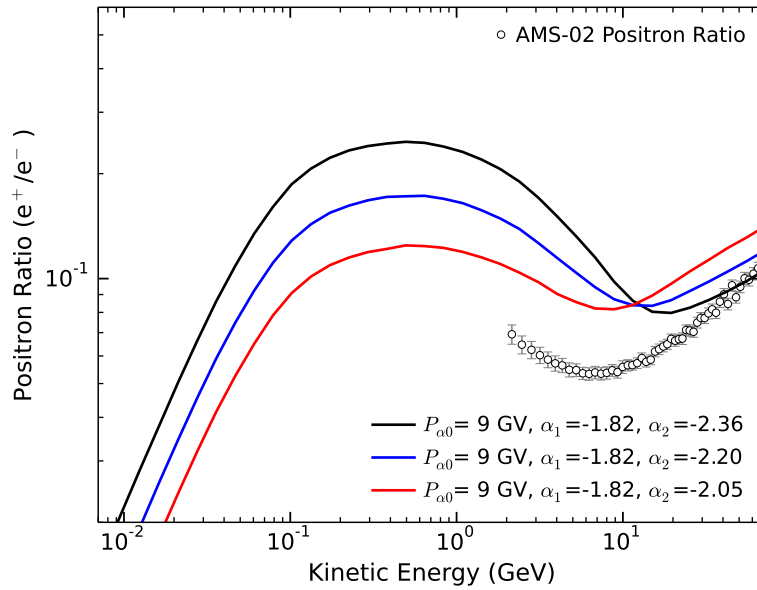


Figure 7.6: The positron ratios (e^+/e^-) corresponding to the reacceleration models used for the proton LIS's of Fig. 7.4. Observations as in Fig. 7.3.

but the general increase in intensity will require larger changes to the modulation parameters to match the observations at the Earth than those used for Figure 6.8.

The calculated positron LIS's for the adjusted $P_{\alpha 0}$ values are shown in Figure 7.8. As with the proton LIS's, the positron LIS's change intensity inversely to the increases or decreases in $P_{\alpha 0}$. These changes are reflected in the large variations in the positron ratios of Figure 7.9. With $P_{\alpha 0} = 40$ GV the ratio has the closest match to observations of any of the source spectrum changes shown. The positron LIS will likely be easily modulated to match the observations, similarly to a plain diffusion positron LIS, but the corresponding proton LIS is quite unfavourable for both the V1 and PAMELA proton observations.

These nuclei source spectrum tests, with the electron reacceleration model, have not resulted in a specific model that shows improvements to matching the proton, positron and positron ratio observations simultaneously. The parameter changes show improvements to either the proton LIS or the positron LIS and ratio, but no parameters combinations show improvements to both. Using the electron reacceleration model as basis to also reproduce the proton observations is possible, but for further progress another approach is required.

7.3 Model improvements from published LIS's

The above approach shows that adding or adjusting parameters for electrons and nuclei into one model is not sufficient to match the relevant observations. The next step into the search for a single model that can calculate a set of LIS's, is to investigate the effect of other propagation effects beyond source injection and diffusion.

The model by Maccione (2013) calculates LIS's from a single propagation model and matches observations at the Earth well for electron, positrons, protons and the B/C ratio. The V1 spectra were not considered in their study. To calculate LIS's they used the DRAGON galactic propagation code (Evoli et al., 2008; Maccione et al., 2011). This code shares many similarities with GALPROP and the propagation parameters used in their study can be implemented in GALPROP to investigate if similar LIS's can be calculated.

The relevant parameters, as required by Eqs. 2.2, 2.4 and 2.5, used in their study are listed here: $K_0 = 2.5 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $\delta_1 = \delta_2 = 0.5$, $\alpha_1 = \alpha_2 = -2.3$, $P_{\alpha e 0} = 6 \text{ GV}$, $\alpha_{e1} = -1.5$, $\alpha_{e2} = -2.65$, $V_A = 18 \text{ km.s}^{-1}$. This model also includes convection, with $dV/dz = 5 \text{ km.s}^{-1} \cdot \text{kpc}^{-1}$. For all model tests shown in the previous chapters, the value convection parameter dV/dz was set to zero, as explained in Section 2.3.1, effectively neglecting convection in the Galaxy. The Alfvén wave speed V_A is lower than the value of 36 km.s^{-1} used in the GALPROP models of the previous sections. These parameters are input into GALPROP as two reacceleration models, one with convection included and one without. All other parameters are kept the same as in the GALPROP reference model.

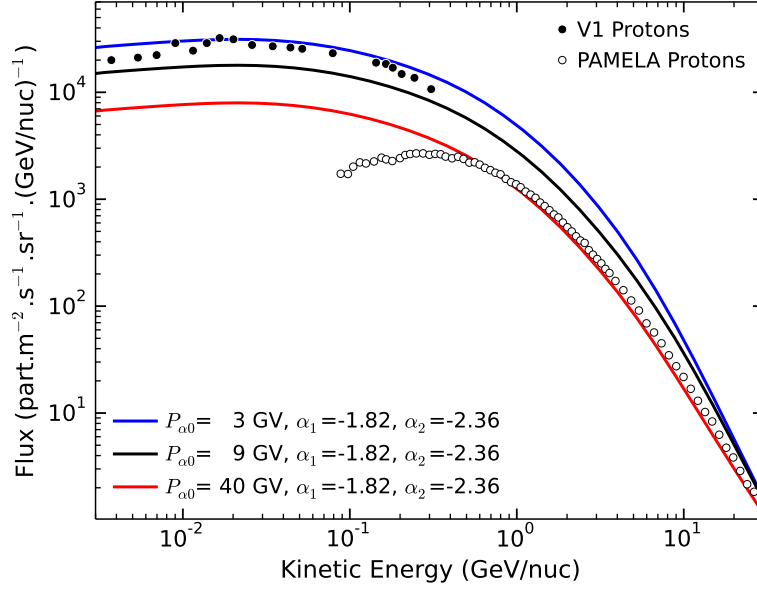


Figure 7.7: The proton reference LIS (black curve), from Fig. 7.1, has a reference rigidity $P_{\alpha 0} = 9$ GV in Eq. 2.4, with $P_{\alpha 0}$ adjusted to 3 GV (blue curve) and 40 GV (red curve) to give the respective LIS's. Observations as in Fig. 7.1.

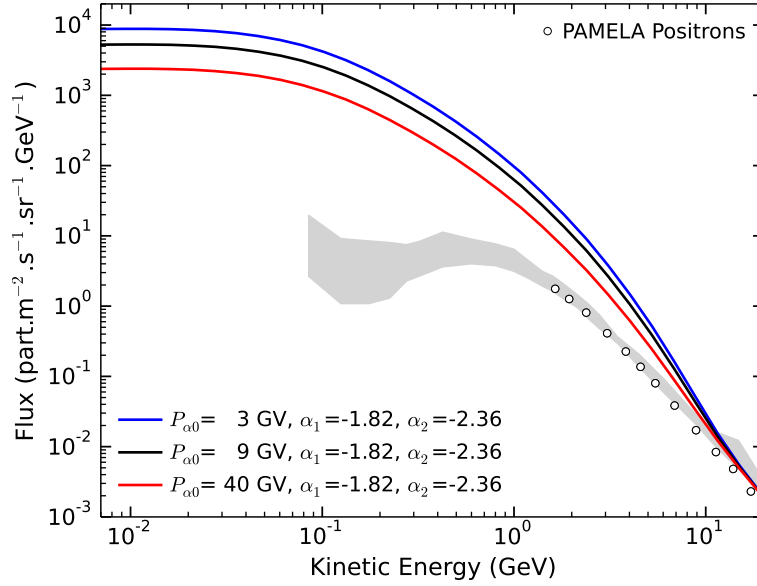


Figure 7.8: The positron LIS's corresponding to the reacceleration models used for the proton LIS's of Fig. 7.7. Observations as in Fig. 7.2.

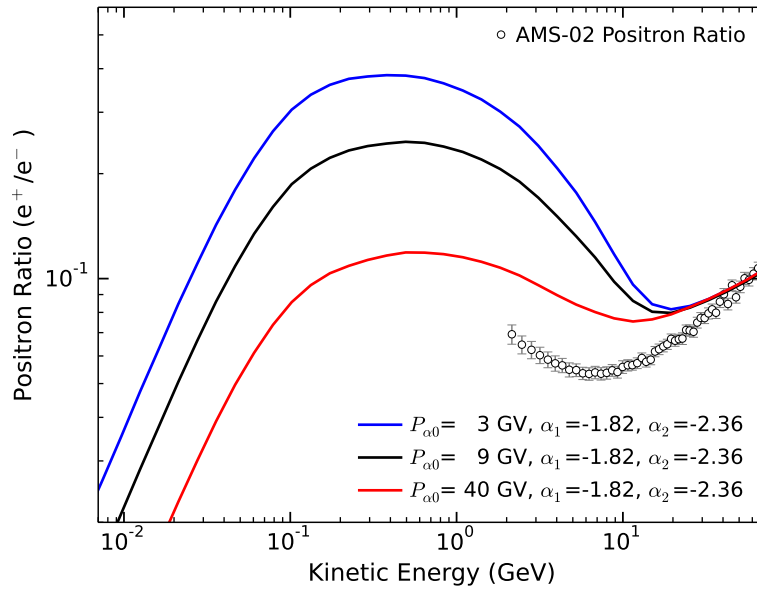


Figure 7.9: The positron ratios (e^+/e^-) corresponding to the reacceleration models used for the proton LIS's of Fig. 7.7. Observations as in Fig. 7.3.

7.3.1 Reproducing electron and positron LIS's

The electron LIS calculated with these parameters, with convection, is shown in Figure 7.10 (black curve). The LIS matches the PAMELA values closely above 2 GeV, but this LIS might underestimate the modulation below 10 GeV when compared to the reacceleration electron LIS of Figure 6.17. The parameters are also implemented in GALPROP with no convection as to have the LIS be more comparable to previous calculations. This electron LIS calculated with no convection (blue curve) shows increased intensity between 0.01 and 3 GeV. This effect is expected as convection in the Galaxy is directed away from the galactic plane, reducing the amount of particles arriving at the Earth. The third electron LIS (red curve) is also calculated without convection, but with simple adjustments to the source parameters ($\alpha_1 = -1.82$, $\alpha_{e1} = -2.0$), in order to simply reproduce the V1 values with the Maccione (2013) parameters. This change to the source spectra, increasing the amount of lower energy electrons at the source, shows that this model can give similar intensity to the V1 values at low energies, but more changes would be needed to better match the values.

The corresponding positron LIS's are shown in Figure 7.11. The addition of convection is seen to have a larger effect on the positron LIS (black curve) than on the electron LIS, without convection the positron intensity is increased for all energies below about 6 GeV. Decreasing the nuclei source spectrum also affects the positron LIS below 6 GeV, decreasing the positron LIS below that of Maccione (2013). At higher energies the three LIS's are the same and all match the PAMELA values well.

The above electron and positron LIS's give the positron ratios (e^+/e^-) of Figure 7.12. All three ratios match the observations much closer than any previous ratios calculated in this study. The two ratios with the source parameters unchanged from Maccione (2013) (black and blue curves) increase rapidly below 4 GeV. This is due to the sensitivity of the ratios to the relatively low intensities of the corresponding electron LIS's. The ratio calculated with the source adjusted LIS's does not show this rapid increase and has a shape more similar to ratios calculated in previous sections, but matches the observations better.

7.3.2 Reproducing nuclei LIS's

The corresponding LIS's for protons are shown in Figure 7.13. The Maccione (2013) parameters give LIS's that match the PAMELA protons well above 10 GeV, while not underestimating modulation, unlike the electron LIS's. The effect of convection on the proton intensities between 0.1 and 10 GeV can also be seen. As with the electron LIS, the nuclei source spectrum was adjusted to give a proton LIS that better matches the V1 observations. Subsequently, the source adjusted proton LIS (red curve) has a greatly decreased intensity at the V1 energies. The corresponding B/C ratios are also shown for the three models in Figure 7.14. The model with convection (black curve) gives a ratio that matches the observations well, whereas without convection (blue curve) the ratio overestimates the observations. The source adjustments only

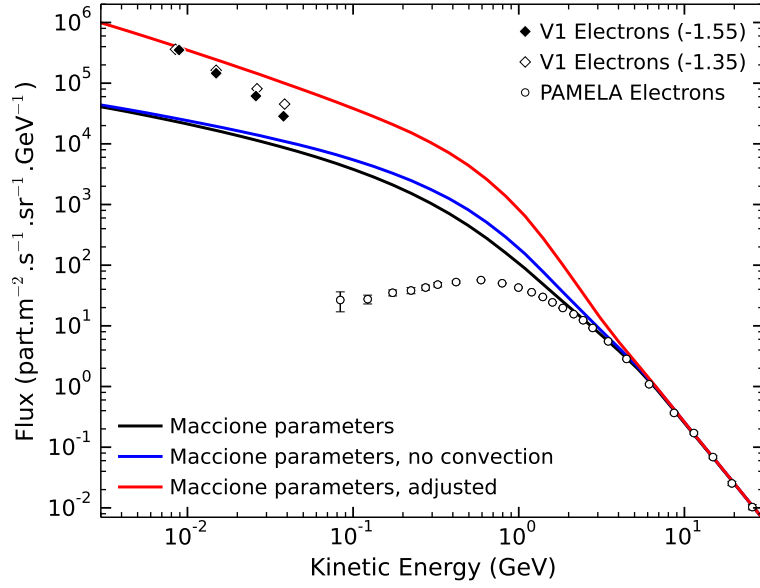


Figure 7.10: The electron LIS's calculated with parameters as presented by Maccione (2013) taking convection into account (black curve). The electron LIS is also calculated with no convection (blue curve) and with adjustments, $\alpha_1 = -1.82$, $\alpha_{e1} = -2.0$, (red curve) to better represent the V1 observations (Stone et al., 2013).

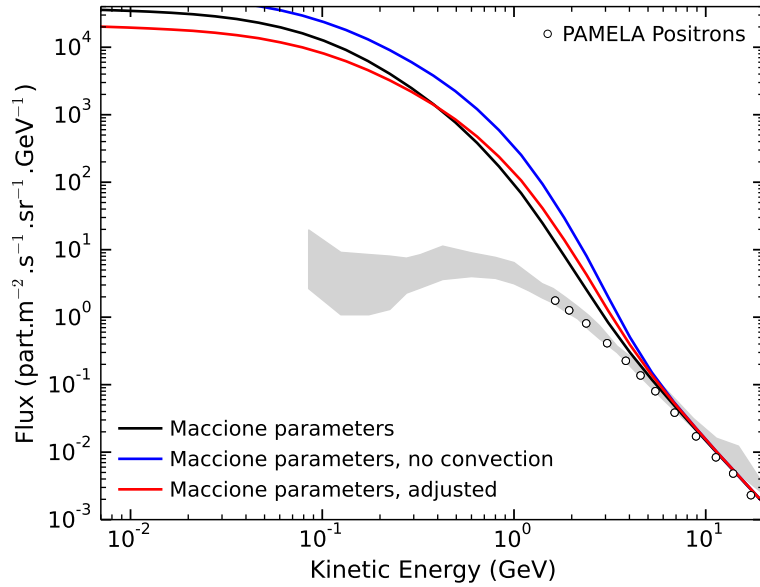


Figure 7.11: The positron LIS's calculated with the Maccione (2013) parameters similarly to Fig. 7.10. Observations as in Fig. 7.2.

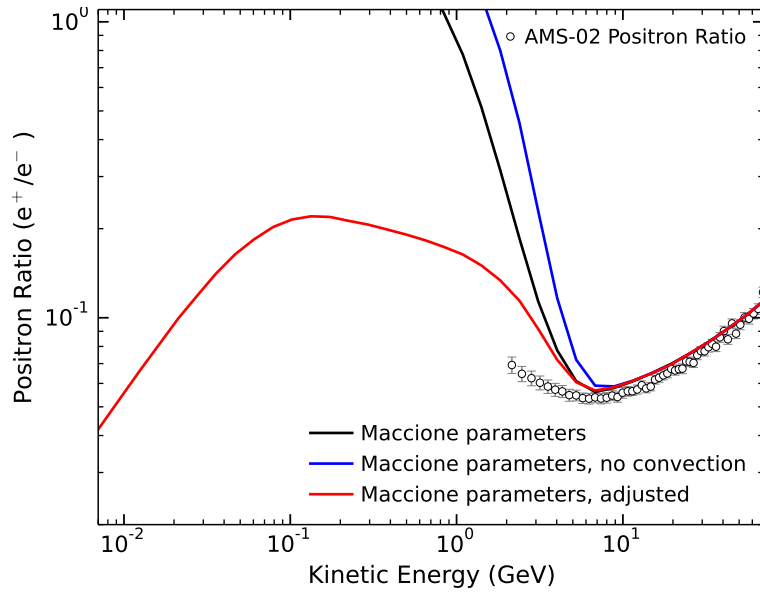


Figure 7.12: The positron ratios (e^+/e^-) calculated from the electron LIS's of Fig. 7.10 and the positron LIS's of Fig. 7.11. Observations as in Fig. 7.3.

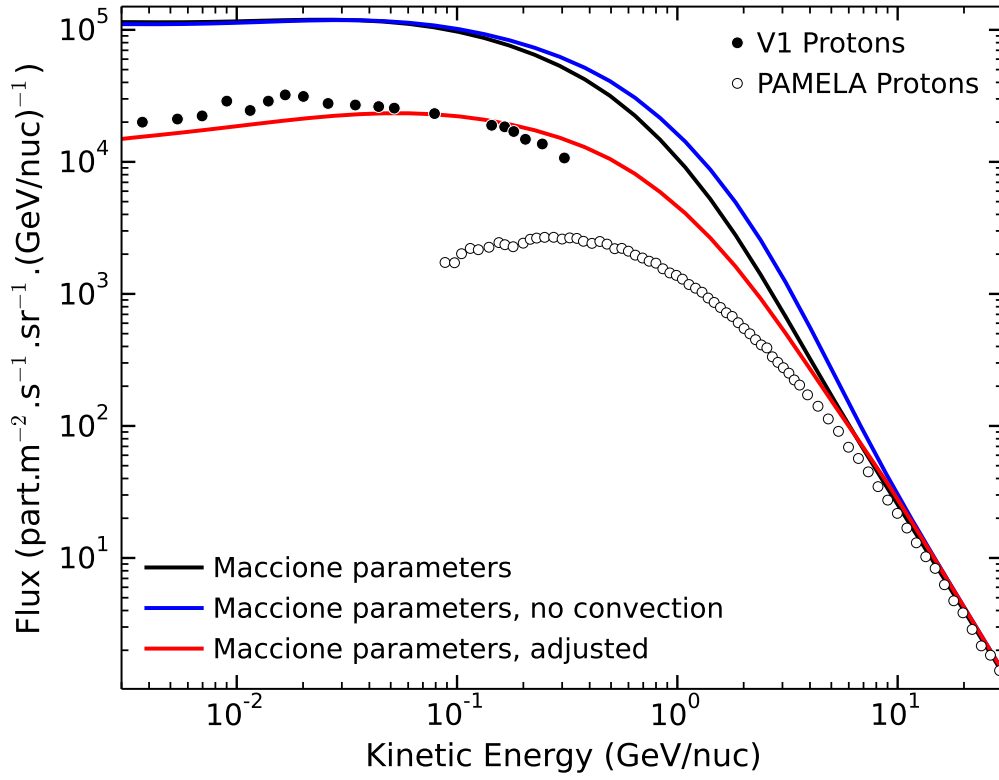


Figure 7.13: The proton LIS's calculated with the Maccione (2013) parameters similarly to Fig. 7.10. Observations as in Fig. 7.1.

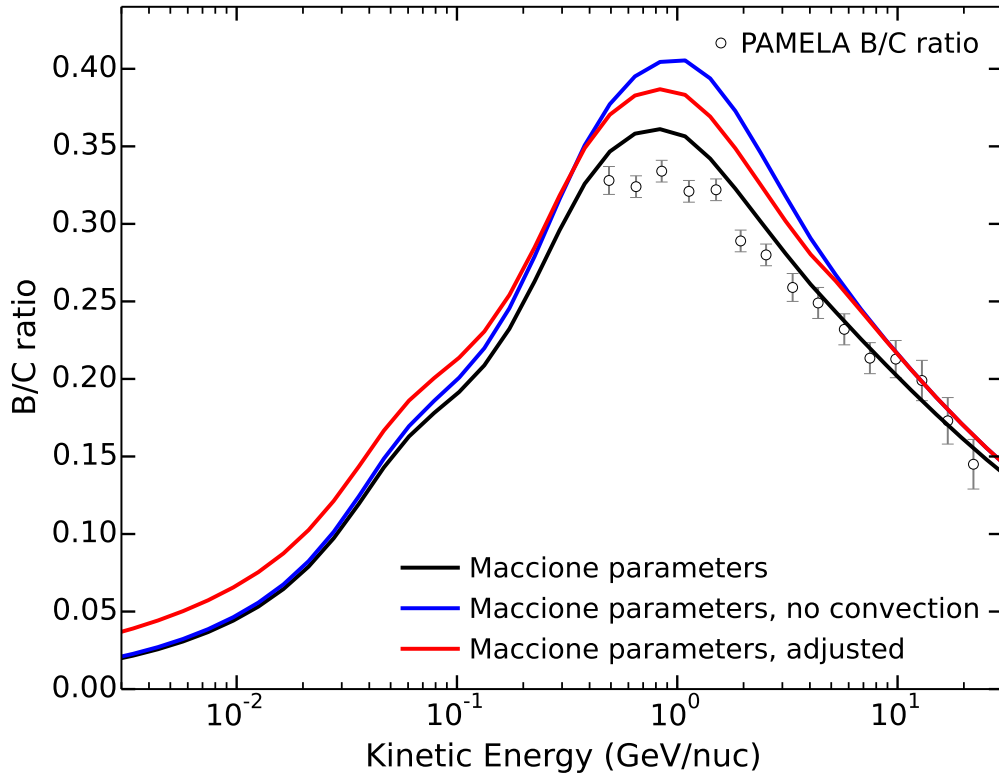


Figure 7.14: The B/C ratios calculated with the Maccione (2013) parameters similarly to Fig. 7.10, compared to the PAMELA B/C observations (Adriani et al., 2014).

result in a small change to the ratio (red curve), decreasing the ratio between 0.4 and 6 GeV. This decrease is too small to match the observations, but does improve the shape for the ratio in this energy range.

When comparing the results of Maccione (2013) to the above calculated LIS's similar features can be seen, although they are not the same at all energies. The electron and proton LIS's clearly show that V1 observations were not considered, as the LIS intensities deviate greatly from the V1 values at low energies, similarly to the reference models in earlier chapters. At the PAMELA energies the calculated LIS's and ratios correspond more closely to those presented by Maccione (2013). Their results, and the tests done here, show that a single model can give LIS's that match electron, positron, proton and B/C observations reasonably well. The effect of adding convection and reducing reacceleration strength is tested next.

7.4 Adjusting convection and reacceleration

A feature of the model used by Maccione (2013), and neglected in previous chapters, is the role of convection in the propagation model. The GALPROP code has the capability to include convection in the CR propagation process. However, in the previous chapters the effect of convection on the calculated LIS's has been considered small and assumed not needed to match the observations. To more explicitly test the effect of including a non-zero convection term in the GALPROP models, the reacceleration model presented in Chapter 5 is implemented again to calculate proton LIS's.

7.4.1 Convection tests

The proton LIS calculated with the model with no convection added, $dV/dz = 0 \text{ km.s}^{-1}.\text{kpc}^{-1}$ (solid black curve), is compared in Figure 7.15 to the LIS's from the models with $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$ (blue curve) and $10 \text{ km.s}^{-1}.\text{kpc}^{-1}$ (red curve), respectively. With dV/dz set to a non-zero value the calculated proton LIS has lower intensity between about 0.01 and 10 GeV, similar to the LIS from the Maccione (2013) parameters in Figure 7.13. This decrease slightly improves the estimation of the highest energy V1 values, but also lowers the estimation of the amount of modulation below 10 GeV.

The corresponding calculated positron LIS's are shown in Figure 7.16. These LIS's also show the decrease in intensity below 10 GeV, but unlike the proton LIS's the decrease extends to the lowest energies of the LIS's. The positron ratios, calculated with the corresponding electron LIS's, also show this effect in Figure 7.17. The stronger convection improves the estimation of the positron ratio observations at the Earth below 10 GeV. These tests show that for convection a value of $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$, as used by Maccione (2013), is an improvement to the model and is to be used for all further GALPROP model tests.

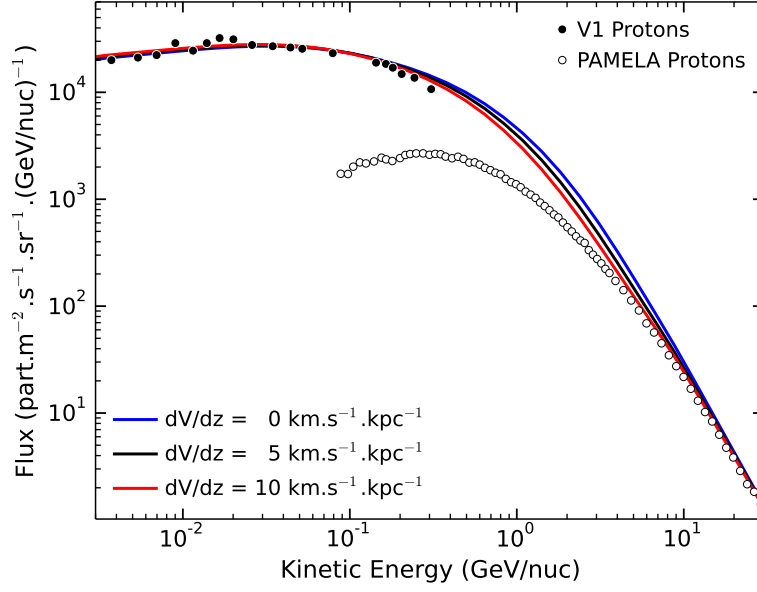


Figure 7.15: The proton LIS calculated from the proton reacceleration model presented in Ch. 5 with no convection (black curve), together with the LIS's calculated with convection added with $5 \text{ km.s}^{-1}.\text{kpc}^{-1}$ (blue line) and $10 \text{ km.s}^{-1}.\text{kpc}^{-1}$ (red curve). Observations as in Fig. 7.1.

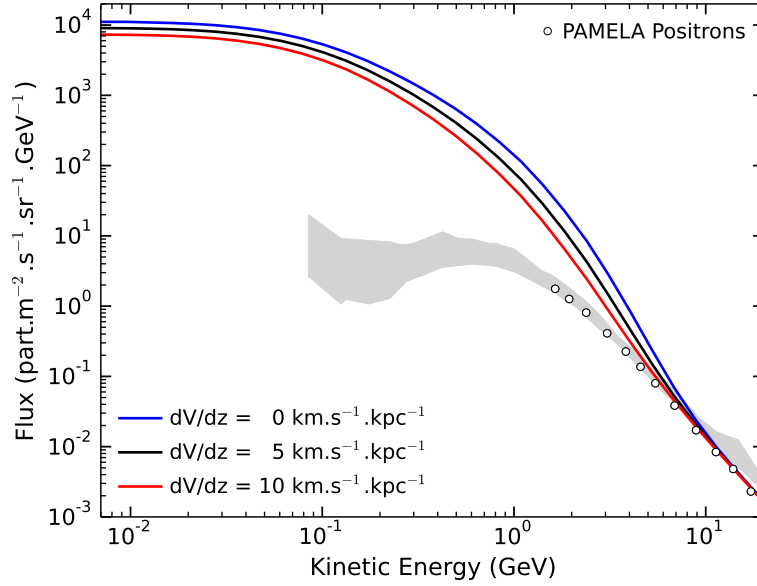


Figure 7.16: The positron LIS's calculated with different convention values, similarly to Fig. 7.15. Observations as in Fig. 7.2.

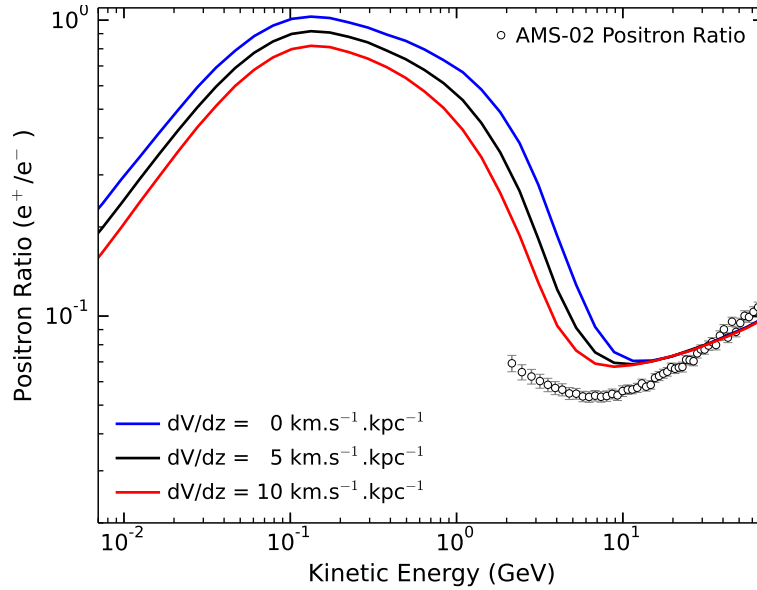


Figure 7.17: The positron ratios (e^+/e^-) calculated with the positron LIS's of Fig. 7.16 and the corresponding electron LIS's. Observations as in Fig. 7.3.

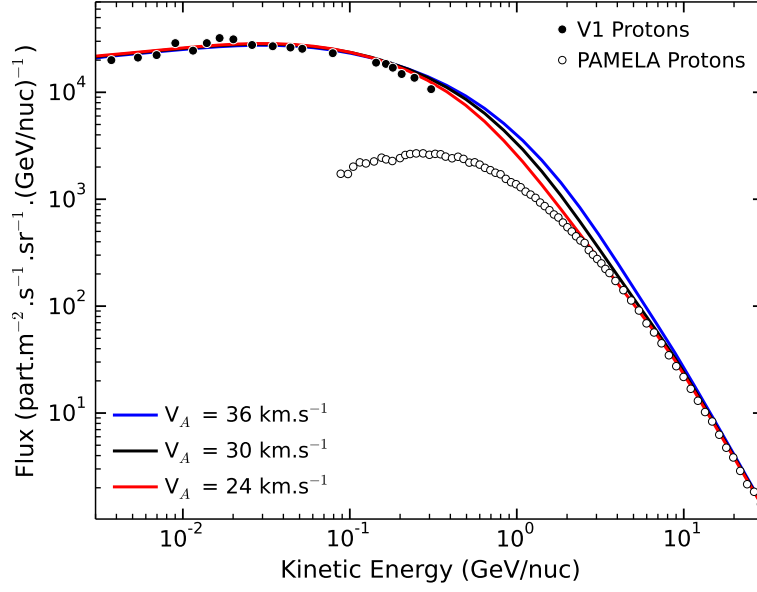


Figure 7.18: The proton LIS calculated with $V_A = 36 \text{ km.s}^{-1}$ and $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$ from Fig. 7.15 (blue curve) is compared to the LIS's calculated with $V_A = 30 \text{ km.s}^{-1}$ (black line) and $V_A = 24 \text{ km.s}^{-1}$ (red line), respectively. Observations as in Fig. 7.1.

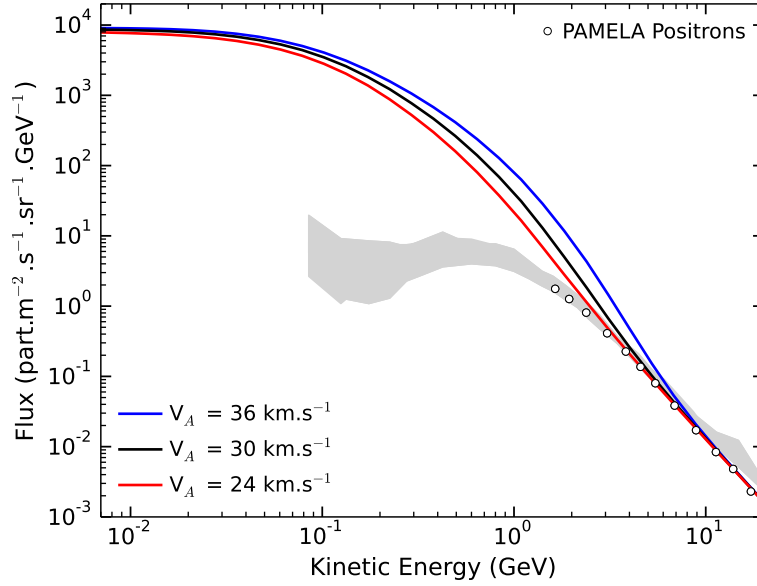


Figure 7.19: The positron LIS's calculated with adjusted Alfvén wave speed similarly to Fig. 7.18. Observations as in Fig. 7.2.

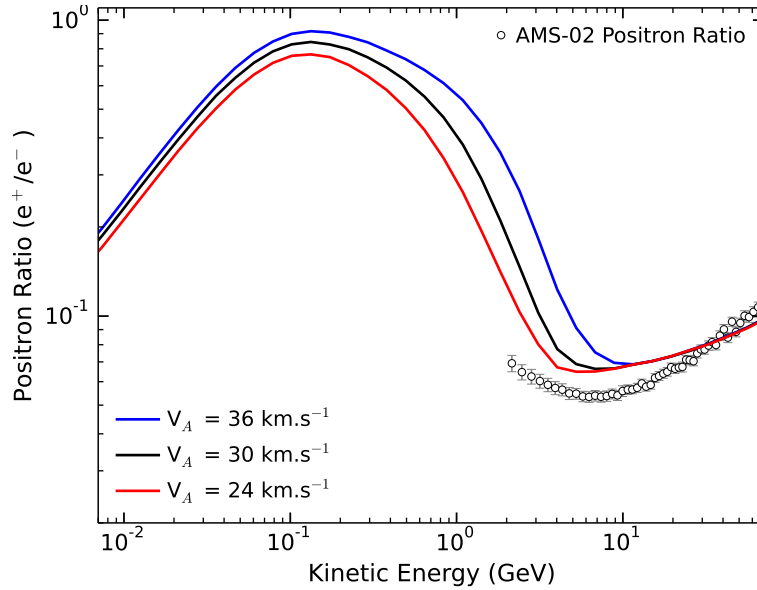


Figure 7.20: The positron ratios (e^+/e^-) calculated with the positron LIS's of Fig 7.18 and the corresponding electron LIS's. Observations as in Fig. 7.3.

7.4.2 Reacceleration tests

In all the tests of the reacceleration model shown in the previous chapters, the Alfvén wave speed (V_A) has been taken as 36 km.s^{-1} . From CR studies, such as by Maccione (2013), this value can be seen to be on the high end for the Alfvén wave speed parameter and can likely be seen as an upper limit of the influence of reacceleration. The effect of lowering the V_A , thus decreasing the strength of the reacceleration, is now tested.

The proton reacceleration LIS shown in Figure 7.15 calculated with $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$, has $V_A = 36 \text{ km.s}^{-1}$ (blue curve) and is compared to the LIS's in Figure 7.18 calculated with the same parameters, but with $V_A = 30 \text{ km.s}^{-1}$ (black curve) and $V_A = 24 \text{ km.s}^{-1}$ (red curve), respectively. This decrease in V_A results in a decrease in the proton intensities for the energy range of about 0.03 to 8 GeV. This effect is similar to increasing the strength of convection and also improves the estimation of the highest energy V1 proton values. For $V_A = 24 \text{ km.s}^{-1}$ the LIS matches the PAMELA values very closely above 3 GeV, effectively neglecting the presence of modulation at these energies.

The corresponding positron LIS's are shown in Figure 7.19. Unlike the proton LIS's, the shapes of the positron LIS's are different to those produced by the changes in convection of Figure 7.16. The different values of V_A lower the positron LIS intensities below 8 GeV, but only has a minor effect on the LIS's below 0.01 GeV. The weaker of reacceleration gives positron LIS shapes that look more similar to those given by the plain diffusion model. Similar to the changes in dV/dz , the lower values for V_A improve the estimation of the positron ratio observations at the Earth below 10 GeV, as shown in Figure 7.20.

From these tests for convection and reacceleration, the values $V_A = 30 \text{ km.s}^{-1}$ and $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$ can now be chosen and kept fixed for further tests to improve the estimation of observations with a single model.

7.5 Finding a model to produce a complete set of LIS's

With the parameter values for convection and reacceleration in the GALPROP model chosen in the previous section, the source spectrum and diffusion parameters can now be revisited in order to further improve the model. The parameters $V_A = 30 \text{ km.s}^{-1}$ and $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$ are now added to the models in further testing. The reference reacceleration model parameters, for Eqs. 2.2, 2.4 and 2.5, are listed in Table 7.1 for comparison.

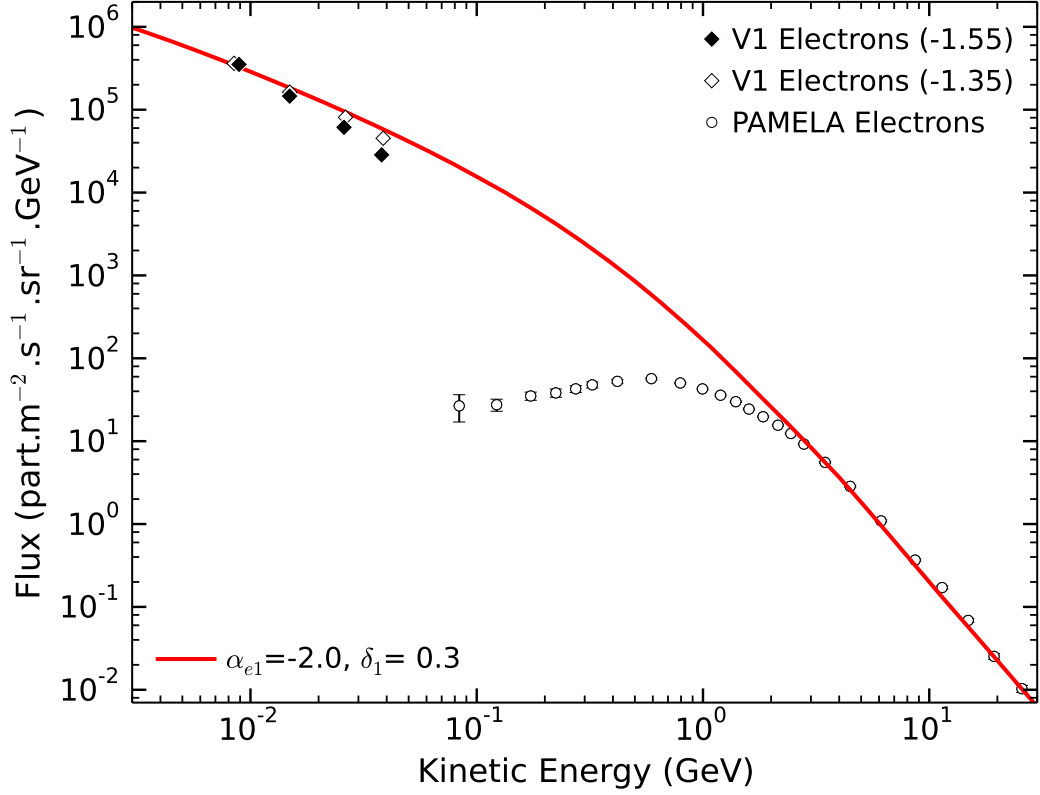


Figure 7.21: The calculated electron LIS for the reacceleration model with $V_A = 30 \text{ km.s}^{-1}$ and $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$. To match the V1 electron observations well, the values $\alpha_{e1} = -2.0$ and $\delta_1 = 0.3$ are needed.

Table 7.1: List of GALPROP model parameters used in Section 7.5.

Model Parameters	Reacc. Reference	Model 1 (Red LIS's)	Model 2 (Blue LIS's)	Model 3 (Green LIS's)
$K_0 (10^{28} \text{ cm}^2 \text{ s}^{-1})$	5.75	5.75	5.10	5.10
$P_0 \text{ (GV)}$	4	4	4	4
δ_1	0.34	0.30	0.30	0.30
δ_2	0.34	0.40	0.40	0.40
$P_{\alpha 0} \text{ (GV)}$	9	9	9	9
α_1	-1.82	-1.82	-1.86	-1.86
α_2	-2.36	-2.36	-2.36	-2.36
$P_{\alpha e 0} \text{ (GV)}$	4	4	4	4
α_{e1}	-1.6	-2.0	-2.0	-1.9
α_{e2}	-2.5	-2.5	-2.5	-2.7
$V_A \text{ (km.s}^{-1}\text{)}$	36	30	30	30
$dV/dz \text{ (km.s}^{-1}.\text{kpc}^{-1}\text{)}$	0	5	5	5

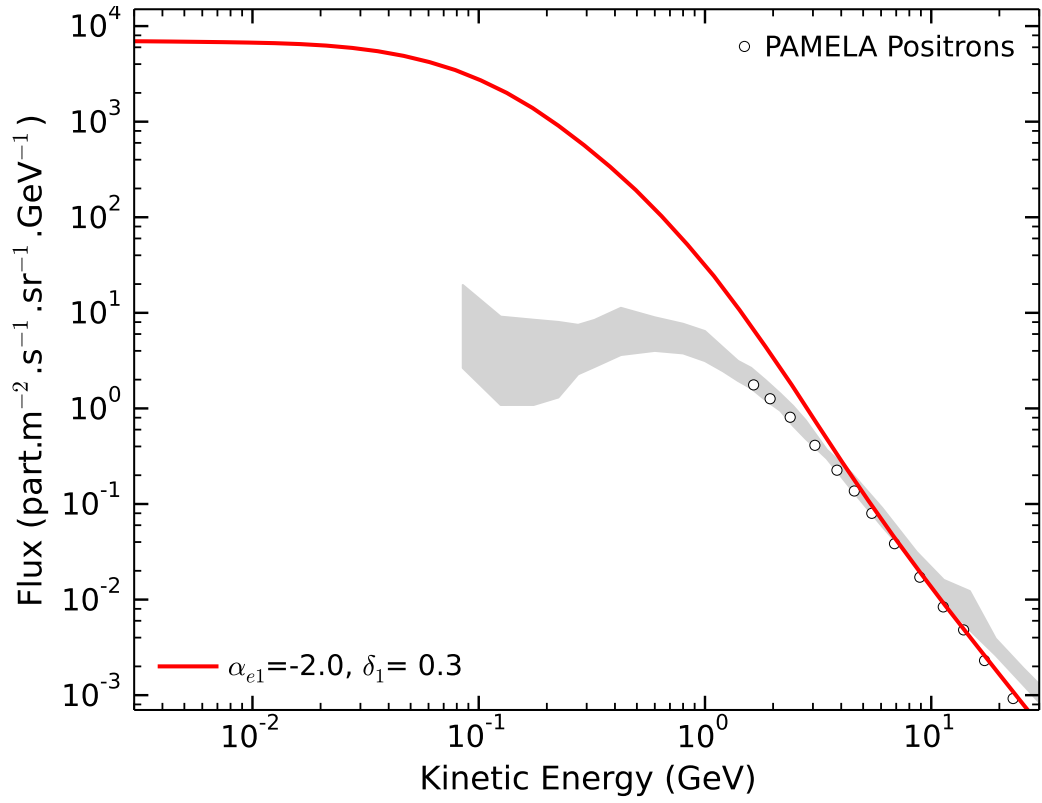


Figure 7.22: The calculated positron LIS corresponding to the electron LIS and model parameters of Fig. 7.21.

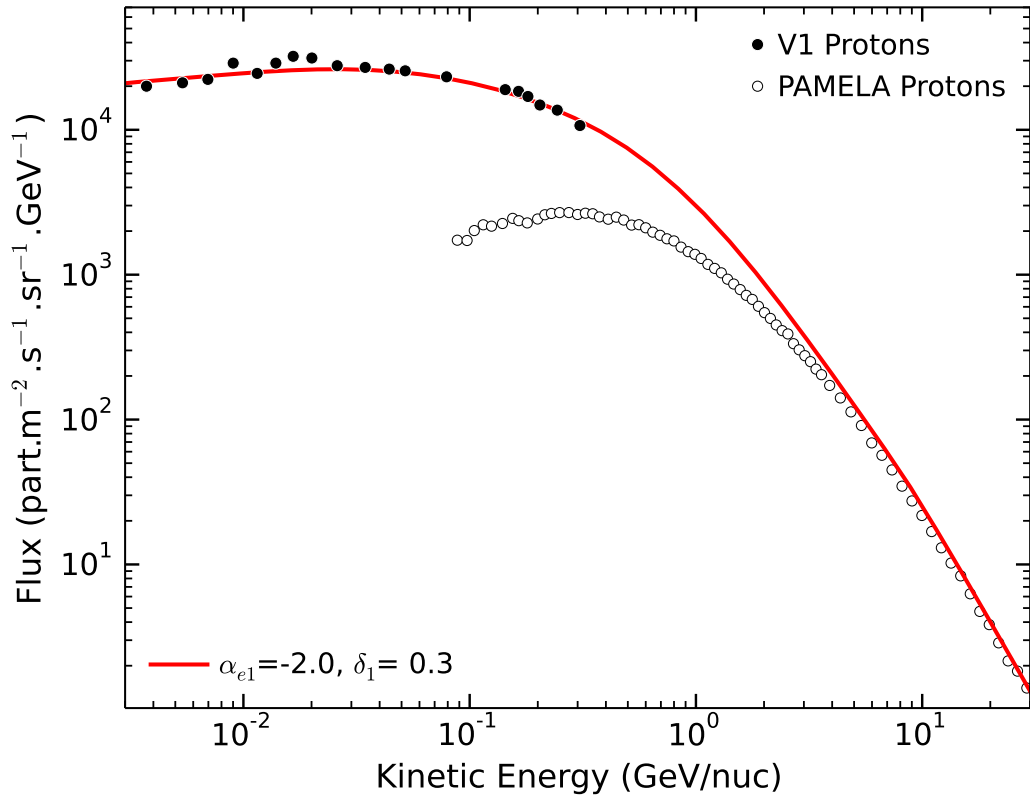


Figure 7.23: The calculated proton LIS corresponding to the electron LIS and model parameters of Fig. 7.21.

With the addition of the adjusted reacceleration and convection values to the set of parameters, the model calculates LIS's that reproduce the proton, positron and positron ratio observations reasonably well. These LIS's can still be improved, and the electron LIS does not yet match the V1 observations as was shown possible in both Chapters 4 and 5.

Firstly the lower energy indices for the diffusion coefficient and the electron source spectrum are changed to values previously shown to reproduce the V1 electron observations well. Figure 7.21 shows the electron LIS calculated with $\alpha_{e1} = -2.0$ and $\delta_1 = 0.3$, listed as model 1 in Table 7.1. These values are chosen to replicate the effect seen from the tests in Chapter 5, where the reacceleration model was used to calculate only the electron LIS. This LIS now matches the V1 electron observations better than, for example, any of the electron LIS's in Figure 7.10. Of the two V1 spectra, the -1.35 index spectrum is still matched better. Looking at the PAMELA observations, this LIS is too low at these energies, because it lies under the observations at the Earth, thus not allowing for any modulation at these energies.

The effect of these electron focused values on proton and positron LIS's is shown in Figures 7.23 and 7.22, respectively. These LIS's are unaffected by changing α_{e1} and are only slightly affected by the new value of δ_1 . The proton LIS still shows a great match to the V1 observations, similarly to Figure 5.11, even with a change in the value of δ_1 . Both the proton and positron LIS's also slightly underestimate modulation effect below 10 GeV.

With the electron LIS now estimating the V1 values well, the three LIS's can now be adjusted to better represent the PAMELA values and still satisfy the modulation requirements. This is attempted by adjusting the value for K_0 , to affect all three LIS's, and the value for α_1 , to affect only the nuclei and positron LIS's. With the values chosen as $K_0 = 5.1 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and $\alpha_1 = -1.86$ in the reacceleration model, listed as model 2 in Table 7.1, the calculated electron LIS is shown in 7.24. This LIS differs only slightly from that of Figure 7.21. While the electron LIS has improved, it does not yet have a shape similar to that of the electron LIS in Figure 6.12 in order to give a good match to the observations at the Earth after modulation.

With α_1 also adjusted, the effect on the proton and positron LIS's are more apparent. This is seen in Figures 7.25, for positrons, and 7.26, for protons. The increase in source nuclei intensity at lower rigidities leads to these two LIS's having increased intensity at all energies below 10 GeV. Both the LIS's should now match the observations well at the Earth after taking into account modulation. This intensity increase also results in the proton LIS giving an incrementally better estimation of the V1 proton values.

Finally the electron source indices are adjusted again to further improve electron and positron LIS's to match the Earth observations taking assumed modulation into account. To improve the positron LIS, while leaving the proton and positron LIS's unchanged, the electron LIS has to be adjusted with the source indices. The improvements made to the electron and positron LIS's at energies above about 5 GeV, in order to account for the PAMELA observations and assumed modulation, have already improved the positron ratio. Finalising the electron LIS shape between

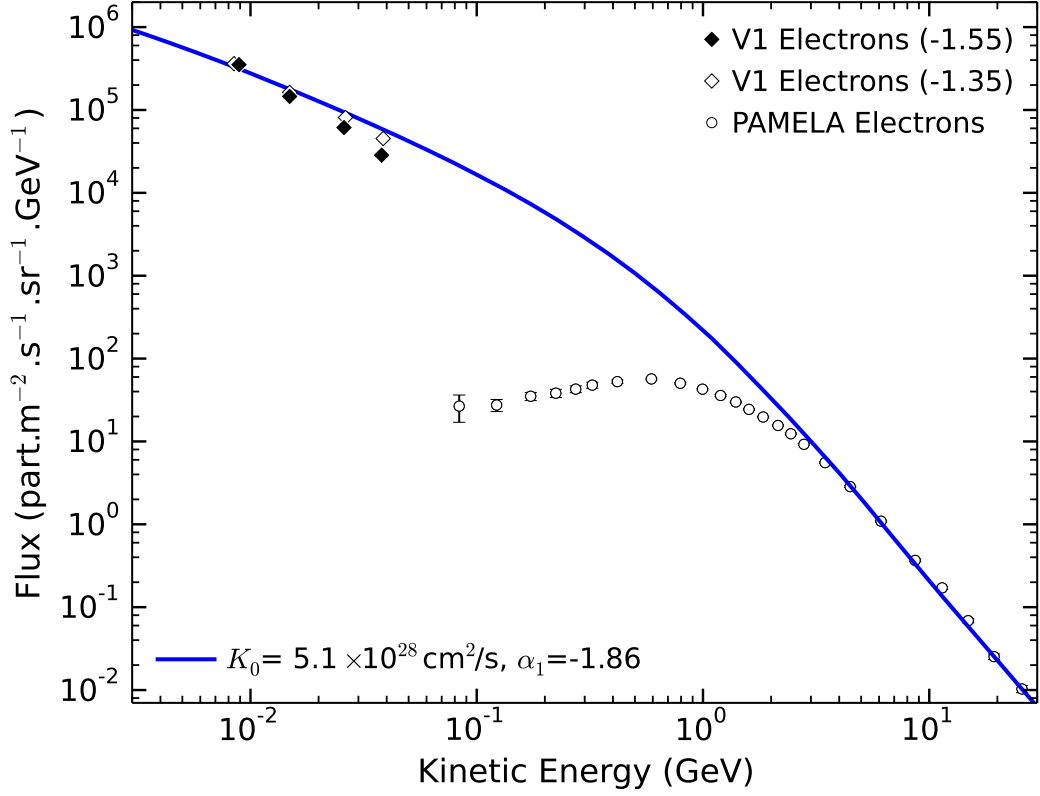


Figure 7.24: The calculated electron LIS for the reacceleration model with $V_A = 30 \text{ km.s}^{-1}$ and $dV/dz = 5 \text{ km.s}^{-1}.\text{kpc}^{-1}$. The value of $K_0 = 5.1 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ is chosen to increase the electron intensity between 200 MeV and 4 GeV slightly, in order to not neglect the assumed modulation. For the nuclei and positron LIS's the value of α_1 is also adjusted to -1.86 .

1 and 10 GeV should then give the desired positron LIS. The electron source indices are adjusted with $\alpha_{e1} = -1.9$ and $\alpha_{e2} = -2.7$, listed as model 3 in Table 7.1. The resulting electron LIS is shown in Figure 7.27 and the corresponding positron ratio in Figure 7.28. The electron LIS now has a shape close to that of the electron LIS in Figure 6.12, matching the V1 and PAMELA values reasonably well. The resulting positron LIS matches the observations at the Earth well, improving on previous tests.

With these adjustments the reacceleration model now calculates LIS's for electron, positrons and protons that match the observations better, whilst also giving an acceptable positron ratio. The corresponding Helium, Carbon, Boron and Oxygen LIS's can also be calculated with this model, as will be shown in the next chapter. These resulting LIS's will also all be tested by modulation modelling as in Chapter 6 and directly comparing with the observations at the Earth.

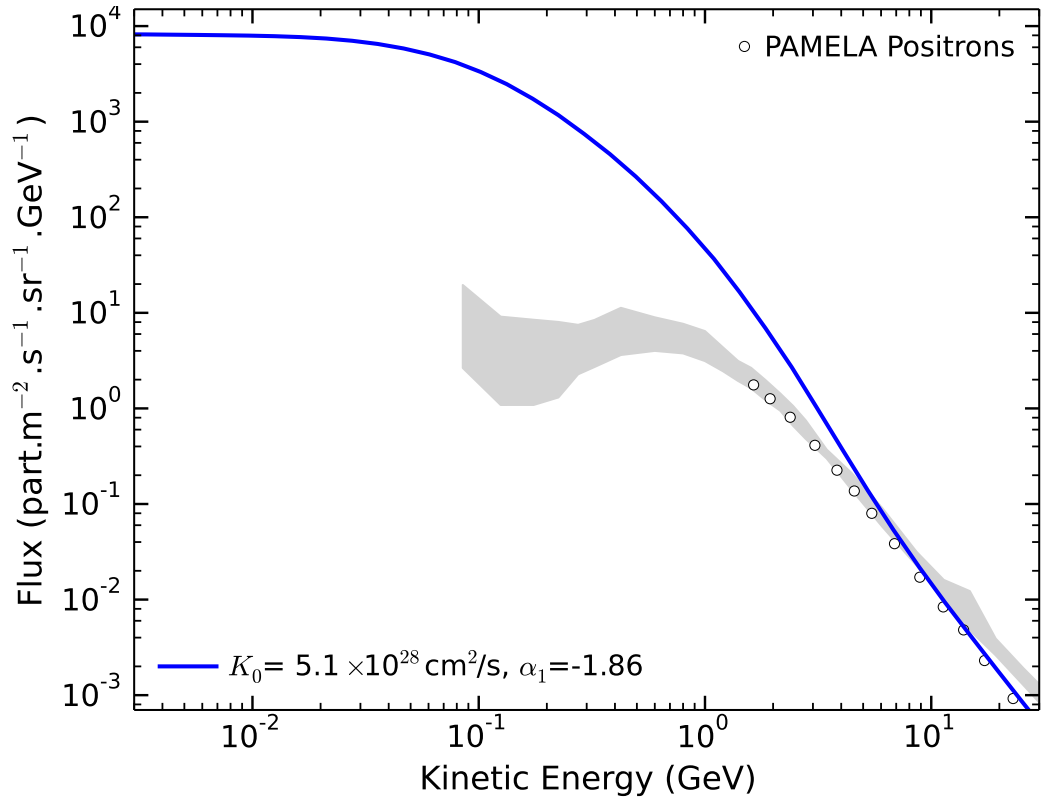


Figure 7.25: The calculated positron LIS corresponding to the electron LIS and model parameters of Fig. 7.24.

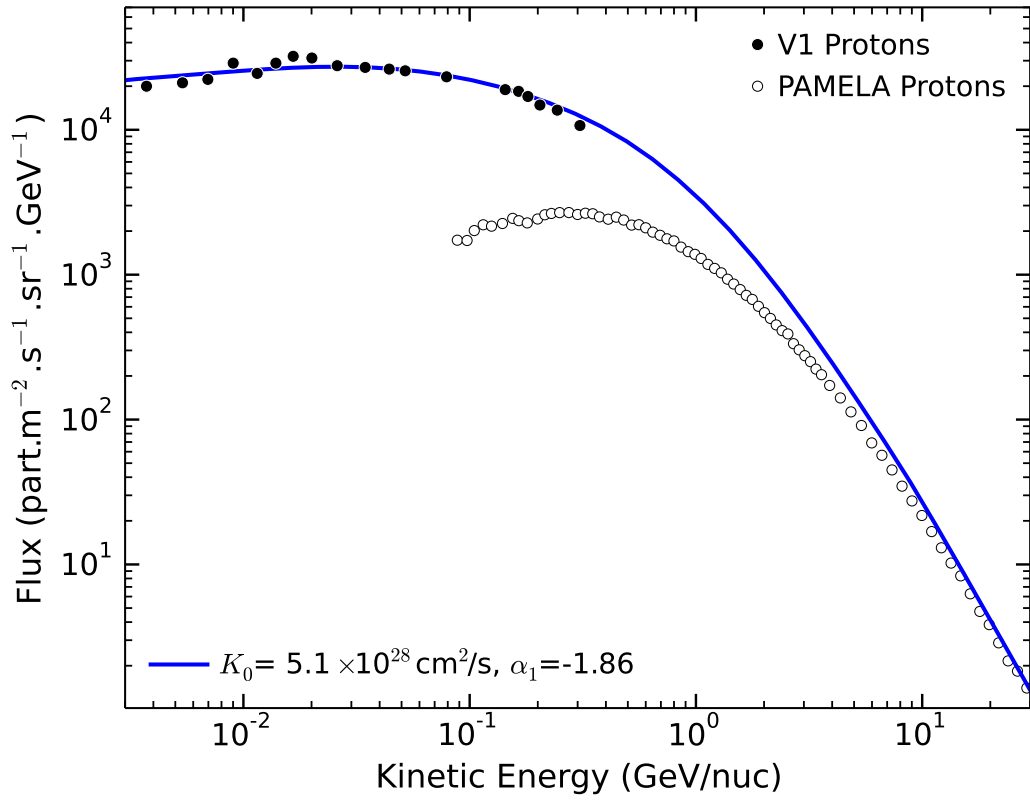


Figure 7.26: The calculated proton LIS corresponding to the electron LIS and model parameters of Fig. 7.24.

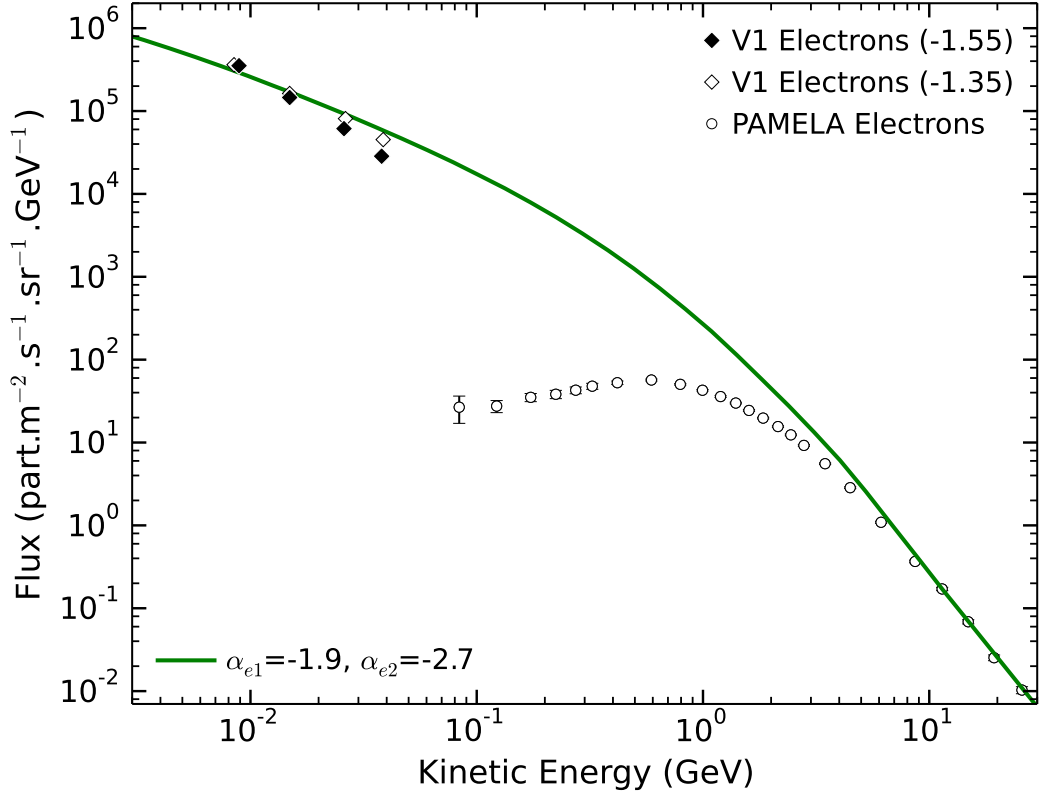


Figure 7.27: The calculated electron LIS for the reacceleration model as in Fig. 7.24, but with the source indices $\alpha_{e1} = -1.9$ and $\alpha_{e2} = -2.7$, in order to improve the electron LIS and positron ratio without changing the other LIS's.

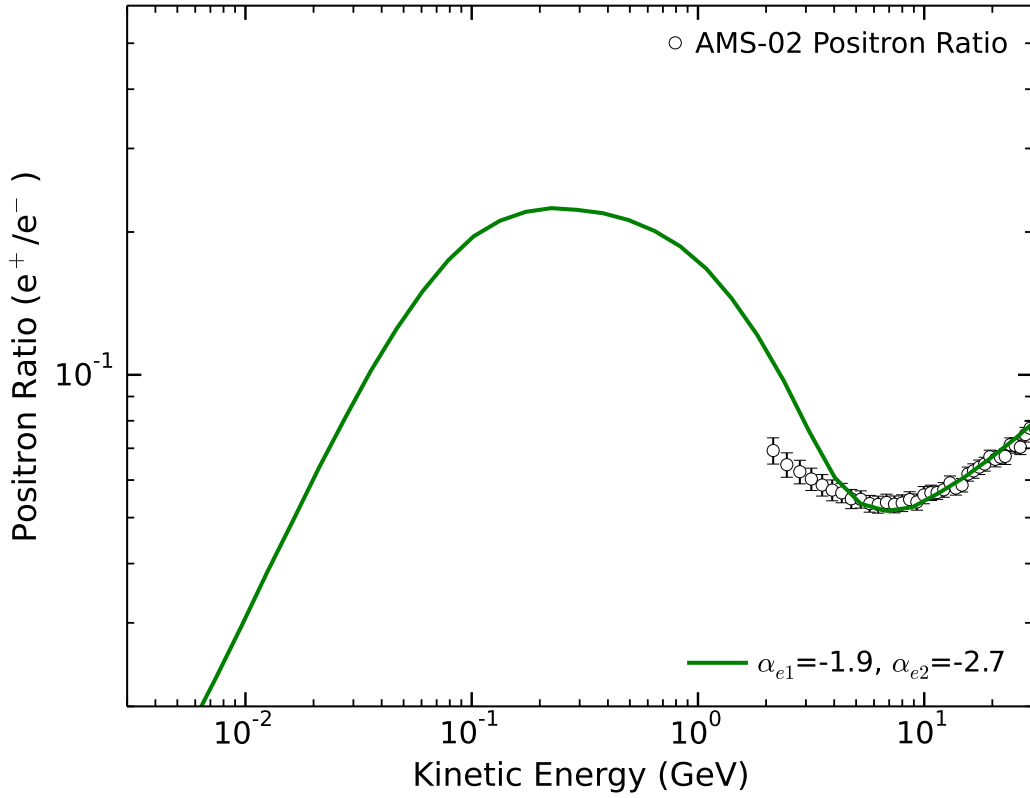


Figure 7.28: The positron ratio corresponding to the electron LIS and model parameters of Fig. 7.27.

7.6 Summary

In order to reproduce the proton, electron and positron LIS's using a single GALPROP model, tests were done by simply using the electron source parameters and nuclei source parameters from Chapter 6 together in the same model. This did not result in the desired results and an other approach was required. The propagation parameter values of Maccione (2013) were subsequently tested, including the addition of convection and adjustment of reacceleration strength. While the LIS's calculated with GALPROP did not reproduce their results exactly, likely due to differences in propagation model codes, the basic concepts could be used to help solve the single model problem.

The lower reacceleration and addition of convection showed promising results while testing the Maccione (2013) parameter values. Values were found for convection and reacceleration that together improved the single model LIS's. From lessons learned in previous chapters, the source spectrum parameters for electrons and nuclei could be adjusted next. These values, together with some changes to the diffusion parameters, resulted in a model that calculates LIS's which match the V1 and PAMELA observations well. These LIS's, and those for Helium, Carbon, Boron and Oxygen, can now be modulated to directly compare with the Earth observations.

Chapter 8

Resulting LIS's and modulated spectra

8.1 Introduction

The resulting LIS's shown in the previous chapter were calculated with a single GALPROP model. This model is a result of testing the diffusion, source input, reacceleration and convection parameters in order to converge on a parameter set that can reasonably reproduce the observed spectra of multiple CR species. This model can now be used to also compute LIS's beyond those of just electrons, positrons and protons. The model parameter values chosen for this model will be listed here for comparison with the values for the reference models and other significant models shown in previous chapters. Using this model the LIS's for Helium, Carbon, Boron and Oxygen are now also presented. The modulated spectra at the Earth are shown for all these LIS's, as well as those for electrons, positrons and protons. Expressions for the calculated LIS's are also given as to serve as input or comparison for other ongoing or future studies.

8.2 Models and parameters values used

8.2.1 GALPROP parameters

The LIS's shown in this chapter are calculated with the GALPROP parameter values listed in Table 8.1, alongside the reference values for the plain diffusion and reacceleration models. Also shown are the values found for the proton reacceleration model presented in Chapter 5, for the calculated LIS's shown in Figure 5.11, and the electron reacceleration model in Chapter 6, for the calculated LIS shown in Figure 6.17. The most significant change to the reference parameter values is the inclusion of non-zero convection and the reduction of the Alfvén wave speed in order to reduce the effect of reacceleration. These changes are the results of testing parameters as used by Maccione (2013) in GALPROP and contributed greatly to the study converging on a single

Table 8.1: List of GALPROP model parameters used.

Model Parameters	Pldff. Reference	Reacc. Reference	Proton Reacc. Model	Electron Reacc. Model	Resulting Model
K_0 ($10^{28} \text{ cm}^2 \text{ s}^{-1}$)	2.20	5.75	5.75	5.75	5.10
P_0 (GV)	3	4	4	4	4
δ_1	0.00	0.34	0.40	0.20	0.30
δ_2	0.60	0.34	0.40	0.34	0.40
$P_{\alpha 0}$ (GV)	40	9	9	9	9
α_1	-2.30	-1.82	-1.82	-1.82	-1.86
α_2	-2.15	-2.36	-2.36	-2.36	-2.36
$P_{\alpha e 0}$ (GV)	4	4	4	4	4
α_{e1}	-2.4	-1.6	-1.6	-2.0	-1.9
α_{e2}	-2.4	-2.5	-2.5	-2.5	-2.7
V_A (km.s^{-1})	0	36	36	36	30
dV/dz ($\text{km.s}^{-1}.\text{kpc}^{-1}$)	0	0	0	0	5

model to reproduce electron, positron and proton observations. This model is characterized by the parameters in the last column of Table 8.1.

Changes to the electron and nuclei source indices for lower energies were found necessary as to update the GALPROP models to take into account the V1 observations. With diffusion having the largest effect on the LIS's, changes to the diffusion parameters were also required to reproduce the observations well, instead of just a rough reproduction. Notably the diffusion index δ_1 does not need to have a negative value in this model. The earlier tests required a negative value for δ_1 in Chapter 4 to emulate the approach by Webber and Higbie (2013) and the subsequent plain diffusion models listed Table 4.1. For the reacceleration model this was seen to not be necessary and δ_1 remained positive for all the reacceleration tests and the resulting model of Table 8.1. The final changes to the model in GALPROP are to the source abundances of Helium and Carbon. The PAMELA observations necessitate decreasing the $^{12}\text{C}_6$ abundance by 10% and increasing the $^4\text{He}_2$ abundance by 5%, similarly to what was done to calculate the Helium LIS of Figure 5.5.

8.2.2 Modulation parameters

To calculate the corresponding modulated spectra at the Earth, the heliospheric modulation code is again used. For electrons and positrons the parameters are implemented as presented by Potgieter et al. (2015). Specifically the parameters: $(K_{\parallel})_0 = 41.822 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$, $a = 0.0$, $b = 1.667$, $c = 4.0$, $P_k = 0.4 \text{ GV}$ in Eqs. 3.3 to 3.6 are used unchanged. Similarly for protons and the CR nuclei the parameters from Vos and Potgieter (2015), $(K_{\parallel})_0 = 68.155 \times 10^{22} \text{ cm}^2 \text{ s}^{-1}$, $a = 0.8$, $b = 2.1$, $c = 2.2$, $P_k = 4.3 \text{ GV}$, are also used unchanged.

8.3 Resulting LIS's, modulated spectra and expressions

The following figures show the LIS's calculated with the above mentioned model parameters as implemented in GALPROP. The LIS's are compared to the relevant V1 and PAMELA observations, as well as AMS-02 observations for the positron ratio. The modulated spectra at the Earth, calculated with the above modulation parameters, are also shown.

These LIS's are presented here as the end results of this study. Expressions for the LIS's were also found that estimate the LIS's within a small maximum margin of error. These expressions are to be used in the future when comparison are made with the results of this study or when these LIS's are used as input for models or calculations.

8.3.1 Electrons

The electron LIS calculated with the resulting parameters of Table 8.1 in GALPROP is shown in Figure 8.1, alongside the modulated spectrum at the Earth. The electron LIS reproduces the V1 values well, favouring the -1.35 power-law. This LIS does not match the V1 power-laws as closely as the plain diffusion LIS's of Figure 4.8, but is a slight improvement on the reacceleration LIS of Figure 6.17. Taking modulation into account the PAMELA values are represented well, with a slight overestimation around 0.7 GeV. The modulation parameters can of course be further adjusted to produce an even better match to the observations at the Earth, as was done in Chapter 6 for protons, but with this small deviation from the observations, little physics insight will be gained by such a tedious procedure.

The computed electron LIS can be approximated (within 5%) over the energy range 4 MeV to 100 GeV by the following expression:

$$J_{\text{elec}}(E) = 255.0 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{-1} \left(\frac{E/E_0 + 0.63}{1.63} \right)^{-2.43} + 6.4 \left(\frac{E}{E_0} \right)^2 \left(\frac{E/E_0 + 15.0}{16.0} \right)^{-26.0}, \quad (8.1)$$

where the CR intensity $J_{\text{elec}}(E)$ (given in $\text{part.m}^2 \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$) is a function of kinetic energy E (given in GeV), $E_0 = 1 \text{ GeV}$ and again with $\beta = v/c$.

8.3.2 Positrons

The corresponding calculated positron LIS is shown in Figure 8.2, alongside the modulated spectrum at the Earth. With no observations outside the heliosphere for positrons, the LIS is hard to constrain at lower energies. With the inclusion of a positron excess, which GALPROP can't calculate, the PAMELA positron values can be reproduced above 6 GeV, but the modulated spectrum lies above the observations below this energy. The modulated spectrum effectively reproduces the upper limit to the PAMELA positron band. While the positron observations are not easy to reproduce, the resulting LIS is an improvement on any LIS shown in previous chapters when considering the positron ratio of Figure 8.3.

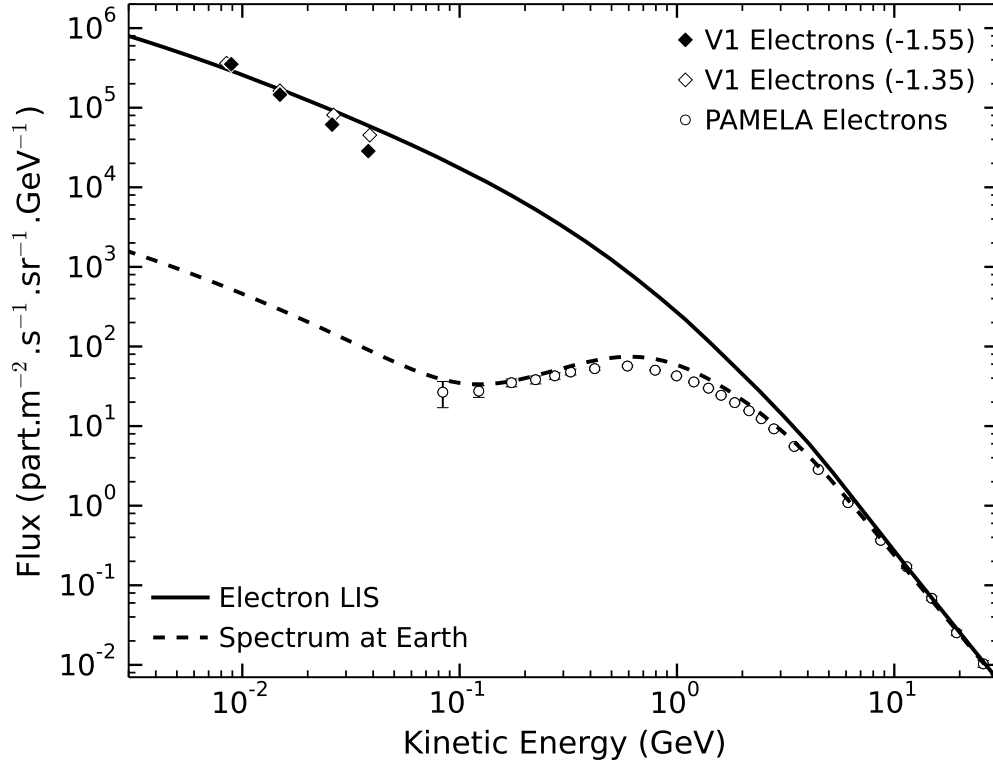


Figure 8.1: The calculated electron LIS (solid black curve) and the modulated electron spectrum at the Earth (dashed black curve) compared to the V1 (Stone et al., 2013) and PAMELA observations (Adriani et al., 2015).

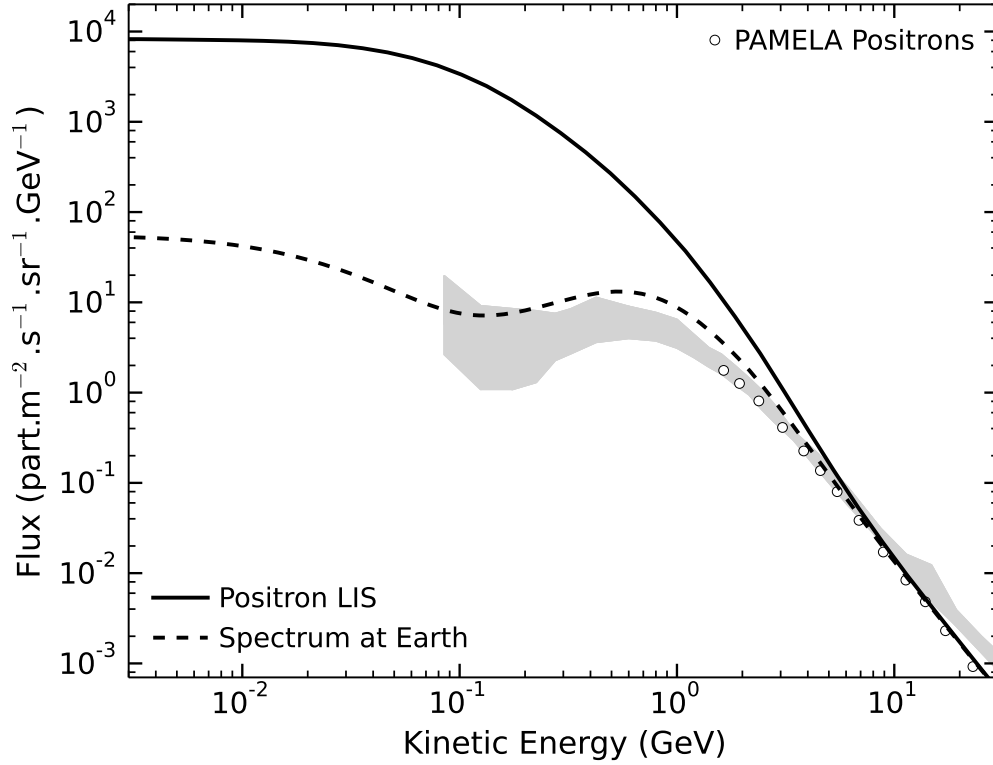


Figure 8.2: The calculated positron LIS (solid black curve) and the modulated positron spectrum at the Earth (dashed black curve) compared to the PAMELA positron observations: three year average (black circles) (Adriani et al., 2013b) and half year variations for Jul 2006 to Dec 2009 (grey band) (Munini, 2016).

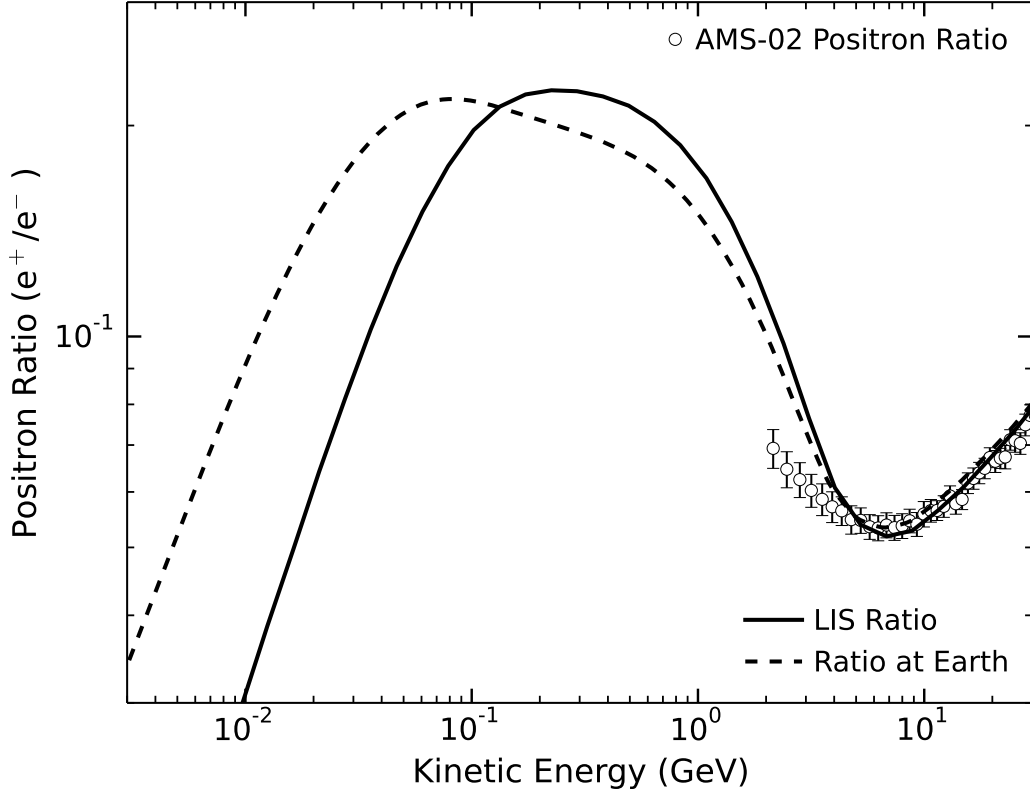


Figure 8.3: The positron ratio (e^+/e^-) (solid black curve), calculated from the electron LIS of Fig. 8.1 and the positron LIS of Fig. 8.2, and the ratio at the Earth (dashed black curve) compared to the AMS-02 observations (Aguilar et al., 2014).

The computed positron LIS can be approximated (within 12%) over the energy range 4 MeV to 100 GeV by the following expression:

$$J_{\text{posi}}(E) = 25.0 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{0.1} \left(\frac{(E/E_0)^{1.1} + 0.2^{1.1}}{1 + 0.2^{1.1}} \right)^{-3.31} + 23.0 \left(\frac{E}{E_0} \right)^{0.5} \left(\frac{E/E_0 + 2.2}{3.2} \right)^{-9.5}, \quad (8.2)$$

where the CR intensity $J_{\text{posi}}(E)$ (given in $\text{part.m}^2 \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$) is a function of kinetic energy E (given in GeV), $E_0 = 1 \text{ GeV}$ and with $\beta = v/c$.

8.3.3 Positron ratio

The positron ratio (e^+/e^-) calculated from the electron LIS of Fig. 8.1 and the positron LIS of Fig. 8.2 is shown in Figure 8.3. The ratio matches the observations closely above about 3 GeV, with the excess that is added to the positron LIS contributing greatly. Below 3 GeV the ratio increases faster than the observations, even with modulation taken into account. While the electron LIS matches the observations well at the Earth, the positron LIS overestimates the observations as previously stated.

This positron ratio, as presented first in Figure 7.28, shows the best reproduction of the observations out of any positron ratio calculated in the previous chapters. With both the shape and the magnitude of the ratio matched well.

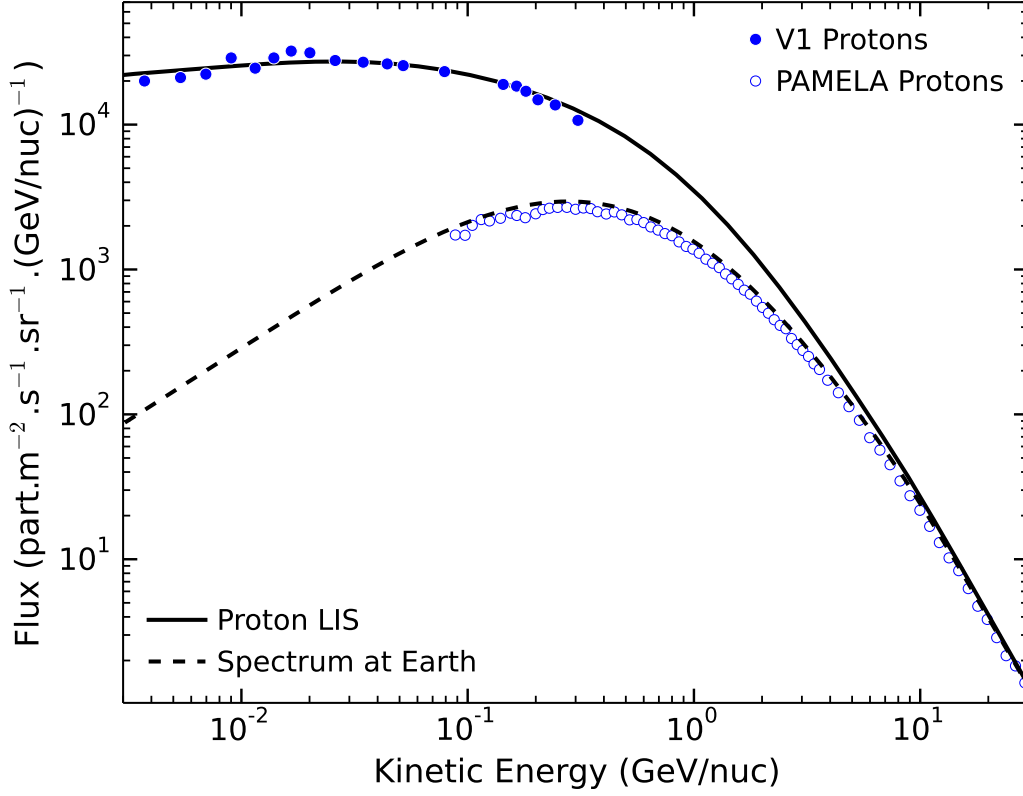


Figure 8.4: The calculated proton LIS (solid black curve) and the modulated proton spectrum at the Earth (dashed black curve) compared to the V1 (Stone et al., 2013) and PAMELA observations (Adriani et al., 2013a).

8.3.4 Protons

As with the electrons and positrons, the proton LIS calculated with the resulting parameters presented in Table 8.1, is shown in Figure 8.4. The LIS reproduces the V1 observations well over the full V1 energy range. The shape of the observed spectrum is more closely reproduced than any of the other calculated proton LIS in the previous chapters. After modulation the spectrum also follows the shape of the PAMELA protons closely, lying only slightly above the observations. Adjustments to the modulation parameters would improve on this spectrum if required. The proton LIS is the most successful calculated LIS in terms of strictly matching the V1 and PAMELA observations. This LIS, calculated while also taking into account the reproduction of the other relevant CR observations, is the main result of this study.

The computed proton LIS can be approximated (within 5%) over the energy range 4 MeV/nuc to 100 GeV/nuc by the following expression:

$$J_p(E) = 2620.0 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{1.1} \left(\frac{(E/E_0)^{0.98} + 0.7^{0.98}}{1 + 0.7^{0.98}} \right)^{-4.0} + 30.0 \left(\frac{E}{E_0} \right)^2 \left(\frac{E/E_0 + 8.0}{9.0} \right)^{-12.0}, \quad (8.3)$$

where the CR intensity $J_p(E)$ (given in $\text{part.m}^2\text{s}^{-1}\text{sr}^{-1}(\text{GeV/nuc})^{-1}$) is a function of kinetic energy E (given in GeV/nuc), $E_0 = 1 \text{ GeV/nuc}$ and with $\beta = v/c$.

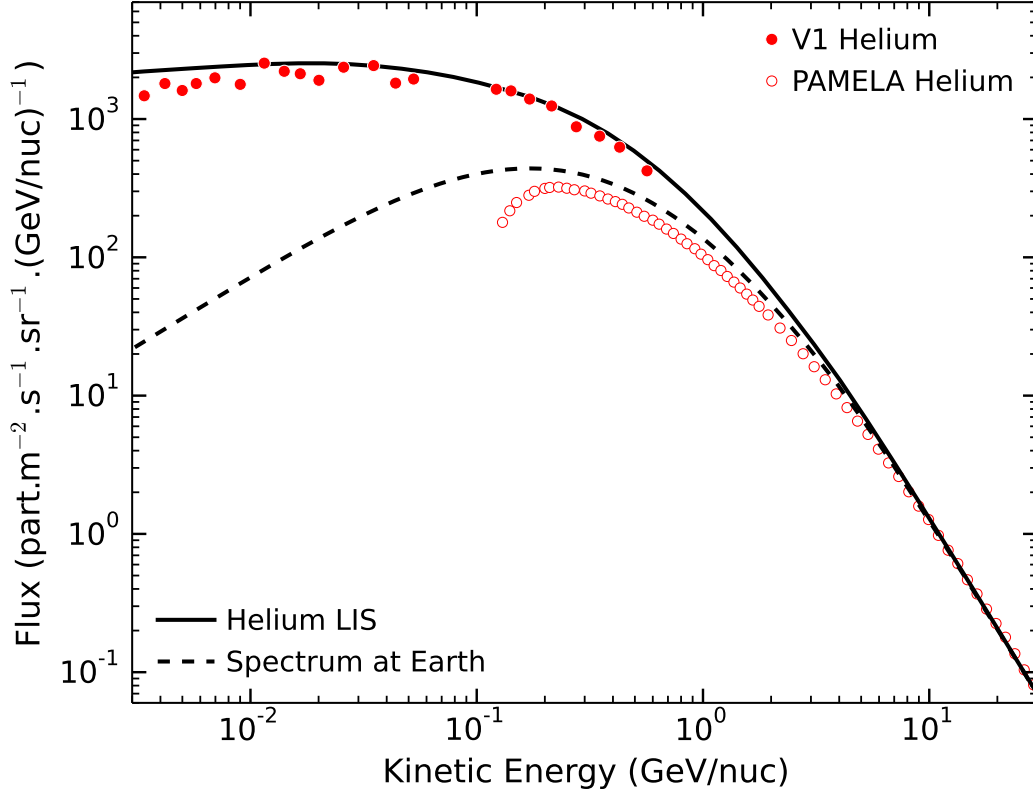


Figure 8.5: The calculated Helium LIS (solid black curve) and the modulated Helium spectrum at the Earth (dashed black curve) compared to the V1 (Stone et al., 2013) and PAMELA observations (Adriani et al., 2011b)

8.3.5 Helium

The corresponding calculated Helium LIS is shown in Figure 8.5. In addition to the parameters of Table 8.1 in GALPROP, the Helium source abundance is also adjusted. An increase of 5% in the Helium abundance is required to more closely match the observations above 10 GeV/nuc. Similarly to the protons, the Helium LIS matches V1 observations well, but is slightly higher than the V1 spectrum at the lowest energies. The modulated spectrum lies above the PAMELA observations, but represents the shape of the observed spectrum well above 0.2 GeV/nuc.

The computed Helium LIS can be approximated (within 8%) over the energy range 4 MeV/nuc to 100 GeV/nuc by the following expression:

$$J_{\text{He}}(E) = 163.4 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{1.1} \left(\frac{(E/E_0)^{0.97} + 0.58^{0.97}}{1 + 0.58^{0.97}} \right)^{-4.0}, \quad (8.4)$$

where the CR intensity $J_{\text{He}}(E)$ (given in $\text{part.m}^2 \text{s}^{-1} \text{sr}^{-1} (\text{GeV/nuc})^{-1}$) is a function of kinetic energy E (given in GeV/nuc), $E_0 = 1 \text{ GeV/nuc}$ and with $\beta = v/c$.

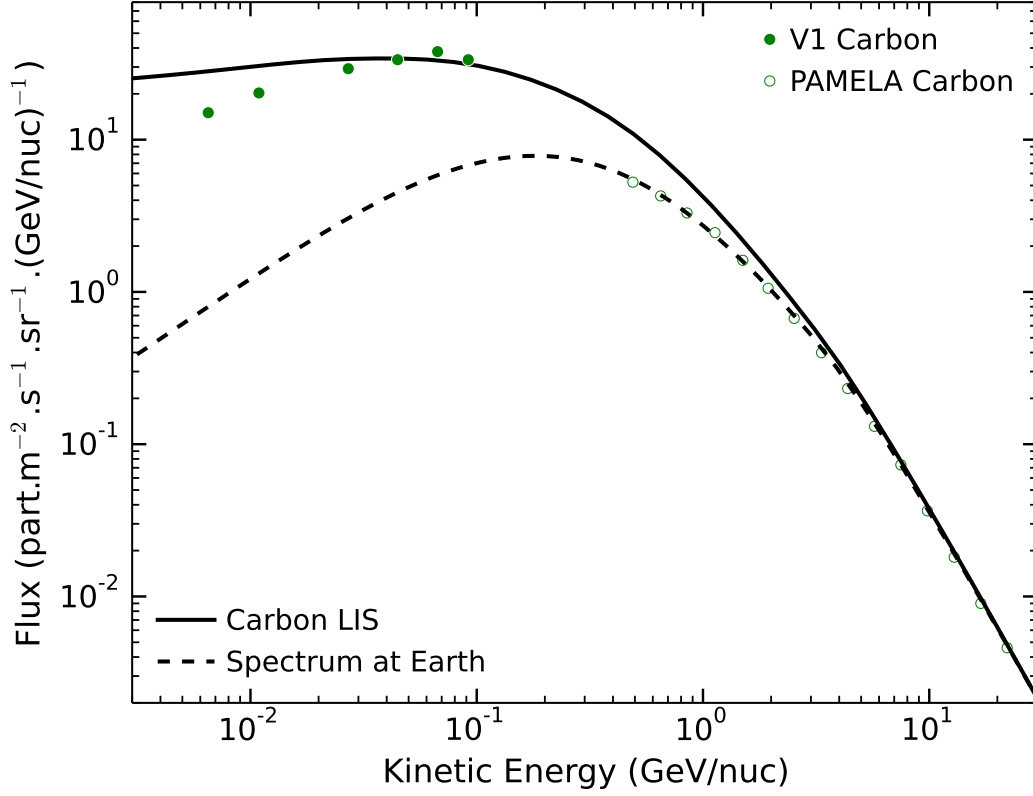


Figure 8.6: The calculated Carbon LIS (solid black curve) and the modulated Carbon spectrum at the Earth (dashed black curve) compared to the V1 (Stone et al., 2013) and PAMELA observations (Adriani et al., 2014).

8.3.6 Carbon

The corresponding calculated Carbon LIS is shown in Figure 8.5. Similarly to the Helium LIS, the Carbon LIS requires a change in the source abundance, a decrease of 10%, to more closely match the observations above 10 GeV/nuc. The V1 Carbon observations have fewer data points than the protons or Helium, and shows a faster decrease in intensity with decreasing energy than what can be replicated with this model. Consequently only the V1 observations above 0.02 GeV/nuc can be reproduced. The modulated spectrum matches the PAMELA values closely.

The computed Carbon LIS can be approximated (within 5%) over the energy range 4 MeV/nuc to 100 GeV/nuc by the following expression:

$$J_C(E) = 3.3 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{1.22} \left(\frac{(E/E_0)^{0.9} + 0.63^{0.9}}{1 + 0.63^{0.9}} \right)^{-4.43}, \quad (8.5)$$

where the CR intensity $J_C(E)$ (given in $\text{part.m}^2\text{s}^{-1}\text{sr}^{-1}(\text{GeV/nuc})^{-1}$) is a function of kinetic energy E (given in GeV/nuc), $E_0 = 1 \text{ GeV/nuc}$ and with $\beta = v/c$.

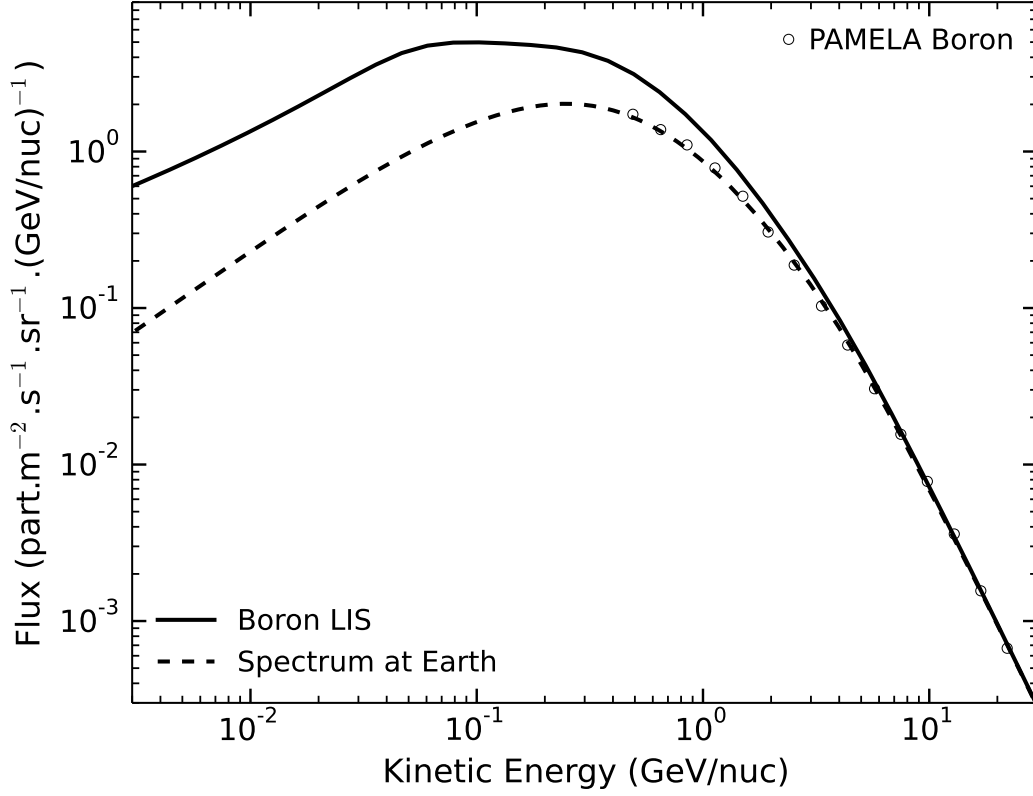


Figure 8.7: The calculated Boron LIS (solid black curve) and the modulated Boron spectrum at the Earth (dashed black curve) compared to the PAMELA observations (Adriani et al., 2014).

8.3.7 Boron

The corresponding calculated Boron LIS is shown in Figure 8.5. The Boron LIS has a different shape than for example the Carbon LIS at lower energies, this is likely to Boron being a secondary CR species. There is no observations for Boron made by V1, but similarly to the Carbon observations, the PAMELA Boron observations are also matched closely with the modulated spectrum.

The computed Boron LIS can be approximated (within 7%) over the energy range 4 MeV/nuc to 100 GeV/nuc by the following expression:

$$J_B(E) = \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{1.7} \left(\frac{E/E_0 + 0.685}{1.685} \right)^{-4.8} + (3.0 \times 10^{-4}) \left(\frac{E}{E_0} \right)^3 \left(\frac{E/E_0 + 0.204}{1.204} \right)^{-11.0}, \quad (8.6)$$

where the CR intensity $J_B(E)$ (given in $\text{part.m}^2 \text{s}^{-1} \text{sr}^{-1} (\text{GeV/nuc})^{-1}$) is a function of kinetic energy E (given in GeV/nuc), $E_0 = 1 \text{ GeV/nuc}$ and with $\beta = v/c$.

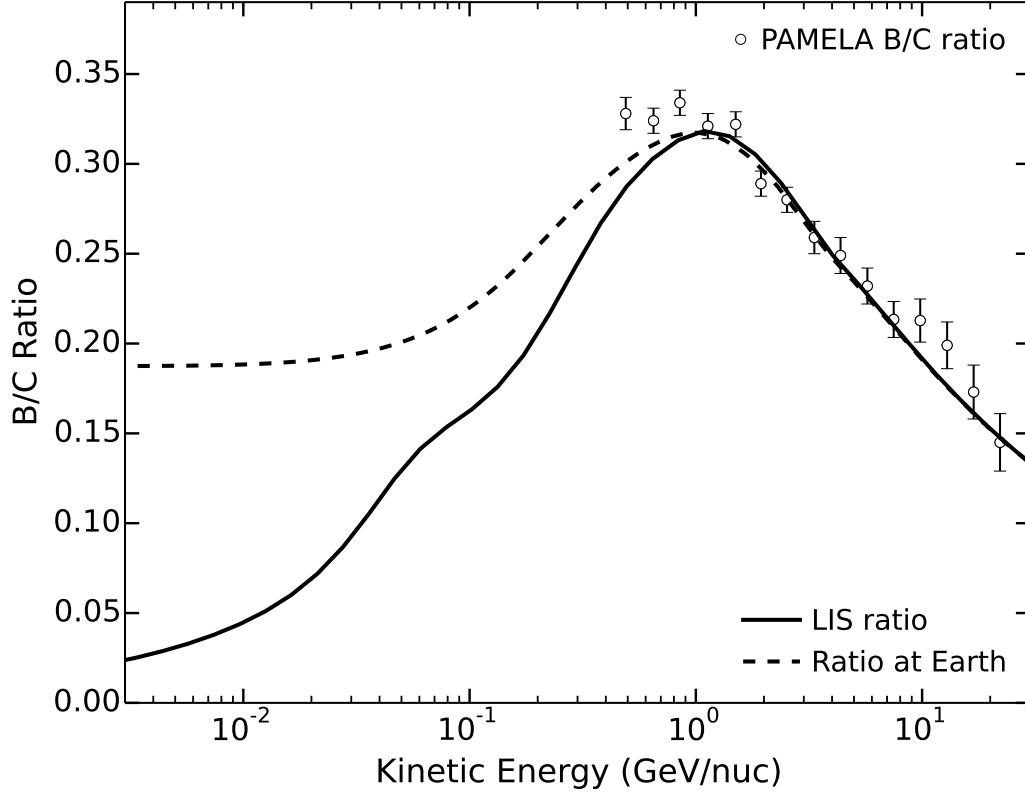


Figure 8.8: The B/C LIS ratio (solid black curve) calculated from the Carbon LIS of Fig. 8.6 and the Boron LIS of Fig. 8.7, compared to the B/C ratio at the Earth (dashed black curve) and the PAMELA observations (Adriani et al., 2014).

8.3.8 B/C ratio

The B/C ratio calculated from the Carbon LIS of Fig. 8.6 and the Boron LIS of Fig. 8.7 is shown in Figure 8.8. Tuning the reacceleration and convection parameters has played a large roll in matching the B/C observations and, together with the Carbon abundance adjustment, has resulted in this being the best B/C ratio calculated in the study. The observed ratio is matched well, but even with modulation taken into account the values below 1 GeV/nuc can't be inferred as closely, so that further improvement is required, which is beyond the scope of the present study.

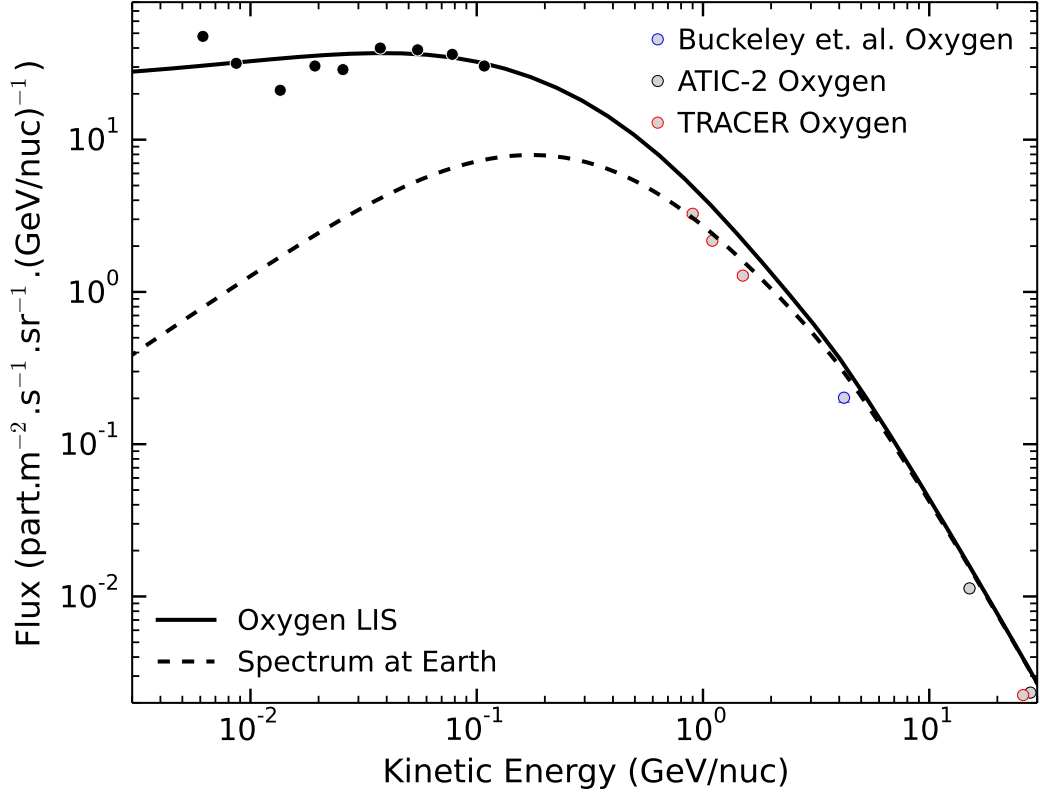


Figure 8.9: The calculated Oxygen LIS (solid black curve) and the modulated Oxygen spectrum at the Earth (dashed black curve) compared to the V1 observations (Stone et al., 2013). Also shown are the observations made at the Earth by Buckley et al. (1994) in 1991 (open blue circles), the ATIC-2 experiment Panov et al. (2009) in 2003 (open black circles) and the TRACER experiment Obermeier et al. (2011) in 2006 (open red circles); all of which were balloon flights.

8.3.9 Oxygen

Lastly the calculated Oxygen LIS is shown in Figure 8.5 as it is also observed by V1, but has not yet been discussed here. The calculated Oxygen LIS has similar shape and intensity to the Carbon LIS and also reproduces the V1 observations well. With no PAMELA observation published for Oxygen, the modulated spectrum is compared to balloon flight observations (Buckley et al., 1994; Panov et al., 2009; Obermeier et al., 2011) and these are reproduced reasonably well considering the various time periods the observations were made.

The computed Oxygen LIS can be approximated (within 5%) over the energy range 4 MeV/nuc to 100 GeV/nuc by the following expression:

$$J_O(E) = 3.3 \frac{1}{\beta^2} \left(\frac{E}{E_0} \right)^{1.23} \left(\frac{(E/E_0)^{0.86} + 0.62^{0.86}}{1 + 0.62^{0.86}} \right)^{-4.62}, \quad (8.7)$$

where the CR intensity $J_O(E)$ (given in $\text{part.m}^2 \text{s}^{-1} \text{sr}^{-1} (\text{GeV/nuc})^{-1}$) is a function of kinetic energy E (given in GeV/nuc), $E_0 = 1 \text{ GeV/nuc}$ and with $\beta = v/c$.

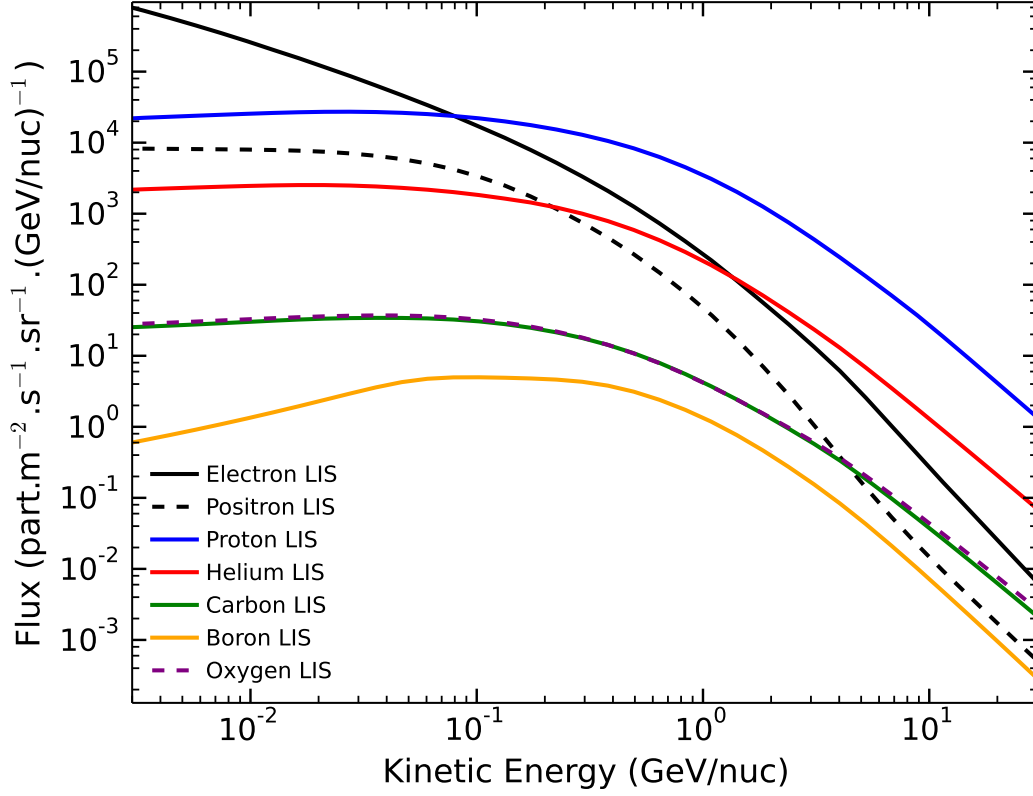


Figure 8.10: The LIS's from Fig's. 8.1 to 8.9 calculated with the resulting model parameters as in Table 8.1. The hadronic CRs are shown as function of kinetic energy (GeV/nuc), together with the electron and positron LIS's on the same axes. Above 0.1 GeV/nuc the protons (solid blue curve) form the bulk of the CRs that arrive at the heliosphere, while below this energy the electrons (solid black curve) take on this role. The calculated Carbon LIS (solid green curve) is seen to be nearly identical to that of the Oxygen LIS (dashed purple curve).

8.4 Summary

The model presented here is the culmination of the tests done in the previous chapters, in order to find a set of parameters in GALPROP that can simultaneously calculate a self-consistent set of LIS's for the relevant CR species. The resulting LIS's are summarized in Figure 8.10, specifically for electrons, positrons, protons, Helium, Carbon, Boron and Oxygen. The relevant V1 observations are reasonably reproduced, to a varying degree, with these calculated LIS's. The LIS's are also all modulated in order to compare the spectra at the Earth to respective observations.

LIS's that could also be calculated with this model, but were considered beyond the scope of this study, are isotopic CR species such as $^3\text{He}_2$ and $^4\text{He}_2$ (see e.g. Menn et al., 2015), heavier nuclei such as Iron, and anti-protons. Specifically for anti-protons, no tests were done beyond a preliminary investigation, as the GALPROP reacceleration model resulted in much lower intensities for anti-protons than would be expected, especially when considering modulation. Positrons posed a challenge to reproduce (see also Vos, 2016; Potgieter et al., 2017) and similar

effort can be expected for anti-protons, as they are also secondary CRs and anti-particles. An anti-proton LIS is therefore not presented here, as a more dedicated investigation will be required. For an such an attempt, published after this study was completed, see Boschini et al. (2017).

For these final results of the study the modulation parameters were kept unchanged from the work of Vos and Potgieter (2015), for protons and nuclei, and Potgieter et al. (2015), for electrons and positrons. Fine-tuning the modulation parameters to very closely match the observations could be done, but such relatively minor improvements are not the purpose of the study. The LIS's presented here are not compared directly to those shown by Vos and Potgieter (2015) and Potgieter et al. (2015). While their LIS's represent the observations more closely, the LIS's were empirically derived and statistically fitted to the relevant observations. In contrast to the LIS's shown in this study are directly affected by the physics included in the GALPROP model. Both approaches serve different goals and therefore should not be directly compared.

Chapter 9

Summary and conclusions

Due to the effect of solar modulation, the LIS's for CRs are still not fully determined over all energy ranges. While numerical modelling, such as with the GALPROP code, can be used to calculate LIS's for a wide set of CR species, the results need to be matched to observations. At low energies the LIS's need to match the V1 observations made beyond the heliopause. For higher energies very precise CR spectra are nowadays observed at the Earth by experiments such as PAMELA. To directly compared these observations to the calculated LIS's below at least 20 GeV, a 3D modulation code is required. This study uniquely aimed to implement the above numerical models and observations to produce LIS's for electrons, positrons and protons simultaneously, while also considering CR Helium, Carbon, Boron and Oxygen. The AMS-02 observations are not yet officially published and therefore not used in this study.

CRs originate in the Galaxy and propagate throughout it to arrive at the Earth. The structure of the Galaxy and its features effect CR propagation. These physical processes, including source spectra, diffusion, reacceleration and convection, need to be taken into account to model CR intensities and calculate LIS's. For this purpose the GALPROP propagation code (Strong et al., 2007; Moskalenko, 2011, 2013) is used, together with the reference parameters derived from the modelling approaches presented by Ptuskin et al. (2006). Before the LIS's can be compared to observations below 20 GeV made inside the heliosphere, the effect of solar modulation needs to be taken properly into account. A comprehensive 3D modulation model (Potgieter and Vos, 2017), using the LIS's as input, is therefore implemented to calculate the CR transport in the heliosphere. This model takes into account the heliospheric convection, diffusion, drift and energy losses caused by the solar wind and the embedded solar magnetic field. With these two models, LIS's can be calculated and tested against the V1 and PAMELA observations simultaneously.

A first step in the study was using the simplest form of the GALPROP model, the plain diffusion model, that has shown success in the past to produce LIS's that fit observations. With this model, electron LIS's were calculated in order to match the two reported electron spectra, with slopes -1.35 and -1.55, observed by V1. The diffusion and source spectrum values were varied

separately and the resulting LIS's are shown in Figure 4.9. The -1.35 spectrum was easiest to reproduce with either adjustments to the source spectrum or diffusion parameter values. The -1.55 spectrum was harder to reproduce with the plain diffusion model, with only diffusion parameter adjustments resulting in reasonable LIS's.

The GALPROP plain diffusion approach was next applied to CR protons and nuclei by investigating the effect of various diffusion parameters, as described in Chapter 2, on the computed LIS's. The resulting LIS's are shown in Figure 5.5. While the proton and Helium observations are matched well, the Carbon and B/C observations could not be matched. To improve the calculated LIS's, the GALPROP reacceleration model was tested instead. Once again the diffusion parameters were systematically adjusted and the resulting LIS's shown in Figure 5.11. With the reacceleration model the observed proton, Helium and Carbon spectra could be matched, while also reproducing the B/C ratio much better than the plain diffusion model.

To further test the LIS's calculated for CR nuclei with the GALPROP reacceleration model, the LIS's were used as input for the 3D modulation code, as described in Chapter 3, to calculate the corresponding spectra at Earth. The modulated spectra match the observational trends, but were improved further by adjusting the heliospheric diffusion parameters in the modulation model and this resulted in reasonable matches to the observations at Earth, shown in Figures 6.8 to 6.10. The electron LIS's calculated with the plain diffusion model were also tested with the modulation model. These spectra did not match the observations well at the Earth and the PAMELA observations are largely underestimated. The electron LIS was therefore revisited with the reacceleration model, similarly to what was done for the proton and nuclei LIS's. This calculated electron LIS is shown in Figure 6.17, it matches the V1 observations well and when modulated reproduces the PAMELA values closely.

The positron LIS was investigated next and LIS's corresponding to the electron and proton results were calculated, both for the GALPROP plain diffusion and reacceleration models. Of these positron LIS's, only the plain diffusion model could reproduce the spectra at the Earth, while neither approach could match the observed positron to electron ratio. To improve the positron LIS and this ratio, while also taking into account electron and proton LIS's, a single model was explored and tested to calculate all three LIS's. The previous models in this study only focused on either the electrons or the protons and nuclei. This single model would be needed as positrons are secondary products related to nuclei, but propagate similarly to electrons. The initial tests did not improve the positron LIS as intended so that the galactic propagation study of Maccione (2013) was used as basis for a different approach, but which did not include V1 observations as done in this thesis. A GALPROP reacceleration model, that also includes convection, was tested by systematically adjusting the source and diffusion parameters. This resulted in the calculated electron LIS of Figure 7.27 and the positron ratio of Figure 7.28, which both match the observations better than any of the previous single model tests in this study.

This model represents the culmination of the tests done in this study and has its defining parameters listed in Table 8.1. With it the LIS's of Figures 8.1 to 8.10, with the latter as a summary

plot of all the LIS's, were calculated. These LIS's for electrons, positrons, protons, Helium, Carbon, Boron and Oxygen, are represented by Eqs. 8.1 to 8.7, respectively. The corresponding modulated spectra were also compared to observations at the Earth and it was seen that all the relevant observations are reasonably reproduced with these calculated LIS's.

A GALPROP plain diffusion model was sufficient when studying electrons, protons and Helium LIS's separately. Including Carbon, the B/C ratio and positrons into the study, the constraints placed on the LIS's by observations necessitated the use of a reacceleration model and ultimately the inclusion of convection. The inclusion of positrons proved the greatest challenge, indication that GALPROP in general is not yet optimally suited to calculate positron LIS's. This likely extends to antiprotons as well, because initial tests done for this thesis were not promising. As such antiprotons are not reported in this study as it would require similar time and effort to the inclusion of positrons, and would be better suited to a dedicated study on the subject.

With the LIS's presented here achieving the goals of this study by reproducing the V1 observations, while also taking into account observations at the Earth using a full 3D modulation approach, steps for future studies can be considered. The aforementioned antiprotons and the ability of GALPROP to fully calculate secondary antiparticles, needs to be investigated in more detail. Isotopic CR observations made by PAMELA, such as deuterium, and the AMS-02 experiment will enable the study of a large number of CR species. Heavier CR nuclei can also be considered for follow-up studies, as well as ratios such as p/He , $^3\text{He}_2/^4\text{He}_2$ and $^{10}\text{Be}_4/^9\text{Be}_4$.

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