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Pedro Ivo Silva Batista

Phenomenology of cosmic ray transport in the galaxy

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Pedro Ivo Silva Batista

Phenomenology of cosmic ray transport in the galaxy

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In memory of my grandfathers.

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*“From each according to his ability,
to each according to his needs.”*
Karl Marx
(Critique of the Gotha Program)

ABSTRACT

BATISTA, P. I. S. **Phenomenology of cosmic ray transport in the galaxy**. 2019. 77p. Dissertation (Master in Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2019.

In this dissertation we provide new benchmark scenarios for galactic cosmic ray propagation in view of the recent precise measurements of the Boron to Carbon flux ratio from the Alpha Magnetic Spectrometer (AMS-02), based on fits to data using the *USINE* code. We identify a general scenario that provides excellent fits to the data and includes all relevant physical processes, the *BIG* model. This model has two limiting regimes: the *SLIM* model, which is characterised by a minimal diffusion-only description, as well as the *QUAINT* model, with reacceleration and convection. Moreover, we present a study of the spectral index of the B/C ratio, aiming at understanding the differences between this observable and the diffusion coefficient spectral index, showing that these two quantities are not interchangeable. We generalize our analysis to all CR nuclei, from H to Fe, and compare to existing AMS-02 measurements.

Keywords: Galactic cosmic rays. Cosmic-ray propagation. Boron-to-Carbon ratio. Diffusion coefficient. Spectral index.

RESUMO

BATISTA, P. I. S. **Fenomenologia do transporte de raios cósmicos na galáxia.** 2019. 77p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2019.

Nesta dissertação nós apresentamos novos cenários de referência para a propagação de raios cósmicos galáticos, tendo em vista medidas precisas feitas recentemente pelo Espectrômetro Magnético Alfa (AMS-02), da razão do fluxo de Boro sobre Carbono (B/C). Os resultados apresentados são baseados em ajustes aos dados usando o código *USINE*. Identificamos um cenário geral que fornece excelentes ajustes aos dados e inclui todos os processos físicos relevantes para a propagação de raios cósmicos, o chamado modelo *BIG*. Este modelo possui dois casos especiais: o modelo *SLIM*, que é caracterizado por uma descrição simplificada com apenas difusão, bem como o modelo chamado *QUAINT*, com reaceleração e convecção. Os três modelos fornecem um excelente ajuste aos dados. Além disso, apresentamos um estudo do índice espectral da razão B/C, visando compreender as diferenças entre o índice espectral desta grandeza e o índice espectral do coeficiente de difusão, mostrando que essas duas grandezas não são equivalentes. Nós generalizamos nossa análise para todos os núcleos de raios cósmicos, de H até Fe, e comparamos com as medidas existentes.

Palavras-chave: Raios cósmicos galáticos. Propagação de raios cósmicos. Razão Boro sobre Carbono. Coeficiente de difusão. Índice espectral.

LIST OF FIGURES

Figure 1 – The “all particle” flux as a function of the total energy from the particle, from GeV to EeV. The arrows indicate the flux value at the corresponding energy.	22
Figure 2 – Galactic and extra-galactic flux multiplied by $E^{2.7}$ as a function of energy. Data taken from (9) and (10). The x-axis for the helium flux is in GeV/n.	23
Figure 3 – Relative abundances in the solar system (from 23) and for Galactic CRs (from 24, 25). Abundances normalized to 10^6 Si.	24
Figure 4 – Logarithmic spiral arms, and the position of the Sun in the galaxy. . .	25
Figure 5 – Isocountours of 610 MHz radio emission from galaxy NGC 4631, together with the optical emission.	26
Figure 6 – Proton flux (multiplied by $E_k^{2.7}$) as a function of kinetic energy. Red points indicate AMS-02 data, compared with previous experiments. . .	28
Figure 7 – Top plot (a): the AMS-02 proton flux multiplied by $R^{2.7}$ as a function of rigidity. The solid curve indicates the fit of equation 2.1 to the data. For illustration, the dashed curve uses the same fit values but with $\Delta\gamma = 0.$, i.e. no break is present. Bottom plot (b): The dependence of the proton flux spectral index on rigidity R.	29
Figure 8 – Comparison of the secondary CR fluxes with the AMS-02 primary cosmic ray fluxes multiplied by $R^{2.7}$ with their total error as a function of rigidity above 30 GV. For display purposes only, the C, O, Li, Be, and B fluxes were rescaled as indicated. For clarity, the He, O, Li, and B data points above 400 GV are displaced horizontally.	30
Figure 9 – Spectral indices of He, C, O, Li, Be and B fluxes as a function of rigidity calculated using equation 2.2.	31
Figure 10 – Schematic description of the stochastic acceleration of charged particles scattering into moving magnetized clouds with random velocities, later called <i>2nd order Fermi mechanism</i>	35
Figure 11 – Example of the <i>1st order Fermi mechanism</i>	36
Figure 12 – The ratios Li/C, Be/C and B/C as measured by AMS-02	41
Figure 13 – Spectral indices of ratios shown in figure 12 as calculated in two rigidity intervals, 60.3-192 GV and 192-3300 GV with equation 2.2	42
Figure 14 – Calculation of the destruction cross-sections for a p + (Be/AL) collision in mb versus the kinetic energy (MeV) of the proton, adjusted to the data in (80)	44

Figure 15 – The solid lines are the calculation yielded by both GALPROP and Webber models for the production of B by ^{12}C , and the dashed lines includes the contribution coming from ghost nuclei. The data (black dots) is from (88)	45
Figure 16 – Schematic view of the Galaxy’s geometry in the “1 D model”.	49
Figure 17 – The B/C ratio prediction as a function of rigidity, obtained with the <i>USINE</i> code. The B/C is generated for different low-rigidity break parameters, namely the spectral index of the diffusion coefficient δ_l in the top panel, the low rigidity break position R_l in the middle panel, and the transition smoothing parameter s_l in the bottom panel.	51
Figure 18 – The B/C ratio prediction as a function of rigidity, obtained with the <i>USINE</i> code. The B/C is generated for different low-rigidity regime parameters, namely the non-relativistic scaling η in the top panel, the velocity V_a in the middle panel, and the velocity V_c for convective winds in the bottom panel.	52
Figure 19 – The B/C ratio prediction as a function of rigidity, obtained with the <i>USINE</i> code. The B/C is generated for different intermediate-rigidity regime parameters, namely the spectral index of the diffusion coefficient δ in the top panel, and the diffusion coefficient normalization K_{10} at 10 GV, in the bottom panel.	53
Figure 20 – The B/C ratio prediction as a function of rigidity, obtained with the <i>USINE</i> code. The B/C is generated for different high-rigidity break parameters, namely the transition of spectral index Δ_h in the top panel, the high rigidity break position R_h in the middle panel, and the transition smoothing parameter s_h in the bottom panel.	53
Figure 21 – Typical times for the physical processes involved in the propagation of CR nuclei, as function of kinetic energy per nucleon.	54
Figure 22 – Best fit B/C curves for <i>BIG</i> , <i>SLIM</i> and <i>QUAINT</i> together with AMS-02 data from (5). The best fit parameters are given in table 2.	58
Figure 23 – <i>Top plot</i> : The C flux rescaled by $R^{2.8}$, as a function of rigidity for the diffusion-only scenario. <i>Bottom plot</i> : Δ_{slope} as a function of rigidity for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.	60

Figure 24 – <i>Top plot:</i> The B flux rescaled by $R^{2.8}$, as a function of rigidity for the diffusion-only scenario. <i>Bottom plot:</i> Δ_{slope} as a function of rigidity for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.	61
Figure 25 – <i>Top plot:</i> B/C ratio as a function of rigidity, for the diffusion-only scenario. <i>Bottom plot:</i> Δ_{slope} as a function of rigidity, for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.	62
Figure 26 – <i>Top plot:</i> The B/C ratio as a function of rigidity, for several values of Δ_h , in a diffusion plus production and destruction scenario. <i>Bottom plot:</i> Δ_{slope} as a function of rigidity, for the same models displayed in the top plot. The vertical dashed line indicates the position of the high-rigidity break at 300 GV.	63
Figure 27 – <i>Top plot:</i> The B/C ratio as a function of rigidity. The red line is for diffusion and production. The other curves are for diffusion and production plus some other effect: the purple line is for destruction; the cyan line is for the upper limit case for the reacceleration of BIG; and the green line is for convection. <i>Bottom plot:</i> Δ_{slope} as a function of rigidity, for the same models displayed in the top plot. The vertical dashed line indicates the position of the break.	64
Figure 28 – The B/C ratio and Δ_{slope} , as a function of rigidity, for BIG, SLIM and <i>QUAINT</i> benchmark results. The vertical dashed line indicates the approximate position of the high-rigidity break, which in this case is set to 200 GV.	64
Figure 29 – Behavior of the observed flux slope, computed at 50 GV, as a function of the atomic number Z, in the frame of the simplified pure diffusion model. The green dashed line indicates the expected behavior for primary species, while the brown dotted line indicates the expected behavior for secondary species.	66
Figure 30 – Relative contributions per production process for elemental fluxes (isotopes not shown) at 50 and 2000 GV (isotopes not shown): primary (black), secondary (1, 2, and > 2 steps in red, blue, and green), radioactive (orange).	66

Figure 31 – Behavior of the observed flux slope, computed at 50 GV, as a function of the atomic number Z , in the frame of the simplified pure diffusion model in black, and with destruction of nuclei in red. We also show for both scenarios, the observed flux slope computed at 2000 GV, as a function of the atomic number, with dashed lines.	67
Figure 32 – Behavior of the observed CR flux slope, computed at 50 GV, as a function of the atomic number Z , in the frame of the <i>BIG</i> model, in comparison with the simplified pure diffusion model, in black. The purple dots show the AMS-02 results.	68

CONTENTS

1	INTRODUCTION	19
2	GALACTIC COSMIC RAYS	21
2.1	Overview of cosmic rays	21
2.1.1	The cosmic-ray spectrum	21
2.1.2	Galactic cosmic rays	22
2.2	The Galaxy	24
2.2.1	The magnetic fields of the Galaxy	25
2.2.2	The interstellar medium composition	25
2.3	Galactic CR measurement in the AMS-02 era	27
2.3.1	Spectral features	27
3	GALACTIC COSMIC-RAYS TRANSPORT: FROM SOURCE TO EARTH	33
3.1	Transport phenomenology	33
3.1.1	Cosmic-ray acceleration in astrophysical sources	34
3.1.2	The transport equation of cosmic rays	38
3.1.3	Spatial diffusion	39
3.1.4	Momentum diffusion: Reacceleration	42
3.1.5	Convection of cosmic rays	43
3.1.6	Collisions of CR nuclei in the ISM	43
3.1.6.1	Ghost nuclei	44
3.1.7	Energy losses in the ISM	45
3.1.7.1	Continuous energy losses: Coulomb and Ionization	46
3.1.7.2	Adiabatic and drift losses	47
4	CONSTRAINING DIFFUSION-BASED MODELS WITH SECONDARY-TO-PRIMARY RATIOS	49
4.1	Propagation models	49
4.1.1	The models: <i>BIG</i> , <i>SLIM</i> and <i>QUAINT</i>	55
4.1.2	Benchmark models	56
5	THE SPECTRAL INDEX OF THE GALACTIC COSMIC-RAY FLUX	59
5.1	B/C spectral index: data versus diffusion coefficient	59
5.1.1	Pure diffusion model	59
5.1.2	Additional propagation phenomena	61
5.2	Flux slope behavior for different species	65

5.2.1 Pure diffusion model 65

5.2.2 Full propagation modeling 67

6 CONCLUSIONS 69

REFERENCES 71

1 INTRODUCTION

More than one hundred years after the discovery of cosmic rays (CRs) many questions about their origin, acceleration and propagation mechanisms are still far from being fully understood. In this dissertation we focus on the interpretation of CR data in the GeV to TeV energy region, that is believed to be dominated by the particles accelerated in the Milky Way. In this energy range we have direct access to the CR composition, using space-based experiments that detect the particles before they interact with the atmosphere. Galactic CRs are mainly made of (fully ionised) hydrogen and heavier nuclei. Primary CR species, like Hydrogen (H), Helium (He) and Carbon (C), are accelerated in astrophysical sources, such as Supernova remnants (SNRs) (1), whereas secondary CR species, like Lithium (Li), Berilium (Be) and Boron (B), are created from the interaction of primaries with the particles and nuclei in the Interstellar Medium. Secondary-to-primary fluxes ratios, such as Boron-to-Carbon (B/C) flux ratio, provide an important observable to study the propagation of CRs in the galaxy (2).

Galactic CR physics recently entered the precision era, with the Alpha Magnetic Spectrometer (AMS-02) (3), operating on board the International Space Station since 2011. The percent level accuracy of AMS-02 data revealed unexpected features in CR fluxes (4), in the GeV to TeV energy range.

The work presented in this dissertation is focused on the interpretation of the AMS-02 data, mainly on the measurement of the B/C ratio (5), aiming at studying the CR transport in the galaxy and constraining propagation models.

The present dissertation is organized as follows: in [chapter 2](#) we provide a general introduction about CRs, focusing on the galactic component, and we also present a review of the latest results from the AMS-02 experiment. In [chapter 3](#), we describe the theoretical framework of the transport of CRs in the galaxy. We describe the processes of acceleration and transport of CRs. In [chapter 4](#), we solve the transport equation using a semi-analytic method. We present our results, consisting in new benchmark scenarios for the CR transport in the galaxy, based on fits to the AMS-02 B/C data with the *USINE* code. We identify a general scenario that provides excellent fits to the data and includes all relevant physical processes, the BIG model. This model has two limiting regimes: the SLIM model, which is characterised by a minimal diffusion-only description, as well as a QUANT model, with reacceleration and convection. In [chapter 5](#), we present a study of the spectral index of the B/C ratio, aiming at understanding the differences between this observable and the diffusion coefficient spectral index. We also generalize our analysis to all CR nuclei, from Hydrogen to Iron (Fe), and compare to existing AMS-02 measurements. Finally, in [chapter 6](#), we present our conclusions.

2 GALACTIC COSMIC RAYS

2.1 Overview of cosmic rays

Cosmic Rays are high energy particles produced in astrophysical sources throughout the universe (6). These particles propagate in and out of our galaxy, and occasionally hit Earth’s atmosphere, where they can be detected and their flux measured. They consist of charged particles, such as ionized atomic nuclei, electrons, and a few anti-matter particles.

2.1.1 The cosmic-ray spectrum

The most important observable to learn about cosmic-ray physics is the spectrum, namely the number of particles per time, surface, solid angle and energy unit (7). The measured “all-particle” CR spectrum is shown in figure 1 as a function of energy. The CR spectrum can be described as a power law in energy, i.e. $\propto E^{-\gamma}$ with an average spectral index $\gamma \sim 2.7$: it decreases by more than thirty orders of magnitude while covering a wide energy range, from hundreds of MeV (10^8 eV) up to energies above 100 EeV (10^{20} eV).

While the lowest energies CRs can be directly detected at Earth due to their high flux, the fast variation of flux in this power-law behavior of the CR spectrum causes the highest energy CRs to be detected only indirectly. Direct measurements of CRs, using balloons and space-based detectors, can be performed up to about the PeV region (10^{15} eV), where the flux is of the order of one particle per square meter per second, and experiments with an area of the order of a few square meters can be used to achieve a significant number of events in a reasonable amount of time of a few years. Above 10^{15} eV, where the flux drops to about one particle per square meter per second, larger detectors are needed to cope with the fainter flux. For this reason the measurement of CRs above the PeV is performed using ground-based detectors, which are focused on the measurement of the particles generated by the cascades that they initiate while reaching the Earth’s atmosphere.

We can highlight some features of the spectrum by multiplying it by a factor $E^{2.7}$, such that if the spectrum is actually described by a single power law with spectral index $\gamma = 2.7$, then it would appear as flat line in the plot, and fine structures can be identified, indicating a change in the spectral index γ . The resulting curve is shown in figure 2. At low energies (below ~ 30 GeV = 30×10^{12} eV) the spectral shape bends down, as a result of the modulation imposed by the presence of a magnetized wind originated from the Sun, which affects the propagation of very low energy particles and prevents them from reaching the solar system (12). The most important features are the *knee*, first identified in (13), at around ~ 3 PeV, where the power law spectral index changes from $\gamma = 2.7$ to

Figure 1 – The “all particle” flux as a function of the total energy from the particle, from GeV to EeV. The arrows indicate the flux value at the corresponding energy.

Source: BIETENHOLZ (8)

3.1, the *second knee* at around 400 PeV, where a second steepening to $\gamma = 3.3$ occurs, and the ankle at about 4 EeV, above which the spectrum flattens to $\gamma = 2.7$.

A sharp cutoff above 10^{19} eV was observed at a statistical significance of 6 standard deviations (14): this suppression can be interpreted as the result of the so-called Greisen-Zatsepin-Kuzmin (GZK) effect, the photo-pion production resulting from the interaction of ultra high energy protons with the Cosmic Micro Wave Background (CMB) photons (15, 16) or as a maximum energy of the extra-galactic sources (17).

2.1.2 Galactic cosmic rays

Galactic cosmic rays (GCRs) are directly detected by balloon and satellite detectors, namely Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) (18), Cosmic Ray Energetics and Mass (CREAM) (19) and the AMS-02

Figure 2 – Galactic and extra-galactic flux multiplied by $E^{2.7}$ as a function of energy. Data taken from (9) and (10). The x-axis for the helium flux is in GeV/n.

Source: MERTSCH (11)

experiments, given the high flux at this energy level. GCRs consists of approximately 90% of protons (ionized hydrogen, H), 8% of helium (He) nuclei, 1% of electrons (e^-) and 1% of heavier nuclei and antimatter (20). We can compare the relative abundances in the Solar system with the abundances of GCR elements, as it is shown in figure 3. Overall, the abundance of elements in CRs is very similar to the abundance found in the solar system, which is the case for instance, of Carbon (C), Oxygen (O) and Nitrogen (N). Some elements are overabundant in cosmic rays with respect to the same elements in the solar system, which is the case of Lithium (Li), Beryllium (Be) and Boron (B), which are expected to be almost absent in the end-products of stellar nucleosynthesis, but can be produced in the process of fragmentation of carbon or oxygen nuclei by collisions, usually referred to as *spallation* (21). The same can occur in the production of galactic Fluorine (F) by the fragmentation of Neon (Ne) and the elements of Scandium (Sc) to Manganese (Mn) from the spallation of Iron (Fe) and Nickel (Ni). As a consequence of this phenomenon, we can divide then CRs in two types: primaries, the ones accelerated in the sources, and secondaries, the by-products of the interaction of the primaries with the Interstellar Medium (ISM). The secondary production of CRs in the galaxy is an indication of the confinement of these particles in the galaxy, since, knowing the cross-sections of the interaction between these primary CR and the background matter, or in other words, the probability of a primary CR to scatter into an ISM target, it is possible to estimate the amount of time required in order to achieve such abundances. It is possible to show

Figure 3 – Relative abundances in the solar system (from 23) and for Galactic CRs (from 24,25). Abundances normalized to 10^6 Si.

Source: MOLLERACH (22)

that a typical propagation time in the galaxy is around $\tau \simeq 3$ Myr (22), while the time required for a relativistic particle to cross the typical kpc sizes of galaxy in a straight line is of order $\sim 10^{-2}$ Myr, hence, much lower than the typical propagation time. Knowing that the ISM is magnetized, as we will discuss further on, this propagation time suggests that GCRs are likely to spend time in diffusive motion through the galaxy, once GCRs are charged particles, therefore, subject to magnetic interactions. From now on, the CR denomination will be referring only to the galactic component.

2.2 The Galaxy

Since CRs spend most of their “life” traveling through the galaxy, it is of our interest to have a description of the medium. CRs couple with the magnetic fields of the galaxy and are subject to drastic deviations on their path. CRs also interact with the ISM, which will be responsible for energy losses and serve as target for the spallation of nuclei. The Milky Way is a barred spiral galaxy (figure 4) with radius around 25 kpc (26,27), where sources and matter are concentrated in a disk of height around 100 pc, as it will be better described next on this section.

Figure 4 – Logarithmic spiral arms, and the position of the Sun in the galaxy.

Source: MOSKALENKO (26)

2.2.1 The magnetic fields of the Galaxy

Observational tracers such as Faraday rotation (29) and polarised dust emission (30) enable a mapping of the galactic magnetic field within the galactic plane. This magnetic field shows a regular component within the spiral arms of the galaxy as seen in figure 4, together with a small-scale turbulent component, and a third anisotropic random component (31, 32). Besides these observations from our galaxy, observations of radio emissions from several nearby galaxies showed a large magnetic structure for distances much bigger than the galactic disk thickness (28). This emission is due to synchrotron emissions from CRs electrons confined within this structure. Figure 5 illustrates this feature for the galaxy NGC 4631 (located ~ 7 Mpc away from the Milky Way), where the radio isocontours are superimposed with the optical emission. This large magnetic structure is known as the magnetic halo of the galaxy, and CRs are believed to be confined within this volume, which extends very far from the galactic disk.

2.2.2 The interstellar medium composition

The interstellar mass is made of gas and dust and amounts to approximately 5% of the visible mass of the galaxy, being concentrated along the galactic plane, with an

Figure 5 – Isocountours of 610 MHz radio emission from galaxy NGC 4631, together with the optical emission.

Source: EBERS (28)

overall density of 1 particle per cubic centimeter. The gas is the most abundant component, therefore the most relevant for the interactions with CRs. The interstellar gas is dominated by hydrogen in its molecular (H_2) and neutral (HI) forms. A lower density of ionized hydrogen (HII) is also present in the ISM and is accountable for the density of free electrons. Heavier elements are also found in the gas, especially helium, that amounts to $\sim 10\%$ of the hydrogen mass (33). Three different phases are encountered in the ISM gas: a cold gas, with temperatures of order ~ 10 K, composed by molecular clouds of H_2 and neutral H and He, spreading to distances up to 10 kpc and 30 kpc, vertically distributed up to 70 pc (34, 35) and ~ 150 pc, respectively. The warm gas of temperatures around 8000 K have a wider vertical distribution, up to 1 kpc, as the hot gas with temperatures of $\sim 10^6$ K spreads through the whole magnetic halo, but with a very low density, although some recent surveys (36, 37) indicates that this form of gas can have a relevant contribution to the mass of the galaxies. Concerning the propagation of CRs in the galaxy, interactions with ISM gas will be considered to happen only in the galactic disk, homogeneously, and will be dominated by the interaction with hydrogen and helium (and electrons).

2.3 Galactic CR measurement in the AMS-02 era

The AMS-02 is a state-of-the-art cosmic ray detector, operating on the International Space Station since May 2011. AMS-02 has collected more than 140 billion events so far, and published precise measurements of cosmic rays in the GeV to TeV range, including the flux of protons and light nuclei up to Oxygen.

2.3.1 Spectral features

The current generation of space-based CR experiments has been providing for the first time percent level precision measurements. These new observations have revealed subtle and unexpected spectral features (4) that require to re-examining or at least improving the theoretical framework used to describe the CR origin and propagation.

In the simplified “conventional scenario” to describe the origin and propagation of CRs up to the knee, the primary CRs (e.g. H, He, C) are accelerated in Supernova remnants (SNR) via diffusive shock acceleration up to PeV energies, while their propagation in the ISM is described by an homogeneous and energy-dependent diffusion coefficient K (discussed in the chapter 3). Once primary CRs are released from the sources, they propagate in the ISM, made mainly by H and He nuclei, where they are confined by the magnetic fields for times of the order of a few million years. When primary particles interact with the ISM they produce secondary CRs, like Li, Be, B as well as antimatter particles such as positrons (e^+) and antiprotons ($\bar{p}$). This theoretical framework provides featureless and universal (species independent) single power-law energy spectra, and it was supported by experimental results up to a decade ago. This model was a reasonable option to describe the CR data until the beginning of 2000, when detectors with large acceptance and good resolution were brought to the uppermost layers of the atmosphere or to space: the first hints of deviations from the single power law were provided by the CREAM balloon experiment, which suggested an indication for a transition in the spectral index of CR proton, helium and heavier nuclei. However, the large uncertainties prevented for an unambiguous claim. The PAMELA Collaboration published in 2011 precise measurement of proton and helium fluxes between 1 GV to 1.2 TV (38), showing a clear feature above 200 GeV. The AMS-02 collaboration in 2015 showed that both the proton (39) and helium spectra cannot be described as a single power law, and that a transition in the spectral index takes place above 200 GeV.

Figure 6 shows AMS-02 measurements of the proton flux, together with data from previous experiments. The first thing to be pointed out in figure 6 is the relatively smaller error bars and the larger energy range covered by AMS-02, in comparison with previous experiments. This unprecedented precision on measurements brought to light new features in the CR spectrum, namely a transition in the spectral index of the spectrum at energies around ~ 200 GeV. The top panel of figure 7 shows the CR proton flux measured by

Figure 6 – Proton flux (multiplied by $E_K^{2.7}$) as a function of kinetic energy. Red points indicate AMS-02 data, compared with previous experiments.

Source: AGUILAR (39)

AMS-02 as a function of rigidity *. To account for the observed transition in the spectral index, the flux can be described as follows:

$$\Phi = C \left(\frac{R}{45 \text{ GV}} \right)^\gamma \left[1 + \left(\frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^s, \quad (2.1)$$

where C is the normalization parameter, γ is the initial spectral index, R_0 is the rigidity where the transition occurs, $\Delta\gamma$ is the variation of spectral index and s is the smoothness of the transition. It was found by the AMS-02 collaboration, when fitting equation 2.1 to the data, values of $\gamma \sim -2.814$, $R_0 \sim 366 \text{ GV}$ and a variation of $\Delta\gamma \sim 0.133$; these results yields to the solid blue line in figure 7. The bottom panel shows a non constant behavior of the flux spectral index, as a function of rigidity. The flux spectral index is defined as:

$$\gamma = d [\log \Phi] / d [\log R] \quad (2.2)$$

The same behavior was observed for other species of CR, in further AMS-02 publications. The three secondary fluxes have an identical rigidity dependence above

* Rigidity is the momentum of the particle over its charge: $R \equiv pc/Ze$, where p is particle's momentum, c as the speed of light, particle's atomic number Z , and the charge of the electron e .

Figure 7 – Top plot (a): the AMS-02 proton flux multiplied by $R^{2.7}$ as a function of rigidity. The solid curve indicates the fit of equation 2.1 to the data. For illustration, the dashed curve uses the same fit values but with $\Delta\gamma = 0$, i.e. no break is present. Bottom plot (b): The dependence of the proton flux spectral index on rigidity R .

Source: AGUILAR (39)

30 GV, as do the three primary fluxes above 60 GV (see figures 8 and 9). The rigidity dependence of primary cosmic rays fluxes and of secondary cosmic rays fluxes are distinctly different. Remarkably, a single power law can no longer describe the CR flux in the GeV to TeV range. Several scenarios were proposed to explain such features, and they can be grouped into two categories: either it is a source effect, either it is a propagation effect. One explanation could be a break in the source spectrum (40, 41), or the contribution of a local source (42, 43).

Based on the latest measurement published by AMS-02, the first evidence for a break in the diffusion coefficient was inferred (44, 45): this break is due to the diffusion effects rather than to source effects. In the present dissertation we will focus on the study

Figure 8 – Comparison of the secondary CR fluxes with the AMS-02 primary cosmic ray fluxes multiplied by $R^{2.7}$ with their total error as a function of rigidity above 30 GV. For display purposes only, the C, O, Li, Be, and B fluxes were rescaled as indicated. For clarity, the He, O, Li, and B data points above 400 GV are displaced horizontally.

Source: AGUILAR (5)

of a diffusive origin of the observed transition in the spectral index in the CR spectrum.

Figure 9 – Spectral indices of He, C, O, Li, Be and B fluxes as a function of rigidity calculated using equation 2.2.

Source: AGUILAR (5)

3 GALACTIC COSMIC-RAYS TRANSPORT: FROM SOURCE TO EARTH

3.1 Transport phenomenology

In this chapter the acceleration and propagation of CRs from their sources until their detection at Earth will be discussed.

We will start with introducing some definitions. The phase space density $f_a(\mathbf{r}, \mathbf{p})$ of a CR species a is defined as:

$$f_a(\mathbf{r}, \mathbf{p}) \equiv \frac{d^6 N_a}{d^3 x d^3 p} = \frac{d^3 n_a}{d^3 p}, \quad (3.1)$$

where n_a is the density of cosmic rays per volume. Assuming that the momentum distribution of the particle is isotropic, we have $\phi_a(\mathbf{r}, p)$, defined as:

$$\phi_a(\mathbf{r}, p) = \frac{dn_a}{dp} = 4\pi p^2 f_a(\mathbf{r}, p). \quad (3.2)$$

We can also express the CR density in terms of energy, by defining:

$$\psi_a(\mathbf{r}, E) = \frac{dn_a}{dE} = \frac{E}{p} \phi_a = 4\pi E p f_a(\mathbf{r}, p). \quad (3.3)$$

Finally, the flux of CRs, defined as the number of particles per unit of energy, time, solid angle and surface, is given by:

$$\mathcal{J}_a(\mathbf{r}, E) = \frac{v}{4\pi} \psi_a(\mathbf{r}, E) = \frac{1}{4\pi} \phi_a = p^2 f_a(\mathbf{r}, p). \quad (3.4)$$

Here we use the relativistic energy of the particle $E^2 = (mc^2)^2 + (pc)^2$, where m is the particle's rest mass. Occasionally we express the energies in units of kinetic energy per nucleon $E_{k/n} = E_k/A$, where E_k is the total kinetic energy and A the number of nucleons. The density of charged particles is commonly described as a function of the *rigidity* of the particle, since it relates to the particle's Larmor radius *. The rigidity is defined as:

$$R \equiv \frac{pc}{Ze} = \frac{p}{Z} = r_L B, \quad (3.5)$$

where Z is the atomic number of the particle, e is the charge of the electron, r_L is the Larmor radius of the particle, and B is the magnitude of the magnetic field of the medium. We also use natural units $c = \hbar = e = 1$. These definitions will serve as base once we start

* The Larmor radius, or gyroradius, is the radius of the circular motion of a charged particle in the presence of a uniform magnetic field.

to describe the physical phenomena that are at play during the propagation of CRs in the galaxy.

3.1.1 Cosmic-ray acceleration in astrophysical sources

In the frame of simplified “conventional scenario” (presented in 6) the primary CRs (e.g. H, He, C) are accelerated in Supernova Remnants (SNR) via diffusive shock acceleration up to PeV energies. This was first shown in (1). By equating the energy density of CRs in the galaxy to the observed one, the power of the sources was found to be:

$$P_{CR} \approx \frac{U_{CR} V_{CR}}{\tau} \approx 10^{40} \text{ erg s}^{-1}, \quad (3.6)$$

where $U_{CR} = 1.5 \text{ eV cm}^{-3}$ is the energy density of CRs in the galaxy, V_{CR} is the volume occupied by CRs, and τ is the typical residence time of CRs in the galaxy.

The kinetic energy of an expanding supernovae shell is of the order of $E_{SNR} \approx 10^{51} \text{ erg}$ (46). Given that the rate of supernovae explosion in the galaxy is around 3 per century we have that the power that supernovae injects into the galaxy is $P_{SNR} \approx 10^{42} \text{ erg s}^{-1}$, and if compared to P_{CR} in equation 3.6, we would have that only around 10% of the energy of a supernovae explosion is required to accelerate CRs. Later on, this evidence became stronger with radio, X-rays and gamma-rays observations (47). SNRs are considered the main accelerators of CRs, but there are some evidences in favor of other astrophysical objects, like pulsars, which may have a large contribution to the CR electron and positron flux (48).

The concept of stochastic acceleration of particles was first proposed by Enrico Fermi in 1949 (50, 51) and it is schematically described in figure 10. The idea is that particles scattering on moving magnetic clouds with random velocities have a chance of gaining or losing energy, while the average energy gain will be positive. To illustrate this concept, we will calculate the average energy gain of a single scattering, following the calculations from ref. (49). Consider a relativistic particle with energy $E_1 \sim p_1 c$ in the galaxy’s frame, with speed $u_1 = \beta c$. Via Lorentz’ transformation, the energy of the particle E'_1 in the cloud’s frame is given by:

$$E'_1 = \gamma E_1 (1 - \beta \cos \theta_1), \quad (3.7)$$

where θ_1 is the angle between particle’s and cloud’s velocities, and γ is the Lorentz factor. The particle’s final energy in the cloud’s frame E'_2 remains unchanged ($E'_2 = E'_1$), but in the galaxy’s frame, the particle’s final energy E_2 is given by:

$$E_2 = \gamma E'_2 (1 + \beta \cos \theta'_2), \quad (3.8)$$

Figure 10 – Schematic description of the stochastic acceleration of charged particles scattering into moving magnetized clouds with random velocities, later called *2nd order Fermi mechanism*.

Source: MORLINO (49)

where θ'_2 is the particle's exit angle in the cloud's frame. The energy gain for a single scattering is then:

$$\frac{\Delta E}{E_1} \equiv \frac{E_2 - E_1}{E_1} = \frac{1 - \beta \cos \theta_1 + \beta \cos \theta'_2 - \beta^2 \cos \theta_1 \cos \theta'_2}{1 - \beta^2} - 1. \quad (3.9)$$

We can now calculate the average energy gain. Assuming that the scattering inside the magnetic cloud is isotropic, we have $\langle \cos \theta'_2 \rangle = 0$. Defining the relative velocity between the particle and the cloud in the galaxy's frame is $\beta_r = 1 - \beta \cos \theta_1$, we have:

$$\langle \cos \theta_1 \rangle = \frac{\int d\Omega \beta_r \cos \theta_1}{\int d\Omega \beta_r} = \frac{\int_{-1}^1 d\cos \theta_1 (1 - \beta \cos \theta_1) \cos \theta_1}{\int_{-1}^1 d\cos \theta_1 (1 - \beta \cos \theta_1)} = -\frac{\beta}{3}. \quad (3.10)$$

Plugging the expression above into eq. 3.9, we have:

$$\frac{\Delta E}{E_1} = \frac{1 + \frac{1}{3}\beta^2}{1 - \beta^2} - 1 \simeq \frac{4}{3}\beta^2, \quad (3.11)$$

where we assumed $\beta \ll 1$, since we are interested in particles to be accelerated to relativistic energies. This energy gain, proportional to β^2 , is of the order of 10^{-8} for typical velocities in the ISM in a single scattering. This mechanism is called *2nd order Fermi mechanism*, and it is the basic mechanism conceived to explain the acceleration of CRs. Fermi's idea was later revisited by several authors, and applied to particles scattering in the proximity of a shock wave (52–55) changing the picture of acceleration of CRs by SNRs. In the “shock

Figure 11 – Example of the 1st order Fermi mechanism

Source: MORLINO (49)

wave frame”, where the shock front is at rest (see figure 11), a particle in the *upstream region* (plasma going towards the shock front with velocity $u_1 \equiv u_{sh}$; u_{sh} is the velocity of the shock front) crosses the shock front to the *downstream region* (plasma moving away from the shock front with velocity u_2) and scatters back to the upstream region, gaining energy. We can calculate the flux J_- of particles coming from the downstream region to the upstream region. The relative velocity between the upstream and downstream plasma is given by $u_r = \beta_r c \equiv u_2 - u_1$, so that we have:

$$J_- = \int \frac{d\Omega}{4\pi} n c \cos \theta = \frac{nc}{4}, \quad (3.12)$$

where n is the isotropic density of particles and J_- is calculated over an hemisphere ($0 \leq \cos \theta \leq \pi/2$). We average the incoming and outgoing angles over the particle flux, over an hemisphere:

$$\langle \cos \theta_1 \rangle = \frac{\int d\Omega (nc \cos \theta_1) \cos \theta_1}{J_-} = -\frac{2}{3} = -\langle \cos \theta'_2 \rangle, \quad (3.13)$$

and plugging in the expression above in equation 3.9, we have an average energy gain of:

$$\frac{\Delta E}{E} = \frac{1 + \frac{4}{3}\beta_r + \frac{4}{9}\beta_r^2}{1 - \beta_r^2} - 1 \sim \frac{4}{3}\beta_r. \quad (3.14)$$

Equation 3.14 gives the energy gain per cycle, and it is proportional to the parameter β_r , i.e. the relative velocity between the upstream and the downstream medium. For this reason this mechanism is commonly dubbed *1st order Fermi mechanism*. Given the typical velocities of the shock waves, together with the dependence on β_r , this mechanism is more efficient in accelerating particles than the random scattering in magnetized clouds.

For each scattering cycle, there is a finite non-zero probability for the particle to escape the acceleration region P_{esc} , with an energy gain $\varepsilon \equiv \Delta E/E = 4\beta/3$. P_{esc} can be written as:

$$P_{esc} = \frac{J_{\infty}}{J_{+}}, \quad (3.15)$$

where J_{∞} is the flux of particles leaving the downstream region towards the infinity, and J_{+} the flux of particles crossing the upstream region towards the downstream region. J_{∞} is simply nu_2 , whereas, with conservation of the flux we have that $J_{+} = J_{\infty} + J_{-}$. Using equations 3.12 and 3.15, P_{esc} is estimated to $4u_2/c$. After a number k of cycles (scattering upstream-downstream-upstream), a particle of initial energy E_0 will have an energy $E = E_0(1 + \varepsilon)^k$. Given that the particle has a probability $1 - P_{esc}$ to be confined in the acceleration region, the number of particles with energy greater than E after k cycles is given by:

$$\begin{aligned} N(> E) &\propto \sum_{i=k}^{\infty} (1 - P_{esc})^i = \frac{(1 - P_{esc})^k}{P_{esc}} = \\ &= \frac{[(1 - P_{esc})^{\ln(E/E_0)}]^{1/\ln(1+\varepsilon)}}{P_{esc}} = \\ &= \frac{1}{P_{esc}} \left[\left(\frac{E}{E_0} \right)^{\ln(E/E_0)} \right]^{1/\ln(1+\varepsilon)} = \\ &= \frac{1}{P_{esc}} \left(\frac{E}{E_0} \right)^{-\zeta} \end{aligned} \quad (3.16)$$

where ζ is defined as $\zeta = -\ln(1 - P_{esc})/\ln(1 + \varepsilon)$.

Finally, the source differential energy spectrum is given by:

$$\frac{dN}{dE} \propto E^{-\alpha}, \quad (3.17)$$

where the spectral index is given by $\alpha = 1 + \zeta$ and is universal, i.e. energy and species independent. The acceleration process is due to the scattering between non-thermal particles and the magnetic turbulence in the shock, where energy is transferred from the plasma bulk from SNRs to CRs particles. In that sense, it is possible to estimate the maximum energy of an accelerator. The maximum energy achieved by an accelerator is a combination between the acceleration time and energy losses rate, as well as the accelerator age. The phase of the accelerator in which the mass of the ejecta starts to be of the same order as the mass around the stellar medium to be accelerated is called Sedov-Taylor phase (56,57). In the Sedov-Taylor phase, the velocity of the front of shock starts to decrease.

The Sedov-Taylor phase is expected to start after only 50-200 years, and it is possible to estimate the maximum energy E_{max} (49) of an accelerator as:

$$E_{max} = 5 \times 10^{13} Z \mathcal{F}(k_{min}) \left(\frac{B_0}{\mu\text{G}} \right) \left(\frac{M_{ej}}{M_\odot} \right)^{-\frac{1}{6}} \left(\frac{E_{SN}}{10^{51}\text{erg}} \right)^{\frac{1}{2}} \left(\frac{n_{ISM}}{\text{cm}^{-3}} \right)^{-\frac{1}{3}} \text{ eV}, \quad (3.18)$$

where Z is the atomic number of the accelerated particle, $\mathcal{F}(k_{min})$ is the normalized energy density that correlates the perturbation δB wave in the regular magnetic field of the medium B_0 . The perturbation δB has a wave number $k_{min} = 1/r_l(E_{max})$ such that particles with the maximum energy resonates with it. M_{ej} is the mass of the ejecta from SNRs which is the order of the mass of the Sun $M_\odot$. In that sense, it is clear to see that in order to reach the energy of the knee $E_{knee} \approx 3 \times 10^{18}$ eV, some strong amplification of the magnetic field surrounding the acceleration region is required. This was proposed in (58), where simulations showed that the magnetic field can be amplified by orders of magnitude by CRs streaming ahead the acceleration region.

The power-law spectrum of equation 3.17 is one of the reasons why Fermi mechanisms are the best candidate to explain the acceleration of CRs in SNRs environments, since the provided source spectrum matches the observed power-law behaviour on the CR spectrum. Therefore, in order to take into account the source spectrum from equation 3.17, we will parametrize the source injection q_a from SNRs as follows:

$$q_a = Q_a E^{-\alpha} \quad (3.19)$$

where Q_a and α will be chosen as model parameters.

3.1.2 The transport equation of cosmic rays

The equation that describes the spatial and energy evolution of CR density in the ISM is called the *transport equation*. From seminal references, such as (59–61), the transport equation in the steady state for the density f_a of a CR species a is given by:

$$\begin{aligned} & \nabla_x \cdot K \nabla_x f_a + \mathbf{V}_c \cdot \nabla_x f_a - \frac{1}{p^2} \frac{\partial}{\partial p} \beta^2 K_{pp} \frac{\partial f_a}{\partial p} - \\ & - \frac{1}{3} (\nabla_x \cdot \mathbf{V}_c) p \frac{\partial f_a}{\partial p} + \frac{1}{p^2} \frac{\partial}{\partial p} [p^2 b_{loss}(p) f_a] + \sigma_a v_a n f_a + \Gamma_a f_a = \\ & = q_a + \sum_{Z_b \geq Z_a}^{Z_{max}} [\sigma_{b \rightarrow a} v_b n + \Gamma_{b \rightarrow a}] f_b, \end{aligned} \quad (3.20)$$

On the first line of the equation we have the diffusion term $(\nabla_x \cdot K \nabla_x f_a)$, the convection $(\mathbf{V}_c \cdot \nabla_x f_a)$ and reacceleration $(\frac{1}{p^2} \frac{\partial}{\partial p} \beta^2 K_{pp} \frac{\partial f_a}{\partial p})$. Diffusion, convection, and reacceleration, are processes caused by the interaction of particles with the turbulent magnetic fields of the galaxy, and will be better described further on the chapter.

In the second line of equation 3.20 we describe adiabatic energy losses ($-\frac{1}{3}(\nabla_x \cdot \mathbf{V}_c)p \frac{\partial f_a}{\partial p}$), continuous energy losses ($\frac{1}{p^2} \frac{\partial}{\partial p} [p^2 b_{loss}(p) f_a]$); and catastrophic losses, namely the fragmentation of nuclei ($\sigma_a v_a n f_a$), and the decay of unstable species ($\Gamma_a f_a$). The energy-loss rate is defined as $b_{loss} \equiv dE/dt$ and sums up the contributions from continuous energy losses such as Coulomb and ionization. σ_a is the total destruction cross-section as particles a collide with velocity v_a into the density n of background matter in the ISM. Finally, if species a is unstable, it will decay with a rate of Γ_a .

Finally, in the third line, we have the source terms: both primary (q_a) and secondary ($\sum_{Z_b \geq Z_a}^{Z_{max}} [\sigma_{b \rightarrow a} v_b n + \Gamma_{b \rightarrow a}] f_b$) injections. The primary injection by astrophysical sources q_a as stated in the previous section, will be parametrized as in equation 3.19. The secondary production is summed over the atomic number Z_b , weighted by the density of progenitor species f_b , and is characterized by both spallation and decay of heavier species b . The spallation of species b into species a is controlled by the production cross-section $\sigma_{b \rightarrow a}$ as the progenitor species collide with targets in the ISM with a velocity v_b . Also, the decay of species b may produce secondaries with a rate $\Gamma_{b \rightarrow a}$.

In the following we will describe in detail the main phenomena that are at play during the propagation of cosmic rays, since they are of great importance in the frame of the work that is presented in this dissertation.

3.1.3 Spatial diffusion

CRs interact with the turbulent magnetic fields and diffuse isotropically and homogeneously through the ISM. The picture of diffusion is the following: CRs travelling through a magnetic field B , have their path tangled by small random fluctuations $\delta B \ll B$, forming a sort of random walk through the galaxy. The macrophysics of such effect, can be simply put in terms of equations 3.21, which is a continuity equation, and 3.22, that is Fick's first law of diffusion (62). Combining these ingredients, we have a diffusion equation 3.23, with a density ψ , a diffusion current j , and a diffusion coefficient K .

$$\frac{\partial \psi}{\partial t} + \nabla \cdot \mathbf{j} = 0 \quad (\text{Continuity equation}), \quad (3.21)$$

$$\mathbf{j} = -K \nabla \psi \quad (\text{Fick's law}), \quad (3.22)$$

$\implies$

$$\frac{\partial \psi}{\partial t} = \nabla \cdot (K \nabla \psi). \quad (3.23)$$

The overall spatial diffusion of particles is controlled by a diffusion coefficient K , rising from a quasi-linear theory (59, 63, 64) as:

$$K = \frac{v l_{mfp}}{3} \simeq \frac{v}{3} \frac{r_L}{|\delta B/B|_{k_L}^2}, \quad (3.24)$$

where v is the particle's velocity, l_{mfp} is the mean free path in the diffusive motion, $r_L = R/B$ is the Larmor radius and $k_L \propto 1/L$ is the turbulence mode in resonance with the particle's Larmor radius. The diffusion coefficient is linked to the magnetic turbulence via $K \propto |\delta B/B|_{k_L}^{-2}$.

The turbulence in the magnetic fields of the galaxy, can present itself in two different scenarios: Kolmogorov turbulence (65), and Iroshnikov-Kraichnan turbulence (66,67). These turbulence scenarios are defined by the spectral index ν of their power spectrum, since that, for a Kolmogorov-like turbulence, we would have $\nu = 5/3$, while for a Iroshnikov-Kraichnan turbulence, we would have that $\nu = 3/2$. These different types of turbulence will tell how efficiently the energy is dissipated from the large scales magnetic fields to the small scale.

In the “conventional scenario” the diffusion coefficient K is described by an effective power law in rigidity with a spectral index δ (e.g. (68,69))

$$K(R) \propto R^\delta. \quad (3.25)$$

such that the spectral index δ is linked to the turbulence power spectrum through the equality $\delta = 2 - \nu$ (70). Hence, when compared to the data, the value of δ indicates what is the dominant type of turbulence occurring in the magnetic fields of the galaxy: $\delta = 1/3$ for a Kolmogorov-like turbulence, and $\delta = 1/2$ for Iroshnikov-Kraichnan turbulence.

Assuming that primary CR species comes only from the injection at SNRs, and that secondaries are originated solely from secondary production ($q_{II} \equiv 0$), a solution of the equation 3.20 for primary species, neglecting all processes but the sources and diffusion, is given by:

$$\psi_I \propto \frac{q_I}{K} \propto R^{-\alpha-\delta}, \quad (3.26)$$

The density ψ_{II} of secondaries would be given by:

$$\psi_{II} \propto \frac{\psi_I}{K} \propto \frac{q_I}{K^2} \propto R^{-\alpha-2\delta}. \quad (3.27)$$

Therefore, the secondary-to-primary ratio using a purely secondary species would be in the form of:

$$\frac{\psi_{II}}{\psi_I} \propto \frac{1}{K} \propto R^{-\delta}. \quad (3.28)$$

The latest AMS-02 data on secondary-to-primary ratios, showed in figure 12, point towards a different scenario, since these quantities cannot be described as a single power law, at it is shown in figure 13.

Figure 12 – The ratios Li/C, Be/C and B/C as measured by AMS-02

Source: AGUILAR (5)

In view of these new spectral features observed in the CR spectrum and also on secondary-to-primary ratios, a single power-law (equation 3.25) can no longer account efficiently for the high rigidity transition in the spectral index.

Based on the B/C measurement published by AMS-02, the first evidence for a break in the diffusion coefficient (44) was inferred: this break is due to the diffusion effects rather than to source effects. A general form for a scalar, homogeneous and isotropic diffusion coefficient K was presented in (45), that features a break in both the low and high rigidity range:

$$K(R) = \beta^\eta K_{10} \left[1 + \left(\frac{R}{R_l} \right)^{\frac{\delta_l - \delta}{s_l}} \right]^{s_l} \left(\frac{R}{R_{10}} \right)^\delta \left[1 + \left(\frac{R}{R_h} \right)^{\frac{\delta - \delta_h}{s_h}} \right]^{-s_h}, \quad (3.29)$$

Three different spectral regimes can be identified for the diffusion coefficient described above:

- The low-rigidity regime, for $R \ll R_l$, where $K \propto R^{\delta_l}$;

Figure 13 – Spectral indices of ratios shown in figure 12 as calculated in two rigidity intervals, 60.3-192 GV and 192-3300 GV with equation 2.2

Source: AGUILAR (5)

- The intermediate-rigidity regime, for $R_l < R < R_h$, where $K \propto R^\delta$;
- The high-rigidity regime, for $R \gg R_h$, where $K \propto R^{\delta_h}$,

where δ_l , δ , and δ_h are the diffusion spectral indices for the low-rigidity, intermediate and high-rigidity respectively, R_l and R_h indicate the rigidity of both low and high-rigidity breaks, s_l and s_h quantifies how smooth is the transition between regimes. The parameter η controls the non-relativistic region of the spectrum, while K_{10} is a normalization parameter and R_{10} that serves as a scaling factor for the intermediate regime, where we have the $R_l < R_{10} < R_h$ hierarchy.

3.1.4 Momentum diffusion: Reacceleration

In the same vein as the spatial diffusion just commented above, the scattering of CR particles onto magnetic field irregularities, cause not only a diffusion in space, but also in the momentum of these particles (52,59). The momentum diffusion $K_{pp} \equiv \langle \frac{\Delta \mathbf{p} \Delta \mathbf{p}}{\Delta t} \rangle$ (71) is linked to the spatial diffusion as follows (72):

$$K(R) \times K_{pp}(R) \approx \frac{1}{9} p^2 V_a^2, \quad (3.30)$$

where V_a takes an effective character as the velocity of perturbations moving through the magnetic field, characterized as a 2st order Fermi mechanism. V_a should be comparable to the Alfvénic speed of perturbations randomly moving through the CR streams (73).

3.1.5 Convection of cosmic rays

The convection of CRs is a collective movement of the plasma outwards the galaxy halo. We can explain the process in a similar fashion as we did for diffusion, considering a CR current defined as $\mathbf{j} = \mathbf{j}_d + \mathbf{j}_c$, where $\mathbf{j}_d$ is the diffusion current from equation 3.22 and $\mathbf{j}_c$ is the convection current given by:

$$\mathbf{j}_c = \mathbf{V}_c \psi, \quad (3.31)$$

where V_c stands for the velocity of the convective winds in the galaxy. Using the continuity equation 3.21, we get the diffusion-convection equation:

$$\frac{\partial \psi}{\partial t} = \nabla \cdot (K \nabla \psi - \mathbf{V}_c \psi). \quad (3.32)$$

These convective winds may present a thermal origin (74,75), or a radiation-pressure origin (76,77), or can be CR-driven (78). In such cases, a pressure gradient is observed that may cause changes in the propagation of CRs. Moreover, thermal and radiation pressure winds are expected to contribute less than the CR-driven winds (79) in the large scales of the magnetic halo of the galaxy.

In order to give a better picture of the convection process, let us discuss some implications of CR-driven winds. As CRs escape the bulk of the galaxy, a gradient pressure is created by a CR density gradient. This pressure gradient exerts then a force on the interstellar matter of the galaxy (78), and once this force overcomes the gravitational force, winds are launched away from the galactic disk (79). These convective winds can cause changes in the propagation of CRs and subsequently, their spectrum.

3.1.6 Collisions of CR nuclei in the ISM

The collisions, both elastic and inelastic, of CR nuclei in the ISM play an important role in the description of the transport of CRs. These interactions are responsible for the creation of secondary CR particles. In equation 3.20, two cross-section terms are shown: σ_a and $\sigma_{b \rightarrow a}$, which are the destruction and production cross-sections respectively. The destruction, or inelastic cross-section σ_a , represents the probability of a CR species a to interact with the ISM, generating in turn any configuration of secondaries. The production cross-section $\sigma_{b \rightarrow a}$, in the same way as the destruction cross-section, represents the probability of a CR species b to interact with the ISM, producing species a by means of any process. Hence, the link between destruction and production cross-sections is given by:

$$\sigma_i^{\text{destruction}} = \sum_{P_k} \sigma_{i \rightarrow p_1 + p_2 \dots + p_n}, \quad (3.33)$$

where P_k is the list of all possible products that can come from the fragmentation of the species i , i.e., in which the sum of the products masses is less than the mass of species i .

Figure 14 – Calculation of the destruction cross-sections for a $p + (\text{Be/Al})$ collision in mb versus the kinetic energy (MeV) of the proton, adjusted to the data in (80)

Source: TRIPATHI (81)

There is a historical effort to reach an effective parametrization of both destruction and production nuclei cross-sections. Concerning the modeling of destruction cross-sections of nuclei, an empirical formula was created (82) from geometrical assumptions on the nuclei shape. National Aeronautics and Space Administration (NASA) released a parametrization for nucleus-nucleus inelastic cross-sections (81), which is dubbed in the present dissertation as *Tripathi99* parametrization, for destruction cross-sections. Figure 14 shows the shape of the cross-section in a $p-(\text{Be/Al})$ collision as a function of the proton kinetic energy for this parametrization.

As for production cross-sections, a final empirical formula was developed and revised by Webber in 2003 (83). Also, the GALPROP numerical code for cosmic-ray transport and diffuse emission production (84) provides a library of cross-sections. A comparison between the GALPROP and Webber models is shown in figure 15 for the production of B by ^{12}C .

3.1.6.1 Ghost nuclei

A subtlety of secondary production and production cross-sections is the so-called *ghost nuclei* (85). Some unstable CR species produced by the spallation of heavier species may decay before interact with an ISM target (86). Thus, these *ghost* nuclei effectively increases the production channel for a given species. For instance, ^{11}Li , ^{11}Be , ^{12}Be , and ^{11}C can decay into ^{11}B . Therefore, the effective production cross-section of ^{11}B from a

nucleus i is given by:

$$\sigma_{i \rightarrow {}^{11}\text{B}}^{\text{effective}} = \sigma_{i \rightarrow {}^{11}\text{B}} + \sum_{\text{ghost} X} Br(X \rightarrow {}^{11}\text{B}) \sigma_{i \rightarrow X} = \quad (3.34)$$

$$\sigma_{i \rightarrow {}^{11}\text{B}} + 78.4\% \sigma_{i \rightarrow {}^{11}\text{Li}} + 97.1\% \sigma_{i \rightarrow {}^{11}\text{Be}} + 0.52\% \sigma_{i \rightarrow {}^{12}\text{Be}} + 100\% \sigma_{i \rightarrow {}^{11}\text{C}},$$

where the percentages correspond to the branching ratios $Br(X \rightarrow {}^{11}\text{B}) \sigma_{i \rightarrow X}$ of the ghosts into ${}^{11}\text{B}$. These branching ratios are recovered from (87). In figure 15 it is possible to observe the impact of *ghost nuclei* as it is added to the production cross-section of ${}^{12}\text{C}$.

Figure 15 – The solid lines are the calculation yielded by both GALPROP and Webber models for the production of B by ${}^{12}\text{C}$, and the dashed lines includes the contribution coming from ghost nuclei. The data (black dots) is from (88)

Source: GÉNOLINI (89)

Furthermore, an extensive study on destruction and production cross-sections was performed in (86) and recent studies point out around $\sim 10\%$ of theoretical uncertainties coming from cross-sections in CR transport theory (68).

3.1.7 Energy losses in the ISM

Last but not least, the final ingredient of CR transport is the energy loss rate during the propagation through the ISM. References (6, 90, 91) provide an extensive discussion on energy losses suffered by CR in their propagation through the galaxy. Summarizing, the energy losses relevant for nuclei propagation are: continuous energy losses such as Coulomb and ionization; adiabatic energy losses due to the expansion of the plasma, and the energy variation rate induced by reacceleration. As these energy losses are strongly dependent on the particle's energy, we must provide a more detailed description of such effects.

3.1.7.1 Continuous energy losses: Coulomb and Ionization

A particle with mass M and charge Z , moving through a fully ionized plasma will scatter dominantly with thermal electrons (91). Hence, the energy loss rate due to Coulomb collisions is given by (92):

$$b_{coul}(E) \approx -4\pi r_e^2 c m_e c^2 Z^2 n_e \ln \Lambda \frac{\beta^2}{x_m^3 + \beta^3}, \quad (3.35)$$

where r_e is the classical electron radius, m_e is the electron rest mass, c is the speed of light, $\beta = v/c$ the nucleon speed, n_e is the density of thermal electrons, $x_m \equiv [3\sqrt{\pi}/4]^{1/3} \sqrt{2kT_e/m_e c^2}$, with T_e as the electron temperature. Also, the Coulomb logarithm $\ln \Lambda$ is written as follows:

$$\ln \Lambda \approx \frac{1}{2} \ln \left(\frac{m_e^2 c^4}{\pi r_e \hbar^2 c^2 n_e} \frac{M \gamma^2 \beta^4}{M + 2\gamma m_e} \right), \quad (3.36)$$

where $\hbar = h/2\pi$ is the Planck constant and γ is the Lorentz factor.

CRs can also ionize neutral matter, transferring energy to the bound electron. Therefore, the energy loss rate due to ionisation is given by (91,92):

$$b_{ion}(E) = -2\pi r_e^2 c m_e c^2 Z^2 \frac{1}{\beta} \sum_{s=\text{H,He}} n_s B_s, \quad (3.37)$$

where we have n_s as the density of species present in the ISM, in our case, H and He. B_s is given by:

$$B_s = \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 Q_{max}}{\tilde{I}_s^2} \right) - 2\beta^2 \right], \quad (3.38)$$

where the maximal energy that can be transferred to the electron is given by Q_{max} , which is written as:

$$Q_{max} \approx \frac{2m_e c^2 \beta^2 \gamma^2}{1 + (2\gamma m_e/M)}, \quad (3.39)$$

with the condition $M \gg m_e$ and $\tilde{I}_s$ is the geometric mean of the ionization and excitation potentials of the atom. For the cases of H and He, we have $\tilde{I}_H = 19$ eV and $\tilde{I}_{He} = 44$ eV respectively.

While Coulomb and ionisation energy losses are relevant for nuclei propagation, Bremsstrahlung and inverse Compton scattering are important processes to describe the propagation of CR electrons and positrons (92).

3.1.7.2 Adiabatic and drift losses

As the plasma expands in the galaxy, CRs loses energy (70,93). We can write the adiabatic energy loss rate as:

$$b_{adia}(E) = -\frac{1}{3} (\nabla \cdot \mathbf{V}_c) \frac{p^2}{E}. \quad (3.40)$$

Finally, the last energy gain/rate is a first order contribution in energy from reacceleration (93,94), dubbed drift in the present contribution. The drift energy loss rate is given by:

$$b_{drift}(E) = -\frac{1 + \beta^2}{E} K_{pp}. \quad (3.41)$$

To summarize, the energy loss term $b_{loss}(E)$ described in 3.20 can be split in different terms, as follows:

$$b_{loss}(E) \equiv b_{coul} + b_{ion} + b_{adia} + b_{drift}. \quad (3.42)$$

In the next chapter we will discuss how the full CR transport equation discussed in this chapter can be solved using a semi-analytic approach with the *USINE* code, and what type of constraints on the propagation of CRs can be derived in view of the most recent AMS-02 data.

4 CONSTRAINING DIFFUSION-BASED MODELS WITH SECONDARY-TO-PRIMARY RATIOS

In this chapter we present our results concerning the study of the CR spectrum, in the context of a diffusive transport of CRs in the galaxy. Our results are also part of the extensive work presented in (44, 45, 68, 95), based on the analysis of AMS-02 data on secondary-to-primary ratios, specially the B/C ratio (5).

We will describe the whole propagation framework used to compute the CR fluxes with the *USINE* code (96), that allows for the calculation of CR fluxes with Z from 1 to 30, as well as anti-protons and anti-deuterons. We present our benchmark results for three different propagation scenarios of CR in the galaxy.

4.1 Propagation models

Following the work presented in (70, 97), we assume a 1D propagation model, where the magnetic halo confining the CRs is an infinite slab in the radial direction and of half-height L , whose value is fixed to 10 kpc, and was found to have a negligible impact on the results. In this model the vertical coordinate z is the only relevant spatial coordinate, and the galactic disk, where the sources of CRs as well as the interstellar medium gas lie, has an effective half-height $h = 100$ pc; the observer is located at $z = 0$. The boundary

Figure 16 – Schematic view of the Galaxy's geometry in the “1 D model”.

Source: GÉNOLINI (68)

conditions $z = \pm L$ are set, such that the density of CRs, ψ , vanishes at these regions. We will take $h \ll L$ (in fact, h is two orders of magnitude less than L), such that the

galactic disk can be modeled as a delta function in $z = 0$, hence $2h\delta(z)$. Energy losses are also considered to be localized in the disk. This geometry is described in figure 16. These approximations are described by the following transformations in equation 3.20:

$$q \rightarrow 2hq\delta(z) \quad (4.1)$$

$$n \rightarrow 2hn\delta(z) \quad (4.2)$$

$$K_{pp} \rightarrow 2hK_{pp}\delta(z) \quad (4.3)$$

$$\nabla_x \cdot \mathbf{V}_c \rightarrow 2h\nabla_x \cdot \mathbf{V}_c\delta(z) \quad (4.4)$$

$$b_{loss} \rightarrow 2hb_{loss}\delta(z) \quad (4.5)$$

where we set the average density of H to $n_H = 0.9 \text{ cm}^{-3}$ and for He, $n_{He} = 0.1 \text{ cm}^{-3}$ (33).

Assuming a steady-state for the density of CRs in the galaxy ($\partial f / \partial t \equiv 0$), and including the transformations 4.1, 4.2, 4.3, 4.4, and 4.5, the transport equation 3.20 becomes:

$$\begin{aligned} \nabla_x (\mathbf{V}_c \psi_a - K \nabla_x \psi_a) - \frac{\partial}{\partial E} \beta^2 K_{pp} \frac{\partial \psi_a}{\partial E} + \frac{\partial}{\partial E} [b_{tot}(E) \psi_a] + \\ + \sigma_a v_a n \psi_a + \Gamma_a \psi_a = q_a + \sum_{\substack{Z_{max} \\ Z_b \geq Z_a}} [\sigma_{b \rightarrow a} v_b n + \Gamma_{b \rightarrow a}] \psi_b, \end{aligned} \quad (4.6)$$

where we rewrite the density f_a in terms of energy $\psi_a = 4\pi E f_a$.

The task is to determine the density ψ_a using equation 4.6 for a given point of the space, which in our case is $z = 0$, where the Earth is located 8.5 kpc away from the galactic center. Since the density ψ_a of a given species a is coupled with the density of every progenitors species (ψ_b in our description) via secondary production, a fully analytical solution of equation 4.6 is an arduous job. In the other hand, numerical solutions (92, 98) are also available, at the expense of high computational costs. In this work, we follow a semi-analytical approach. For this sufficiently simple geometry, ψ_a can be written as expansions of Bessel eigenfunctions (99), and equation 4.6 can be solved for each species of interest, in the data energy range (GeV to a few TeV). Calculations are performed using the *USINE* code (96).

In chapter 3 we described all the physical phenomena concerning the propagation of CRs in the galaxy. Most of these propagation effects are described by effective parameters that will be used to reproduce the measured flux of CRs on Earth, in particular the B/C flux ratio provided by the AMS-02 experiment (5). Let us recall these parameters:

- The velocities V_c and V_a , for the convective wind and the velocity of small perturbations moving through the magnetic field respectively, encoding the convection and reacceleration of CRs;

- The diffusion coefficient $K(R)$ (see eq. 3.29) is described by means of 9 parameters: η , R_l , δ_l , s_l , K_{10} , δ , R_h , δ_h , and s_h .

Figure 17 – The B/C ratio prediction as a function of rigidity, obtained with the *USINE* code. The B/C is generated for different low-rigidity break parameters, namely the spectral index of the diffusion coefficient δ_l in the top panel, the low rigidity break position R_l in the middle panel, and the transition smoothing parameter s_l in the bottom panel.

Source: By the author

Figures 17 and 18 show the influence of the low rigidity regime parameters on the B/C, in the rigidity range between 1 and 80 GV. The results for the intermediate rigidity regime parameters K_{10} and δ are shown in figure 19, and in figure 20 the results for the high rigidity regime parameters $\Delta_h \equiv \delta_h - \delta$, R_h and s_h are displayed. It is clear that the B/C ratio is heavily influenced by these parameters, reinforcing the importance of a precise determination of their values, in order to better reproduce recent measurements.

We can compare the timescales of the phenomena included in equation 4.6. Figure 21 shows a comparison of the characteristic timescales for each relevant effect taking place inside the galactic disk, for the propagation of ^{12}C , as a function of the kinetic energy per nucleon ($E_{k/n}$) (89), with a given set of propagation parameters. It is important that we know what are the dominant phenomena in the data energy range. In that sense, effects with shorter characteristic times dominates the propagation, hence, influencing more the CR fluxes. The lowest energies (below 1 GeV/n) are dominated by energy losses with τ_{losses} adding up the contributions from Coulomb, ionisation and adiabatic energy losses timescales. As the energy increases, the leakage time τ_{leak} , which sums up the the

Figure 18 – The B/C ratio prediction as a function of rigidity, obtained with the *USINE* code. The B/C is generated for different low-rigidity regime parameters, namely the non-relativistic scaling η in the top panel, the velocity V_a in the middle panel, and the velocity V_c for convective winds in the bottom panel.

Source: By the author

contributions of diffusion (τ_{diff}), convection (τ_{conv}) and fragmentation (τ_{frag} , or in other words, the mean free path between collisions), starts to dominate around 2 GeV/nuc, while diffusion dominates the propagation around 10 GeV/nuc. Therefore, we should expect, in terms of rigidity, that around 5 GV *, the propagation of CRs to be predominantly diffusive. Recalling that the data in our analysis starts at $R \sim 1$ GV, effects such as convection, reacceleration and energy losses should influence only the first points of the spectrum. Motivated by these results combined, three different propagation scenarios are proposed in order to reproduce and hint the causes of the spectral features of the CR spectrum.

* Assuming natural units and relativistic regime we have for ^{12}C ($Z = 6$ and $A = 12$), that $R [\mathcal{O}(1 \text{ GV})] \sim 2 \times E_{k/n} [\mathcal{O}(1 \text{ GeV/nuc})]$.

Figure 19 – The B/C ratio prediction as a function of rigidity, obtained with the *USINE* code. The B/C is generated for different intermediate-rigidity regime parameters, namely the spectral index of the diffusion coefficient δ in the top panel, and the diffusion coefficient normalization K_{10} at 10 GV, in the bottom panel.

Source: By the author

Figure 20 – The B/C ratio prediction as a function of rigidity, obtained with the *USINE* code. The B/C is generated for different high-rigidity break parameters, namely the transition of spectral index Δ_h in the top panel, the high rigidity break position R_h in the middle panel, and the transition smoothing parameter s_h in the bottom panel.

Source: By the author

Figure 21 – Typical times for the physical processes involved in the propagation of CR nuclei, as function of kinetic energy per nucleon.

Source: GÉNOLINI (89)

Table 1 – Summary of the parameters included in the *BIG*, *SLIM* and *QUAINT* propagation models

Parameters / Models	<i>BIG</i>	<i>SLIM</i>	<i>QUAINT</i>
Low rigidity regime			
δ_l	YES	YES	NO
R_l	YES	YES	NO
s_l	YES	YES	NO
η	YES	NO	YES
V_a	YES	NO	YES
V_c	YES	NO	YES
Intermediate rigidity regime			
K_{10}	YES	YES	YES
δ	YES	YES	YES
High rigidity regime			
R_h	YES	YES	YES
δ_h	YES	YES	YES
s_h	YES	YES	YES

Source: By the author

4.1.1 The models: *BIG*, *SLIM* and *QUAINT*

As discussed in (45), we aim at finding the best sets of propagation parameters within the context of a CR transport dominated by diffusion. A new propagation model (dubbed *BIG* in the following) was first proposed in (45). It includes a diffusion coefficient with a double break, as well as convection and reacceleration. The corresponding propagation parameters are displayed in table 1, together with the propagation parameters for two limiting cases (called *SLIM* and *QUAINT*). The *SLIM* model is a subpart of *BIG*, in which the low energy effects, convection and reacceleration, are not considered. It relies solely on the diffusion to describe the low and high rigidity spectral transitions observed in the B/C data. Therefore, in the frame of the *SLIM* model, the spectral transitions are only due to a change in the properties of the interaction between CRs and the galactic magnetic fields.

The *QUAINT* model, based on the propagation model proposed in (44), accounts for reacceleration and convection in the CR propagation, as well as the high-rigidity break in the diffusion coefficient, while excluding the low rigidity break. The interplay of a strong reacceleration with the parameter η showed to be effective in modeling B/C data (97, 100). Thus, with *QUAINT*, we test the possibility of the low rigidity transition in the data to be induced by reacceleration and convection, also including a non-trivial, negative, value

of the parameter η .

4.1.2 Benchmark models

Being able to calculate fluxes and secondary-to-primary ratios, we want to adjust our models to the data, following a χ^2 minimisation procedure. We follow the method proposed in (95), which includes the use of a covariance error matrix, in order to properly account for systematic errors coming from the CR measurements. The χ_{cov}^2 function to be further minimised is defined as:

$$\chi_{cov}^2 = \sum_{\alpha} \sum_{i,j=1}^{n_E, n_E} (\text{data}_i - \text{model}_i) (C_{ij}^{\alpha})^{-1} (\text{data}_j - \text{model}_j), \quad (4.7)$$

where the sums in equation 4.7 are performed over the number α of sources of errors (four in total, the statistical uncertainty plus three systematics) and over the number of experimental data points n_E . C_{ij}^{α} is the covariance matrix built in (95). In this way, χ_{cov}^2 is essentially a function of our model parameters. By finding the χ_{cov}^2 minimum, we find the value for each parameter that causes the model to better describe the data. The minimisations are performed within *USINE*, using with the Minuit package (101) from the ROOT library.

At an early stage of our analysis, we realized that for all models, the low rigidity parameter s_l can be fixed to 0.05 (45), i.e., will not be accounted as a free parameter of the model, since it does not improve the quality of the fit while enlarging the errors on the parameters. The same goes for η in models *BIG* and *SLIM*, which for these models, is fixed to 1. In the other hand, η plays an important role for model *QUAINT* as stated previously, and if it is otherwise fixed to $\eta = 1$, yields a $\chi_{cov}^2 > 2$.

Then our benchmark models resumes to:

- The 1-D model for the galaxy with the half thickness of the magnetic halo $L = 10$ kpc, and the half height of the galactic disk $h = 100$ pc;
- Destruction cross-sections from Tripathi 99 (81);
- Production cross-sections from GALPROP tables (84);
- **9 free** parameters for *BIG* model: δ_l , R_l , V_a , V_c , K_{10} , δ , R_h , δ_h , s_h ;
- **7 free** parameters for *SLIM* model: δ_l , R_l , K_{10} , δ , R_h , δ_h , s_h ;
- **7 free** parameters for *QUAINT* model: V_a , V_c , K_{10} , δ , R_h , δ_h , s_h .
- AMS-02 B/C ratio and the covariance matrix as inputs.

The results are shown in table 2. The fit is performed over the data rigidity range 2 - 3000 GV, with 67 data points. The errors on the parameters are shown to their full extent provided after the minimisation.

Table 2 – Benchmark results (post-fit) for *BIG*, *SLIM* and *QUAINT* models.

Parameters / Models	<i>BIG</i>	<i>SLIM</i>	<i>QUAINT</i>
δ_l [-]	-1.01 ± 0.43	-0.95 ± 0.34	NA
R_l [GV]	4.572 ± 0.277	4.463 ± 0.172	NA
s_l [-]	0.05 (fixed)	0.05 (fixed)	0.05 (fixed)
η [-]	1 (fixed)	1 (fixed)	-0.672 ± 0.505
V_a [km/s]	0 ± 38.4	NA	68.54 ± 6.67
V_c [km/s]	2.35 ± 4.29	NA	19.73 ± 2.41
K_{10} [kpc ² /Myr]	0.2266 ± 0.0553	0.25401 ± 0.00883	0.0917 ± 0.0116
δ [-]	0.5 ± 0.1	0.5395 ± 0.0231	0.899 ± 0.151
R_h [GV]	157.3 ± 85.6	175 ± 138	118 ± 41
$\Delta_h \equiv \delta - \delta_h$ [-]	0.3 ± 0.239	0.263 ± 0.146	0.565 ± 0.147
s_h [-]	0.111 ± 0.206	0.08 ± 0.13	0.227 ± 0.227
χ^2/DOF	57.8/58 = 0.99	58.1/60 = 0.96	60.1/59 = 1.01

Source: By the author

The resulting curves after the minimisation are shown in figure 22. It is clear by visual inspection that all three models can describe both low and high rigidity features of the spectrum within at least 1σ , which again is confirmed precisely by the values of χ^2/DOF on table 2. Although it is not possible to differentiate statistically between models - all χ^2/DOF are similar, close to 1 -, some remarks can be done by looking at the three rigidity regimes. All three models are compatible in the high-rigidity region, when diffusion is expected to be the dominant process, although *QUAINT* showed a more pronounced high rigidity break ($\Delta_h \sim 0.5$) than the other models. In fact, for all three rigidity regimes, *BIG* and *SLIM* models presents very similar behaviour, with consistent parameters values within errors. Low values of velocities V_a and V_c in *BIG* model hints that the low-rigidity break on the diffusion coefficient may be sufficient to describe the low-rigidity feature of the spectrum. Therefore, both low and high rigidity spectral changes may be caused rather by diffusion effects than convection or reacceleration. The *QUAINT* model deviates from other models, specially in the intermediate regime, where the parameter $\delta \sim 0.9$ does not point to any of the existing predictions ($1/3$ for Kolmogorov or $1/2$ for Iroshnikov-Kraichnan turbulence model respectively), whereas *BIG* and *SLIM* models are consistently compatible with ~ 0.5 . Lastly, a next step of this analysis would be the use of other secondary-to-primary ratios with their respective covariance matrices in order to constrain even more the propagation of CRs in the galaxy, and following, for instance, by calculating the fluxes of other species and comparing them to the data.

Figure 22 – Best fit B/C curves for *BIG*, *SLIM* and *QUAINT* together with AMS-02 data from (5). The best fit parameters are given in table 2.

Source: By the author

5 THE SPECTRAL INDEX OF THE GALACTIC COSMIC-RAY FLUX

There is a common misconception about the fact that high-energy B/C data directly provides the slope of the diffusion coefficient, implying that additional effects at play (convection, acceleration, and destruction) can be neglected. In this section we will show the results obtained using the *USINE* code, taking into account all the relevant processes that are at play during the CR transport in the galaxy. In particular, we computed the variation of the B/C spectral index with respect to the diffusion coefficient spectral index, for different transport models, and we compared it to the AMS-02 data. Furthermore, we have studied the behavior of the flux spectral index for different CR species, from H to Fe.

5.1 B/C spectral index: data versus diffusion coefficient

5.1.1 Pure diffusion model

A diffusion-dominated propagation is expected to happen for rigidity above ~ 5 GV, as it can be deduced from figure 21. *USINE* allows to study different propagation processes individually: in this way we are able to compute the CR fluxes, and the flux ratios, by solving a propagation equation in which diffusion is the only considered process, alongside with a primary injection from SNRs.

Figure 23 shows the C flux for purely diffusive propagation model ($\sigma_{b \rightarrow a} = 0$) in black at the top panel, for a source spectral index $\alpha = 2.23$, and using the BIG benchmark results, for the propagation parameters (table 2). Since every species of CR is expected to have some secondary contribution in its spectrum, the red curve in the top panel shows the C flux considering diffusion plus secondary production ($\sigma_{b \rightarrow a} > 0$). We can define the flux slope $\gamma_{observed}$ as:

$$\gamma_{observed} = d [\log \Phi] / d [\log R], \quad (5.1)$$

where Φ can represent any CR flux or flux ratio.

In a simplified purely diffusive propagation model, the primary flux slope $\gamma_{expected}^P$ is expected to be equal to:

$$\gamma_{expected}^P = -\alpha - \delta. \quad (5.2)$$

Therefore, we can define the quantity Δ_{slope} as:

$$\Delta_{slope} = \gamma_{observed} - \gamma_{expected}^P, \quad (5.3)$$

Figure 23 – *Top plot:* The C flux rescaled by $R^{2.8}$, as a function of rigidity for the diffusion-only scenario. *Bottom plot:* Δ_{slope} as a function of rigidity for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.

Source: By the author

in such manner that $\Delta_{\text{slope}} = 0$ below the break in the diffusion coefficient, and $\Delta_{\text{slope}} = \Delta_h$ above the break. Δ_{slope} is calculated for each point of the C flux and it is displayed in the bottom panel of figure 23. Focusing on the black curve, it is easy to check that Δ_{slope} matches our predictions: $\Delta_{\text{slope}} = 0$ below the break, and $\Delta_{\text{slope}} = \Delta_h$ above the break. As soon as additional processes are included, like the production of secondary species (necessary to produce the B, and consequently to have a B/C ratio), the flux slope deviates from the expected behavior. The impact of secondary production suggests that the understanding of the B/C spectral index is not straightforward. In order to investigate the difference between the B/C slope and the diffusion coefficient slope, we expand the definition of γ_{expected} to secondary species and ratios, with the help of equations 3.26, 3.27, and 3.28 such that:

$$\gamma_{\text{expected}} = \begin{cases} -\alpha - \delta, & \text{if primaries,} \\ -\alpha - 2\delta, & \text{if secondaries,} \\ -\delta, & \text{if ratios.} \end{cases} \quad (5.4)$$

in a way that, for purely-diffusive propagation, $\Delta_{slope} = 0$ below the break, whereas above the break, $\Delta_{slope} = \Delta_h$ for primaries and ratios, and $\Delta_{slope} = 2\Delta_h$ for secondaries.

Figure 24 – *Top plot*: The B flux rescaled by $R^{2.8}$, as a function of rigidity for the diffusion-only scenario. *Bottom plot*: Δ_{slope} as a function of rigidity for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.

Source: By the author

Using the same approach, the results for B and the B/C are shown in figures 24 and 25, respectively. To summarize the results of this first study, we have shown that a purely-diffusive regime is achieved for rigidities higher than the value of the break in the diffusion coefficient. This implies that the B/C spectral index $\gamma_{observed}$ should not be interpreted as the spectral index of the diffusion coefficient δ , already in the diffusion-only scenario.

5.1.2 Additional propagation phenomena

Since every production of a species means the complete fragmentation of its progenitor, a full observation of the impact of nuclei interactions with the background matter in the galaxy must include the so-called “destruction term” in equation 4.6 ($\sigma_a v_a n > 0$). Focusing now only on the B/C ratio, figure 26 shows the calculation of the B/C flux for several values of the spectral index variation Δ_h . It is expected that, as the value of Δ_h increases, the diffusion starts to dominate sooner. The results show

Figure 25 – *Top plot:* B/C ratio as a function of rigidity, for the diffusion-only scenario. *Bottom plot:* Δ_{slope} as a function of rigidity, for the diffusion-only scenario. The black line indicates only diffusion, while the red line indicates a diffusion plus secondary production scenario. The vertical dashed line indicates the position of the high-rigidity break, which in this case is set to 300 GV.

Source: By the author

for rigidities below the break, inelastic collisions have a strong impact. Nonetheless, the high-rigidity break in the diffusion coefficient shapes Δ_{slope} in the region above the break (i.e. 200 GV). However, since Δ_{slope} is not equal to Δ_h , for any of the Δ_h values, it is fair to say that the purely diffusive regime is never achieved, even for rigidities up to 10^6 GV. Therefore, the spectral index of the B/C ratio have an impact from nuclei destruction over, at least, the whole data range.

Furthermore, additional effects such as reacceleration and convection are included. Figure 27 shows different propagation scenarios, in which these processes are included one by one, on top of diffusion and secondary production. As expected, convection and reacceleration have little impact on rigidities above the break, compared to destruction of nuclei. In the other hand, in the crucial region to probe the assumed equality $\gamma_{observed} = \delta$, the intermediate rigidity regime, these effects have a sizeable impact, especially reacceleration.

Finally, we now focus on the full propagation models: *BIG*, *SLIM* and *QUAINT*. Figure 28 shows the results obtained with these models, where all transport processes are taken into account. Δ_{slope} is neither close to 0 below the break, nor to Δ_h above the break. We can thus conclude that the spectral index $\gamma_{observed}$ does not reflect the diffusion

Figure 26 – *Top plot:* The B/C ratio as a function of rigidity, for several values of Δ_h , in a diffusion plus production and destruction scenario. *Bottom plot:* Δ_{slope} as a function of rigidity, for the same models displayed in the top plot. The vertical dashed line indicates the position of the high-rigidity break at 300 GV.

Source: By the author

coefficient spectral index δ , and the two quantities are not interchangeable, as discussed in the literature (5, 102).

Figure 27 – *Top plot:* The B/C ratio as a function of rigidity. The red line is for diffusion and production. The other curves are for diffusion and production plus some other effect: the purple line is for destruction; the cyan line is for the upper limit case for the reacceleration of BIG; and the green line is for convection. *Bottom plot:* Δ_{slope} as a function of rigidity, for the same models displayed in the top plot. The vertical dashed line indicates the position of the break.

Source: By the author

Figure 28 – The B/C ratio and Δ_{slope} , as a function of rigidity, for BIG, SLIM and *QUAIN* benchmark results. The vertical dashed line indicates the approximate position of the high-rigidity break, which in this case is set to 200 GV.

Source: By the author

5.2 Flux slope behavior for different species

We now extend our analysis to all CR nuclei species, from H to Fe. The inelastic cross-sections of heavier species are larger than those for lighter ones (86), therefore, the fluxes of heavier species are expected to be more impacted. This should reflect in the data, where a softening of the spectrum is expected with an increasing Z . Furthermore, we also account for other propagation effects in the CR flux.

5.2.1 Pure diffusion model

We approach the analysis starting again with a purely diffusive scenario with secondary production, in the frame of the *BIG* propagation model (see table 2). Figure 29 shows $\gamma_{observed}$ as a function of the atomic number Z , computed with *USINE* at 50 GV. For comparison, the expectations for the spectral indices of primaries and secondaries are plotted, as the green and orange dashed lines, respectively. The observed behaviour is due to the fact that only H, O and Fe are close to be fully primary species, while all other species including He, C and Si, have a non negligible secondary component, coming from inelastic interactions of heavier species. Secondary components are expected to be softer than primaries, such that the spectral indices of all species are shaped by these phenomena. Moreover, the secondary production can take place in one or multiple steps (86), shaping the spectral index even strongly. The higher the fractional contribution of multi-step secondary production, the higher the deviation with respect to the expected behavior.

Figure 30 shows the relative contributions per production process for elemental fluxes (from H to Fe) at 50 and 2000 GV. The species with the highest primary content are H, O, Si, and Fe (black), while Li, Be, B, F, and Cl to V have the highest secondary component from both single (red) and multi-step production (blue and green).

Figure 29 – Behavior of the observed flux slope, computed at 50 GV, as a function of the atomic number Z , in the frame of the simplified pure diffusion model. The green dashed line indicates the expected behavior for primary species, while the brown dotted line indicates the expected behavior for secondary species.

Source: By the author

Figure 30 – Relative contributions per production process for elemental fluxes (isotopes not shown) at 50 and 2000 GV (isotopes not shown): primary (black), secondary (1, 2, and > 2 steps in red, blue, and green), radioactive (orange).

Source: By the author

5.2.2 Full propagation modeling

When all transport effects are accounted for, we find that inelastic collisions play the most relevant effect, further reducing the differences in the CR fluxes slopes. Figure 31 shows a significant change in spectral index once CR destruction is no longer neglected, for both 50 and 2000 GV. Nuclei destruction has the most impact on the spectral index, rather than other phenomena such as convection and reacceleration. This is shown in figure 32, where the blue curve is exactly the same as the red curve in figure 31. Also, if we are to compare γ_{observed} of H and Fe between the full modeling and the diffusion-only case, there is a clear softening of Fe whereas a minimal change occur for H. Another feature is the data spectral indices, for He, C, O, Li, Be, and B by the AMS-02 experiment (5). Their method is different from ours since the spectral index is calculated from a given rigidity interval, whereas we calculate it locally at 50 GV. Still, our results do not differ much from the measured results. This indicates that, with further data on heavier species, our propagation models can have further constraints and the CR transport puzzle will become closer to the resolution.

Figure 31 – Behavior of the observed flux slope, computed at 50 GV, as a function of the atomic number Z , in the frame of the simplified pure diffusion model in black, and with destruction of nuclei in red. We also show for both scenarios, the observed flux slope computed at 2000 GV, as a function of the atomic number, with dashed lines.

Source: By the author

Figure 32 – Behavior of the observed CR flux slope, computed at 50 GV, as a function of the atomic number Z , in the frame of the *BIG* model, in comparison with the simplified pure diffusion model, in black. The purple dots show the AMS-02 results.

Source: By the author

6 CONCLUSIONS

The unprecedented percent level precision measurement of the current generation space-based experiments, and in particular of the AMS-02 detector, revealed unexpected features in galactic CR fluxes. A spectral index transition is observed in the fluxes of both primary and secondary CR species above 200 GeV. Strong evidence points towards a diffusive origin for this feature.

In this work we used the B/C data from the AMS-02 experiment to study the CR transport in the galaxy, and to establish new benchmark scenarios for propagation. We included all the relevant physical phenomena, including diffusion, reacceleration, convection and inelastic collisions, and we used an updated parametrization of the diffusion coefficient, that accounts for the spectral features observed in the data. We computed the CR fluxes and flux ratios and compared to the AMS-02 data, via the use of the χ^2 method, with the *USINE* propagation code. We identified three benchmark propagation models, called *BIG*, *SLIM* and *QUAINT* models, which provide excellent fits to the AMS-02 data, with a $\chi^2/DOF \sim 1$ for all models. After we determined the best propagation parameters for each model, we focused on the most general one, the *BIG* model, to study the spectral index of the B/C ratio, often interpreted as the diffusion coefficient spectral index. This would be a reasonable statement if diffusion was the only process at play for these energies. However, since we cannot decouple the CR flux from secondary production, we found out that, even in a simplified scenario, where only diffusion and secondary production are taken into account, the B/C spectral index is not the same as the diffusion coefficient spectral index δ . This becomes even more clear as more effects are accounted in the CR propagation, specially the destruction of nuclei following inelastic collisions in the interstellar medium. We extend our study to all CR species, from H to Fe.

In this work we have achieved two main results. First, we have derived new benchmark scenarios for the propagation of galactic CRs. Second, we have studied the CR diffusion coefficient, and we have compared it to the B/C data slope, showing that they are not interchangeable quantities. Our results are included in a paper that was recently published in the high impact journal *Physical Review D* (45), and they will be presented at the upcoming International Cosmic Ray Conference, that will be held at the end of July 2019 in Madison, Wisconsin, USA. Another finding of our study is the determination of the diffusion coefficient spectral index δ for the *BIG*, *SLIM* and *QUAINT* models. We found $\delta \sim [0.5, 0.54, 0.89]$ for *BIG*, *SLIM* and *QUAINT*, respectively. The values of δ found for *BIG* and *SLIM* point to a Iroshnikov-Kraichnan turbulence in the magnetic fields of the galaxy. However, the space dependence of the diffusion process cannot be investigated by means of a semi-analytic approach, in which strong assumptions on the

geometry of the galaxy are made. For this reason, further study is needed. A natural extension of this analysis is to use more data on secondary-to-primary ratios, alongside their covariance matrices in order to achieve better precision on the determination of propagation parameters.

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