

## TeV cosmic-ray proton and helium spectra in the myriad model

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**Abstract:** Recent measurements of cosmic ray proton and helium spectra show a hardening above a few hundred GeV. This excess is hard to understand in the framework of the conventional models of Galactic cosmic ray production and propagation. We propose to explain this anomaly by the presence of local sources (myriad model). We consistently derive the proton and helium fluxes between 50 GeV and 100 TeV by taking both local and remote sources for which a unique injection rate is assumed into account. We find cosmic ray propagation parameters compatible with B/C measurements for which the proton and helium spectra agree remarkably with the PAMELA and CREAM measurements over four decades in energy.

**Keywords:** icrc2013, cosmic rays, proton, helium, local sources

### 1 Introduction

The  $\sim E^{-2.7}$  energy behavior of primary cosmic rays is fairly well understood if one assumes that these cosmic rays are accelerated by energetic events such as supernova explosion shocks, that are distributed evenly in the disk of our Galaxy. Once injected inside the Galactic magnetic halo with a rate  $q \propto \mathcal{R}^{-\alpha}$  where  $\mathcal{R} \equiv p/Ze$  stands for the rigidity and  $\alpha \simeq 2.15 \pm 0.15$ , particles are subsequently scattered by the turbulent irregularities of the Galactic magnetic field. Their transport is described phenomenologically by space diffusion with a coefficient  $K \propto \mathcal{R}^{\delta}$  whose energy dependence is characterized by the index  $\delta$ . The boron-to-carbon ratio (B/C) is a tracer of cosmic ray (CR) propagation that points towards a value of  $\delta \in [0.4, 0.85]$  for the diffusion index (see [1]). At high energy, the flux of a given primary CR species above the Earth is given by  $\Phi \propto q/K$  and decreases with energy as  $1/E^{\alpha+\delta}$ . Its spectrum exhibits power-law behavior whose index is the sum of  $\alpha$  and  $\delta$ .

However, this is challenged by the recent measurements of the absolute high-energy CR proton and helium spectra that have been recently reported by CREAM [2, 3] and PAMELA [4] experiments. Explanations of this anomaly have been tentatively given ever since its discovery (see [5] and references therein).

This paper computes the proton and helium spectra within the usual framework of diffusive propagation, and we use the propagation parameters consistent with B/C spectra, while taking the known local sources of cosmic rays into account. We build a catalog of nearby and recent sources (see [5]) from the Green catalog [6] and the ATNF pulsar database [7]. We explore all the propagation parameters consistent with the observed B/C ratio at low energy.

Our goal is to investigate whether one can set new constraints on these parameters when using the proton and helium spectra observed by PAMELA and CREAM. We show that the proton and helium spectral hardening above 250 GeV/nuc can indeed be attributed to the known local sources of cosmic rays. In our approach, there is no

need to modify the conventional CR propagation model. In particular, the variations with CR energy in the injection rate  $q$  of individual sources and of the space diffusion coefficient  $K$  are power laws that are characterized by the spectral indices  $\alpha$  and  $\delta$  respectively. This idea has already been suggested recently by [10], who explain the hardening with very few sources (mainly Monogem Ring), and by [11] who consider a catalog of ten nearby sources. The principal weakness of these analyses is the lack of a consistent treatment of the CR spectra in the entire energy range extending from tens of GeV up to a few PeV. This is particularly clear in [11] where the proton and helium anomaly is derived from a handful of local sources, whereas the low-energy spectra of these species are not calculated but merely fitted in order to get a value for  $\alpha$  once  $\delta$  has been chosen. It should be noted that the magnitude of the CR proton (helium) flux is related over the entire energy range to the injection rate  $q$  of individual sources. The low-energy (power-law regime) and high-energy (spectral hardening) parts of the CR spectra are connected to each other. A consistent treatment of the problem requires that the proton and helium fluxes are calculated over the entire energy range. A crucial problem is also to understand why just a few local sources could explain the spectral hardening at high energies, whereas the bulk of the Galactic sources is required in order to account for the power-law behavior of the fluxes below 250 GeV/nuc. This aspect, which is not addressed in the above-mentioned analyses, bears upon the more general question of the discrete nature of the sources. In the conventional model of CR propagation, these are treated as a jelly spreading over the Galactic disk and continuously accelerating cosmic rays. The question arises then as to why and in which conditions that scheme breaks down at high energies where local and discrete objects come into play.

The results presented here are based on a detailed investigation of that question. [9] have recently shown how to reconcile the presence of discrete sources with the conven-

tional description of CR production and propagation, in a more theoretical analysis. We briefly recall the salient features of their analysis, before extending it to the general study, leaning on the use of the catalog that can be found in [5].

## 2 The proton and helium anomaly in light of local sources.

### 2.1 Cosmic ray propagation with discrete sources.

Once accelerated by the sources that lie within the Galactic disk, CR nuclei diffuse, due to scattering on the irregularities of the Galactic magnetic field. The diffusion coefficient  $K = K_0 \beta \mathcal{R}^\delta$  accounts for that process, where  $K_0$  is a normalization constant and  $\beta$  denotes the particle velocity. The magnetic halo (MH) inside which cosmic rays propagate before escaping into intergalactic space is assumed to be a flat cylindrical domain that matches the circular structure of the Milky Way. The Galactic disk is sandwiched between two confinement layers whose thickness  $L$  is unknown. Stellar winds combine to generate a Galactic convection that wipes cosmic rays away from the disk, with velocity  $V_c(z) = V_c \text{sign}(z)$ . The CR nuclei also undergo collisions with the interstellar medium (ISM). Above a few GeV, diffusive re-acceleration and energy losses may be disregarded.

The CR transport parameters  $K_0$ ,  $\delta$ ,  $L$  and  $V_c$  can be constrained from the B/C ratio – see for instance [1], [14] and [15]. The CR proton density at the Earth may be computed once the CR proton injection term  $q_{\text{acc}}(\mathbf{x}_S, t_S)$  at the source located at  $\mathbf{x}_S$  and at time  $t_S$  is known. In the conventional approach, the CR source term  $q_{\text{acc}}$  is a continuous function of space and time. Steady state is moreover assumed. This is an oversimplification insofar as CR sources are actually discrete, with an average supernova explosion rate  $\nu$  of 0.8 to 3 events per century [18].

In the stochastic treatment developed by [9], sources are modeled as point-like objects, and the production rate of CR nuclei through acceleration is given by

$$q_{\text{acc}}(\mathbf{x}_S, t_S) = \sum_{i \in \mathcal{P}} q_i \delta^3(\mathbf{x}_S - \mathbf{x}_i) \delta(t_S - t_i), \quad (1)$$

where each source  $i$  that belongs to the population  $\mathcal{P}$  contributes a factor  $q_i$  at position  $\mathbf{x}_i$  and time  $t_i$ . The total flux  $\Phi \equiv (1/4\pi)\beta\psi$  at the Earth depends on the precise locations and ages of all the sources and varies from one particular population  $\mathcal{P}$  to another. Because we do not know the actual distribution of the Galactic sources that have generated the observed CR flux, we must rely on a statistical analysis and consider the position and age of each source as random variables. The CR flux  $\Phi(E)$  at a given energy  $E$  behaves as a stochastic variable whose probability distribution function  $p(\Phi)$  has been studied in [9]. The conventional CR model is recovered by taking the statistical average of the flux over the ensemble of all possible populations  $\mathcal{P}$ . This average flux  $\bar{\Phi}$  turns out to be the solution of the diffusion equation with a continuous source term  $q_{\text{acc}}$ . More exciting is the spread of the flux  $\Phi$  around its average value  $\bar{\Phi}$ . Using a Monte Carlo approach, [9] have shown that if the magnetic halo is thin, the statistical fluctuations of the flux may be significant. The residence time  $\tau_{\text{dif}} \sim L^2/K$  of CR nuclei within the magnetic halo decreases with its thickness  $L$ . The number

$N$  of sources that contribute to the signal above the Earth scales as  $\nu \tau_{\text{dif}}$ . The smaller  $L$ , the smaller  $N$  and the larger the flux variance. Should the magnetic halo be thin enough, we expect fluctuations in the flux, especially at high energies where  $K$  becomes large. In this case, the hardening of the proton and helium spectra appears to be a mere fluctuation of the CR flux, and its probability to occur is not vanishingly small.

According to this line of reasoning, the proton and helium anomaly results from the particular configuration of the actual CR sources. These objects are incidentally known in the nearby region for which catalogs of SNR and pulsars are available. The domain extending 2 kpc around the Earth and encompassing objects that have exploded less than 30,000 years ago is defined as the local region. The catalogs are no longer complete outside these limits and fail to be reliable. In the conventional CR model, the local sources would yield an average contribution  $\bar{\Phi}_{\text{loc}}$  whereas the actual objects yield a much larger flux  $\Phi_{\text{cat}}$ . Denoting the flux from the other sources by  $\Phi_{\text{ext}}$ , we infer a total signal above the Earth

$$\Phi = \Phi_{\text{cat}} + \Phi_{\text{ext}}, \quad (2)$$

to be compared to the prediction of the conventional steady-state model

$$\bar{\Phi} = \bar{\Phi}_{\text{loc}} + \bar{\Phi}_{\text{ext}}. \quad (3)$$

The flux produced by the external sources has a very small variance as shown in [9]. We may then identify  $\Phi_{\text{ext}}$  with its statistical average  $\bar{\Phi}_{\text{ext}}$ .

### 2.2 Scan of the parameter space

The CR propagation parameters giving a good agreement with the secondary-to-primary B/C measurements have been determined by [1] using the same propagation model as the one described above. For each of these 1,600 different sets of parameters, CR propagation is specified by  $K_0$ ,  $\delta$ ,  $V_c$  and  $L$ . The injection rate of CR species  $j$  is assumed to generically be of the form

$$q_j(p) = q_j^0 \left( @ < \frac{p}{1 \text{ GeV/nuc}} \right)^{-\alpha_j}, \quad (4)$$

and to be the same for all CR sources. They are specified by the parameters  $q_p^0$ ,  $q_{\text{He}}^0$ ,  $\alpha_p$ , and  $\alpha_{\text{He}}$ . The final ingredient is the average supernova explosion rate  $\nu$ . We used these parameters to compute the proton and helium fluxes  $\bar{\Phi}_{\text{ext}} + \Phi_{\text{cat}}$  over an energy range extending from 50 GeV/nuc to 100 TeV/nuc, in order to compare them with the PAMELA [4] and CREAM [2] data. At high energy, solar modulation has little effect on the CR flux, and it has not been taken into account in this study. The quality of the fit to the data is gauged by the proton and helium chi-squares  $\chi_p^2$  and  $\chi_{\text{He}}^2$ . Our calculation of the local contribution  $\Phi_{\text{cat}}$  to the flux is based on the Green catalog [6] and on the ATNF pulsar database [7].

We performed a scan over the CR propagation parameters derived by [1]. For a given set of these CR parameters, we adjusted the source parameters  $q_p^0$ ,  $q_{\text{He}}^0$ ,  $\alpha_p$ ,  $\alpha_{\text{He}}$ , and  $\nu$  to get the lowest value for the total chi-square  $\chi_p^2 + \chi_{\text{He}}^2$ . We first set the injection indices  $\alpha_p$  and  $\alpha_{\text{He}}$ , as well as the explosion rate  $\nu$ , and determined the best-fit values for the injection normalizations  $q_p^0$  and  $q_{\text{He}}^0$ . We then varied  $\nu$  from 0.5 to 3.5 century<sup>-1</sup> and the injection indices  $\alpha_p$  and  $\alpha_{\text{He}}$  from 1.75 to 2.35 to get the best adjustment of the

model	$K_0$ [kpc <sup>2</sup> /yr]	$\delta$	$L$ [kpc]	$V_c$ [kpc/yr]	$q_p^0$ [GeV <sup>-1</sup> ]	$q_{He}^0$ [(GeV/n) <sup>-1</sup> ]
A	$2.4 \times 10^{-9}$	0.85	1.5	$1.38 \times 10^{-8}$	$1.17 \times 10^{52}$	$3.22 \times 10^{51}$
B	$2.4 \times 10^{-9}$	0.85	1.5	$1.38 \times 10^{-8}$	$0.53 \times 10^{52}$	$1.06 \times 10^{51}$
MED	$1.12 \times 10^{-9}$	0.7	4	$1.23 \times 10^{-8}$	$15.8 \times 10^{51}$	$3.14 \times 10^{51}$
model	$\alpha_p + \delta$	$\alpha_{He} + \delta$	$v$ [century <sup>-1</sup> ]	H injection	He injection	$\chi^2/\text{dof}$
A	2.9	2.8	0.8	0.19	0.05	0.61
B	2.85	2.7	1.4	0.12	0.07	1.09
MED	2.85	2.7	0.8	0.148	0.07	1.3

**Table 1:** Sets of CR injection and propagation parameters discussed in the text. The diffusion coefficient normalization  $K_0$  and spectral index  $\delta$ , halo half height  $L$ , and convective velocity  $V_c$  describe the diffusion model. The source terms  $q_p^0$  and  $q_{He}^0$  and spectral source indices  $\alpha_p$  and  $\alpha_{He}$  describe the individual sources. The “injection” terms give the fraction of the supernova energy that is injected into cosmic ray acceleration, between 1 GeV and  $10^6$  GeV.

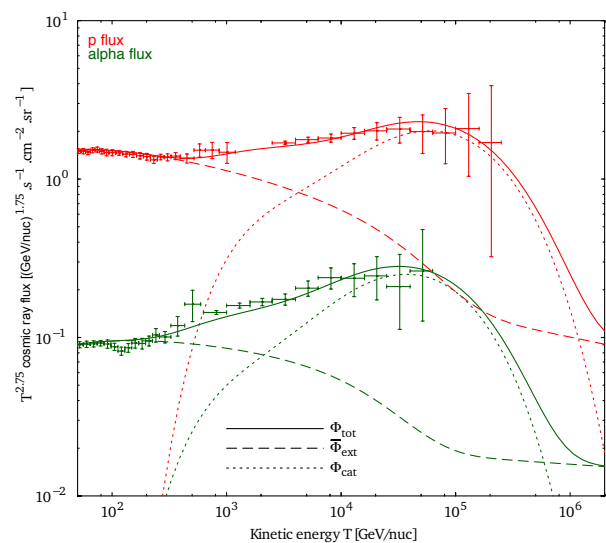
source parameters to the CREAM and PAMELA data. The injection indices  $\alpha_p$  and  $\alpha_{He}$  are determined independently of each other. Observations point towards slightly different power laws for the proton and helium fluxes at energies below 250 GeV/nuc.

### 2.3 Grammages

The propagation parameters described above were chosen to give the right B/C at relatively low energy (below  $\sim 10$  GeV), in a diffusion model where the sources were assumed to be continuously distributed in the Galactic disk. This does not contradict the central hypothesis of our analysis: discrete sources. Indeed, [8] showed that the path-length distribution for discrete sources is very close to the distribution obtained for continuous sources. Moreover, at a few GeV, the distance  $r \sim \sqrt{Kt}$  over which diffusion is effective for  $t \lesssim 30,000$  yr is a few parsecs, which is much smaller than 2 kpc. This means that most sources that contribute to the B/C at these energies are not in the region we defined as “local”, or stated otherwise, the contribution of the discrete sources of our catalog to the observed B/C is negligible at a few GeV and below.

### 2.4 Results

The range of spectra obtained by the scan described above is very large, with some of them much higher and others much lower than the measured spectra, for protons and helium. However, we find that some of the parameter sets compatible with B/C give a good agreement with measurements. Model A yields the best  $\chi^2$ , and the resulting spectra are shown in Fig. 1, with the corresponding parameters are reproduced in Table 1. The CR parameters of model B are the same as for model A. The average supernova rate has been fixed to a value of 1.4 per century. The resulting spectra are shown in Fig. 2. Model C corresponds to the MED configuration and best fits the B/C. The half thickness  $L$  of the magnetic halo is 4 kpc. The resulting spectra are shown in Fig. 3. The agreement with the CREAM and PAMELA proton and helium excess is still reasonable. These sets of CR injection and propagation parameters featured in this table have been shown in [1] to be compatible with the B/C, and they provide reasonable to very good fits to the PAMELA and CREAM data from 50 GeV/nuc to 100 TeV/nuc. The proton and helium fluxes are simultaneously adjusted with the same values of  $K_0$ ,  $\delta$ ,  $L$ , and  $V_c$ . The injection indices  $\alpha_p$  and  $\alpha_{He}$  are determined independently. The average supernova explosion rate per century is denoted by  $v$ . The re-



**Figure 1:** Proton (upper curve) and helium (lower curve) spectra in the range extending from 50 GeV/nuc to 100 TeV/nuc, for the propagation parameters of model A (see Table 1), giving the best fit to the PAMELA [4] and CREAM [2] data : supernovae explosion rate  $v = 0.8$  century<sup>-1</sup>. Solid lines show the total flux, short-dashed lines show the flux due to the sources of the catalog, and the long-dashed curve the flux due to the rest of the sources.

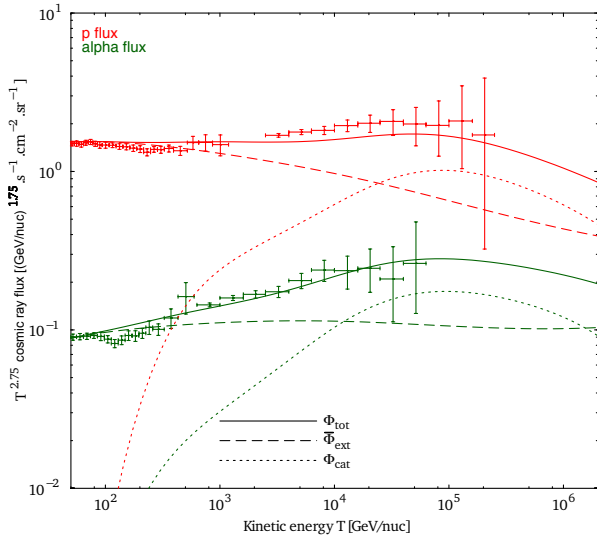
sults of the fits to the proton and helium spectra are gauged by the total reduced chi-square  $\chi_{\text{red}}^2$  (see Table 1).

## 3 Discussion of the results.

This excellent agreement makes us confident that the proton and helium anomaly can actually be explained by existing local sources that have been extracted from SNR and pulsar surveys. The model that we have presented here is quite simple, but refining it is beyond the scope of this paper. Some directions can nevertheless be given for improving the solution we just sketched.

As a start, the best fits are obtained for a rather low value of the magnetic halo thickness  $L$ . This trend can be understood as follows. As already explained, the thinner the magnetic halo, the smaller the number  $N$  of sources that contribute to the total signal and the greater the injection





**Figure 2:** Same as before, for the MED propagation parameters (see Table 1).

rate  $q$  of individual sources. The contributions  $\Phi_{\text{cat}}$  and  $\bar{\Phi}_{\text{loc}}$  from the local region are no longer swamped in the total flux when  $L$  is low. This may be a problem since recent studies [16, 17] of the gamma-ray and synchrotron diffuse emissions seem to favor rather high values of  $L$ . A possible improvement of our model would be to distribute the CR sources within spiral arms and to take into account the rotation of the Galaxy. The sources that we have considered here to derive the contribution  $\bar{\Phi}_{\text{ext}}$  to the flux are equally spread along the azimuthal direction. It would be interesting to investigate whether  $\bar{\Phi}_{\text{ext}}$  decreases in a more realistic setup.

To get a significant injection rate  $q$ , we are naturally driven towards a low supernova explosion rate  $\nu$ . The values found for models A and B are close to 1 explosion per century, at the lower edge of the plausible range, although not exclusively [18].

The local sources that we have extracted from the catalogs correspond to a higher rate  $\nu$  of 3.3 events per century. Because the Sun lies near two Galactic arms, the average explosion rate in our neighborhood could reasonably be higher than the mean rate of the Galaxy. This is actually supported by our catalog. As shown in Fig. 7 of [9], the number of known sources in our vicinity is compatible with a value of  $\nu$  greater than three explosions per century for the past  $3 \times 10^4$  years (depending on the radial distribution of the CR sources along the Galactic disk). Taking the Galactic spiral arms and their rotation into account could lead to a higher value of the average explosion rate and alleviate the apparent discrepancy between the average and local values of  $\nu$ .

Finally, we modeled the supernova explosions as point-like events. Cosmic rays are believed to be accelerated in the shocks that follow these explosions and which propagate in the ISM during  $10^5$  years. The injection sites are more spherical shells than points. Depending on the CR energy, [11] quote escape times between 500 and  $10^5$  years after the stellar explosion. The injection takes place from a remnant whose radius varies from 5 to 100 pc. Taking the actual structure of CR accelerators into account could substantially modify the contribution  $\Phi_{\text{cat}}$  to the total signal, allowing greater values of  $L$  to provide acceptable fits to the

PAMELA and CREAM data. The simplistic solution to the proton and helium anomaly that we have sketched in this paper is definitely promising in spite of the problems we mentioned and it should motivate further investigations.

## 4 Conclusions.

Taking the discreteness of cosmic ray sources in the solar neighborhood into account, we found that the proton and helium spectra computed in a diffusion model agree with the PAMELA and CREAM measurements over four decades in energy, for some cosmic ray propagation parameters that are also compatible with B/C measurements. Even if the excess at high energy happened not to be confirmed by further measurements and analysis, the proton and helium spectra could be used to put severe constraints on the parameters describing the diffusion of cosmic rays in our Galaxy. We expect that the study of the anisotropy induced by the discreteness of the sources will also provide very valuable information on the source distribution, as well as on the propagation parameters.

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