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The TeV-scale cosmic ray proton and helium spectra: Contributions from the local sources

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Abstract. Recent measurements of cosmic ray proton and helium spectra show a hardening above a few hundreds of GeV. This excess is hard to understand in the framework of the conventional models of galactic cosmic ray production and propagation. Here, we propose to explain this anomaly by the presence of local sources. Cosmic ray propagation is described as a diffusion process taking place inside a two-zone magnetic halo. We calculate the proton and helium fluxes at the Earth between 50 GeV and 100 TeV. Improving over a similar analysis, we consistently derive these fluxes by taking into account both local and remote sources for which a unique injection rate is assumed. We find cosmic ray propagation parameters for which the proton and helium spectra remarkably agree with the PAMELA and CREAM measurements over four decades in energy.

Keywords. PAMELA–CREAM anomaly; cosmic ray nuclei (proton–helium) spectrum; diffusion and transport of cosmic ray.

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1. General presentation of CR fluxes

Understanding of the origin and propagation of cosmic rays (CR) in the Galaxy is a long-standing puzzle whose solution indeed needs a combination of several different observations in a wide energy range. The most realistic description of CR propagation is given by diffusion models. Two main approaches have been developed so far: analytical (or semi-analytical) diffusion models and fully numerical diffusion models. Well-known realizations of these two different approaches are respectively the two-zone model with USINE code [1–3] and the GALPROP package [4,5] which has led to the DRAGON code [6,7]. In the conventional scheme, primary cosmic ray nuclei are accelerated by the shocks of supernova explosions of massive stars. They are 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

$\alpha \simeq 2.15 \pm 0.15$. The particles are subsequently scattered by the turbulent irregularities of the Galactic magnetic field. Their transport is described phenomenologically by space diffusion with the coefficient $K \propto \mathcal{R}^{\delta}$, whose energy dependence is characterized by the index δ. The boron-to-carbon (B/C) ratio is a tracer of cosmic ray propagation and points towards a value of $\delta \in [0.4, 0.85]$ for the diffusion index. At high energy, the flux of a given primary CR species on Earth is given by $\Phi \propto q/K$ and falls with energy typically as $1/E^{\alpha+\delta}$. Its spectrum exhibits a power-law behaviour whose index is the sum of α and δ. So far, it has been generally understood that the spectrum of primary cosmic rays approximately behaves as $E^{-2.7}$ until the knee, which is a bend downwards at around 3 PeV. The spectrum beyond the knee falls approximately as $E^{-3.1}$.

2. Observations of the CR proton and helium anomaly

Measurements of the absolute high-energy CR proton and helium spectra have been reported recently by CREAM [8,9] and PAMELA [10] experiments. Observations point towards an excess in the CR proton and helium fluxes above 250 GeV/nuc. The single power-law hypothesis is rejected at 95% CL. The hardening of the proton spectrum occurs at 232^{+35}_{-30} GeV with a change of the spectral index from $2.85 \pm 0.015 \pm 0.004$ to $2.67 \pm 0.03 \pm 0.05$. For the helium data, the spectral index varies from $2.766 \pm 0.01 \pm 0.027$ to $2.477 \pm 0.06 \pm 0.03$ with the hardening setting in at 243^{+27}_{-31} GeV/nuc. These results challenge the conventional scenarios proposed so far to model galactic cosmic rays. They indicate the presence of an anomalous behaviour of the CR proton and helium spectra in the 100 GeV–100 TeV energy range.

3. Explanations so far for the proton and helium anomaly

Explanations of this anomaly have been tentatively given since its discovery. They mainly imply a modification of the energy behaviour of either the injection spectrum $q(E)$ or the diffusion coefficient $K(E)$. A break in α could arise from a modification of the conventional diffusive shock acceleration (DSA) scheme, as suggested by Malkov *et al* [11] and Ohira and Ioka [12]. In the same vein, the possibility of different classes of CR sources has been proposed some time ago by Stanev *et al* [13] and Zatsepin and Sokolskaya [14]. For instance, cosmic rays accelerated in the magnetized winds of exploding Wolf–Rayet and red supergiant stars could have a double spectrum, with a hard component produced in the polar cap regions of these objects. According to Biermann *et al* [15], this hard component would take over the smooth one above a few hundreds of GeV, hence the observed break in the proton and helium spectra. Not so different is the proposition of Yuan *et al* [16] where a spread in the injection index α is introduced. Another direction implies a modification of the diffusion coefficient K. As proposed by Ave *et al* [17], the proton and helium anomaly could be due to a welcome, but unexpected, decrease of the spectral index δ at high energy. Recently, Blasi *et al* [18] have given some theoretical motivations to such changes in diffusion. A local variation of K could also have a similar effect as suggested by Tomassetti [19]. Finally, inspired by Hörandel *et al* [20], Blasi and Amato [21] have invoked an unusually strong spallation of the CR species on the galactic gas. This possibility has been recently criticized in a detailed analysis carried out by Vladimirov *et al* [22] of some of the above-mentioned solutions to the CR proton and helium anomaly.

4. Our explanation of the proton and helium anomaly

In this article, we show that the proton and helium spectral hardening above 250 GeV/nuc can be attributed to local sources of cosmic rays, whose presence is associated with known supernova remnants (SNR) and pulsars. These objects can be found in astronomical catalogs such as the Green catalog [23] which can be completed with the ATNF pulsar database [24,25]. In our approach, there is no need to modify the conventional CR propagation model. In particular, the variations with CR energy of the injection rate q of individual sources and of the space diffusion coefficient K are power laws respectively characterized by the spectral indices α and δ. This idea has already been suggested recently by Erlykin and Wolfendale [26], who explain the hardening with very few sources (mainly Monogem Ring) and by Thoudam and Hörandel [27], who consider a catalog of 10 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 ref. [27], 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 α once δ 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 with 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 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 to account for the power-law behaviour 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 discreet 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 to understand why and in which conditions that scheme breaks down at high energies where local and point-like objects come into play. The results presented here are based on a detailed investigation of that question. Bernard *et al* [28] have recently shown how to reconcile the presence of point-like sources with the conventional description of CR production and propagation. We briefly recall the salient features of their analysis.

5. Our model of CR propagation with discreet sources

Once accelerated by the sources that lie within the galactic disk, CR nuclei diffuse 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 the normalization constant and β denotes the particle velocity. The magnetic halo, inside which cosmic rays propagate before escaping into intergalactic space, is assumed to be a flat cylindrical domain which matches the circular structure of the Milky Way. The galactic disk is sandwiched between two confinement layers whose thickness L is unknown and turns out to be crucial in our investigation. Stellar winds combine to generate a galactic convection that wipes cosmic rays away from the disk, with velocity $V_c(z) = V_c\ \text{sign}(z)$. CR nuclei also undergo collisions with the interstellar medium (ISM) with a rate $\Gamma_{\rm sp} = \sigma_{\rm col}\,\beta\,n_{\rm ISM}$. Above a few GeV, diffusive re-acceleration and energy losses may be disregarded and the master equation for the space and energy number density $\psi \equiv {\rm d}n/{\rm d}T$ of a given CR species simplifies into the diffusion equation

$$\frac{\partial \psi}{\partial t} + \partial_z (V_c \psi) - K(E)\Delta\psi + \Gamma_{\rm sp}\psi = q_{\rm acc}. \qquad (1)$$

The CR transport parameters K_0, δ, L and V_c can be weakly constrained from the B/C ratio (see for instance [1,29,30]). In the conventional approach, the CR source term $q_{\rm acc}$ is a continuous function of space and time. Steady state is assumed. This is an oversimplification insofar as CR sources are actually point-like, with an average supernova explosion rate ν of 1 to 3 events per century. In the stochastic treatment developed by Bernard *et al* [28], the production rate of CR nuclei through acceleration is given by

$$q_{\rm acc}(\mathbf{x}_S, t_S) = \sum_{i\in\mathcal{P}} q_i \delta^3(\mathbf{x}_S - \mathbf{x}_i)\delta(t_S - t_i), \qquad (2)$$

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 $\Phi \equiv (1/4\pi)\beta\psi$ on 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 [28]. 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 eq. (1) with a continuous source term $q_{\rm acc}$. More exciting is the spread of the flux Φ around its average value $\bar{\Phi}$. Using a Monte Carlo approach, Bernard *et al* [28] have shown that if the magnetic halo is thin, the statistical fluctuations of the flux may be significant. The residence time $\tau_{\rm dif} \sim L^2/K$ of the CR nuclei within the magnetic halo decreases with its thickness L. The number N of the sources that contribute to the signal at the Earth scales as $\nu\tau_{\rm dif}$. When L is smaller, N will be smaller and flux variance will be larger. Should the magnetic halo be sufficiently thin, we expect fluctuations of 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 whose 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 and fail to be reliable. In the conventional CR model, the local sources would yield an average contribution $\bar{\Phi}_{\mathrm{loc}}$, whereas the actual objects yield a much larger flux Φ_{cat}. Denoting the flux from other sources by Φ_{ext}, we infer a total signal on the Earth

$$\Phi = \Phi_{\mathrm{cat}} + \Phi_{\mathrm{ext}}, \tag{3}$$

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

$$\bar{\Phi} = \bar{\Phi}_{\mathrm{loc}} + \bar{\Phi}_{\mathrm{ext}}. \tag{4}$$

The flux produced by the external sources has a very small variance as shown in ref. [28]. We may then identify Φ_{ext} with its statistical average $\bar{\Phi}_{\mathrm{ext}}$.

6. Our exploration of the CR parameters and our results

We have performed a scan over the CR parameters in order to fit the PAMELA [10] and CREAM [8] data over an energy range extending from 50 GeV/nuc to 100 TeV/nuc. For each model, CR propagation is described by K_0, δ and L. At high energy, galactic convection and solar modulation have little effect on the CR flux. That is why we have set V_c and the Fisk potential ϕ_{F} equal to 0 during the scan. The injection indices α_{p} and α_{He} are independently adjusted to the proton and helium spectra. Observations point towards slightly different power laws for these fluxes at energies below 250 GeV/nuc. The last injection parameter which we have considered is the average supernova explosion rate ν in the Galaxy. Each CR configuration is then characterized by six parameters. The quality of the fits to the proton and helium data is respectively gauged by the reduced chi-squares

Table 1. The two sets of CR injection and propagation parameters featured in this table provide 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, δ and L. The injection indices α_{p} and α_{He} are determined independently of each other. The average supernova explosion rate is denoted by ν. The results of the fits to the proton and helium spectra are respectively gauged by χ^2_{p} and χ^2_{He}. Model A corresponds to the best fit and is featured in figure 1. The agreement with the observations is remarkable even down to 1 GeV and spans five orders of magnitude. Model B belongs to a set of CR parameters which have been shown in ref. [1] to be compatible with the B/C ratio. Although the total χ^2 is the same as for Model A, the agreement with the data is not as good below 100 GeV.

Model	K_0 $(\mathrm{kpc^2\,Myr^{-1}})$	δ	L (kpc)	V_c (km s^{-1})	α_{p}	α_{He}	ν (century^{-1})	χ^2_{p}	χ^2_{He}
A	1.29×10^{-2}	0.63	1	0	2.23	2.14	1.09	0.33	0.54
B	5.10×10^{-3}	0.75	2	11.5	2.11	2.00	0.80	0.28	0.59

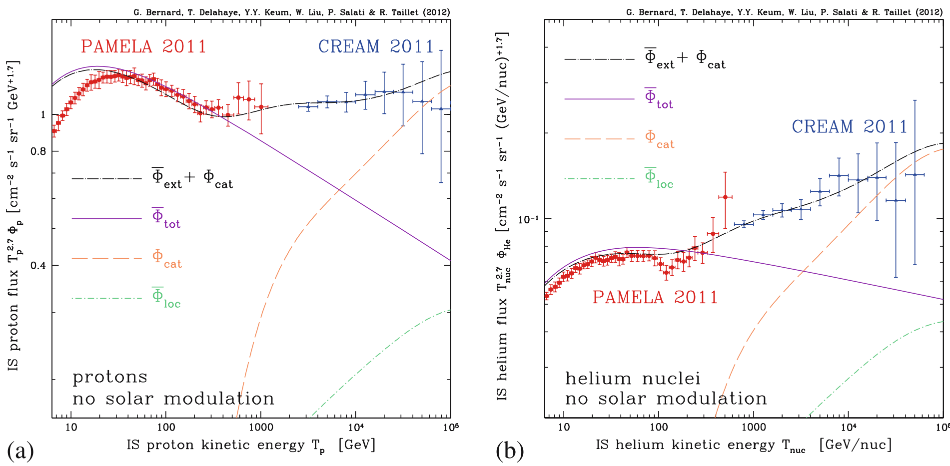

Figure 1. (**a**) Proton and (**b**) helium spectra in the range extending from 5 GeV/nuc to 100 TeV/nuc. The solid purple line indicates $\bar{\Phi}$, the mean flux produced by a continuous distribution of all the galactic sources. It corresponds to the prediction of the conventional steady-state propagation model. The dotted short-dashed green curve indicates $\bar{\Phi}_{loc}$, the mean flux obtained by randomly picking local sources (less than 2 kpc away and younger than 30,000 years). The long-dashed red line indicates Φ_{cat}, produced by the sources of our neighbourhood found in SNR and pulsars catalogs. Twenty objects contribute to the signal displayed here. The dotted long-dashed black curve features the sum of the contributions from the local catalog sources Φ_{cat} and from the continuous distribution of the far away sources $\bar{\Phi}_{ext}$. Solar modulation is switched on with a Fisk potential ϕ_F of 475 MV. Data are from PAMELA [10] and CREAM [8]. The CR propagation parameters used to get this plot correspond to Model A of table 1.

χ_p^2 and χ_{He}^2. We have found many models which reproduce fairly well the power-law regime and the hardening of both the proton and helium fluxes. The two configurations of table 1 adjust the PAMELA and CREAM spectra particularly well.

7. Discussion and conclusion

This excellent agreement makes us confident that the proton and helium anomaly can actually be explained by the existing local sources which have been extracted from SNR and pulsar survey (figures 1 and 2). The model which we have presented here is quite simple. Refining it is beyond the scope of this article. Some directions can nevertheless be given to improve the solution which we have just sketched. To commence, the best fit is obtained for a rather small value of the magnetic halo thickness L. This is not only true for models A and B but is a general trend which is easy to understand. As already explained, the thinner the magnetic halo, the smaller the number N of the sources which contribute to the total signal and larger the injection rate q of individual sources. The contributions Φ_{cat} and

$\bar{\Phi}_{\rm loc}$ from the local region are no longer swamped in the total flux when L is small. This may be a problem as recent studies [31,32] of the γ-ray and synchrotron diffuse emissions seem to favour rather large values of L. A possible improvement of our model would be to distribute the CR sources within the spiral arms and to take into account the rotation of the Galaxy. The sources which we have considered here to derive the contribution $\bar{\Phi}_{\rm ext}$ to the flux are equally spread along the azimuthal direction. It would be interesting to investigate if $\bar{\Phi}_{\rm ext}$ decreases in a more realistic set-up. Notice also that in order to get a significant injection rate q, we are naturally driven towards a small supernova explosion rate ν. The values found for models A and B are close to 1 explosion per century, at the lower edge of the plausible range. The local sources which we have extracted from the catalogs correspond to a larger rate ν of 3.3 events per century. As the Sun lies near two Galactic arms, the average explosion rate in our neighbourhood can reasonably be higher than the mean rate of the Galaxy. This is actually supported by our catalog. The number of known sources (as shown in figure 7 of ref. [28]) in our vicinity is compatible with ν larger than three explosions per century for the past 3×10^4 years (depending on the radial distribution of the CR sources along the galactic disk). Taking into account the galactic spiral arms and their rotation could lead to a larger value of the average explosion rate and alleviate the apparent discrepancy between the average and local values of ν. Finally, we have modelled the supernova explosions as point-like events. Cosmic rays are believed to be accelerated in the shocks which follow these explosions and which propagate in the ISM during 10^5 years. The injection sites are spherical shells rather than

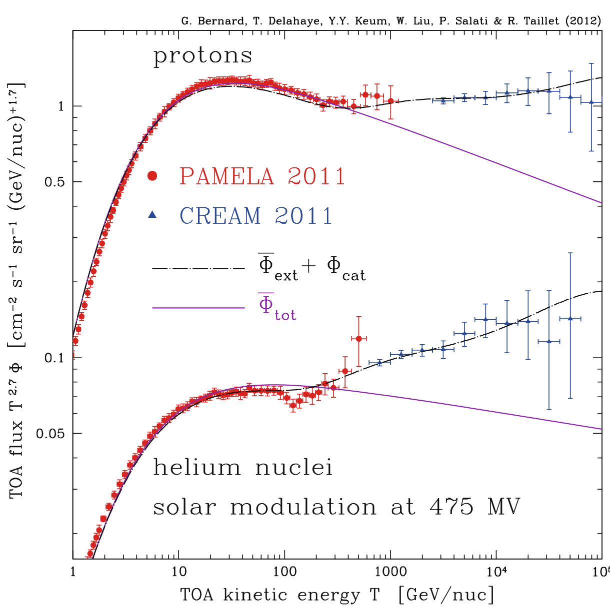

Figure 2. Comparison between proton and helium absolute fluxes from 1 GeV/nuc to 100 TeV/nuc. The fluxes are expressed in terms of kinetic energy per nucleon. Error bars of the CREAM and PAMELA data are statistical. The shaded area represent the estimated systematic uncertainty.

points. Depending on the CR energy, Thoudam and Hörandel [27] 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 into account the actual structure of CR accelerators could substantially modify the contribution Φ_{cat} to the total signal, allowing larger values of L to provide acceptable fits to the PAMELA and CREAM data. The simplistic solution to the proton and helium anomaly which we have sketched in this article is definitely exciting in spite of the above-mentioned problems and should motivate further investigations.

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