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Diffusion coefficient and acceleration spectrum from direct measurements of charged cosmic ray nuclei

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We discuss the potential of different experimental configurations directly measuring charged cosmic ray nuclei at energies $\geq$100 GeV/n. Using a two-zone diffusion model for the propagation of stable cosmic rays, we generate different predictions of the primary and secondary fluxes of light nuclei. It is shown that the new detectors exploiting the long and ultra long duration balloon technology can determine the diffusion coefficient slope δ through the measurement of the B/C ratio, with an uncertainty of about 10-15% if systematic errors are low enough. Only satellite based detectors are able to reach very high accuracy even in case of more important systematics. Furthermore, we show that no uncertainties other than those on δ affect the determination of the acceleration slope α, which can be studied by these apparatus through the measurement of light nuclei fluxes, thus providing valuable information on the acceleration mechanisms.

1. Introduction

Galactic cosmic ray particles are most probably accelerated by supernova remnants; their diffusion in the Galaxy is driven by the turbulent galactic magnetic field. While the low energy tail of the cosmic ray particles undergo solar modulation, and mechanisms like electromagnetic energy losses, convection and reacceleration play a major role in shaping their spectra, at higher energy they are mostly depending on acceleration and diffusion, the other effects becoming negligible.

The most realistic description of CR propagation is given by diffusion models, in which the several free parameters inherent to a specific model need to be fixed by observations. A wealth of experimental measurements are available, with different degrees of accuracy in the region up to 100 GeV/n; on the contrary, the higher energy region is poorly known: the most recent direct measurements in this region have been provided by the series of balloon flights of JACEE [1] and RUNJOB [2], while most of the data results from indirect measurements, by means of ground arrays observing air showers. New data have recently been added by the ATIC Collaboration [3], connecting the lowest energy region to the highest energy available data. The new CREAM project [4] has been developed and is now in data taking phase, with the aim of dramatically increasing the available statistics in the energy region up to 500 TeV.

In the present paper, we explore the performances required for new detectors to disentangle the fundamental parameters describing the propagation of nuclei at energies above about 100 GeV/n and below the knee region, focusing on the possibilities to measure the diffusion coefficient slope by means of the boron-to-carbon (B/C) data and the acceleration spectrum by means of primary light nuclei fluxes such as the carbon one.

2. The diffusion model

The most realistic propagation models are widely recognized to be the diffusion ones; in [5], a two-zones diffusion model has been developed and shown to reproduce several observed species in the low-energy part of the CR spectrum ($\sim$ 0.1-100 GeV/n). In this model, the Galaxy is cylindrically shaped (with R=20 kpc), with a thin disc (half-hight h=0.1 kpc) containing the sources and the interstellar medium (ISM) surrounded by a diffusive halo of half-thickness $L \sim$ 2-15 kpc.

The transport equation for the nucleus j in a diffusion model can be written as:

$$K(E)\left(\frac{\partial^2}{\partial z^2}+\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r})\right)N^j(E,r,z)-V_c\frac{\partial}{\partial z}N^j(E,r,z) \quad (1)$$

$$+2h\delta(z)\left(q_0^jQ_j(E)q(r)+\sum_{k=1}^{j-1}\Gamma^{kj}N^k(E,r,0)-\Gamma^jN^j(E,r,0)\right)$$

$$=2h\delta(z)\frac{\partial}{\partial E}\left\{b^j(E)N^j(E,r,0)-d^j(E)\frac{\partial}{\partial E}N^j(E,r,0)\right\}$$

Steady-state has been assumed and $N^j(E,r,z)$ is the differential density of the nucleus j as a function of energy E and galactic coordinates (r,z). The first term represents diffusion, which depends on the rigidity $R=p/Z$ of the particle; the diffusion coefficient is usually assumed to have the form: $K(E)=K_0\beta R^\delta$. V_c is the convection velocity, assumed here to be constant throughout the Galaxy (except in the thin disk). The second term of Eq.(1) takes into account all the sources of cosmic rays; the acceleration spectrum, determined by SNRs and superbubbles, follows a power-law in momentum, $Q(E)\propto p^{-\alpha}$, with α located somewhere between 2.0 and 2.5. The right-hand side contains the terms responsible of the energetic changes suffered by charged particles during propagation; all energy losses and gains are however effective only in the low-energy tail of the CR spectrum and are thus irrelevant in the analysis carried in the following of our paper, which deals with E$\geq$ 100 GeV/n.

The above-described diffusion model has been tested on the B/C and sub-Fe/Fe ratios and shown to fit well existing data, which mostly lie in the low-energy tail of the galactic CR spectrum; further details on this model can be found in [5, 6].

3. Results

Studies on the propagation parameters in the high energy region can be performed by experimental apparatus with: (i) high exposure (e.g., about 53 m^2sr days are needed to detect 10 carbon nuclei above 10 TeV/n); (ii) energy resolution such that changes of slope in the energy spectra can be detected (e.g. 40 % energy resolution is enough to see an increase of 0.3 in the spectral slope above the knee of 0.3); (iii) good charge resolution: at least 0.2 charge unit are necessary to compare B/C data with models around 1 TeV/n.

The expected number of events N(>E) can be calculated by assuming an input spectrum $dN/dE=C_0E^{-\gamma}$ $m^{-2}s^{-1}sr^{-1}(GeV/n)^{-1}$ and an experimental exposure. The poissonian fluctuations of the number of events are taken into account and the energy of each event is randomly sampled from the power law spectrum. The detector response is modeled as a Gaussian distribution with mean equal to the input energy and width given by the energy resolution. In the following, a constant 40% energy resolution will be assumed; the case for resolutions either decreasing or increasing with energy have been checked. The detection efficiency is here assumed not to depend on energy and must be included in the systematic uncertainties.

As working examples, we consider three different collecting powers Γ = 1.3, 5 and 10 m^2sr, similar to the quoted geometrical factors of some of the current and future experiments and a set of exposure times of 30, 100 and 1000 days, which roughly correspond to long and ultra long duration balloon flights and satellite conditions, respectively.

3.1 B/C measurement

The measure of the ratio between secondary (produced by spallation in the interstellar medium) and primary nuclei gives information on the diffusion properties; in particular, the boron-to-carbon ratio is very sensitive to any change in the model parameters and it is also the best measured quantity, at least in the low energy range. At high energy, the B/C ratio is mainly shaped by the diffusion coefficient slope δ; the constant K_0 in the diffusion coefficient enters with the source abundances in the global normalisation of B/C, so that its precise value is of scarce relevance in the B/C predictions. We identify five cases with $\delta = 0.3, 0.46, 0.6, 0.7, 0.85$, respectively, all the other propagation parameters $(K_0, L, V_c, V_A, \alpha)$ having been fixed according to the best fits to B/C data [6]. We have checked that the injection spectrum has no relevance in the calculation of this ratio.

Following the procedure outlined above, the expected number of carbon and boron events for the selected experimental configurations and input fluxes are simulated; their ratio is shown in Fig.1 for the case corresponding to $\delta = 0.6$, not including systematic errors. The five curves shown in the Figure refer to the 5 considered cases in the model: note that at energies $\simeq$ 10 TeV/n the predictions for the two extreme cases $\delta = 0.3$ and $\delta = 0.85$ differ by more than one order of magnitude.

In order to evaluate the accuracy in the determination of δ, a χ^2 minimization procedure was performed on the simulated B/C data, leaving δ, K_0, L and V_c as free parameters. Different levels of systematic uncertainties are added in quadrature to the statistical error. The effect of K_0, L and V_c is expected to be reabsorbed in a global normalization of the spectra, and in fact the resulting χ^2 shows no structure with respect to these parameters; on the other hand, we can always identify a minimum for δ.

We find that δ can be determined with significance level of 15% or 10% respectively for the 500 m^2 sr days or 10000 m^2 sr days simulated experiment, if the systematic errors are of order 10%. Very low accuracy is predicted in this case from the lowest exposure experiment (39 m^2 sr days), for which the same significance can be obtained only if systematics are negligible. The above results are derived including systematic uncertainties which are assumed to be independent on energy: while this is true for trigger efficiency or event reconstruction, or even for Monte Carlo corrections, other systematic errors like those due to energy resolution will depend on energy and could alter the considered fluxes. Correction factors due e.g. to selection efficiencies or interaction losses in the detector would increase the maximum energy at which B/C can be measured with a significant number of events. The inclusion of a finite energy resolution produces a distortion in the B/C measure which reflects the change in the carbon and even more in the boron spectrum due to the energy fluctuations; the effect is obviously bigger for higher values of δ.

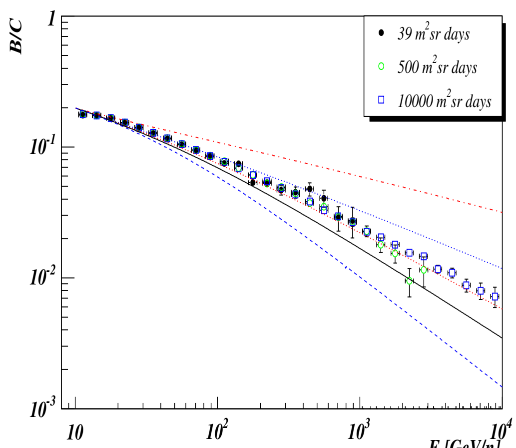

Figure 1. B/C ratio as expected for the input case corresponding to $\delta = 0.6$ and 3 different experimental exposures. The 5 model predictions correspond to δ=0.3 to 0.85 from top to bottom respectively.

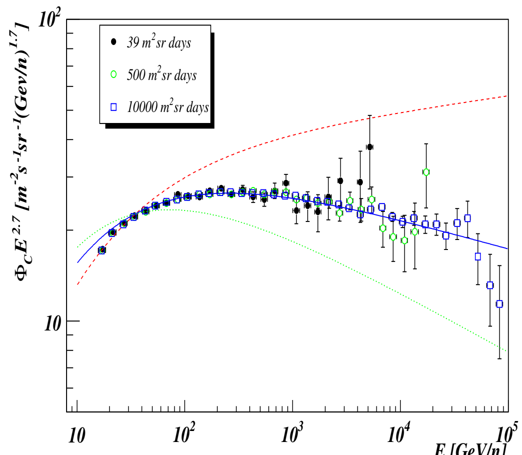

Figure 2. Expected Carbon flux for input cases with $\alpha = 2.05$ and $\delta = 0.6$ for three different exposures. The 3 curves show the expected flux for $\delta = 0.6$ and α=1.9,2.05,2.2 from top to bottom respectively.

3.2 Primary nuclei flux measurement

The determination of primary fluxes trace back to the acceleration sites, thus giving insights on the diffusion and acceleration properties. Data about fluxes of primary nuclei were collected in the past for $Z \leq 26$ up to few TeV/n, but with decreasing statistical significance as the energy grows. At the highest energies, the only available data sets come from emulsion chamber experiments like [1, 2] which measure groups of elements. More recently, the first data from a one day test flight of TRACER have been published for $Z \geq 8$ nuclei [7].
The propagation model we used for the previous analysis has been employed to qualitatively reproduce the data at the energies in discussion, without caring much about the level of agreement with lower energy data (in fact, the study of the propagation of primaries at low energies is beyond the scope of the present paper). The normalization is referred to the fluxes measured at 35 GeV/n, where the total error is of the order of 15%. Fig.2 shows the expected flux of carbon events for the 3 different exposures; the input flux is computed by assuming δ=0.6 for the diffusion slope and α=2.05 for the acceleration spectrum. For comparison, the expected fluxes for δ=0.6 and α=1.9,2.05,2.2 from top to bottom respectively.
With a χ^2 minimization procedure, the expected data are fitted to a power law and the slope γ is determined with an error lower than 1% in a range ΔE=0.1-10 TeV/n. The effect of adding a constant systematic error of 10% is of more than doubling the error on γ. This result implies that the experimental errors on the carbon flux (the same conclusion is reached for oxygen) will not add any uncertainty in the determination of the acceleration power law index α other than the one carried by the diffusion slope δ.

4. Conclusion

Different predictions on the primary and secondary fluxes of galatic nuclei have been generated using a two-zones diffusion model. They have been used to derive the expected number of events in different experimental configurations, each exploiting large collecting factors in the high energy region ($\geq$ 100 GeV/n).
We showed that
1. the measurement of the B/C ratio will allow an experimental determination of the diffusion slope δ; experiments reaching collecting powers of hundreds m^2sr days can fix δ at about 85% confidence level even in presence of important systematic errors;
2. the measurement of single fluxes will give information on the acceleration spectrum: it has been shown that no further uncertainty other than that induced by the error on δ affects the acceleration slope α.
Finally, we point out that a better understanding of the propagation parameters will also help in the search for new physics, e.g.indirect signals of dark matter pairs annihilating in the galactic halo [8].

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