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Expected boron to carbon at TeV energies

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Abstract: The propagation of cosmic rays (CR) in the Galaxy is studied using the ratio of secondary to primary CR abundances. These ratios are used to constrain quantities such as the average amount of material CRs traverse between creation and observation. The characteristic time of escape can also be determined. GALPROP is a time based Galactic CR propagation model that has become widely used since its creation more than a decade ago and which has continued to evolve as new measurements become available. In this paper, we use GALPROP to predict the B/C spectrum and to compare it with previous measurements, and also describe some recent experimental developments to bear on this in the near future.

Introduction

The propagation of cosmic rays in the Galaxy can be studied using the energy dependent ratio of secondary to primary cosmic ray (CR) abundances, where primary CRs are created at the source and secondaries are created via spallation of primaries with the ISM. These ratios typically include B/C, Be/C, and (Sc+Ti+V+Cr)/Fe. The ratio of boron to carbon is the easiest to measure due to the decrease in CR flux for heavier nuclei, and provides insight into the usefulness of these ratios. The boron component measured by CR experiments is almost entirely created by spallation of carbon nuclei and therefore gives a measure of the amount of material CR primaries traverse from creation to observation.

The CR propagation model GALPROP was developed by Strong and Moskalenko [1] in order to study the source composition and propagation processes of CRs in the Galaxy, as well as gamma ray bursts and other phenomena. GALPROP is a software package that solves the time dependent propagation equation. Over the past decade GALPROP has become a very robust and commonly used standard in CR propagation analysis. Current B/C ratio data extends to the $100\mathrm{GeV}$ range and GALPROP's predicted B/C spectrum follows this data closely, as will be shown shortly. The future results of the CREAM experiment will also be discussed.

B/C ratio

Galactic CR propagation has historically been studied using the Weighted Slabs solution to the Leaky Box model [2]. The Leaky Box model is a phenomenological model that treats the escape of CRs from the Galaxy like that of a characteristic escape length. The weighted slab solution treats the CR flux as a beam of particles traversing slabs of material with thickness, $\mathrm{d}x$. Using this method gives a propagation equation of

$$\begin{aligned}\frac{\mathrm{d}N_i}{\mathrm{d}x} &= \frac{\partial}{\partial E}\left\{\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_i N_i\right\} \\ &- \frac{N_o}{\overline{A}}\sigma_i N_i + \sum_{j>i}\frac{N_o}{\overline{A}}\sigma_{ij}N_j \\ &- \frac{N_i}{\gamma\beta cn\overline{A}T_i} + \sum_{j>i}\frac{N_j}{\gamma\beta cn\overline{A}T_j}. \quad (1)\end{aligned}$$

Here N_i is the abundance of the i^{th} CR species. The first term represents ionization energy loss (i.e. Bethe-Bloch). The second term is the loss of species i due to spallation with the ISM, which has a mean molar mass of $\overline{A}$. N_o is Avagadro's number. The next term is the gain of species i due to spallation of species j with the ISM, where $j > i$. The last two terms are the loss of species i due to the nuclear decay of species i or the gain of species i due to the nuclear decay of species j, T_i and T_j being the half-life of the species i and j, respectively. Here $\mathrm{d}x$ is measured as grammage, $\mathrm{g/cm^2}$ [2].

For energies above a few MeV the ionization energy loss may be neglected in Equation 1. The boron and carbon flux is dominated by their respective stable isotopes therefore the nuclear decay terms can also be neglected. The majority of boron CRs observed were created by carbon spallation with the ISM and most carbon nuclei observed originate from the source which allows most spallation terms to be omitted except that of carbon into boron. With these assumptions and setting $i =$boron and $j =$carbon, one has

$$\frac{\mathrm{d}N_B}{\mathrm{d}x} = \frac{N_o}{\overline{A}}(-\sigma_B N_B + \sigma_{CB} N_C). \qquad (2)$$

For small $\mathrm{d}x$, $\mathrm{d}N_B \sim N_B$ because the initial abundance of boron is approximately zero, and solving for the B/C ratio

$$\frac{N_B}{N_C} = \sigma_{CB}\left(\frac{\overline{A}}{N_o \Delta x} + \sigma_B\right)^{-1} \qquad (3)$$

One can calculate the total inelastic cross sections for boron and carbon on protons from the empirical formulas developed by Silberburg and Tsoa [3], which become relatively energy independent in this energy range. The B/C ratio can be measured and the amount of material traversed, Δx, can be calculated. This approximation under-predicts the amount of material by a few $\mathrm{g/cm^2}$ when compared to the numerical solution of the propagation equation, but is useful for showing how the ratio of boron to carbon is related to the material traversed by primary CRs.

The GALPROP Model

The GALPROP software package has been under continual development for over a decade by Strong and Moskalenko, and is described in detail in [1]. GALPROP performs a time evolution of the time dependent Galactic CR propagation equation:

$$\begin{aligned}\frac{\partial \Psi(\vec{r},p,t)}{\partial t} &= q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\Psi - \vec{V}\Psi) \\ &+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\Psi \\ &- \frac{\partial}{\partial p}\left[\dot{p}\Psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\Psi\right] \\ &- \frac{1}{\tau_f}\Psi - \frac{1}{\tau_r}\Psi. \qquad (4)\end{aligned}$$

This equation represents the time dependent change in the CR density, Ψ, with each term on the right hand side being a process of loss or gain of the CR species. q is the source term, which includes the initial spectrum of CRs created at the source and the creation of lighter CRs due to the spallation of heavier CRs. The second term expresses CR diffusion and convection. The reacceleration term is next and is treated as diffusion in momentum space. Then there are terms for momentum loss or gain and the loss/gain due to scattering off frozen-in magnetic fields created by non-uniform gas flow. The last two terms represent the characteristic loss due to fragmentation and radioactive decay. For a more in depth explanation see [1].

GALPROP uses this time dependent propagation equation and a characteristic solar abundance to evolve the Galactic CR density from the time that all the sources turn on to the time at which the system reaches equilibrium with creation and Galactic escape. This equilibrium is considered to be significant because of the isotropy in CR arrival directions and their constant flux spectrum. The source spectrum can be iteratively changed until the predicted spectrum at the Earth approximately reproduces observed data. Most parameters can be set by the user, including the source abundances, size of the Galaxy, CR source distribution, and time step size used in the time evolution. One can also turn on or off processes like reacceleration and tracking of certain particles in order to determine their significance.

The GALPROP results presented here were produced using all terms in Eqn. 4 in a 2D cylindrically symmetric Galactic coordinate system. Turning off reacceleration and convection processes did not noticeably affect the B or C spectra, except to slightly increase the flux around $1\mathrm{GeV/nucleon}$ when reacceleration is not considered. A power law in momentum is used as the injection spectrum and the distribution of CR sources is selected using the CR distribution determined from the anal-

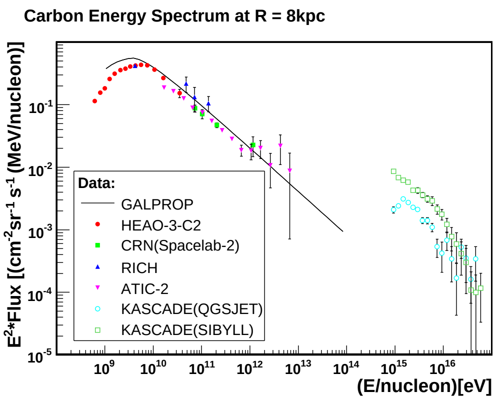

Figure 1: Plot of the predicted carbon spectrum from GALPROP with current data points overlaid as detailed in the plot. KASCADE was used to represent ground array data and to place it in relation to direct measurement experiments without any renormalization. The KASCADE data is their CNO group spectrum so it is expected to be ~ 2.5 times that of the actual carbon spectrum. This data was produced using two different models of hadronic interactions in the atmosphere, QGSJET and SIBYLL [5]. Data taken from [6, 7, 8, 5].

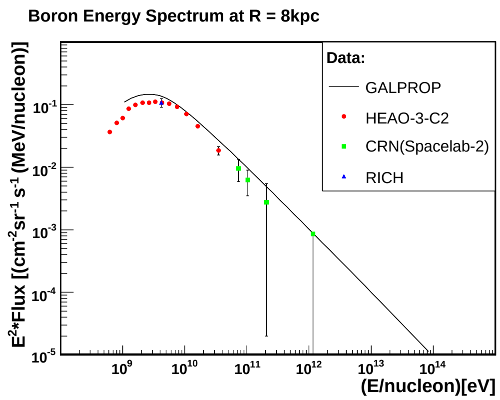

Figure 2: Predicted boron spectrum from GALPROP with current measurements overlaid as detailed in the plot. Data taken from [6, 7, 8, 5].

ysis of EGRET γ-ray data. The relative source abundances are set by hand, however, values determined from various experiments are used (for a list of these experiments see [4]). The ISM is assumed to have a p/He ratio of 0.11 and heavier elements are not included because they do not play a significant role in CR spallation [1].

The predicted carbon spectrum, as seen at Earth (Galactic radius of 8kpc), is shown in Figure 1. The GALPROP proton flux at $100\text{GeV}/\text{nucleon}$ is normalized to ACE data [1] and all other elements are scaled by the same constant so the relative abundances remain those calculated by the model. This plot shows the prediction of GALPROP as compared to current direct measurements.

We include data from KASCADE in order to illustrate the level of agreement between the direct balloon measurements and the indirect technique of air shower measurements. Although, the data shown is that of the KASCADE CNO group and thus is expected to be about 2.5 times that of the true carbon spectrum. Ground array measurements require resorting to models (QGSJET and SIBYLL) to determine the particle charge and energy above the atmosphere, and thus the traditional normalization done with direct measurements does not hold the same meaning. Therefore, no renormalization has been performed on the KASCADE data and it is shown as published [5].

Figure 2 shows the predicted boron spectrum as calculated by GALPROP. Due to the reduced flux of boron secondaries this spectrum is much harder to measure as evidenced by the errors near $100\text{GeV}/\text{nucleon}$ and fewer experiments. Figures 1 and 2 show excellent agreement between GALPROP and observed data.

The boron to carbon ratio is shown in Fig. 3. The lack of statistics in the boron spectrum measurements are more visible in this plot. As discuss above, this ratio is important in understanding the propagation of CRs in the Galaxy and is not limited to the amount of material traversed by the CRs. The diffusion coefficient, in Eqn. 4, is a power law function of rigidity as follows, $D_{xx} = D_0 R^{\delta}$. Figure 3 shows the effect of different indices in the GALPROP model. Extending the B/C spectrum to higher energies will constrain this parameter, which current empirical models predict as $\delta \sim 0.6$ [1, 9].

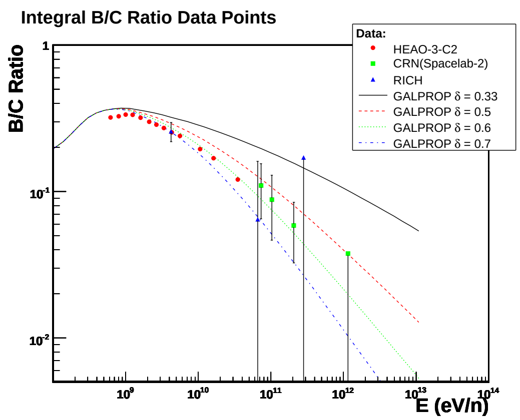

Figure 3: Plot of the predicted B/C ratio from GALPROP with current data points overlaid as detailed in the plot. Data taken from [6, 7, 8, 5]. The lines represent the expected spectra for differring power law diffusion indices.

CREAM B/C Data

The Cosmic Ray Energetics And Mass (CREAM) experiment has flown two Long Duration Balloon (LDB) payloads from McMurdo Station, Antarctica, with a total flight time of 70 days. One of the goals of this experiment is to extend to B/C ratio spectrum to the $500\mathrm{GeV}/\mathrm{nucleon}$ range. This would allow the predictions of the diffusion coefficient from various models to be tested as discussed in [9] and shown in Fig. 3. Beyond this energy range, measurements of B/C must be made by space borne experiments because the boron production in the atmospheric overburden (about $5\mathrm{g}/\mathrm{cm}^2$) becomes comparable to the expected flux of boron secondaries above the atmosphere. Preliminary carbon and oxygen spectra that extend to almost $100\mathrm{TeV}$ are being presented at this conference [10, 11, 12]. B/C ratio data is anticipated.

Conclusion

The predicted GALPROP B/C ratio spectrum is consistent with current measurements up to energies of $\sim 100\mathrm{GeV}/\mathrm{nucleon}$. Future CREAM results will extend this ratio to even higher energies and provide further confirmation of the GALPROP model. Continued testing of the GALPROP software will help maintain this consistent and comprehensive model and provide insight into ways of improving it.

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References

[1] A. Strong, I. Moskalenko, V. PtuskinAstro-ph/0701517v1.
[2] J. Lezniak, AP & SS 63 (1979) 279.
[3] L. S. et al., Phys. Rev. C 47 (3) (1993) 1225–1236.
[4] A. Strong, I. MoskalenkoGALPROP Manual available at http://galprop.stanford.edu/.
[5] K. K. et al.Astro-ph/0405608.
[6] S. S. et al., Ap. J. 349 (1990) 625–633.
[7] J. E. et al., Astron. Astrophys. 233 (1990) 96–111.
[8] J. B. et al., Ap. J. 429 (1994) 736–747.
[9] A. Castellina, F. DonatoAstro-ph/0504149v2.
[10] S. Wakely, 30th Int. Cosmic Ray Conf., 2007, this conference.
[11] R. Zei, 30th Int. Cosmic Ray Conf., 2007, this conference.
[12] H. A. et al., 30th Int. Cosmic Ray Conf., 2007, this conference.