Galactic propagation of cosmic rays and the B/C ratio

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Abstract: The TRACER detector has provided a comprehensive set of measurements on the energy spectra and composition of cosmic-ray nuclei over a wide range of energies. The first LDB flight in 2003 covered the primary nuclei from oxygen to iron, while the second flight in 2006 also extended to the lower charge numbers, including the secondary element boron. A model of Galactic propagation is required in order to deduce the composition and spectra at the sources from the data measured in situ. At the same time, the measurements themselves place constraints on the parameters of the propagation model which are not known a-priori. In order to study these constraints, a simple Leaky-Box model with energy-dependent propagation path length, or the GALPROP simulation package is used. The results of the measurement are fitted to the models, using a small number of free parameters: the power-law index of the energy spectrum at the source, and the form of the energy-dependence of the propagation path length. The results on the boron-to-carbon (B/C) abundance ratio from the 2006 flight indicate (albeit with considerable statistical uncertainty) that the propagation path length may well approach an energy-independent residual value at high energy. The Leaky-Box interpretation of the TRACER results, as well as a comparison with GALPROP, indicate a rather soft power-law spectrum at the cosmic-ray source.

Keywords: The keywords

1 Introduction

In order to determine the energy spectra and composition of cosmic rays at their sources, the effects of propagation through the interstellar medium (ISM) must be understood. Specifically, the energy-dependent leakage of cosmic rays from the Galaxy needs to be known. This energy dependence is commonly investigated with measurements of the abundance of secondary cosmic-ray nuclei produced in spallation processes (like boron), relative to the abundance of their parent primary cosmic-ray species (like carbon). Such studies provide a direct measurement of the Galactic propagation path length Λ_{esc} of cosmic rays. In general, it has been found that Λ_{esc} decreases with energy, perhaps in form of a power law $\propto E^{-\delta}$.

A previous study [3] based on the 2003 measurements of TRACER of the energy spectra of primary cosmic-ray elements (oxygen to iron) has led to the conclusion that the energy spectra at the source should be rather soft. In this study, it was assumed that all elements have a source energy spectrum with the same power-law index α, and that the energy dependence of the escape path length Λ_{esc} above ~ 20 GeV amu^{-1} can be described as

$$\Lambda_{esc}(E) = CE^{-\delta} + \Lambda_0, \quad (1)$$

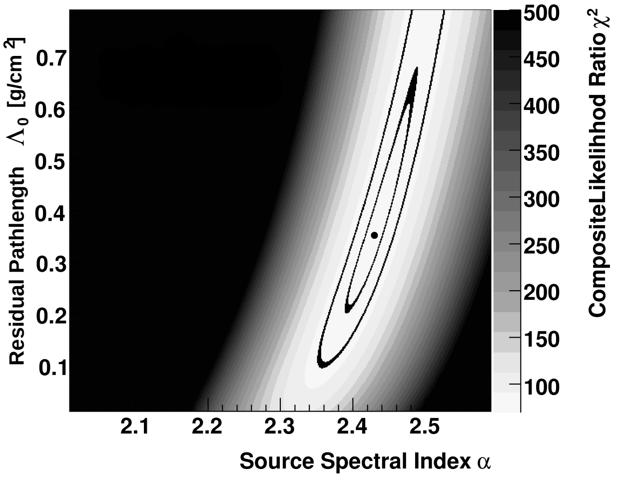

Figure 1: Likelihood map of the parameter space of residual path length versus source spectral index. Best fit values, 1σ, and 3σ contours based on the spectra of eight primary elements from oxygen to iron are indicated. [3]

with $\delta = 0.6$. Thus, the escape path length was assumed to exhibit the same energy dependence that was proposed in

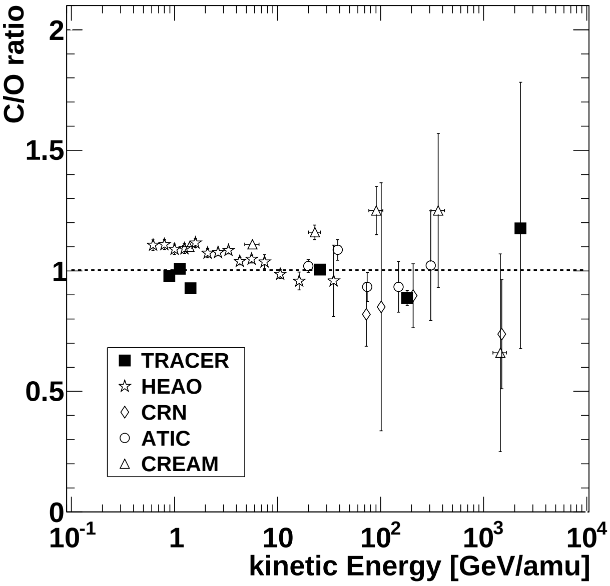

Figure 2: The carbon-to-oxygen abundance ratio as a function of kinetic energy per nucleon. Error bars are statistical only. Previous results from HEAO [6], CRN [11], ATIC [9], and CREAM [2] are shown for comparison.

earlier work [11, 14], but was allowed to reach an asymptotic, energy-independent residual value Λ_0. The measured spectra of the primary cosmic-ray nuclei were then fit to this model, with α and Λ_0 as free parameters. Figure 1 illustrates the results.

The best fit clearly favors a surprisingly soft source spectrum with an index α that could be as large as 2.4. However, the path length Λ_0 is not strongly constrained, and the fit cannot exclude $\Lambda_0 = 0$. Clearly, further insight requires direct measurements of the escape path length at high energy.

Therefore, another balloon flight of TRACER, also discussed at this conference [4], was conducted in 2006. For this flight, major upgrades were incorporated in the detector system to include measurements of the light secondary nucleus boron ($Z = 5$), relative to the abundance of its primary parent nuclei carbon ($Z = 6$) and oxygen ($Z = 8$) [8]. The resulting energy spectra for these nuclei lead to new constraints on the source and propagation parameters. These will be discussed in the following in the context of a Leaky-Box propagation model, and of the numerical GALPROP [10] model.

2 The Leaky-Box Model

The Leaky-Box model in its simplest form describes the differential intensity N_i of a cosmic-ray species i as

$$N_i = \frac{1}{\Lambda_{esc}^{-1} + \Lambda_i^{-1}} \times \left(\frac{Q_i}{\beta c \rho} + \sum_{k>i} \frac{N_k}{\lambda_{k \to i}} \right), \qquad (2)$$

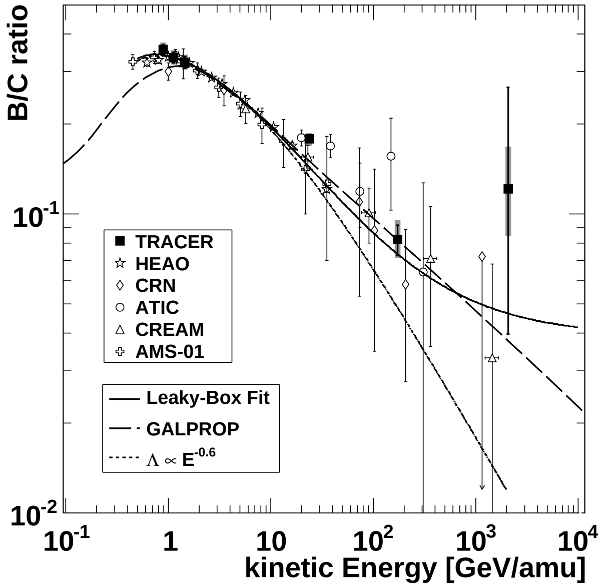

Figure 3: The boron-to-carbon abundance ratio as a function of kinetic energy per nucleon. Error bars are statistical (thin) and systematic (thick). Previous measurements are shown from HEAO [6], CRN [11], ATIC [9], CREAM [2] and AMS-01 [1]. Also shown is the parametrization by [14] (dotted), by the GALPROP model (dashed), and a fit to the Leaky/Box model (solid).

with the source spectrum Q_i and gains by spallation of heavier nuclei N_k with production path lengths $\lambda_{k \to i}$, and the losses through spallation in the ISM and leakage from the Galaxy expressed with path lengths Λ_i and Λ_{esc}, respectively; ρ is the mass density of interstellar matter. Note that Λ_{esc} depends on energy while Λ_i depends on the mass number A of the cosmic-ray nucleus, but is assumed to be energy independent for relativistic energies. For purely secondary elements, the source term Q_i is zero and for the abundant primary elements production by spallation is insignificant. For the intensity ratio of boron to carbon, one then obtains

$$\frac{N_B}{N_C} = \frac{\lambda_{\to B}^{-1}}{\Lambda_{esc}^{-1} + \Lambda_B^{-1}}, \qquad (3)$$

where $\lambda_{\to B}$ is an effective production path length also taking into account contributions from oxygen:

$$\lambda_{\to B}^{-1} = \lambda_{C \to B}^{-1} + N_O(0)/N_C(0) \cdot \lambda_{O \to B}^{-1}. \qquad (4)$$

The spallation and production path lengths in Eq. (3) can be evaluated using total and partial cross sections, as given by a geometrical parametrization [5, 13, 7] and by Weber *et al.* [12]. Therefore, the only unknown quantity in Equation (3) is the escape path length Λ_{esc}.

3 Measured Abundance Ratios

The measured abundance ratio of the primary elements carbon and oxygen is shown in Figure 2. The present result is in good agreement with previous data [2, 6, 9, 11]. The ratio is close to unity over the entire range from below 1 GeV amu^{-1} to above 1 TeV amu^{-1}, although the uncertainties remain large at the high energies. The energy dependence of this ratio seems to be insignificant, although a slight decline as indicated by the HEAO data at low energies cannot be excluded.

The boron-to-carbon abundance ratio is shown in Figure 3. The present measurement is shown together with previous data from [1, 2, 6, 9, 11]. The measurement now extends to 2 TeV amu^{-1}, although the uncertainties remain very large at the highest energy. Also shown in Figure 3 is an extrapolation corresponding to an $E^{-0.6}$ dependence of Λ_{esc}, and including a turnover at low energy as parametrized by Yanasak *et al.* [14]. Almost all data points above 30 GeV amu^{-1} exceed this extrapolation of the B/C ratio.

4 Galactic Propagation and Source Spectrum

The TRACER data shown in Figure 3 are now used to derive constraints on the parameters describing the B/C ratio according to equation (3). To express Λ_{esc} we use the parametrization given in Equation 1, with the propagation index δ and the residual path length Λ_0 as free parameters. The result of the fit is a χ^2 contour maps that is shown in the upper panel of Figure 4. As can be seen, the propagation index is well constrained, whereas the residual path length is still not well defined. The TRACER data indicate best fits for $\delta = 0.53 \pm 0.06$ and $\Lambda_0 = 0.31^{+0.55}_{-0.31}$ g/cm^2. Note that the propagation index δ is commensurate with the value $\delta = 0.6$ that was derived previously from measurements at lower energy. This value is also in agreement with the assumption made in the previous analysis [3] of the earlier TRACER measurement of primary cosmic-ray elements, mentioned above.

The lower panel in Figure 4 shows the results of the fit if all available data are included. Now one obtains $\delta = 0.64 \pm 0.02$ and $\Lambda_0 = 0.7 \pm 0.2$ g/cm^2. While the propagation index remains commensurate with the previous result, the fit now indicates a residual path length that indeed is likely to be non-zero. The solid line in Figure 3 corresponds to this Leaky-Box fit to all data.

As a next step, one may use the results on the propagation parameters to obtain the source energy spectrum of cosmic rays, with the assumption that the source spectrum is a power law with the same spectral index α for all primary species. The cosmic-ray energy spectra N_i, as measured with TRACER, are fit to Equation 2 with α as a free parameter and the spallation path length taken from published parametrizations [5, 13]. The result is shown for oxygen in Figure 5. The best fit value for the source spectral index is $\alpha = 2.37 \pm 0.12$. As in our previous analysis [3] the source energy spectrum is rather soft. The corresponding fit to the observed energy spectrum (dashed line in Figure 5), is not a straight power law. However, the curvature of the spectrum is hidden within the uncertainties of the data.

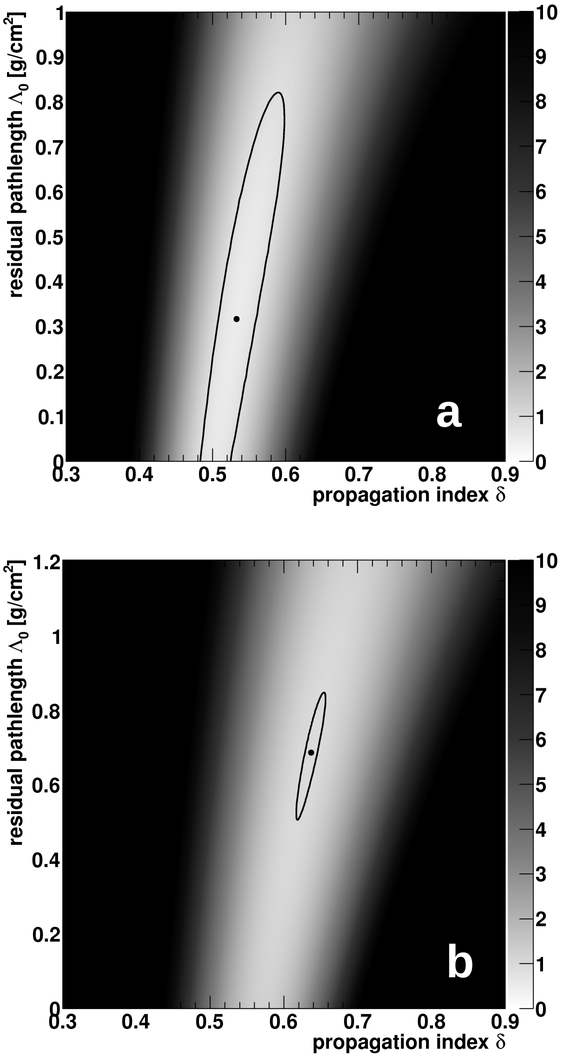

Figure 4: χ^2 map in the parameter space of δ vs. Λ_0 for the Leaky-Box fit to TRACER data (a) and all data (b). The best fit values and the 1σ contours are indicated.

5 GALPROP Propagation Model

The GALPROP model [10], a numerical simulation of cosmic rays in the Galaxy, can be used to generate estimates of the boron-to-carbon abundance ratio. The standard input parameters of GALPROP are chosen to describe most cosmic-ray measurements correctly. The model includes reacceleration and energy dependent diffusion, $D \propto E^{0.34}$, but does not specify a quantity that would correspond to the residual path length Λ_0.

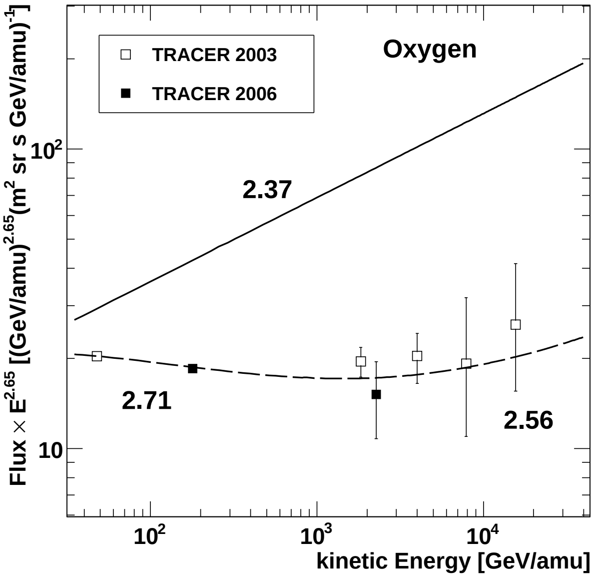

Figure 5: Energy spectrum of oxygen as measured by TRACER in its two flights. The fitted source spectrum is shown as a solid line. The corresponding, observed spectrum is shown as a dashed line. Spectral indices are indicated.

The dashed line in Figure 3 is the expected boron-to-carbon ratio according to the GALPROP model. If the source spectral index is taken to be 2.34, the model describes the the data well, albeit without asymptotic saturation at highest energies. However, the preferred value of the source spectral index, $\alpha = 2.34$, agrees remarkably well with the conclusions from the Leaky-Box model, and again indicates a soft energy spectrum at the cosmic-ray source.

6 Discussion

We have used recent measurements of the energy spectra of cosmic-ray nuclei to derive constraints on the propagation and source parameters at high energies. Previous to this work, the energy spectra of primary nuclei, reported from the TRACER 2003 balloon flight, had been interpreted on the basis of a simple Leaky-Box model and found to be consistent with a relatively soft power law spectrum at the source ($\alpha \approx 2.4$) [3]. This conclusion assumed that the propagation path length decreased with energy as $E^{-0.6}$.

With the data from the TRACER flight of 2006, and with other recent data, measurements of the B/C abundance ratio lead to direct information on the energy dependence of the propagation path length. Using the leaky-box approximation, we obtain a propagation index $\delta = 0.53 \pm 0.06$, which agrees well with the previous value $\delta = 0.6$. However, there is an indication that the propagation path length approaches a residual value Λ_0 of a few tenths of one g/cm^2. Uncertainty about the precise value of Λ_0 remains, and can only be reduced with more precise measurements of the B/C ratio at high energies.

We have also compared the measurements with the predictions of the numerical GALPROP code. This code predicts a steep decrease of the B/C ratio, just like the leaky box model above, but now this slope is the result of combining a slower energy dependence of the diffusion coefficient ($\sim E^{0.34}$) with energy shifts at low energy due to Galactic re-acceleration. This model does not predict a non-zero residual path length.

Questions remain when one asks about the physical meaning of these parameters: Is the energy dependence of the propagation path length as described in Eq. (1) with $\delta = 0.6$ consistent with the current understanding of cosmic-ray diffusion? And where is the matter corresponding to Λ_0 located: distributed in the interstellar space, in the close surroundings of the cosmic-ray source, or perhaps associated with a minimum galactic distance of the nearest cosmic-ray sources?

Most interesting seems to be the fact that both, GALPROP and the Leaky Box model, lead to an energy spectrum at the cosmic-ray source which is softer, about $E^{-2.35}$ for all nuclear components, than predicted by most current shock acceleration models. Furthermore, one may question the validity of the assumption of a strict power law behavior at the source. It would be highly interesting to investigate whether there are deviations from a power law behavior of the measured spectra, as Figure 5 seems to predict. Once again, this is a question which can only be answered with data with much better statistical accuracy than currently available.

Thus, in summary, it is encouraging that recent cosmic-ray measurements are beginning to probe details of the source and propagation characteristics that have remained unexplored for a long time, and one should look forward to the improved precision that future observations may provide.

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