

# Observations of the Li, Be, and B isotopes and constraints on cosmic-ray propagation

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## Abstract

The abundance of Li, Be, and B isotopes in galactic cosmic rays (GCR) between  $E=50$ -200 MeV/nucleon has been observed by the Cosmic Ray Isotope Spectrometer (CRIS) on NASA's ACE mission since 1997 with high statistical accuracy. Precise observations of Li, Be, B can be used to constrain GCR propagation models. We find that a diffusive reacceleration model with parameters that best match CRIS results (e.g. B/C, Li/C, etc) are also consistent with other GCR observations. A  $\sim 15$ –20% overproduction of Li and Be in the model predictions is attributed to uncertainties in the production cross-section data. The latter becomes a significant limitation to the study of rare GCR species that are generated predominantly via spallation.

*Key words:* cosmic rays, Galaxy: general, Galaxy: abundances, Galaxy: evolution, ISM: general

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## 1. Introduction

The enormous excess of the abundances of Li, Be, and B (LiBeB) relative to C, N, and O in GCRs by a factor of  $\sim 10^4$  compared with solar system abundances is attributed to the fragmentation of primary GCR nuclei, mainly C, N, and O, on interstellar H and He atoms (Freier et al., 1959). Observations of secondary GCRs such as LiBeB thus

provide strong constraints on propagation models of GCRs within the Galaxy, since the production of these light isotopes depends on the amount of matter traversed during propagation. B/C ratio is often used to tune propagation parameters, such that the model predictions agree automatically with B/C. Li and Be are particularly interesting since their production depends not only on the interaction of CNO, but also on “tertiary” interac-

tions in the ISM (e.g. B, Be  $\rightarrow$  Li), and therefore may provide further restrictions on propagation models. In particular, one might expect to observe a stronger energy dependence of Li/C and Be/C ratios compared to the B/C ratio. In addition, establishing the details of GCR propagation in the Galaxy will be beneficial for other studies, such as searches for signatures of exotic physics in GCR, spectra and origin of galactic and extragalactic  $\gamma$ -ray background, nucleosynthesis, and solar modulation (e.g., Moskalenko et al., 2005).

The Cosmic Ray Isotope Spectrometer (CRIS) on the NASA/ACE spacecraft (Stone et al., 1998) measures the isotopic composition of elements with  $2 \leq Z \leq 30$  in the energy range from  $\sim 30$ –500 MeV/nucleon since 1997 with unprecedented precision. High statistics allows LiBeB to be studied over an extended energy range ( $\sim 50$ –200 MeV/nucleon) for the first time. We present absolute intensities and relative elemental and isotopic abundances of GCR LiBeB observed by CRIS during near solar minimum conditions, and we compare these results with observations from previous instruments. We also discuss the implications of these observations in the context of a GCR transport model, GALPROP. GALPROP has recently been improved to predict LiBeB GCR isotopic abundances, including re-examined fragmentation cross sections used as input to the model. The precision of the data set from CRIS is high enough (e.g., de Nolfo et al., 2001) to require a re-evaluation of the contributing uncertainties in the model calculations, particularly the uncertainties in the isotopic cross-sections.

## 2. Intensities and Elemental Abundances

The absolute intensities of Li, Be, B, and C as measured by CRIS are shown in Fig. 1a (solid circles). The data set considered for this study covers near solar minimum conditions between 1998 Jan. 1 and 1999 Jan. 23. Excluding periods of intense solar activity, the total time period corresponds to 311 days (for details see de Nolfo et al., 2003). The uncertainties shown in Fig. 1a for CRIS observations include both statistical and systematic un-

certainties. The statistical uncertainties are typically small, ranging from 0.5% for C to 5% for Li. The systematic uncertainties result from the various correction factors within the calculation for the absolute intensity such as uncertainties in the determination of the geometry factor (2%), spallation loss within the instrument (1–5%), and the tracking efficiency of the Scintillating Optical Fiber Hodoscope (SOFT) (Stone et al., 1998) ( $<1\%$  for  $Z > 5$  and up to 6% for Li).

The elemental and isotopic ratios observed by CRIS are shown in Fig. 1b and Fig. 2 for solar minimum conditions. The ratios of the spallogenic nuclei (B, Be, and Li) to mostly primary nuclei such as C are particularly important in constraining propagation models since these ratios are sensitive to the amount of material traversed by GCRs from the source to detection at Earth. In addition, abundance ratios tend to be less sensitive to instrumental uncertainties than absolute intensities. In Fig. 1b, the experimental error bars include both systematic and statistical uncertainties.

In Fig. 1, CRIS results are compared with previous observations. A direct comparison of CRIS results with previous observations is complicated at these energies by the effects of solar modulation. The effect of solar modulation is approximated by the spherically symmetric model of Fisk (1971), characterized by the solar modulation parameter  $\phi$  (Gleeson and Axford, 1968). Levels of modulation are determined for a given source spectrum by matching post-propagation interstellar spectra as predicted by GALPROP to CRIS at low energies and to HEAO-3 at high energies. The average amount of solar modulation experienced by particles observed by CRIS during near-solar minimum conditions corresponds to  $\phi \approx 550$  MV. While the modulation parameter can be used to characterize the amount of modulation experienced during a specific time period, the derived value of  $\phi$  also depends on the initial choice of the source spectrum and thus on the propagated interstellar spectrum adopted as input in the solar modulation calculation. For instance, the solar modulation adopted for CRIS during solar minimum is closer to  $\phi = \sim 400$  MV based on predictions from the Leaky Box Model (Davis et al., 2001; Niebur et al., 2003).

CRIS observations are in good agreement with

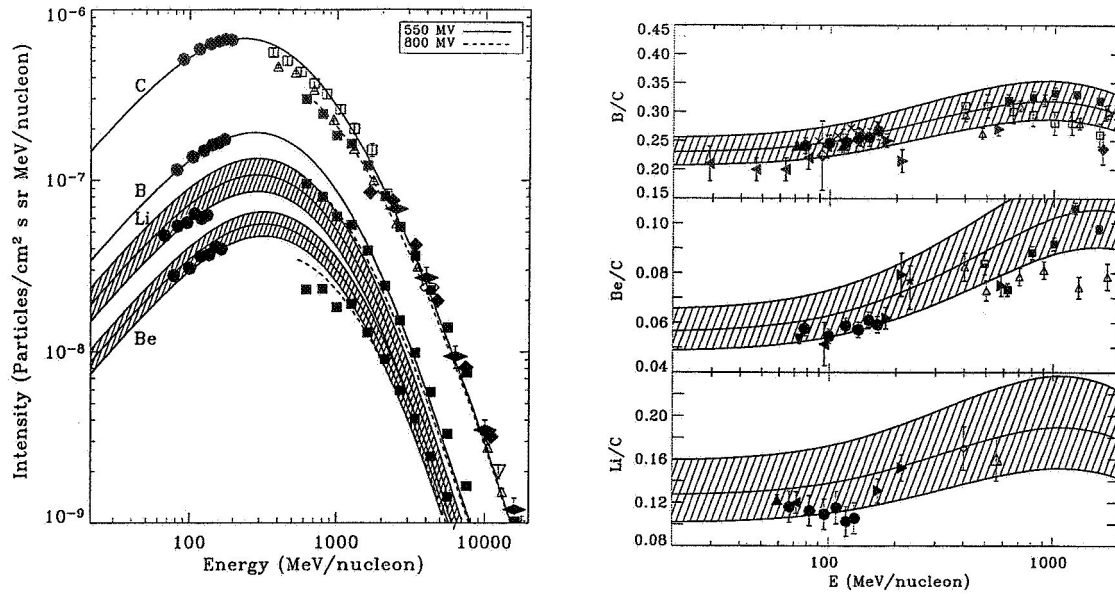


Fig. 1. [a] Intensities of C, B, Be, and Li shown for two levels of solar modulation ( $\phi = 550$  (solid curve) and 800 MV (dashed curve)) corresponding to the epoch when the experimental data were taken, and [b] relative elemental abundances compared with previous observations. The experimental data is compared with the results of a propagation model GALPROP. See text for details. (Symbols refer to CRIS:  $\bullet$ , Maehl et al. 1977:  $\square$ , Webber et al. 1972:  $\triangle$ , Englemann et al. 1990:  $\blacksquare$ , Orth et al. 1978:  $\blacklozenge$ , Buffington et al. 1978:  $\diamond$ , Simon et al. 1980:  $\blacklozenge$ , Buckley et al. 1994:  $\square$ , Chapel and Webber 1981:  $\nabla$ , Lezniak et al. 1978:  $\triangle$ , Muller et al. 1991:  $\dagger$ , Dwyer et al. 1978:  $\triangleright$ , Webber et al. 1977:  $\blacktriangleright$ , Garcia-Munoz et al. 1987:  $\blacktriangleleft$ , Duvernois et al. 1996:  $*$ , Mewaldt et al. 1981:  $\blacklozenge$ , Wiedenbeck and Greiner 1980:  $\dagger$ , Webber et al. 2002:  $\blacktriangledown$ , Hagen et al. 1977:  $\star$ , Fisher et al. 1976:  $\blacksquare$ , Juliusson et al. 1974:  $+$ , Garcia-Munoz et al. 1977:  $\circ$ , Connell et al. 2001:  $\times$ , Krombel et al. 1988:  $\triangleleft$ , Lukasiak et al. 1999:  $\blacktriangle$ ).

the previous observations of Voyager 1, 2 and IMP 7, 8, both of which were made during near solar modulation conditions similar to CRIS. The Voyager data were accumulated over 21 years with a weighted average solar modulation level of  $\phi=450$  MV. This may not be a good representation of the actual modulation level experienced over 21 years (Connell et al., 1998) and thus complicates a comparison with CRIS data. At higher energies, the modulation level determined for HEAO-3 data (Englemann et al., 1990) corresponds to  $\phi\sim 800$  MV (Davis et al., 2000).

### 3. GCR Propagation Calculations

To interpret the CRIS observations of LiBeB spectra and isotopic abundances, we use the diffusive reacceleration model (Seo and Ptuskin,

1994). “Reacceleration” is a distributed acceleration of particles due to scattering on random hydromagnetic waves moving at Alfvén speed in the interstellar medium (Fermi 2nd-order mechanism). The model reproduces the peak near 1000 MeV/nucleon in the ratios of secondary to primary nuclei in a physically motivated way (where the parameters are: normalization and index of the diffusion coefficient, the Alfvén speed, and the size of the galactic halo), and is consistent with the K-capture parent/daughter nuclei ratio (Jones et al., 2001a; Niebur et al., 2003).

While the diffusive reacceleration model successfully reproduces data on GCR nuclear species (Moskalenko et al., 2002), it underproduces GCR antiprotons by a factor of  $\sim 2$  at 2 GeV, which may be a signature of new effects. In particular, the propagation of low-energy particles may be aligned to the magnetic field lines instead of

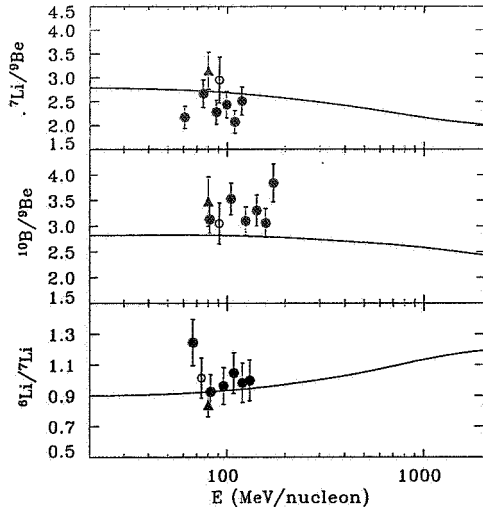


Fig. 2. Isotopic ratios of  ${}^6\text{Li}/{}^7\text{Li}$ ,  ${}^{10}\text{B}/{}^9\text{Be}$ , and  ${}^7\text{Li}/{}^9\text{Be}$  compared with previous data and with the predictions of GALPROP. (Data from CRIS:  $\bullet$ , Garcia-Munoz et al. 1977:  $\circ$ , Lukasiak et al. 1999:  $\blacktriangle$ )

isotropic diffusion (Moskalenko et al., 2002), our local environment (the Local Bubble) may produce a fresh “unprocessed” nuclei component in GCR at low energy (Davis et al., 2000; Moskalenko et al., 2003b), or a more intense nucleon spectra in distant regions could yield more antiprotons and diffuse  $\gamma$ -rays (Strong et al., 2004). New accurate data on LiBeB spectra and isotopic abundances by CRIS may be used to test further the reacceleration model (Moskalenko et al., 2003a).

In our calculations we use the propagation model GALPROP as described in detail elsewhere (Strong and Moskalenko, 1998; Moskalenko et al., 2002; Strong et al., 2004). The model is designed to perform GCR propagation calculations for nuclei ( $Z \leq 28$ ), antiprotons, electrons and positrons, and computes  $\gamma$ -rays and synchrotron emission in the same framework. GALPROP solves the transport equation with a given source distribution and boundary conditions (free escape) for all GCR species. This includes a Galactic wind (convection), diffusive reacceleration, energy losses, nuclear fragmentation, radioactive decay, and production of secondary particles and isotopes.

The code includes cross-section measurements and energy dependent fitting functions (Strong and Moskalenko, 2001). The nuclear reaction net-

work is built using the Nuclear Data Sheets. The isotopic cross section database is built using the extensive T16 Los Alamos compilation of the cross sections (Mashnik et al., 1998) and modern nuclear codes CEM2k and LAQGSM (Mashnik et al., 2004). The most important isotopic production cross sections ( ${}^2\text{H}$ ,  ${}^3\text{H}$ ,  ${}^3\text{He}$ , Li, Be, B, Al, Cl, Sc, Ti, V, Mn) are calculated using our fits to major production channels (e.g., Moskalenko et al., 2001, 2003b; Moskalenko and Mashnik, 2003). Other cross sections are calculated using phenomenological approximations by Webber et al. (1990) (code WNEWTR.FOR versions of 1993 and 2003) and/or Silberberg and Tsao (Silberberg et al., 1998) (code YIELDX\_011000.FOR version of 2000) renormalized to the data where it exists. For  $pA$  inelastic cross section we adapted the parametrization by Barashenkov and Polanski (code CROSEC, Barashenkov, 1993; Barashenkov and Polanski, 1994).

The propagation equation is solved numerically starting at the heaviest nucleus (i.e.,  ${}^{64}\text{Ni}$ ), computing all the resulting secondary source functions, and then proceeds to the nuclei with  $A-1$ . The procedure is repeated down to  $A=1$ . To account for some special  $\beta^-$ -decay cases (e.g.,  ${}^{10}\text{Be} \rightarrow {}^{10}\text{B}$ ) the whole loop is repeated twice. The current version employs a full 3-dimensional spatial grid for all GCR species, but for the purposes of this study the 2D cylindrically symmetrical option is sufficient.

For a given size of Galactic halo, matching the propagation model predictions to the observations of GCR B/C both at low energy with CRIS data and at high energy with HEAO-3 data (Englemann et al., 1990) determines the diffusion coefficient as a function of momentum and the Alfvén speed. The halo size 4 kpc is based on constraints set by the radioactive isotopes  ${}^{10}\text{Be}$ ,  ${}^{26}\text{Al}$ ,  ${}^{36}\text{Cl}$ , and  ${}^{54}\text{Mn}$  (Strong and Moskalenko, 2001; Moskalenko et al., 2001). Assuming a Kolmogorov spectrum of interstellar turbulence, it yields  $6.5 \times 10^{28} \beta (\rho/4 \text{ GV})^\delta \text{ (cm}^2 \text{ s}^{-1}\text{)}$ , where  $\rho$  is the rigidity,  $\delta=1/3$ , the Alfvén speed  $v_A = 35 \text{ km s}^{-1}$ , and the exact values of the reacceleration parameters depend mainly on the adopted cross-sections. The diffusion coefficient is assumed to be independent on the spatial coordinates. While there is no a clear evidence that the diffusion co-

efficient should be distinctly different in the disk and in the halo, this minimizes the number of parameters to be determined from the data. The current state of the data on radioactive isotopes do not warrant more a complicated approach. The measured isotopes to-date ( $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ , and  $^{54}\text{Mn}$ ) all have halves lives around 1 Myrs. To test the diffusion coefficient at different distances from the Sun and in the halo, one needs accurate measurements of radioactive isotopic abundances in CRs that include isotopes with different lifetimes (e.g.  $^{14}\text{C}$ ). Heavy elements that have large fragmentation cross sections may provide another way to test the characteristics of the local interstellar medium (Moskalenko et al., 2005).

Supernova remnants (SNR) are believed to be the primary sources of Galactic cosmic rays. Observations of X-ray (Koyama et al., 1995) and  $\gamma$ -ray emission (Aharonian et al., 2005, 2006) from SNR shocks reveal the presence of energetic particles thus testifying to efficient acceleration processes. The predicted spectrum of accelerated particles has power-law in rigidity with index which may vary around  $-2.0$  (e.g., Ellison & Cassam-Chenaï, 2005; Berezhko & Völk, 2006). Such a hard injection spectrum poses a difficulty in reconciling the propagated spectrum with the direct CR measurements, assuming the Kolmogorov spectrum of interstellar turbulence. The latter is favored by the data (Woo & Armstrong, 1979; Saur & Bieber, 1999) and MHD simulations (Verma et al., 1996). In our calculations, the injection spectrum is tuned to match the spectra of primary GCR nuclei for a given propagation model. For the reacceleration model, the injection spectrum is taken as a power-law in rigidity with index 2.1 below 9 GV and 2.42 above 9 GV, where the injection index at high energies is fixed by the rigidity dependence of the diffusion coefficient  $\propto \rho^{1/3}$ . The source abundances are tuned to match the ACE/CRIS elemental and isotopic abundances (Wiedenbeck et al., 2001). Generally, the injection spectrum is model dependent: different propagation models assume a different rigidity dependence of the diffusion coefficient while the propagated spectra are tuned to the same local data. For reacceleration, this requires a change in the injection spectrum index. At low energies, direct measurements of the interstel-

lar spectrum are impossible due to the solar modulation, while indirect observations of the proton spectrum via pionic gamma rays by EGRET are not accurate enough and cannot be used to fix the spectrum below a few GeV. The spectrum of CR nucleons below  $\sim 10\text{GeV/nucleon}$  is thus tuned to the local data assuming modulation models, which are in turn, approximate and also rely on the interstellar spectrum.

With the availability of precise GCR data from CRIS, uncertainties in the fragmentation cross sections have become a significant limitation to the study of rare GCR species that are generated predominantly via spallation (Yanasak et al., 2001; Moskalenko et al., 2001). A review of current cross sections (Moskalenko and Mashnik, 2003) was undertaken for the dominant reactions involving the production of LiBeB as well as products decaying to LiBeB species (e.g.,  $^6\text{He}$ ,  $^{10,11}\text{C}$ ). For instance,  $\beta^-$ -decay of  $^{10}\text{Be}$  contributes significantly to  $^{10}\text{B}$ , while  $^7\text{Be}$  may produce some  $^7\text{Li}$  via electron capture. Sisterson et al. (1997) have surveyed partial  $^{7,10}\text{Be}$  production cross sections for fragmentation of O on hydrogen over a range of energies  $E \sim 30\text{--}500\text{ MeV/nucleon}$ . Higher energy cross-section measurements ( $E \sim 365\text{--}600\text{ MeV/nucleon}$ , from Webber et al., 1990, 1998) for  $\text{p+CNO} \rightarrow \text{LiBeB}$  reactions have also been made. Michel et al. (1995) gives  $^{7,10}\text{Be}$  production cross sections for fragmentation of CNO on hydrogen over a range of energies  $E \sim 800\text{--}2600\text{ MeV/nucleon}$ . In addition, measurements for  $\text{He+CN} \rightarrow \text{BeB}$  reactions at 600 MeV/nucleon (Webber et al., 1990) and  $\alpha + \alpha \rightarrow \text{Li}, ^7\text{Be}$  at 60–160 MeV (Mercer et al., 1997) are available.

Li, Be, and B in cosmic rays are mainly produced from the interaction of CNO nuclei with interstellar hydrogen. Some of the dominant reactions, such as  $^{12}\text{C} \rightarrow ^6\text{Li}, ^{7,9,10}\text{Be}, ^{11}\text{B}$ ,  $^{14}\text{N} \rightarrow ^7\text{Be}, ^{16}\text{O} \rightarrow ^6\text{Li}, ^{7,10}\text{Be}, ^{9,11}\text{B}$ , are constrained by the data. The cross sections for the production of boron are better known than for the lighter isotopes of beryllium and lithium, since the main contribution to boron production is from CNO and  $^{11}\text{B} \rightarrow \text{B}$ . Thus the model parameters are rather tightly constrained by the measured B/C ratio at low and high energies. However, some channels of Be and Li show a spread in the data between 10-20% or greater. For

example,  ${}^7\text{Be}$  production by CNO nuclei shows a spread by a factor of  $\sim 2$  at energies below a few 100 MeV/nucleon. Some important channels are represented by one or few data points in a narrow energy range (e.g.,  ${}^{11}\text{B}$ , C, O  $\rightarrow$   ${}^{10}\text{B}$ ,  ${}^{11}\text{B} \rightarrow$   ${}^9\text{Be}$ ), while some are not measured at all (e.g.,  ${}^{10}\text{B}$ , N  $\rightarrow$   ${}^9\text{Be}$ , B, Be  $\rightarrow$   ${}^7\text{Be}$ ). The production of Li isotopes is particularly poorly measured. There are only a few data points for Li production by CNO nuclei. The data on Li isotopic production by  ${}^7\text{Li}$ , Be, B nuclei are absent, while a contribution from spallation of these isotopes may exceed  $\sim 35\%$ . See Moskalenko and Mashnik (2003) for more details.

When there is no data, the production cross sections are calculated using the semi-empirical parametrizations. This translates to about a 15% overall uncertainty in the isotopic production ( $\sim 20\%$  for Li), given that typical cross section uncertainties of semi-empirical parametrizations are of the order of  $\sim 50\%$ .

The solid curves in Figs. 1 and 2 correspond to GALPROP predictions modulated assuming a modulation parameter of 550 MV, corresponding to the time period covered in this study (Jan. 1, 1998 to Jan. 23, 1999). The dashed curves in Fig. 1a refer to modulated GALPROP predictions with  $\phi=800$  MV, appropriate for the modulation level during HEAO-3 observations. The model is tuned to match the observations of C and B intensities and the B/C ratio from CRIS (Fig. 1a/b). However, Be and Li intensities and the ratios Li/C and Be/C are  $\sim 10\text{--}20\%$  lower than predicted by the model, although still consistent within the uncertainty determined for the propagation calculation (shown as the hatched region). The isotopic ratios shown in Fig. 2 are also in good agreement with the model predictions. The model uncertainties are mostly due to uncertainties in the cross sections of tertiary interactions such as the production of Be and Li from isotopes of Li, Be, and B as discussed above. Further work is required to pin down these uncertainties.

## 4. Conclusion

We have made GCR LiBeB abundance measurements using the CRIS instrument during near solar minimum conditions in 1998–1999. The isotopic ratios of LiBeB are in agreement with previous measurements of GCR light isotopes, particularly for those experiments acquiring data during periods of solar modulation levels similar to the modulation levels in 1998–1999 covered by CRIS. The reacceleration model gives a satisfactory prediction for GCR primary and secondary species with  $Z \geq 3$ , and shows good agreement with relative isotopic abundances (Jones et al., 2001b; Moskalenko et al., 2002). In some cases, notably  $(p, \alpha) + (\text{Li, Be, B}) \rightarrow \text{Be, Li}$ , a lack of cross-section measurements limits the reliability of model predictions. Understanding the subtle differences between the model predictions and experimental data now hinges on more precise cross section measurements, especially for reactions involving the production of the light isotopes of LiBeB.

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