Proceedings of ICRC 2001: 1831 © Copernicus Gesellschaft 2001

ICRC 2001

The cosmic-ray contribution to libeb: interpretation of LiBeB abundances from CRIS

N. E. Yanasak[1], G. A. de Nolfo[2], W. R. Binns[3], E. R. Christian[2], A. C. Cummings[1], A. J. Davis[1], J. S. George[1], M. H. Israel[3], P. L. Hink[3], R. A. Leske[1], M. Lijowski[3], R. A. Mewaldt[1], E. C. Stone[1], T. T. von Rosenvinge[2], and M. E. Wiedenbeck[4]

[1]California Institute of Technology, Pasadena, CA, 91125
[2]Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA
[3]Dept. of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130 USA
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA

Abstract.
The bulk of galactic Li, Be, and B (LiBeB) abundances is believed to be created during energetic inelastic collisions of cosmic-ray and interstellar medium (ISM) nuclei. Additional sources such as big bang nucleosynthesis or neutrino-driven spallation within Type II supernovae may also add a small contribution. However, measurements of the elemental ratios Be/H, B/H, and Fe/H in old, low-metallicity halo stars indicate an overabundance of LiBeB that can not be accounted for by fragmentation of cosmic-ray CNO. This interpretation assumes that the ISM in any epoch serves as a source of material both for star formation and for cosmic rays, which contribute fragmentation material in later epochs. We have simulated cosmic-ray transport using a simple model and present an interpretation of the abundance measurements from the Cosmic Ray Isotope Spectrometer (CRIS) during the past three years. We will discuss the implications on cosmic-ray LiBeB production at lower energies.

1 Introduction

It has been generally accepted that most of the Li, Be, and B (LiBeB) in the present Galaxy has been produced by inelastic collisions between galactic cosmic rays (GCRs) and the interstellar medium (ISM). These species arise from fragmentation of C, N, and O (CNO) in the ISM by GCR p and He, fragmentation of GCR CNO species by ISM p and He, and $\alpha - \alpha$ fusion in collisions between GCR and ISM nuclei (Reeves et al., 1970). Many previous studies have shown that these mechanisms generally account for all of the present-day local abundances of ^{6}Li, ^{9}Be, and ^{10}B (Reeves, 1994). Other sources of ^{7}Li and ^{11}B are required, leading to the suggestion that a significant component of ^{7}Li in the ISM results from Big Bang nucleosynthesis (King et al., 1977). Calculations by Woosley and Weaver (1995) suggest small contributions to ^{7}Li and ^{11}B galactic abundances from neutrino-driven spallation of ^{12}C within Type II supernovae.

Contrary to the spallogenic origin of LiBeB, the observed elemental ratios Be/H, B/H, and Fe/H in low-metallicity old halo stars indicate an overabundance of LiBeB in early epochs that cannot be accounted for by GCR fragmentation (e.g., Lemoine et al., 1998). This interpretation assumes that the average ISM in any epoch serves as a source of material both for star formation and for GCRs in that epoch (Vangioni-Flam et al., 1990), and that these contribute LiBeB and other fragmentation products to the ISM at later times. To explain both GCR spallogenic calculations and halo star abundances, possible solutions are that LiBeB species are created predominantly via fragmentation in the ISM of low-energy C,O nuclei from SN II and Wolf-Rayet stars (Casse et al, 1995), or that GCRs are accelerated out of the metal-enriched supernova ejecta in superbubbles (Higdon et al, 1999).

To investigate the origin of the LiBeB species, a precise simulation of GCR transport is needed. Our group has been using a simple transport model to study GCR propagation in the galaxy for $3 \leq Z \leq 28$, based upon the formalism of Meneguzzi et al. (1971). Because of their importance in any transport model, we re-examined fragmentation cross sections by surveying scientific literature appearing after the work of Read and Viola (1984), and we have calculated the uncertainties that cross sections contribute to our model predictions. To test our model predictions, we used new abundance measurements made by the Cosmic Ray Isotope Spectrometer (CRIS) during the past three years (de Nolfo et al., 2001).

2 Propagation Model and Cross Sections

A steady-state, leaky-box model (e.g., Meneguzzi et al., 1971) was used for calculating the post-propagation GCR abundances observed by CRIS. A thorough review of the model input parameters (e.g., ISM composition) was con-

Correspondence to: G. A. de Nolfo
(georgia@cosray2.gsfc.nasa.gov)

ducted by Yanasak et al. (2001) to insure consistency with current literature. These parameters are similar to Davis et al. (2000), with a slight adjustment in the mean GCR pathlength for escape to account for the lower ISM fraction of ionized H used in this study. Abundance predictions for Z>4 are identical for both models.

With the availability of precise cosmic-ray data from CRIS, uncertainties in the fragmentation cross sections have become a dominant limitation to the study of rare cosmic-ray species generated via spallation (Yanasak et al., 2001). Partial and total fragmentation cross sections for nuclei of mass A=9–56 were previously updated in Yanasak et al. (2001). For this study, cross sections were re-examined for reactions involving ^{7}Be, Li isotopes, and products decaying to LiBeB species (e.g., ^{6}He, ^{10,11}C). The "excitation functions" of Read and Viola (1984) (hereafter, RV) provide a useful estimate of isobaric production cross sections as a function of energy. However, species such as ^{7}Be and ^{10}Be, which ultimately decay to ^{7}Li and ^{10}B, are present in the GCRs, and their production cross sections are necessary for our model.

In this study, three different methods for evaluating partial cross sections were used. For reactions having many cross-section measurements, a function was defined that could be interpolated to determine a cross-section value at a particular energy (Method 1). For reactions with a small number of measurements, the excitation functions of RV were used for the energy dependence, normalized for agreement with available cross-section data (Method 2). Finally, in cases where the parent nucleus is not CNO, the energy dependence of Silberberg et al. (1998) was used (Method 3a), and the cross sections for He-induced fragmentation were scaled using the parameterization of Hirzebruch et al. (1993). This scaling results in cross sections that are $\lesssim$20% higher than if the scaling function of Tsao et al. (1998) were used. However, no difference in the final LiBeB predictions is discernable using either method. For collisions with parent species A>16, the Silberberg et al. (1998) energy dependence was normalized to cross-section data where it exists (Method 3b). For the methods described above, the isobaric cross-section data compiled in RV were compared to the sum of partial cross sections as a check.

For each method, an average cross-section uncertainty was determined. For Methods 2 and 3b where few cross-section measurements exist, the average uncertainty was taken as $\sigma = 1/\sqrt{\sum_i (1/\sigma_i^2)}$, where σ_i is an individual measurement uncertainty. For Method 1, an average percent deviation off the function weighted by measurement uncertainties was calculated as well as a reduced χ^2 comparing the measurements with the average. For most reactions, χ^2 was smaller than one, and the uncertainty was taken as the reduced standard deviation. For a few reactions, fluctuations not represented by the measurement uncertainties result in a large χ^2, and in these cases, the actual reduced standard deviation was estimated by making $\sigma^2 = \chi^2/\sqrt{\sum_i (1/\sigma_i^2)}$. For Methods 1, 2, and 3b, the average cross-section uncertainties for a reaction are $\sim$ 6%, 13%, and 14% respectively. To estimate the uncertainty for reactions without any measurements (Method 3a), Silberberg et al. (1998) estimate a general uncertainty in their formulae of 20%. We found a similar spread in the measurement distribution around their formulae for reactions

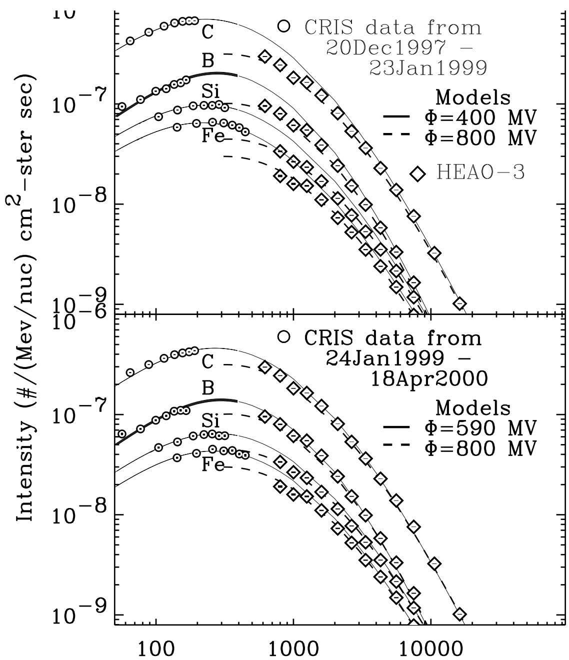

Fig. 1. Flux measurements from CRIS for B and abundant primary GCR species. Data from the HEAO-3 spacecraft are shown for comparison (Englemann et al., 1990). Also shown are predictions for CRIS spectra from our model (solid line), uncertainties for B predictions (thick line below 400 MeV/nucleon), and model predictions at a higher level of modulation ϕ=800 MV comparable to HEAO-3 data (dashed line).

with many cross-section measurements; however, we find a significantly larger spread for ISM helium reactions (from $\sim 0.4 - 2.0$). For our estimates, we use 40% uncertainty for these reactions. In addition to these uncertainties, the contribution from tertiary reactions (e.g., p+B→Li,Be) are not negligible. Using cross-section measurements for the p+B→Be reactions, tertiary reactions contribute 1% uncertainty to the total Be abundance. Unfortunately, no high energy measurements of p+B→Li exist. Although the uncertainty for this reaction is unknown, a 20% cross-section uncertainty from Silberberg et al. (1998) results in a maximum 3% Li abundance uncertainty.

Using the average cross-section uncertainties, the amount of uncertainty in the total predicted LiBeB abundances was calculated assuming a steady-state solution of the leaky-box model, following the formalism of Wiedenbeck (1983) adapted for use with secondary GCR species. Adding the abundance uncertainties in quadrature to uncertainties from tertiary reactions, we find that cross-section uncertainties affect the total predicted LiBeB elemental abundances by ~4.3%, 2.9%, and 2.5% for Li, Be, and B, assuming all cross-section experimental measurements in this discussion were uncorrelated. Correlated data would increase the uncertainties somewhat. However, for the dominant reactions, a large number of independent experiments (>70) contribute to the measurement data, so uncertainty correlations are suppressed in general.

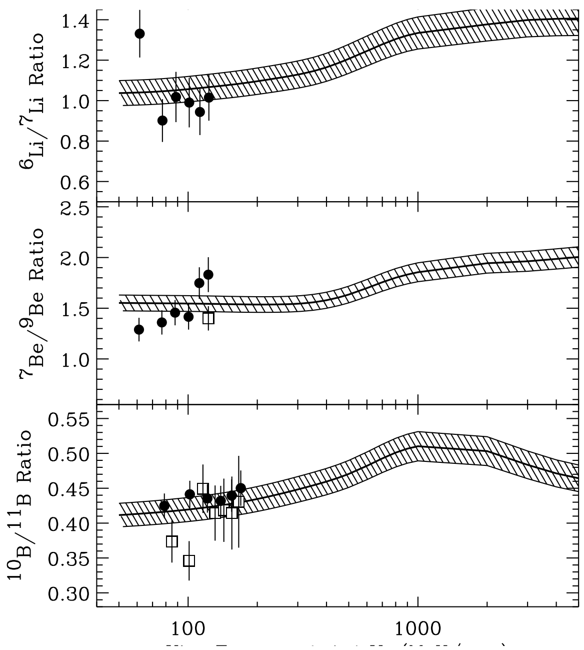

Fig. 2. Relative isotopic abundances from CRIS (filled circles), from ISEE-3 (open squares, from (Krombel and Wiedenbeck, 1988; Wiedenbeck and Greiner, 1980)), and model predictions (solid line). The hatched region indicates 1 σ cross-section uncertainties.

Our steady-state model implicitly uses an exponential GCR pathlength distribution. The mean ISM pathlength was adjusted to match B/C, F/Ne, P/S, and (Sc+Ti+V)/Fe ratios from CRIS, using HEAO-3 data at higher energies for consistency (Englemann et al., 1990). The spherically-symmetric model described by Fisk (1971) was used to simulate solar modulation of the GCR spectra, and modulation levels were determined by choosing a source spectrum and matching post-propagation spectral shapes in our model to HEAO-3 and CRIS data (Davis et al., 2000).

3 Discussion

Predictions for the GCR spectrum of B and other GCR dominant nuclei C, Si, and Fe are shown in Figure 1. The thicker curve overlying the predicted B spectrum at E$\lesssim$400 MeV/nucleon is the uncertainty from cross sections. Data from CRIS and HEAO-3 (Englemann et al., 1990) match both the absolute intensities and energy dependences of the predicted spectra well for B, C, Si, and Fe during both time periods chosen.

Figure 2 shows comparisons between isotopic ratios from model predictions, CRIS data from the first period in Figure 1 (de Nolfo et al., 2001), and ISEE-3 data (Krombel and Wiedenbeck, 1988; Wiedenbeck and Greiner, 1980). The hatched regions shown in Figure 2 are 1 σ cross-section uncertainties, somewhat larger than those described in Section 2 because individual isotopes are considered. The combined statistical and systematic uncertainties for CRIS data are shown in this figure. The average values of the data and the model generally agree. Although the model uncertainties prevent a high-precision comparison of energy dependences with the data, the CRIS ^{7}Be/^{9}Be ratio shows more energy dependence than expected.

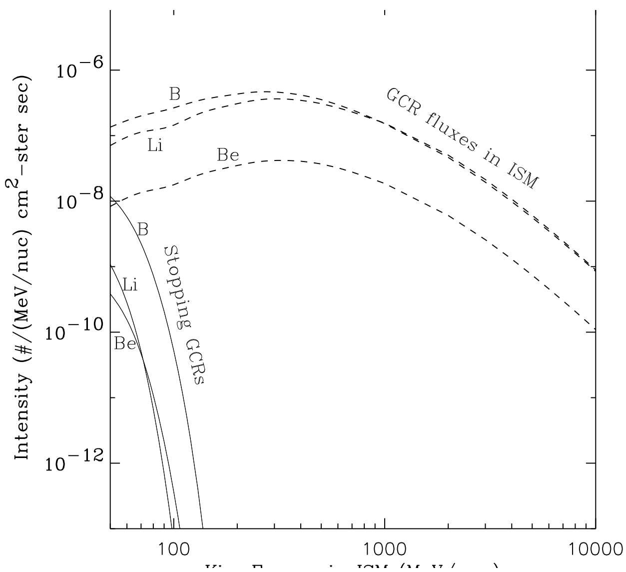

Fig. 3. Predicted GCR LiBeB fluxes in the ISM vs. energy (dashed line). The solid lines indicate the estimated fraction of the GCR LiBeB flux that will thermalize in the Galaxy.

Figure 3 shows the estimated flux of GCR LiBeB that will become thermalized before escape from the Galaxy. The range of GCR LiBeB for $E_{\rm ISM}$ >200 MeV/nucleon is much greater than the mean pathlength, which decreases strongly with decreasing energy. Below this energy, little is known about the energy dependence of the pathlength. Assuming a constant value of 4 g/cm^2 for the mean pathlength at low energies to match the value at 200 MeV/nucleon, approximately 10% of GCR LiBeB with $E_{\rm ISM} = 50$ MeV/nucleon will stop in the Galaxy. Essentially all of the GCR LiBeB that thermalizes is produced below 100 MeV/nucleon.

Fragmentation of ISM C,O by GCR p,He produces most of the galactic LiBeB in the present epoch. Virtually all of the ISM LiBeB produced by GCR p,He of any energy quickly becomes thermalized. Dashed lines in Figure 4 show GCR spectra for p,He in the ISM which match data in Seo et al. (1991), although other GCR measurements exist (e.g., Reimer et al., 1998) that may require somewhat different model spectra at low-energies. Using these spectra, one can calculate the flux of cosmic rays, ν_i, that fragments an ISM species j to produce an LiBeB particle of species i before escaping the galaxy using the formula $\nu_i \approx \sigma_{j\to i,(p,\alpha)}\Phi_{(p,\alpha)}n_j$, where $\Phi_{(p,\alpha)}$ is the GCR intensity, $\sigma_{j\to i}$ is the Production cross section for i via collisions of GCRs and j, and n_j is the ISM column density of j. Solid lines in Figure 4 show the flux of GCR p and

He, ν_i, that produce LiBeB, illustrating that the majority of LiBeB produced in this manner results from GCRs with $E_{\rm ISM}$=200-2000 MeV/nucleon. By integrating the solid

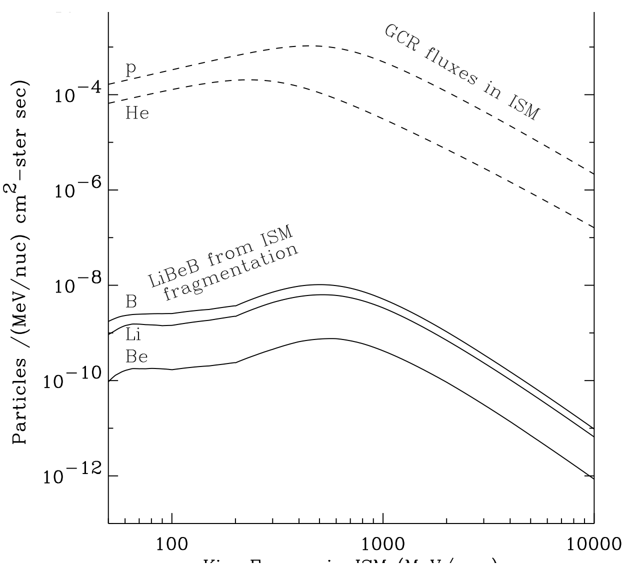

Fig. 4. Contribution of GCR p,He to galactic LiBeB. The dashed lines are GCR spectra in the ISM consistent with data measurements of Seo et al. (1991). The solid lines represent the flux of cosmic rays that interact with the ISM to produce LiBeB particles.

lines in Figure 4 over energy, we determined that ~4% of the LiBeB from GCR p,He interactions with ISM C,O is produced below a GCR energy $E_{\rm ISM}$ <200 MeV/nucleon, and ~12% of the LiBeB is produced from GCR interactions with $E_{\rm ISM}$ >2000 MeV/nucleon. So, precise cross-section values at low energy are less important for these reactions than those at energies $E \sim 200 - 2000$ MeV/nucleon. Although low-energy cross sections are important for reactions involving heavier GCR parents, a comparison of the solid lines in Figures 3 and 4 integrated over energy demonstrates that LiBeB produced as GCR secondaries will only contribute a few percent to the galactic LiBeB of spallogenic origin. The exact amount depends on the mean pathlength below 100 MeV/nucleon, which is unknown at this time.

4 Conclusions

We have surveyed model parameters at GCR energies probed by CRIS ($E_{\rm ISM}$ ~200-500 MeV/nucleon). Our model gives a satisfactory prediction for GCR primary and secondary species with Z≥4, and shows good agreement with relative isotopic abundances. In some cases (notably (p,He)+B→Li), a lack of cross-section measurements limits our understanding of the model inputs. However, with additional measurements made since RV, uncertainties for the cross sections for some reactions have improved, and we have estimated the magnitude of uncertainties in our model predictions. We have shown that essentially all of the thermalized LiBeB produced by fragmentation of heavy GCRs is produced below 100 MeV/nucleon, that the majority of LiBeB from GCR p and He interactions is produced between 200-2000 MeV/nucleon, and that the heavy GCR fragmentation can only contribute a few percent to the spallogenic LiBeB. Future work will include predicting the relative amount of LiBeB produced via GCR p and He and heavy GCRs. We will also investigate the low-energy contribution from $\alpha - \alpha$ fusion to ^{6,7}Li.

Acknowledgements. This research was supported by NASA at the California Institute of Technology, (grant NAG5-6912), the Jet Propulsion Laboratory, the NASA/Goddard Space Flight Center, and Washington University.

References

Casse, M., Lehoucq, R., and Vangioni-Flam, E., *Nature, 373*, 318, 1995.

Davis, A. J, et al. *Acceleration and Transport of Energetic Particles Observed in the Heliosphere: ACE 2000 Symposium*, eds. R. Mewaldt, et al., *AIP Conference Proceedings #528*, 421, 2000.

de Nolfo, G. A., et al., *Proc. 27th Int. Cosmic-Ray Conf. (Hamburg)*, 2001, submitted.

Englemann, et al., *Astron. Astrophys., 233*, 96, 1990.

Fisk, L. A., *J. Geophys. Res., 76*, 221, 1971.

Higdon, H. C., Lingenfelter, R. E., and Ramaty, R., *Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 4*, 144, 1999.

Hirzebruch, S. E., Winkel, E., and Heinrich, W., *Proc. 23rd Int. Cosmic-Ray Conf. (Calgary), 2*, 175, 1993.

King, C. H., Austin, S. M., Rossner, H. H., and Chien, W. S., *Phys. Rev. C, 16*, 1712, 1977.

Krombel, K. E., and Wiedenbeck, M. E., *Astrophys. J.*, 328, 940, 1988.

Lemoine, M., and Vangioni-Flam, E., and Casse, M., *Astrophys. J., 499*, 735, 1998.

Lukasiak, A., McDonald, F. B., and Webber, W. R., *Proc. 26rd Int. Cosmic-Ray Conf. (Salt Lake City), 3*, 41, 1999.

Meneguzzi, M., Audouze, J., and Reeves, H., *Astron. Astrophys., 15*, 337, 1971.

Read, S. M. and Viola, V. E., (RV), *Atomic Data Nucl. Data Tables, 7A*, 233, 1984.

Reeves, H., Fowler, W. A., and Hoyle, F., *Nature Phys. Sci., 226*, 727, 1970

Reeves, H., *Rev. Mod. Phys., 66*, 193, 1994.

Reimer, O., et al., *Astrophys. J., 496*, 490, 1998.

Seo, E. S., Ormes, J. F., Streitmatter, R. E., Stochaj, S. J., Jones, W. V., Stephens, S. A., and Bowen, T., *Astrophys. J., 378*, 763, 1991.

Silberberg, R., Tsao, C. H., and Barghouty, A. F., *Astrophys. J., 501*, 911, 1998.

Tsao, C. H., Silberberg, R., and Barghouty, A. F., *Astrophys. J., 501*, 920, 1998.

Vangioni-Flam, E., Casse, M., Audouze, J., and Oberto, Y., *Astrophys. J., 364*, 568, 1990.

Wiedenbeck, M. E., and Greiner, D. E., *Astrophys. J. Lett., 239*, L139, 1980.

Wiedenbeck, M. E., *Composition and Origin of Cosmic Rays*, ed. M. M. Shapiro, *343*, 1983.

Woosley, S. E., and Weaver, T. A., *Astrophys. J. Supp., 101*, 181, 1995.

Yanasak, N. E., et al., *Astrophys. J.*, 2001, submitted.