Light Element Evolution in the Galactic Halo

Andreu Alibés
Department of Astronomy, University of Barcelona, Martí i Franquès 1, E-08028, Barcelona, Spain. E-mail: aalibes@quasar.am.ub.es

Ramon Canal
Department of Astronomy, University of Barcelona, Martí i Franquès 1, E-08028, Barcelona, Spain. E-mail: ramon@mizar.am.ub.es
Institut d’Estudis Espacials de Catalunya/UB, Edif. Nexus-104, Gran Capità 2-4, Barcelona, Spain

Abstract.
Using a time-dependent Galactic Cosmic Ray flux proportional to the halo Star Formation Rate and including astration and neutrino-induced nucleosynthesis, we have studied the evolution of lithium, beryllium and boron in the halo. Our results set limits to the production of LiBeB by the neutrino-induced nucleosynthesis in massive stars, in order to reproduce the observed constancy of Be/Fe and B/Fe ratios, the lithium plateau and the isotopic ratios evolution.

1. Introduction
Light-element evolution due to spallation reactions between Galactic Cosmic Rays and the Interstellar Medium has been intensively studied in the last thirty years, since the pioneering work of Meneguzzi, Audouze and Reeves (1971). In recent years, lithium, beryllium and boron (LiBeB) abundances have been measured in low-metallicity stars and new constraints have been set on the evolutionary models. The Spite plateau ($T_{eff} > 5700$ K and $[Fe/H] < -1.0$) for lithium and the [Be] and [B] vs [Fe/H] linear relationship are the main characteristics of LiBeB abundances in halo stars. Our main objective has been to reproduce those observational results and also to get isotopic ratios that agree with the few data available. In our evolution code, a simple astration model has been used and the possibility of neutrino-induced nucleosynthesis has been considered.

2. Model
Using a burst of 1 Gyr as halo star formation rate, we have calculated the age-metallicity relation, including just yields from gravitational supernovae (type Ib and II) (fig. 1). We have not considered yields from type Ia supernovae due to the longer lifetime of their progenitors.
Figure 1.  *Halo star formation rate and halo age-metallicity relation*

We have used equation (1) for the evolution of the five stable isotopes ($^6$Li, $^7$Li, $^9$Be, $^{10}$B and $^{11}$B)

$$\frac{d(X_L(t)\sigma_g(t))}{dt} = A \cdot Q_L(t) - X_L(t) \int \text{IMF}(m) \cdot SFR(t) \ dm +$$

$$\int f_L(m) \cdot X_L(t - \tau_m) \cdot \text{IMF}(m) \cdot SFR(t - \tau_m) \ dm +$$

$$\int_{12}^{40} \frac{m_{\nu L}(m, [Fe/H])}{m} \cdot SFR(t - \tau_m) \cdot \text{IMF}(m) \ dm$$

(1)

- The first term on the right side represents the contribution of spallation reactions of Galactic Cosmic Rays with the Interstellar Medium. We have considered a Galactic Cosmic Ray flux proportional to the star formation rate, which seems reasonable if we take type II supernovae as the mechanism that accelerates Cosmic Rays. This rate has been calculated with the Ramaty et al. (1997)’s code, using:

1. the new [O/Fe] vs [Fe/H] data from Israeli et al. (1998)
2. a type II SNe ejecta as composition of GCR (table 1).

| SNII ejecta composition |
|-------------------------|
| $He/e/H = 0.20$        | $[He/e/H] = 0.521$ |
| $C/H = 2.1 \cdot 10^{-3}$ | $[C/H] = 0.709$ |
| $N/H = 5.8 \cdot 10^{-4}$ | $[N/H] = 0.825$ |
| $O/H = 1.2 \cdot 10^{-2}$ | $[O/H] = 1.23$ |
3. a shock accelerated spectrum (eq. 2) with $E_0 = 100$ MeV/n

\[ q(E) \propto \frac{E^{-2.2}}{\beta} e^{-E/E_0} \]  

4. $\Lambda = 10$ g/cm$^2$, escape length

Other spectra, $E_0$ and escape length have been tried, but those finally chosen give the best agreement with the data.

- The second term represents the amount of each light element that goes into new-born stars.

- The third term represents the amount of each light element that each star returns to the interstellar medium after its death. We have used a shell-model star with light elements homogeneously distributed and the reaction rates of Caughlan and Fowler (1988). We have let the star evolve during all its lifetime and then we have obtained the mass fraction of the ejected material where each light nuclide has not been totally destroyed. We represent this function by $f_L(m)$ (fig. 2).

- Finally, the fourth term is the contribution of neutrino-induced nucleosynthesis to the LiBeB evolution.

3. Results

3.1. GCR nucleosynthesis alone

As a first step in our calculations, we didn’t include the yields from the neutrino-induced nucleosynthesis in massive stars. The LiBeB evolution that is obtained agrees with the observed evolution: the lithium plateau is well fitted (fig. 3) and the slope of 1 in the beryllium and boron versus metallicity relationships is reproduced (fig. 4).
Concerning light-element ratios, $^{6}\text{Li}/^{7}\text{Li}$ and Li/B evolution are reproduced and B/Be evolution is close to the average value of 15. However, the evolution of the boron isotopic ratio needs some other production site for $^{11}\text{B}$, in order to get at $[\text{Fe/H}]=-1$ a value close to the solar $^{11}\text{B}/^{10}\text{B} = 4.05 \pm 0.2$ (fig. 5).

3.2. Limits to the neutrino-induced nucleosynthesis

In the next step, the yields of neutrino-induced nucleosynthesis theoretically calculated by Woosley & Weaver (1995) are included. When the full yields are used ($\alpha_\nu = 1.0$), neither the lithium plateau nor the linear boron evolution are appreciably affected (fig. 6), in spite of the production of $^{7}\text{Li}$ and $^{11}\text{B}$ by the $\nu$-process.

To reproduce the LiBeB isotopic ratios would be the main way of setting limits to the contribution of neutrino-induced nucleosynthesis to the light-element evolution in the halo. In spite of the lack of LiBeB isotopic ratios data, several facts can be considered: i) $\nu$-process doesn’t affect the elements evolution; ii)
if we consider that the subsequent disk evolution doesn’t produce any change in the $^{11}\text{B}/^{10}\text{B}$ ratio, a $\alpha_\nu = 0.85$ would be necessary; iii) if this ratio changes in the disk evolution, values from $\alpha_\nu = 0.5$ to 1.0 should be considered (fig. 7). A galactic halo+disk model (work in preparation) will restrict better this parameter.

4. Conclusions

In the Galactic Halo, as it has been found for the light element evolution in the disk, Galactic Cosmic Ray Nucleosynthesis alone can not be the only source of LiBeB. As the existence of Low Energy Cosmic Rays is nowadays doubtful, the $\nu$-process (Woosley et al. 1990) is another possible source, mainly for $^7\text{Li}$ and $^{11}\text{B}$. If neutrino-induced nucleosynthesis contributes to LiBeB evolution, Woosley & Weaver’s yields must be revised, due to the uncertainties involved in its calculation, in order to reproduce the isotopes evolution. To constrain further the range of parameters of our model, more measurements for the light-element ratios would be required, especially those on $^{11}\text{B}/^{10}\text{B}$.

Acknowledgments. We thank Dr. R. Ramaty for kindly providing us with his numerical code for cosmic-ray induced nucleosynthesis.

References

Caughlan, G.R., & Fowler, W.A. 1988, At. Data Nucl. Data Tables, 40, 284
Figure 6. *Lithium and boron evolution including ν-process (α_ν = 1.0)*

Figure 7. *Light-element isotopic ratios evolution including ν-process*

García López, R.J., Lambert, D.L., Edvardsson, B., Gustafsson, B., Kiselman, D., & Rebolo, R. 1998, ApJ, 500, 241
Hobbs, L.M., & Thorburn, J.A. 1997, ApJ, 491, 772
Israelian, G., García López, R.J., & Rebolo, R. 1998, ApJ, 507, 805
Meneguzzi, M., Audouze, J., Reeves, H. 1971, A&A, 15, 337
Molaro, P., Bonifacio, P., Castelli, F., & Pasquini, L., 1997, A&A, 319, 593
Ramaty, R., Kozlovsky, B., Lingenfelter, R.E., & Reeves, H. 1997, ApJ, 488, 730
Smith, V.S., Lambert, D.L., & Nissen, P.E. 1998, ApJ, 506, 405
Woosley, S.E., Hartmann, D.H., Hoffman, R.D., & Haxton, W.C. 1990 ApJ, 356, 272
Woosley, S.E., & Weaver, T.A. 1995, ApJS, 101, 181