In this article we study the Galactic evolution of the LiBeB elements within the framework of a detailed model of the chemical evolution of the Galaxy that includes Galactic cosmic-ray (GCR) nucleosynthesis by particles accelerated in superbubbles. The chemical composition of the superbubble consists of varying portions of interstellar medium (ISM) and freshly supernova-synthesized material. The observational trends of $^6$Li evolution are nicely reproduced by models in which GCRs come from a mixture of 25% supernova material with 75% ISM, except for $^6$Li, for which perhaps an extra source is required at low metallicities. To account for $^7$Li evolution, several additional sources have been considered (neutrino-induced nucleosynthesis, nova outbursts, and C stars). The model fulfills the energetic requirements for GCR acceleration.

**Subject headings:** cosmic rays — ISM: abundances

---

1. INTRODUCTION

The evolution of the light nuclides ($^6$Li, $^7$Li, $^9$Be, $^{10}$B, and $^{11}$B) has been, since the early 1970s, a major topic in the studies of Galactic chemical evolution. The theoretical scenario for the synthesis of lithium, beryllium, and boron has remained unchanged for years since the pioneering work of Meneguzzi, Audouze, & Reeves (1971). Recent observations (see, e.g., Molaro et al. 1997; Boesgaard et al. 1999a) have revealed an almost linear correlation of both Be and B with Fe at low metallicities. This new trend seems to rule out the common view of Galactic cosmic-ray (GCR) particles being accelerated from material of the interstellar medium (ISM), as the latter predicts a quadratic dependence on metallicity, and it has motivated models of LiBeB nucleosynthesis that consider new sites for the production and acceleration of the GCRs (Ramaty et al. 2000; Fields et al. 2000; Parizot & Drury 2000). A source of low-energy cosmic rays, enriched in C and O, was one of the first suggested solutions to the problem, mainly inspired by gamma-ray observations in Orion, which, however, once revised, appeared spurious (Bloomen et al. 1999). That has led, temporarily at least, to the discarding of the low-energy component hypothesis.

Scenarios in which the composition of the GCRs was identical to that of the ejecta from individual supernovae have also been ruled out by observations with the *Cosmic Ray Isotope Spectrometer (CRIS)* on board the *Advanced Composition Explorer (ACE)* that measured the abundance of the radioactive isotope $^{59}$Ni and its decay product $^{59}$Co in current-epoch GCRs (Binnings et al. 1999). $^{59}$Ni decays by electron capture with a half-life of $7.6 \times 10^4$ yr, but it does not decay if it is accelerated. The abundance measurements show a very small amount of $^{59}$Ni in GCRs, and so there must be a minimum delay of $10^3$ yr between the explosive nucleosynthesis of the material entering in GCRs and its acceleration. Such a delay, however, could be accounted for in models in which the GCRs originated in a superbubble (SB) region of hot, rarefied, metal-rich gas swept out by the collective effects of massive star winds and supernova explosions.

In the SB scenario of Ramaty et al. (2000), LiBeB nucleosynthesis is a primary mechanism (i.e., production $\propto O$), since the composition of the GCRs, which exclusively come from the ejecta of supernovae inside the SB, does not change in time, and is quite metal-rich. Other authors preferred a combination of a primary and a secondary (i.e., production $\propto O^2$) mechanism. Parizot & Drury (2000) considered also an SB scenario for the acceleration of GCRs, but they adopted a composition of the SB material that is a mixture of ISM plus 2% or 3% of supernova (SN) ejecta, according to nonmagnetic SB models. On the other hand, Fields et al. (2000) combined two sources of GCRs: one accelerated from the ISM that has a secondary character, and a second component coming from SB and made of pure ejecta of SNe, having thus a primary behavior. In the last two cases, the primary mechanism dominates at low metallicities, while the secondary one takes over when the ISM becomes more metal enriched. Nevertheless, despite the fact that it seemed that the old secondary-only GCR nucleosynthesis paradigm was unable to reproduce the Be and B versus Fe slope, Fields & Olive (1999) succeeded in doing so by using the recently observed O/Fe relationship, with a single slope $\approx -0.35$ for [O/Fe] versus [Fe/H] at all metallicities (Israelian, Garcia López, & Rebolo 1998; Boesgaard et al. 1999b; Israeli et al. 2001). The situation regarding [O/Fe] evolution is, however, far from being clear, as stated in Fulbright & Kraft (1999).

Most of the models for light-element evolution published in recent years used analytical approximations for the evolution of some of the important elements in the LiBeB synthesis: carbon, nitrogen, oxygen, and iron (Fields & Olive 1999b; Fields et al. 2000; Parizot & Drury 2000; Ramaty et al. 2000). Some were closed models (Vangioni-Flam et al. 1998; Fields & Olive 1999; Fields et al. 2000), which are unable to solve the G dwarf problem, as stated in Pagel (1997).

Concerning lithium evolution, several works have recently been published involving different types of possible stellar sources (Romano et al. 1999), one of which, massive asymptotic giant branch (AGB) stars, seems to have been...
recently ruled out as an important source (Ventura, D’Antona, & Mazzitelli 2000). Casuso & Beckman (2000) have proposed a model that only considers GCR nucleosynthesis, but with a GCR rate proportional to the gas ejection rate from stars with masses lower than 3 $M_\odot$.

In this article we analyze the evolution of the light elements by means of a detailed numerical model for the Galactic chemical evolution (Alibés, Labay, & Canal 2001; hereafter ALC01). Our model assumes that the Galaxy builds by infall of extragalactic material, in an inside-out scenario for Galaxy formation, and adequately reproduces the main solar neighborhood observational constraints: age-metallicity relation, G dwarf metallicity distribution, current star formation (SFR) and supernova rates, and the evolution of the main elements up to the iron peak (see figures and tables in ALC01). In § 2 the model is briefly described, and the results are presented in § 3. The conclusions are given in § 4.

2. THE MODEL

We solve numerically the classical equations for the chemical evolution of the Galaxy, relaxing the instantaneous recycling approximation. The same ingredients as in ALC01 are used for our LiBeB evolution model. That includes the double infall of Chiappini, Matteucci, & Gratton (1997), given by

$$\frac{d\sigma(t)}{dt} = A e^{-t/\tau_T} + B e^{-(t-t_{\max})/\tau_D},$$

(1)

where $\sigma(t)$ is the total surface mass density, $\tau_T$ and $\tau_D$ are the characteristic infall timescales for the halo-thick disk phase and for the thin disk phase, respectively, and $t_{\max}$ is the time of maximum accretion into the thin disk. We take $t_{\max} = \tau_T = 1$ Gyr and $\tau_D = 7$ Gyr. The coefficients $A$ and $B$ are fixed by imposing the condition that they reproduce the current solar neighborhood values of the total and halo mass surface densities.

An enriched infall model is adopted, which accretes primordial matter during the first Gyr and then begins to incorporate slightly enriched material, with a metallicity of $Z = 0.1 Z_\odot$, as suggested by the recent observations by Wakker et al. (1999) of a massive ($\sim 10^7 M_\odot$) metal-enriched ($0.09 Z_\odot$) cloud that is now falling into the disk. We have also considered the more usual assumption of a primordial composition for the whole infall process. Although in the first case there is a small contribution to the light-element abundances from the infall, the final results for both types of infall are almost indistinguishable, as we show later.

The initial mass function (IMF) used, $\Psi$, is that of Kroupa, Tout, & Gilmore (1993), which takes different slopes for $M/M_\odot \leq 0.5$, $0.5 \leq M/M_\odot \leq 1.0$, and $M/M_\odot \geq 1.0$. The range of stellar masses considered goes from 0.08 to 100 $M_\odot$.

The star formation rate is from Dopita & Ryder (1994) (eq. [2]) with $m = 5/3$, $n = 1/3$, and $\nu = 1.2$:

$$\Psi(r, t) = \nu \frac{\sigma^m(r, t) \sigma^n(r, t)}{\sigma^{n+m-1}(r, t)} \ M_\odot \ pc^{-2} \ Gyr^{-1},$$

(2)

applied to the solar Galactocentric distance of 8.5 kpc.

To account for the CNO evolution, some of the most recent and most extensive (both in mass and metallicity) yield calculations are used: van den Hoek & Groenewegen (1997) for low- and intermediate-mass stars, Woosley & Weaver (1995)$^2$ for Type II supernovae, and model W7 from Thielemann et al. (1996) for Type Ia supernovae. Our results for the CNO evolution are shown in Figure 1 for the two infall compositions. Carbon and nitrogen follow the observational data, while [O/Fe] shows a gradual increase toward low metallicity with a slope of $\sim 0.28$. This value is slightly lower than the values obtained from observations of the O I triplet (Abia & Rebolo 1989; Israelian et al. 1998, 2001; Boesgaard et al. 1999b) of $\sim -0.35$.

2.1. LiBeB Sources

In Meneguzzi et al. (1971), only spallation reactions induced by GCRs and big bang nucleosynthesis of $^7$Li were considered as sources of LiBeB. Since then, several stellar mechanisms have been proposed as sources of some of the light elements: the $\nu$-process (possible solution to the solar system boron and lithium isotopic ratios problem), nova outbursts (possible producers of $^7$Li), and C stars (identified producers of $^7$Li). All of them are included in our evolution code. Massive AGB stars are not included as a source of $^7$Li, since recent works (Ventura et al. 2000) insist on their small contribution to the evolution of this isotope.

2.1.1. Big Bang Nucleosynthesis

$^7$Li is the only light element that is produced in a significant amount in standard big bang nucleosynthesis (BBN) models. In nonstandard BBN, some amount of other isotopes could also be produced, but the data available at low

$^2$ The reader is reminded here that, as in our previous solar neighborhood model (ALC01), only half of the iron yields calculated by these authors are adopted.
metallicities do not indicate the presence of any kind of abundance plateau for them. A BBN contribution of $^{7}\text{Li} = 2.2^3$ has been included according to Molaro (1999), which ensures the existence of the lithium or Spite plateau (Spite & Spite 1982) up to $[\text{Fe}/\text{H}] \approx -1.5$. Because of this BBN production of $^{7}\text{Li}$, open- and closed-box models of Li evolution do not give the same results, since in closed-box models all the primordial lithium is already in place when the evolution begins. Therefore, closed-box models with the same nucleosynthetic prescriptions as open ones do produce an overabundance of Li at $[\text{Fe}/\text{H}] = 0$ by a factor of $\sim 1.6$. This is not the case for Be and B, for which open- and closed-box models give similar results.

2.1.2. Galactic Cosmic-Ray Nucleosynthesis

As in Parizot & Drury (2000), we adopt a composition of the GCRs ($X_{\text{GCR}}$) corresponding to their being accelerated inside a superbubble, in which newly synthesized material ejected by a supernova ($X_{\text{ej}}$) is accelerated by the shock waves generated by other SNe and mixed with the ISM of that epoch ($X_{\text{ISM}}$). The evolution of the latter being that shown in Figure 1:

$$X_{\text{GCR}}(t) = \alpha_{\text{ej}} X_{\text{ej}}(t) + (1 - \alpha_{\text{ej}}) X_{\text{ISM}}(t).$$ (3)

Different compositions of the GCRs are used by changing the free parameter $\alpha_{\text{ej}}$ in equation (3). For $\alpha_{\text{ej}} = 0$, we have pure ISM CR composition, and for $\alpha_{\text{ej}} = 1$, pure Type II supernova composition.

The CR source spectrum considered is the so-called shock-acceleration spectrum

$$q(E) \propto E^{-\gamma} e^{-E/E_0},$$ (4)

where $E$ and $E_0$ are the particle momentum and kinetic energy, both per nucleon; $\beta = v/c$; and, for the two parameters, we have chosen $s = 2.2$ and $E_0 = 10$ GeV nucleon$^{-1}$. Here $E_0$ takes into account the possibility that the spectrum is cut off at high energies. Since a leaky-box model for GCR propagation is adopted, an escape path of CRs from the Galaxy of $X_{\text{esc}} = 10$ g cm$^{-2}$ has been included in the propagation calculations.

For the calculation of the production rate by spallation reactions, we have used a revised version of the LiBeB code from Ramaty et al. (1997), which includes the cross sections of Read & Viola (1984) and takes into account all the possible reactions leading to any LiBeB isotope, both direct and inverse [including two-step processes such as $^{16}\text{O}(p, \alpha)^{12}\text{C}(p, \alpha)^{7}\text{Li}$]. Since GCR particles are supposed to come from the material inside an SB, the GCR flux, and therefore the spallation reaction production rate, is made proportional to the Type II supernova rate.

We do not consider any low-energy cosmic rays (LECRs), since the only observational evidence of this type of CR, spotted in the Orion star formation region, has been withdrawn (Bloemen et al. 1999). Future X-ray and gamma-ray line observations should clarify whether LECRs actually exist.

2.1.3. The $\nu$-Process

Woosley & Weaver (1995), in their calculations of the yields from Type II supernovae, took into account the contribution from the neutrino-induced nucleosynthesis, i.e., the spallation reactions between the huge flux of neutrinos ejected by the explosion and the newly synthesized material in the intermediate layers of the star. This primary mechanism, which has not been observationally corroborated, produces mainly $^{7}\text{Li}$ and $^{11}\text{B}$, so it could be quite important, because GCR nucleosynthesis alone cannot reproduce the solar system lithium and boron isotopic ratios. Since these yields are quite uncertain because the flux intensity and energy spectrum of the neutrinos are not well known, a correction factor, $f_N$, is introduced, its value obtained by fitting the meteoritic boron isotopic ratio.

2.1.4. Novae

Nova outbursts could be important nucleosynthetic sites for those elements that have overproduction factors there, relative to solar, above 1000. According to the recent yields for CO and ONe nova outbursts from José & Hernanz (1998), that is the case for $^{7}\text{Li}$ (nova outbursts produce, during the thermonuclear runaway, $^{7}\text{Be}$, which decays into $^{7}\text{Li}$). We have thus adopted a $^{7}\text{Li}$ average yield per nova outburst of $1.03 \times 10^{-10} M_\odot$, taking into account that 30% of the nova outbursts come from ONe white dwarfs and an outburst rate given by the equation

$$\frac{dR_{\text{outbursts}}}{dt} = D \int_{M(t)+0.5}^{0.5} \frac{\Phi(M_B)}{M_B} dM_B$$
$$\times \int_{f_0}^{f_{\text{hu}}} f(\mu) \Psi[t - \tau_{\text{MB}}(1-\mu) - \tau_\text{cool}] d\mu,$$ (5)

where $D$ ensures that the current nova outburst rate is $\sim 40$ yr$^{-1}$ (Hatano et al. 1997). $M_B$ is the binary mass, $\mu$ is the ratio of the mass of the secondary star to that of the whole binary system, and finally, $f(\mu)$ is the binary mass ratio distribution function of Greggio & Renzini (1993). The time for the WD to cool enough to be able to start producing outbursts, $\tau_\text{cool}$, is set to 1 Gyr. $^{7}\text{Li}$ production by nova outbursts could be confirmed by the future International Gamma-Ray Astrophysical Laboratory (INTEGRAL) mission.

2.1.5. C Stars

Even if supernovae ($\nu$-process) and novae are theoretically possible sources of $^{7}\text{Li}$, carbon-rich stars (C stars) with $C/O > 1$ give the only undeniable evidence for a stellar origin of this isotope, since they are seen to be Li-rich. The majority of them show low carbon isotopic ratios ($^{13}\text{C}/^{12}\text{C} < 15$) and are of J type (Abia & Isern 1997), with masses lower than $2.3 M_\odot$. The mechanism by which $^{7}\text{Li}$ is produced and ejected to the ISM is not well established, so the only way to estimate the yield is empirical. Abia, Isern, & Canal (1993) statistically analyzed the contribution of C stars to the $^{7}\text{Li}$ nucleosynthesis and suggested a time-dependent production rate,

$$S_7(t) = S_7^0 \frac{f_0}{f_M} \frac{\Phi(M)\Psi(t - \tau_M) dM}{\int_{M_0}^{M_0} \Phi(M)\Psi(t - \tau_M) dM},$$ (6)

where $M_l = 1.2 M_\odot$ and $M_u = 3 M_\odot$. They estimated empir-
has survived and has been ejected from each star $\frac{7}{4}$ Gyr. The authors point out that this $^{7}\text{Li}$ production rate can only be a lower limit, and they needed to increase it to $6 \times 10^{-3} \text{ M}_\odot \text{pc}^{-2} \text{Gyr}^{-1}$ (Abia, Isern, & Canal 1995) in order to obtain a good fit to the solar system data. In the present model, this rate only has to be increased up to $1.5 \times 10^{-8} \text{ M}_\odot \text{pc}^{-2} \text{Gyr}^{-1}$.

### 2.2. Destruction of LiBeB

Traditionally, LiBeB isotopes are supposed to be completely destroyed in stars, so when they die they do not contribute to the ISM abundance. This assumption has been checked by means of main-sequence stellar models (Hansen & Kawaler 1994) that include all the nuclear reactions involved in LiBeB destruction, whose rates are taken from Caughlan & Fowler (1988). We have evaluated, for the whole range of stellar masses, the fraction of each LiBeB isotope that survives and is ejected from the star. Our results are displayed in Figure 2. As expected, the two lithium isotopes are the most fragile ones within the LiBeB group, and they are almost completely destroyed in stars over a wide range of stellar masses. Beryllium and both boron isotopes are more resistant, since they are destroyed at higher temperatures, but nevertheless the fraction of the original BeB that survives is, as in the case of the lithium isotopes, very small.

These destruction terms are included in our calculations, and there are only minute differences in the final results as compared with those obtained assuming complete destruction.

### 3. RESULTS

We have analyzed the evolution of the light elements, taking into account all the sources described in §2.1 and the restrictions that energetics puts on the spectrum and composition of GCRs. In Table 1 a summary of all the different sources considered is presented. It is important to note that no other combination of the contribution from the different sources could reproduce all the constraints considered (lithium plateau, beryllium evolution vs. iron, and solar system boron isotopic ratio and lithium abundance).

#### 3.1. Abundances Evolution

Concerning the GCR composition, we show in the left panel of Figure 3 that for values of $\alpha_{ej}$ (see eq. [3]) near 0.25 (solid line), good fits to the observed Be and B evolution as a function of $[\text{Fe}/\text{H}]$ are obtained. The $\chi^2$ test gives an interval for the possible $\alpha_{ej}$ values of $(0.12, 0.41)$ for a level of confidence of 90%. For values of $\alpha_{ej}$ near 0 (GCRs made only from accelerated ISM), a slope of 2 results, while if taking a value of $\alpha_{ej}$ close to 1 (GCRs made of SNe ejecta), the contribution from GCR nucleosynthesis to LiBeB evolution at low metallicities is too large. The preceding means that a double origin for the composition of GCRs must be considered, since both a pure Type II supernova composition and a pure ISM composition can be rejected. Such a mixture is not well explained in nonmagnetic SB models (which favor $\alpha_{ej} \approx 0.02$), unless we assume that the bulk of the GCRs come from the central part of the SB, where the SN ejecta material would be more dominant (Higdon et al. 1998). However, magnetic SB models (Tomisaka 1992) give higher values for $\alpha_{ej}$, because magnetic fields reduce heat conduction and thus the evaporation of the ISM shell surrounding the SB. The value of $\alpha_{ej}$ for these latter models is close to our best fit. In the right panel of Figure 3, we compare the evolution, in the $\alpha_{ej} = 0.25$ case, for the two different infall compositions. One sees that the evolution is practically unaffected by the chemical composition of the accreted matter, as long as its enrichment remains moderate.

The very recent beryllium abundance determination in the very metal poor halo star G64–12 ($[\text{Fe}/\text{H}] = -3.30$ and $[\text{Be}] = -1.1$) by Primas et al. (2000) is not well fitted. As stated by the authors, this value would suggest either a flattening of the Be versus Fe relationship at low metallicities or dispersion of values in the early Galaxy. More low-metallicity data are needed to confirm either of these suggestions.

Parizot (2000), also within the framework of an SB model for the acceleration of GCRs, analyzed the proportion of pure ejecta of supernovae accelerated in superbubbles (our

### TABLE 1

| Source      | Isotopes Produced | Contribution | Fixed by  |
|-------------|-------------------|--------------|-----------|
| BBN        | $^{7}\text{Li}$  | $[^{7}\text{Li}] = 2.2$ | Li plateau|
| GCRN       | LiBeB             | $\alpha_{ej} = 0.25$ | Be vs. Fe |
| $\alpha$-process | $^{7}\text{Li}$ and $^{11}\text{B}$ | $f_{ej} = 0.29$ | $(11\text{B}/10\text{B})$ | |
| Novae      | $^{7}\text{Li}$  | Averaged yield |           |
| C stars    | $^{7}\text{Li}$  | $S_{ej} = 1.5 \times 10^{-8} \text{ M}_\odot \text{pc}^{-2} \text{Gyr}^{-1}$ | $^{7}\text{Li}$ |
parameter $\alpha_{ej}$. He found a best value of 0.03 when adopting a GCR energy spectrum $q(E) \propto E^{-1} \exp(-E/E_0)$, with a rather low cutoff energy of $E_0 = 500$ MeV nucleon$^{-1}$, which is supposed to mimic the results of particle acceleration in SB by a collection of weak shocks. Thus, our best value of $\alpha_{ej} = 0.25$ is a factor of $\sim 8$ larger than the result obtained by Parizot (2000). Such discrepancy comes in part from the higher efficiency of his weak SB spectrum. Had this spectrum been used instead of that in equation (4), a larger Be production per erg would have been obtained, by a factor of $\sim 2.2$, thus reducing by the same factor our mixing coefficient $\alpha_{ej}$. A further factor of $\sim 3$ is due to the fact that Parizot (2000) did not calculate the evolution of the actual Be/O abundance ratio, but only that of the Be/O production ratio, by dividing the yields of Be and O per supernova. In that way, stellar astration, which is important for late times and high metallicities, was not taken into account. Astration severely reduces the abundance of Be but not that of O, thus lowering the Be/O abundance ratio at late times (Fields et al. 2001). Our model, neglecting stellar astration, produces a Be abundance at $[\text{Fe/H}] = 0$ that is $\sim 3$ times larger than the value measured in the solar system. Finally, the study by Parizot (2000) does not follow the detailed evolution of the composition of the ISM by means of a chemical evolution model. Instead, he assumes solar composition scaled with metallicity, i.e., O/H, which translates into overestimated C and N abundances, both in the ISM and in the $1 - \alpha_{ej}$ fraction of GCRs accelerated from the ISM.

Since beryllium is supposed to be produced only by GCRs, and therefore its abundance is expected to be directly dependent on the oxygen abundance in the ISM, it is interesting to compare our model results with the observational data in a [Be] versus [O/H] plot (Fig. 4). We notice that if we use the oxygen calculated in ALC01, the best value of the parameter $\alpha_{ej}$ does not seem to be the same as that obtained from the [Be] versus [Fe/H] plot. This flaw was expected, since our calculated oxygen evolution does not perfectly fit the data from Israelian et al. (1998, 2001) and Boesgaard et al. (1999b), although our results are closer to them than those obtained in other recently published Galactic chemical evolution models. However, when their relationship for [O/Fe] versus [Fe/H] is used to transform the Be-Fe plot to a Be-O one, a reasonable fit is recovered for $\alpha_{ej} = 0.25$, at least for the low-metallicity region, where our results closely follow the mean trend of the data. At high metallicity we slightly overpredict the Boesgaard et al. (1999a) data, but the solar system value is still well reproduced.

In Figure 5, the evolution of total lithium and $^6$Li are shown—in the left panel for several values of the parameter $\alpha_{ej}$ and in the right panel for the two infall compositions and fixed $\alpha_{ej}$. The lithium plateau is well reproduced, as well as the upper envelope of the Population I stars and the solar system value. As shown in Figure 6, the increase of the lith-
ium abundance for $[\text{Fe}/\text{H}] > -1.5$ is due to the contribution from the neutrino-induced nucleosynthesis, and continues by the additional Li from C stars and nova outbursts, whose contribution is delayed to intermediate and high metallicities because of the long lifetimes of the low-mass progenitors of those objects. C stars are the main contributors at high metallicities, as is clearly seen in the figure. The parameter $\alpha_{ej}$ has little effect on the lithium evolution, because at low metallicities, where changes of this parameter make the GCR nucleosynthesis production rate change, the Li from the big bang and the $\alpha + \alpha$ reactions dominate. In the case of $^6$Li, the less abundant lithium isotope that is still not sufficiently measured at low metallicities, our model reproduces the solar system value but not the low-metallicity observations. As indicated by Ramaty et al. (2000), this may suggest the need for an extra source of $^6$Li in the Galaxy. A possible solution to this defect of $^6$Li production would be a higher primordial value (some nonstandard BBN models produce large $^6$Li abundances; Jedamzik & Rehm 2001), but that would also mean the existence of plateaus at low metallicities for Be and B (or a $^7$Li primordial value not compatible with the Spite plateau), which have not been observed up to now.

As happens for Be and B, the Li evolution is almost independent of the assumed composition of the infalling matter.

### 3.2. Ratios Evolution

Isotopic and elemental ratios are crucial to analyzing the importance of the different contributions to LiBeB abundances. The boron isotopic ratio shows, for a given value of $\alpha_{ej}$, the importance of the neutrino-induced nucleosynthesis. This source is necessary to reach the solar system value. On the other hand, the boron over beryllium ratio data are quite constant at all metallicities, implying that the $\nu$-process cannot be dominant. The data on the next element ratio considered, Li/B, show a steep descent from the large value at low metallicities, due to the Li plateau, down to the solar value. Finally, there are quite a few available data for $^6$Li, so the lithium isotopic data are not a strong constraint, the solar system data excepted.

In all cases we have used a value of the parameter that restricts the contribution of the neutrino-induced nucleosynthesis of $f_\nu = 0.29$ (similar to that found by Ramaty et al. 2000), which allows us to reproduce the solar system boron isotopic ratio, as displayed in the top panel of Figure 7. Higher values of $f_\nu$ would increase the ratio $^{11}\text{B}/^{10}\text{B}$ up to values not allowed by the solar system data. We see that the ratio is quite constant during the halo phase (a higher ratio for lower values of $\alpha_{ej}$) because of the contribution of the $\nu$-process and the primary character of GCR nucleosynthesis in those early epochs, and it decreases toward the solar system value when the secondary behavior of the GCRs becomes important enough. The lack of data at low metallicity hinders a more firm conclusion, but the descending trend after $[\text{Fe}/\text{H}] = 0$ is compatible with the current ISM ratio ($3.4 \pm 0.7$; Lambert et al. 1998).
A similar behavior is shown by the B/Be ratio (Fig. 7, bottom panel). The constant ratio is higher for lower values of \( \alpha_{\text{sh}} \), and the standard GCR nucleosynthesis also dominates at high metallicity.

Finally, the two other ratios considered include lithium (Fig. 8, with \(^6\text{Li}/^7\text{Li}\) in the top panel and Li/B in the bottom one). As we have already pointed out, our model cannot account for the \(^6\text{Li}\) at low metallicities, so the lithium isotopic ratio obtained is much lower than the nonzero \(^6\text{Li}/^7\text{Li}\) data around \([\text{Fe/H}] = -2.5\). The values at intermediate metallicities are not reproduced, since the stars where they have been measured may have suffered some amount of lithium destruction (more important in the case of \(^6\text{Li}\) than for \(^7\text{Li}\)). For the Li/B ratio, this lack of \(^6\text{Li}\) is not important and our models fit well the available data.

### 3.3. Energetics

Since supernovae, either individually or in SB, are supposed to be the site of GCR acceleration, the total energy of a SN explosion must be larger than the energy of the GCR particles produced by it. The mean value of the Be/Fe ratio in low-metallicity stars measured by Molaro et al. (1997) and Boesgaard et al. (1999a) is about \(1.37 \times 10^{-6}\), and the average yield of \(^{56}\text{Fe}\) from a SN, according to ALC01 prescriptions, is \(Q_{\text{SN}}(\text{Fe}) = 0.0515 \ M_\odot \equiv 1.1 \times 10^{54}\) atoms. Then, as shown by Ramaty et al. (1997), one can evaluate the number of atoms of Be produced by each SN event:

\[
Q_{\text{SN}}(\text{Be}) = \frac{\text{Be}}{\text{Fe}} Q_{\text{SN}}(\text{Fe}) \approx 1.5 \times 10^{48}\text{ atoms}.
\]

We have also evaluated the number of atoms of beryllium produced per erg \(Q(\text{Be})/W\); Fig. 9, top panel), so we can show in the bottom panel the amount of energy per SN required to accelerate GCRs, as

\[
W_{\text{GCR}}^{\text{SN}} = \frac{Q_{\text{SN}}(\text{Be})}{Q(\text{Be})/W}.
\]

Since the early Galaxy was poor in metals, more energy per SN was required to account for the Be/Fe ratio than in the present day, when the secondary mechanism also contributes to the synthesis of Be. In the halo phase, the value of \(W_{\text{GCR}}^{\text{SN}}\) is about \(2 \times 10^{50}\) ergs, so the energy constraint is fulfilled because only 15%–20% of the kinetic energy of any supernova has to be involved in GCR acceleration.

### 4. CONCLUSIONS

The results of a recent and successful Galactic chemical evolution model are applied to the particular problem of the light elements. To calculate the LiBeBe evolution, it is necessary to know which are the abundances of hydrogen, helium, and the CNO nuclei in the ISM, since they are the main targets of the GCRs to produce lithium, beryllium, and boron. The evolution of iron is also important, because traditionally the light-element evolution has been plotted in [LiBeBe] versus [Fe/H] graphs and iron has been taken as representative of the metallicity of the stars for which LiBeBe have been measured. In order to achieve this goal, we have used some of the latest and most complete calculations of the yields from different types of stellar scenarios for nucleo-
synthesis: low- and intermediate-mass stars, Type Ia and II supernovae, and nova outbursts.

Our calculations show that a mixture of 25% of SN ejecta (with upper and lower limits of 12% and 41%, respectively) and 75% of ISM, for the GCR composition, can account for the linear trend of BeB versus Fe. If the O/Fe versus Fe relationship of Boesgaard et al. (1999b) (somewhat steeper than the one obtained by ALC01) is used, an acceptable fit to the Be versus O plot is also obtained.

On the other hand, the lithium plateau is easily reproduced with a BBN contribution, as usual, and the increase of the Li abundance after the halo phase is quite nicely reproduced as well by taking into account several sources (the v-process, nova outbursts, and C stars).

Concerning the isotopic evolution, our model fails to reproduce the early-time \(^{6}\text{Li}/^{7}\text{Li}\) ratio because of a lack of \(^{6}\text{Li}\) at low metallicities. We point out the necessity of an extra source for this isotope. The other calculated ratios, however, nicely reproduce the data.

Finally, the energy problem has been addressed, in order to check that not too large a fraction of the supernova energy is required to produce the light elements.

This work has been supported by the DGESIC grant PB98-1183-C03-01 and the DGI grant AYA2000-0983. We thank the late R. Ramaty for kindly providing us with his numerical code for cosmic-ray–induced nucleosynthesis of the light elements.

Abia, C., & Isen, J. 1997, MNRAS, 289, L11
Abia, C., Isen, J., & Canal, R. 1993, A&A, 275, 96

Fulbright, J. P., & Kraft, R. P. 1999, AJ, 118, 527
Fulbright, J. P. 2000, AJ, 120, 1841

REFERENCES

Globular clusters: studies and evolution, ed. J. Hesser et al. (Cambridge: Cambridge Univ. Press)

Hog, S., Fabricius, C., & Minniti, D. 1999, A&A, 343, 521
Hobbs, L. M. 1999, in ASP Conf. Ser. 171, LiBeB, Cosmic Rays and Related X- and Gamma-Rays, ed. R. Ramaty et al. (San Francisco: ASP), 96

Bloomen, H., et al. 1999, ApJ, 521, L137
Boesgaard, A. M., King, J. R., & Lambert, D. L. 2000, ApJ, 533, 978
Molaro, P. 1999, in ASP Conf. Ser. 171, LiBeB, Cosmic Rays and Related X- and Gamma-Rays, ed. R. Ramaty et al. (San Francisco: ASP), 6