ABSTRACT

Recently, new observations of $^6\text{Li}$ in Population II stars of the Galactic halo have shown a surprisingly high abundance of this isotope, about a thousand times higher than its predicted primordial value. In previous papers, a cosmological model for the cosmic-ray-induced production of this isotope in the intergalactic medium (IGM) has been developed to explain the observed abundance at low metallicity. In this paper, given this constraint on the $^6\text{Li}$, we calculate the nonthermal evolution with redshift of D, Be, and B in the IGM. In addition to cosmological cosmic ray interactions in the IGM, we include additional processes driven by supernova explosions: neutrino spallation and a low-energy component in the structures ejected by outflows to the IGM. We take into account CNO CRs impinging on the intergalactic gas. Although subdominant in the Galactic disk, this process is shown to produce the bulk of Be and B in the IGM, due to the differential metal enrichment between structures (where CRs originate) and the IGM. We also consider the resulting extragalactic gamma-ray background, which we find to be well below existing data. The computation is performed in the framework of hierarchical structure formation, considering several star formation histories, including Population III stars. We find that D production is negligible and that a potentially detectable Be and B plateau is produced by these processes at the time of the formation of the Galaxy ($z \sim 3$).

Subject headings: cosmic rays — cosmology: observations — intergalactic medium — nuclear reactions, nucleosynthesis, abundances

Online material: color figures

1. INTRODUCTION

Big bang nucleosynthesis (BBN), together with Galactic cosmic-ray nucleosynthesis (GRN), has revealed a consistent picture of the origin and evolution of deuterium, helium, lithium, beryllium and boron. This combination involves very different aspects of nucleosynthesis, including primordial nonthermal and stellar nucleosynthesis, all of which are correlated through cosmic and chemical evolution. There is one single free parameter in the standard model of BBN, the baryon density, which has now been determined with high precision by the Wilkinson Microwave Anisotropy Probe (WMAP; Spergel et al. 2007), rendering BBN a parameter-free theory (Cyburt et al. 2002, 2003). The derived BBN value of D/H is in agreement with that deduced from observations ($D/H = 2.84 \pm 0.26 \times 10^{-5}$ (O'Meara et al. 2006 and references therein). This is a key success of big bang cosmology.

Unlike deuterium, which is observed in high-redshift quasar absorption systems, the LiBeB abundances are primarily determined from observations of the atmospheres of stars in the halo of our Galaxy. Low-metallicity stars (Population II stars) offer various constraints on the early evolution of those light elements, assuming that time and metallicity are correlated. Until recently, the evolution of the abundances of $^6\text{Li}$, $^7\text{Li}$, $^9\text{Be}$, and $^{10,11}\text{B}$ could be explained in the context of GRN, along with the primordial value of $^7\text{Li}$ from BBN, which forms the Spite plateau (Spite & Spite 1982) for stars with metallicity lower than about [Fe/H] = $-1.5$ (for a review see Vangioni-Flam et al. 2000). The first observations of $^6\text{Li}$ at [Fe/H] $\simeq -2$ (Smith et al. 1993; Hobbs & Thorbum 1994, 1997; Smith et al. 1998; Cayrel et al. 1999; Nissen et al. 2000) were entirely consistent with the predicted abundances of $^6\text{Li}/^7\text{Li} \approx 0.5$ in standard GRN models (Steigman et al. 1993; Fields & Olive 1999; Vangioni-Flam et al. 1999).

Unfortunately, recent observations have led to two distinct Li problems. First, given the baryon density inferred from WMAP, the BBN predicted values of $^7\text{Li}$ are $^7\text{Li}/^H = 4.27^{+1.02}_{-0.83} \times 10^{-10}$ (Cyburt et al. 2001, 2003; Cyburt 2004), $^7\text{Li}/^H = 4.9^{+1.4}_{-1.2} \times 10^{-10}$ (Cuoco et al. 2004), or $^7\text{Li}/^H = 4.15^{+0.49}_{-0.45} \times 10^{-10}$ (Coc et al. 2004). These values are all significantly larger than most determinations of the lithium ($^7\text{Li}/^7\text{Li}$) abundance in Population II stars, which are in the range $1-2 \times 10^{-10}$ (see, e.g., Spite & Spite 1982; Ryan et al. 2000; Bonifacio et al. 2007). These values are also larger than a recent determination by Meléndez & Ramírez (2004) based on a higher temperature scale. This is still an open question, which will not be addressed in this paper. Second, recent observations of $^6\text{Li}$ at low metallicity (Asplund et al. 2006; Inoue et al. 2005) indicate a value of $[^6\text{Li}] = \log^6\text{Li}/^H + 12 = 0.8$, which appears to be independent of metallicity, in sharp contrast to what is expected from GRN models, and is more consistent with a pregalactic origin. While BBN does produce a primordial abundance of $^6\text{Li}$, it is at a level about 1000 times below these recent observations (Thomas et al. 1993; Vangioni-Flam et al. 1999). GRN builds on the BBN value, yielding a $^6\text{Li}$ abundance which is proportional to metallicity. Thus, an additional source of $^6\text{Li}$ is required at low metallicity ([Fe/H] < $-2$), and different scenarios have been discussed which include the production of $^6\text{Li}$ during the epoch of structure formation (Suzuki & Inoue 2002; Nakamura et al. 2006; Tatischeff & Thibaud 2007) or through the decay of relic particles during the epoch of big bang nucleosynthesis (e.g., Kawasaki et al. 2005; Jedamzik et al. 2006; Kusakabe et al. 2006; Pospelov 2006; Cyburt et al. 2006).

In previous papers (Rollinde et al. 2005, 2006, hereafter RVOI, RVOII), we investigated the possibility of high-redshift
cosmological cosmic rays (CCRs), accelerated by the winds of Population III supernovae, and thus related the nonthermal production of $^6$Li to an early population of massive stars. The star formation history was computed in the framework of the hierarchical structure formation scenario, as described in Daigne et al. (2006). RVOII showed that the production of $^6$Li by the interaction of CCRs with the IGM provides a simple way to explain the observed $^6$Li abundance, within a global hierarchical structure formation scenario that accounts for reionization, the star formation rate (SFR) at redshift $z \lesssim 6$, and the observed chemical abundances in damped Ly$\alpha$ absorbers and in the intergalactic medium. The additional amount of $^7$Li produced is negligible, so that the discrepancy between the theoretical prediction and the observed $^7$Li abundance is not worsened.

Here, we examine the consequences of the CCR production of $^6$Li on the abundances of the related Be and B isotopes. The CCR spallation of $\beta$ and $\alpha$-particles on CNO in the IGM, as well as the reverse process of the spallation of CNO in CCRs on H and He in the IGM, are considered in computing the IGM abundances of the LiBeB elements. As a consistency check, we also compute the abundance of D in the IGM and the extragalactic gamma-ray flux of the LiBeB elements. As a consistency check, we also compute the SN-driven outflows that enrich the IGM. The same SN rate will be used here to derive the flux of CCRs. The efficiency for the escape of these CCRs is discussed below.

2. THE CCR SCENARIO AND PRODUCTION MECHANISMS

Our modeling of the nucleosynthesis by CCRs is based on the global scenario for hierarchical structure growth and cosmic star formation, as developed by Daigne et al. (2006). This model is based on a Press & Schechter (PS) formalism, and satisfies a number of observational constraints, such as star formation rates at $z \lesssim 6$ and reionization at high $z$, as well as the abundances of several trace elements in the ISM and IGM.

Baryons are divided into three reservoirs: the gas (“ISM”), the stars and their remnants (“stars”), and the medium in between collapsed structures (“IGM”). The evolution of the baryonic mass of these reservoirs accounts for the accretion of baryons from the IGM, the formation of stars, the ejection of enriched gas by stars, and the outflow of baryons from the structures into the IGM (hereafter referred to as simply “outflow”). This outflow is driven by supernova (SN) energetics and the gravitational potential of the structure. The chemical evolution of both ISM and IGM is followed simultaneously. While the evolution of the collapsed structures is constrained by the PS formalism, the history of star formation depends on the minimum mass $M_{\text{min}}$ of dark matter halos of star-forming structures, the normalization of the SFR that describes the efficiency of star formation ($\nu$ in Daigne et al. 2006), and the initial mass function (IMF) describing the massive mode of star. Here we have adopted the best-fit model with $M_{\text{min}} = 10^7 M_\odot$ (see § 4). Although the star formation rate at redshifts $z \lesssim 6$ is relatively well measured (Hopkins 2004; Hopkins & Beacom 2006), the choice of the SFR at higher redshifts could introduce an uncertainty in our results. However, this is constrained by several factors pertaining to the chemical evolution as described in Daigne et al. (2006). The choice of the massive mode, as described below, introduced the largest uncertainty in our results concerning CCRs. Once the IMF and SFR are specified, one can compute the SN-driven outflows that enrich the IGM. The same SN rate will be used here to derive the flux of CCRs. The efficiency for the escape of these CCRs is discussed below in § 2.2.

The models considered in Daigne et al. (2006) were all bimodal models of star formation. Each model contained a normal mode of stars with masses between 0.1 and 100 $M_\odot$, and an IMF with a near Salpeter slope. The SFR of the normal mode peaks at $z \approx 3$. In addition to a normal mode of star formation, there is a massive component which dominates star formation at high redshift. Here, we consider two possibilities for the massive mode. First, as in RVOII, we consider a model in which the massive mode corresponds to stars with masses in the range $40 - 100 M_\odot$ (model 1). These stars terminate as type II SNe. Second, we consider a model in which the massive mode corresponds to stars with masses in the range $270 - 500 M_\odot$ (model 2b). These massive stars are assumed to terminate as black holes through total collapse and do not contribute to any metal enrichment in either the ISM or IGM. It is, however, unclear whether these implosions are responsible for the acceleration of cosmic rays. Energy must get out during the collapse, but this may be entirely in the form of neutrinos and gravitational waves. We have not included any contribution to the flux of CCRs from the massive component of model 2b stars.

2.1. CCR Origin

CCRs are made by elements initially present in the ISM, accelerated by the SN shock waves, and then expelled from the structures. Nucleosynthesis occurs when they finally interact with the elements present in the IGM.

We compute the energy and flux of CCRs as in RVOI and RVOII. The fraction of the total energy injected in CCRs is $\epsilon_{\text{CR}}/100$ (where 99% of the energy is emitted in the form of neutrinos), with an efficiency $\epsilon_{\text{CR}}$ for CR acceleration. The total kinetic energy $E$ per SN in CCRs is $E_{\text{II}} = 10^{51.5} \epsilon_{\text{CR}}$ ergs for stars which leave neutron stars as remnants, i.e., stars with masses $8 M_\odot < m < 30 M_\odot$, and are associated with normal SNe II. For more massive stars, up to $1000 M_\odot$, we take the total energy of core collapse to be $0.3$ times the mass of the He core, with $M_{\text{He}} = 0.17 (m - 20 M_\odot)$ (Heger et al. 2003). Thus, for the massive mode (associated with Population III) of model 1, which is dominated by $40 M_\odot$ stars, we have $E_{\text{III}} = 10^{52.8} \epsilon_{\text{CR}}$ ergs. In RVOII, $\epsilon_{\text{III}}$, which within reason is a free parameter for each model, was taken to be $0.15$ for model 1.

2.1.1. CCR Spectra

As in RVOI and RVOII, the source spectra are taken to be power laws in momentum, $dQ/dp \propto p^{-\gamma}$ (Drury 1983; Blandford & Eichler 1987, or Jones 1994 for a brief introduction). The CR
proton flux is normalized to the total kinetic energy injected by the SN.

In our scenario, we have considered a simplified picture for CCR generation, where the source and propagated spectra are equal. In RVOI and RVOII, the CR spectral index was taken to be $\gamma = 3$. This is consistent with the limited scope of our scenario, where the details of injection, propagation in the structure, escape, and propagation in the IGM are advantageously described by a single phenomenological source/propagated power-law spectrum. We will come back to and comment further on this issue in our conclusions.

Given this phenomenological approach, we choose to stay as close as possible to existing data. Because of the lack of a sound description of CR spectra at all redshifts, a possible and conservative choice for describing the CR spectra of heavy elements (CNO) is to match the observed present-day Galactic CR spectrum. Indeed, a departure from a pure power law is observed at low energy: this is caused by the well-understood galactic confinement and preferential destruction of heavier elements compared to lighter ones (see, e.g., Fig. 1 of Maurin et al. 2004). For simplicity, we assume a pure power law for $p$ and $\alpha$ particles, with spectral index $\gamma_p$ and $\gamma_{\alpha}$. In addition, the spectrum for CNO is modeled as a broken power law:

$$\frac{dQ_{\text{CNO}}}{dp} \propto \begin{cases} \rho^{-\gamma_{\text{He}}} & \text{if } E \geq E_0, \\ \rho^{-\gamma_{\text{CNO}}} & \text{otherwise.} \end{cases} \tag{1}$$

Based on observations of the H, He, and CNO spectra (see Fig. 13 in Hörandel 2007), we set $\gamma_p \approx \gamma_{\text{He}} \equiv \gamma \approx 3$, and $\gamma_{\text{C}} \approx \gamma_{\text{N}} \approx \gamma_{\text{O}} \approx 1.5$, with $E_0 = 8$ GeV nucleon$^{-1}$. Such a parameterization will prove to be crucial to the resulting BeB production (%3.3).

In the following, all CCRs above a given energy $E_{\text{cut}} = 1$ MeV nucleon$^{-1}$ are assumed to efficiently escape from the structures.

### 2.1.2. CCR and IGM Abundances

The abundance pattern in the CRs is linked to the abundance in the ISM. In Galactic cosmic rays (GCRs), significant deviations for some elements are observed due to differing acceleration efficiencies (e.g., Ellison et al. 1997; Meyer et al. 1997). The same behavior is assumed for CCRs. It is convenient to define the abundances of different species $i = \{\text{He}, \text{C}, \text{N}, \text{O}\}$ relative to H in CCRs, the ISM and the IGM:

$$F_i \equiv \frac{\Phi_i}{\Phi_p}, \quad n_i \equiv \frac{n_{\text{ISM}}}{n_{\text{H}}}, \quad \bar{f}_i \equiv \frac{n_{\text{IGM}}}{n_{\text{H}}}, \tag{2}$$

where $\Phi_i$ is the CCR flux for species $i$ and $n_i$ is the respective number density. The quantity $F_i$ is related to the interstellar abundances by

$$F_i = \eta_i f_i, \tag{3}$$

and $\eta_i$ is matched to the abundance pattern observed in the GCR fluxes (see Table 1 of Meyer et al. 1998): $\eta_{\text{He}} = 0.7$, $\eta_{\text{C}} = 8.45$, $\eta_{\text{O}} = 5$, and $\eta_{\text{N}} = 1.47$. Abundances in the ISM ($f_i$) and in the IGM ($\bar{f}_i$) are computed as in Daigne et al. (2006). In the following, we always assume $f_{\text{He}} = f_{\text{He}} = 0.08$. The abundances of metals, on the other hand, $f_{\text{CNO}}$ and $\bar{f}_{\text{CNO}}$, do depend on $z$.

The BeB production in the IGM depends on both $F_i$ and $\bar{f}_i$. Their evolution with redshift for C and O are displayed in Figure 1 for the two SFR models considered. Note that the contributions of reactions involving the CCR flux of N (not shown in the figure) are always negligible compared to C and O. Note also that the CR fluxes and IGM enrichment in model 2b evolve more slowly than in model 1, due to the presumption that the very massive Population III stars associated with model 2b provide neither metal enrichment nor a source for cosmic rays. In model 2b, both originate from the normal mode, whereas in model 1, CRs and metal enrichment receive contributions from the normal mode and massive mode at higher redshift.

### 2.2. Cosmic Ray Escape Efficiency

In RVOI and RVOII, the efficiency of secondary CR escape from the ISM of early galactic structures (hereafter simply “galaxies”) into the IGM was always assumed to be high. However, as shown in RVOII, the effects of CR heating of the IGM, required a certain degree of confinement of CR propagation and $^6$Li production to regions that will develop into the warm-hot IGM. Here we present a physical justification of these assumptions.

In accordance with Daigne et al. (2006), we can evaluate the mass $\bar{M}(z)$ of a typical galaxy at redshift $z$ as the mass-weighted average over the Press-Schechter mass function of collapsed dark matter halos $f_{\text{PS}}(M,z)$,

$$\bar{M}(z) = \frac{\int_{M_{\min}}^{\infty} dM M^2 f_{\text{PS}}(M,z)}{\int_{M_{\min}}^{\infty} dM f_{\text{PS}}(M,z)}, \tag{4}$$

where $M_{\min} = 10^7 M_\odot$. The average ISM density and radius of the halo can be estimated respectively as

$$\rho_{\text{ISM}}(z) = (\Omega_b/\Omega_m) \Delta(z) \rho_c(z), \tag{5}$$

and

$$R(z) = \left[ \frac{3 \bar{M}(z)}{4 \pi \rho_c(z) \Delta(z)} \right]^{1/3}, \tag{6}$$

where $\rho_c(z)$ is the critical density of the universe at $z$, and $\Delta(z)$ is the density contrast of halos virializing at $z$ (e.g., Barkana & Loeb 2001).
CR escape out of the ISM can be mediated either by diffusion or by advection in a galactic outflow. The CR diffusion coefficient $\kappa$ is governed by magnetic fields within early galaxies and is quite uncertain. Here we follow the plausible physical prescription of Jubelgas et al. (2006) and assume $\kappa(p, z) = 3 \times 10^{27} \text{cm}^2 \text{s}^{-1}/(p/m_p c)^{1.3}(n_{\text{ISM}}/\text{cm}^{-3})^{-1/2},$ where $p$ is the CR momentum. Note that we have normalized to the present-day Galactic value at unit ISM number density $n_{\text{ISM}}$, and neglected the weak dependence on ISM temperature. The timescale for diffusive escape is

$$\tau_{\text{diff}}(p, z) = R(z)^2/4\kappa(p, z).$$

Alternatively, CRs may escape by being advected in supernova-driven outflows of ISM gas into the IGM. The timescale for advective escape is simply

$$\tau_{\text{adv}}(z) = R(z)/v_{\text{esc}}(z),$$

where $v_{\text{esc}}(z)$ can be evaluated as in Daigne et al. (2006).

Ionization losses within the ISM may deplete LiBeB-producing, low-energy CRs before they manage to escape. The ionization loss timescale for a CR particle of velocity $\beta c$, charge $Z$, and mass $A m_p$ in a medium of neutral H is

$$\tau_{\text{ion}}(\beta, z) = (A m_p m_e c^3/4\pi Z^2 e^4) \beta(\gamma - 1) \times \left[\ln \left(2 m_p c^2 \gamma^2 \beta^3 / I_H\right) + \beta^2\right]^{-1} n_{\text{ISM}},$$

where $\gamma = (1 - \beta^2)^{-1/2}$ is the particle Lorentz factor and $I_H = 13.6 \text{ eV}$ is the H ionization potential (e.g., Longair 1992).

In Figure 2, $\tau_{\text{age}}$, $\tau_{\text{diff}}$, and $\tau_{\text{ion}}$, the latter two for $\alpha$ particles of kinetic energy $30 \text{ MeV nucleon}^{-1}$, as functions of $z$ are compared with the age of the universe $\tau_{\text{age}}$, a rough measure of the available time at $z$. We can see that the timescales for CR escape out of the ISM by either diffusion or advection are always much shorter than $\tau_{\text{age}}$ at all $z$, with diffusion dominating over advection above $z \sim 7$. This justifies the assumption of RVOII regarding efficient CR escape into the IGM. However, we see that in some cases ionization losses in the ISM can become important on the escape timescales, and such effects should be included in future, more detailed studies.

While the timescales for advection and diffusion indicate that CRs eventually escape to the IGM, it is important to consider the spallation timescales to determine whether there are any potential effects on the CR spectrum. A simple estimate of the spallation timescale, $\tau_{\text{spal}} = (n_{\text{ISM}}/\beta \sigma_{\text{spal}})$, shows that spallation indeed occurs on timescales shorter than those associated with escape. Noting that the total destruction cross section is roughly constant above a few hundred MeV and using $\sigma_{\text{spal}} \sim 30 \text{ m barn}$, $\sigma_{\text{spal}} \sim 100 \text{ m barn}$, and $\sigma_{\text{spal}} \sim 1000 \text{ m barn}$, one finds timescales on the order of $\tau_{\text{spal}} \lesssim 10^6$ yr. This implies that within structures and certainly within volumes associated with the warm-hot IGM, we expect the effects of confinement to play a role, and hence allows us to assume a spectrum with a propagated slope of $\gamma = -3$ for $\rho$ and $\alpha$ particles and a flattened spectrum of the form given in equation (1) for CNO.

We note that the above estimate of $\rho_{\text{ISM}}$ should become increasingly inappropriate at lower $z$ when the total halo mass approaches Milky Way scales and the gas within them collapses to a thin disk via efficient radiative cooling. Then the ISM will have a much higher density within a small disk scale height, and much lower density for the remaining halo volume. The same would be true if CRs were accelerated from a rotationally supported disk (at higher densities than the halo density discussed above) formed from cooler star forming gas (Mo et al. 1998; Kravtsov et al. 2004). The CR diffusion time out of the disk should be less than $\tau_{\text{diff}}$ at low $z$, as evidenced by the known CR escape time out of the current Galactic disk ($\sim 10^7$ yr for GeV CRs), and that out of the halo into the IGM should also be less by virtue of the low gas density in the halo.

2.3. Low-Energy Component and Neutrino Spallation

In the past it has been shown that, besides standard CRs, there is a need for an additional source of LiBeB in the structures, since standard CRs do not reproduce either (1) the meteoritic $^{11}$B/$^{10}$B isotopic ratio or (2) the linear (rather than quadratic) proportionality between Be (and B) and Fe in the halo phase. These two constraints can be satisfied by taking into account two additional sources of LiBeB (Vangioni-Flam et al. 2000): (1) the neutrino spallation in the He and C shells of SNe, which synthesizes $^7$Li and $^{11}$B, and (2) the break-up of low-energy nuclei injected in molecular clouds, which produces all LiBeB isotopes.

Those additional processes, as well as their nucleosynthesis products, take place in the structure during SN explosion. They are computed according to Olive et al. (1994), Cassé et al. (1995), and Vangioni-Flam et al. (1996). Once they are produced in situ, the LiBeB products are ejected and mixed in the local ISM of the structure. They are subsequently ejected into the IGM through the global outflow of the ISM, as computed by Daigne et al. (2006; see their Fig. 9). Note that this source of LiBeB is distinct from and not correlated with the CCR production described above. In the rest of the paper, the term “outflow” is specifically used to describe this process.

3. RESULTS

For all elements X, primordial abundances are assumed at the initial redshift $z = 30$ of the model. The production of X by CCR interactions in the IGM is integrated down to $z = 0$. In addition, the abundance of each element is affected by outflows: these
contributions are shown separately in the figures. The calculation for D, Be, and B production follows closely that of the \( ^{6}\text{Li} \), as given, for example, in RVOI. The full calculation is then compared to a simplified calculation (eq. [A7] and values gathered in Table 1; Appendix A). Note that throughout the paper, \( E \) denotes the kinetic energy per nucleon.

### 3.1. Lithium

The abundance of lithium in the IGM increases with decreasing redshift due to the interaction of CR \( \alpha \) particles with He at rest in the IGM (the cross section peaks at 10 MeV nucleon \(^{-1} \)). Since the total energy in CRs is proportional to \( \epsilon_{\text{CR}} \), the amount of lithium produced depends on both \( \gamma \) and \( \epsilon_{\text{CR}} \), and of course on the assumed model for star formation. Note that lithium is also produced through CNO interactions with H and He at rest. These are taken into account in the calculation, but the contribution to the total abundance of Li is always subdominant in this context (§ 2.1.1).

We have constrained \( \epsilon_{\text{CR}} \) to ensure a PIE of \( ^{6}\text{Li} \) with abundance \( ^{6}\text{Li}/H = 10^{-11.2} \) at \( z = 3 \). The results for model 1 and model 2b are shown in Figure 3 (dashed and solid lines, respectively). Model 1 has already been discussed in RVOI, and it was determined there that \( \epsilon_{\text{CR}} \approx 0.15 \) was necessary to produce the requisite amount of \( ^{6}\text{Li} \). In model 2b, however, Population III stars terminate as black holes, with no assumed production of cosmic rays. Thus, the lithium production is delayed and a higher efficiency is required, \( \epsilon_{\text{CR}} \approx 0.5 \). Such a high value is consistent with those found in diffusive shock acceleration models (Berezhko & Volk 1997, 2000, 2006; Berezhko & Ellison 1999; Blasi et al. 2005; Ellison & Cassam-Chenai 2005; Kang & Jones 2006; Ellison et al. 2007), as confirmed by recent comparison with observations of supernova remnants (e.g., Berezhko & Volk 2004; Warren et al. 2005).

The additional lithium due to outflows from the inner regions (as discussed in § 2.3) is small (dotted lines in Fig. 3) compared to the \( ^{6}\text{Li} \) production by CR interactions with the IGM. Also shown in Figure 3 is the evolution of \( ^{7}\text{Li} \), assuming the initial primordial value of \( ^{7}\text{Li}/H = 4.15 \times 10^{-10} \) determined by BBN at the WMAP value for the baryon density (Coc et al. 2004): as already emphasized in RVOI, the additional CCR production of \( ^{7}\text{Li} \) is negligible compared to that produced by BBN.

### 3.2. Deuterium

There are two main production reactions for deuterium, namely \( p-H \) and \( p-\text{He} \). For the simplified calculation, assuming \( \gamma = 3 \) and the two extreme cases for \( I(\gamma, p_{1}, p_{2}) \), as given in equation (A6), we obtain

\[
[D_{\text{ph}}/^{6}\text{Li}] \approx 5, \quad [D_{\text{ph}}/^{6}\text{Li}] \approx 50. \tag{10}
\]

---

**TABLE 1**

| \( t + j \rightarrow X \) | \( \sigma_{i}^{\text{P}} \) (mbarn) | \( E_{1} \) (GeV nucleon \(^{-1} \)) | \( E_{2} \) (GeV nucleon \(^{-1} \)) |
|--------------------------|---------------------------------|-------------------------------|-------------------------------|
| \( \alpha + \text{He} \rightarrow ^{6}\text{Li} \)......... | 20 | 0.01 | 0.02 |
| \( p + \text{H} \rightarrow \text{D} \).......... | 1 | 0.4 | 0.8 |
| \( p + \text{He} \rightarrow \text{D} \).......... | 12 | 0.05 | \( \infty \) |
| \( p + \text{C} \rightarrow ^{9}\text{Be} \).......... | 6 | 1.0 | \( \infty \) |
| \( p + \text{O} \rightarrow ^{9}\text{Be} \).......... | 5 | 0.05 | \( \infty \) |
| \( p + \text{C} \rightarrow ^{6}\text{B} \).......... | 90 | 0.015 | \( \infty \) |
| \( p + \text{O} \rightarrow ^{6}\text{B} \).......... | 50 | 0.04 | \( \infty \) |

---

This makes a total contribution of about \( D^{6}\text{Li} \approx 100 \) coming from \( p-H \), \( p-\text{He} \), and the numerically similar reverse process \( \alpha-p \), independent of the redshift. This is consistent with the constant value of 70 derived in the exact calculation. Thus, the additional production of deuterium by CCRs at \( z = 3 \) is about \( 3.1 \times 10^{-10} \) and is therefore well below the observed abundance \( D/H \approx 2 \times 10^{-5} \) (O’Meara et al. 2006).

### 3.3. BeB

Beryllium and boron are produced via spallation interaction between protons or \( \alpha \)-particles in CRs and CNO elements in the IGM. The reverse reactions, which correspond to CNO CRs spalling on H and He of the IGM, is in fact dominant. This can be understood as the metallicity in the ISM (where CRs originate) always being larger than that in the IGM. In contrast to the galactic disk, the heavy nuclei component of CCRs becomes important due to the metal deficiency of the IGM. Qualitatively, the ratio of the forward to reverse processes is given by

\[
\frac{(\text{BeB})_{\text{OH}}}{(\text{BeB})_{\text{OH}}} = \frac{\gamma_{0}}{F_{\alpha}} = \frac{[O/H]_{\text{ISM}}}{[O/H]_{\text{IGM}}}, \tag{11}
\]

where \( \gamma_{0} \), \( F \), and \( \eta \) are defined in equations (2) and (3). From the calculated abundances of Daigne et al. (2006), the metallicity ratio between the IGM and CRs is \( \leq 10^{-2} \) (see, e.g., Fig. 1), so that the forward process is \( \sim 10^{-3} \) smaller than the reverse. For the reverse process, equation (A7) does not apply in principle, since \( F_{\gamma} \) no longer factors out of the \( z \) integrand. However, in the CRs, \( F_{\gamma} \approx 10^{-4} \) and \( F_{\alpha} \approx 10^{-3} \) (see Fig. 1). An upper limit to the production of \( ^{9}\text{Be} \) would then be, for \( \gamma_{0} = 3, [\text{BeOH}/^{6}\text{Li}] \approx 0.3 \). This
compares well with the full calculation (upper solid line in Fig. 4). The leading contribution of the reverse process is confirmed in Figure 4 for the full calculation in model 2b (upper solid line, compared to dashed line); the same is also true for model 1. The dominant channel is actually O+H. Nevertheless, all nuclei are accounted for in the full calculation below. As one can see in Figure 4, adopting the spectral break, i.e., \( \gamma_O = 1.5 \) as described in § 2.1.1, decreases the contribution of the reverse process and as a result lowers the Be abundance, as shown by the thick solid curve compared to the upper thin curve with \( \gamma_O = 3 \).

The results from the full calculation of the BeB abundances for models 1 and 2b are given in Figures 5 and 6. Note once again that BeB production in model 2b is delayed due to the lack of metal enrichment in the ISM from the massive mode in this model. At \( z = 3 \), we find \( ^9\text{Be}/\text{H} = 10^{-12.9} \) in model 1 (dashed lines) and \( ^{10,11}\text{B}/\text{H} = 10^{-13.3} \) in model 2b (solid lines). This is compatible with the observed abundance at the lowest metallicity, \( \text{[Fe/H]} = -3.3, ^9\text{Be}/\text{H} \sim 10^{-12.8} \) in G64-12 (Primas et al. 2000a). For boron, we find \( \text{B}/\text{H} = 10^{-11.9} \) in model 1 and \( \text{B}/\text{H} = 10^{-12.25} \) in model 2b. These values are somewhat below the observed boron abundance at low metallicity, \( \text{B}/\text{H} \sim 10^{-11.3} \) at \( \text{[Fe/H]} = -3.0 \) in BD = 13 3442 (Primas et al. 1998), although \( \text{B}/\text{H} \) is as low as \( 10^{-12} \) at \( \text{[Fe/H]} = -2.9 \) in BD = 23 3130 (García-López et al. 1998). Note, however, that unlike beryllium abundances, the boron abundances in particular are very sensitive to the assumed effective temperature. The abundances quoted above were determined using temperatures based on the infrared flux method (IRFM; Alonso et al. 1996). The boron abundance in BD = 13 3442 would be \( 10^{-10.7} \) (Fields et al. 2005) had we adopted the temperature derived by Meléndez & Ramírez (2004). Of course, Li also scales with temperature, and at higher effective temperatures, the level of the \( ^6\text{Li} \) plateau would be raised forcing one to large CR efficiencies.

![Fig. 4.](image1)

![Fig. 5.](image2)

Our results can be cast in terms of abundance ratios of \( ^9\text{Be}/^6\text{Li} \) and \( ^{10,11}\text{B}/^6\text{Li} \),

\[
[ ^9\text{Be}/^6\text{Li} ] \approx 0.020 \quad [ ^{10,11}\text{B}/^6\text{Li} ] \approx 0.20 \quad (12)
\]

for model 1 and

\[
[ ^9\text{Be}/^6\text{Li} ] \approx 0.008 \quad [ ^{10,11}\text{B}/^6\text{Li} ] \approx 0.09 \quad (13)
\]

![Fig. 6.](image3)
for model 2b. These predicted ratios are independent of the efficiency $c_{\text{CR}}$ and can be compared to the few examples where observational determinations of $^6\text{Li}$ and Be exist in the same star. Restricting our attention to only those stars with [Fe/H] < $-2.6$, we have Be abundance measurements in two stars, G64-12 (Primas et al. 2000a) and LP 815–43 (Primas et al. 2000b), for which there are reliable $^6\text{Li}/^7\text{Li}$ determinations (Asplund et al. 2006; Inoue et al. 2005). When corrected for stellar temperature differences, we find $^9\text{Be}/^6\text{Li}$= 0.005 ± 0.003 for G64-12 and 0.011 ± 0.007 for LP 815–43. Unfortunately, there are no very low metallicity stars with both $^6\text{Li}$ and Be abundance measurements.

The predicted PIE at $z = 3$ for both elements is of the same order as the abundances observed at the lowest metallicity. Thus, we expect a plateau in both Be and B at low metallicity similar to the abundances observed at the lowest metallicity stars. It will be interesting to see whether future determinations of Be at low metallicity confirm the existence of a Be plateau.

We have also computed the production of Be through LEC nucleosynthesis and neutrino spallation via outflow to the IGM. In all cases, the abundance produced by these processes is less at small redshift, although the abundance of $^{11}\text{Be}$ produced by the $\nu$-process is not negligible at higher redshift. These results are displayed by the thin lines in Figures 5 and 6.

### 3.4. Pionic Production of Gamma Rays

The interaction of the CCRs with the IGM also produces gamma rays. Our calculation closely follows that given in Pavlidou & Fields (2002). Assuming isotropic production, the extragalactic differential flux of $\gamma$-rays at Earth in the flat $\Lambda$CDM cosmology is

$$\frac{dE}{dE} = \frac{c}{4\pi H_0} \int_0^\infty dz \frac{q_\gamma(z, E')}{(1 + z)^2 \sqrt{\Omega_\Lambda} + (1 + z)^3 \Omega_M},$$

(14)

The $\gamma$-ray source function $q_\gamma(z, E')$ is calculated using the simplified analytic formula of Pfommer & Ensslin (2004):

$$q_\gamma(z, E') \approx \sigma_{pp} \phi_p(E') n_{\text{IGM}}(z) \frac{E'}{m_p} \left( \frac{2 E'_y}{E'} \right)^{\delta_e} \left( \frac{2 E'_\gamma}{E'} \right)^{-\delta_e} \frac{4 m_p}{3 \alpha_e} \left( \frac{2 E'_y}{m_p} \right)^{\delta_e} \left( \frac{2 E'_\gamma}{m_p} \right)^{-\delta_e} \frac{4 m_p}{3 \alpha_e}$$

(15)

with $\zeta = 2$, $\delta_e = 0.14 \alpha_e^{-1.6} + 0.44$, and $\sigma_{pp} = 32(0.96 + e^{4.8-2.4z})$ mbar. The same input fluxes and IGM densities are taken as for the D and LiBeB calculations. Figure 7 shows that the total $\gamma$-ray flux produced by CCRs is negligible compared to the observed EGRB.

### 4. DISCUSSION AND CONCLUSIONS

Our initial motivation to study CCRs at high redshift was to find a physical origin for the anomalously high abundance of $^6\text{Li}$ observed in metal-poor halo stars. A cosmic history for structure formation that reproduces standard observations (Daigne et al. 2006) provides enough energy in SNe to produce a $^6\text{Li}$ plateau at the level of log $[^6\text{Li}/\text{H}] \approx -11.2$ via $\alpha + \chi$ interactions of CCRs with the IGM. Note that the $^6\text{Li}$ produced by outflows (via neutrino spallation and LEC) is negligible.

In this paper, we considered two models of star formation histories differing by their Population III stars. The massive component of model 1 ($40-100 ~M_\odot$) injects a lot of energy in CCRs, so that the necessary fraction $c_{\text{CR}}$ is low ($\sim0.15$). On the other hand, the stars associated with the massive component of model 2b ($260-500 ~M_\odot$) are assumed to collapse into black holes without injecting, a priori, any energy in CCRs. Consequently, the fraction $c_{\text{CR}}$ associated with SNe in the normal mode must be higher ($\sim0.5$). This figure would be reduced if supermassive stars produce CCRs.

We confirm, as in RVOII, that the $^7\text{Li}$ primordial abundance always dominates any additional production by CCRs. The same conclusion holds for deuterium. Similarly, the observed EGRB is much larger than the intensity of photons produced by the decay of pions produced by CCR proton collisions.

In the same cosmological context, we explored the production of other light elements (BeB). To that end, it is necessary to track the abundances of metals (CNO) in the ISM and IGM. We have shown that the reverse process (i.e., CNO CCRs on H and He IGM gas) is the dominant channel to synthesize BeB. This is in contrast to the production of BeB in the Galactic disk, where the reverse process contributes roughly 20% (Meneguzzi et al. 1971). This is easily understood, as the metal enrichment in CCRs is inherited from structure abundances, which are far higher than those in the IGM. Note that we also checked that the neutrino spallation and LEC processes are negligible in the IGM BeB budget at the time of Galactic formation, i.e., $z \sim 3$. In all models considered, we have shown that BeB synthesized at $z \sim 3$ is at the level of the observed abundances in the lowest metallicity stars. This is the first theoretical indication of a plateau for these elements which does not resort to exotic models of BBN. This results is in contrast to that found in the structure formation scenario (Suzuki & Inoue 2002), where the medium responsible for cosmic ray acceleration contains very few if any metals, and therefore the CR nucleosynthetic contribution to Be and B in the IGM should be minimal. The latest observations of Be in low-metallicity halo stars, which indicate a hint of a plateau (Fields et al. 2005), would then favor a CCR scenario.

Note that these results have been obtained with several assumptions about the CCR spectra. To some extent, our modeling, be it for light elements ($p$-He) or metals (CNO), is limited. Indeed, two...
fundamental ingredients for the calculation are (1) the low-energy form of the source spectra for protons and (2) the propagated fluxes to plug into the IGM. The first item is crucial for determining the acceleration efficiency $\epsilon_{CR}$. For example, changing $\gamma \approx 3$ to $\gamma \approx 2$ (hence taking a more conventional spectral index for the sources) would lead to an unphysical value of $\epsilon_{CR} > 1$. However, we expect that propagation effects on scales of the order of the warm-hot IGM would lead to a steeper spectrum (i.e., $\gamma = 3$ for $p$ and $\alpha$ particles) and a flattening of the CNO spectrum of the form we have assumed here. The second item involves several issues that are intimately connected: the details of CR escape and confinement between the structures, the warm-hot IGM, and cooler IGM is related to whether or not the propagated spectrum displays a spectral index close to the standard source index ($\gamma \approx 2$) or closer to a diffused spectrum ($\gamma \approx 3$) and, more importantly, how this evolves with $z$. Without some degree of confinement on the scale of the warm-hot IGM, we would be forced to take the same spectrum for $p$, He, and CNO nuclei (as would be more natural for complete escape to the IGM), and this would lead to an overproduction of $^9$Be (in fact, we derive in Fig. 4 an upper limit of 1.5 for the slope of the CNO spectrum). Our simple estimate of the spallation timescale within structures indicates that confinement is indeed playing a role, and changes to the CR source spectrum will occur. In addition to the confinement of CRs, recent results from observations and simulations indicate that outflows from galaxies may not in fact be leaving the gravitational potential of hosts (e.g., Mac Low & Ferrara 1999; Tassis et al. 2008; van Eymeren et al. 2007). This confinement would then limit the global outflow from the ISM into the IGM, which would lower the contribution of the in situ nucleosynthetic processes ($\S$2.3). Thus, all curves labeled “outflow” would be lowered. The escape efficiency of CRs would not be affected.

Another source of uncertainty comes from the model used for the formation history, detailed in Daigne et al. (2006). The amplitude of the nucleosynthetic production the light elements is proportional to $\epsilon_{CR}$ times the SN rate, or equivalently the star formation rate. On the one hand, the global amplitude of the SFR can be modified. A factor of 2 is acceptable within the SFR errors (Hopkins 2004; Hopkins & Beacom 2006; Daigne et al. 2006). Note that assuming different values for $M_{\text{min}}$ yields differences in the SFR smaller than this uncertainty (Fig. 3 of Daigne et al. 2006). This uncertainty is then combined with that in $\epsilon_{CR}$. However, one should recall that it is this product that is fixed to match the abundance of $^6$Li to its plateau value, and as a result, the abundances of Be and B are not as strongly affected. On the other hand, the IMF, particularly the massive mode, is much less certain. The normal mode is well constrained by the SFR at low redshift. Although the SFR is poorly constrained at high redshift, the PS framework does not allow for arbitrary histories. Nevertheless, different massive modes for the stars can be assumed. This will naturally induce a different history for the LiBeB pollution of the IGM. Since the lithium abundance is constrained at $z \approx 3$, the required efficiency will be somewhat different, but the PIE for BeB should be similar to within a factor of 2. To conclude, the main source of uncertainties for the LiBeB abundance in the IGM is the choice of the massive mode, and the scenario for the confinement and propagation of CRs.

All of these elements clearly call for a more coherent and refined calculation. As just outlined, one issue concerns the description of CR propagation in realistic structures, evolving with redshift, which also allows for differentiated production in situ and in outside structures. Another important issue is the possibility for heterogeneity in metallicities at a given time (e.g., Salvadori et al. 2007), which cannot be handled in the homogeneous paradigm developed in Daigne et al. (2006). This question could be addressed when $^6$Li and $^9$Be are observed simultaneously. Finally, we note that B can be observed directly in high-redshift objects, as achieved for a damped Ly$\alpha$ system at $z = 2.6$ (Prochaska et al. 2003). Observations at even higher $z$ may be possible through absorption lines in gamma-ray bursts (J. Prochaska 2007, private communication), which should provide very valuable constraints on early LiBeB production scenarios.

We warmly thank Don Ellison, Torsten Ensslin, and Tom Jones for their help. We thank E. Thiebaut and D. Munro for freely distributing his Yorick programming language (available at http://yorick.sourceforge.net/), which we used to implement part of our analysis. The work of E. V. and K. O. has been supported by the collaboration INSU-CNRS France/US. The work of K. A. O. was partially supported by DOE grant DE-FG02-94ER-40823.

**APPENDIX A**

**SIMPLIFIED CALCULATION FOR D-Be-B**

The calculation for D, Be, and B production follows closely that given for $^6$Li, for example, in RVOI. In this appendix, we estimate the relative efficiency of various channels, as well as the relative efficiency of the D, Be, and B production with respect to the $^6$Li production. In some cases, the latter is independent of $z$. Below, $E$ denotes the kinetic energy per nucleon.

The abundance of the element X relative to H is given by

$$\frac{[X/H]}{[H]} = \sum_{\text{CR}} \sum_{j=\text{IGM}} \int_{z_{\text{in}}}^{\infty} \int_{E_{\text{min}}}^{\infty} \bar{f}_j \sigma_{ij}^X(E_p) F_j(E_p, z) dE_p \left| \frac{dE_p}{dz} \right| dz, \quad (A1)$$

where $F_j(E_p, z)$ is the accumulated CR proton flux in the IGM (in proper units), $\sigma_{ij}^X(E_p)$ is the production cross section of X in the reaction $(i \rightarrow j)$, and $f_i$ and $F_j$ are defined in equations (2) and (3). Note that $^6$Li is only produced by CR $\alpha$ particles with energy four times the final lithium energy. As a consequence, the above formula also applies to $[^6\text{Li}/H]$, but an extra factor of 1/4 must be added. Two simplifications are made:

1. All cross sections $\sigma_{ij}^X(E)$ are approximated as a constant in the range $E_1 - E_2$ and zero elsewhere, i.e.

$$\sigma_{ij}^X(E) = \sigma_{ij}^X \Theta(E - E_1) \Theta(E_2 - E). \quad (A2)$$

The values of the cross sections for the main processes are given in Table 1.
where we write
\[ I(\gamma, p_1(E_1), p_2(E_2)) \equiv \int_{p_1}^{p_2} \frac{p^{\gamma+1}}{\sqrt{p^2 + m_p^2}} \, dp, \]  
and where \( p(E) \) is the CR proton momentum for a given kinetic energy per nucleon, \( E \). This function can be integrated as a hyperbolic function, but for the purpose of a simplified calculation, it is good enough to consider the two limits, which apply either when the production is at very low energy (e.g., for \( ^6\text{Li} \)), or at GeV nucleon\(^{-1} \) energies:
\[ I_{p \ll m_p} \approx \left[ \frac{p^{\gamma+3}}{2 - \gamma} \right]_{p_1}^{p_2} \]  
and  
\[ I_{\gamma \approx 1} \approx \left[ \frac{p^{\gamma+1}}{\gamma} \right]_{p_1}^{p_2}. \]

We shall now write a simplified expression for the comparison of the production of \( X \) with respect to \( ^6\text{Li} \). The integration over \( z \) cancels out, and this results in
\[ \frac{[X/6\text{Li}]}{1(X^\text{Li})} \equiv I_1^X, \]
where we write \( I(\gamma, p_1(E_1), p_2(E_2)) \equiv I_j^X \) for short.

REFERENCES

Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, A&AS, 117, 227
Asplund, M., Lambert, D. L., Nissen, P. L., Primas, F., & Smith, V. V. 2006, ApJ, 644, 229
Barkana, R., & Loeb, A. 2001, Phys. Rep., 349, 125
Berezhko, E. G., & Ellison, D. C. 1999, ApJ, 526, 385
Berezhko, E. G., & Völk, H. J. 1997, Astropart. Phys., 7, 183
———. 2000, A&A, 357, 283
———. 2004, A&A, 419, 27
———. 2006, A&A, 451, 981
Blandford, R., & Eichler, D. 1987, Phys. Rep., 154, 1
Blasi, P., Gabici, S., & Vannoni, G. 2005, MRNAS, 361, 907
Bonifacio, P., et al. 2007, A&A, 462, 851
Cassé, M., Lefloch, R., & Vangioni-Flam, E. 1995, Nature, 373, 38
Cayrel, R., Spite, M., Spite, F., Vangioni-Flam, E., Cassé, M., & Audouze, J. 1999, A&A, 343, 923
Coc, A., Vangioni-Flam, E., Descouvemont, P., Adahchour, A., & Angulo, C. 2004, ApJ, 600, 544
Cuoco, A., Iocco, I., Mangano, G., Pisanti, O., & Serpico, P. D. 2004, Int. Mod. Phys. A, 19, 4431
Cyburt, R. H. 2004, Phys. Rev. D, 70, 023505
Cyburt, R. H., Ellis, J., Fields, B. D., Olive, K. A., & Spanos, V. C. 2006, J. Cosmol. Astropart. Phys., 11, 14
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2001, NewA, 6, 215
———. 2002, Astropart. Phys., 17, 87
———. 2003, Phys. Lett. B, 567, 227
Daigne, F., Olive, K. A., Silk, J., Stoehr, F., & Vangioni-Flam, E. 2006, ApJ, 647, 773
Drury, L. O’C. 1983, Rep. Prog. Phys., 46, 973
Ellison, D. C., & Cassam-Chenaï, G. 2005, ApJ, 632, 920
Ellison, D. C., Drury, L. O., & Meyer, J.-P. 1997, ApJ, 487, 197
Ellison, D. C., Patnaude, D. J., Slane, P., Blasi, P., & Gabici, S. 2007, ApJ, 661, 879
Fields, B. D., & Olive, K. A. 1999, NewA, 4, 255
Fields, B. D., Olive, K. A., & Vangioni-Flam, E. 2005, ApJ, 623, 1083
Fields, B. D., & Prodanovic, T. 2005, ApJ, 623, 877
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Heger, A., Kolbe, E., Haxton, W. C., Langanke, K., Martínez-Pinedo, G., & Woosley, S. E. 2005, Phys. Lett. B, 606, 258
Hobbs, L. M., & Thorburn, J. A. 1994, ApJ, 428, L25
Hobbs, L. M., & Thorburn, J. A. 1997, ApJ, 491, 772
García-López, R. J., et al. 1998, ApJ, 500, 241
Hopkins, A. M. 2004, ApJ, 615, 209
Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142
Hörandel, J. 2007, Adv. Space Res., submitted (presented at 36th COSPAR Scientific Assembly, Beijing, China; astro-ph/0702370)
Inoue, S., et al. 2005, in IAU Symp. 228, From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution, ed. V. Hill, P. Francois, & F. Primas (Cambridge: Cambridge Univ. Press), 59
Jedamzik, K., Choi, K. Y., Roszkowski, L., & Ruiz de Austri, R. 2006, J. Cosmol. Astropart. Phys., 07, 007
Jones, F. C. 1994, ApJS, 90, 561
Jubelgas, M., Springel, V., Ensslin, T. A., & Pfrommer, C 2006, A&A, submitted (astro-ph/0603485)
Kang, H., & Jones, T. W. 2006, Astropart. Phys., 25, 246
Kawasaki, M., Kohri, K., & Moroi, T. 2005, Phys. Rev. D, 71, 083502
Kravtsov, A. V., Gnedin, O. Y., & Klypin, A. A. 2004, ApJ, 609, 482
Kusakabe, M., Kajino, T., & Mathews, G. J. 2006, Phys. Rev. D, 74, 023526
Longair, M. S. 1992, High Energy Astrophysics, Vol. 1 (Cambridge: Cambridge Univ. Press), 59
Mac Low, M., & Ferrara, A. 1999, ApJ, 513, 142
Maurin, D., Taillet, R., Donato, F., Salati, P., Barrau, A., & Boudoul, G. 2004, in Recent Research Developments in Astronomy and Astrophysics 2 (Kerala: Research Signpost), 193
Meléndez, J., & Ramírez, I. 2004, ApJ, 615, L33
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337
Meyer, J.-P., Drury, L. O., & Ellison, D. C. 1997, ApJ, 487, 182
———. 1998, Space Sci. Rev., 86, 179
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
Nakamura, K., Inoue, S., Wania, S., & Shigeyama, T. 2006, ApJ, 643, L115
Nissen, P. E., Asplund, M., Hill, V., & D’Odorico, S. 2000, A&A, 357, L49
Olive, K. A., Prantzos, N., Scully, S., & Vangioni-Flam, E. 1994, ApJ, 424, 666
O’Meara, J. M., Burles, S., Prochaska, J. X., Prochter, G. E., Bernstein, R. A., & Burgess, K. M. 2006, ApJ, 649, L61
Pavlidou, V., & Fields, B. D. 2002, ApJ, 575, L5
Pfrommer, C., & Ensslin, T. A. 2004, A&A, 413, 17
Pospelov, M. 2006, preprint (hep-ph/0605215).
Primas, F., Asplund, M., Nissen, P. E., & Hill, V. 2000a, A&A, 364, L42
Primas, F., Duncan, D. K., Peterson, R. C., & Thorburn, J. A. 1999, A&A, 343, 545
Primas, F., Molaro, P., Bonifacio, P., & Hill, V. 2000b, A&A, 362, 666
Prochaska, J. X., Howk, J. C., & Wolfe, A. M. 2003, Nature, 423, 57
Rollinde, E., Vangioni, E., & Olive, K. 2005, ApJ, 627, 666 (RVOI)
———. 2006, ApJ, 651, 658 (RVOII)
Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., & Norris, J. E. 2000, ApJ, 530, L57
Salvadori, S., Schneider, R., & Ferrara, A. 2007, MNRAS, 381, 647
Silk, J., & Schramm, D. N. 1992, ApJ, 393, L9
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1993, ApJ, 408, 262
———. 1998, ApJ, 506, 405
Spergel, D. N., et al. 2007, ApJS, 170, 377
Spite, F., & Spite, M. 1982, A&A, 115, 357

Steigman, G., Fields, B. D., Olive, K. A., Schramm, D. N., & Walker, T. P. 1993, ApJ, 415, L35
Strong, A. W., Moskalenko, I. V., & Ptuskin, V. S. 2007, Annu. Rev. Nucl. Part. Sci., 57, 285
Strong, A. W., Moskalenko, I. V., & Reimer, O. 2004, ApJ, 613, 962
Suzuki, T. K., & Inoue, S. 2002, ApJ, 573, 168
Tassis, K., Kravtsov, A. V., & Gnedin, N. Y. 2008, ApJ, in press (astro-ph/ 0609763)
Tatischeff, V., & Thibaud, J. 2007, A&A, 469, 265
Thomas, D., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 406, 569
van Eymeren, J., Bomans, D. J., Weis, & Dettmar, R.-J. 2007, A&A, 474, 67
Vangioni-Flam, E., Cassé, M., & Audouze, J. 2000, Phys. Rep., 333, 365
Vangioni-Flam, E., Cassé, M., Field, B., & Olive, K. A. 1996, ApJ, 468, 199
Vangioni-Flam, E., et al. 1999, NewA, 4, 245
Warren, J. S., Hughes, J. P., Badenes, C., Ghavamian, P., McKee, C. F., Moffett, D., Plucinsky, P. P., Rakowski, C., Reynoso, E., & Slane, P. 2005, ApJ, 634, 376
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272