Spallogenic Light Elements and Cosmic-Ray Origin

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Abstract.

Using a Monte Carlo code which incorporates hitherto ignored effects, the delayed mixing into the ISM of the nucleosynthetic yields of supernovae and the relationship between these yields and the supernova ejecta kinetic energy (including events with very large ejecta energies, e.g. collapsars/hypernovae), we tested the viability of the three recent evolutionary models for the origin of the spallogenic light elements, specifically Be. We find that the CRI, in which the cosmic rays are accelerated out of an ISM which is increasingly metal poor at early times, significantly under-predicts the measured Be abundance at the lowest [Fe/H], the increase in [O/Fe] with decreasing [Fe/H] indicated by recent data notwithstanding. We also find that the CRS, in which cosmic rays with composition similar to that of the current epoch cosmic rays are accelerated out of fresh supernova ejecta and thus maintain a constant metallicity at all epochs, can account for the measured Be abundances with an acceleration efficiency that is in good agreement with the current epoch cosmic-ray data. In addition, we show that the LECR, in which a postulated low energy component also accelerated out of fresh ejecta coexists with the CRI cosmic rays, can account for the observations as well, except that the required acceleration efficiency becomes prohibitively large for some of the parameters that have been previously assumed for this as-yet undetected cosmic-ray component.

1. Introduction

Recent measurements (see Vangioni-Flam et al. 1998, hereafter VF98) of Be and B abundances in low-metallicity stars provide important new clues as to the source of the cosmic-ray nuclei that are in conflict with the current paradigm (hereafter the CRI model) of cosmic-ray acceleration out of the average inter-stellar medium (ISM). In particular, these measurements show that the ratio of spallation-produced Be to supernova-nucleosynthetic Fe is very nearly independent of metallicity, rather than being proportional to the metallicity, as would be expected if all the cosmic rays were accelerated out of the average ISM.
To explain these results, we proposed (Ramaty et al. 1997; Ramaty, Kozlovsky & Lingenfelter 1998a; Lingenfelter, Ramaty & Kozlovsky 1998; Higdon, Lingenfelter & Ramaty 1998; Ramaty, Lingenfelter & Kozlovsky 1998b) an alternative model for the origin of the cosmic rays and of the spallogenic light elements, \( ^6\text{Li} \), \( \text{Be} \) and part of the B. Specifically we developed a model (hereafter CRS) in which the cosmic rays are accelerated out of fresh supernova ejecta and at all epochs of Galactic evolution these light elements were produced by spallation interactions of such cosmic rays with the ambient ISM. This model differs from the traditional CRI approach in which the present epoch cosmic rays are accelerated out an ambient medium of solar composition (suggested to be the ISM, Meyer, Drury & Ellison 1997), and at all past epochs the composition of the source particles of the cosmic rays that produce the light elements (e.g. Prantzos, Cassé, & Vangioni-Flam 1993) was that of the average ISM at that epoch. However, the new Be abundance data show that the dependence of \( \log(\text{Be}/\text{H}) \) on \( [\text{Fe}/\text{H}] = \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_\odot \) is essentially linear, not quadratic as predicted by this model. As an alternative, hybrid models for the origin of the spallogenic light elements were developed (Cassé, Lehoucq & Vangioni-Flam 1995; Vangioni-Flam et al. 1996; Ramaty, Kozlovsky, & Lingenfelter 1996; Vangioni-Flam, Cassé, & Ramaty 1997). In these models (hereafter LECR), a separate low energy cosmic-ray component, also accelerated out of fresh nucleosynthetic matter, was suggested to coexist with the CRI cosmic rays and to dominate the Be and B production, particularly in the early Galaxy. Both the CRS and LECR models thus predict a linear evolution of the Be abundance, while the CRI model does not. Fields & Olive (1999a), however, recently suggested that the latter model might still be viable, based on their re-analysis of the data, including O in low metallicity stars (Israelian, Garcia Lopez, & Rebolo 1998).

The three models (CRI, CRS, LECR) involve different current epoch cosmic-ray origin scenarios. While the CRI scenario posits acceleration from the average ISM (Ellison, Drury & Meyer 1997), CRS assumes that the cosmic rays are accelerated out of fresh supernova ejecta. We have shown (Lingenfelter et al. 1998) that the standard arguments against such an ejecta origin (e.g. Meyer et al. 1997) can be answered (see §4), with the most likely scenario involving the collective acceleration by successive supernova shocks of ejecta-enriched matter in the interiors of superbubbles (Higdon et al. 1998). This scenario can also account for the delay between nucleosynthesis and acceleration (time scales of \( \sim 10^5 \) yr), suggested by the recent \( ^{59}\text{Co} \) and \( ^{59}\text{Ni} \) observations (Binn & Fleishman 1992). Moreover, these hot, low density superbubbles are, in fact, the “hot phase” of the interstellar medium where shock acceleration of cosmic rays is expected (e.g. Axford 1981; Bykov & Fleishman 1992) to be most effective because the energy losses of the accelerated particles are minimized and the supernova shocks do not suffer major radiative losses, as they would in a denser medium.

The LECR scenario was motivated by the reported (Bloemen et al. 1994; 1997), but recently retracted (Bloemen et al. 1999), detection with COMPTEL/CGRO of C and O nuclear gamma-ray lines from the Orion star formation region. These gamma rays were attributed to a postulated low energy cosmic-ray component, which was highly enriched in C and O relative to protons and \( \alpha \) particles (see Ramaty 1996 for review and Ramaty et al. 1996 for extensive calculations of light element production by LECRs). It was suggested (Bykov &
Bloemen 1994; Ramaty et al. 1996; Parizot, Cassé, & Vangioni-Flam 1997) that such enriched LECRs might be accelerated out of metal-rich winds of massive stars and the ejecta of supernovae from massive star progenitors which explode within the bubble around the star formation region due to their very short lifetimes. It was further suggested (Parizot et al. 1997) that acceleration by an ensemble of shocks in superbubbles (Bykov & Fleishman 1992) would produce the distinct low energy cosmic-ray component involved in the LECR model. But the cosmic-ray spectrum predicted by Bykov & Fleishman (1992) is identical to the Galactic cosmic-ray spectrum except that it is cut-off (becomes harder) at low energies. Following the reported detection of nuclear gamma-ray lines from Orion, the Bykov & Fleishman (1992) model was modified (Bykov & Bloemen 1994) by lowering the shock compression ratio, so that the ensuing weak shocks would produce a much softer high energy cosmic-ray spectrum which was necessary to explain the lack of the pion-decay radiation that would have had to accompany the now-withdrawn nuclear line emission. Thus, new gamma-ray line data are needed to determine the role of the LECR component.

Concerning B, it is well known (e.g. Ramaty et al. 1997) that the CRS and CRI models cannot account for the measured meteoritic $^{11}\text{B}/^{10}\text{B}$. A likely solution is some additional $^{11}\text{B}$ production by $\nu$-induced $^{12}\text{C}$ spallation in supernovae (Woosley & Weaver 1995). As we have dealt with such B production in our previous studies, we do not consider B in the present paper. Both the CRS and CRI models can account for the $^{6}\text{Li}$-to-Be abundance ratio in meteorites. There are, however, indications that at low metallicities $^{6}\text{Li}/\text{Be}$ exceeds the meteoritic value (Smith, Lambert, & Nissen 1998). The origin of this excess, not discussed in the present paper, remains uncertain (see, however, Vangioni-Flam et al. 1999 and Fields & Olive 1999b).

Figure 1. Evolution of (a) - star ($>10\text{M}_\odot$) formation rate, and O and Fe production rates; (b) - ISM Fe abundance for two Fe mixing times with models (TS, SN and SN+CS) of Ni-Fe ejecta as functions of core-collapse supernova progenitor mass (see text).
2. Fe and O Production and Evolution

We consider a one-zone model and limit our treatment to the first $10^9$ years of Galactic evolution, because this low metallicity era conveys the most unambiguous information on cosmic-ray origin. We allow the ISM mass to accumulate exponentially, $dM_{\text{ISM}}(t)/dt = 10^{11} M_\odot e^{-t/\tau}$. As we found that the relevant abundance ratios are not significantly affected by the value of $\tau$, we only show results for $\tau = 10$ Myr. We remove ISM mass by star formation and outflow, taking the star formation rate proportional to the ISM mass, $\Psi = \alpha M_{\text{ISM}}$, and the outflow proportional to $\Psi$, $O = \beta \Psi$ (Prantzos, Cassé, & Vangioni-Flam 1993). Again, since our results do not depend appreciably on $\alpha$ and $\beta$ (see Ramaty et al. 1998b), we only show results for $\alpha = 0.6 \text{Gyr}^{-1}$ and $\beta = 1$. We set up a grid of 30 time bins, ranging from 0 to 1 Gyr, and accumulate mass into these bins by the above prescription. Then for each bin we generate an ensemble of stellar masses normalized to the assumed star formation rate and distributed according to the Salpeter IMF up to $100 M_\odot$. Starting from the first bin and advancing in time, we calculate the removed mass and the returned mass for each star in the ensemble, the latter depending on stellar lifetimes and the remnant mass (e.g. Prantzos et al. 1993). We note that only $>2 M_\odot$ stars return mass for $t < 1$ Gyr. The resultant star formation rate for stars of mass exceeding $10 M_\odot$ is shown by the top curve in Figure 1a.

| M(progenitor) | 12 | 13 | 15 | 18 | 20 | 22 | 25 | 30 | 35 | 40 | >40 |
|--------------|----|----|----|----|----|----|----|----|----|----|-----|
| $M_O(\text{TS})^a$ | 0.065 | 0.12 | 0.4 | 0.7 | 1.3 | 1.8 | 2.9 | 4.3 | 6.0 | 8.0 | 12  |
| $M_F(\text{TS})^a$ | 0.01 | 0.012 | 0.03 | 0.055 | 0.1 | 0.12 | 0.15 | 0.25 | 0.3 | 0.35 | 0.5 |
| $M_O(\text{SN})^b$ | 0.15 | 0.18 | 0.38 | 0.77 | 1.51 | 1.73 | 2.78 | 4.07 | 5.55 | 6.2 | 6.2 |
| $M_F(\text{SN})^b$ | 0.054 | 0.089 | 0.064 | 0.16 | 0.09 | 0.12 | 0.20 | 0 | 0 | 0 | 0 |

$^a$Shigeyama & Tsujimoto 1998; Tsujimoto & Shigeyama 1998
$^b$Woosley & Weaver 1995

Galactic Fe and O production is due to the $>10 M_\odot$ stars which explode as core collapse supernovae. In each time bin and for each star in the ensemble, we calculate the ejected O and Fe masses for three cases. The first case (TS) is based on the yields given by Shigeyama & Tsujimoto (1998) and Tsujimoto & Shigeyama (1998), which represent the best observationally determined values of observed abundance patterns in extremely low metallicity stars. These are bracketed by the yields of Woosley & Weaver (1995, hereafter WW95) at metallicity $10^{-4}$ of the solar value for high ($>20 M_\odot$) mass progenitors with ejecta kinetic energy, $W_{SN}$, ranging from about 1 to $3 \times 10^{51}$ erg. In the second case (SN), which we chose in order to maximize the relative Be production efficiency, we take the minimum Ni-Fe yield models of WW95, which practically vanish at progenitor masses of $30 M_\odot$ and above. Specifically, we use the ejecta corresponding to the lowest $W_{SN}$ at $30 M_\odot$, and those at intermediate $W_{SN}$ at 35 and $40 M_\odot$, because these still yield vanishing Ni-Fe yields but finite O yields, thereby providing a good fit to the O-to-Fe abundance ratio, as we shall see. As no calculations for progenitors more massive than $40 M_\odot$ are available in WW95, we assume that the ejected O and Fe masses for such progenitors are equal to those of $40 M_\odot$. We summarize the masses for both the TS and SN
cases in Table 1. Even though these yields depend on the \(W_{SN}\) employed by WW95, they are within 30% of \(\sim 1.5 \times 10^{51}\) erg, so we assume this value for the entire progenitor mass range from 10 to 100 M\(_{\odot}\) in both the TS and SN cases.

We also explore another case (SN+CS), based of the possible existence of a rare class of much more energetic supernovae that could enhance the Be production efficiency by imparting an order of magnitude more energy to cosmic rays with only modestly increased Fe yields. Such “collapsars” (CS, also referred to as hypernovae), whose ejecta jets are driven by black hole accretion of “failed supernovae”, were suggested (Woosley 1993; Woosley, Eastman & Schmidt 1998; MacFadyen & Woosley 1998) as possible sources of gamma-ray bursts. The discovery of the Type Ic supernova SN1998bw (Galama et al. 1998) in the error box of the gamma-ray burst GRB980425 seems to support such a connection. Various models (Hoflich, Wheeler & Wang 1998; Iwamoto et al. 1998; Woosley, Eastman & Schmidt 1998), with ejecta kinetic energies \(W_{SN}\) ranging from 2 to \(28 \times 10^{51}\) erg, are quite consistent with the observations of this supernova. We incorporate such Type Ic supernovae by replacing 3% of the supernovae for the SN case by collapsars, based on their estimated Galactic rate of \(10^{-3}\) yr\(^{-1}\) (Hansen 1999). For the remaining 97%, we keep \(W_{SN} = 1.5 \times 10^{51}\) erg with ejected masses as given in Table 1, but to maximize the Be production of the additional Type Ic’s, we adopt the largest ejecta energy in the Woosley et al. (1998) calculations, \(W_{SN}=2.8 \times 10^{52}\) erg, corresponding to ejected \(^{56}\)Ni and \(^{16}\)O masses of 0.49 and 2.8 M\(_{\odot}\) respectively, and a progenitor mass of 40 M\(_{\odot}\). Since the rate of gamma-ray bursts is only \(\sim 10^{-7}\) yr\(^{-1}\) per galaxy, if their emission is not beamed, the Type Ic rate of \(10^{-3}\) yr\(^{-1}\) implies that only a very small fraction of the Type Ic supernovae produce gamma-ray bursts, or that their gamma ray emission is beamed into a very small solid angle.

The resultant O and Fe production rates as functions of time are also shown in Figure 1a for the TS, SN and SN+CS cases. The delay of a few Myr of the onset of the O and Fe production relative to the star formation rate, due to the lifetimes of the progenitors, can be clearly seen. There is an additional delay between the onset of O and Fe production in the SN case, because here the supernovae from the most massive, short-lived, progenitors produce O but not Fe. The incorporation of the collapsars (CS) shortens this delay, but its effect on the overall Fe production is quite small. There is no delay between the O and Fe production in the TS case.

We calculate the O and Fe contents of the ISM by delaying, due to transport and mixing, the deposition of these synthesized products. In the simulation we choose the mixing times randomly in the interval \(0-\tau_{mix}\) and allow for the possibility that \(\tau_{Fe}\) \(>\tau_{O}\). We choose, arbitrarily, a short mixing time \(\tau_{O}=1\) Myr, but consider two values for Fe, \(\tau_{Fe}=1\) and 30 Myr, the latter based on a scenario in which the bulk of the ejected Fe would be incorporated into high velocity refractory dust grains. This is supported both by observations (Kozasa, Hasegawa & Nomoto 1991) suggesting the massive condensation of iron oxide and other refractory grains at velocities \(\sim 2,500\) km s\(^{-1}\) in the supernova 1987A and by observations (Naya et al. 1996) of the Galactic 1.809 MeV gamma-ray line resulting from the decay of \(^{26}\)Al, most likely produced in Type II supernovae (e.g. WW95). The observed width of the Al line implies that the radioactive aluminum is still moving at velocities \(>450\)
Figure 2. O-to-Fe abundance ratio as a function of [Fe/H]. TS, SN and SN+CS assume different O and Ni-Fe ejecta yields as functions of core-collapse supernova progenitor mass; also shown is the dependence of [O/Fe] on the Fe mixing time which could become quite long as a result of the incorporation of the ejected Fe into high velocity dust.

The calculated O-to-Fe abundance ratio ([O/Fe]≡log(O/Fe)-log(O/Fe)⊙), together with recent data (Israelian et al. 1998), are shown in Figure 2, where we compare the predictions of the TS and SN cases (panel a) and those of the SN and SN+CS cases (panel b). We see that if \( \tau_{\text{Fe}}(\text{mix})=30 \text{ Myr} \), all cases are consistent with the data (the decrease of [O/Fe] for [Fe/H] > \(-1\)) is due to the onset of contributions from Type Ia supernovae which eject large Fe masses but not much O. For smaller \( \tau_{\text{Fe}}(\text{mix}) \), even though [O/Fe] is lower at low [Fe/H], both the SN and SN+CS cases remain consistent with the data and the inconsistency of the TS case is limited to just the lowest values of [Fe/H]. It is interesting to note that, unlike [O/Fe], the abundance ratios of the \( \alpha \)-nuclei Mg, Si, Ca and Ti relative to Fe do not increase with decreasing [Fe/H] below [Fe/H]=\(-1\) (Ryan, Norris, & Beers 1996). This may be consistent with the fact...
that these elements are also refractory, and thus are affected by mixing in the same way as is Fe.

3. Be Production and Evolution

The Be yield per supernova depends on several factors (e.g. Ramaty et al. 1997): the composition of both the accelerated particles and the ambient medium, the energy spectrum of the accelerated particles, the energy per supernova imparted to the accelerated particles, and the interaction model for the accelerated particles, characterized by a path length for escape from the Galaxy, $X_{\text{esc}}$. For the CRS model at all past epochs the accelerated particle composition is identical to the current epoch cosmic-ray source composition. For the CRI model the composition of the accelerated particles depends on $[\text{Fe/H}]$, being derived from the ISM composition at the same $[\text{Fe/H}]$ by applying the enhancement factors that modify the current epoch ISM to yield the current epoch cosmic-ray source, within the Ellison et al. (1997) shock acceleration theory. For the LECR model the accelerated particle composition at all past epochs is also identical to the current epoch cosmic-ray source composition, except for the variant LECR(metal), for which only C and heavier nuclei are assumed to be accelerated. The ambient medium composition is solar, scaled with $10^{[\text{Fe/H}]}$, except that for O the scaling is given by $O/H = (O/H)_\odot 10^{0.6[\text{Fe/H}]}$, which provides a good fit to the data on the dependence of the O abundance on $[\text{Fe/H}]$ (Israelian et al. 1998, figure 6). The accelerated particle source energy spectra are given by an expression appropriate for shock acceleration, $q(E) \propto (p^{-2.2}/c\beta)\exp(-E/E_0)$, where $p, c\beta$ and $E$
Figure 4. Be/Fe evolution for 2 models, 3 cases and 2 values of the Fe mixing time. The cosmic-ray composition is independent of [Fe/H] for the CRS model and is that of the ISM, modified by shock acceleration theory, for the CRI model. The Fe ejecta as a function of supernova progenitor mass are those of WW95 for the SN case, of collapsar (hypernova) augmented WW95 ejecta in the SN+CS case, and of Shigeyama & Tsujimoto (1998) and Tsujimoto & Shigeyama (1998) for the TS case. The average energy supplied to the cosmic rays for all models and cases, $1.5 \times 10^{50}$ erg, is the same as that required for the current epoch cosmic rays. The evolution is limited to 1 Gyr corresponding to [Fe/H] $\approx -1$. The decrease of Be/Fe at higher [Fe/H] is due to the Type Ia supernovae which are not included. Data compilation by VF98.

are particle momentum/nucleon, velocity and energy/nucleon, respectively, and $E_0$ is a turnover energy that we take equal to 10 GeV/nucleon for the CRS and CRI models (implying a spectrum extending to ultrarelativistic energies) and to various nonrelativistic values for the LECR and LECR(metal) models.

We derive Q/W (Ramaty et al. 1997), the total number of Be nuclei produced by an accelerated particle distribution normalized to unit cosmic-ray energy, for a given source energy spectrum and composition, and interacting in an ambient medium of given composition. Q/W is shown in Figure 3a as a function of the [Fe/H] of the ambient medium, for the CRS and CRI models. For the CRS model, it is essentially constant for [Fe/H] $< -1$, increasing slowly thereafter, but by no more than a factor of 2. For the CRI model, Q/W is a strong function of [Fe/H], increasing from a value at [Fe/H] = -3 that is almost 2 orders of magnitude smaller than the corresponding Q/W for the CRS model.

The Be production per supernova is $(Q/W)\eta W_{SN}$, where $\eta$ is the acceleration efficiency. As already detailed, the ejecta kinetic energy, $W_{SN}$, is $1.5 \times 10^{51}$ erg for all supernovae in the TS and SN cases and for 97% of the supernovae in the SN+CS case. For the remaining 3% (the collapsars), $W_{SN} = 2.8 \times 10^{52}$ erg. Since both CRS and CRI are current epoch cosmic-ray models, $\eta W_{SN}$ must equal the cosmic-ray energy input per supernova, $\approx 1.5 \times 10^{50}$ erg (e.g. Lingenfelter et al. 1998). We take $\eta$ independent of progenitor mass and the average over the employed supernova ensemble. This implies that $\eta = 0.1$ for both the TS
and SN cases, but, because of the extra energy due to the collapsars, \( \eta = 0.06 \) for the SN+CS case. We subsequently delay the Be deposition into the ISM because of the finite propagation and interaction time of the accelerated particles. The delay depends on the ISM density, and on the energy spectrum and composition of the accelerated particles. Using our Be production code (Ramaty et al. 1997), we derived the appropriate distributions, which for an ISM density of 1 atom cm\(^{-3}\) correspond to an average delay of several Myr for both the CRS and CRI models. All our calculations are for such delay times, except that for the LECR models the delay is negligible. The resultant Be production rates as function of time are shown in Figure 3b for the TS, SN and SN+CS cases, and for the two Fe mixing times. We see that for the CRI model at early times, there is significant dependence of the Be production on the employed case and on the Fe mixing time, due to the dependence of the Be production on the ISM composition. Specifically, since the Fe abundance at early times is increasingly larger for the SN, SN+CS and TS cases, respectively (Figure 1b), the corresponding O abundance is also larger, leading to larger values of Q/W (Figure 3a), and thus to larger Be production. For essentially the same reason, the Be production is also larger for the shorter Fe mixing time. These dependencies are absent for the CRS model, since here the Be production is independent of the ambient medium composition. The small increase for the SN+CS case at early times is due to the extra available collapsar energy.

The evolution of Be/Fe for the CRS and CRI models, the SN, SN+CS and TS ejecta cases, and the two Fe mixing times, is shown in Figure 4. We see that the predictions of CRS model, for both the SN and SN+CS cases (panels a and b), and the TS case (panel b), provide good fits to the data, independent of the Fe mixing time. The fact that the implied energy in cosmic rays per supernova, \( 1.5 \times 10^{50} \) erg, is very nearly the same as the value obtained from current epoch cosmic-ray data, provides strong evidence for the validity of the CRS model. On the other hand, for the CRI model the predicted Be/Fe does not fit the data. This result differs from that of Fields & Olive (1999a, hereafter OF) who concluded, for their best set of parameters, that the excess energy per supernova needed at [Fe/H] = −3 only exceeds the current value by about a factor of 5 (see figure 9 in OF), whereas our calculations imply a discrepancy of about 100. To understand the origin of the factor of 20 difference, we first note that OF modified the VF98 Be data so that their approximation at [Fe/H] = −3, \( \log(\text{Be/Fe}) \cong -6.4 \) (see figure 3 in OF), is lower by a factor of 4 than the constant value of −5.84 (VF98) which we use. The rest of the discrepancy is probably caused by differences in the employed Fe ejected masses, particularly those relevant at the lowest metallicities. These masses are not quoted by OF, but from their equation (30) we conclude that the ejected Fe/O decreases with decreasing [Fe/H] as \( 10^{0.31\text{[Fe/H]}} \), so that at [Fe/H] = −3 Fe/O is lowered by factors of 4 and 9, relative the corresponding values at [Fe/H] = −1 and 0, respectively. But from our Figure 1, we see that for all cases and mixing times, at times later than those needed to achieve [Fe/H] = −3, the Fe/O production ratio is essentially constant. So it appears that OF could have concluded that the energetics do not present a problem for the CRI model because they have modified the Be data and they chose to employ ejected Fe masses which, even though not listed in their paper, appear to be quite small at early times. On the other hand, we have employed
both calculated and measured Fe masses, and showed that these are consistent with the O/Fe abundance data, particularly if delayed mixing of Fe into the ISM is taken into account.

We carried out similar Be production calculations for the LECR models. The resulting $Q/W$, shown in Figure 5, while essentially independent of $[\text{Fe/H}]$, decrease rapidly with decreasing $E_0$, the turnover energy that defines the high energy cutoff of the LECR spectrum. At 70 MeV/nucleon, $Q/W$ is close to its maximum (see Ramaty et al. 1997, Figure 8). Even though the evolutionary curves, log(Be/Fe) vs. $[\text{Fe/H}]$ (not shown), provide good fits to the data, the required acceleration efficiency $\eta$ becomes prohibitively large in some cases. We have derived $\eta$ by normalizing the evolutionary curves at $[\text{Fe/H}] \approx -1$ to log(Be/Fe) = -5.84, the best fitting constant to the Be/Fe data for $[\text{Fe/H}] < -1$ (VF98), and by using the values of $W_{\text{SN}}$ detailed above for the SN, SN+CS and TS cases, the values of $Q/W$ for the 3 turnover energies for the LECR and LECR(metal) models in Figure 5, and, exploring the suggestion (VF98 and references therein) that only supernovae from the most massive progenitors ($>60 M_\odot$) contribute to LECR acceleration, for 3 such low-mass cutoffs ($M_{\text{cut}}$). The results are given in Table 2. By requiring that the efficiency $\eta$ be significantly less than 1, we see that if the LECRs were to be the dominant source of Be in the early Galaxy, $M_{\text{cut}} = 60 M_\odot$ is only possible if the acceleration of protons and $\alpha$ particles is suppressed and if $E_0 > 30$ MeV/nucleon. Likewise, acceleration of metals only is also required if $E_0$ were 10 MeV/nucleon. Clearly, nuclear gamma-ray line measurements are needed to determine the intensity of a possible LECR component and whether it could be a significant contributor to spallogenic light element production.

Figure 5. Number of Be atoms produced per unit available energy for the LECR and LECR(metal) models. Both the LECR and LECR(metal) compositions are identical to that of the cosmic rays in the CRS model, except that protons and $\alpha$ particles are absent for LECR(metal). $E_0$ is the turnover energy that effectively cuts off the spectrum at high energies.
Table 2. Required acceleration efficiencies (fractions of $1.5 \times 10^{51}$ erg/supernova or $2.8 \times 10^{52}$ erg/collapsar) for the LECR and LECR(metal) models for 3 values of $E_0$ (in MeV/nucleon) and 3 low mass cutoffs for the supernova progenitors that accelerate LECRs; for each $E_0$ and $M_{\text{cut}}$, the 3 values correspond to the SN, SN+CS and TS cases, respectively.

| $E_0$ | $M_{\text{cut}}$=10$M_\odot$ | $M_{\text{cut}}$=30$M_\odot$ | $M_{\text{cut}}$=60$M_\odot$ |
|-------|------------------------------|------------------------------|------------------------------|
|       | LECR: p, o, metals           | LECR: metals only            | LECR(metal): metals only     |
| 10    | 2.12 1.62 3.48               | 10.8 3.26 17.7               | 43.7 53.6 71.5               |
| 30    | 0.24 0.18 0.39               | 1.22 0.37 2.00               | 4.96 6.09 8.15               |
| 70    | 0.08 0.06 0.14               | 0.42 0.13 0.69               | 1.71 2.10 2.81               |

4. CRI vs. CRS for the Current Epoch Cosmic Rays

The arguments that have been made (e.g. Meyer et al. 1997) to support cosmic-ray acceleration out of average ISM material rather than from fresh nucleosynthetic matter (the CRI vs. CRS paradigm), and the counter-arguments (Lingenfelter et al. 1998), based on acceleration in supernova ejecta-enriched superbubbles (Higdon et al. 1998) are the following:

i) The enrichment of the cosmic-ray source abundances relative to solar abundances in refractory elements relative to volatile elements. But the refractory grains formed in supernova ejecta are depleted in volatiles, as are the grains in the average ISM, and since the freshly formed grains still move at high velocities in the superbubbles, their erosion products are much more readily accelerated than volatile ions of the ambient gas.

ii) The similarity of the cosmic-ray source and solar abundance ratios of refractory elements, mainly Mg, Al, Si, Ca, and Fe. But the nucleosynthetic yields of these elements, averaged over initial mass function and the relative contributions of the various supernova types, are consistent with both cosmic-ray source and solar abundances, which in fact the supernovae have produced.

iii) The presence of s-elements in the cosmic rays, which are not synthesized in supernova explosions. But s-elements are present in supernova ejecta along with the other much more abundant products of pre-supernova burning since they are made in the cores of the pre-supernova stars and are ejected both in the explosions and in strong stellar winds. Very significant overabundances of the prominent s-process products, Sr and Ba, relative to Fe were observed in SN1987A (e.g. Mazzali, Lucy & Butler 1992). In addition to the presence of s-elements, the observed enrichment of r-process nuclei in the cosmic rays, especially the strong Pt peak (Waddington 1996), provides direct support for a supernova origin.

iv) The delayed acceleration of the cosmic rays. This is based on the recent ACE measurements (Binns et al. 1999) of cosmic ray $^{59}$Co and $^{59}$Ni, showing that these isotopes could not have been accelerated from fresh supernova ejecta less than $7.5 \times 10^4$ yrs after the explosion. This result can only argue against cosmic-ray acceleration of supernova ejecta by the shock of the same supernova
(Lingenfelter et al. 1998), and not the collective acceleration by successive supernova shocks of ejecta-enriched matter in the interiors of superbubbles (Higdon et al. 1998) where supernova explosions occur every $10^5$ yr. These hot, low-density bubbles, which reach dimensions of several hundred pc, are generated by the winds and ejecta of supernova explosions of massive stars formed in giant molecular cloud OB associations, that last for tens of Myr. Since these bubbles expand with shell velocities much faster than the dispersion velocities of the O and B star progenitors of the supernovae that power them, the bulk of the supernovae occur in their cores. The expanding remnants of each of these supernovae only fill $<1\%$ of this core before they slow down to sonic velocities. Thus, the bulk of these supernovae remnants, together with their metal-rich grain and gas ejecta, are well confined within the cores of superbubbles. Consequently, the bulk of the metals of this hot phase of the ISM originate from recent nucleosynthesis, within the lifetime of the superbubble, and thus multiple supernova shocks (every $\sim 10^5$ yr) accelerate accumulated supernova ejecta on average time scales at least as long as the delay implied by the $^{59}$Co and $^{59}$Ni data.

In addition, cosmic-ray source injection from refractory grains formed in supernova ejecta can explain the longstanding puzzle of the cosmic-ray C and O abundances. The cosmic-ray source C/Fe and O/Fe are much lower than both the solar values and those in the icy grains (Savage & Sembach 1996) that contain a major fraction of the C and O in the ISM. O/Fe is lower than the solar value because only a fraction of the O is trapped in refractory oxides, primarily Al$_2$O$_3$, MgSiO$_3$, Fe$_3$O$_4$, and CaO. Similarly C condenses in refractory grains of graphite and amorphous carbon, as well as metal carbides, such as SiC, as have been detected in presolar material in meteorites. These refractory O/Fe and the supernova averaged C/Fe are in good agreement with the required cosmic-ray source values (Lingenfelter et al. 1998).

5. Conclusions

To test the viability of the models that have been proposed for the origin of the spallogenic light elements, we developed a new evolutionary Monte-Carlo code which allows the investigation of hitherto ignored effects, the delayed mixing into the interstellar medium (ISM) of the synthesized Fe due to its incorporation into high velocity dust grains and the relationship between the supernova nucleosynthetic yields and the ejecta kinetic energy, including events with very large ejecta energies (e.g. collapsars/hypernovae). The models are: the traditional CRI, in which the cosmic rays are accelerated out of an ISM which is increasingly metal poor at early times; the CRS, in which cosmic rays with composition similar to that of the current epoch cosmic rays are accelerated out of fresh supernova ejecta and thus maintain a constant metallicity at all epochs; and the LECR, in which a postulated low energy component, also accelerated out of fresh ejecta, coexists with the CRI cosmic rays.

By including the delayed mixing, we find that several sets of O and Fe ejecta yields, based on both observations and nucleosynthetic calculations, can account for the new data that indicate a monotonically increasing [O/Fe] with decreasing [Fe/H]. We provide arguments showing that the bulk of the synthesized Fe
probably resides in refractory dust grains which could travel much farther before they came to rest than the volatiles trapped in the plasma which are more rapidly slowed by the swept up gas and magnetic fields. Thus, there could be a delay between the effective deposition times into the ISM of refractories, such as Fe, and volatiles such as O, of which only a fraction is condensed in oxide grains. We suggest that this difference in volatility between the synthesized O and Fe is a likely cause for the increase of [O/Fe] with decreasing [Fe/H]. In support of this suggestion we point out that, unlike O, there appears to be no increase with decreasing [Fe/H] of the abundances of the α nuclei Mg, Si, Ca and Ti relative to Fe below [Fe/H] = −1 (Ryan et al. 1996), consistent with the fact that these elements are also refractory, and thus should mix in the same way as Fe.

We use three sets of O and Fe nucleosynthetic yields, their corresponding ejecta kinetic energies, and a cosmic-ray acceleration efficiency consistent with current epoch cosmic-ray data, to show that the CRI model significantly under-predicts the measured Be abundance at the lowest [Fe/H], the increase in [O/Fe] notwithstanding. On the other hand, the CRS model can account for the measured Be abundances with an acceleration efficiency that is in good agreement with the cosmic-ray data. To further compare these models, we review the arguments against cosmic-ray acceleration out of supernova ejecta and indicate how they are resolved in the CRS model by averaging the nucleosynthetic yields over initial mass function and the relative contributions of the various supernova types, by accelerating grain erosion products in supernova produced superbubbles, and by taking into account the products of burning in the cores of pre-supernova stars. As suggested by Westphal et al. (1998), the measurement of cosmic-ray actinides with lifetimes comparable to the age of the cosmic rays (a few tens of Myr) could distinguish between the CRI and CRS models.

The LECR model can also account for the observations, except that the required acceleration efficiency becomes prohibitively large for some of the parameters that have been previously assumed for this as-yet undetected cosmic-ray component. Future gamma-ray line observations could establish the contribution of LECRs to the origin of the spallogenic light elements.

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