The Origin of Present Day Cosmic Rays: 
Fresh SN Ejecta or Interstellar Medium Material? 
I Cosmic Ray Composition and SN Nucleosynthesis. 

A Conflict with the Early Galactic Evolution of Be? *

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Abstract. We show that the composition of present day cosmic rays is inconsistent with a significant acceleration of SN ejecta material (even if a preferential acceleration of ejecta grain material is assumed). Current cosmic rays must result essentially from the acceleration of interstellar gas and grain material, with a “solar mix” composition, plus of circumstellar material (Wolf-Rayet wind $^{22}$Ne- and $^{12}$C-rich material). The cosmic ray source composition derived from observations, indeed, shows no anomaly related to SN nucleosynthesis. Specifically: (i) The cosmic ray source FeNi/MgSiCa ratios have precisely the solar mix values, while FeNi are predominantly synthesized in SN Ia’s, and MgSiCa in SN II’s. To be understood in terms of an acceleration of SN ejecta, this would require tight conditions on the acceleration efficiencies of the ejecta of the various SN Ia’s and SN II’s of all masses. (ii) The lack of a deficiency of the main-s-process elements, not synthesized in any SN, relative to all elements made in SNe, is clearly inconsistent with a significant acceleration of SN ejecta material. (iii) With the exception of the $^{22}$Ne and related $^{12}$C excesses, suggesting the acceleration of Wolf-Rayet wind material, all determined cosmic ray isotope ratios are consistent with solar mix. (iv) The absence of $^{59}$Ni in cosmic rays implies that the time delay between the SN nucleosynthesis of Fe peak nuclei and their acceleration is $\gtrsim 10^5$ yr. (v) As discussed in Ellison & Meyer, this volume, the physics of SNR’s and of cosmic ray shock acceleration implies that the acceleration of interior ejecta material is insignificant, as compared to that of interstellar and/or circumstellar material outside the forward shock. Predominant acceleration of current cosmic rays out of superbubble material also seems implausible.

These conclusions regarding current cosmic rays do not necessarily conflict with the linear evolution of Be/H in the early Galaxy. With the near absence of heavy elements in the early Galactic ISM, indeed, the acceleration of even a minute amount of freshly processed material in the early

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Galaxy (SN ejecta ? Wolf-Rayet winds ? superbubbles ?) must have played a dominant role for the generation of Be from C and O. The “Be indicator” is, indeed, blind to a possibly dominant early Galactic cosmic ray component originating in the ISM then composed of virtually pure H and He.

1. Introduction

1.1. The Early Galactic Evolution of the Be Abundance

1.1.1. The situation, based on the conventional determinations of the evolution of the Galactic O/H ratio

Observations indicate that the Galactic Be/H and B/H ratios increase close to linearly with Fe/H, at least in the early Galaxy, for [Fe/H] between – 3 and – 0.5 \(^1\) (e.g., Molaro et al. 1997; Duncan et al. 1997; García López et al. 1998; Vangioni-Flam et al. 1998a for a review). Now, the significant correlation is not Be/H vs. Fe/H, but rather Be/H vs. O/H, since O is, with C, the principal progenitor of Be \(^2\).

On the other hand, the conventional studies of the evolution of the O/Fe ratio, largely based on [OI] forbidden line observations, indicate a constancy of O/Fe at a value of \(\sim 2.5 \times \) solar, from [Fe/H] \(\sim – 1\) down to \(-3\) (Pagel & Tautvaisiene 1995; McWilliam 1997). The linear correlation \(\text{Be/H} \propto \text{Fe/H}\) thus translates into a linear correlation with O/H as well, i.e. \(\text{Be/H} \propto \text{O/H}\). This implies that, in the early Galaxy, the Be production rate \(\frac{d}{dt}\text{Be}\) was independent of the Galactic abundance of its major progenitor, O, i.e. that Be is “primary”.

Now, Be can be synthesized only by high energy spallation of essentially CNO nuclei interacting with protons \(^3\). There exists two channels for these interactions: (i) the spallation of ISM CNO, at rest, by cosmic ray protons, producing Be at rest in the ISM (“Be\(_{\text{ism}}\)”), and (ii) the spallation of fast cosmic ray CNO’s on ISM protons at rest, producing fast Be nuclei (“Be\(_{\text{fast}}\)”).

Since the Be\(_{\text{ism}}\) component originates in the ISM CNO nuclei, its production rate \(\frac{d}{dt}\text{Be\(_{\text{ism}}\)}\) increases roughly as the Galactic O/H \(\frac{d}{dt}\text{Be\(_{\text{ism}}\)} \propto \text{O/H}\),

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1 As usual \([A/B]\) denotes \(\log_{10}(A/B) – \log_{10}(A/B)_{\odot}\), where A and B are the abundances of two elements.

2 From here on, we will consider only Be. The Be and B origins and histories share many similarities. But, contrary to Be, which can be made only by proton and \(\alpha\)-particle induced spallation of heavier nuclei in space, \(^{11}\)B can be made by neutrino induced spallation in Type-II SNe, as well (Woosley & Weaver 1995; Timmes et al. 1995). In addition, the particle induced spallation yields of \(^{11}\)B are particularly sensitive to the exact shape of the interacting particle spectrum at low energies (e.g., Meneguzzi & Reeves 1975; Ramaty et al. 1997). So, the interpretation of behavior of B is less straightforward than that of Be.

3 For legibility, we denote by “interacting with protons” what should actually read “interacting with protons and \(\alpha\)-particles”, since the latter also play a significant role. Note also that the role of N is small, compared to those of C and O.
so that the Be$_{\text{ism}}$ component is purely “secondary” ($\text{Be}_{\text{ism}}/H \propto O/H^2$) \footnote{This assumes that the interacting cosmic ray protons are not essentially low energy particles ($\sim$10’s of MeV/nucleon) with a small stopping range, confined within regions locally enriched in heavy elements, such as superbubbles. This possibility seems very unlikely, since superbubbles have very low densities, so that even low energy particles will mainly interact (and be stopped) in nearby dense ISM clouds, rather than within the enriched superbubble material itself (e.g., Bykov 1995). This is all the more so, that only the central part of superbubbles is actually enriched, the gas in most of their volume being dominated by material evaporated from nearby dense clouds (Higdon et al. 1998).}. As for the Be$_{\text{fast}}$ component, it has a primary or a secondary character, according to whether the cosmic rays has been accelerated out of (i) the general ISM ($d/dt$ Be$_{\text{fast}} \propto O/H$ : secondary), or (ii) freshly processed material, such as SN ejecta or Wolf-Rayet star wind material, in which the large CNO abundance is independent of Galactic O/H (primary). Therefore, only a Be production controlled by the spallation of cosmic ray CNO nuclei accelerated out of freshly processed material can account for the primary character of the observed evolution of the early Galactic Be/H ratio. This implies, in particular, that, in the early Galaxy, most cosmic ray CNO nuclei originated, not in the ISM, but in fresh sources of nucleosynthesis, and most plausibly from SNII ejecta (e.g., Duncan et al. 1992; Feltzing & Gustafsson 1994; Vangioni-Flam & Cassé 1996; Ramaty et al. 1997,1998; Lingenfelter et al. 1998; Vangioni-Flam et al. 1998a; Higdon et al. 1998).

This is, actually, not a surprise. In the early Galaxy, indeed, there was very little CNO in the ISM, so that very little Be could originate in the spallation of any material originating in it (i.e., both of ISM CNO, and of cosmic ray CNO accelerated out of this ISM). Therefore, any contribution, however minor, to cosmic rays from freshly synthesized, CNO-enriched material could easily yield a dominant contribution to the Be production, and make Be evolve as a primary in the early Galaxy – until a significant amount of CNO resided in the ISM (§ 3).

1.1.2. The situation, based on the recent determinations of the evolution of the Galactic O/H ratio (with OH molecular lines)

Recent studies, based on OH molecular line observations, yield a different evolution of the Galactic O/Fe ratio with Fe/H: O/Fe seems to continuously increase with decreasing Fe/H from $[\text{Fe}/H] \sim 0$ down to $-3$, with a slope of $\sim -0.35$ (Israelian et al. 1998; Boesgaard et al. 1999). If this is correct, the linear evolution Be/H $\propto$ Fe/H translates into a new relationship Be/H $\propto$ O/H$^{1.35}$. A more elaborate treatment by Fields & Olive (1998) yields Be/H $\propto$ O/H$^{1.3}$ to $1.8$. The validity of the new O abundance determinations based on OH lines is currently a matter of debate (Vangioni-Flam et al. 1998b; Cayrel 1999) \footnote{The new OH molecular line studies imply high O abundances for the very early Galaxy, which might also pose energetic problems for their production. This behavior of O/H would also have to be understood along with the behavior of the other $\alpha$-elements (“$\alpha$”), presumably synthesized in the same Type-II SNae, which apparently do not show a similar increase of the “$\alpha$”/Fe ratio in the $[\text{Fe}/H] \sim -1$ to $-4$ range (e.g., Pagel & Tautvaisiene 1995; McWilliam 1997).}.

\footnote{For legibility, we denote by “SN II” all massive star SNae of Type II and Ib.}
These new data on the Galactic O/H thus imply a Be production rate $d/dt$ Be which increases with O/H, but not as fast as $d/dt$ Be $\propto$ O/H, as would be the case if Be were purely “secondary” (Be/H $\propto$ O/H$^2$). If they are valid, we should have had, in the early Galaxy, significant Be contributions from spallation of both cosmic ray CNO accelerated out of freshly processed material (primary), and of CNO originating in the ISM (CNO at rest in the ISM, broken up by the cosmic ray protons, and/or cosmic ray CNO nuclei accelerated out of the ISM material, both secondary).

1.2. The Current Galactic Cosmic Ray Source (GCRS) Material

On the other hand, the observed composition of the current cosmic rays seems to imply an acceleration out of interstellar and/or circumstellar material, with a preferential acceleration of the grain material over the gas-phase ions, and not an acceleration of SN ejecta (Meyer et al. 1997,1998; Ellison et al. 1997; Ellison & Meyer 1999).

The current cosmic ray source composition is shown in Fig. 1, compared to that of the Sun, versus mass $A$. The elements are sorted according to their volatility. The refractory elements, locked in grains in the ISM, are found globally enhanced relative to the volatile ones, which remain in the gas-phase. For the volatile elements, the enhancements increase with mass $A^7$. For the refractory elements, by contrast, there is only a very weak increase of the enhancements with mass $A$, if any $^8$(Meyer et al. 1997,1998).

These contrasting behaviors are simultaneously interpreted in terms of an acceleration of the external (interstellar and/or circumstellar) material traversed by the SNR shocks, which get smoothed by the backpressure of the accelerated particles which is always substantial if the acceleration is efficient. This smoothed (i.e., nonlinear) shock acceleration leads to a higher acceleration efficiency for ions with higher mass-to-charge ratio $A/Q$, which “see” a larger fraction of the entire shock velocity gap at each crossing of the shock. For the volatile elements, the observed increase of the enhancements with $A$ just reflects this increase of the acceleration efficiency for ions with higher $A/Q$ ratio in the gas-phase. On the other hand, dust grains are slightly charged, and should behave like ions with huge $A/Q$ ratios of order $\sim 10^8$. As such, they are very efficiently accelerated up to $\sim 0.1$ MeV/nucleon, where the friction on the gas both cancels the acceleration and sputters off some $10^{-4}$ of the grain mass. Refractory element ions are thus injected at $\sim 0.1$ MeV/nucleon. These then get further accelerated, with high efficiency, as individual ions. Since in the crucial, early phases, the refractory elements are accelerated, not as individual ions, but as constituents of entire grains, their enhancements are expected to be roughly

$^7$Except for H, which has a high thermal speed possibly comparable to the viscous subshock speeds, C, which has a large Wolf-Rayet component and is partly locked in grains, and O, also partly locked in grains.

$^8$This is evident from the behavior (shown in Fig. 1) of those refractory elements whose cosmic ray source abundance is accurately determined, i.e. Mg, Al, Si, Ca, Fe, Ni and, to a lesser degree, Sr, Zr ($A \approx 24$ to $\sim 90$); see § 2.3. The absolute source abundances of the elements from Mo upward ($A \gtrsim 95$) are affected by large, partly systematic, uncertainties.
Figure 1. The Galactic Cosmic Ray Source (GCRS) to Solar abundance ratios in the $\sim$ GeV range, versus element mass $A$, with the elements sorted according to their volatility (after Meyer et al. 1998 and Westphal et al. 1998). See text §1.2. Normalized to H, at a given energy/nucleon. The point for C is plotted as an upper limit, since its total source abundance includes a specific $^{12}$C contribution associated with a $^{22}$Ne-rich component presumably from WR star wind material; we propose an estimate of the non-WR C source abundance (which may still be an overestimate, since we did not consider any preferential acceleration of C – particularly locked in grains in the C-rich WR wind material – relative to $^{22}$Ne in the WR component); for Ne, we have plotted the $^{20}$Ne abundance. “Pt”, “Pb”, and “Act” stand for $Z = 74$–$80$, $81$–$83$, and $90$–$92$, respectively, the latter being normalized to the relevant undecayed, proto-solar abundances. We have marked by a dashed error bar and a “?” sign those ultra-heavy elements whose source abundance relative to Fe is quite uncertain; but the relative abundances of neighboring elements (e.g., the “Pb”/“Pt”, “Act”/“Pt” ratios) is much better determined. The lines roughly fitting the “highly-volatile” and the “refractory” element points are just to guide the eye; they are represented solid in the well determined range, and extrapolated dashed in the much less well established, very heavy element, range. Note that these lines are not the predictions from the Ellison et al. (1997) model. In fact, the Ellison et al. model does not predict a strict power law for the highly-volatile element enhancements, and matches the H and He observations better than the power law shown here.
independent of their mass, as observed (Ellison et al. 1997; Ellison & Meyer 1999).

Note that we have definite evidence for the presence of a nucleosynthetically peculiar component in cosmic rays: the observed $^{22}\text{Ne}$ excess by a factor of $\sim 4.5$ in the cosmic ray sources. This $^{22}\text{Ne}$ excess strongly suggests the presence of a Helium-burning material component in cosmic rays, most likely originating in WC-type Wolf-Rayet star (WR) wind material. An associated $^{12}\text{C}$ excess is expected, which has been assessed in Meyer et al. (1997), and is, indeed, suggested by the recent isotopic observations (see § 2.4). Fig. 1 therefore shows both the total cosmic ray $\text{C}$ abundance and the estimated non-WR component (which may still be an overestimate, see caption). Note that, in the above SNR shock acceleration scenario, the shocks associated with the most massive SNe will naturally accelerate the (external) pre-SN WR wind material, which is enriched in $^{22}\text{Ne}$ and $^{12}\text{C}$ (Meyer et al. 1997).

1.3. The puzzle – Our Questioning

With current cosmic rays, some $\sim 93\%$ of the Be produced is of secondary origin. Consider, indeed, the two channels for Be production mentioned in § 1.1.1. (i) The spallation of ISM CNO by cosmic ray protons, $\text{Be}_{\text{ism}}$; this component is purely secondary. (ii) The spallation of fast cosmic ray CNO’s on ISM protons, $\text{Be}_{\text{fast}}$; this component, by contrast, is only $\sim 64\%$ secondary, and $\sim 36\%$ primary, due to the large contribution of WR star wind material to the cosmic ray $\text{C}$

Now, for standard cosmic ray spectral shapes, this $\text{Be}_{\text{fast}}$ component makes up only some $20\%$ of the total galactic Be, because most of the formed Be nuclei escape the Galaxy or break up (Meneguzzi & Reeves 1975)\textsuperscript{10}. Altogether, for standard cosmic ray spectra, only $\sim 7\%$ of the currently produced Be is of primary origin.

Recently, Ramaty et al. (1997,1998) and Lingenfelter et al. (1998) have contended that the evolution of Be/H in the early Galaxy requires that current cosmic rays are accelerated out of fresh SN ejecta. Along this line, Lingenfelter et al. (1998) have argued that a preferential acceleration of grain over gas-phase material within fresh SN ejecta might account for the observed cos-

\textsuperscript{9}The main progenitors of the $\text{Be}_{\text{fast}}$ component are, indeed, the cosmic ray O and C nuclei. The role of N is small, and will be neglected in a first approximation. According to the analysis of Meyer et al. (1997,1998), the cosmic ray O originates entirely in the ISM (with some $\sim 20\%$ of the O locked in grains), so that O is a secondary progenitor. As for C, at least $\sim 75\%$ – so, say, $85\%$ – of its source abundance originates in WC-type WR star wind material (see Fig. 1 caption). This WR C has been ultimately produced out of the stellar H (first turned into $^4\text{He}$, and then into $^{12}\text{C}$), and has therefore a primary character (Meyer et al. 1997). Now, in current $\sim \text{GeV}$ cosmic rays propagating in the Galaxy, the C/O ratio is $\sim 1.09$, with $\sim 0.69$ accelerated out of WR wind material, $\sim 0.12$ accelerated out of the ISM, and $\sim 0.28$ resulting from, mainly O, spallation (Engelmann et al. 1990; Meyer et al. 1998). Further, the weighted ratio of the p- and $\alpha$-induced, high energy spallation cross sections for $^9\text{Be}$ formation from $^{12}\text{C}$ and from $^{16}\text{O}$ is $\sim 1.22$ (Ramaty et al. 1997). With these figures, we find that altogether, about $\sim 36\%$ of the currently produced $\text{Be}_{\text{fast}}$ is of primary origin.

\textsuperscript{10}This may, however, not be true if there exists in the ISM, a “carrot” of intense cosmic ray fluxes at such low energies ($\lesssim 100\text{ MeV/nucleon}$) that they cannot be observed within the Solar cavity, being excluded by the interaction with the expanding Solar wind (e.g., Meneguzzi & Reeves 1975).
mic ray composition and for its acceleration – as well as such an acceleration out of interstellar and/or circumstellar material.

Here we wish to reexamine whether current cosmic rays could be accelerated out of fresh SN ejecta material. We will conclude that this seems impossible, in view of two types of difficulties: (i) difficulties with the observed cosmic ray composition, discussed in terms of SN nucleosynthesis in § 2, and (ii) difficulties with the SNR physics and the shock acceleration of ejecta material, discussed in a companion paper by Ellison & Meyer (1999).

We will then ask ourselves whether these conclusions regarding current cosmic rays necessarily conflict with the early Galactic evolution of Be/H, and conclude that it may not. Finally, we suggest possible ways out of this apparent contradiction (§ 3).

Note that in the same spirit, but along a different line, Higdon et al. (1998) have later suggested that current cosmic rays might be accelerated out of superbubble material enriched in fresh nucleosynthesis products. This also seems very difficult, both in view of the observed cosmic ray composition (§ 3.2.3) and of the superbubble physics (Ellison & Meyer 1999).

2. Is the Composition of Current Cosmic Rays Consistent with the Acceleration of Fresh SN Ejecta?

2.1. The Nucleosynthetic Origins and Abundances of the Cosmic Ray Elements

Fig. 2, like Fig. 1, shows the GCRS/Solar enhancements versus mass, but with the elements sorted, this time, according to their nucleosynthetic origin. We have, nevertheless, still indicated whether an element is a full-fledged refractory (closed symbols, or “×”), or not (open symbols, for all more or less volatile elements). The elements have been sorted into four types of nucleosynthetic origins:

(i) Explosive nucleosynthesis in SN II, i.e. in massive stars with > 8 $M_\odot$ initial mass. This includes O, $^{20}$Ne, Mg, Al, Si, P, S, Ar, Ca, and the predominantly r-process elements Se, Xe, Pt-group, Actinides (triangles).

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11 In the context of nucleosynthesis, it is important to recall the significance of the “solar” or, better, “solar mix” abundances. The “solar mix” abundances result from the cumulated contributions of the nucleosynthetic yields of many different types of stars (over a wide range of masses and life times) throughout the life of the Galaxy until the birth of the Sun, which has led to the solar and to the, roughly similar, current local ISM composition.

12 References for nucleosynthetic origins, general: Anders & Grevesse (1989); Wheeler et al. 1989; Edvardsson et al. (1993); Pagel & Tautvaisienë (1995); Woosley & Weaver (1995); Timmes et al. (1995); McWilliam (1997); Arnould & Takahashi (1999).

13 References for SN II nucleosynthesis: Arnett (1995); Woosley & Weaver (1995); Timmes et al. (1995); Thielemann et al. (1996); Nomoto et al. (1997).

14 Pt-group: $Z = 74$–80, Pb-group: $Z = 81$–83, Actinides: $Z = 90$–92.
Figure 2. The same GCRS to Solar abundance ratios as in Fig. 1, with the elements sorted, this time, in terms of their nucleosynthetic origin. Explanations in the text, § 2.1.

(ii) Quiescent weak-s-process in massive stars with $> 15 \, M_\odot$ initial mass; the material is also ejected in the SN II explosion, and possibly in stellar winds. This group includes the predominantly s-elements with mass $A \lesssim 87$, i.e. Ga and Ge (squares).

(iii) Quiescent main-s-process, taking place in low mass, $1 - 3 \, M_\odot$ stars during the AGB phase. This group includes the predominantly s-elements with mass $A \gtrsim 87$, i.e. Sr, Zr, Ba, Ce, Pb-group (circles).

(iv) Explosive nucleosynthesis in SN Ia, i.e. in intermediate–lower mass star binary systems having formed a white dwarf, with initial masses of $4 - 8 \, M_\odot$ for

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15References for the s-process, general (weak and main): e.g., Käppeler et al. (1989); Palme & Beer (1993); Meyer (1994); Beer et al. (1997); Gallino et al. (1998).

16The limit between the predominance of the weak- and of the main-s-process is, of course, not abrupt, and somewhat model dependent. For species with $A \leq 85$, the weak-s-process is clearly predominant, while the main-s-process clearly dominates for $A \geq 88$ (e.g., Käppeler et al. 1989; Beer et al. 1992; Baraffe et al. 1992; Raiteri et al. 1993; Palme & Beer 1993; Gallino et al. 1998). Note that the solar Sr ($Z = 38$), with essentially three isotopes ($^{84}$Sr, $^{85}$Sr, $^{86}$Sr), is 83 % $^{84}$Sr (Anders & Grevesse 1989). So, Sr is essentially a main-s-process element.
the white dwarf progenitor and $1 - 3 \, M_\odot$ for the companion \footnote{References for SN Ia nucleosynthesis: Thielemann et al. (1986); Edvardsson et al. (1993); Yoshii et al. (1996); Kobayashi et al. (1998). See discussion of the Fe,Co,Ni nucleosynthesis sites in § 2.3.1.}

This group includes Fe and Ni ("\times" signs).

For C, both the total, presumably WR wind dominated, and the non-WR cosmic ray C points have been tentatively denoted by squares, indicative of a predominantly quiescent origin in massive stars, with wind or explosive ejection (like the weak-s elements) \footnote{References for C and N nucleosynthesis: Wheeler et al. (1989); Pagel (1992,1994); Andersson & Edvardsson (1994); Timmes et al. (1995); McWilliam (1997); Portinari et al. (1998); Gustafsson et al. (1999).}

The N point has been denoted by a circle, since N seems predominantly, though not entirely, made in low mass stars (like the main-s elements). But C and N are, anyhow, not important for the subsequent discussion.

In Fig. 2, we have omitted Na, Cu, and Zn, whose nucleosynthetic origin isn’t firmly established (Edvardsson et al. 1993; Timmes et al. 1995; McWilliam 1997), Mo and Kr, which have comparable s- and r-process contributions, as well as H and He.

2.2. The $^{20}$Ne/Mg and S,Ar/Si,Ca Ratios

The low GCRS $^{20}$Ne/Mg and S,Ar/Si,Ca ratios cannot be explained in terms of SN nucleosynthesis. On the other hand, all these elements are believed to be essentially synthesized in Type II SNæ, and their average relative abundances in SNII ejecta should be similar to the solar mix or ISM ones. Therefore, a preferential acceleration of grain material over gas ions may yield similar GCRS ratios if applied to, either ISM material, or SN ejecta. If it accounts for these ratios for an accelerated ISM material (Meyer et al. 1997), it may as well account for them for an accelerated ejecta material (Lingenfelter et al. 1998).

So, as noted by Lingenfelter et al. (1998), the low GCRS $^{20}$Ne/Mg and S,Ar/Si,Ca ratios do not allow one to discriminate between an acceleration of ISM or SN ejecta material, provided that a preferential acceleration of grain over gas-phase material can actually work in both environments (discussion in Ellison & Meyer 1999).

\footnote{Regarding C, we have a special situation, in view of the specific cosmic ray $^{12}$C component associated with the $^{22}$Ne excess, presumably accelerated out of WR wind material (§ 1.2). The total cosmic ray C abundance, probably dominated by this WR component, has been denoted by a square in Fig. 2 (like weak-s elements, quiescent origin in massive stars, and wind or explosive ejection). As for the non-WR cosmic ray C, it refers to the nucleosynthetic origin of the general C abundance in the Galaxy, which is currently a hot issue; there are probably significant contributions from stars of very different masses; following Gustafsson et al. (1999), who conclude that WR winds should also play a dominant role in the synthesis of the Galactic C, we tentatively also plot the non-WR C point with a square.}
2.3. The Refractory Elements of Various Nucleosynthetic Origins

We now consider only the 12 refractory elements, whose cosmic ray source abundances and nucleosynthetic origin are reasonably well determined: Mg, Al, Si, Fe, Ni, Sr, Zr, Ba, Ce, Pt-group, Actinides.

As shown in Fig. 2, they are all found to be in proportions close to the solar mix ones in the cosmic ray sources: to within 20% for Mg, Al, Si, Fe, Ni, to within a factor of $\sim 1.5$ for Sr and Zr, and a factor of $\sim 3$ (upward) for Ba, Ce, Pt-group and Actinides (Meyer et al. 1997,1998; Westphal et al. 1998) $^{20}$. This fact is very unlikely to be fortuitous, and strongly suggests that no strong fractionation related to, either chemistry, or atomic physics, or nucleosynthetic origin is at work among them $^{21}$.

Now, these elements are synthesized in very different environments:

| Elements    | Mg, Si, Ca | Fe, Ni | Sr, Zr, Ba, Ce | Pt-gr, Act. |
|-------------|------------|--------|----------------|-------------|
| made by     | expl. O, Si-burn. | e-process | main-s-process | r-process |
| in          | SN II      | SN Ia  | AGB-stars      | SN II       |
| with initial masses | $> 8 \ M_\odot$ | $4 - 8 \ M_\odot$ | $1 - 3 \ M_\odot$ | $> 8 \ M_\odot$ |
|             | $+ 1 - 3 \ M_\odot$ |        |                |             |

Nevertheless, as we have just seen, they are all found to have nearly solar proportions in cosmic ray sources!

We now investigate more closely the significance of two ratios in the GCRS: the Fe, Ni/Mg, Si, Ca and the main-s-elements/all-others ratios.

2.3.1. The Fe, Ni/Mg, Si, Ca ratios

Virtually all the galactic Mg, Si, Ca is synthesized in SN II’s. By contrast, about $\sim 70\%$ of the Fe, Co, Ni is synthesized in SN Ia’s, and only $\sim 30\%$ in SN II’s (e.g., Edvardsson et al. 1993; Pagel & Tautvaišienė 1995; Timmes et al. 1995; Yoshii et al. 1996) $^{22}$. Nevertheless, the cosmic ray source Fe, Ni/Mg, Si, Ca ratios are equal to those in the solar mix, to within 20%.

20 There are still possible systematic errors on the Ba, Ce, Pt-group and Actinide cosmic ray source abundances relative to much lighter elements, such as Fe – mainly due to our poor knowledge of the precise shape of the cosmic ray interstellar pathlength distribution below $\sim 1$ g cm$^{-2}$ (see Meyer et al. 1997).

21 There may be a weak, smooth increase of the GCRS abundances with mass, among the refractory elements; see interpretation in Meyer et al. (1997).

22 This estimate is mainly derived from the contrasted evolutions of the galactic Fe/H and O, Mg, Si, Ca/H ratios, the latter elements being all made in SN II’s. It may be noted that the nominal model of Woosley & Weaver (1995) and Timmes et al. (1995) attributes a twice larger fraction of Fe to SN II’s; but the Fe yield of SN II’s is very dependent on the poorly known mass-cut; Timmes et al. (1995) have actually noted that a twice smaller Fe contribution of SN II’s fits the galactic evolution data better, as well as the SN 1987A observations. Note also that Co and Ni are, like Fe, predominantly made in SN Ia’s, as evidenced by the constancy of the galactic Co/Fe and Ni/Fe ratios versus Fe/H (Gratton & Sneden 1991; Edvardsson et al. 1993; McWilliam 1997).
Lingenfelter et al. (1998) have shown that an average of the calculated yields of the various types of SNæ over the Initial Mass Function (IMF) leads to Fe,Ni/Mg,Si,Ca ratios consistent with the (equal) solar mix and cosmic ray source ratios. Basically, this amounts to showing that the current SN Ia and SN II models, together with the estimated IMF, can, by and large, account for the solar mix Fe,Ni/Mg,Si,Ca ratios. This applies to the SNR grain material as well, since all these elements are believed to be soon entirely locked in grains in SNR’s.

Lingenfelter et al. therefore contend that the cosmic ray Fe,Ni/Mg,Si,Ca ratios are accounted for, if cosmic rays are accelerated from SNR grain material. This is, however, true only if the relative contributions of the various SN Ia’s and SN II’s are equal, to within 20%, for (i) the galactic enrichment of each of the various species, and (ii) the corresponding amount of cosmic ray accelerated material. This requires that the cosmic ray acceleration yields follow, without any bias, the yields for the enrichment of the various elements for all SNæ. While this is not impossible, it does not seem likely since these various objects, SN Ia’s and SN II’s of all masses, have very different layer structures, ejection speeds, ejecta masses, and ISM environments.

2.3.2. The main-s-process elements (A > 87)

2.3.2.1. Main point! As discussed in § 2.1, s-process species must be subdivided between weak-s species with A < ∼ 87, made in massive stars (no observed GCR refractory), and main-s species with A > ∼ 87, synthesized in low mass, 1 – 3 $M_\odot$ stars during the AGB phase. Here, we are interested in these main-s elements, for which we have a sample of four refractory elements with determined GCRS abundance: Sr, Zr, Ba, Ce.

These main-s elements are definitely not made, to a significant fraction, in any type of SN (§ 2.1)! Nevertheless, they are not underabundant in GCRS’s, relative to Mg, Al, Si, Ca, Fe, Ni, Pt-group, and Actinides, which are all made in SNae (Fig. 2). So, we conclude that SN nucleosynthesis cannot control the current GCRS composition (Prantzos et al. 1993).

2.3.2.2. Observed Ba enrichment in SN 1987A? Ba is an almost pure main-s element. Now, Mazzali et al. (1992) have reported the observation of a Ba/Fe enhancement by a factor of 3.7 in SN 1987A. This has led Lingenfelter et al. (1998) to question the conventional views on the origin of the main-s-process elements in low mass AGB stars, and to suggest that they may largely originate in SN II nucleosynthesis. The lack of a relative deficiency of the main-s elements in cosmic rays would then no longer conflict with a SN ejecta origin of the cosmic ray material. We think that this questioning of the low mass star origin of the main-s elements is not justified, on three grounds:

(i) First, the reality of the observed Ba enhancement is far from certain. It is based on an analysis of Ba II lines, whose atomic physics is not at all well under control. Earlier analysis had actually led to Ba/Fe enhancements by factors of 10 to 20. This factor has been reduced to ~ 3.7 in Mazzali et al.’s study, due to their consideration of line blocking, leading to a higher predicted Ba II/Ba III line strength ratio. The authors themselves are remarkably prudent regarding their analysis, stating: “We also cannot rule out the possibility that
other recombination mechanisms, which we have not considered in this work, may be important as well. The fact that [...] suggests that perhaps no real s-process elements overabundance is present in SN 1987A”.

(ii) Second, main-s-process nucleosynthesis in SN IIs, if significant, would be expected to yield larger excesses of lighter elements. In particular, the $^{38}$Sr excess is expected to be significantly larger than that of $^{56}$Ba (Prantzos et al. 1988). Now, Mazzali et al.’s analysis yields a Sr/Fe excess by a factor of $\sim 1.5$ only! This does not add credibility to the abundance analysis.

(iii) The evolution of the galactic Ba abundance over the range [Fe/H] = – 2 to 0 shows beyond doubt that Ba is, indeed, predominantly produced by low mass stars (Edvardsson et al. 1993; Gratton & Sneden 1994; McWilliam 1997; Mashonkina et al. 1999).

We conclude that the existing Ba observations in SN 1987A do not justify a questioning of the predominantly low mass star origin of the main-s elements.

2.4. The GCRS Isotope Ratios

As well known, the GCRS $^{22}$Ne/$^{20}$Ne ratio is about 4.5 times solar, and this suggests the presence of a He-burning material component in GCRS’s, probably originating in WC-type WR star wind material (§ 1.2). An associated $^{12}$C excess is expected, which is, indeed, suggested by the recent analysis of the $^{13}$C/$^{12}$C ratio (Duvernois et al. 1996; Webber et al. 1996).

With this sole exception, the outcome of a large number of recent studies of the isotopic ratios shows that the GCRS isotopic ratios of all other measured elements (N, O, Mg, Si, S, Ca, Fe, Co, Ni, Cu, Zn) are consistent with the solar mix.

2.5. The $^{59}$Ni Clock

2.5.1. General

$^{59}$Ni is an unstable isotope which decays by electron capture with a period $\tau_{ec} = 1.1 \times 10^5$ yr, provided that it is not fully stripped. In the conventional view, the stable galactic $^{59}$Co has been initially synthesized as $^{59}$Ni. So, if cosmic rays are accelerated out of fresh SN ejecta $\lesssim 10^5$ yr after the explosive nucleosynthesis, the initial $^{59}$Ni nuclei have not had enough time to decay before they are fully stripped by the acceleration, and are preserved in cosmic rays. If, by contrast, cosmic rays originate in “old” ISM (or even circumstellar) material, the initial $^{59}$Ni nuclei have had plenty of time to decay before their acceleration, and no $^{59}$Ni should be observed in cosmic rays (Soutoul et al. 1978).

References for GCRS isotope ratios: Leske 1993 (Fe, Co, Ni); DuVernois et al. 1996 (C, N, O, Ne, Mg, Si); Westphal et al. 1996 (Fe, Ni); Webber et al. 1996 (C, N, O), 1997 (Ne, Mg, Si, S); Connell & Simpson 1997 (Fe, Co, Ni); Lukasiak et al. 1997a (Co, Ni), 1997b (Ca, Fe); George & Wiedenbeck 1998 (Cu, Zn).

Connell & Simpson (1997) have reported source $^{54}$Fe/$^{56}$Fe and $^{57}$Fe/$^{56}$Fe enhancements by factors of $\sim 1.2$ to 1.6 and of $\sim 1.6$, respectively. The source $^{54}$Fe/$^{56}$Fe excess is sensitive to the interstellar propagation calculation and to the $^{54}$Mn lifetime. Its high value is not confirmed by the studies of Leske (1993) and Lukasiak et al. (1997b). As for the $^{57}$Fe/$^{56}$Fe ratio, mass 57 seems very poorly resolved in Connell & Simpson’s data.
We have observations of the cosmic ray $^{59}$Ni abundance by Connell & Simpson (1997) and Lukasiak (1997a), which have been recently outclassed by the new ACE data (Wiedenbeck et al. 1999), shown in Fig. 3. These data show that $< 25\%$ of the mass 59 material has been accelerated in the form of the $^{59}$Ni. So, it seems that all, or most of, the $^{59}$Ni has decayed in the cosmic ray source material, i.e. that the acceleration took place $\gtrsim 10^5$ yr after the explosive nucleosynthesis. Since the typical time for dilution of the SN ejecta is a few $10^4$ yr, this implies that cosmic rays do not originate in fresh ejecta material.

![Figure 3](image.png)

**Figure 3.** The $^{59}$Ni/$^{60}$Ni ratio, as observed by the ACE/CRIS instrument (upper limit; hatched), and as calculated as a function of the time elapsed between the SN explosive nucleosynthesis and the acceleration of the cosmic ray particles (§ 2.5). The calculated curve are labeled by the fraction of the mass 59 initially synthesized in the form of $^{59}$Ni; the 0 % level corresponds to the secondary production of $^{59}$Ni.

After Wiedenbeck et al. (1999).

### 2.5.2. Discussion: A direct nucleosynthesis of $^{59}$Co ?

This is all true, provided that most of the $^{59}$Co has, indeed, been first synthesized in the form of $^{59}$Ni in the SNe associated with cosmic ray acceleration ! Otherwise, the test on the time delay is not applicable. With the ACE data, indicating that in the cosmic ray sources $^{59}$Ni/($^{59}$Ni+$^{59}$Co) $< 0.25$, it is actually sufficient that $\gtrsim 25\%$ of the $^{59}$Co has been synthesized in the form of $^{59}$Ni for the test to work.

Lingenfelter et al. (1998) have questioned that most of the $^{59}$Co has been first synthesized in the form of $^{59}$Ni. Based on Woosley & Weaver (1995)’s models

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The relevance of the $^{59}$Ni test to nucleosynthesis could, however, be invalid, if supposedly accelerated $^{59}$Ni nuclei can pick up electrons during their interstellar propagation, allowing them to decay “en route”. But the ACE data refer to the energy range 120 – 600 MeV/nucleon. In view of the roughly flat shape of the observed cosmic ray energy spectra in this range, a major fraction of the observed particles lie towards the upper part of this range, where electron pick up can be excluded (even if there exists a moderate amount of interstellar re-acceleration).
for SN II, they have estimated that as much as \( \sim 50\% \) of the cosmic ray \(^{59}\)Co has been directly synthesized as \(^{59}\)Co. We now reexamine this situation.

Actually, only \( \sim 30\% \) of the galactic Fe,Co,Ni has been synthesized in SN II’s, and as much as \( \sim 70\% \) in SN Ia’s (see discussion in § 2.3.1) Let us now examine, in turn, the mass 59 production of SN II’s and SN Ia’s.

(i) In SN II’s, the e-process produces only \(^{59}\)Ni, essentially no \(^{59}\)Co (e.g., Thielemann et al. 1996). However, \(^{59}\)Co can be produced directly by two processes: the pre-SN weak-s-process, and neutrino spallation (Woosley & Weaver 1995; Chieffi et al. 1998). While the SN II initial \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) ratio depends on the stellar mass and is very sensitive to the mass cut for massive stars, Lingenfelter et al. (1998) have performed an averaging of the Weaver & Woosley yields over the IMF, and obtained an overall \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) ratio of \( \sim 0.50 \) for all SN II’s.

(ii) In SN Ia’s, the e-process similarly produces only \(^{59}\)Ni, essentially no \(^{59}\)Co (e.g., Thielemann et al. 1986). But there exists no weak-s-process and neutrino spallation. So, there is no direct \(^{59}\)Co synthesis, and the \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) ratio is 1 for SN Ia’s.

We conclude that, even if SN II’s made all mass 59 in the form of \(^{59}\)Co, all SN Ia’s and II together would yield an initial \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) of \( \sim 0.70 \). This represents a lower limit. With Lingenfelter et al.’s estimate of an IMF-averaged \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) \( \sim 0.50 \) for SN II’s only, we would get a total initial \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) of \( \sim 0.85 \). So, in any case, the initial \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) is \( > 0.70 \), which is much larger than the upper limit of 0.25 found for the cosmic ray sources.

Thus, if the yields of cosmic ray Fe, Co, and Ni from the various types of SNæ are at all similar to those for galactic nucleosynthesis, these considerations apply to cosmic rays. Then, the ACE data prove that the acceleration took place \( \geq 10^5 \) yr after the explosive nucleosynthesis, and that no fresh SN ejecta are accelerated.

2.6. Current Cosmic Rays and Acceleration of Fresh SN Ejecta?

Conclusions

For three fundamental reasons, we conclude that fresh SN ejecta cannot be a significant source of the current cosmic ray material:

(i) The cosmic ray source composition shows no anomaly related to SN nucleosynthesis.

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\(^{26}\)In Thielemann et al. (1996), no \(^{59}\)Co seems to be made directly, because this study does not include the pre-SN weak-s-process and the neutrino spallation.

\(^{27}\)Quite extreme and contradictory assumptions would be required for this conclusion not to be valid! It would require that essentially only SNII’s accelerate cosmic rays, which we have no reason to believe. And even then, Lingenfelter et al’s IMF-average over SNII’s yields \(^{59}\)Ni/\(^{59}\)Ni+\(^{59}\)Co) ratios of \( \sim 0.50 \gg 0.25 \). So, for the \(^{59}\)Ni evidence not to be relevant, one would have to require that cosmic rays are accelerated specifically by those SNII’s that produce essentially no \(^{59}\)Ni, thus producing all their \(^{59}\)Co directly. A very far fetched hypothesis indeed! In Woosley & Weaver’s work, actually, this total lack of \(^{59}\)Ni production happens in some of the massive star (\( \geq 30 \) \( M_\odot \)) models which, due to the mass cut, also produce no dominant \(^{56}\)Ni, and hence eventually very little \(^{56}\)Fe, at variance with the cosmic ray Fe/Mg,Si ratio.
First, the cosmic ray source FeNi/MgSiCa ratios have precisely the solar mix values; if cosmic rays originate in SN ejecta, this requires that the efficiency of accelerating the ejected material is nearly identical for the various layers of any particular SN, as well as for the various SN Ia’s and SN II’s of all masses; while not impossible, this does not seem likely (§2.3.1).

Further, the main-s-process elements, which are not significantly synthesized in any type of SN, are not underabundant relative to all elements synthesized in SNæ; this is clearly inconsistent with a significant acceleration of fresh SN ejecta (§2.3.2).

Finally, almost all cosmic ray source isotopic ratios are consistent with the solar mix. There is one exception: a large \(^{22}\text{Ne}\) and probably \(^{12}\text{C}\) excess, which is indicative of an acceleration of pure He-burning, Wolf-Rayet star wind circumstellar material, not of SN ejecta material (§1.2 and 2.4).

(ii) The absence of \(^{59}\text{Ni}\) in cosmic rays implies that the time delay between the SN nucleosynthesis of Fe peak nuclei and their acceleration is \(\gtrsim 10^5\) yr (§2.5).

(iii) The physics of SNR’s and of cosmic ray shock acceleration makes a significant acceleration of interior ejecta material very difficult; the acceleration of external, interstellar and/or circumstellar material is expected to be largely dominant. This is discussed in the companion paper by Ellison & Meyer (1999).

3. A Conflict between the Linear Evolution of Be/H in the Early Galaxy, and the Absence of Fresh SN Ejecta in Current Cosmic Rays?

Do we have a conflict between (i) the early Galactic evolution of Be/H, indicating that most of the cosmic ray CNO was then originating in freshly synthesized material, and (ii) the current cosmic ray composition and acceleration conditions, indicating that most current cosmic rays do not originate in fresh SN ejecta, but rather in interstellar and/or circumstellar material. Not necessarily! Cosmic rays, indeed, need not be the same now, and in the early Galaxy! We may also note that, for the current epoch, we know the cosmic ray composition, but not the rate of the Be/H evolution, while for the early Galaxy, we know the rate of Be/H evolution, but not the cosmic ray composition!

We will first ask ourselves whether the Be/H evolution actually requires a predominance of cosmic rays accelerated out of fresh nucleosynthesis products in the early Galaxy. Then, we will very briefly explore possible sources for such freshly synthesized cosmic rays in the early Galaxy.

3.1. Were the Be Producing Cosmic Rays Representative of the Bulk of the Cosmic Rays in the Early Galaxy?

First, is there really a contradiction?

As discussed in §1.1.1, there was very little CNO in the ISM in the early Galaxy, so that almost no Be could be produced by the spallation of both

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\(^{28}\)With currently \(\sim 38\%\) of the source, and \(\sim 33\%\) of the propagating CNO originating in freshly synthesized WR wind material. This fresh WR CNO is responsible for \(\sim 7\%\) of the currently produced Be. See footnote in §1.3.
ISM CNO by cosmic ray protons \( (\text{Be}_{\text{sm}}, \text{dominant in the current Be production}) \), and of cosmic ray CNO \textit{accelerated out of the ISM} on ISM Hydrogen. Only cosmic rays accelerated out of freshly synthesized, locally CNO-enriched, material could yield a significant contribution to the Be production. \textit{In earlier times, any such contribution to the Be production, however limited, must therefore have been dominant.} It is thus not surprising to have Be evolve as a primary in the very early Galaxy.

Did these CNO enriched cosmic rays represent the bulk of the cosmic rays in the early Galaxy? We don’t know. There may have then existed many more cosmic rays accelerated out of the then metal-poor ISM, essentially composed of protons and \( \alpha \)-particles only, which could not produce any Be. The “Be indicator” is blind to them.

We see two avenues to set upper limits to such an hypothetical H,He-rich cosmic ray component of interstellar origin: \( (i) \) the energetics, and \( (ii) \) the evolution of \( ^6\text{Li} \), which can be produced by \( \alpha-\alpha \) reactions.

\section*{3.2. Possible Sources for Freshly Synthesized Cosmic Rays in the Early Galaxy}

With the above considerations in mind, we now consider three possible sources for freshly synthesized, CNO-rich cosmic rays in the early Galaxy.

\subsection*{3.2.1 Directly Accelerated SN Ejecta in the Early Galaxy}

One may wonder if the direct acceleration, by each particular SNR, of \textit{even a small amount} of its own SN ejecta material might have yielded, in the early Galaxy, a \textit{comparatively} significant contribution to the formation of Be. Such an acceleration of some ejecta material can take place in two ways: \( (i) \) There will always be some acceleration by the reverse shock. Even if this acceleration is small overall, it might be more efficient for producing Be than for producing cosmic ray particles since, even if the accelerated particles are later adiabatically decelerated and never escape, the Be they have produced will survive. In addition, both the Be created in flight, \( \text{Be}_{\text{fast}} \), and at rest, \( \text{Be}_{\text{rest}} \), are created out of material highly enriched in CNO, and \textit{none} will escape the Galaxy (Parizot & Drury 1999). \( (ii) \) The forward shock may be overcome by clumps of fast-moving ejecta, which get later accelerated as ”external” material (Jun & Norman 1996). This, however, should concern only a small part of the total ejecta mass.

On the other hand, both phenomena can occur only in the very early phases of the SNR lifetime. Further, the \textit{total} ejecta mass is but \( \sim 2 \times 10^{-3} \) to \( 3 \times 10^{-2} \) of the total ISM mass swept by the forward shock, and this is true in the early Galaxy as well as to-day (Drury & Keane 1995; Parizot & Drury 1999; Ellison & Meyer 1999). All in all, the acceleration of their own ejecta by SNR’s seems to be a comparatively small phenomenon, even in the early Galaxy (Parizot & Drury 1999).

\subsection*{3.2.2 Wolf-Rayet’s in the Early Galaxy ?}

As discussed in § 1.2 and 1.3, a significant fraction \( (\sim 33 \%) \) of the \textit{current} propagating cosmic ray CNO is primary, originating in WR star wind material.
It is responsible for some $\sim 7\%$ of the currently produced Be. One may, of course, wonder: could this component have been larger in the early Galaxy?

The answer is a definite: no, there were fewer WR’s than to-day! As compared to O-stars, the observed number of WR stars, indeed, strongly decreases for decreasing metallicity (e.g., Maeder & Conti 1994; Maeder & Meynet 1994)\(^{29}\). In relative terms – as compared to cosmic rays accelerated out of the then CNO-poor ISM –, however, the WR component could have played a significant role for the Be production in the early Galaxy\(^{30}\).

### 3.2.3 SNæ Exploding Within Superbubbles in the Early Galaxy

Another way to have an acceleration of material enriched in freshly synthesized heavy elements is to consider an OB association forming a superbubble, within which some of the ambient material has been locally enriched by the WR winds and the ejecta of the previously exploded SNæ. This ambient superbubble material can be accelerated, both by the expanding forward shock waves of individual SNR’s, and by a general turbulence developing within the superbubble medium. This possibility has been considered by a number of authors recently (Bykov 1995, 1999; Parizot et al. 1998; Parizot 1998; Vangioni-Flam et al. 1998a; Higdon et al. 1998; Parizot & Drury 1999; Ellison & Meyer 1999)\(^{31}\).

Clearly, such a superbubble component, enriched in fresh nucleosynthesis products, cannot be dominant among current cosmic rays. Difficulties encountered by this hypothesis, in terms of the superbubble and the acceleration physics, are discussed in the companion paper by Ellison & Meyer (1999).

Regarding composition, arguments similar to those developed in §2 against a predominance of SN ejecta among current cosmic rays, also apply here. Essentially, OB associations contain only SNII’s, and no SNIa’s. Now, the nearly solar value of the cosmic ray source Fe,Ni/Mg,Si,Ca ratios is clearly inconsistent with the acceleration out of a medium enriched by massive SNII’s only, with no SNIa’s contribution. Roughly, one would then expect a 3-fold relative deficiency

\(^{29}\)The basic interpretation for this decrease is that the huge WR winds are primarily driven by the radiation pressure exerted on the heavy elements in the outer stellar layers. Since, in the early Galaxy, there were essentially no heavy elements in the outer, un-processed, layers, the stellar peeling off process could not be initiated. So, it was difficult to produce single WR’s in the early Galaxy. More precisely, the stellar mass threshold for the onset of the WR phenomenon increases with decreasing metallicity. Other factors probably play a role. Binarity can probably induce WR winds, although there is no clear evidence for a larger fraction of binaries among WR’s in metal-poor galaxies (SMC) (e.g., Moffat 1995), and the importance of the role of binarity in initiating the WR phenomenon is currently controversial (Maeder & Meynet 1994; Maeder & Conti 1994; Vanbeveren et al. 1997, 1998). Rotational mixing of massive stars layers may also play a role in enriching the outer layers in heavy elements.

\(^{30}\)Note, however, that this possible early Galactic WR production of Be refers to the Be\(_{\text{fast}}\) component only (§1.1), which currently accounts for only $\sim 20\%$ of the forming Be (§1.3). The same remark applies to the contribution of the SNæ exploding within superbubbles, discussed just below (§3.2.3; see also footnote in §1.1.1).

\(^{31}\)Sometimes in connection with the high nuclear $\gamma$-ray fluxes earlier reported for the Orion nebula, which have not been confirmed since then (Bloemen 1999). These data implied large accelerated particle fluxes, strictly limited to low energies. Associated theoretical work referenced in the above papers.
of Fe,Ni (§ 2.3.1). The lack of a relative main-s-process element deficiency is also inconsistent with a significant acceleration of current cosmic rays out of such a medium (§ 2.3.2).

Could superbubbles have played a more important role in the generation of cosmic ray CNO nuclei in the early Galaxy? The possibility that a larger fraction of massive stars might have formed within large OB associations in the gas-rich, very active, early Galaxy could be explored. But in any case, in relative terms – as compared to cosmic rays accelerated out of the then CNO-poor ISM – such a superbubble contribution could have played a significant role for the Be production in the early Galaxy.

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