Li, Be, B and Cosmic Rays in the Galaxy

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Abstract. A short overview is presented of current issues concerning the production and evolution of Li, Be and B in the Milky Way. It is argued that the currently popular idea that Galactic Cosmic rays are accelerated inside metal-rich superbubbles (which leads “naturally” to the production of primary Be and B, as observed) encounters the same problems as the previously popular idea of supernovae accelerating their own ejecta. A major challenge to theories of light element production is presented by the recent (and still preliminary) data suggesting a surprisingly high and \( \sim \) constant abundance of \( ^{6}\text{Li} \) in halo stars; attempts to explain such a “plateau” are critically examined.

1 The 1970s: problems with late \( ^{7}\text{Li}, ^{11}\text{B} \)

The idea that the light and fragile elements Li, Be and B are produced by the interaction of the energetic nuclei of galactic cosmic rays (CGR) with the nuclei of the interstellar medium (ISM) was introduced 35 years ago (Reeves et al. 1970, Meneguzzi et al. 1971). In those early works it was shown that, taking into account the relevant cross-sections and with plausible assumptions about the GCR properties (injected and propagated spectra, intensities etc.; see Fig. 1, right column) one may reproduce reasonably well the abundances of those light elements observed in meteorites and in GCR.

Two problems were identified with the GCR production, compared to meteoritic composition: the \( ^{7}\text{Li}/^{6}\text{Li} \) ratio (~2 in GCR but \( \sim 12 \) in meteorites) and the \( ^{11}\text{B}/^{10}\text{B} \) ratio (~2.5 in GCR but \( \sim 4 \) in meteorites). Modern solutions to those problems involve stellar production of \( \sim 70\% \) of \( ^{7}\text{Li} \) (in the hot envelopes of AGB stars and/or novae) and of \( \sim 40\% \) of \( ^{11}\text{B} \) (through \( \nu \)-induced spallation of \( ^{12}\text{C} \) in SNII). In both cases, however, uncertainties in the yields are such that observations are used to constrain the yields of the candidate sources rather than to confirm the validity of the scenario.

2 The 1980s: the Li plateau; primordial, but low or high?

One of the major cosmological developments of the 1980s was the discovery of the Li plateau in low metallicity halo stars (Spite and Spite 1982, see Fig. 1 top left panel). The unique behaviour of that element, i.e. the constancy of the Li/H ratio with metallicity, strongly suggests a primordial origin. The observed value has been extensively used (along with those of D and \( ^{4}\text{He} \)) to constrain the
physics of primordial nucleosynthesis and, in particular, the baryonic density of
the Universe (e.g. Steigman, this meeting). In particular, the difference between
the observed plateau value (Ryan et al. 1999) and the Li abundance correspond-
ing to the baryonic density derived from WMAP data (Fig. 1) is rather high
(∼0.5 dex) and points to a failure of our understanding, of either stellar atmos-
pheres, primordial nucleosynthesis or Li depletion in stars (e.g. Lambert 2004
and references therein).

3 The 1990s: problems with early Be and B (primaries!)

Observations of halo stars in the 90s revealed a linear relationship between Be/H
(as well as B/H) and Fe/H. That was unexpected, since Be and B were thought
to be produced as secondaries, by spallation of the increasingly abundant CNO
nuclei. Only the Li isotopes, produced at low metallicities mostly by \(\alpha + \alpha\)
fusion reactions (Steigman and Walker 1992) are produced as primaries. The
only way to produce primary Be and B is by assuming that GCR have always
the same CNO content (Duncan et al. 1992). The most convincing argument in
that respect is the “energetics argument” put forward by Ramaty et al. (1997):
if SN are the main source of GCR energy, there is a limit to the amount of
light elements produced per SN, which depends on GCR and ISM composition.
If the metal content of both ISM and GCR becomes low, there is simply not
enough energy in GCR to keep the Be and B yields constant (as required by
observations). Since the ISM metallicity certainly increases with time, the only
possibility to have \(\sim\)constant LiBeB yields is by assuming that GCR have a
\(\sim\)constant metallicity.

A \(\sim\)constant abundance of C and O in GCR can naturally be understood if
SN accelerate their own ejecta. However, the absence of unstable \(^{59}\)Ni (decaying
through \(e^-\)-capture within \(10^5\) yr) from observed GCR suggests that acceleration
occurs \(>10^5\) yr after the explosion (Wiedenbeck et al. 1999) when SN ejecta
are presumably diluted in the ISM. Higdon et al. (1998) suggested that GCR
are accelerated in superbubbles (SB), enriched by the ejecta of many SN as to
have a large and \(\sim\)constant metallicity. Since then, this became by default, the
”standard” scenario for the production of primary Be and B by GCR, invoked
in almost every work on that topic.

However, the SB scenario suffers from (at least) two problems. First, core
collapse SN are observationally associated to HII regions (van Dyk et al. 1996)
and it is well known that the metallicity of HII regions reflects the one of the
ambient ISM (i.e. it can be very low, as in IZw18) rather than the one of SN.
Moreover, Higdon et al. (1998) evaluated the time interval \(\Delta t\) between SN ex-
splosions in a SB to a comfortable \(\Delta t \sim 3 \times 10^5\) yr, leaving enough time to \(^{59}\)Ni
to decay before the next SN explosion and subsequent acceleration. However, SB
are constantly powered not only by SN but also by the strong winds of massive
stars (with integrated energy and acceleration efficiency similar to the SN one,
e.g. Parizot et al. 2004), which should continuously accelerate \(^{59}\)Ni, as soon as
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Fig. 1. Left and middle columns: Evolution of LiBeB with two different compositions assumed for GCR (1) \( X_{GCR}(t) = f_{\text{ENH}} X_{\text{ISM}}(t) \) always (dotted curves) and (2) \( X_{GCR} = f_{\text{ENH}} X_\odot \) always, (solid curve), i.e. metallicity dependent and independent compositions, respectively (X representing mass fraction); in both cases, the enhancement factor \( f_{\text{ENH}} \) is such as to match the present day observed GCR composition, which is enriched in C (by \( \sim 8 \)), N (by \( \sim 2 \)) and O (by \( \sim 5 \)), i.e. the “metallicity” of the GCR fluid today is about 5 times solar in the solar vicinity. In both cases, the GCR injection spectrum is \( Q(E,t) = S q(E) R_{SN}(t) \), where \( R_{SN}(t) \) is the SN rate, \( q(E) \) is displayed in right bottom panel and the normalisation factor \( S \) is such that the energy of all nuclei in GCR is \( \sum X_i q(E) \int q(E)E=dE=\epsilon_{\text{CR}} E_{KIN} \) (where the kinetic energy \( E_{KIN}=1.5 \times 10^{51} \) ergs per SN and \( \epsilon_{\text{CR}} \sim 0.1-0.2 \) is a typical acceleration efficiency of SN). Model (2) produces naturally primary Be and B with reasonable (and metallicity \( \sim \)independent) values of \( \epsilon_{\text{CR}} \), while Model (1) requires metallicity dependent values which become unacceptably large at low metallicities (middle bottom panel). Despite its success with Be and B, Model (2) cannot produce the Li6 plateau. The evolution of C,N,O,Fe is followed with metallicity dependent yields, but no Li7 from Hot-bottom burning in AGB stars or B11 from \( \nu \)-nucleosynthesis in massive stars is included. As a result, the abundances of Li7, B11 and Li6/Li7 at [Fe/H]=0 differ from their solar values (by factors 6, 2 and 6, respectively). Production cross-sections from \(^{12}\text{C}+p\) (for all light isotopes) and from \( \alpha+\alpha \) (for Li6, Li7), as well as GCR spectra at the source (injection) and after propagation (equilibrium) are displayed in the right column. The equilibrium spectrum should be folded with the corresponding cross-sections and abundances to calculate relevant production rates of LiBeB. Energies are in MeV/nucleon.
Fig. 2. Left: Schematic evolution of the light elements, from H to O, in the local Galaxy, according to observations (the evolution of B, similar to the one of Be, is not shown for clarity). Right top: Schematic evolution of abundance ratios Be/C and Li6/He (by number) in the local Galaxy. Those ratios are chosen because Be is produced mainly by C (and N,O, which display similar evolution) while Li6 is produced mainly by $\alpha + \alpha$ (especially in the early Galaxy, while production by CNO becomes important later). In both cases, the constancy of those ratios is reminiscent of an “equilibrium” process (with the production rate balanced by the destruction rate, as e.g. in the CNO cycle operating at equilibrium). In GCR, the light isotopes are certainly at equilibrium with their “father” nuclei, since the observed abundances (Right bottom) correspond indeed to such equilibrium values (ratios displayed at Right top); moreover, the ratio of $(X/Y)_{GCR}/(X/Y)_{ISM}$ is the same for Be/C and Li6/He (around $10^6$). However, although it is easy to understand equilibrium abundances of light elements in GCR (where production and destruction by the abundant H and He of the ISM medium are rapid), it is difficult to conceive such an equilibrium situation for the nuclei residing in the ISM (where production and destruction by the rarefied H and He gas of the GCR are very slow).

it is ejected from SN explosions. Thus, SB suffer exactly from the same problem that plagued SN as accelerators of metal rich ejecta.

The problem of the acceleration site of GCR (so crucial for the observed linearity of Be and B vs Fe) has not found a satisfactory explanation yet.
| Problem | Suggested solution | Comments |
|---------|-------------------|----------|
| Late Li: \(^{7}\)Li/\(^{6}\)Li | Late \(^{7}\)Li (but not \(^{6}\)Li) from AGB and novae | Plausible, but Li yields of AGB and rates/yields of novae VERY uncertain |
| Solar value=12 but GCR=2 | | |
| Late B: \(^{11}\)B/\(^{10}\)B | 40% of \(^{11}\)B produced by \(\nu\)-nucleosynthesis in SNII | Plausible, although \(\nu\)-spectra are uncertain Produces primary \(^{11}\)B |
| Solar value=4 but GCR=2.5 | | |
| Early Be and B | GCR metallicity always the same, originating in SN ejecta or in Superbubbles (SB) | Problem with absence of unstable \(^{59}\)Ni in GCR; it becomes stable if directly accelerated in SN or continuously accelerated in SB by stellar winds |
| Observations: primaries, while “Standard” GCR produce secondaries | | |
| Early \(^{6}\)Li/H: | 1) Primordial, non-standard production in BBN | Particles and cross-sections unknown |
| A too high “plateau” | 2) Pre-galactic production during structure formation | CR energetics unknown; hard to explain “plateau” |
| 3) Equilibrium: \(^{6}\)Li/\(\alpha\) \(\sim\) const. | Production=Destruction | Requires too rapid reactions, incompatible with GCR densities |

4 The 2000s: a \(^{6}\)Li plateau? primordial or (pre-)galactic?

The recent report of a “plateau” for \(^{6}\)Li/H in halo stars (Asplund et al. this meeting) gives a new twist to the LiBeB saga. The detected \(^{6}\)Li/H (and corresponding \(^{7}\)Li/\(^{6}\)Li ) value at [Fe/H]=−2.8 is much larger than expected if GCR are the only source of the observed Be/H and \(^{6}\)Li/H in that star (see Fig. 1). A few explanations have been proposed for such a high early amount of \(^{6}\)Li:

1) Primordial, non-standard, production during Big Bang Nucleosynthesis (BBN): the decay/annihilation of some massive particle (e.g. neutralino) releases energetic nucleons/photons which produce \(^{3}\)He or \(^{3}\)H by spallation/photodisintegration of \(^{4}\)He, while subsequent fusion reactions between \(^{4}\)He and \(^{3}\)He or \(^{3}\)H create \(^{6}\)Li (e.g. Jedamzik 2004). Observations of \(^{6}\)Li/H constrain then the masses/cross-sections/densities of the massive particle.

2) Pre-galactic, by fusion reactions of \(^{4}\)He nuclei, accelerated by the energy released during structure formation (Suzuki and Inoue 2002); in that case, CR energetics are decoupled from SN energetics. In view of the many uncertainties related to the behaviour of the baryonic component during structure formation, the energetics of CR in that scenario are very poorly known/constrained at
present. Moreover, in order to explain the observed $^6\text{Li}$ “plateau” the effect must end (or drastically decrease) before the first stars form and explode releasing Fe, otherwise $^6\text{Li}/\text{H}$ would continue increasing at metallicities $[\text{Fe/H}] > -3$. But this runs against our current understanding of structure formation, which suggests that merging of sub-structures continues with mildly reduced intensity during a large fraction of the Galaxy’s early life (e.g. Helmi et al. 2003).

3) A third possibility is suggested by the observed $\sim$-constancy of $^6\text{Li}/\text{He}$ and Be/C with $[\text{Fe/H}]$ (Fig. 3 right top), reminiscent of an equilibrium process. Indeed, the abundances of the LiBeB isotopes in GCR are much higher than the solar ones (right bottom) and are in equilibrium with those of the progenitor He,C,N,O nuclei, i.e. the ratio of daughter/progenitor abundances in GCR is roughly equal to the one of the corresponding production/destruction spallation cross-sections. The advantage of that idea is that it explains at one stroke both the primary Be and B (always at equilibrium with progenitor CNO nuclei) and the $^6\text{Li}$ plateau (with $^6\text{Li}$ at equilibrium with progenitor $^4\text{He}$). However, equilibrium requires very fast production and destruction reactions (with timescales shorter than the evolutionary timescale of the system); this certainly happens inside GCR (with the fast GCR particles interacting with the numerous ISM nuclei) but the opposite does not hold.

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1 Fields and Prodanovic (2004) suggest that the associated production of $\gamma$-rays (from decaying pions, produced by energetic $p+p$ reactions) could contribute significantly to the extragalactic $\gamma$-ray background; see also Prantzos and Cassé (1994).

2 The interaction timescale is: $\tau \sim (n/\sigma v)^{-1}$. For GCR $^6\text{Li}$ interacting with ISM protons of density $n_p \sim 1 \text{ cm}^{-3}$ one has $\tau \sim 10^7$ yr, but for ISM $^6\text{Li}$ interacting with GCR protons of $n_p \sim 10^{-9} \text{ cm}^{-3}$ (corresponding to the observed energy density of 1 eV/cm$^3$) $\tau$ is a billion times larger ($\sigma \sim 400$ mb being the destruction cross-section).