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Origin of cosmic rays and evolution of spallogenic nuclides Li, Be and B

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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. In particular, the observed "primary-like" evolution of Be is re-assessed in the light of a novel idea: it is argued that Galactic Cosmic Rays are accelerated from the wind material of *rotating* massive stars, hit by the forward shock of the subsequent supernova explosions. The pre-galactic levels of both Li isotopes remain controversial at present, making it difficult to predict their Galactic evolution. A quantitative estimate is provided of the contributions of various candidate sources to the solar abundance of Li.

1. Introduction

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 40 years ago (Reeves *et al.* 1970, Meneguzzi *et al.* 1971, hereafter MAR). In those early works it was shown that, taking into account the relevant cross-sections and with plausible assumptions about the GCR properties - source composition, intensity and spectrum - one may reproduce reasonably well the abundances of those light elements observed in GCR and in meteorites (pre-solar).

Among the required ingredients for such a calculation, the relevant spallation cross sections of CNO nuclei are accurately measured in the laboratory. The source composition and the equilibrium energy spectrum of GCR are inferred from a combination of observations and models of GCR propagation in the Milky Way (e.g. in the framework of the so-called "leaky box" model). Once the equilibrium spectra of GCR in the ISM are established, the calculation of the resulting abundances of LiBeB is straightforward, at least to first order†. The production rate (s^{-1}) of the abundance $Y_L = N_L/N_H$ (by number) of LiBeB nuclei is given by

$$\frac{dY_L}{dt} = F_{p,a}^{GCR}\sigma_{pa+CNO}Y_{CNO}^{ISM} + F_{CNO}^{GCR}\sigma_{pa+CNO}Y_{p,a}^{ISM}P_L + F_a^{GCR}\sigma_{a+a}Y_a^{ISM}P_L \quad (1.1)$$

where: F $(cm^{-2} s^{-1})$ is the average GCR flux of protons, alphas or CNO, Y the abundances by number of those nuclei in the ISM, and σ (cm^2) is the average (over the equilibrium energy spectrum of GCR) cross-section for the corresponding spallation reactions producing LiBeB. The first term in the right hand member of this equation (fast protons and alphas hitting CNO nuclei of the ISM) is known as the "direct" term, the second one (fast CNO nuclei being fragmented on ISM protons and alphas) is the "reverse" term and the last one involves "spallation-fusion" reactions, concerning only the Li isotopes. P_L is the probability that nuclide L (produced at high energy) will be

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† The full calculation should include production by spallation of other primary and secondary nuclides, such as ^{13}C; however, this has only second order effects.
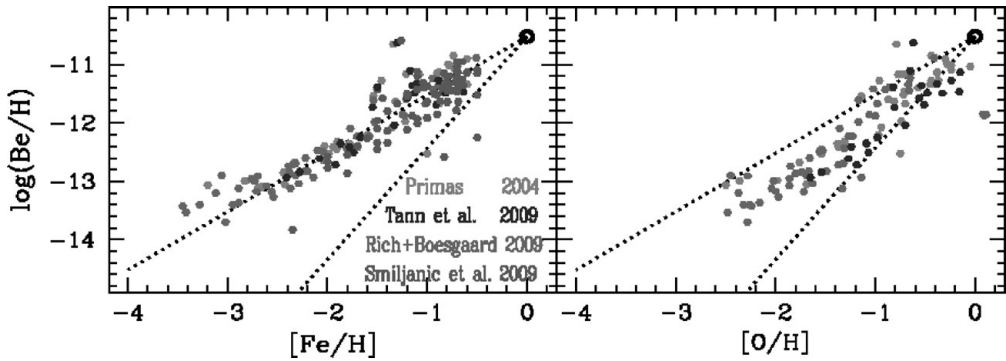
Figure 1. Observations of Be vs. Fe (*left*) and vs. O (*right*). In both panels, dotted lines indicate slopes of 1 (primary) and 2 (secondary). Be clearly behaves as a primary vs. Fe, whereas there is more scatter in the data vs. O.

thermalized and remain in the ISM (see, e.g. Prantzos 2006). Obviously, the GCR flux term $F_{CNO}^{GCR} \propto Y_{CNO}^{GCR}$ is proportional to the abundances of CNO nuclei in GCR, a fact of paramount importance for the evolution of Be and B (see next sections).

Substituting appropriate values for GCR fluxes ($F_p^{GCR} \sim 10$ p cm^{-2} s^{-1} for protons and scaled values for other GCR nuclei), for the corresponding cross sections (averaged over the GCR equilibrium spectrum $\sigma_{p,a+CNO\longrightarrow Be} \sim 10^{-26}$ cm^{-2}) and for ISM abundances $Y_{CNO} \sim 10^{-3}$, and integrating for $\Delta t \sim 10^{10}$ yr, one finds $Y_{Be} \sim 2\,10^{-11}$, i.e. approximately the meteoritic Be value. Satisfactory results are also obtained for ^{6}Li and ^{10}B.

Two problems were identified with the GCR production, compared to meteoritic composition: the ^{7}Li/^{6}Li ratio (~ 2 in GCR, but ~ 12 in meteorites) and the ^{11}B/^{10}B ratio (~ 2.5 in GCR, but ~ 4 in meteorites). It was then suggested in MAR that supplementary sources are needed for ^{7}Li and ^{11}B. Modern solutions to those problems involve *stellar* production of $\sim 60\%$ of ^{7}Li (in the hot envelopes of AGB stars and/or novae, see Sec. 7) and of $\sim 40\%$ of ^{11}B (through ν-induced spallation of ^{12}C in SN, see Sec. 5). 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. Primary Be: the problem

Observations of halo stars in the 90s revealed a linear relationship between Be/H and Fe/H (Gilmore *et al.* 1991, Ryan *et al.* 1992) as well as between B/H and Fe/H (Duncan *et al.* 1992). That was unexpected, since Be and B were thought to be produced as *secondaries*, by spallation of the increasingly abundant CNO nuclei. Indeed, the first two terms in Eq. 1.1 were thought to evolve in the same way with time (or metallicity), since the composition of GCR Y_{CNO}^{GCR} was supposed to evolve in step with the one of the ISM Y_{CNO}^{ISM}. Only the Li isotopes, produced at low metallicities mostly by $\alpha + \alpha$ reactions were thought to be produced as primaries (Steigman and Walker 1992) . The only way to produce primary Be is by assuming that GCR have always the same CNO content, as suggested in Duncan *et al.* (1992). Other efforts to enhance the early production of Be, by e.g. invoking a better confinement - and thus, higher fluxes - of GCR in the early Galaxy (Prantzos *et al.* 1993) failed. The reason for that failure was clearly revealed by 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 is
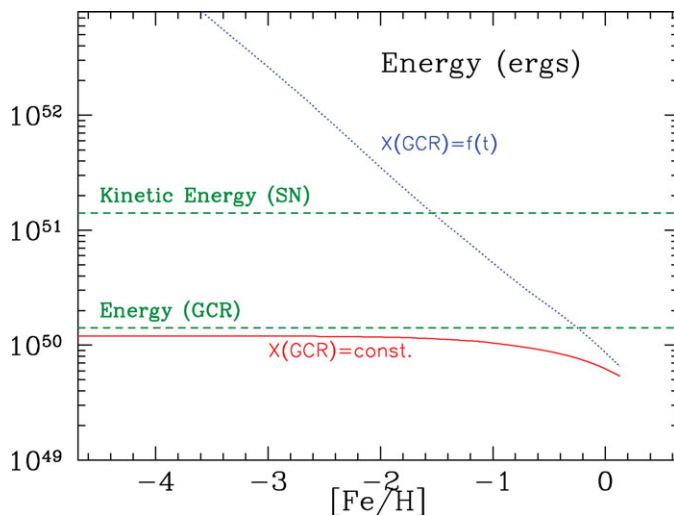
Figure 2. Energy input required from energetic particles accelerated by one CCSN in order to produce a given mass of Be, such as to have [Be/Fe] = 0 (solar), assuming that a core collapse SN produces, on average, 0.1 $M_\odot$ of Fe. *Solid* curve corresponds to the case of a constant composition for GCR, *dotted* curve corresponds to a time variable composition, following the one of the ISM. In the former case, the required energy is approximately equal to the energy imparted to energetic particles by supernovae, namely ~0.1 of their kinetic energy of ~1.5 10^{51} ergs; in the latter case, the energy required to keep [Be/Fe] = 0 becomes much larger than the total kinetic energy of a CCSN for metallicities [Fe/H]⩽-1.6.

low, there is simply not enough energy in GCR to keep the Be yields constant (Fig. 2)†. Since the ISM metallicity certainly increases with time, the "direct" component in Eq. 1.1 produces only secondary LiBeB. The only possibility to have ~constant LiBeB yields is by assuming that the "reverse" component is primary, i.e. that GCR have a ~constant metallicity. This has profound implications for our understanding of the GCR origin. It should be noted that before those Be and B observations, no one would have the idea to ask "what was the GCR composition in the early Galaxy?".
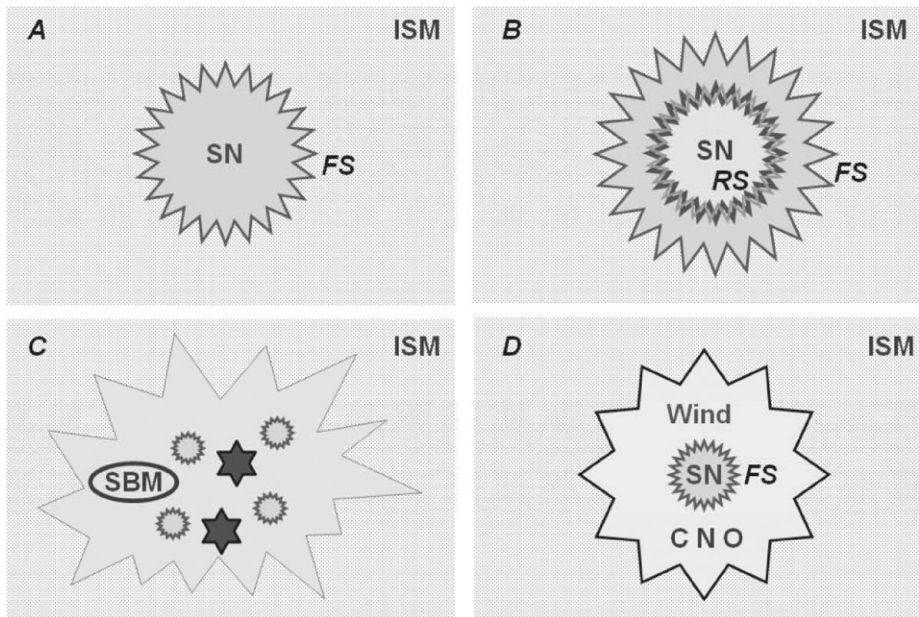
3. Origin of cosmic rays

For quite some time it was thought that GCR originate from the average ISM, where they are accelerated by the *forward shocks* of SN explosions (Fig. 3.A). However, this can only produce secondary Be.

A ~constant abundance of C and O in GCR can "naturally" be understood if SN accelerate their own ejecta, trough their *reverse schock* (Ramaty *et al.* 1997, see Fig. 3.B). 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 already diluted in the ISM. Furthermore, the reverse shock has only a small fraction of the SN kinetic energy, while observed GCR require a large fraction of it‡.

† For reasons unknown to the author, the energetics argument was obviously not understood by many prolific researchers in the field in the late 90ies.

‡ The power of GCR is estimated to ~10^{41} erg s^{-1} galaxywide, i.e. about 10% of the kinetic energy of SN, which is ~10^{42} erg s^{-1} (assuming 3 SN/century for the Milky Way, each one endowed with an average kinetic energy of 1.5 10^{51} ergs).

Figure 3. Scenarios for the origin of Galactic cosmic rays (GCR). *A*: GCR originate from the interstellar medium (ISM) and are accelerated from the forward shock (FS) of supernovae (SN). *B*: GCR originate from the interior of supernovae and are accelerated by the reverse shock (RS), propagating inwards. *C*: GCR originate from superbubble material (SBM), enriched by the metals ejected by supernovae and massive star winds; they are accelerated by the forward shocks of supernovae *and* stellar winds. *D*: GCR originate from the wind material of massive *rotating* stars, *always rich in CNO* (but not in heavier nuclei); they are accelerated by the forward shock of the SN explosion.

Higdon *et al.* (1998) suggested that GCR are accelerated out of *superbubbles* (SB) material (Fig. 3.C), enriched by the ejecta of many SN as to have a large and ∼constant metallicity. In this scenario, it is the forward shocks of SN that accelerate material ejected from other, previously exploded SN. Furthermore, it has been argued that in such an environment GCR could be accelerated to higher energies than in a single SN remnant (Parizot *et al.* 2004). That scenario has also been invoked in order to explain the present day source isotopic composition of GCR (Binns *et al.* 2005, Rauch *et al.* 2009). Notice that the main feature of that composition, namely a large $^{22}Ne/^{20}Ne$ ratio, is explained as due to the contribution of winds from Wolf-Rayet (WR) stars (e.g. Prantzos *et al.* 1987), and the SB scenario offers a plausible (but not unique) framework in bringing together contributions from both SN and WR stars.

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 Δt between SN explosions in a SB to a comfortable $\Delta t \sim 3\ 10^5$ yr, leaving enough time to ^{59}Ni to decay before the next SN explosion and subsequent acceleration. However, Prantzos (2005) noticed that 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 it is ejected from SN explosions. Binns *et al.* (2008) argued that the problem may be alleviated from the fact that only the most massive (and thus,
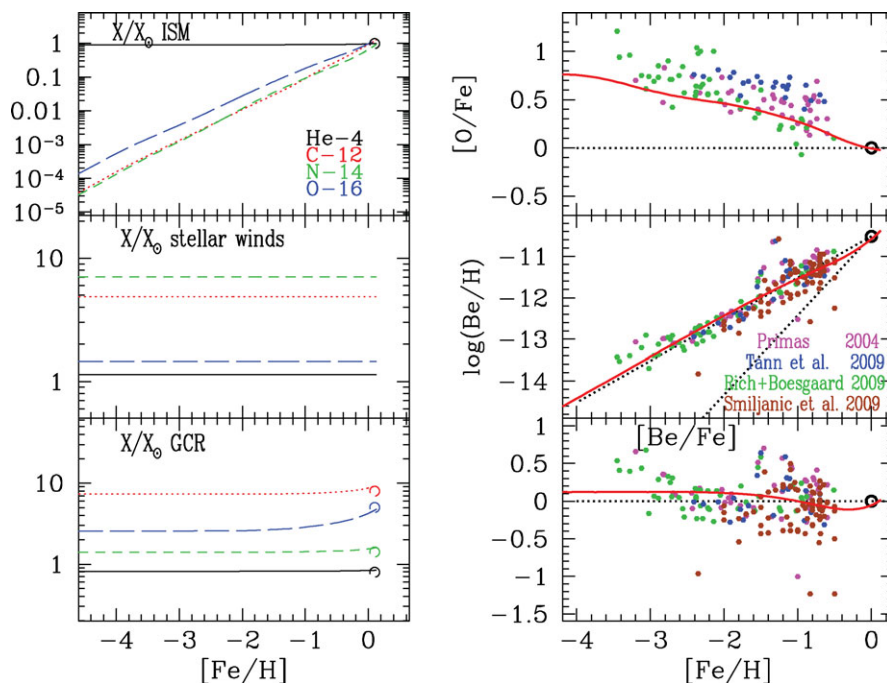
Figure 4. *Left:* Evolution of the chemical composition (in corresponding solar abundances) of He-4 (*solid*), C-12 (*dotted*), N (*short dashed*) and O (*long dashed*)in: ISM (*top*), massive star winds (*middle*) and GCR (*bottom*). *Dots* in lower panel indicate estimated GCR source composition (from Elison *et al.* 1997). *Right*: Evolution (*solid curves* of O/Fe (*top*), Be/H (*middle*) and Be/Fe (*bottom*); *dotted lines* indicate solar values in top and bottom panels, primary and secondary Be in middle panel.

short-lived) stars of an OB association emit strong winds; during the late (and longest) fraction of the lifetime of the SB (a few 10^7 years) particles are accelerated episodically (by SN explosions only) and no more continuously. Still, it is hard to imagine that superbubbles have always the same average metallicity, especially during the early Galaxy evolution, where metals were easily expelled out of the shallow potential wells of the small sub-units forming the Galactic halo (e.g. Prantzos 2008).

4. Cosmic rays from stellar winds and primary Be

In this work we propose a different explanation for the origin of GCR, which can also provide a satisfactory explanation for the primary nature of Be evolution. We first notice that there is now substantial evidence that GCR are indeed accelerated in SN remnants (e.g. Berezhko *et al.* 2009 and references therein). We then notice that, contrary to the case of non-rotating massive stars, which lose mass only at high metallicity, *rotating* massive stars display substantial mass loss down at very low (or even zero) metallicities (e.g. Meynet, this volume). The winds of those stars are enriched in CNO (products of H and He burning *within* the star itself) at all metallicities and at about the same level; it is precisely this enrichment of the WR winds at all metallicities that allows us to understand the observed primary behaviour of N down to the lowest metallicity halo stars (Chiappini *et al.* 2006). This gives some confidence in using the same model results to predict the composition of GCR over the history of the Milky Way.
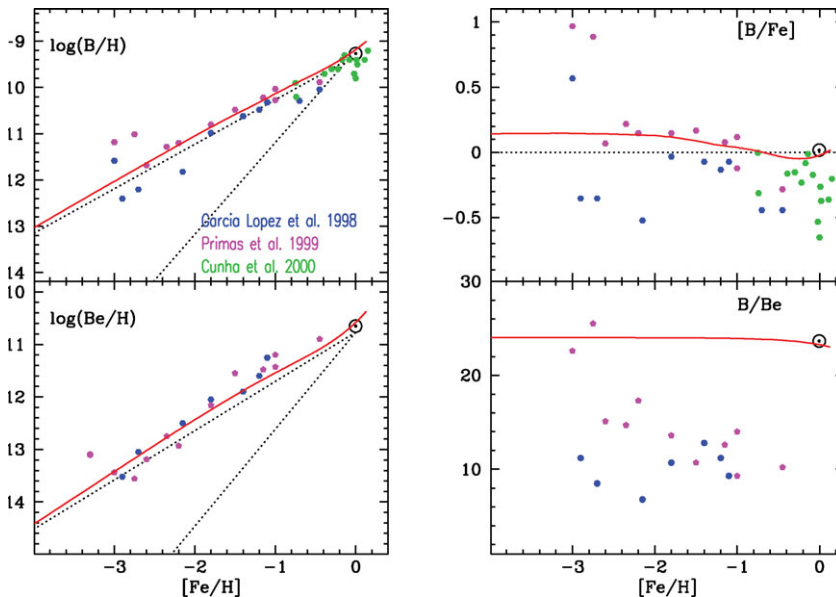
Figure 5. *Left:* Evolution of B (*top*) and Be (*bottom*); in both panels, *dotted lines* indicate primary and secondary evolution and *solid* curves indicate model evolution, including apropriately normalised ν-yields for ^{11}B. *Right*: Evolution of B/Fe (*top*) and B/Be (*bottom*). In the latter case, data indicate a subsolar mean value of B/Be$\sim$14, compatible with exclusively GCR production of both elements, but the uncertainties (not shown here) are too large to allow conclusions.

We assume then that GCR are accelerated when the forward shocks of SN propagate into the previously ejected envelopes of rotating massive stars, which have been partially mixed with the surrounding ISM. The calculation of the resulting GCR composition $Y^{GCR}(M)$ is far from trivial: it will be mostly $Y^{Wind}(M)$ in the case of SN with initial mass $M > 20$ M$_\odot$ (having lost a large fraction of their mass in the wind) and mostly Y^{ISM} in the case of M=10-20 M$_\odot$ stars, having suffered low mass losses. For ilustration purposes we adopt here, as a function of metallicity Z, $Y^{GCR}_{paCNO}(Z)$=0.5 $[Y^{Wind}_{paCNO}(Z)+Y^{ISM}_{paCNO}(Z)]$, where $Y^{Wind}(Z)$ is provided by the Geneva models (G. Meynet, private communication) and is integrated over a stellar IMF, whereas $Y^{ISM}(Z)$ is provided by the chemical evolution model (left panels in Fig. 4).

The calculation of the Be evolution is then straightforward and nicely fits the data (right panels in Fig. 4); it is the first time that such a calculation is performed *not by assuming* a given $Y^{GCR}_{paCNO}(Z)$ but by *calculating* it in a (hopefully) realistic way.

5. Boron-11 from ν-nucleosynthesis?

As mentioned in Sec. 2, a supplementary source of ^{11}B is required in order to obtain the meteoritic ^{11}B/^{10}B = 4 ratio. That source may be the ν-process in SN, extensively studied in Woosley *et al.* (1990): a fraction of the most energetic among the $\sim$10^{59} neutrinos of a SN explosion spallate ^{12}C nuclei in the C-shell of the stellar envelope to provide ^{11}B (but no other light nuclide). Soon after the HST observations of the primary behaviour of B (Duncan *et al.* 1992) it was realised that the ν-process can provide just such a primary B (Olive *et al.* 1994). But, if Be is produced as primary by GCR (Sec. 5), then more than $\sim$50% of B is also produced as primary, leaving a rather small role to the ν-process. In fact, the large uncertainties in the ν yields of ^{11}B do not allow an accurate evaluation of
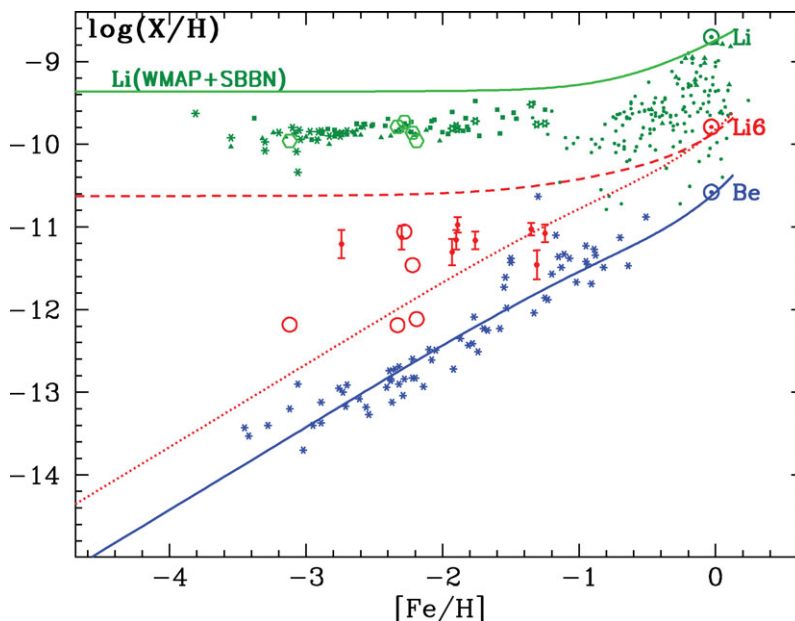
Figure 6. Evolution of total Li (*upper* set of data points and *solid* curve for model assuming high primordial ^{7}Li), Be (*lower* set of points and *solid* curve) and ^{6}Li (*intermediate* set of points and curves). ^{6}Li data are from Asplund *et al.* (2006, small filled circles with error bars) and Garcia-Perez *et al.* (2009, large open circles with - large - error bars not displayed), while model curves are for a canonical ("low") pre-galactic ^{6}Li (*dotted*) and a "high" pre-galactic ^{6}Li (*dashed*). In the latter case, a minimum amunt of depletion within stars (equal to that of ^{7}Li) has been conservatively assumed.

the B evolution: rather the B evolution (resulting from both GCR and ν-process) has to be used in order to constrain the B yields of SN.

The results of such an "exercise" appear in Fig. 5. In order to fit the observations, the ν yields of Woosley and Weaver (1995) had to be divided by a factor of $\sim$6, otherwise B/H and B/Fe would be overproduced. Notice the model B/Be ratio is always $\sim$24 (i.e. solar), substantially higher than the observed, but *highly uncertain*, B/Be$\sim$14 ratio in halo stars (which is consistent with pure GCR production of both elements!). Clearly, future observations with HST are required to clarify that important issue.

6. Early ^{7}Li and ^{6}Li: "high" or "low"?

For a long time, the Li "plateau" in low metallicity halo stars (discovered by Spite and Spite 1982) was considered to reflect the primordial abundance of ^{7}Li. However, the precise determination of baryonic density through observations of the cosmic microwave background, combined to results of standard Big bang nucleosynthesis (SBBN), suggests that the true value of primordial ^{7}Li should be 2-3 times higher. It is not yet clear whether this discrepancy is due to some problems with SBBN, whether non-standard particle physics might cure it, or whether primordial ^{7}Li is depleted in the surface convective zones of low metallicity stars with such an astonishing uniformity (see many contributions in this volume). Other suggestions, like e.g. astration by a pre-galactic Pop. III population of massive stars (Piau *et al.* 2006) face severe problems of metal overproduction (Prantzos 2006). This issue, one of the most important ones for our understanding of mixing in
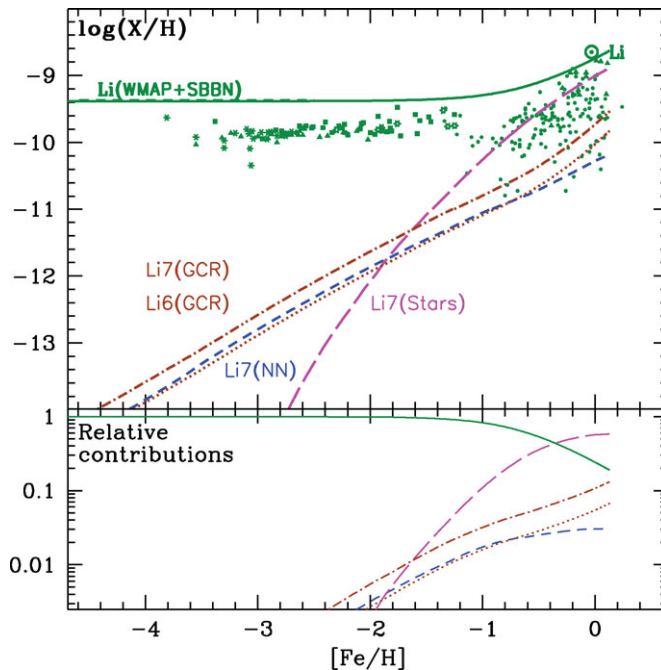
Figure 7. Evolution of total Li (*top*) and percentages of its various components (*bottom*): Li-7 from GCR (*dot-dashed*), Li-6 from GCR (*dotted*), Li-7 from ν-nucleosynthesis (NN, *dashed*) and Li-7 from a delayed stellar source (novae and/or AGB stars, *long dashed*). *Solid* curves indicate total Li (*upper* panel) and primordial ^{7}Li (*lower* panel).

stellar interiors, has also important implications for the chemical evolution of Li, as we shall see below.

The report of an "upper envelope" for ^{6}Li/H in low metallicity halo stars (Asplund *et al.* 2006) gave a new twist to the LiBeB saga. The reported ^{6}Li/H value at [Fe/H] = -2.7 is much larger (by a factor of 20-30) than expected if GCR are the only source of the observed ^{6}Li/H in that star, assuming that GCR can account for the observed evolution of Be (see Fig. 6). But, if it turns out that the true primordial Li is the one corresponding to the WMAP+SBBN value, then the initial ^{6}Li values in halo stars should be at least a factor of 3 higher than evaluated by Asplund *et al.* (2006, see Fig. 6). It should be noticed, however, that such high ^{6}Li values are not obtained in other investigations (Cayrel *et al.* 2008, Steffen *et al.* 2009).

In the past few years, the possibility of important pre-galactic production of ^{6}Li by non-standard GCR has drawn considerable attention from theoreticians, who proposed several scenarios:

1) Primordial, non-standard, production during Big Bang Nucleosynthesis: 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, and this meeting). 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 by massive stars (Reeves 2005) or by shocks induced during structure formation (Suzuki and Inoue 2002).
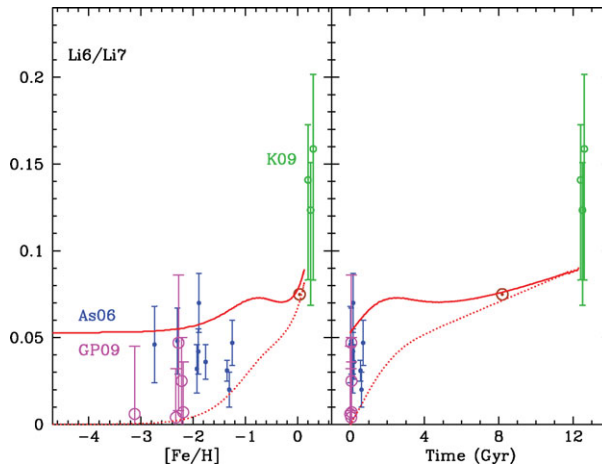
Figure 8. *Left:* Evolution of Li6/Li7 ratio as a function of [Fe/H] (*left*) and of time (*right*). Data are from Asplund *et al.* (2006, As06), Garcia-Perez *et al.* (2009, GP09) and Kawanomoto *et al.* (2009, K09). *Solid* curves corerspond to a "high" pre-galactic Li-6 and *dotted* curves to standard (low) pre-galactic Li-6.

3) In situ production by stellar flares, through ^{3}He$+^4$He reactions involving large amounts of accelerated ^{3}He (Tatischeff and Thibaud, 2007).

Prantzos (2006) showed that the energetics of ^{6}Li production by accelerated particles constrain severely any scenario proposed in category (2) above, including jets accelerated by massive black holes [this holds also for the "stellar flare" scenario, the parameters of which have to be pushed to their extreme values in order to obtain the "upper envelope" of the Asplund *et al.* (2006) observations]. This difficulty is confirmed by Evoli *et al.* (2008), who calculated pre-galactic ^{6}Li production by $\alpha + \alpha$ reactions with a semi-analytical model for the evolution of the early Milky Way; they found maximum values shorter by factors >10 (and plausible values shorter by 3 orders of magnitude) than the values reported by Asplund *et al.* (2006).

7. Evolution of Li and ^{6}Li/^{7}Li

Since GCR can only produce a ^{7}Li/^{6}Li ratio of $\sim$2, instead of the meteoritic (pre-solar) value of $\sim$12, another source of ^{7}Li had to be found. In the two decades following the original MAR paper, four such sources were identified: three possible stellar sources and the hot early Universe of the Big Bang. The latter has certainly operated, as testified by the observed Li "plateau" in low metallicity halo stars; depending on the true primordial value (see Fig. 7), it may contribute from 8 to 20% of the solar ^{7}Li. Among the stellar sources, observational evidence exists only for AGB stars, where high Li abundances have been detected in some cases. But the corresponding model yields (from ^{3}He$+^4$He in the bottom of the convective envelope) are highly uncertain, and this is also the case for the other two candidate sources of novae (from explosive H-burning) and core collapse SN (from ν-induced nucleosynthesis); notice that both novae and AGBs enter the Galactic scene with some time delay ("slow" ^{7}Li component), contrary to SN and GCR.

^{7}Li is thus the only isotope having three distinctively different types of sources: stellar, BBN and GCR. *Assuming* that the ν-yields of ^{7}Li are well established (through the corresponding ^{11}B yields, see Sec. 6), one may try to estimate the evolution of the remaining "slow" stellar contribution to ^{7}Li, from the combined action of novae and

AGB stars, i.e. by removing from the observed evolutionary curve of Li/H vs Fe/H the BBN, GCR and ν contributions. The result of such an exercise is displayed in Fig. 7. The "slow" stellar component contributes from 50-65% of the solar ^{7}Li (depending on whether high or low primordial ^{7}Li is adopted); similar numbers are found in the analysis of Matteucci (this volume).

Finally, Fig. 8 displays the evolution of ^{6}Li/^{7}Li ratio, compared to data for the early halo (highly uncertain, see previous section) and in the nearby Galactic disk (along three different lines of sight). Theoretical predictions depend on the adopted pre-galactic ^{6}Li/^{7}Li ratio, but a generic feature is a late rise of ^{6}Li/^{7}Li, due to the late secondary production of ^{6}Li from GCR.

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