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Boron production revisited

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Abstract. The spallative production of light elements by cosmic rays is re-evaluated in the light of recent measurements and theoretical developments. We investigate the possible role of large fluxes of particles in the range 10–30 MeV/n, as suggested by the measurement of the ^{11}B/^{10}B, ^{6}Li/^{9}Be and B/Be abundance ratios. The limitations imposed by the global energetics, the power and the consequent heating and ionization of the interstellar medium are considered.

1 Introduction

The light elements (Li, Be and B, or LiBeB) are thought to be produced in the interstellar medium (ISM) by spallation reactions induced by energetic particles (EPs), consisting in the collision at high energy of light nuclei (H or He) with heavier ones (C and O mostly). In order to explain the observed LiBeB abundances in the ISM, one has to identify the EPs responsible for the spallation reactions and determine their power, energy spectrum and composition. One natural energetic component to be considered is the Galactic cosmic rays (GCRs), whose spectrum, flux and composition are known, at least at energies above a few hundreds of MeV/n, where the solar modulation effect is not too important.

General calculations of the GCR-induced LiBeB production were performed by Reeves et al. (1970) and Meneguzzi et al. (1971), showing that when integrated over the Galactic lifetime, an average GCR flux comparable to that measured today can account for the production of all the LiBeB nuclei present in the Galaxy. Although very encouraging, these are only order-of-magnitude calculations, as the global energetics of the cosmic rays is not fully known. Indeed, what we measure is the flux of GCRs at Earth, from which we can derive a local CR energy density of $\epsilon_{\rm CR} \sim 1\,{\rm eV/cm^3}$. To deduce the total energy and power of CRs in the Galaxy, one needs to know the volume where they are confined as well as their confinement time, both of which can only be roughly estimated, and depend on the propagation model adopted. The total LiBeB production is thus hard to determine precisely.

However, independently of such a normalization, one can study the production ratios of the various LiBeB isotopes, which only depend on the spectrum and composition of the EPs. Apart from the observed over-abundance of Li, which can be accounted for by other production mechanisms, it has been known for many years that the GCRs do not reproduce correctly the ^{11}B/^{10}B ratio in the solar system. The measured ratio is around 4, while the GCRs produce the boron isotopes in a ratio of less than 2.5. This is the so-called 'boron problem'. Likewise, the observed B/Be ratio is higher than predicted.

Two mechanisms have been suggested to improve the situation: i) the contribution of a significant amount of low energy cosmic-rays (LECRs), whose detection is prevented by the solar modulation effect, but which produce boron with a high isotopic ratio, due to the larger energy threshold for ^{10}B production (Meneguzzi and Reeves, 1975); and ii) the contribution of neutrino-induced spallation in supernova (SN) explosions – the so-called ν-process, which produces ^{11}B but no ^{10}B nuclei (Woosley et al., 1990, Woosley and Weaver, 1995). It is generally considered that the former effect, i), is insufficient (i.e. raises energetics problems), and that the latter, ii), is consequently required, although a reliable quantitative estimate of the B production in SNe has not yet been obtained. In this paper, we investigate how good the arguments for the ν-process are, and re-evaluate the efficiency of LECRs in reproducing the LiBeB data, in the light of recent observations.

2 Observational chemical and energetics constraints

Let us first state the problem in quantitative terms. Boron and beryllium abundances have been measured in meteorites and give a reliable value for the isotopic and elemental ratios in the solar system: $^{11}{\rm B}/^{10}{\rm B} = 4.05 \pm 0.2$ (Chaussidon and Robert, 1995), and ${\rm B/Be} = 23 \pm 5$ (Grevesse et al., 1996). In the Sun itself, the B/Be ratio is found to be somewhat larger, but this is probably due to some Be depletion (King et al., 1997). As for the ISM and stellar values, the uncertainties are of course larger but the results are in good agreement: $\log({\rm B/Be}) = 1.31 \pm 0.2$ in Pop II stars (García-Lopéz et al., 1998), i.e. B/Be between 13 and 32, and Lambert et al. (1998) find an average of $^{11}{\rm B}/^{10}{\rm B} = 3.4 \pm 0.7$ in the line of sight in front of δ Sco, κ Ori and ζ Oph. Likewise, Proffit et al. (1999) find for two B-type stars, HD 886 and HD 35299: $^{11}{\rm B}/^{10}{\rm B} = 4.7^{+1.1}_{-1.0}$ and $^{11}{\rm B}/^{10}{\rm B} = 3.7^{+0.8}_{-0.6}$, respectively.

Concerning the energetics, it should be realised that the production of light elements by spallation is costly, because

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many EPs are required to produce one isotope. Most EPs are simply decelerated by Coulombian interactions or escape from the Galaxy. In order to produce the observed number of light elements, one has to impart to the EPs a significant fraction of the available mechanical energy in the ISM. In this paper, we focus by convention on the energetics of Be production, and then analyse the relative production of the various LiBeB isotopes with respect to Be. To do so, we define the *cost of a Be nucleus* as the quantity of energy, in ergs, which has to be injected in the form of EPs (CRs and/or other components) in order to produce one nucleus of Be. This cost depends on the EP spectrum and composition, as well as on the 'propagation model' describing the transport of the EPs in the Galaxy.

A natural source of energy for the EPs is the mechanical energy released in SN explosions. The explosion energy can vary by as much as one order of magnitude from one SN to another, but an average value of $E_{\rm SN} = 10^{51}$ erg may be considered a reasonable estimate (e.g. Hughes et al., 1998). Assuming a SN explosion rate of 3/century, which is also uncertain by about of factor of 2, one derives an energy input rate of $\dot{E}_{\rm SN} \sim 10^{42}$ erg/s. A similar value for the mechanical energy generated by a distribution of stars with standard initial mass function has been derived by Robert (1998), taking into account both SN explosions and stellar winds. Combining the derived energy yield of the stellar activity, $\sim 10^{49}\,{\rm erg/M_\odot^{-1}}$, with a Galactic birth rate of $\sim 3\,{\rm M_\odot}$/yr, one find a total mechanical power of $\sim 10^{42}$ erg/s.

An estimate of the power required to maintain the locally observed distribution of GCRs over their confinement volume gives $\dot{E}_{\rm GCR} \sim 10^{41}$ erg/s, with uncertainties of *at least* a factor of 2 as well, depending on the propagation model and the actual confinement volume and spatial distribution of GCRs. The fact that $\dot{E}_{\rm GCR}$ represents about 10% of $\dot{E}_{\rm SN}$ is one of the main arguments in favour of a SN origin of GCRs (but see Parizot et al., 2001).

The above-mentioned uncertainties do not allow us to normalize the GCR-induced nucleosynthesis models and calculate precisely the production of light elements in the Galaxy. However, il is always possible to calculate the number of LiBeB nuclei that can be produced *per erg of particles injected*. This is done below, separately for GCRs, LECRs and for a mixture of both components. It is important to realize, however, that such a mixture must satisfy a global energetics requirement: the observed heating and ionization state of the ISM appears to require a rate of energy deposition of $\sim 10^{42}$ erg/s, with an uncertainty factor of about three each side (e.g. Dalgarno and McCray, 1972).

In conclusion, there is some room between the inferred power of GCRs and i) on the one hand the actual rate of mechanical energy release in the ISM from stellar activity, and ii) on the second hand the total ionizing power inferred from observation. Therefore, additional components of EPs can exist besides GCRs, and even be dominant in some energy ranges. In particular, low energy cosmic rays (LECRs) which cannot penetrate and be observed in the solar system may be present in large numbers in the general ISM or most probably close to their acceleration sources (because of their low range). The power imparted to these LECRs, however, cannot be much in excess of $\sim 10^{42}$ erg/s, without violating the observed ISM heating and ionization rates. In the following, we shall investigate the ability of possible LECRs to solve the B and B/Be problems, and measure their energy in units of the GCR energy in the Galaxy. The above constraint then indicates that the LECR power should not be much greater than about 10 times the GCR power.

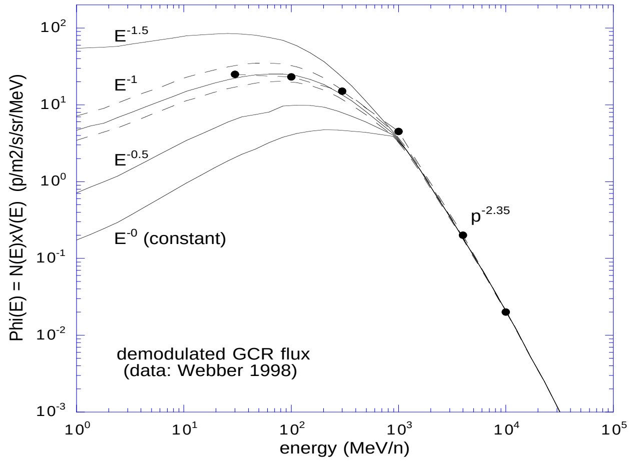

Fig. 1. Propagated spectra for different CR source spectra with having the same shape at high energy, namely a power law with logarithmic index 2.35 (e.g. Strong and Moskalenko, 2001), but different different shapes below 1 GeV/n, as indicated by the labels. The dots are samples from the demodulated GCR spectrum given by Webber (1998). The assumed mean path-length of the GCRs is in $E^{0.36}$, normalized to $10\,{\rm g/cm^2}$ at 1 GV, except for dashed lines where it is 6 and $14\,{\rm g/cm^2}$ (from top to bottom)

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3 LiBeB production by GCRs and LECRs

3.1 GCRs

To calculate the LiBeB production by GCRs, we need to extrapolate the GCR fluxes to energies lower than what is accessible to direct measurement, because spallation reactions are more efficient in the energy range 10–200 MeV/n. We use a standard propagation model to derive a plausible GCR source spectrum from the observed fluxes in the solar system, at various distances from the sun. These data are taken from Webber (1998). In Fig. 1 we show the inferred demodulated GCR spectrum in the solar neighbourhood, together with our calculated propagated spectra corresponding to various source spectra. The propagation model is a standard leaky box with an escape path length in $E^{0.36}$ normalized to $\Lambda_{\rm esc}(1\,{\rm GeV/n}) = 10\,{\rm g/cm^2}$ (slightly model-dependent). As can be seen, a source spectrum in E^{-1} up to a break energy of 1 GeV/n, followed by a power-law spectrum in $p^{-2.35}$ fits the data reasonably well, which is an interesting result in itself, as this spectrum is reminiscent of the spectrum arising

Table 1. Be production efficiency and LiBeB production ratios by various components of energetic particles.

component	GCR	LECR	LECR	LECR	LECR
E_0(MeV/n)	-	10	15	20	30
erg/Be	114	1120	261	117	48
B/Be	12.5	51.1	34.8	28.7	23.3
Li/Be	8.47	450	163	91.4	47.8
^{11}B/^{10}B	2.23	5.17	4.18	3.72	3.26
^{6}Li/^{9}Be	3.31	120	49.3	29.5	16.6
^{7}Li/^{6}Li	1.55	2.76	2.31	2.09	1.87

naturally from multi-shock acceleration inside superbubbles (Bykov and Fleishman, 1992; Parizot, 2000).

Our expression for the GCR source spectrum then reads: $Q(E) = Q_0 E^{-1}$ for $E < 1$ GeV, and $Q(E) = B\,p^{-2.35}$ for $E > 1$ GeV, where $A = 5.8\,10^{-10}\,\mathrm{part/s/cm^3/MeV}$ and where B ensures continuity. Integrating this spectrum over energy, one finds an energy density of $\simeq 1\,\mathrm{eV/cm^3}$. Integrating in the same way the source spectrum, one finds an energy injection rate of $\sim 6\,10^{29}\,\mathrm{erg/s/pc^3}$. The corresponding cost of a Be nucleus and the values of the various LiBeB production ratios are given in Table 1. It can be seen that the GCR-induced spallation indeed leads to B/Be and ^{11}B/^{10}B ratios below the observed values. The calculated cost of a Be nucleus, namely 114 erg, can be translated into a Be production rate of $\mathrm{dBe/d}t \sim 9\,10^{38}\,\mathrm{s^{-1}}$, if one accepts the value of $\dot{E}_{\mathrm{GCR}} \sim 10^{41}$ erg/s for the total GCR power. From this, one can estimate the indicative *irradiation time* required to produce the $\sim 3\,10^{56}$ atoms of Be present in the Galaxy (assuming a constant production rate and neglecting astration and Galactic outflow): $\tau_{\mathrm{irr}} \equiv N(\mathrm{Be})/(\mathrm{dBe/d}t) \sim 10^{10}$ yr. The fact that τ_{irr} is of the same order as the age of the Galaxy is the heart of the GCR-induced nuclesynthesis model for light elements.

3.2 LECRs

In addition to the above GCRs, we consider a distribution of LECRs with a characteristic energy E_0, represented by the energy source spectrum $Q(E) = Q_0 E^{-1}\exp(-E/E_0)$. This spectrum has only one free parameter and exhibits a reasonable extrapolation at low E (of course, a mono-energetic distribution would be more efficient in producing LiBeB, but would not be realistic). The above spectrum allows us to investigate, from the phenomenological point of view, the 'typical energy' of LECRs able to solve the above-mentionned boron problem. Just as for GCRs, we have calculated the cost of a Be nucleus and the LiBeB production ratios, for different values of the cut-off energy, E_0. The results are shown in Table 1.

As expected, the B/Be and ^{11}B/^{10}B ratios obtained with LECR-induced spallation are much higher than in the case of GCRs. On the other hand, the cost of a Be is quite high for very low values of E_0, indicating that a large amount of energy has to be imparted to LECRs to modify significantly the GCR ratios.

3.3 GCRs + LECRs

The Be cost and LiBeB ratios obtained for a mixture of GCRs and LECRs depend on the relative weight of both components. In Fig. 2a, we show the ^{11}B/^{10}B ratio as a function of the Be cost for various relative contributions of LECRs. We note $n = \dot{E}_{\mathrm{LECR}}/\dot{E}_{\mathrm{GCR}}$ the ratio of the power imarted to LECRS to that of GCRs. As mentioned above, n should not be much greater than 10. For each value of n, we also investigate various LECR spectra, corresponding to different cut-off energies, E_0, as indicated on the figure. As can be seen, ^{11}B/^{10}B ratios within the observational error bars for the general ISM can be obtained for a wide range of parameters, namely for cut-off energies of order 10–50 MeV/n and for n =1–10. At high n and low E_0, however, the cost of a Be nucleus becomes quite high, requiring a large EP power, up to 10^{42} erg/s. On the other hand, LECRs with between 1 and 3 times the GCR power and a typical energy of 15–30 MeV/n appear to satisfy the observational constraints without changing the global energetics significantly. For $n = 2$ and $E_0 = 5$ MeV/n, for example, one gets $^{11}\mathrm{B}/^{10}\mathrm{B} = 3.41$, right in the middle of the error bars for Pop I stars, and a Be cost of 183 erg. Assuming a standard GCR power of 10^{41} erg/s, the total EP power in this case is $3\,10^{41}$ erg/s, implying an irradiation timescale of 6 Gyr, quite a reasonable value. Alternatively, a value of $5\,10^{40}$ erg/s for the actual GCR power would imply a total EP power of $1.5\,10^{41}$ erg/s and an irradiation timescale of 12 Gyr.

It can also be seen from Fig. 2a that the high values of the ^{11}B/^{10}B ratio observed in meteorites require a larger value of n, but still allowed by the ISM heating and ionization constraints. On the other hand, such models would also lead to a quite large B/Be ratio, as shown in Fig. 2b, maybe in excess of the meteoritic value. Letting aside meteorites, which may not be representative of the general ISM, Fig. 2b shows that virtually all of our models are compatible with the observed ^{11}B/^{10}B and B/Be ratios, without the help of neutrino-induced spallation.

In addition to Be and B, we have calculate the Li production by the same mixtures of GCRs and LECRs. The results are shown in Fig. 3. The high Li production (in comparison with GCR results) is due to the enhanced contribution of $\alpha+\alpha$ fusion reactions, whose cross-section decreases rapidly above a few tens of MeV/n. As can be seen, the GCR+LECR model cannot be reconciled with the meteoritic value. However, a large range of parameters can account for the values inferred for the general ISM. We should also note that a composition of LECRs poorer in He (or richer in C and O) than the GCRs would considerably reduce the ^{6}Li/^{9}Be production ratio. Observations of LECR-induced gamma-ray lines would considerably help determining the LECR composition and thereby reduce the large uncertainty on the ^{6}Li/^{9}Be production ratio.

In conclusion, the most important results of these calculations are the following. As seen in Fig. 2 and 3, spallation reactions induced by low-energy cosmic rays in the interstellar medium increase the ^{11}B/^{10}B ratio, the B/Be ratio and the

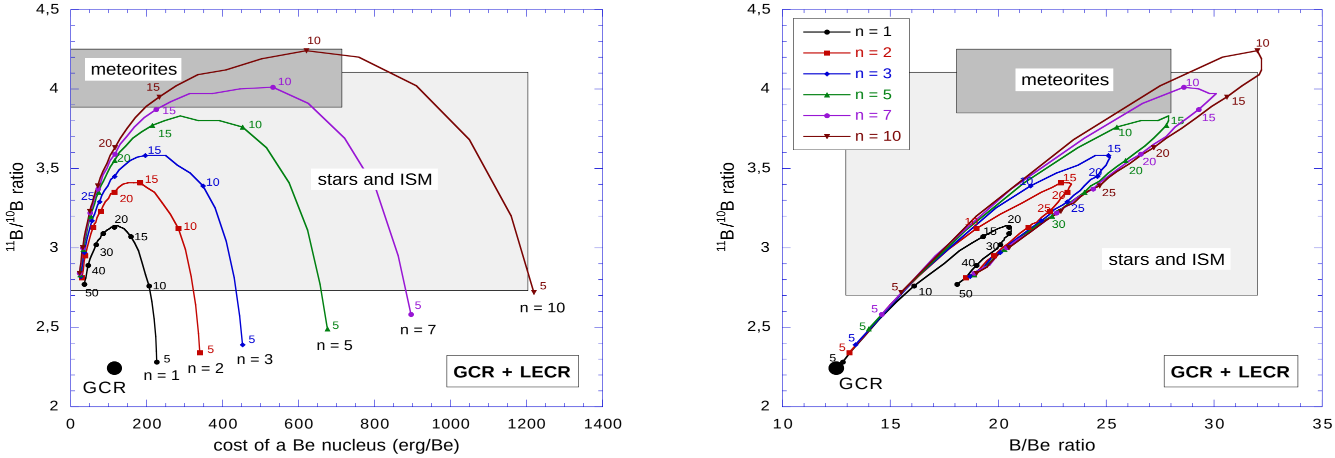

Fig. 2. Calculated ^{11}B/^{10}B ratio as a function of i) the cost of a Be nucleus (left) and ii) the B/Be ratio (right). The different curves correspond to different values of $n = \dot{E}_{\rm LECR}/\dot{E}_{\rm GCR}$. Bullets indicate the value of the cut-off energy E_0 of the LECR spectrum, also indicated as a label: 5, 10, 15, 20, 25, 30, 40 and 50 MeV/n. The shaded area correspond to the observational error boxes, for meteorites and the general ISM. The upper limit on the Be cost corresponds to an irradiation time required to produced the observed amount of Be, of 7 and 12 Gyr respectively, assuming a constant irradiation with a total power of 10^{42} erg/s (see text). The point corresponding to GCR-induced production alone is also shown.

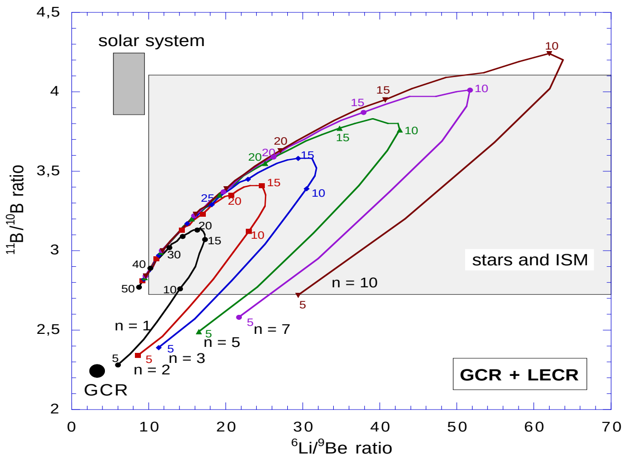

Fig. 3. ^{11}B/^{10}B as a function of ^{6}Li/^{9}Be. The models and labels are the same as in Fig. 2. The limits on the ^{6}Li/^{9}Be ratio come from the combination of the Li/Be ratio with the wide range of variations of the ^{7}Li/^{6}Li ratio observed in the ISM, from 2 to 12, notably in Ophiucus (Lemoine et al., 1995) and Perseus (Knauth et al., 2000).

^{6}Li/^{9}Be ratio over the value obtained with the GCR alone, bringing all three ratios in better agreement with the stellar observations, without violating the constraints imposed by ISM heating and ionization state. However the solar system boron isotopic ratio appears to be outside of the range of the cosmic rays. This fact raises the question of possible local inhomogeneities in the solar system. This possibility is further raised by the observations of large inhomogeneities in the lithium isotopic ratio in the ISM. Further observational work will be needed to determine whether the meteorites are representative of the general ISM.

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