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Implications of the B/Be and $^{11}\text{B}/^{10}\text{B}$ Ratios

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Abstract: Beryllium and boron are widely believed to be produced primarily by cosmic-ray nucleosynthesis. However the observed abundance ratios of B/Be and $^{11}\text{B}/^{10}\text{B}$ may indicate that an additional source for boron (presumably ^{11}B) is needed. Neutrino-process nucleosynthesis in supernovae may be such a source. When the ^{11}B yield from the neutrino process is normalized to obtain the correct $^{11}\text{B}/^{10}\text{B}$ ratio, one obtains a predictions that B/Be is large (much larger than the nearly model independent prediction of cosmic-ray nucleosynthesis), around 40 for $[\text{Fe}/\text{H}] = -2.6$. Large values of B/Be may be supported by recent NLTE analyses of boron observations.

A comparison of observed abundance ratios and their theoretical predictions is a good test of models of galactic cosmic-ray nucleosynthesis [1-5] and galactic chemical evolution [2]; it may have implications for big bang nucleosynthesis as well [3,6]. The ratios of interest are $^6\text{Li}/^7\text{Li}$, Li/Be, B/Be, and potentially $^{11}\text{B}/^{10}\text{B}$. In the case of $^6\text{Li}/^7\text{Li}$ where the theoretical prediction of about 0.9 (from cosmic-ray nucleosynthesis) is robust, the observation of ^6Li [7] is a good indication that Li is not strongly depleted in stars (at least not by nuclear burning) [4]. The Li/Be ratio which can be used to probe the compatibility between cosmic-ray and big bang nucleosynthesis [3,6] is much more model-dependent [5] and may take values anywhere from 10 to 1000. There is as yet no data on the $^{11}\text{B}/^{10}\text{B}$ ratio in Pop II objects, but such data would be very interesting. Standard cosmic ray nucleosynthesis models predict $^{11}\text{B}/^{10}\text{B} \approx 2.5$. Finally that brings us to the B/Be ratio which like the $^6\text{Li}/^7\text{Li}$ ratio is robust [3,5] and is an excellent tool to probe theoretical models. The standard model prediction for B/Be is 12 to 14.

In the table below, the available data for B is shown with the corresponding observed abundances of Be. The boron data is taken from [8] for the three stars shown. In addition, for HD140283, the data reflects the measurement by [9] as well. The source of the Be data is given in the final column. As one can see from the B/Be ratios in table, some of the LTE ratios are in agreement with standard cosmic-ray nucleosynthesis model predictions, but most of them are on the low side of the prediction. For example, the overall average in the case of

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HD140283, gives B/Be = 6 ± 2 . Effort has been concentrated for the most part in determining how low the B/Be can be made within the context of cosmic-ray nucleosynthesis. In [3], it was argued on the basis of spallation cross-sections that the extreme lower limit is B/Be > 7.

Table 1. Observed Pop II abundances of Be and B

Star([Fe/H])	[Be]	[B]	LTE B/Be	B/Be	Source
HD 19445(-2.1)	-0.14 ± 0.1	0.4 ± 0.2	3.4 ± 1.8	~ 8	[10]
HD 140283(-2.7)	-1.25 ± 0.4	-0.16 ± 0.14	12 ± 12	$34 - 50$	[11]
HD 140283(-2.8)	-0.97 ± 0.25	-0.16 ± 0.14	7 ± 5	$23 - 33$	[12]
HD 140283(-2.7)	-0.78 ± 0.14	-0.16 ± 0.14	5 ± 2	$14 - 21$	[10]
HD 140283(-2.5)	< -0.90	-0.16 ± 0.14	> 7	$> 21 - 30$	[13]
HD 201891(-1.3)	0.65 ± 0.1	1.7 ± 0.4	10 ± 10	~ 14.5	[14],[10]

Recently, Kiselman [15] has performed a re-analysis of the inferred B abundance from the data. In the original analysis of [8], abundances based on the BI and BeII spectral lines were extracted using the assumption of local thermodynamic equilibrium (LTE). The beryllium abundance is believed to be relatively insensitive to this approximation but it was recognized in [8] that a non-LTE (NLTE) analysis could be a potentially important correction to the boron abundance. An overall upward correction to the boron abundance of 0.46 - 0.62 dex or a factor ~ 3 was found [15]. The table, also reflects the NLTE corrected B/Be ratio (the second column of B/Be). The weighted average of the three positive observations of Be for HD140283 (corrected for differing surface gravities) is $[\text{Be}] = -0.93 \pm .12$. After the Kiselman correction we find that B/Be = $17 - 25$ [16], using the central value of Be.

In [16], we considered various cosmic-ray source spectra which are power law in momentum and total energy with escape path-lengths, Λ , between 10 - 1000 g/cm². The resulting ratios for Li/Be and B/Be are shown in Figures 1 and 2, for the momentum spectrum. The solid lines correspond to $\Lambda = 10$ g/cm² and the broken lines to $\Lambda = 1000$ g/cm². Assuming that Be is produced solely by cosmic ray nucleosynthesis and that Li is predominantly produced in the big bang, the B/Be ratio can be constrained to Li/Be < 1000; a very conservative bound based on the consistency of the Be observations [3]. From the Figures it is clear that B/Be < 14. A similar result is obtained for the energy spectrum as well.

Given the upper limit B/Be < 14, and the NLTE values in the table, we can pose the question as to whether an additional source of B is needed. The apparent lack of boron production in standard cosmic ray models is compounded when one notes that the observed isotopic ratio in the solar neighborhood $^{11}\text{B}/^{10}\text{B} = 4$ relative to the prediction of 2.5.

A potentially important source for ^{11}B production has been found to result from neutrino induced nucleosynthesis in type II supernovae [17]. The core collapse of a massive star into a neutron star creates a flux of neutrinos so great that in spite of the small cross sections involved, it may still induce substantial

Fig. 1. Li/Be production rates for a source spectrum $q(p) \propto p^{-\gamma}$, plotted as a function of spectral index γ

Fig. 2. As in Figure 1, for the ratio of B/Be

nucleosynthesis. It was found that considerable ^{11}B production can result as the flux of neutrinos passes through the He, C, and Si shells of the stellar envelope, primarily by neutrino spallation of ^{12}C . The dominant product is ^{11}B since it is favored for ν -spallation to knock out a single nucleon. In addition, some synthesis of ^7Li and ^{10}B takes place by this process but the production rate seems quite low.

An important aspect of the calculation in [17] is the full treatment of pre- and post-shock nucleosynthesis. Since the duration of the neutrino burst exceeds the time scale for the passage of the shock through the inner layers of the exploding star, ν -process nucleosynthesis can continue after the passage of the shock. In the outer layers, however, the destruction of fragile isotopes is a significant effect and is, for example, responsible for the destruction of ^9Be . Uncertainties in the calculation arise primarily from the assumed neutrino temperature and the cross sections for boron production. This process is attractive however as it naturally creates ^{11}B without much ^{10}B , and so provides the needed source of ^{11}B to augment the cosmic ray production and so reproduce the $^{11}\text{B}/^{10}\text{B}$ ratio [18].

Indeed, the ^{11}B yields from these processes [19] were incorporated in a chemical evolution model [18]. Respecting the overall constraints imposed by the LiBeB observations in halo stars, we were able to obtain a solar isotopic ratio $^{11}\text{B}/^{10}\text{B} \approx 4$. Using the boron isotopic ratio to normalize the ν -process yields, it was shown that neutrino process nucleosynthesis leads to a relatively model independent prediction that the B/Be elemental ratio is large (> 50) at low metallicities ($[\text{Fe}/\text{H}] < -3.0$), assuming still that Be is produced as a secondary element as is the case in the conventional scenario of galactic cosmic-ray nucleosynthesis. In particular, at the metallicity corresponding to that of HD140283, $[\text{Fe}/\text{H}] \lesssim -2.6$, it was predicted that the B/Be ratio should be close to 40. Though still on the high side, this is in overall good agreement with the NLTE corrected values shown in the data Table. In the Figure 3 the B/Be ratio is shown as a function of $[\text{Fe}/\text{H}]$. The theoretical curves are compared to available data. As one can readily see, the primary component of ^{11}B greatly enhances the B/Be ratio at low metallicities.

Fig. 3. The B/Be ratio as a function of $[\text{Fe}/\text{H}]$ with (solid) and without (dashed) ν -process nucleosynthesis included. Also shown is the B/Be ratio in an enhanced model [2] (dotted)

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