The Light Elements and Their Evolution
IAU Symposium, Vol. 198, *2000*
L. da Silva, M. Spite, J. R. de Medeiros, eds.

The Abundance of Boron in Disk-Metallicity Stars

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Abstract. Although the behavior of boron versus metallicity has been probed in a fairly large sample of halo dwarfs with HST, it is only very recently that boron abundances have been derived systematically in solar metallicity dwarfs. This effort began with a re-analysis of the solar spectrum with modern atomic data and model atmospheres so that the Sun could be adopted as a standard for the calibration of a line list in the region of the B I transition at 2497 Å. The solar analysis indicates that boron is not depleted in the solar photosphere. From a subsequent study of a sample of 14 field F/G-dwarfs with roughly solar metallicities, it is found that the behavior of boron versus [Fe/H] follows the linear trend that is observed for the halo stars. The average B/Be obtained for solar metallicity stars is 27±5 compared to the solar ratio of 23. The determination of boron abundances in the young B-type and G-type stars of the Orion association reveals a behavior of boron and oxygen in Orion that is opposite of the positive correlation which is observed for the field stars: the boron and oxygen abundances are anticorrelated.

1. Introduction

The main sources of the light element boron in the Galaxy are spallation reactions occurring between energetic particles and interstellar nuclei. There are three categories of these processes. The first consists of accelerated protons and α-particles hitting CNO nuclei in the ISM to produce boron in the form of ^{10}B and ^{11}B. The second one is the so-called reverse process, where CNO nuclei, accelerated presumably by type II supernovae (SN II), hit interstellar H and He to produce also ^{10}B and ^{11}B. Another possibility is the production of boron in SN II from neutrino-induced nucleosynthesis (the ν-process). The neutrinos result from core collapse and produce primarily ^{11}B from interactions between ν's and ^{12}C in the C-rich shell of the progenitor star.

Observations of boron (together with beryllium) hold the possibility of discriminating between the various production mechanisms, and, in particular, the ν-process contribution. However, boron observations are still rather sparse. This is because boron is not observable from the ground, having strong transitions only in the ultraviolet, with B I observable in cooler stars (with roughly solar temperatures), and B II and B III in the hotter stars. The use of HST for UV spectroscopic analyses of boron in a variety of stars at different metallicities has provided the primary data set from which derived stellar boron abundances can be compared to model predictions for boron production and chemical evolution.

The first fairly large sample of stellar boron abundances was provided by Boesgaard & Heacox (1978) from Copernicus observations of B II at 1362 Å in 18 A and B field stars spanning a range in T_{eff} between 9000 and 25000K. Their analysis assumed the validity of LTE and an average of log ϵ(B)=2.3 ± 0.2 was obtained for the boron abundances of the studied stars. The first detection of boron in the solar photosphere was reported by Kohl, Parkinson & Withbroe (1977). They analyzed the B I resonnance transition at 2497 Å in rocket spectra obtained at solar disk center. The derived boron abundance was log ϵ(B)=2.6 ± 0.3.

After these two pioneer boron studies, it was only in the early 90's that routine access to boron spectroscopy in the ultraviolet became possible with the Hubble Space Telescope; data on the behavior of boron with [Fe/H] has since then increased considerably. In particular, the first extensive study of boron with metallicity was done by Duncan et al. (1997). From the analysis of B I in a sample of eight halo stars with metallicities ranging from [Fe/H]=-3.0 to -0.4 the surprising linear behavior of boron with metallicity was first established. In fact, this linear behavior had already been suggested from a previous study by Duncan, Lambert & Lemke (1992) that contained a small sample of 3 metal-poor dwarfs. Other studies expanded the boron data set, as well as probed boron abundances in dwarfs with the lowest metallicities (Primas et al. 1999 and García-López et al. 1998). All these observational results suggested that the production of boron in the Galaxy was directly related to the production of the heavier element Fe. The relation of boron and Fe for solar metallicity stars remained to be investigated. In the following section, we will discuss the re-analysis of the solar spectrum and the photospheric boron abundance in the Sun, the boron results for field dwarfs with roughly solar metallicity, and the boron abundances observed for a sample which constitutes a truly young population of the Galactic disk: B- and G- type stellar members of the Orion association.

2. Boron Abundances of Disk-Metallicity Stars

The spectra of solar-type solar-metallicity stars in the vicinity of the B I transition at 2497 Å are severely blended with large numbers of overlapping lines such that there are no regions free of line absorption. Moreover, knowledge of the atomic data in this ultraviolet region of the spectrum is still limited. The first attempts to synthesize the B I region in the spectra of dwarfs of roughly solar metallicity immediately revealed a significant mismatch between the adopted line list (in this case taken as the line list compiled by in Duncan et al. 1998) and the observed spectra. The line list, although it represented an updated compilation of the available atomic data, seemed to have a large number of missing lines that were present in the observed spectra and not matched by the synthetic one. A reasonable strategy was then to adopt the Sun as a standard and do a homogeneous and self-consistent analysis for all dwarfs with roughly solar metallicities that had been observed for boron with the Hubble Space Telescope.

2.1. The Photospheric Solar Boron Abundance

The first step towards a homogeneous boron abundance analysis of solar metallicity stars was to fine-tune the line list compiled by Duncan et al. (1998) in order to achieve the best possible fit to the disk-center spectrum of the Sun. The selection of the Sun as a standard ensures that a direct comparison can be done between disk stars and the Sun. The same solar spectrum that had been previously analyzed by Kohl et al. (1977) was also used by Cunha & Smith (1999) to re-derive the solar photospheric boron abundance. The adopted procedure to adjust the line list consisted of the following: when there was a line missing in the synthetic spectrum, a 'fake' Fe I line was added with an arbitrary excitation potential. The values of oscillator strengths for those lines which did not have accurate laboratory measurements were adjusted until the observed intensities could be matched by the synthesis, while the lines with accurate laboratory f-values were kept untouched.

The continous opacity in the spectral region of the B I transition (2500 Å) is dominated by the photoionization of Mg I. This is an important source of opacity that needs to be considered in boron abundance calculations, especially in metal-rich stars ([Fe/H]>-1). Synthetic spectra were calculated with the adoption of a more recent value for the photoionization cross-section of Mg I at 2500 Å that was taken from the Opacity Project; σ(Mg I)= 18 X 10^{-18} cm^2 (Butler, Mendozza & von Zeipen 1993). This value for the b-f cross-section is significantly lower than the published value from ~40 years ago that was adopted in the previous study of boron in the Sun: the experimental cross-section from Botticher (1958; σ(Mg I)= 45 X 10^{-18} cm^2). We note that the experimental value by Gingerich et al. (1971) with σ(Mg I)= 25 X 10^{-18} cm^2, as well as the theoretical value by Peach (1970; σ(Mg I)= 16 X 10^{-18} cm^2) became available in the early 1970's. In Cunha & Smith (1999) it is shown that the choice of the photoionization cross-section of Mg I has a measurable effect on the derived boron abundances in the Sun. They find that the adoption of lower values of σ(Mg I) in the calculations produces a better agreement between the solar observations and model intensities at the solar limb. For the higher values of σ(Mg I), the calculated model continuum intensities were already below the lowest possible definable continuum (the lowest possible continuum would be defined by the points of highest intensity in the observed spectrum). This inconsistency was also recognized in the calculations by Kohl et al. (1977), who argued that non-LTE effects in Mg I, that were not being considered, could be responsible for the effect.

This most recently derived photospheric boron abundance of log ϵ(B)= 2.70 with estimated statistical uncertainties of -0.12 and +0.21 (Cunha & Smith 1999) is in good agreement with the meteoritic abundance obtained by Zhai & Shaw (1994; log ϵ(B)=2.78), indicating that boron is not depleted in the Sun. This boron result is in line with the lack of Be depletion in the Sun as recently argued by Balachandran & Bell (1998). We note, however, that a modest Be depletion (of ~0.4 dex) would also be consistent with no boron depletion.

2.2. Boron in a Sample of Dwarfs with [Fe/H]>-1.0

A relatively large number of solar type dwarfs have been observed with the Goddard High Resolution Spectrograph (GHRS) in the spectral region that contains the B I transition at 2497 Å. Recently, Cunha et al. (2000a) selected 14 stars from the HST archive and analyzed the B I region to derive boron abundances from synthetic spectra calculated with the known sources of opacities. Their studied sample consisted of dwarfs which spanned a range in effective temperatures from 5650 to 6700K and metallicities [Fe/H] ranging between -0.75 and +0.15. Their boron analysis was done consistently relative to the Sun with the adoption of a line list adjusted in order to produce a good fit to the solar spectrum, as discussed above. Although the solar line list had the addition of fake Fe I lines (to properly fit the solar spectrum) it produced, in general, a very good fit of the B I region for most of the sample stars, even for those stars that were considerably hotter than the Sun. The good fits of the boron region obtained for stars spanning a large range in T_{eff} indicates that an accurate set of boron abundances can be derived.

One of the results of the Cunha et al.'s (2000a) study was that those sample stars with metallicities close to solar, showed boron abundances that were approximately solar as well. Concerning the boron-to-beryllium ratios for these stars, the average ratio obtained was 27±5, also in rough agreement with what is observed in the Sun (B/Be=23) and higher than the predictions of Galactic cosmic-ray models that find B/Be $\sim$ 10-15.

In order to investigate the relation of boron and iron in disk stars, it was necessary to isolate, from the sample studied by Cunha et al. (2000a), those dwarfs that have undepleted Li (and Be) abundances. (Li is severely depleted before B starts to suffer significant depletion in the stellar interior). The behavior of boron and metallicity obtained then is shown in the top panel of Figure 1 where are gathered, from several studies in the literature, the boron abundances for the halo stars, as well as Cunha et al.'s results for the disk stars. The target stars shown represent nearly all the stars (with undepleted Li) that have been observed with the Hubble Space Telescope for boron. The results for the disk-metallicity stars (represented by filled circles) seem to indicate an extension of the behavior observed for the halo stars: a linear relation extends from the low metallicities in the halo to high metallicities around [Fe/H]=+0.15. A least-squares fit to all the abundance points in the figure (except the four points that represent the two stars with lowest metallicities and controversial boron detections) indicates a slope of $\sim$0.9 with a correlation coefficient of 0.98. A change in slope at disk to halo metallicities does not seem to be obvious from this data set but has not been investigated in detail. However, it is important to note that the Fe abundances shown may suffer from departures from LTE and point out the recent non-LTE results by Thévenin & Idiart (1999) that indicate significant revisions to LTE Fe abundances derived for cool stars, especially with low metallicities. Adoption of their non-LTE Fe abundances would result in a different relation between B and Fe. (See discussion by Idiart & Thévenin in these procedings).

The relation of B with [Fe/H] can constrain the possible origins of boron; however, the production of boron is not directly related to the synthesis of Fe itself. Perhaps a more revealing comparison element is oxygen since a significant fraction of boron is produced primarily by cosmic-ray interactions with atoms in the ISM (spallation reactions between protons and α-particles with C, N, and O nuclei), thus the most direct metallicity indicator for the B abundance

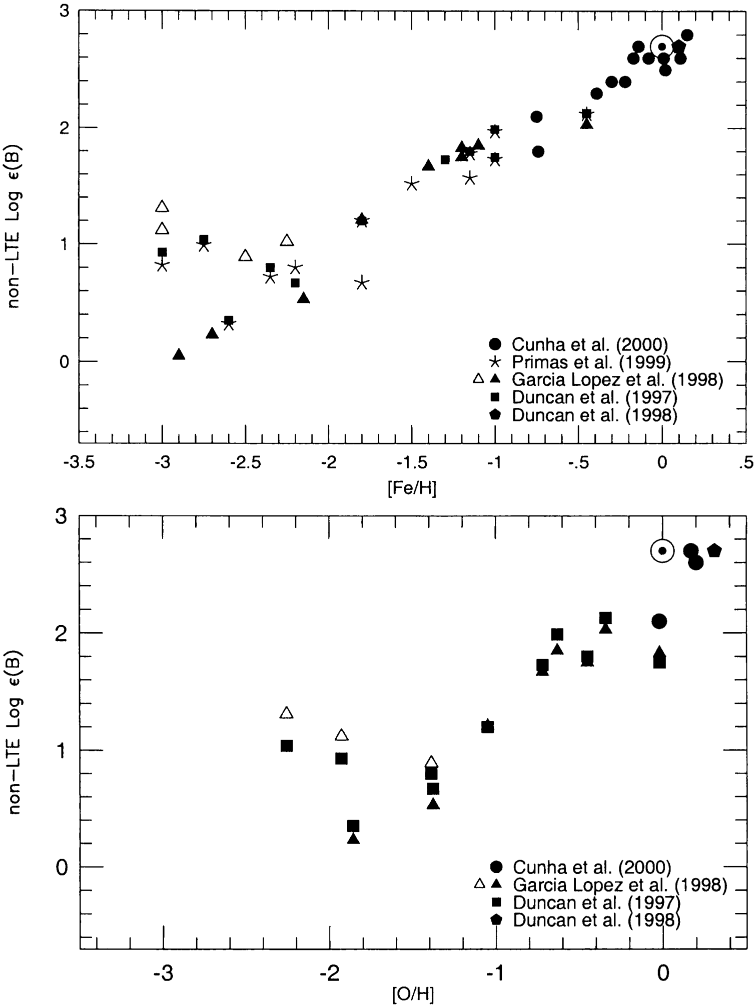

Figure 1. *Top panel*: The behavior of boron and iron in Galactic field halo and disk dwarfs with undepleted Li. The non-LTE boron and [Fe/H] abundances were gathered from the literature according to the references listed in the Figure. Because of the different values of [Fe/H] adopted by the different studies, a single star may not be represented by a unique [Fe/H]. *Bottom panel*: The behavior of boron and oxygen for a sample of halo and disk dwarfs. The adopted oxygen abundances represent a simple average of the oxygen abundances found in the literature and the non-LTE boron abundances are from the references listed in the Figure.

is the most abundant member of the CNO trio, which is oxygen. Abundances of oxygen, however, are more difficult to derive than iron. In particular, the oxygen abundances in metal poor stars are still a matter of debate and the flat behavior of [O/Fe] versus [Fe/H] for halo metallicities (below [Fe/H]$\sim$-1.0) is being questioned (see e.g. Israelian et al. 1998, Boesgaard et al. 1999, but also Fulbright & Kraft 1999).

Duncan et al. (1997) have collected the various oxygen abundance determinations from the literature for the metal poor stars in their sample and they find that the oxygen abundances for a given star show a considerable scatter. In the bottom panel of Figure 1 we plot the behavior of boron versus oxygen in field dwarfs and, unlike Duncan et al. (1997) who assumed a mean relation for [O/Fe] versus [Fe/H] in order to obtain oxygen abundances for their individual stars, here, we have taken the simple average of the different oxygen measurements for each star and plotted them versus their derived non-LTE boron abundances. The observed points in this figure suggest that the behavior of boron and oxygen for stars with oxygen abundances [O/H] larger than $\sim$ -2.0 is roughly linear with a slope of nearly 1.0. However, the reality of the suggested slope 1.0 linear relation (primary behavior) between boron and oxygen needs further investigation, due to the small number of oxygen abundance points and principally because the derived oxygen abundances from different sources are significantly discrepant. We note that Fields et al. (2000) identify the presence of a secondary component in the observed data for [O/H] $\gtrsim$ -1.4, when they assemble the different oxygen abundances determinations that adopt a consistent effective temperature scale. (The different stellar parameter scales were ignored in our discussion, where we have simply averaged the oxygen abundances obtained from different sources in the literature). In fact, Fields et al. conclude that this secondary component (a quadratic relation between boron and oxygen) dominates at high metallicities, being identifiable in two distinct and independant sets of adopted stellar parameter scales. For the low metallicity stars, the uncertainties in the derived oxygen abundances are larger. As pointed out by Fields et al. (2000) the behavior of boron and oxygen and the existence, or not, of a primary component (linear slope 1.0 relation) at low metallicities depends on the particular set of adopted stellar parameters used to calculate the oxygen abundances. Before any firmer conclusions can be reached about the presence (or not) of a primary plus a secondary component in the behavior of boron and oxygen, more (and more reliable) oxygen abundance points are needed.

At the metal poor end, not only are the oxygen abundances controversial, but also the boron abundances derived for the most metal poor dwarfs. From analysis of the same HST spectra, different studies do not agree on boron abundance values for low metallicity stars with T_{eff} > 6000K: García-López et al. (1998) argued that only boron abundance upper limits could be derived for such stars, while Duncan et al. (1997) and Primas et al. (1999) obtained boron abundance values for dwarfs with such effective temperatures and low metallicities. Depending on which set of boron abundances is taken (upper limits or detections) a distinct general behavior for boron versus oxygen could be inferred: if the boron abundance results from Duncan et al. (1997) and Primas et al. (1999) for the two stars with lowest [O/H] in Figure 1 are adopted, there would be some indication of a possible change of slope in boron versus oxygen at values of [O/H] $\lesssim$ -1.9. (A similar behavior would be seen for Fe in the top panel of this figure).

Moreover, there would exist a significant spread in the boron abundance at a given oxygen abundance. Note (in the bottom panel of Figure 1) that the two stars at [O/H] $\sim$ -1.9 (represented by filled squares) show a spread in boron of roughly 0.6 dex. However, if the boron abundaces for the two stars with lowest [O/H] in Figure 1 are in fact only upper limits, as argued by García-López et al. (1998), these could have boron abundances in agreement with the general trend which is observed for boron and oxygen in higher metallicities. But, of course, the 'real' trend also depends on the 'real' oxygen abundances for these stars. The final word on boron, and oxygen, is still to come with more observations of boron, especially in low metallicity stars, and reliable and self-consistent oxygen abundance determinations for the whole sample of stars observed for boron.

2.3. Boron Abundances in the Orion Association

An important step in trying to isolate the contributions of the different processes to the production of boron in the Galaxy comes from the study of a sample of stars from nearly the same birthplace and birthdate in the Galaxy but having different oxygen abundances. The Orion association is a perfect environment in this context as it contains member stars which have a spread in their oxygen abundances: the oxygen abundance spread amounts to a factor of $\sim$ 6 and is interpreted as the result from self-enrichment over the lifetime of the association ($\sim 10^7$ yr) by very massive SN II, whose dominant nucleosynthetic product is oxygen (Cunha & Lambert 1994 and Cunha, Smith & Lambert 1998).

In a previous study of boron in Orion stars based on HST GHRS spectra, Cunha et al. (1997) obtained spectra of B II at 1362 Å in a sample of four main-sequence B-stars in the Orion association. They selected four target stars, with two stars having low oxygen abundances and two having slightly higher oxygen abundances. The derived LTE abundances were rather low (when compared to the meteoritic value) and ranged between log ϵ(B)=1.6-2.0. However, the derivation of reliable B abundances (from B II) required a non-LTE analysis which indicated a large correction (up to $\sim$1.0 dex) to the derived LTE abundances. Concerning the behavior of boron and oxygen in this quartet of stars, the expectation would be a positive correlation, as observed for the general field stars. However, the particular situation in an OB association where there is evidence of self-enrichment has never been studied. The results obtained for the B-stars did not reveal a positive correlation of boron and oxygen, instead a slight negative trend was observed such that the boron abundances in the O-rich stars were some 0.4 lower than in the O-poor stars. But conclusions relied on the validity large non-LTE corrections applied to the LTE abundances. In this context, it is worth noting that the derived LTE abundances were similar to the interstellar abundances measured in the direction of the Orion association by Lambert et al. (1998: log ϵ(B)$\sim$2.0), while the non-LTE corrections would increase the boron abundances in the Orion stars to the interval between logϵ(B)=2.5 and 2.9 (which encompasses the meteoritic value).

An important confirmation of the large non-LTE corrections derived for B II in Cunha et al. (1997) has now been obtained by Lambert et al. (2000) from calculations of boron abundances from B III at 2066 Å in one of the Orion targets that had been previously analyzed for B II. Their results indicate a high (close to meteoritic) B abundance, definitely not as low as the ISM, for the

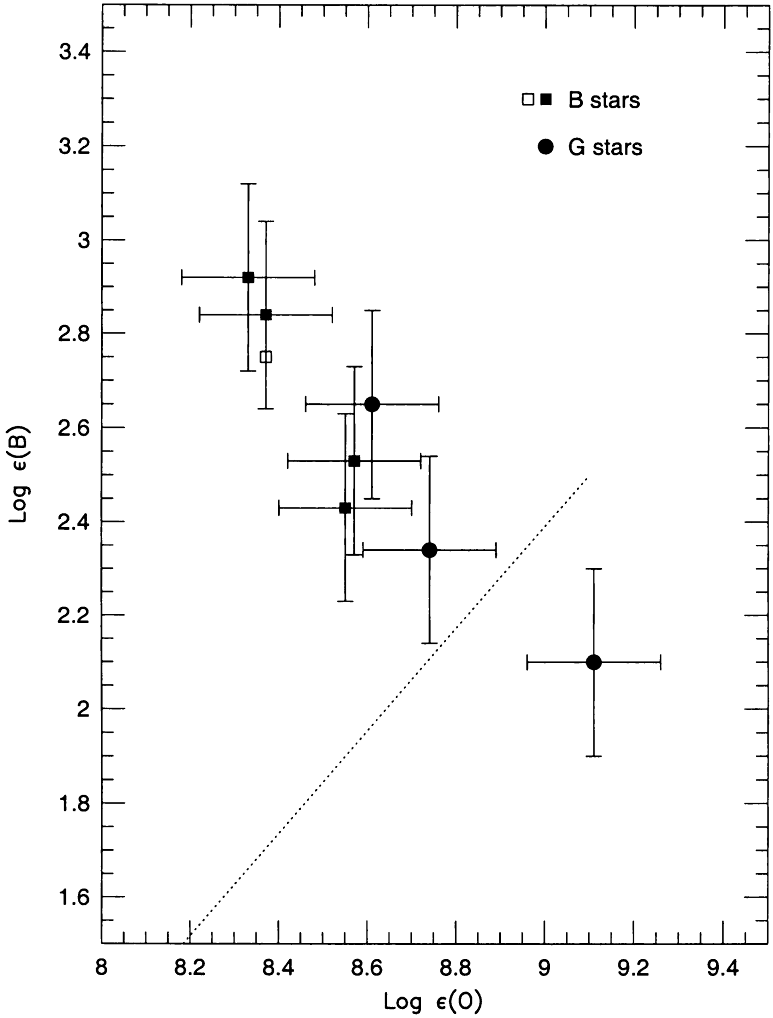

Figure 2. The anticorrelation of boron versus oxygen obtained for the young Orion association. The filled and open squares represent the four B-type stars analyzed for boron in Cunha et al. (1997) and Lambert et al. (2000), and for oxygen in Cunha & Lambert (1994); while the three G-type dwarfs analyzed in Cunha, Smith & Lambert (1999) and Cunha et al. (2000b) are represented by filled circles. Their oxygen abundances are from Cunha et al. (1998). The errorbars represent the estimated uncertainties in the derived boron and oxygen abundances. Also shown, for comparison, is the general trend observed for the field stars, with a least-squares fit (dotted line) calculated for the boron and oxygen abundance points in Figure 1. We have excluded from the fit the three stars that have boron upper limits in García-López et al. 1998) and adopted average boron values for each star.

studied stars. Unlike B II, B III is major ionization stage at the T_{eff}'s of the target stars with very small non-LTE corrections. These B III results bolster our confidence in the non-LTE abundances derived for the B-type stars.

As a further step to investigate the behavior of boron with oxygen in the young Orion members, Cunha et al. (1999) and Cunha et al. (2000b) analyzed three cooler lower mass stellar members of Orion (of spectral type G and masses $\sim$1-2M$\odot$) with oxygen abundance values similar to the oxygen-rich B-type stars and higher. These stars were observed with the GHRS and STIS on the HST and the observed sample was selected from Orion G-dwarfs with Li abundances that are undepleted (or nearly undepleted).

When the boron results obtained for the B-type stars in the Orion association are put together with the abundances obtained for the three G-type stars, a puzzling behavior seems to emerge. These boron results, plus the stars' respective oxygen abundances, are shown in Figure 2. The trend displayed is obvious: boron seems to decline with increasing oxygen. In principle, this observed anticorrelation of boron versus oxygen can set limits on boron production via ν-nucleosynthesis. Qualitatively, if the ν-process contribution were significant, one should expect that the boron abundance would increase with oxygen. But the observed trend for Orion is opposite. One possible explanation for the anticorrelation is to assume that the ν-process is negligible. However, this is not the only possibility. As discussed in Cunha et al. (2000b) the anticorrelation of boron and oxygen in Orion can be explained by a simple model in which two components of gas are poorly mixed: the SN II ejecta and the ambient medium which is B-enriched by spallation reactions. (According to superbubble (SB) models (Parizot 1998) boron production takes place in the SB supershells.) Therefore the ambient gas component could be significantly larger than the boron component ejected by the SN II. Such a scenario would still, qualitatively, accomodate the observed anticorrelation of boron and oxygen in the Orion association. A study of beryllium (together with boron) in Orion stellar members with undepleted Li would provide strong constraints on the ν-process contribution to boron production.

I would like to thank the organizers of the IAU Symposium 198 for the travel grant to attend the meeting.

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