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Beryllium and boron in metal-poor stars

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Abstract. Knowledge of lithium, beryllium, and boron abundances in stars of the Galactic halo and disk plays a major role in our understanding of Big Bang nucleosynthesis, cosmic-ray physics, and stellar interiors. ^{9}Be and ^{10}B are believed to originate entirely from spallation reactions in the interstellar medium (ISM) between α-particles and protons and heavy nuclei like carbon, nitrogen, and oxygen (CNO), whereas ^{11}B may have an extra production channel via neutrino-spallation. Beryllium and boron are both observationally challenging, with their main resonant doublets falling respectively at 313 nm and at 250 nm. The advent of 8-10m class telescopes equipped with highly sensitive (in the near-UV/blue) spectrographs has opened up a new era of Be abundance studies. Here, I will review and discuss the most interesting results of recent observational campaigns in terms of formation and evolution of these two light elements.

Keywords. Galaxy: halo, abundances, evolution – stars: Population II, abundances, atmospheres, interiors

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1. Introduction

After hydrogen (H), helium (He), and lithium (Li), beryllium (Be) and boron (B) complete the group of the so-called light elements, all covered in great detail during this Symposium. All these elements share a common feature concerning their origin: they can not be produced in stellar interiors, where in fact most of them get destroyed. Deuterium, He, and Li have a strong cosmological component responsible for their formation, hence they offer important insights on the primordial abundances of their isotopes in the early Universe. On the contrary, Be and B are formed via spallation reactions between CNO atoms and α+p particles.

For a long time, it was believed that these reactions take mostly place in the interstellar medium, where alphas and protons (carried by cosmic rays – CR – traveling across the Galaxy) would end up hitting target nuclei like CNO, spallating into atoms of beryllium and boron (cf Reeves *et al.* 1970, Meneguzzi *et al.* 1971). One of the earliest observational findings supporting this scenario was the beryllium-to-hydrogen ratios observed in young stars ($\sim 10^{-11}$) in the 70s (e.g. Boesgaard 1976, Boesgaard *et al.* 1977) which was found to match rather closely the theoretical prediction of Be formation when integrated along the entire history of the Galaxy. In other words, the abundances derived in a few Population I (Pop I) objects were approximately matching the product of the formation rate of Be† $\times$ the abundance ratio of these targets with respect to hydrogen ($\sim 10^{-3}$) in space $\times$ the age of the Galaxy.

Indeed, the observed CR flux, integrated over 10^{10} years of Galactic evolution, seems sufficient to produce the solar abundances of B, Be, and ^{6}Li, despite, e.g., the failure in reproducing the observed solar B isotopic ratio. CR spallation in the general ISM has

† described by Reeves *et al.* (1970) to be the product between the flux of high-energy protons (~ 16 cm^{-2} sec) $\times$ the cross sections for ^{9}Be formation by proton collision on the most abundant targets, ^{16}O and ^{12}C (~ 5 mb)

therefore been mostly accepted for 25 years as the main origin of these light elements. However, as I will show in the next section, the first observational studies carried out at 4m ground-based telescopes and with the Hubble Space Telescope (HST) showed some surprising results that triggered a revision of the above described scenario.

Last but not least, the light elements Li, Be, and B, when measured in the same object(s) can be successfully used as diagnostics in the study of stellar mixing. Because they burn at relatively low, but slightly different (and increasing) temperatures, they are expected to show different degrees of depletion and/or dilution at different times. Lithium, which is destroyed at the lowest temperature of all three elements ($T_B \simeq 2.5\times10^6$ K) should deplete first, followed by Be ($T_B \simeq 3.5 \times10^6$ K) and B ($T_B \simeq 5\times10^6$ K). Unfortunately, there are large discrepancies in the size of the data samples that have been looked at, which clearly correlate with the observational difficulties in detecting a given transition: lithium, with its main resonant doublet falling in the optical, at 670 nm, is the most studied of the three, followed by beryllium (main resonant doublet very close to the atmospheric cut-off, at 313 nm), and boron (resonant doublet at 250 nm and single feature at 209 nm), which requires a telescope in space.

2. A bit of (observational) history

The first attempts to detect beryllium in Population II (Pop II) stars were made in the mid-late 80s (e.g. Molaro *et al.* 1984, Rebolo *et al.* 1988) with, respectively, the International Ultraviolet Explorer (IUE) and the 2.5m Isaac Newton Telescope. Unfortunately, these studies succeeded only in measuring beryllium in the Pop I stars of their targeted samples, but failed to detect it in the most metal-poor, Pop II objects, for which only upper limits were derived.

These attempts were then followed by (somewhat larger) observational campaigns in the early 90s (Ryan *et al.* 1992, Gilmore *et al.* 1992, Boesgaard & King 1993), which used 4m class telescopes, equipped with spectrographs with a higher sensitivity in the blue. Ryan *et al.* (1992) and Boesgaard & King (1993) found a quadratic dependence of Be abundances from metallicity and oxygen, thus confirming the CR spallation scenario as the main production channel for beryllium. On the contrary, the study by Gilmore *et al.* (1992) uncovered a different trend, a linear slope between Be and Fe,O which confirmed some of the very early results obtained with HST for stellar boron abundances (see below).

For boron, after the pioneering work by Boesgaard & Heacox (1973, 1978) who looked at early-type stars (similar to what was done in the very early works for beryllium), one has to wait until the launch of the Hubble Space Telescope for the first measurements of boron abundances in metal-poor stars (Duncan *et al.* 1992). The sample consisted of 3 metal-poor stars, which these investigators surprisingly found to follow a linear relation. According to the authors, this implied that the evolution of boron cannot depend on metallicity, hence the spallation reactions cannot possibly take place in the interstellar medium, whose metal content keeps increasing as the Galaxy evolves. Instead, they proposed a "reverse" spallation reaction scenario as the one dominating the early phases of the Galaxy, in which it is the CNO (especially oxygen) in the CRs (under the assumption that they remain constant) that hit protons and α-particles in the ISM. For the record, it is important to note that this reverse mechanism had already been mentioned by Reeves and collaborators, but thought to be negligible, hence it had basically been ignored.

Needless to say, both findings (Gilmore *et al.* 1992 for beryllium and Duncan *et al.* 1992 for boron) have had a very strong impact on this field of research. In the following sections, I will mostly focus on beryllium, since it is the element for which most progress

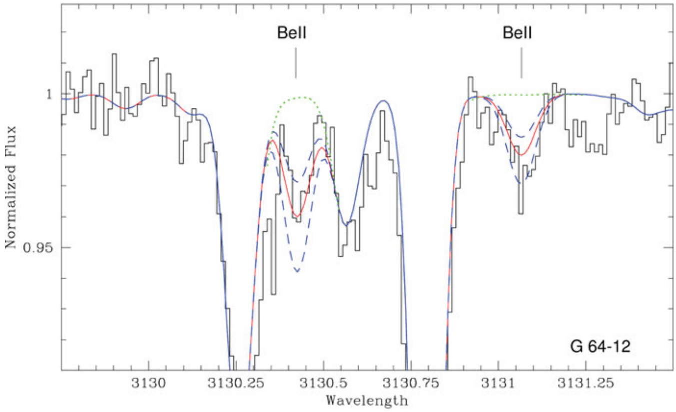

Figure 1. Best-fit spectrum synthesis (continuous curve) of the Be II doublet in one of the most metal-poor stars ever studied for beryllium, G 064-012 ([Fe/H]$\simeq -3.2$, histogram). Overplotted are also two spectrum syntheses computed with +/- 0.15 dex with respect to the best-fit Be value (dashed curves) and one synthesis computed without any beryllium (dotted curve). (From Primas *et al.* 200b).

has been made in the last decade. I will come back to boron towards the end of this review.

3. The impact of 8-10m class telescopes and efficient spectrographs

The advent of high-resolution spectrographs very sensitive in the near-UV on 8-10m class telescopes marked a new observational era, especially for studies of beryllium abundances in metal-poor stars. The observational progress achieved at the Be wavelengths (313 nm) over a bit more than one decade is remarkable: one went from having to integrate 6,000 s on a $V_{mag} = 8$ star in order to obtain a spectrum with a resolving power of R$\simeq$11,000 and S/N = 37 (1988, Isaac Newton Telescope) to 3,000 s, R $\simeq$ 25,000 and S/N = 55 (1993, Canada-France-Hawaii Telescope) and to 1,800 s, R $\simeq$ 45,000 and S/N = 120 (2000, Very Large Telescope).

Boesgaard *et al.* (1999) presented the first systematic analysis of Be in a sample of 22 halo stars plus 5 disk stars observed with HIRES at Keck (Vogt *et al.* 1994) pushing the detection of Be in stars with metallicities approaching one thousandth less than solar. The major result from this study was a much more robust confirmation of the linear dependence between Be and Fe already found by Gilmore *et al.* (1992) based only on 6 objects. Furthermore, Boesgaard *et al.* (1999) confirmed a similar correlation also between Be and O.

Primas *et al.* (2000a,b) explored the capabilities of the high-resolution echelle spectrograph UVES (Dekker *et al.* 2000) at the VLT and recorded the first detection of Be in two stars with metallicities below one thousandth solar ([Fe/H] = −3.15, cf Figure 1).

Finally, Pasquini *et al.* (2004, 2007) detected for the first time with UVES at the VLT beryllium in turn-off stars of metal-poor globular clusters, like NGC 6397 and NGC 6752.

In more recent years, several Be studies have been conducted, which looked at different aspects of the formation of this light isotope, both in more metal-rich/solar-metallicity stars and metal-poor objects. Very recently, an upper limit has been derived on the Be content of a very metal-poor ([Fe/H] = −3.7), carbon-rich subgiant star (Ito *et al.* 2009). The three most recent analyses (Smiljanic *et al.* 2009, Rich & Boesgaard 2009, Tan *et al.* 2009) that have looked at stellar samples covering a wide range of metallicities, all

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addressed issues like the formation and evolution of Be along the Galactic history. All three studies have presented the trends of Be *vs* iron and *vs* oxygen (or versus an average ratio of the alpha elements) and similar results are found: the correlation coefficient between Be and Fe ranges between 0.97 and 1.2, and they all seem to find a steeper relation when Be is compared to O, which seems to imply a faster increase of Be in the Galaxy with respect to oxygen.

Based on our current understanding of the formation of beryllium, it is indeed more important to relate Be to O: oxygen atoms are the main target nuclei of spallation reactions, hence such a relation should be more straightforward to interpret. In practice, accurate measurements of stellar oxygen abundances remain hard to achieve, due to a variety of oxygen abundance indicators that need to be used in different types of stars and that suffer from different systematic uncertainties that have not always been carefully evaluated. For instance, UV OH lines, basically the only ones available in dwarf stars at very low metallicities, give a very different trend of [O/Fe] *vs* [Fe/H], which seems to be due to the usage of unsuitable model atmospheres and model atoms (ignoring NLTE and 3D effects). The oxygen triplet, on the other hand, possibly detectable in the most metal-poor stars for which a Be detection has been achieved, is highly sensitive to the assumed stellar effective temperature, which in this case becomes the largest source of error on the final determination of the oxygen abundance. The O forbidden line (at 630 nm), the cleanest of all indicators, becomes quickly undetectable in dwarfs as one reaches metallicities around one hundredth less than solar.

3.1. *Main recent findings and remaining open issues*

All most recent studies of beryllium abundances in Galactic stars seem to agree on a few main findings: *a)* Be closely follows Fe; *b)* the slope between Be and O seems to be slightly steeper than with respect to Fe; *c)* the dispersion around the trends is very small in the most metal-poor stars but it increases at higher metallicities. The metallicity range around the so-called halo-disk transition seems to be characterized by significant scatter.

As already pointed out above, the uncertainty affecting our current determination of stellar oxygen abundances remains one of the main issues in order to properly interpret the Be *vs* O trend, if the correlation is truly different from a linear one. This uncertainty affects also another important test that has been attempted in recent years: the utilization of Be as a cosmic clock. The idea is based on the fact that if Be is produced via a primary process, this process would then become a global one instead of a local one, like, e.g., the production of heavier nuclei in supernovae explosions. Beryllium abundances are then expected to show smaller dispersion compared to elements like O and/or Fe, making Be a possibly more reliable cosmo-chronometer than the commonly used ratios like [Fe/H] and/or [O/H]. Pasquini *et al.* (2005) were the first ones to test this idea, by investigating the evolution of the star formation rate in the early Galaxy using Be and O abundances. In order to do so, they compared O *vs* Be observed trends for stars belonging to two separate kinematical classes, the *accretion* and the *dissipative* components (roughly corresponding to the halo and thick disk populations), as identified by Gratton *et al.* (2003). They found out that these two samples seem to show different evolutions. Unfortunately, the sample size was rather limited and the sample splitting was not as clean as wished for such a comparison (for instance, they ended up with representatives of the *dissipative* component belonging to the halo, but with kinematical characteristics of the thick disk). This prevented these authors from drawing firm conclusions on the usefulness of Be as a cosmo-chronometer. Subsequent attempts also failed to fully prove the concept. Tan *et al.* (2009), following Pasquini *et al.* (2005) did not succeed in obtaining a clearer separation between the *dissipative* and the *accretion* components (cf their

Fig. 9). Smiljanic *et al.* (2009) presented [O/Fe] and [α/Fe] ratios as a function of Be for a large data sample, and tried to similarly distinguish between halo and thick disk stars. Indeed, they found a possible separation, but also here abundances were too scattered (especially the alpha abundances, since they were taken from the literature) to be able to draw firm conclusions.

4. Shedding new light on Be formation and evolution

Our observational campaign, aimed at investigating the formation and evolution of Be across the Galactic history, has been carried out at the VLT with the UVES spectrograph. The sample includes more than 50 stars, spanning a wide range in metallicities (from −3.3 to −0.5). The objects are mostly dwarf or subgiant stars, belonging to both the halo and disk populations. All observed spectra have a resolving power of at least 40,000 and S/N ratios are of the order of 100 or higher at the Be II transitions. At redder wavelengths (since we took advantage of the dichroic mode of UVES) both S/N ratios and resolving power are higher, respectively, above 2–300 and R $\simeq$ 55,000.

Stellar parameters of our sample were determined from Strömgren photometry (effective temperatures, also cross-checked both with V-K colour indices and with H-α fitting), from Hipparcos parallaxes (gravities), and from ionized Fe lines (metallicities). We used 1-D OSMARCS model atmospheres (Gustafsson *et al.* 2008) and we corrected our derived Be abundances for NLTE corrections (García Pérez, *priv. comm.*). We also derived lithium, oxygen, and other abundances, like Mg.

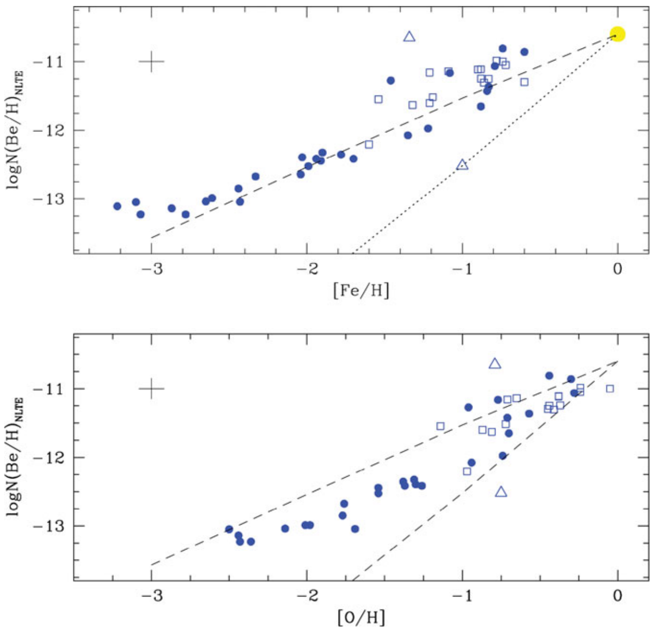

Figure 2. Our derived Be abundances *vs* metallicity (*top*) and [O/H] (*bottom*). Typical errorbars are shown in the upper left corner of each plot. Dashed and dotted line represent respectively a linear and quadratic relation. Symbols: filled circles represent halo stars, open squares disk objects. The two open triangles represent two particular disk objects, one depleted in its Be content and one instead with a very high content of Be (as well as many other elemental abundances).

Figure 2 presents our Be results at large. The Be *vs* Fe trend follows a linear slope, with very little scatter below a metallicity of [Fe/H] = −1.5, and a significantly increased dispersion around the halo-disk transition. If we display our Be abundances *vs* oxygen (which is a mix of abundances derived from the forbidden line at 630 nm and the triplet at 770 nm), the slope does not seem to change much but the trend may be more difficult to interpret, especially at higher metallicities (see caption for more details). Furthermore, we have added a few more Be detections below [Fe/H] = −3.0, which seem to fall a bit above the unitary slope trend identified by the rest of the sample. This feature, together with the need to correctly understand the larger dispersion at higher metallicities, are the main highlights of this study, thus they deserve to be discussed in more detail.

4.1. *The very metal-poor tail of the Be evolution*

The 4-5 most metal-poor stars of our sample seem to have slightly higher Be abundances with respect to the trend of unitary slope, i.e. the metal-poor tail of the Be *vs* Fe evolutionary trend seems to show some flattening (cf Fig. 2). What does this mean ? Certainly, it does not carry any significance for a possible primordial production of beryllium; rather, some of the theoretical scenarios proposed in the past for the production of Be atoms in the early Galaxy predicted the appearance of such a plateau, when the masses of the supernova progenitors were in the range of 40-60 $M_{\odot}$ (cf Vangioni-Flam *et al.* 1998).

However, before looking for exotic explanations for such feature, it is important to note that one other study that has succeeded in detecting Be in stars with a metallicity less than one thousandth solar does not agree with our finding. At least, not at first sight. Rich & Boesgaard (2009, but also Boesgaard, this volume), in fact, claim that their most metal-poor stars continue to follow the linear trend of the more metal-rich objects (cf their, e.g., Fig. 4). A closer look at both samples shows that most stars are actually in common, but analyzed with very different stellar parameters. If we correct their Be abundances on our stellar parameters scale, we obtain a satisfactory overlap, which demonstrates that the differences between these two sets of results rely only on different input parameters, not on the observed spectra and not on the different model atmospheres and/or analytical tools used during the analysis (reassuring!). Figure 3 shows the results of this test.

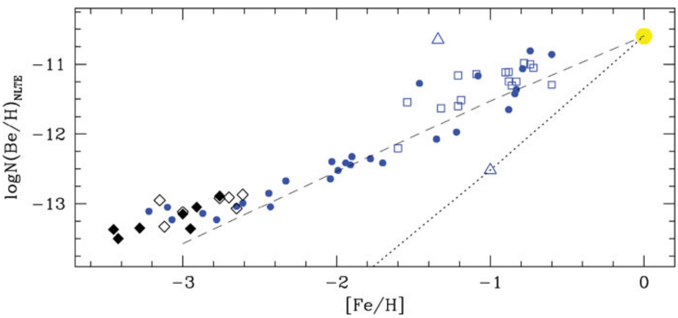

Figure 3. Same as the top panel of Fig. 2, this time with overplotted the most metal-poor data points from Rich & Boesgaard (2009): filled diamonds as in original paper, open diamonds corrected on our stellar parameters scale (see text for more details).

4.2. *Be at the halo-disk transition: real scatter ?*

The larger dispersion detected at higher metallicities is present in both plots of Be trends, *vs* Fe and O. The second plot is certainly more worrisome than the first one, since Be and O are expected to be well correlated. Figure 2 shows that all in a sudden, when a metallicity of [Fe/H] = −1.5 or [O/H] = −1.2 is reached, the tight correlation between,

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e.g., Be and O becomes looser: there are stars with the same content of oxygen, but with highly different contents of Be.

Since these metallicities map what we commonly call the halo-disk transition, the first attempt to shed some light into this region was to separate the objects kinematically, by associating them to the halo or to the disk component (cf caption of Fig. 2 for symbols coding). Unfortunately, not much was gained. This confirms earlier attempts made by Smiljanic *et al.* (2009) and Tan *et al.* (2009) who tried to associate stars to the *dissipative* vs *accretion* components and failed in finding a clear and convincing separation in their Be evolutionary trends.

Nissen & Schuster (2009) have determined very accurate abundances of several alpha elements in a large sample of halo-disk transition stars. The entire analysis has been carried out strictly differentially and this has allowed these authors to achieve very small error-bars on each data point and notably reduce spurious sources of scatter in the data. This work is an extension of Nissen & Schuster (1997), at a much higher accuracy. Their main finding (cf their Figs. 1 and 2) is a clear separation between halo-low and halo-high stars (where low/high refers to a low/high content of α-elements respectively) and with the halo-high overlapping the group of thick disk stars.

If we now use the accurate [α/Fe] ratios that Nissen & Schuster (2009) have derived for those stars for which we also have Be, we recover as well a very clear separation (in, e.g., a plot of [α/Fe] *vs* Be) between halo-low and halo-high, with the latter overlapping the thick disk stars. This splitting now helps us also to interpret the dispersion revealed by Fig. 2. The formerly very confusing halo-disk transition region now appears to be populated by objects that belong to distinct groups: the halo-low stars seem to continue the trend identified by the more metal-poor stars, possibly making the slope a bit steeper, whereas the halo-high stars seem to follow a shallower relation, and at similar oxygen contents have a much higher content of Be. The thick-disk partly overlaps with the halo-high but, with the exclusion of one object, seems to follow a slope more similar to the halo-lows.

Let's make one step further. If we now look at the plot of Be *vs* [α/H] (cf Fig. 4), the picture becomes even clearer and confirms what we just said. Halo-lows are a continuation of the more metal-poor stars trend, the thick-disk seems indeed to fall more closely the halo-low than the halo-high, though some overlap is present, especially at the highest metallicities; the halo-high show a flatter trend. As it can be seen in Fig. 4, there are some data points without any α-abundance-group identification (open circles), which are very important in order to confirm or not our preliminary findings. Still, this is an important step forward, in the interpretation of the dispersion now found by several recent studies.

5. Boron: fewer data and slower progress

For boron, the situation has not changed much during the last 10 years. Stellar boron abundances are inferred from the analysis of the B I resonant doublet at 250 nm, hence one needs to go into space. After a burst of studies that followed the launch of the Hubble Space Telescope and that lasted approximately a decade, very few abundance studies in metal-poor halo stars, if any, have been carried out during the last decade. More work has been carried out in stars at higher metallicities (cf Cunha, this volume) and in massive stars (cf Kaufer, this volume).

Therefore, when reviewing the formation and evolution of boron in the early Galaxy, one needs to go back to the second half of the 90s, basically to the works of Duncan *et al.* (1997), García López *et al.* (1998), and Primas *et al.* (1998, 1999). The B *vs*

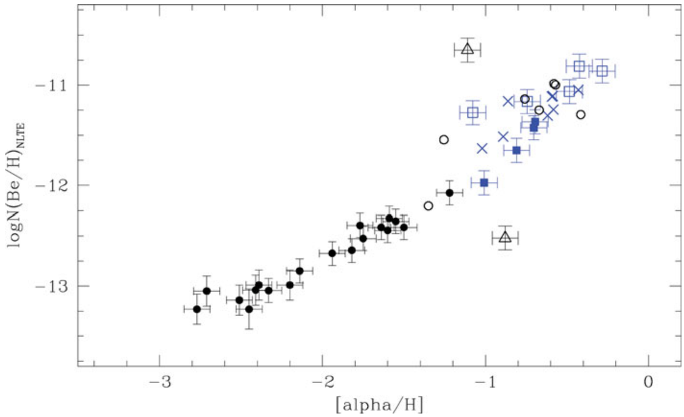

Figure 4. Be *vs* [α/H] trend, showing a much clearer separation (wrt, e.g., Fig. 2) among the three distinct α-element abundance groups, halo-low (filled squares), halo-high (open squares), and thick disk stars (crosses). Open circles represent disk stars which are not in the sample of Nissen & Schuster (2009); filled circles and open triangles as in Figs. 2 and 3.

Fe,O relations found by these authors confirmed the earlier results obtained by Duncan *et al.* (1992) from only three objects, i.e. a primary origin also for this spallative element.

One very recent progress possibly worth mentioning here is the recent re-calculation of the B I lines formation under NLTE conditions carried out by Tan et al (*priv. comm.*). These NLTE corrections seem to differ significantly from those applied in earlier studies (e.g. Kiselman 1994) and to reconcile the B trends (vs Fe and vs O) with the trends recently found also for Be.

6. Constraining stellar mixing with Li, Be, and B

Simultaneous knowledge of Li, Be, and B abundances in the same target(s) is an important diagnostic to investigate mixing mechanisms at work in the outermost layers of stellar photospheres. Because this elemental trio burns at different and slightly increasing temperatures, one expects that Li, which is saved in the outermost layers, will burn first, before Be starts to be affected by any depletion mechanism.

It is important to note that this type of investigations has so far assumed that a Spite-plateau lithium abundance (i.e. the canonical value found in metal-poor Galactic halo stars of A(Li) $\simeq$ 2.2) represents an un-depleted abundance of the lithium stellar content of that given object. But after WMAP (Dunkley *et al.* 2009 and references therein), we now have a very precise prediction of the primordial lithium abundance in the Standard Big Bang framework (A(Li)$= 2.72 \pm 0.06$, Cyburt *et al.* 2008), which instead hints at a rather large depletion of the lithium content that we measure today in the oldest stars of our Galaxy. This of course does not affect the basic depletion/dilution trend of the three light isotopes, but it may have significant implications on how we interpret the comparison of Li, Be, and B abundances in the same objects, especially as far as the amounts of depletion/dilution are concerned.

What still works well is of course a differential analysis among stars that share similar characteristics in, e.g., their stellar parameters. We know several pairs of stars that have an identical lithium content, that are indistinguishable as far as effective temperature, gravity and metallicity are concerned, but have very different Be and B abundances. Some of these have the same Be content, but differ in their B signatures (cf Fig. 5, dotted and thin lines – does this imply that there could be another production mechanism for

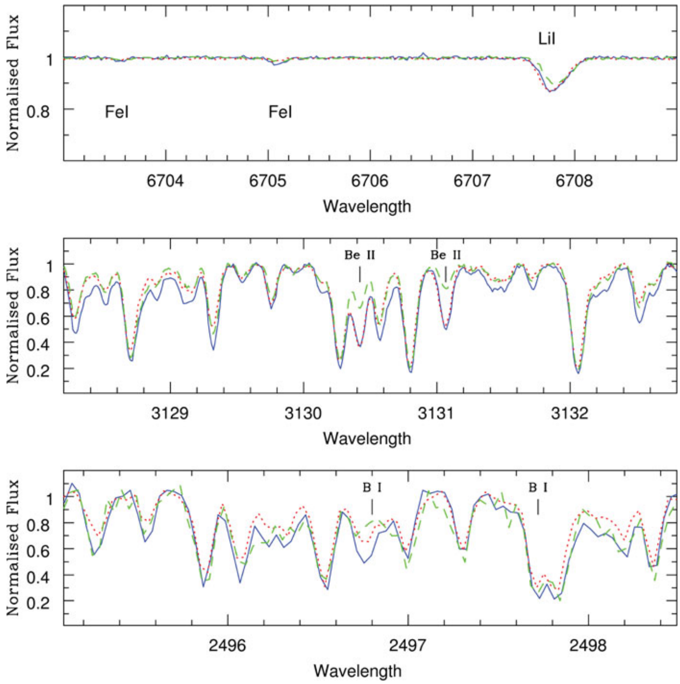

Figure 5. Observed spectra of three different stars overplotted respectively in the Li, Be, and B spectral regions (from *top* to *bottom*). The stars have very similar stellar parameters and Li contents, but show some differences in Be and/or B.

boron, like the often proposed ν-spallation?), others instead have different Be and B contents, for which it then becomes important to see how the degree of depletion of each element compares to the other (cf Fig. 5, dashed and thin line).

An example is given in Fig. 5, where observed spectra of three different objects are shown and overplotted. These three objects have very similar stellar parameters and Li contents, but one of them has much less beryllium and boron (dashed spectrum), and the other two share a similar content of beryllium but have a puzzling different B content!

7. Concluding remarks and acknowledgments

Remarkable observational progress has been made in the last decade, especially as far as Be studies are concerned. In this review, I have shown that the combination of higher quality data and highly accurate measurements of abundances (e.g., α-elements) is now starting to shed new light on the interpretation of some specific features of the Be evolutionary trend (e.g. the dispersion at the halo-disk transition). Progress in studies concerning B abundances has lagged behind, mostly due to the unavailability during the last 4-5 years of the Space Telescope Imaging Spectrograph on board of the Hubble Space Telescope (due to a mechanical/technical failure). But after the successful NASA Service Mission #4, STIS is again operational, therefore new abundance studies of boron in metal-poor stars will hopefully come soon.

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