Session III

Abundances of Li, Be and B: Observations

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The light elements in the light of 3D and non-LTE effects

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Abstract. In this review we discuss possible systematic errors inherent in classical 1D LTE abundance analyses of late-type stars for the light elements (here: H, He, Li, Be and B). The advent of realistic 3D hydrodynamical model atmospheres and the availability of non-LTE line formation codes place the stellar analyses on a much firmer footing and indeed drastically modify the astrophysical interpretations in many cases, especially at low metallicities. For the $T_{\rm eff}$-sensitive hydrogen lines both stellar granulation and non-LTE are likely important but the combination of the two has not yet been fully explored. A fortuitous near-cancellation of significant but opposite 3D and non-LTE effects leaves the derived ^{7}Li abundances largely unaffected but new atomic collisional data should be taken into account. We also discuss the impact on 3D non-LTE line formation on the estimated lithium isotopic abundances in halo stars in light of recent claims that convective line asymmetries can mimic the presence of ^{6}Li. While Be only have relatively minor non-LTE abundance corrections, B is sensitive even if the latest calculations imply smaller non-LTE effects than previously thought.

Keywords. convection, line: formation, radiative transfer, Sun: abundances, Sun: atmosphere, stars: abundances, stars: atmospheres, stars: Population II, Galaxy: abundances

1. Stellar model atmospheres and spectral line formation

Stellar chemical compositions are not observed: to decipher the spectral fingerprints in terms of abundances requires realistic models for the stellar atmospheres and the line formation processes. Traditionally abundance analyses of late-type stars have been carried out relying on 1D, time-independent, hydrostatic model atmospheres, which treat convection with the rudimentary mixing length theory. All of these are dubious approximations as even a casual glance at the solar atmosphere will immediately reveal. The solar atmosphere, as for other late-type stars, is dominated by granulation, which is the observational manifestation of convection: an evolving pattern of broad, warm upflows in the midst of narrow cool downdrafts. Because of the great temperature sensitivity of the opacity, the temperature drops precipitously as the ascending gas nears the optical surface before it overturns and is accelerated downwards. The temperature contrast is therefore very pronounced in the photospheric layers, amounting to > 1000 K at the optical surface for the Sun (even when averaged over surfaces of equal optical depths these rms-differences amount to ≈ 400 K). In addition to ignoring such atmospheric inhomogeneities, 1D model atmospheres can not be expected to have the correct mean temperature stratification because of the simplified convection treatment and the neglect of convective overshoot. Even small temperature differences can propagate to very large changes in the emergent stellar spectrum because of the non-linearities in the radiative transfer and the extreme opacity variations.

Over the past decade or so, 3D, time-dependent, hydrodynamical model atmospheres for a range of stellar parameters have started to be developed and applied to stellar abundance work (e.g. Asplund 2005, and references therein). Such 3D models solve the standard hydrodynamical conservation equations coupled with a simultaneous solution of the 3D radiative transfer equation and therefore self-consistently predict the convective and radiative energy transport (see e.g. Nordlund *et al.* 2009, for further details). To make the 3D modelling computationally tractable, the radiative transfer is not solved for the many thousands of wavelength points as routinely done in 1D model atmosphere codes. Instead the frequencies are sorted in opacity and more recently also in wavelength space for $\approx 4-20$ bins for which the radiative transfer is solved. The resulting total radiative heating/cooling as a function of atmospheric depth is surprisingly well reproduced. The 3D models are based on similarly realistic microphysics (equation-of-state and continuous/line opacities) as employed in standard 1D model atmospheres. Currently there are mainly four different codes being used to develop 3D models – STAGGER (e.g. Nordlund *et al.* 2009), CO5BOLD (e.g. Ludwig *et al.* 2009b), MURAM (e.g. Vögler *et al.* 2005) and ANTARES (e.g. Muthsam *et al.* 2009) – although essentially all abundance related work to date has been performed within the first two collaborations.

Being more sophisticated in the modelling does not automatically translate to being more realistic. Over the past few years, substantial effort has therefore been dedicated to verify the suitability of the 3D models for quantitive stellar spectroscopy using an arsenal of observational diagnostics. Some of the striking successes are that the 3D models accurately predict the detailed solar granulation properties (e.g. Nordlund *et al.* 2009) as well as spectral line profiles, including their asymmetries and shifts (e.g. Asplund *et al.* 2000), which strongly suggests that the 3D modelling captures the essence of the real atmospheric structure and macroscopic gas motions. Another crucial test is the continuum center-to-limb variation, which is an excellent probe of the mean temperature stratification in the solar atmosphere. As shown in Fig. 1, the latest generation of 3D models computed with the STAGGER code reproduces the observations extremely well (Pereira *et al.* 2010); the CO5BOLD solar model does a similarly good job (H.-G. Ludwig, private communication). This is a remarkable achievement. The 3D solar model not only outperforms all tested theoretical 1D model atmospheres like the Kurucz, MARCS and PHOENIX flavours in this respect, it also does noticeably better than the Holweger & Müller (1974) semi-empirical model, which was constructed largely to fulfill this observational constraint. The 3D solar model also performs very well when confronted with other tests, such as the spectral energy distribution, H lines (Pereira *et al.* 2010) and spatially resolved line profiles (Pereira *et al.* 2009a,b). In all aspects the most recent 3D solar models are clearly highly realistic and can therefore safely be trusted for abundance analysis purposes (Asplund *et al.* 2009).

The success in the solar case gives some credence to the 3D modelling being similarly realistic also for other stars for which far fewer indisputable observational tests are available. 3D models now exist for a sizable portion of the HR-diagram covering essentially spectral types A, F, G, K, M and even later (e.g. Collet *et al.* 2007; Ludwig *et al.* 2009b). Both dwarfs, subgiants, giants and even some supergiants have been simulated and for a wide range of metallicities. Qualitatively the granulation behaves similarly to the Sun for most of these stars but typically the convection becomes more vigorous towards higher $T_{\rm eff}$ and lower $\log g$. Perhaps the most marked difference compared with 1D models are apparent at low [Fe/H], where 3D models have much cooler temperatures in the optically thin regime (Asplund *et al.* 1999). This is a natural consequence of the dominance of adiabatic heating over radiative heating in absence of a heavy line-blanketing at low metallicities. The low temperatures are bound to affect especially minority species, low

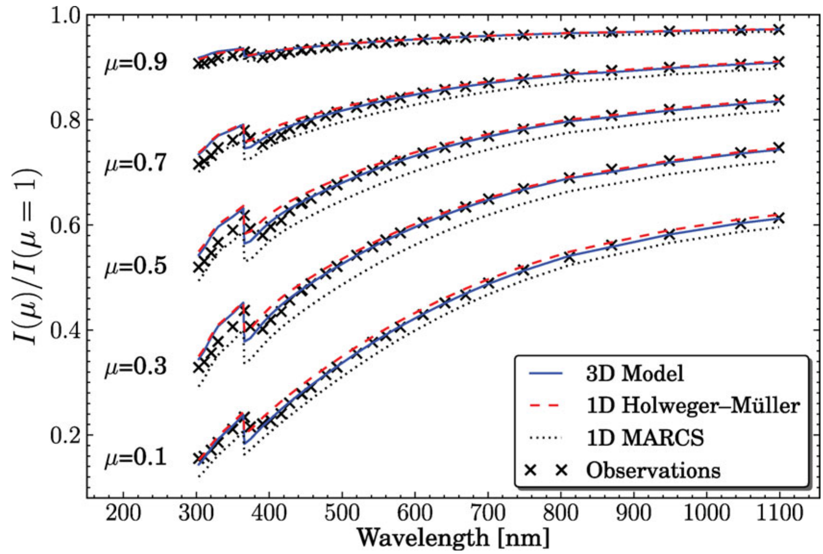

Figure 1. Comparison of the observed continuum center-to-limb variation as a function of wavelength (Neckel & Labs 1994) against the predictions for different solar model atmospheres. The 3D solar model employed by Asplund *et al.* (2009) outperforms the 1D theoretical MARCS model and even the 1D semi-empirical Holweger & Müller (1974) model atmosphere.

excitation lines and molecules, with 3D LTE abundance corrections often amounting to $> +0.5$ dex (e.g. Asplund 2005). One should be aware though that the steep temperature gradients may significantly enhance the non-LTE effects compared to the 1D case.

With a stellar model atmosphere it is possible to compute the emergent spectrum, which normally for late-type stars is done within the LTE approximation and in 1D. It should not come as a surprise that this approach often leads to severe systematic errors. In recent years, efforts towards rectifying these shortcomings have mainly focused on 1D non-LTE investigations and 3D LTE calculations, but the combination of 3D and non-LTE is still largely unexplored (e.g. Asplund 2005, and references therein). When solving the non-LTE problem one must solve the rate equations for all relevant levels involving both radiative and collisional transitions coupled with a simultaneous solution of the radiative transfer equation for all necessary frequencies. Needless to say, it rapidly becomes far more cumbersome than in LTE with a great deal of additional atomic data that must be considered. While the radiative processes like transition probabilities and photo-ionization cross-sections are now in reasonably good shape – especially for the non-complicated cases like the light elements – the main uncertainty in non-LTE calculations often stems from the poorly known collisional excitation and ionization due to electrons and H as well as charge transfer reactions. Especially the inelastic H collisions are a major problem in stellar abundance analyses. Mostly simple but likely erroneous classical recipes like the Drawin (1968) formula are applied, often with an additional ad-hoc scaling factor. For a few elements, Li being a notable case in point, detailed quantum mechanical or laboratory measurements exist (e.g. Belyaev & Barklem 2003), which reveal that the Drawin (1968) formula typically overestimates the real cross-sections by several orders of magnitude. An alternative approach is to attempt to calibrate the unknown collisional rates using various observations, such as obtaining consistent results from different lines or using center-to-limb variations. Not surprisingly, such empirical procedures suggest a range of scaling factors, from $\leqslant 0.1$ for Mn (Bergemann & Gehren 2008), to ≈ 1 for O

(Pereira *et al.* 2009a) or even > 1 for Fe (Korn *et al.* 2003). Whether these are realistic values, or merely artificial results due to too simplified modelling (e.g. 1D) remains to be seen. It is also worth remembering that a common scaling factor for all transitions within the same species, let alone between different elements, is highly unlikely. In spite of the remaining uncertainties introduced by our still poor handle on all atomic data, the alternative of relying on the LTE approximation will most often lead to even more severe systematic errors.

2. The light elements

2.1. *Hydrogen*

As the most abundant element and the main provider of continuous opacity, it is not possible to derive the stellar H abundance spectroscopically. The H lines are still of great use in stellar physics as a probe of the atmospheric conditions. In late-type stars the wings of the Balmer lines reflect the effective temperature and the temperature gradient near the continuum forming layers with only a relatively small gravity dependence. The great temperature sensitivity arises from the high excitation potential of the lower level ($\chi_{\rm exc} = 10.2\,$eV) of the Balmer lines. Fortunately, both the Stark broadening and self-broadening are now well established (e.g. Barklem *et al.* 2000; Allard *et al.* 2008); the new broadening results in significantly lower $T_{\rm eff}$, especially at low [Fe/H].

The H lines are however sensitive to the convection treatment, which in 1D normally is estimated by the mixing length theory (MLT) and its inherent four free parameters. Before comparing the best-fitting $\alpha_{\rm MLT}$ and $T_{\rm eff}$ between different studies it is therefore important to bear in mind the various flavours of MLT existing in different 1D model atmospheres. Given the rudimentary nature of MLT to describe the correct convective energy transport and overshoot near/in the optical surface, 1D-based $T_{\rm eff}$-scales from H lines will always be uncertain in an absolute sense even if highly accurate relative values can be obtained (e.g. Asplund *et al.* 2006). As explained above, 3D hydrodynamical models do provide an attractive alternative through their self-consistent computation of the convection without the need to invoke free parameters. Ludwig *et al.* (2009a) have investigated the 3D LTE formation of Hα, Hβ and $H\gamma$ lines for six different 3D models, including the Sun and metal-poor dwarfs/subgiants and compared with 1D models computed with identical microphysics but with different MLT implementations; see also Sbordone *et al.* (2010) for further discussions. Ludwig *et al.* (2009a) found a very complex dependence on the 3D corrections to the 1D-based estimates of $T_{\rm eff}$ with differences amounting to $\pm 300\,$K depending on the line in consideration and the $T_{\rm eff}$, [Fe/H] and $\alpha_{\rm MLT}$ of the 1D model. An extra complication arises from the different line shapes in 3D and 1D, which can not be directly translated to a $T_{\rm eff}$ difference without specifying exactly which wavelength regions have been used for the comparison. The prospect for using pre-tabulated 3D corrections to 1D-based $T_{\rm eff}$ estimates is therefore not encouraging. It would be advantageous to directly compare observations with 3D predictions, which should be possible in the near future with the advent of grids of 3D models.

Until recently it has always been argued that the wings of the H Balmer wings are formed in LTE. Barklem (2007) has investigated whether this is indeed correct and found that it is not necessarily so. In particular he found that electron collisions are not sufficient to establish LTE. In terms of $T_{\rm eff}$, the non-LTE calculations would imply $\geqslant 100\,$K higher values than in LTE. This however depends crucially on the still uncertain inelastic H collisions – improved atomic physics calculations are clearly needed to resolve this issue. It would also be necessary to perform 3D non-LTE H line computations, especially at low metallicity. Such calculations have recently been performed in the solar case with encouraging results (Pereira *et al.* 2010).

2.2. *Helium*

While in hot stars the very highly excited transitions of He I enable a determination of the He abundance (see Kaufer, these proceedings), in late-type stars the corresponding atomic levels are not sufficiently populated at typical photospheric temperatures. Instead the He I lines (e.g. 1083.0 nm) have a chromospheric origin and can neither probe the He abundance nor the photospheric temperature structure.

2.3. *Lithium*

Stellar Li abundance are usually determined only from the resonance line at 670.7 nm but in exceptional cases also from the weaker subordinate line at 610.4 nm. Contrary to most elements, the simplicity of the Li atom has enabled quantum mechanical calculations of all atomic data necessary for non-LTE investigations, especially of cross-sections for collisional excitation and charge transfer with neutral hydrogen (Barklem *et al.* 2003). The widely used study of Carlsson *et al.* (1994) mapped out the non-LTE effects in late-type stars and their detailed variation with metallicity, effective temperature, surface gravity, and lithium line strength. Recently, Lind *et al.* (2009a) revisited the 1D non-LTE line formation with improved collisional data and treatment of line-blocking (see Fig. 2). The investigations have shown that two competing effects govern the population levels of Li. Over-ionization from the first excited level of Li I is prominent at low effective temperatures due to a strong $J_\nu - B_\nu$ excess bluewards of the photo-ionization threshold at 350 nm. When the Li line is weak, the balance between UV over-ionization from the first excited state and over-recombination to higher excited levels determines the population levels of Li I. The resulting non-LTE corrections are typically minor, smaller than ± 0.1 dex, but increasing up to $+0.5$ dex in red giants. However, when the line is close to saturation, the loss of line photons establishes an efficient recombination and de-excitation ladder, which increases the population of low-excited levels of neutral Li. Furthermore, the scattering-dominated resonance line source function drops far below B_ν. The non-LTE corrections then change sign and reach -0.5 dex in extreme cases. Lind *et al.* (2009a) have made available convenient routines to interpolate the non-LTE corrections for a wide range of stellar parameters and Li abundances.

In LTE the Li I level populations depend on the local conditions, especially the gas temperature. The much cooler mean temperature stratifications in 3D models than corresponding 1D models at low metallicity translate to a 3D LTE abundance correction of ≈ -0.3 dex for the Li I 670.8 nm resonance line in metal-poor dwarfs and subgiants (e.g. Asplund *et al.* 1999). In addition, the presence of atmospheric inhomogeneities typically also increase the line strength. One should be aware however that the steeper temperature gradients in the 3D models are likely to boost the over-ionization. Spatially resolved observations of the solar surface show how the line actually is weaker in the bright, granular upflows, despite the drastic drop in temperature that they undergo. This can be understood since the intense UV radiation field in the granules produces pronounced over-ionization (Kiselman 1997).

Asplund *et al.* (2003) performed full 3D non-LTE computations for the Sun and two metal-poor stars using a 21-level Li model atom. They concluded that the line strengthening due to the cooler temperatures in the upper atmospheric layers on the one hand and line weakening from increased over-ionization on the other hand largely cancel each other. Barklem *et al.* (2003) updated these results in light of new collisional data, especially charge transfer reactions and reached similar conclusions. The 3D non-LTE calculations

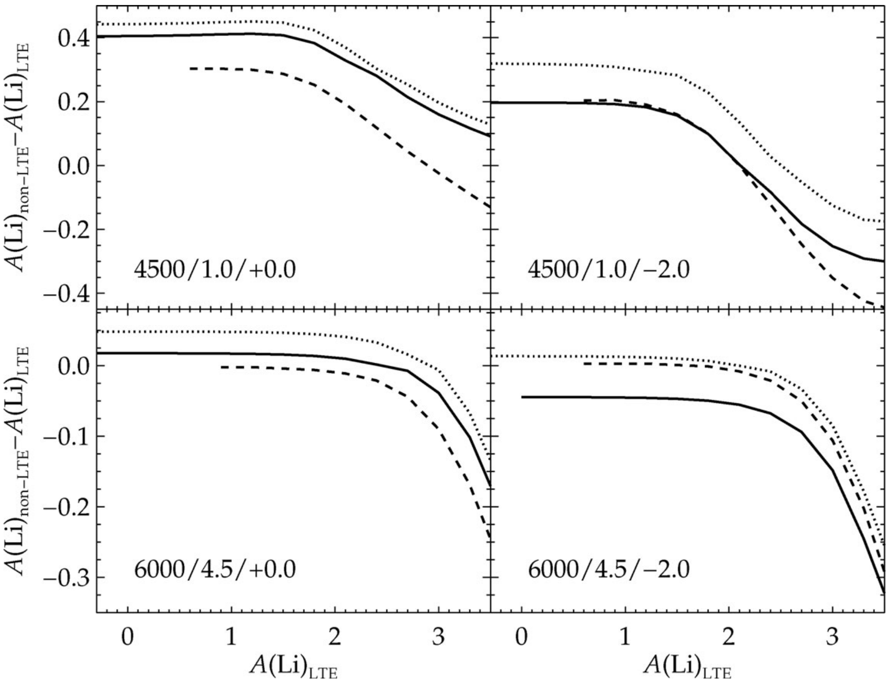

Figure 2. The 1D non-LTE abundance corrections for a selection of stellar parameters (labelled with $T_{\mathrm{eff}}\,/\log g/[\mathrm{Fe/H}]$) from the study of Lind *et al.* (2009a). The solid line denotes the case with all transitions considered while the dotted line correspond to the case when the charge transfer reactions of Barklem *et al.* (2003) are ignored. Also shown as dashed lines are the non-LTE corrections from Carlsson *et al.* (1994).

thus agree with the 1D non-LTE results to within 0.05–0.1 dex. In fact, even better agreement between the two is seen in the recent study of extremely metal-poor stars by Sbordone *et al.* (2010) with difference of < 0.03 dex, at least compared with the particular family of 1D model atmospheres they used. Sbordone *et al.* (2010) used a smaller atom (8 levels) but computed for more 3D models. They also provided a very handy functional relation between the Li abundance and the line strength, which allows direct computation of the 3D non-LTE based abundance without invoking any particular 1D model atmosphere. The Spite & Spite (1982) Li-plateau as inferred from 1D analyses is thus unlikely to be seriously in danger although the exact slope with for example [Fe/H] may be affected (e.g. Asplund *et al.* 2006; Sbordone *et al.* 2010), which deserves to be studied closer with improved 3D non-LTE calculations.

2.4. $^6Li/^7Li$

The minor isotope ^{6}Li can be detected through the isotopic shift in the Li I 670.8 nm line. The distortion of the line profile is very small and therefore necessitates extremely high-quality spectra ($S/N > 400$, $\lambda/\Delta\lambda > 100,000$ and minimal fringing). At solar metallicity, possible blending lines must also be carefully evaluated (Israelian *et al.* 2003), a problem which however disappears at low [Fe/H]. The first positive detection in a halo star was claimed by Smith *et al.* (1993) for HD 84937. Asplund *et al.* (2006) boosted the number of $> 2\sigma$ detections to 10 (including HD 84937) using high-quality VLT/UVES spectra analysed both in 1D and 3D LTE. The derived ^{6}Li abundance at [Fe/H]< -2.5 can not be easily accommodated with standard Galactic cosmic ray production, which has spurred

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a number of studies of more speculative production channels, including non-standard Big Bang nucleosynthesis with supersymmetric particles (e.g. Jedamzik & Pospelov 2009).

Several potential problems linger over the published ^{6}Li/^{7}Li analyses. García Pérez *et al.* (2009) have suggested that residual fringing in the observed spectra can cause large uncertainties. Their Subaru/HDS spectra are, however, much more inflicted by fringing than the VLT/UVES spectra of Asplund *et al.* (2006), who furthermore carefully assessed their possible impact on the results. More worrisome is the restriction to 1D or 3D LTE line formation. The atmospheric convective motions typically result in C-shaped line asymmetries (e.g. Asplund *et al.* 2000), which can thus mimic the presence of ^{6}Li. Indeed, Cayrel *et al.* (2007) have argued based on 3D non-LTE calculations that the Asplund *et al.* (2006) results must be reevaluated. Steffen *et al.* (2010) have considered this in more detail and concluded that the derived ^{6}Li/^{7}Li ratios in a 1D analysis are overestimated by typically 0.015, which if true could explain the tendency for most stars with non-significant detections in the Asplund *et al.* (2006) sample to cluster around ^{6}Li/^{7}Li$\approx$ 0.01. Furthermore, Steffen *et al.* (2010) argue that by taking this convective effect into account, only 4 out of 10 stars would remain as $> 2\sigma$ detections.

We argue that the Steffen *et al.* (2010) results should not be over-interpreted, since there are subtle but crucial differences in the analyses. Steffen *et al.* (2010) rely only on the Li line itself to determine all parameters: ^{7}Li and ^{6}Li abundances, wavelength shift and intrinsic line broadening (rotation in 3D but in 1D also macro-/microturbelence) while Asplund *et al.* (2006) rely on a range of Fe, Ca etc lines to first determine the line broadening which is then fixed for the Li profile fitting. Since the other lines are also asymmetric, this is accounted for in the profile fitting through a slightly larger required broadening, which then compensates for the use of symmetric Li lines in 1D. Asplund *et al.* (2006) also did a 3D LTE analysis for all lines and found very similar results as in 1D but with much improved profile fits. We have also performed 3D non-LTE line calculations for Li similar to Steffen *et al.* (2010) and can in fact exactly reproduce their results and their claimed 0.015 effect in ^{6}Li/^{7}Li when only using the Li line and not any other lines. We argue though that this does not make full use of the information encoded in the spectra due to the degeneracy between the four fitting parameters. Indeed, their procedure is akin to determining the D abundance in QSO absorption systems only from the Lyα line without first resolving the intrinsic velocity structure of the H I clouds from other metallic lines. Similarly problematic is to rely on 3D non-LTE for Li but 3D LTE for the other lines, in view of the likely pronounced non-LTE effects. The only way forward to convincingly demonstrate whether or not ^{6}Li is present in detectable amounts in the atmospheres of halo turn-off stars is to perform full 3D non-LTE calculations for all lines considered. We are currently working on this and will report the results elsewhere.

In summary, it is not yet possible to say that ^{6}Li has definitely been detected but it is definitely too early to say that ^{6}Li has not been detected. We also note that even Steffen *et al.* (2010) agree that ^{6}Li is present in HD 84937 and a few other stars. Since ^{6}Li is always destroyed and more so than ^{7}Li, one would still end up with a very significant cosmological ^{6}Li problem when invoking stellar depletion to solve the cosmological ^{7}Li problem (e.g. Asplund *et al.* 2006; Korn *et al.* 2006; Lind *et al.* 2009b).

2.5. *Beryllium*

In late-type stars the Be abundance can in practice only be derived from the resonance doublet of Be II at 313 nm. In contrast to Li and B, Be is normally present in significant amounts in both neutral and singly ionized form due to its high ionization potential, which makes Be less prone to over-ionization. The Be II line formation proceeds under non-LTE

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conditions but because the two dominant non-LTE effects – over-ionization and over-excitation – largely compensate each other the resulting non-LTE abundance corrections are typically minor (Garcia Lopez *et al.* 1995). Both the lower and upper level of the doublet are over-populated relative to the LTE prediction. Be I tends to be somewhat over-ionized due to a UV radiation excess ($J_\nu/B_\nu > 1$), which simultaneously produce an over-excitation of the upper level of the Be II 313 nm transitions. García Pérez *et al.* (2010) have investigated the non-LTE line formation of the Be II 313 nm doublet across a wide range of stellar parameters. They found that at solar metallicity the two effects almost perfectly balance each other with the resulting non-LTE abundance corrections amounting to $|\Delta \log \epsilon_{\rm Be}| \leqslant 0.05$ dex. At low metallicity the non-LTE corrections are positive ($\Delta \log \epsilon_{\rm Be} \approx 0.1$ dex) for $T_{\rm eff} \geqslant 6000$ K and negative ($\Delta \log \epsilon_{\rm Be} \approx -0.1$ dex) for lower $T_{\rm eff}$. While the non-LTE effects will not qualitatively change the conclusions for the metallicity evolution of Be (Primas and Boesgaard, these proceedings), accounting for the new non-LTE calculations will tend to make the slope somewhat shallower.

The 3D line formation of the Be II lines have so far only been investigated for the Sun (Asplund *et al.* 2009). The Be II lines are not very sensitive to 3D effects at least within the LTE approximation. The 3D non-LTE case has not yet been investigated but given the relatively modest non-LTE effects in 1D one would not expect a great difference in 3D, although this prediction should be verified with detailed calculations.

2.6. *Boron*

As for Be, both over-ionization and over-excitation are at play in the formation of the B I resonance lines at 249.7 nm and 209.0 nm but because B I is the minority ionization stage for $T_{\rm eff} \geqslant 6000$ K the effects on the resulting line profiles are much more dramatic (Kiselman & Carlsson 1996). The over-ionization is largely driven by photo-ionization from the excited B I levels since $J_\nu/B_\nu > 1$ at the relevant wavelengths. It is also assisted by pumping in the B I resonance lines, which produces a sufficient over-population of these upper levels. The same pumping results in a substantial increase in the line source function $S_\nu/B_\nu \approx J_\nu/B_\nu > 1$ for the 249.7 and 209.0 nm lines. Thus, in contrast to the case of Be, for the B I resonance lines the two non-LTE effects work in tandem to decrease the non-LTE line strengths substantially compared with the LTE prediction.

Kiselman & Carlsson (1996) computed non-LTE abundance corrections for the B I lines for a grid of MARCS 1D model atmospheres. The non-LTE effects grow in size towards higher $T_{\rm eff}$ and lower [Fe/H]. Indeed, they found non-LTE abundance corrections as large as $> +0.5$ for typical turn-off halo stars. As both non-LTE processes feed on the UV radiation field, it is important to include background line opacities both for the calculations of the photo-ionization rates and the resonance lines, which Kiselman & Carlsson (1996) did in a somewhat approximate manner. Recently, Tan *et al.* (2010) confirmed the importance of over-ionization and pumping but they obtained markedly less severe non-LTE effects, which can be traced to a more complete treatment of the line-blocking. Their estimated non-LTE abundance corrections amount to $\approx +0.3$ dex at the lowest [Fe/H], when not including the highly uncertain inelastic H collisions according to Drawin (1968); the corrections would be $\approx +0.1$ dex when this formula would be applied without any further scaling factor. As shown in Fig. 3, the new non-LTE results of Tan *et al.* (2010) make the resulting evolution of B as a function of metallicity somewhat steeper with a slope of ≈ 1.3. The reader is referred to Primas (these proceedings) for a discussion of the astrophysical implications of such a correlation.

With the exception of the Sun (Asplund *et al.* 2009), the 3D line formation of the B I lines has not been investigated, neither in LTE nor in non-LTE. In view of the prominent non-LTE effects and the general expectation that they would become even

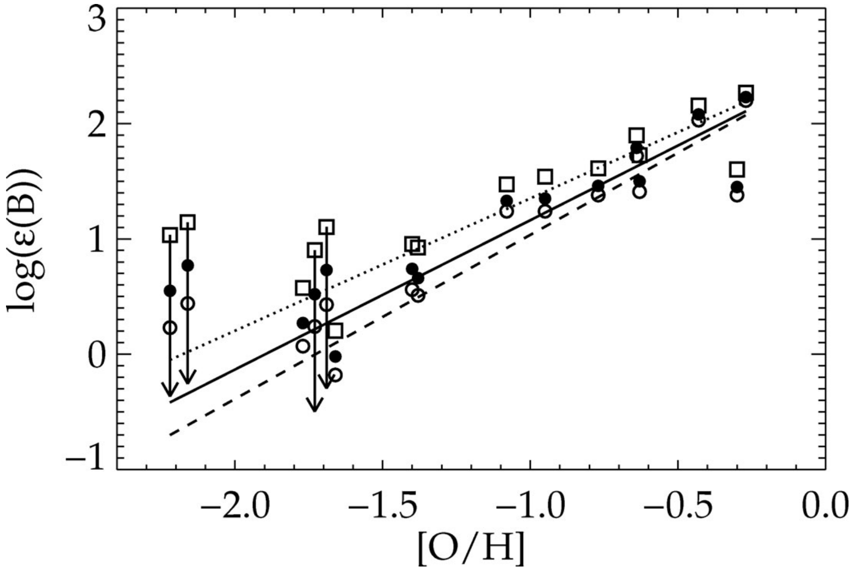

Figure 3. The derived stellar B abundances in halo stars (Tan *et al.* 2010) as a function of [O/H] for LTE (open circles with dashed line the least square fit) and non-LTE (filled circles and solid line); upper limits are marked with arrows. The O abundances have been corrected for non-LTE effects according to Fabbian *et al.* (2009). Also shown are the LTE-based B abundances of Tan *et al.* (2010) but corrected according to the non-LTE calculations of Kiselman & Carlsson (1996) (open squares and dotted line). Inelastic H collisions have not been included for the B non-LTE results but for O according to the Drawin (1968) formula.

more pronounced in 3D due to the atmospheric inhomogeneities, performing detailed 3D non-LTE calculations for B I should have a high priority.

3. Concluding remarks

Important progress has been made over the last decade in terms of improving the abundance analyses of the light elements in late-type stars by accounting for non-LTE as well as 3D effects. The non-LTE line formation of the resonance lines of Li I, Be II, and B I share common properties, but the final non-LTE abundance corrections are always element specific. Especially differences in ionization potential and the extent to which UV radiative transitions contribute to the excitation and ionization balance govern the LTE departures. There are however still several outstanding analysis problems.

Signs are that the new generation of 3D hydrodynamical model atmospheres are indeed highly realistic and thus trustworthy for abundance purposes as they successfully reproduce most, if not all, observational tests they have been exposed to. The key development for the future will be to make such 3D models generally available for a wide range of stellar parameters and actually to get stellar abundance practitioners to start using them routinely. The main obstacle here will likely be to overcome old habits rather than say lack of computational power, since it is now possible to perform a 3D-based solar/stellar abundance analysis for thousands of lines, at least in LTE (Asplund *et al.* 2009). On the non-LTE side, the challenges are two-fold: improving the necessary atomic data, especially for collisions, and to couple the non-LTE line formation with 3D model atmospheres, which is still very much unchartered territory. This is now certainly feasible but will require additional (wo)manpower. Only then can we with some degree of confidence argue that our analysis efforts match the investments in obtaining impressive observational data. As outlined above, such modelling efforts will no doubt lead to many reinterpretations of observations with profound implications for our understanding of stellar, galactic and cosmic evolution in general and the light elements in particular.

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