Light Elements in the Universe
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Discussion D: Observational problems with Li, Be and B

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Abstract. In Discussion D the following problems were addressed: Has ^{6}Li really been detected in the atmospheres of metal-poor halo stars? Is there a downward trend or increased scatter of Li abundances in stars on the 'Li-plateau' at metallicities [Fe/H] $\lesssim -2.5$? Are there significant differences of Li abundances in main-sequence, turn-off, and sub-giant stars in globular clusters? Is the Li abundance in solar-type stars related to the presence of planets? How does the Be abundance in dwarf stars increase with the heavy-element abundance, and is there a cosmic scatter in Be at a given [Fe/H]? The discussion of these problems is summarized and some suggestions for future observational and theoretical studies are mentioned.

Keywords. stars: abundances, atmospheres, interiors – planetary systems – ISM: abundances – early universe

1. Introduction

Observational problems with lithium and beryllium, which have attracted much attention in recent years, were taken up during Discussion D. Boron, on the other hand, was not included in the discussion, because observational progress for this element has been slow in recent years due to the 5-year hiatus in the UV high-resolution instrumentation at the HST. In the following, I briefly report on the main subjects of the discussion.

2. ^{6}Li in the atmospheres of metal-poor halo stars

The discussion focused on the claimed 1D LTE (> 2-sigma) detections of ^{6}Li in warm, metal-poor halo dwarf stars by Asplund *et al.* (2006) and Asplund & Meléndez (2008) including the very metal-poor stars G 64-12 with $^6\mathrm{Li}/^7\mathrm{Li} = 0.059 \pm 0.021$ and G 64-37 with $^6\mathrm{Li}/^7\mathrm{Li} = 0.111 \pm 0.032$. As emphasized by Martin Asplund, one may question a detection of ^{6}Li for a given star, but the collective distribution of $^6\mathrm{Li}/^7\mathrm{Li}$ can only be explained if ^{6}Li is present in the atmospheres of some of these metal-poor stars.

According to Martin Asplund (this volume), the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio derived from the profile of the Li I 6708 Å resonance line does not change significantly if a 3D non-LTE analysis is applied instead of a 1D LTE analysis. Matthias Steffen (this volume), on the other hand, finds that the derived $^6\mathrm{Li}/^7\mathrm{Li}$ ratio is 0.01 to 0.02 smaller when using 3D non-LTE instead of 1D LTE. If such a zero-point shift in the derived $^6\mathrm{Li}/^7\mathrm{Li}$ values is included, then the distribution of $^6\mathrm{Li}/^7\mathrm{Li}$ is more compatible with the absence of ^{6}Li in the stellar atmospheres, although a few stars, such as HD 84937, still seem to have ^{6}Li detected at the 2-sigma level.

The difference in the estimation of the 3D (convective) effects on the derived value of $^6\mathrm{Li}/^7\mathrm{Li}$ may be connected to the way the analysis of the spectra is performed. Asplund *et al.* use other lines than Li I 6708 Å to determine the line broadening arising from the projected stellar rotation velocity, $V_{rot} \sin i$, whereas Steffen *et al.* assume a value

$V_{rot} \sin i = 0$ or 2 km s^{-1} and use only the Li line itself. Clearly, further 3D non-LTE studies are needed, and checks of line asymmetries induced by 3D convective motions should be performed for spectral lines that are formed in the same way and at the same atmospheric depth as the Li I line such as the K I 7698 Å line in the spectrum of HD 84937 (Smith *et al.* 2001) and the Na I D lines in the very metal-poor stars G 64-12 and G 64-37.

As emphasized by several participants, a clear detection of the ^{6}Li isotope at a level of ^{6}Li/^{7}Li ~ 0.05 in metal-poor halo stars with metallicities [Fe/H] $\lesssim -3$ would have profound effects on our understanding of the formation of Li. As shown by Nikos Prantzos (this volume) cosmic ray processes cannot explain the corresponding high ^{6}Li/Be ratio at [Fe/H] ~ -3. Pre-galactic production of ^{6}Li or non-standard Big-Bang nucleosynthesis have to be invoked (Karsten Jedamzik, this volume).

Concern was raised about the quality of the high-resolution spectra that have been used to determine ^{6}Li/^{7}Li. High resolution ($R \gtrsim 10^5$), and high signal-to-noise ($S/N \gtrsim 500$) are needed. In addition, one has to be very careful with the flat-fielding and rectification of the spectra to ensure that the continuum near the Li I 6708 Å line is accurate to better than 0.2 %. In this connection, it was mentioned that the non-detection of ^{6}Li in G 64-37 (^{6}Li/^{7}Li $= 0.01 \pm 0.04$) by García Pérez *et al.* (2009) (in contrast to the 3-sigma detection by Asplund & Meléndez quoted above) may be due to problems with residual fringes after flat-fielding of the Subaru/HDS spectra, as also discussed by García Pérez *et al.* themselves.

When discussing the Li isotope ratio, it should not be forgotten that ^{6}Li has been clearly detected in nearby interstellar clouds. As a new development in this field, Christopher Howk (this volume) presented the first measurements of the Li I 6708 Å line associated with gas in the Small Magellanic Cloud, which is known to be about a factor of four more metal-poor than the Sun. The high-resolution spectrum, which was taken with UVES and has a S/N of 250, suggests that ^{6}Li is present corresponding to ^{6}Li/^{7}Li ~ 0.12. A still higher S/N spectrum is needed to confirm this interesting detection of ^{6}Li in a metal-poor galaxy.

3. The 'Spite plateau' at the lowest metallicities

Sbordone *et al.* (this volume) presented evidence that halo stars with $T_{\rm eff} \gtrsim 5900$ K and [Fe/H] < -2.5 show a decline and increasing scatter of Li abundances as a function of decreasing metallicity. At [Fe/H] ~ -3.5, the average Li abundance, A(Li) $= \log(N_{\rm Li}/N_{\rm H}) + 12$, is 1.9 dex and the scatter is around 0.2 dex. In contrast, the Li abundance for halo stars with metallicities in the range $-2.5 <$ [Fe/H] < -1.5 is nearly constant at a level of A(Li) $= 2.2$ with a scatter of 0.05 dex only. It was emphasized that this result does not depend on the effective temperature scale applied.

Meléndez *et al.* (this volume) find, however, that the increased scatter in Li abundance below [Fe/H] $= -2.5$ goes away if one selects the 'plateau' stars according to the condition $T_{\rm eff} > 5850 - 180$ [Fe/H] K, i.e. with a strong metallicity dependence in the temperature limit; at [Fe/H] $= -3.0$ only stars with $T_{\rm eff} > 6390$ K are included. Still, there is a tendency that stars with [Fe/H] < -2.5 have a 0.1 dex lower Li abundance than stars with [Fe/H] > -2.5.

Meléndez *et al.* (this volume) suggest that the turbulent diffusion models of Richard *et al.* (2005) can explain the large difference between the Li abundance predicted from WMAP + SBBN (A(Li) ~ 2.7) and the abundance of the plateau stars (A(Li) ~ 2.2), if models with a high parameter of turbulent mixing ($T6.25$) are adopted. The same models introduce a rather strong dependence of Li depletion on stellar mass, which may explain the scatter in A(Li) at the lowest metallicities, but turbulent diffusion models with

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metallicities below [Fe/H] = −2.0 are still to be calculated. It would also be important to obtain a better understanding of the free parameter in the turbulent diffusion models from physical principles.

The derived stellar Li abundances depend critically on the adopted effective temperatures; if $T_{\rm eff}$ is increased by 100 K, A(Li) increases by 0.07 dex. Over the years, there has been much discussion of the effective temperature scale for late-type stars especially for the metal-poor halo stars. Recent calibrations based on the IRFM method (González Hernández & Bonifacio 2009; Casagrande *et al.* 2009) agree, however, very well, and point to a fairly high temperature scale, i.e $T_{\rm eff} \sim 6500$ K for a very metal-poor star at the turn-off point. It is interesting that new 3D calculations of the profiles of Balmer lines (Ludwig *et al.* 2009) support such high temperatures. Further work on 3D non-LTE modelling of Balmer lines and comparison with observed profiles is, however, needed.

4. Lithium in globular clusters

Recent studies of Li abundance differences along the evolutionary sequence of stars in NGC 6397 were reviewed by Andreas Korn (this volume) and further discussed by Karin Lind (this volume) and Jonay González Hernández (this volume). Both high-resolution VLT/UVES spectra of 18 stars analyzed by Korn *et al.* (2007) and medium-resolution GIRAFFE spectra for 349 stars analyzed by Lind *et al.* (2009) suggest that the turn-off stars in NGC 6397 are more Li-poor, by about 0.1 dex, than subgiants which have not yet undergone dredge-up. Based on VLT/GIRAFFE spectra González Hernández *et al.* (2009) also find a difference of about 0.1 dex between 84 subgiants and 79 main-sequence stars in NGC 6397 selected in a narrow color range $0.57 < B - V < 0.63$. This suggests that Li sinks by diffusion during the MS/TO phase but to a depth low enough to prevent Li destruction such that some Li can be restored into the atmosphere, when a star evolves to the SG stage and the convection zone deepens.

It was noted that the two Li studies of NGC 6397 by Lind *et al.* and González Hernández *et al.* do not agree concerning the details of the trend of A(Li) as a function of $T_{\rm eff}$. The Lind *et al.* results suggest that A(Li) decreases with increasing $T_{\rm eff}$ along the subgiant branch, whereas González Hernández *et al.* find the opposite trend. Karin Lind warned that these trends are somewhat uncertain, because of correlated errors in $T_{\rm eff}$ and A(Li). Jonay González Hernández stressed that the turbulent diffusion model by Richard *et al.* (2005), which explains the difference between the WMAP based Li abundance, A(Li) ~ 2.7, and the overall level of A(Li) ~ 2.3 in the globular cluster stars, i.e. the $T6.25$ model, does not explain the observed difference between A(Li) in SG and MS stars. Clearly, more work is needed. Li data for other globular clusters than NGC 6397 would be very important.

Piercarlo Bonifacio (this volume) presented a study of Li abundances in turnoff and subgiant stars belonging to ω Cen based on high-resolution spectra obtained with the ESO VLT. He considered ω Cen as the nucleus of an external galaxy that has been accreted by the Milky Way. According to Villanova *et al.* (2007), the stars observed span an age range of five Gyr. The preliminary results show that 30 stars with metallicities in the range $-1.9 <$ [Fe/H] < -1.5 are distributed along a Li 'plateau' with A(Li) ~ 2.1 and a scatter of the order of 0.1 dex. Given the five Gyr age-spread and the constancy of A(Li) at 2.1 dex, Piercarlo Bonifacio pointed out that it is difficult to explain the difference in A(Li) with respect to a primordial Li abundance of 2.7 dex by intrinsic stellar depletion. Li depletion in an early generation of massive stars, as suggested by Piau *et al.* (2006), was also considered an unlikely explanation by Piercarlo Bonifacio, because it seems surprising if this scenario would lead to the same depletion in the Milky

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Way and in an external galaxy. Nikos Prantzos remarked that the suggestion of Piau *et al.* is excluded because Li astration in massive Pop III stars would be accompanied by heavy element production to a level much higher than we are observing in the very metal-poor halo stars.

5. Lithium in solar-type stars

Garik Israelian (this volume) described a new investigation of the Li abundance in Sun-like stars with and without detected planets based on spectra obtained with the HARPS spectrograph at the ESO 3.6 m telescope. For a limited range of ± 80 K around the solar effective temperature, only two out of 24 stars with detected planets have A(Li) > 1.5, whereas 29 out of 60 stars without detected planets have A(Li) > 1.5 (Israelian *et al.* 2009). Furthermore, there are no systematic differences in metallicity and age (as estimated from chromospheric activity) between stars with and without detected planets that could explain the difference in A(Li). Hence, there seems to be evidence for enhanced Li depletion in Sun-like stars with orbiting planets. Israelian *et al.* suggest that the presence of a planetary system affects the angular momentum evolution of a star in a way that leads to a higher degree of rotational mixing of Li to interior regions, where it can be destroyed.

Meléndez *et al.* (this volume), on the other hand, find that solar-analogue stars with and without detected giant planets follow the same relation between atmospheric Li abundance and stellar age (determined from isochrones). This relation agrees well with that predicted by Charbonnel & Talon (2005) from models including the influence of gravity waves on the internal rotation of the Sun. Meléndez *et al.* also find that solar-twin stars (mass $M = (1.00 \pm 0.04)\,M_{\rm Sun}$ and metallicity [Fe/H] $= 0.0 \pm 0.1$) having the same *chemical* terrestrial planet signature as the Sun (Meléndez *et al.* 2009) follow the same Li vs. age relation as solar twins without the signature of terrestrial planets. These investigations suggest that one has to select stars with and and without planets in narrow mass, age and metallicity ranges before comparing their Li abundances. More work on larger samples of solar-twin stars is needed before final conclusions on Li differences between stars with and without planets can be made.

6. The Galactic evolution of beryllium

The formation and evolution of beryllium were discussed in talks by Ann Boesgaard, Francesca Primas and Rodolfo Smiljanic (this volume).

Beryllium abundances derived from Keck/HIRES spectra by Rich & Boesgaard (2009) for 49 stars ranging in metallicity from [Fe/H] $= -3.5$ to -0.5 and with oxygen abundances derived from OH lines in the UV suggest that the slope of log (Be) vs. log (O) may change from ~ 0.75 for stars with [O/H] < -1.6 to ~ 1.6 for stars with [O/H] > -1.6. As suggested by Ann Boesgaard, this could be due to a change in the dominant production mechanisms for Be. In the early Galaxy, Be formed by a primary process, i.e. high energy CNO atoms from supernovae hitting interstellar protons, whereas at later times the dominant (secondary) reaction is high energy protons from SNe hitting interstellar CNO.

Smiljanic *et al.* (2009) have used VLT/UVES spectra to determine Be abundances in a sample of 90 stars with metallicities mostly in the range $-2.0 <$ [Fe/H] < -0.5. Atmospheric parameters and abundances of the α-capture elements (Mg, Si, Ca, Ti) were adopted from literature. Li abundances are used to eliminate stars, possibly affected by depletion, from the sample. Interestingly, there is a significant scatter of Be at a given

[Fe/H]: the halo stars tend to split into two populations one with low Be and α/Fe, and another one with high Be and α/Fe like in the thick disk stars.

Francesca Primas (this volume) presented new Be data based on UVES spectra, which show that the two distinct populations of low-α and high-α halo stars discovered by Nissen & Schuster (2009) define different trends in the log (Be) - [Fe/H] diagram, thus confirming the results of Smiljanic *et al.* (2009). Furthermore, a hint of a flattening of the beryllium evolutionary trend at the lowest metallicities, [Fe/H] $\lesssim -2.5$, is found. As noted by Nikos Prantzos, this may be a signature of Be production by hypernovae.

From these works, it is clear that the evolution of Be in the Milky Way is more complicated than thought before, and that further studies of Be abundances in a larger sample of halo and disk stars may reveal interesting information about cosmic-ray processes and Galactic evolution. Investigations of non-LTE and 3D effects are, however, important in order to obtain accurate abundances of Be as well as Fe, O and the α-capture elements.

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