Boron in the extreme Pop II star HD140283 and the production of light elements in the Early Galaxy*

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Abstract. Using observations of the 2496.7 Å B line with the HST GHRS at a nominal resolution of 90,000, we have found the abundance of boron of HD 140283 to be $\log \epsilon_B (= 12 + \log (N_B/N_H)) = 0.34 \pm 0.20$. This result is found when a significant non-LTE effect in the formation of the B line is taken into account. The resulting $N_B/N_{Be}$ ratio is about 17 (in the range 9 – 34), which is in very good agreement with what is expected from spallation by cosmic rays. We conclude that this origin of Be and B in the Early Galaxy is the most probable of recently suggested formation mechanisms.

Key words: Galaxy: abundances – Stars: abundances – Line: formation

1. Introduction

The detection of beryllium in the Extreme Population II star HD 140283 ([Fe/H] $\approx -2.7$) by Gilmore, Edvardsson & Nissen (1991) indicated a value of log(Be/H) of about $-13$, a factor of more than 1000 times greater than the primordial value predicted by the Standard Big Bang Model. (Here and below the notation Be/H is shorthand for $N_{Be}/N_{H}$.) This relatively high abundance was not expected, and it is still not quite clear where and how the beryllium was formed: in the interstellar medium (ISM) in the Early Galaxy, in supernovae or their immediate neighbourhood, close to other high-energy objects, or possibly in the Big Bang.

Although it seemed that the Be abundances could indicate an inhomogeneous Big Bang (see, e.g., Kajino & Boyd 1990) this possibility was questioned on theoretical grounds (e.g., Terasawa & Sato 1990, Thomas et al. 1993 and references given therein). Also, the approximately linear relation between Be and O abundances found for Pop II dwarfs by Gilmore et al. (1992) suggested a non-cosmological origin of the Be in HD 140283 and a gradual build-up of the element in the Halo. However, the relation found deviates considerably from the quadratic behaviour of single-zone models for spallation in the ISM of the Early Galaxy (cf. Vangioni-Flam et al. 1990). This has lead to several modified scenarios for cosmic ray spallation in the Early Galaxy (for references, see Sect. 4). Neutrino-induced spallation in supernovae may contribute significantly to some light-element abundances (Woosley et al. 1990) and possibly also to Be (Malaney 1992). A fourth possibility is that a fraction of the beryllium in HD 140283 was produced by other (pregalactic) processes (e.g. by “photo erosion” at an early active galactic nucleus, Boyd & Fencl 1991).

Duncan, Lambert & Lemke (1992) searched for the B line in the spectrum of HD 140283, using Hubble Space Telescope (HST) observations at a spectral resolution of about 25,000. The line was tentatively identified and an abundance of about log(B/H) = −12.1 was estimated by an LTE abundance analysis. The resulting abundance ratio of B/Be = 10 is consistent with spallation; however, this result is very uncertain and the ratio may sooner be regarded a rough upper limit since the line observed is a blend of three lines, Co I, B I and Fe I, which could not be resolved at the spectral resolu-

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tion used. Thus, observations at considerably higher spectral resolution and high signal to noise were needed. Here, we present such observations in Sect. 2. The spectra are analysed in Sect. 3 and the results are discussed in Sect. 4.

2. Observations and data reductions

2.1. Observations

The wavelength region around the resonance lines of B I at 2497 Å was observed with the Goddard High Resolution Spectrograph (GHRS) of the Hubble Space Telescope on September 5, 1992 (proposal No. 3479) and continued on February 15 and 21, 1993 (proposal extension No. 4766). A description of the spectrograph and general observational techniques may be found in the manual by Duncan (1992). The target was found each time without any reported problem by the standard onboard target acquisition procedures. The Echelle B grating and the Small Science Aperture (SSA), 0′′.25 by 0′′.25, was used which optimally enables a resolving power $R = \lambda/\Delta\lambda = 90,000$. A spectral range of about 12 Å centered near $\lambda_{vac} = 2494$ Å sub-stepping pattern (No. 7) of 4 times 1/4 diode steps was used to fully sample the spectrum projected on the 500 science diodes to obtain the highest resolution. In order to enable background subtraction we used 6% of the exposure time to expose the Echelle inter-order regions on both sides of the spectrum. A typical set of 4 sub-steps and 2 background observations of Sept. 1992 are shown in Fig. 1.

![Fig. 1a-f. 4 sub-step exposures on HD 140283, and 2 background observations. Mean count levels are 1.5 counts per diode for the stellar spectra and 0.03 counts for the background. The total exposure time was 81.6 seconds with 94% of the time spent for the stellar spectra.](image)

The observations were performed as many short integrations to avoid as much as possible the GIMP (geometrical image motion problem), which may move the spectrum across the Digicon detector and degrade the spectral resolution. Furthermore, to minimise the impact of diode-to-diode sensitivity differences, the spectra were obtained at four different detector positions (FP-SPLIT=4).

The 1992 data were acquired during 9 spacecraft orbits with all exposures for each FP-split position taken consecutively (first 65 exposures in the first position, then 65 in the second position etc.). The S/N ratio of this observation turned out to be lower than what was hoped for, why the rest of the observing time allotment was utilized for the same star with small modifications (which gave the programme a new identification number). For the 1993 observations, the procedure was altered somewhat in an attempt to improve the relative wavelength calibration between separate orbits. One wavelength calibration spectrum (Pt-Ne lamp) was obtained in the beginning of each spacecraft orbit. This procedure resulted in 7 spacecraft orbits being used for each of the two observations in 1993.

The four FP-split observations were taken consecutively for each exposure.

The summed exposure times (on star) for each date were $5^h32^m23^s$; Sept. 5, 1992; 65 exposures (each consisting of 4 FP-splits × 4 sub-steps), $2^h58^m59^s$; Feb. 15, 1993; 35 exposures and $2^h40^m38^s$; Feb. 21, 1993; 32 exposures. The reported continuum fluxes at the three occasions were, respectively, $0.69 \cdot 10^{-12}$, $0.85 \cdot 10^{-12}$ and $1.88 \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. We attribute these differences to pointing errors with the small aperture. If the highest flux level had been obtained at all three occasions, 85% more photons would have been registered, corresponding to 36% higher a S/N ratio of the final spectrum. Thanks to improved onboard acquisition procedures (“SSA peak-up”) we believe that such pointing errors are now avoidable.

2.2. Data reductions

The data reductions were performed using the IRAF/STSDAS software under guidance of Dr. Jeremy Walsh at the European Coordination Facility (ECF) in Garching bei München, Germany, in October 1992 and September 1993. The most important aim of the data reductions was to wavelength align the very large number of short exposures as well as possible before adding them to a final spectrum. Each short exposure has a very low S/N ratio (cf. Fig. 1), and slow, unpredictable drifts in the wavelength direction make their co-addition difficult. Any mis-alignment will cause a degradation of the high spectral resolution sought in this project.

As a starting point for the reductions we used the standard STScI processed files (this processing procedure is called “pipelining”). The pipeline files contain the combinations of each set of four 500 diode sub-step spectra to a 2000 channel fully-sampled spectrum, with the background subtracted and converted from counts to flux units. The pipelining takes into account: correction for individual diode responses, vignetting, background subtraction, echelle blaze function removal and the conversion to absolute flux. The conversion to absolute flux can, however not take telescope pointing into account, why the resulting absolute fluxes are lower limits to the true absolute fluxes. Preliminary wavelength scale files are also provided by the pipeline process.

We used the STSDAS version 1.1 for the reductions of the 1992 data. We aligned the 4 FP-SPLIT files for each of the 65 exposures, which resulted in 65 separate spectra. Their relative wavelength offsets were determined by auto-correlation and then added together. As an alternative, we attempted to use the recorded FP-SPLIT wavelengths
with a correction for the GIMP effect as determined from the relevant component of the geomagnetic field in the GHRS for each integration. The method to extract the relevant data was devised by Dr. J. Walsh, but in this case, it did not result in any discernible improvement over the standard STSDAS procedures.

For the 1993 data we used version 1.2 of STSDAS. We attempted to use the wavelength calibration files obtained during each orbit to guide in the spectral alignment, but this did not significantly improve the result. The spectra resulting from the three observing dates are shown in Fig. 2.

**Fig. 2a-c.** The summed spectra obtained at our 3 observing dates before wavelength normalisation and continuum rectification. The dotted lines show the estimated continuum position.

The channel width is 5.9506 mA and from the variance of the channel-to-channel flux we estimate the continuum S/N ratio per channel of the final spectrum, shown in Fig. 3, to be about 33. This is close to the statistical S/N ratio expected from the about 1400 counts per channel accumulated in the continuum.

**Fig. 3.** The final spectrum after wavelength and continuum normalisation

From our theoretical models, the continuum level of HD 140283 was estimated to increase by 1.8% per 10 Å at 2500 Å. A good continuum window appears around $\lambda_{\text{obs}} = 2498.8$ (in Fig. 2, compare also with Fig. 1 of Duncan et al. 1992). Fixing a straight line through the noise at this point to the standard flux calibrated spectra with a slope of 1.8% per 10 Å gives a very reasonable continuum placement, cf. Figs. 2 and 3. We adopt this continuum level and estimate a maximum uncertainty of 2% in the continuum. The resulting line blocking in this wavelength region is 16.5% for HD 140283.

In Fig. 4 we compare the equivalent widths of several absorption features in our spectrum with those measured from the lower resolution GRS spectrum of HD 140283 by Duncan et al. (1992). For 11 lines between 2491 and 2495 Å there is a systematic difference of 6.7 mA with a scatter of 5.9 mA (Duncan et al. minus us). This is probably caused by a lower continuum placement in this region in our spectrum. For 13 lines in the wavelength region containing the Balmer lines, 2495 – 2499 Å, the equivalent widths agree very well: the difference is $1.2 \pm 3.1$ mA.

**Fig. 4.** Comparison of our equivalent widths with those of Duncan et al. (1992). The line shows loci for identical equivalent widths.

### 3. The boron abundance

#### 3.1. LTE abundance analysis and error estimates

The abundance analysis was based on the methods used in Gilmore et al. (1992). The theoretical model atmospheres were described in Edvardsson et al. (1993). The effective temperature, $5680$ K, and surface gravity $g = 3.5$ was adopted from Nissen (1993) who estimates an interstellar reddening $E_{B-V} = 0.020$ for HD 140283 based on $uvby\beta$ photometry and interstellar Na I D-line absorption. Our recent analyses (Gilmore et al. 1991, 1992; Nissen et al. 1993) based the effective temperature estimate of this star on the assumption that the star is unaffected by interstellar reddening. The overall metallicity $[\text{Fe/H}] = -2.64$ was adopted from Nissen et al. (1993), with a modification due to our 140 K higher $T_\text{eff}$. The microturbulence parameter was taken to be $\xi_t = 1.5 \text{ km s}^{-1}$. These atmospheric parameters are very similar to values used by Duncan et al. (1992) and other recent work on this star.

The line list was taken from Duncan et al. (1992), with a modified wavelength of 2496.716 Å (Pickering 1993) for the Co I line which blends with the primary Balmer line at 2496.772 Å. We consider the line identifications to be reliable, and, in particular, we find it very unlikely that there should be other blending lines than the Co I line that contribute significantly to the 2496.772 Å feature, i.e. it is very unlikely that the observed feature is not the boron line. The oscillator strengths for all except the Balmer lines were adjusted to fit the lines observed in the GRS spectrum. Adjustments of the $gf$ values were, however, usually unnecessary. In particular, the Co I 2496.716 Å line and the Fe I 2496.870 Å line closest to the 2496.772 Å line were not changed. To account for the combined effects of macroturbulence, rotational broadening and instrumental profile the synthetic spectrum was convolved with a Gaussian profile with a FWHM of 5.5 km s$^{-1}$ (45 mA). Our best fit synthetic spectrum is shown in Fig. 5, and corresponds to an LTE boron abundance of $\log N_B = 12 + \frac{\log N_B}{12}$ of $-0.20$. In panel b the observed spectrum was convolved by a three-point triangular profile of the shape 0.25, 0.50, 0.25.

The other line of the Balmer doublet, $\lambda = 2497.723$ Å, has twice as large transition probability as the 2496.772 Å line, but since it is blended by stronger Fe I and Fe II lines with poorly known transition probabilities it is currently not useful as a reliable boron abundance indicator.

To explore the sensitivity of our LTE boron abundance to various sources of uncertainties, detailed syn-
We have made non-LTE calculations for the current model atmosphere using the same methods and the same atomic model as in Kiselman (1994). The result is that the LTE abundance should be increased with $+0.54\text{dex}$. The main uncertainty in this figure comes from the effect of blending by other lines in the B i resonance lines which causes a moderation of the optical pumping effect of unknown magnitude. Most of the atomic data is of considerable accuracy and should cause smaller errors. From numerical experiments with the adopted model atmosphere, we estimate the maximal allowed range of the non-LTE abundance correction to be between $+0.30\text{dex}$ and $+0.60\text{dex}$. The non-LTE effects also cause greater sensitivity of the equivalent width to the atmospheric parameters. The effect increases in magnitude with $0.07\text{dex}$ when $T_{\text{eff}}$ is increased by $100\text{K}$ and decreases with $0.09\text{dex}$ when $\log g$ is increased by $0.5\text{dex}$ (Kiselman 1994).

Beryllium has not yet been the subject of an extensive non-LTE investigation. If the same general mechanisms as in the boron case should apply also for beryllium, we may expect that the overionisation of Be i and the optical pumping in the observed ultraviolet Be ii line will tend to cancel the effect of each other in the abundance estimate from Be ii. We therefore expect that the departures from LTE will be small for the observed 3131 Å line. Indeed, preliminary calculations using a 93-level model shows that the equivalent width of the 3131 Å line is only $0.06\text{dex}$ weaker than in LTE. It seems reasonable to assume that the non-LTE effect for the beryllium abundance is $0.0 \pm 0.2\text{dex}$ (maximum error).

4. Discussion

The B/Be abundance ratio depends on the origins of the two elements, as discussed below, and is therefore a valuable clue to their formation. The beryllium abundance of HD 140283 was determined by Gilmore et al. (1991 and 1992) from the Be ii resonance doublet at 3131 Å. The weighted mean result given by the latter investigation was $\log \epsilon_{\text{Be}} = -0.97 \pm 0.25$, which, when scaled to our effective temperature, is translated to $-0.90 \pm 0.25$. It should be mentioned here that Ryan et al. (1992) used spectra of somewhat lower spectral resolution and their result for HD 140283 corresponds to $\log \epsilon_{\text{Be}} = -1.13 \pm 0.4$ at our surface gravity.

The abundance ratio $N_B/N_{\text{Be}}$ found in this study is 17, when corrections (+0.5 dex for B; 0.0 dex for Be) for departures from LTE have been applied. What errors can be ascribed to this ratio? The observational errors in B abundance amount to about 0.14 dex (rms); those due to errors in the fundamental parameters for HD 140283 to 0.12 dex, and those resulting from errors in the non-LTE analysis to 0.1 dex. For the Be abundance, the corresponding errors are 0.17 dex, 0.11 dex and 0.1 dex, respectively. Taking the correlated effects of parameter uncertainties into consideration, and adding the abundance errors quadratically (in

Fig. 5a-b. Comparison of observed (solid lines) and synthetic spectra calculated in LTE (dashed lines). In b the observed spectrum has been somewhat smoothed. The short-dashed line shows our best synthetic spectrum, $\log \epsilon_b(\text{LTE}) = -0.20$ and the long-dashed lines are synthetic spectra with $\pm 0.3 \text{dex}$ varied boron abundances. The dotted line shows the synthetic spectrum with only the boron line, which has an equivalent width of 5.0 mÅ. The boron line is about 2/3 as strong as was suggested in the lower resolution study of Duncan et al. 1992 (cf. their Fig. 9)

3.2. Non-LTE line formation

Kiselman (1994) investigated the statistical equilibrium of neutral boron in solar-type stars and found that significant departures from LTE are expected in a metal-poor star such as HD 140283. The departures consist of an overionisation effect driven by the optical pumping in the ultraviolet resonance lines together with the pumping in the observed 2496.7 Å line itself. The overionisation decreases the line opacity and the optical pumping raises the line source function above the Planckian value. These effects combine to make the line weaker than in LTE. An LTE analysis will thus underestimate the boron abundance. The boron line is about 2/3 as strong as was suggested in the lower resolution study of Duncan et al. 1992 (cf. their Fig. 9).
found a high value (significantly higher B/Be ratios. Also, Olive et al. (1993) showed that the inhomogeneous Big Bang nucleosynthesis, at least in the form currently conceived, is not responsible for the Be and B abundances found in HD 140283.

The photoerosion network calculations by Boyd & Fencl (1991) give B/Be ratios > 10, with low values only for gamma ray fluxes great enough, or irradiation times long enough for quasi-equilibrium to be nearly established. E.g., we estimate from Fig. 1 of Boyd & Fencl (1991) that an integrated photon flux from 2 MeV to infinity of at least $10^{49}$ photons cm$^{-2}$ s$^{-1}$ will be needed for at least 10$^9$ years in order to give a B/Be ratio lower than 30. Assuming the Galaxy to be a representative large spiral, we have found this flux to be compatible with the observed $\gamma$-ray background (cf. Prantzos & Cassé and references therein), provided that the flux is concentrated into objects with a total surface area on the order 1 (ly)$^2$. In order to convert enough carbon and oxygen into beryllium and boron it is required that a fraction, $X$, of all matter in the halo gas is exposed to this flux and that this material is efficiently mixed into the ISM prior to star formation. If the production of carbon and oxygen is not spatially strongly correlated with the $\gamma$-ray flux, $X$ is as great as $10^{-4}$, which seems to lead to very severe dynamical problems. Even if the heavy target nuclei are produced by the $\gamma$ radiating objects themselves, major dynamical problems would still remain.

We find these different alternatives to cosmic ray spallation improbable as explanations of the Be and B abundances, while, on the other hand, the observed B/Be ratio agrees very well with that expected from cosmic ray spallation which supports this origin. Additional support to the latter hypothesis, as compared with that of a cosmological or other primordial but not that of a stellar origin, is given by the linear relation between the B and O abundances found by Gilmore et al. (1992). This linear relation is, however, not in itself trivial to understand in terms of cosmic ray spallation (for different cosmic ray spallation scenarios, see Duncan et al. 1992, Pranzos et al. 1993, Pranzos & Cassé 1993, Pagel 1993, Feltzing & Gustafsson 1994). We conclude, however, that cosmic ray spallation is the probable origin of both Be and B in Population II stars.

Finally we note that the solar system meteoritic $N_B/N_{Be}$ ratio 28 ± 4 (Anders & Grevesse 1989) is within our limits of uncertainty, implying that the same process...
could in principle be responsible for the production of B and Be throughout the history of the Galaxy.

Observations of Be and B abundances for stars with $[\text{Fe/H}] < -3.0$ and of $^{11}\text{B}/^{10}\text{B}$ ratios for Pop II stars would give further important clues for distinguishing between the different formation mechanisms, and also make it possible to further constrain the cosmic-ray spallation hypothesis. Current observational resources make both these goals marginally achievable.

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