A&A manuscript no.
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7(08.09.2 BD −13 3442; 08.01.1; 08.01.3; 09.03.2; 10.01.1; 10.05.1)

ASTRONOMY AND ASTROPHYSICS

Boron in the very metal-poor star BD −13 3442*

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Received ; accepted

Abstract. The Goddard High Resolution Spectrograph (GHRS) of the *Hubble Space Telescope (HST)* has been used to observe the boron 2500 Å region of BD −13 3442. At a metallicity of [Fe/H]=−3.00 this is the most metal-poor star ever observed for B. Nearly 26 hours of exposure time resulted in a detection. Spectrum synthesis using the latest Kurucz model atmospheres yields an LTE boron abundance of log ϵ(B)= $+0.01 \pm 0.20$. This value is consistent with the linear relation of slope ~1.0 between log $\epsilon(B_{LTE})$ and [Fe/H] found for 10 halo and disk stars by Duncan et al. (1997). Using the NLTE correction of Kiselman & Carlsson (1996), the NLTE boron abundance is log ϵ(B)= $+0.93 \pm 0.20$. This is also consistent with the NLTE relation determined by Duncan et al. (1997) where the slope of log $\epsilon(B_{NLTE})$ vs. [Fe/H] is ~0.7.

These data support a model in which most production of B and Be comes from the spallation of energetic C and O nuclei onto protons and He nuclei, probably in the vicinity of massive supernovae in star-forming regions, rather than the spallation of cosmic ray protons and alpha particles onto CNO nuclei in the general interstellar medium.

Key words: stars: individual: BD −13 3442 — stars:abundances — stars: atmospheres.

1. Introduction

The light elements lithium, beryllium, and boron are of great interest out of proportion to their very low abundances, having implications in Big Bang Nucleosynthesis and stellar structure, as well as in constraints on models of galactic chemical evolution.

The "canonical" theory of the origin of the elements Li, Be, and B was first presented by Reeves, Fowler, & Hoyle (1970) and further developed by Meneguzzi, Audouze, & Reeves (1971), and then Reeves, Audouze, Fowler, & Schramm (1973). In this model, most light element formation can be accounted for by galactic cosmic rays (GCR) impinging on the interstellar medium (ISM), assuming a constant flux of GCRs through the life of the Galaxy and making reasonable assumptions about CR confinement by the Galactic magnetic field. Meneguzzi et al. (1971) also introduced the idea of a large (up to three orders of magnitude) increase in the low energy (5-40 MeV nucleon^{-1}) CR flux; since CRs in this energy range are mostly shielded from the Solar System by the solar wind, they are not detectable. This additional CR flux increased the production of all light elements and matched the isotopic ratios and total abundances to the accuracy known at the time.

Reeves & Meyer (1978) added the additional constraint that models should match not only present-day abundances but their evolution throughout the life of the Galaxy. Their conclusions were similar to MAR, except that they had to introduce infall of light-element-free matter into the Galactic disk to match the evolution with time. In retrospect, it can be seen that the data they were fitting were sparse and not very precise. With the launch of the the *Hubble Space Telescope* (*HST*) and the availability of uv-sensitive CCD detectors (B is usually observed at λ2500 and Be at λ3130), data are now much more numer-

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* This research was based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

ous and accurate, and abundances can be traced from the epoch of formation of the Galactic halo until the present day.

In the past several years, the evolution of Li, Be, and B has been used as a test of different models of the chemical and dynamical evolution of the Galaxy. For example, in the models of Vangioni-Flam et al. (1990), Ryan et al. (1992), and Prantzos et al. (PCV; 1993), light element production depends on the intensity and shape of the GCR spectrum, which in turn depends on the supernova (SN) and massive star formation rates. It also depends on the rise of the (progenitor) CNO abundances and the decline of the gas mass fraction, which is affected by rates of infall of fresh (unprocessed) material and outflow, e.g. by SN heating. Other things being equal, at early times when target CNO abundances were low, light element production would be much lower for a given CR flux than presently, when the ISM abundances are higher. PCV found that even with these numerous adjustable parameters, no time-independent CR spectrum can reproduce the evolution of light element abundances. By assuming a very particular form of time variation of the CR flux (greatly enhanced at early epochs), they were able to (barely) fit the evolution of the abundances.

The present investigation supports a different solution to the problem of the origin of the light elements. Duncan et al. (1997) present B abundances in a large number of stars ranging in metallicity from ∼solar to [Fe/H] ∼ −2.8. They find that (LTE) B follows metals in direct proportion from the earliest times (very metal-poor stars) to the present, with little if any change of slope between halo and disk metallicities. A straightforward interpretation of this is that the rate of production of B and Be does *not* depend on the CNO abundances in the ISM, and that the production site is associated with the production site for metals. This would be true if the spallation process most important for light element production is not primarily protons and α particles colliding with CNO nuclei in the ISM but rather C and O nuclei colliding with ambient protons and α particles, probably in regions of massive star formation (cf. Vangioni-Flam et al. 1996 and Ramaty et al. 1997).

This paper focuses specifically on the B measurement in BD −13 3442; it is consistent with (and was used to help determine) the relationships between LTE and NLTE B and [Fe/H] seen in Duncan et al. (1997). The data suggest that B production at the lowest metallicities occurs in the same way as today, and thus support the new description of galactic light element production.

It is possible that recent GRO satellite observations of gamma rays from the Orion Nebula (Bloemen et al. 1994; Bykov & Bloemen 1994) provide direct evidence of C and O spallation occurring today, even though not all instruments on GRO detected evidence of such spallation (Murphy et al. 1996). The light element data alone, however, are the strongest evidence in support of a new model of their production.

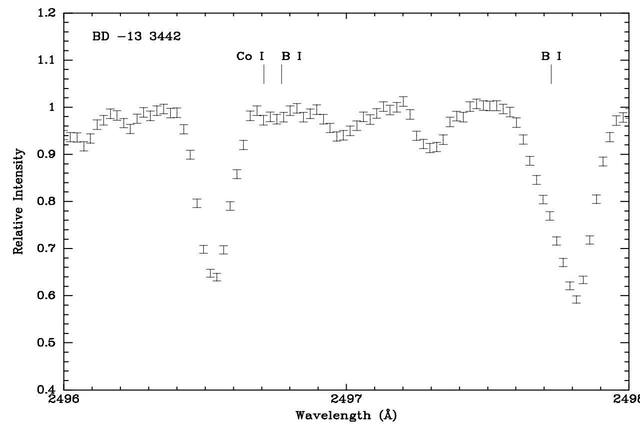

Fig. 1. Spectrum of BD −13 3442. The instrumental resolution is 0.096 Å, and the observational data shown are oversampled by a factor of about 2.

2. Observations and data reduction

The Goddard High-Resolution Spectrograph (GHRS) of the *Hubble Space Telescope* (*HST*) was used with the G270M grating to obtain spectra of resolution 26 000 (0.025 Å pixel^{-1}) in the λ2500 B I region of BD −13 3442. Data was collected for a total of 25.39 hours exposure time in six separate visits of the satellite over several months from December 1994 to May 1995. The S/N of the final spectrum was 100 per pixel (200 per resolution element), limited only by photon statistics. The spectrum obtained appears in Fig. 1.

These data were combined with that from 10 other stars, including three previously analyzed by Duncan, Lambert, & Lemke (1992) and seven new stars ([Fe/H] = −0.45 to −2.75), in a separate investigation (Duncan et al. 1997). Special care was taken to analyze each of the stars in a similar manner, and the stars from Duncan, Lambert, & Lemke (1992) were re-analyzed to assure consistency. See Duncan et al. (1997) for more details.

Data reduction followed the standard *HST* procedure, using the IRAF stsdas package, combining the quarter-stepped, FP-SPLIT data within each visit with the tasks poffsets and specalign, which perform a generalized least-squares solution for the photocathode granularity and the true spectrum. Since specalign equally weights the input spectra, exposures from separate visits were shifted and combined using the separate tasks shiftlines and scombine, weighting the data by the number of counts in the raw spectrum from each visit. By comparing subsets of the data, it was confirmed that the photon statistics limit was reached and that the line in question was present in both data sets if the data was arbitrarily divided in half, and not substantially altered by any exposure or by texture on the photocathode.

3. Abundance analysis

Spectrum synthesis using the latest Kurucz model atmospheres was used to determine log ϵ(B), with particular attention paid to the errors. An accurate determination of the uncertainties is required in the subsequent discussion of the results, to permit judgement of the goodness-of-fit of models of Galactic chemical evolution and to discriminate among the different proposed mechanisms of light element formation, particularly because this star is the most metal-poor yet investigated for boron.

3.1. Spectrum synthesis

Spectrum synthesis was done using the SYNTHE program distributed by Kurucz (1993) on CD-ROM. This program assumes local thermodynamic equilibrium (LTE) in determining level populations and calculating the emergent spectrum. Scripts written by Steve Allen (UC Santa Cruz) were used to run the program on Unix SparcStations. The most recent grid of model atmospheres, also released by Kurucz on CD-ROM, includes the blanketing of almost 60 million lines, both atomic and molecular. As in our parallel study of the Galactic evolution of boron, (Duncan et al. 1997), we used the linelist of the Duncan et al. (1997b) study of B in the Hyades giants, which consists almost entirely of laboratory-measured lines. It has been carefully tested in order to fit both the Hyades giants and various metal-poor stars in the B λ2500 region. This list was constructed by starting with Kurucz's LOWLINES list (CD-ROM # 1), adjusting (reducing) some *gf* values where necessary, and adding some predicted Fe I lines in order to achieve a good match to the absorption features near the B I lines. The *gf* value for the Co I 2496.708 Å line which blends with the short wavelength component of the B I doublet is the same as that of the higher resolution study of Edvardsson et al. (1994). In our linelist, the *gf* values and wavelengths of the B I resonant doublet were selected from O'Brian & Lawler (1992). They differ by only 0.03 dex and <0.01 Å from the values given by Kurucz. Our abundances are derived from fitting the shorter wavelength, less blended component of the B doublet, with the longer wavelength component examined as a consistency check.

As in Duncan et al. (1997), the Kurucz default abundance of log ϵ(B)=2.57 is used as our solar B value. This decision affects the choice of the zero point of the abundance scale and does not affect the interpretation of trends in the B data discussed in the present paper.

The Kurucz model grid is given in steps of 250 K in $T_{\rm eff}$, 0.50 in $\log g$, and 0.50 dex in [Fe/H] (at least for halo stars). We determined the physical parameters and their uncertainties for the program star from an extensive search of the literature and performed calculations at the nearest grid points. Within the range of values determined from the literature, models from the Kurucz grid which best fit our entire uv spectrum were chosen. Experiments with linear interpolation between grid models were also performed.

Table 1. Stellar parameters and B abundances

star	$T_{\rm eff}$	$\log g$	[Fe/H]	$\log\epsilon(B)_{LTE}$	$\log\epsilon(B)_{NLTE}$
BD −13 3442	6250	3.75	−3.00	0.01	0.93
BD +3 740	6125	3.5	−2.75	0.22	1.04
HD 140283	5640	3.5	−2.60	−0.10	0.35

The Kurucz models we used assume all metals scale together, whereas it is known that α-elements are enhanced at low metallicities. In Duncan et al. (1997), testing showed that the effect of α-enhancement on the structure of the model atmosphere produces very small effects on the calculated B abundances. In particular, the three stars originally studied by Duncan, Lambert, & Lemke (1992) were analyzed by them using atmospheres with α-enhanced composition from Gustafsson et al. (1975). Analyzing them with the methods of the present paper produced differences in B abundance within 0.04 dex, much lower than the other errors associated with the abundance determination. The direct effect of an enhanced Co abundance could be larger due to the particular line Co I 2496.708 Å which is blended with the shorter wavelength B component. This is discussed further in the section on uncertainties.

The atmospheric models we used were computed with a microturbulent velocity of 2 km s^{-1}. We did not find it necessary to change to the commonly accepted value of 1.5 km s^{-1} for halo stars (Magain 1989), because analysis of several curves of growth showed that the dependence of B abundances on this stellar parameter is negligible, though microturbulence would affect the blending Co line, which we discuss more fully below.

Fig. 2 presents spectrum synthesis fits for BD −13 3442; the fits presented are calculated to have log ϵ(B)=+0.3, +0.1, and −0.4, the latter indicates what the abundance would be if this star had the solar B to metals ratio. Table 1 presents the stellar parameters and B abundance for BD −13 3442.

Table 1 also presents parameters from the three most metal-poor stars of our recent study (Duncan et al. 1997): HD 140283, which for several years was the most metal-poor star with detected B (Duncan et al. 1992), and BD +3 740. The metallicities determined by us for these stars are consistent with the ranges found by other workers (see compilation by Cayrel de Strobel et al. 1997). Fig. 3 compares the observed spectra of BD −13 3442 with that of HD 140283 and BD +3 740. It is clear that BD −13 3442 is the most metal-poor of the three stars.

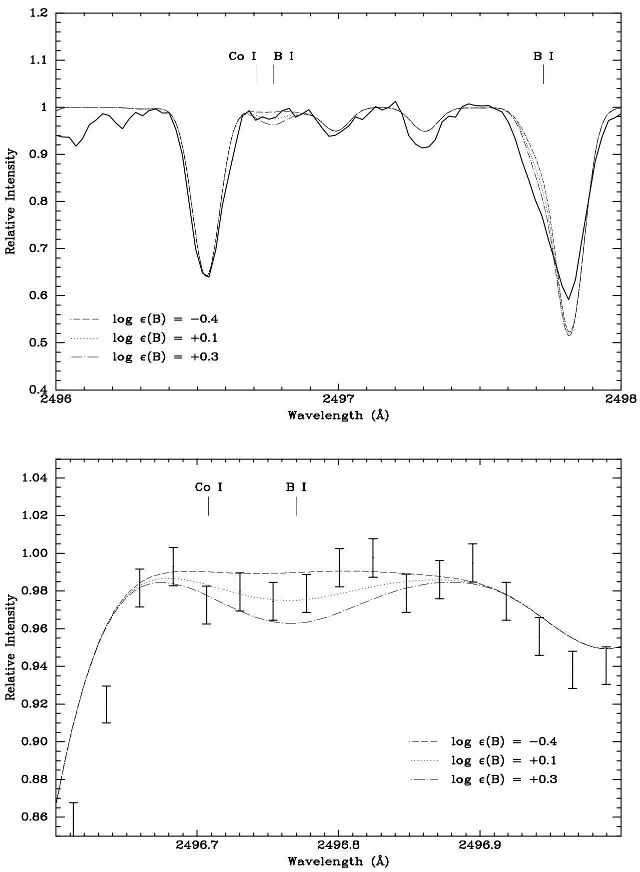

Fig. 2. a Spectrum synthesis fits for BD −13 3442. **b** Enlarged view of fits near the B lines.

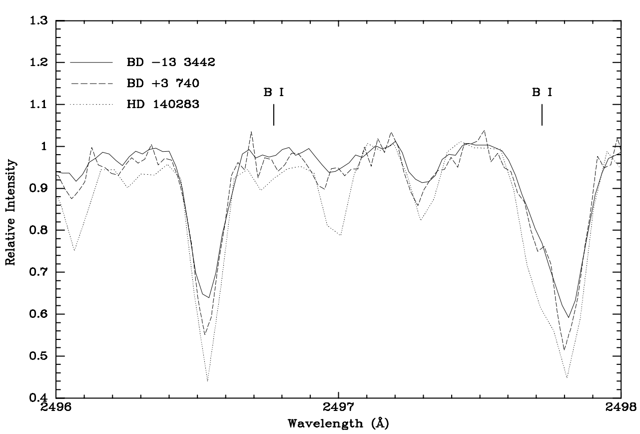

Fig. 3. Comparison of BD −13 3442, HD 140283, and BD +3 740.

3.2. Uncertainties

Considerable care was taken in determining the error of the abundance determination. Sources of error we considered included uncertainties in stellar $T_{\rm eff}$, $\log g$, and [Fe/H] (all of which change the atmosphere used in the analysis), continuum placement, photon statistics in the points defining the line itself, and the effect of metal lines which blend with the B features.

In such a metal-poor star the continuum is relatively easy to define but the B line is weak. Table 2 presents, in order, effects due to uncertainties in stellar $T_{\rm eff}$, $\log g$, [Fe/H], continuum location and photon statistics in the B line, as well as the total (net) error. We quantified the dependence of the B abundance on changes in the main stellar parameters by running multiple syntheses and curves of growth, although curves of growth are less reliable since the B lines are blended. From available literature determinations for this star, we considered ±75 K, ±0.30, and ±0.10 dex to be typical uncertainties to be associated with $T_{\rm eff}$, $\log g$, and [Fe/H] respectively. Errors for BD +3 740 and HD 140283 are also included in Table 2 for comparison.

Uncertainty in stellar metallicity in metal-poor stars causes error due to lines which blend with the B features. At our resolution, the Co I 2496.708 Å feature blends with B I 2496.772 Å. Assumption of a higher metallicity attributes more of the blend to Co, decreasing the derived B abundance, and vice-versa for a lower assumed metallicity. The column "[Fe/H]" in Table 2 gives the amount of this direct effect when the metallicity is uncertain by ±0.1 dex.

McWilliam et al. (1995) studied Co in their spectroscopic analysis of the most metal-poor stars. They present evidence that Co remains scaled-solar to [Fe/H] ~ -2.5, but that it increases by ∼0.5 dex as [Fe/H] decreases to −3.0. Since our spectra do not resolve the Co-B blend, overabundance of Co means that the B abundances should be decreased. However, the blend between the Co and B features is only partial and an increase in Co of a given amount produces a decrease in B abundance of a smaller amount. Synthesis testing with [Co/H] increased by 0.1 and 0.3 dex caused a decrease in B abundance of about 0.05 and 0.15 dex respectively. The data are not consistent with [Co/H] enhanced by 0.5 dex. Since we have no way of deblending the lines, this error is not included in Table 2; it should be considered a systematic effect which could affect the derived abundance, and at worst case, our abundance represents an upper limit. That this effect is unlikely to be large is supported by the good agreement of the B abundance derived by Duncan et al. (1997) for the slightly more metal-rich star HD 140283 with that of the higher resolution study of Edvardsson et al. (1993), which partially resolves the Co-B blend. The spectrum for BD −13 3442 is similar in resolution to that for HD 140283 in Duncan et al. (1997).

3.3. NLTE abundances

The largest source of systematic errors in our B abundance is likely to be due to NLTE effects. As calculated by Kiselman (1994), and Kiselman & Carlsson (1996), NLTE effects increase B abundances most significantly in

Table 2. Uncertainties affecting the derived B abundance

star	$T_{\rm eff}$ ±75 K	$\log g$ ±0.30	[Fe/H] ±0.10	Continuum ±0.5%	Photon Statistics	**Net Error**
BD −13 3442	±0.09	±0.03	±0.10	±0.10	±0.10	**±0.20**
BD +3 740[a]	±0.08	±0.05	±0.10	±0.10[b]	±0.23	**±0.29**
HD 140283[c]	±0.08	±0.05	±0.10	±0.10[d]	±0.06	**±0.18**

[a] Final boron abundance 0.22 LTE and 1.04 NLTE.
[b] ±1.5% in the continuum.
[c] Final boron abundance −0.10 LTE and 0.35 NLTE.
[d] ±1.5% in the continuum.

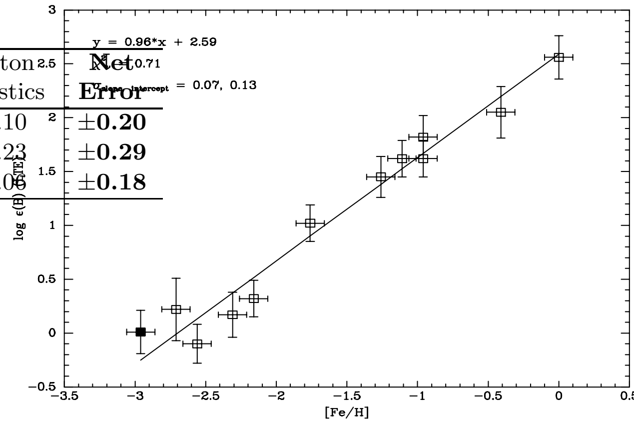

Fig. 4. LTE B abundances from Duncan et al. (1997) with the program star highlighted.

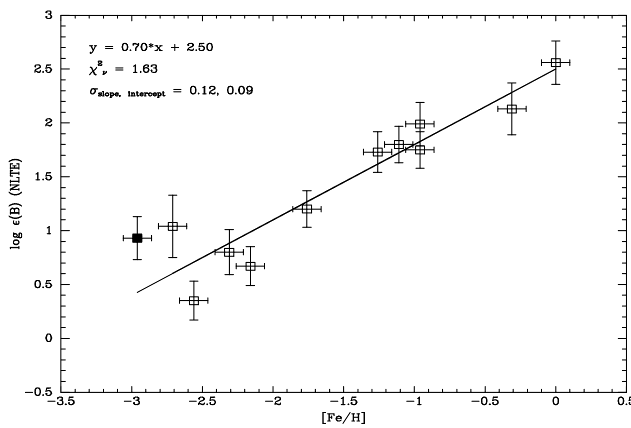

Fig. 5. NLTE B abundances from Duncan et al. (1997) with the program star highlighted.

the most metal-poor stars. The relatively hot uv radiation fields in metal-poor stars drive the detailed balance of the B resonance lines away from statistical equilibrium. Overionization and optical pumping tend to weaken the B I 2498 Å doublet, which leads to an underestimate of the B abundance. NLTE calculations are difficult, being limited both by the incomplete understanding of the atomic physics involved and especially by the uncertainties in the uv flux values at the precise absorption wavelengths. The Kiselman & Carlsson (1996) study is improved over the Kiselman (1994) one in that it models the effects of large numbers of lines in the background radiation field, which tend to decrease NLTE effects. Results of the two studies differ by approximately 0.1 dex; present NLTE calculations are necessarily less accurate than that amount. The Kiselman & Carlsson NLTE correction for BD −13 3442 is +0.92 dex.

4. Discussion

Fig. 4 shows the LTE abundances as a function of [Fe/H] from stars analyzed in the larger investigation of Duncan et al. (1997), with the point for BD −13 3442 from the present investigation emphasized. It can be seen that there is an approximately linear relation between log $\epsilon({\rm B_{LTE}})$ and [Fe/H] over both disk and halo metallicities, and that BD −13 3442 is consistent with this relationship. A least-squares fit to all the data of Fig. 4 (allowing for errors in both coordinates) yields a slope of 0.96±0.07 and a reduced chi square, χ^2_ν, of 0.71, indicating an excellent fit. If NLTE abundances are used, as shown in Fig. 5, the slope is 0.70±0.07 and $\chi^2_\nu = 1.63$. Although it is true that BD −13 3442 is used to determine this line, it is important to note that this star is quite consistent with the trend defined by the other stars. Inspection and χ^2_ν tests confirm this.

4.1. Comparison to standard models and a new model for light element production

The slope of close to 1 suggesting a primary process is *not* expected from canonical models of CR spallation in the ISM, which predict a secondary process and thus a steeper relation. In a secondary process the rate of light element production depends on the product of the abundance of target CNO nuclei and the CR flux, both of which vary with time. If SNe are the source of the target nuclei and the ISM is well-mixed, the ISM metallicity is proportional to the integral (total) number of SN up to a given time. If, as is commonly supposed, SNe also seed the acceleration mechanism which produces CRs, the CR flux is proportional to the SN rate. The result is light element abundances which vary quadratically with the metallicity of the ISM, or a logarithmic slope of 2 (Prantzos et al. 1993). Figs. 4 and 5 show that such a slope is certainly not consistent with our data. Duncan et al. (1997) discuss these issues in greater detail.

As was discussed by Duncan, Lambert, and Lemke (1992), the data for the first three metal-poor stars observed for B already seemed to show a linear (in the log) relationship with [Fe/H], suggesting some primary production mechanism rather than the secondary mechanism in the ISM described above. This idea has been modelled in detail by Cassé et al. (1995), Ramaty et al. (1995 and 1997), Lemoine et al. (1997), and Vangioni-Flam et al. (1996). In the new scenario, B and Be are primarily produced by the spallation of C and O onto protons and α particles. Such a process could occur near massive star SNe, where the particle flux would be very non-solar in composition; depleted in H and He and especially enriched in O and C. Vangioni-Flam et al. find that a composition matching either winds from massive (Wolf-Rayet; WR) stars in star-forming regions or massive star SNe produce a flux of O and C which, after further acceleration, can reproduce both the magnitude and slope of B production seen in Figs. 4 and 5 through collisions with protons and α particles. As Ramaty et al. point out, production of some additional ^{11}B by the neutrino process (Woosley et al. 1990) is not ruled out, and may be favored on energetic grounds. Nevertheless the bulk of the B and Be would be produced from the spallation process.

Although the NLTE correction to the B abundance of BD −13 3442 is relatively large and tends to raise the B abundance above the line in Fig. 5, two other effects not included here would tend to move it closer to the curve. One is the effect of the blending Co line discussed above, which could reduce the B abundance as much as ∼0.15 dex. The other is the fact that if the spallation producing light elements is caused by O (and to a lesser extent C), log ϵ(B) should be plotted against [O/H] rather than [Fe/H]. As is well-known, very metal-poor stars are overabundant in O compared to Fe (moving points representing the most metal-poor stars to the right in a figure with O on the x-axis). Duncan et al. (1997) make such a plot, and demonstrate that although the measurement errors in O are greater than those for Fe, when all the metal-poor stars are considered together a straight line of slope 1.10±0.14 fits the LTE abundances, and one of slope 0.82±0.10 the NLTE abundances. However, oxygen abundance measurements are also surrounded by greater uncertainty than are iron measurements, and systematic errors in the oxygen abundance which depend on metallicity will affect the derived slope.

5. Summary

The present investigation has presented an analysis of B in BD −13 3442. At a metallicity of [Fe/H]=−3.0, this is the most metal-poor star ever observed for B. Careful spectrum synthesis was performed to determine both the B abundance and its uncertainty. NLTE corrections were also considered.

We find that BD −13 3442 is consistent with the straight line of slope close to 1 between log ϵ(B) vs. [Fe/H] or log ϵ(B) vs. [O/H] found by Duncan et al. (1997). This suggests that the production of light elements such as B and Be is directly related to the production of heavier elements. Canonical models which only include spallation by the process of protons and α particles impinging onto the general Galactic ISM predict a steeper relation which fails to fit all the data now available.

Spallation via the reverse process of energetic C and O nuclei onto protons and α particles does much better in explaining the linear relationship observed. This reverse process was historically discarded as a minor effect (e.g. 20% according to the calculations of Walker et al. 1993) since the canonical theory assumed a CR and ISM composition similar to that in the solar system. A population of low-energy CRs enriched in C and O and depleted in H and He can produce light elements by spallation onto the ambient medium. The metallicity of the medium would have little effect, and the process would operate the same throughout the life of the Galaxy, leading to the observed slope of 1. A model in which most light element production comes from CR spallation of C and O nuclei onto protons and α particles in the vicinity of massive supernovae in star-forming regions fits the data well. If particle compositions are taken from calculations of either massive star SNe or WR stars, spallation can reproduce both the magnitude and slope of the observed B evolution (Ramaty et al. 1996) while maintaining consistency with the other light element abundances. The observations of B in BD −13 3442 provide the strongest evidence of how CR spallation operated in the very early galaxy.

Acknowledgements. We thank Michel Cassé, Reuven Ramaty, Hubert Reeves, Elizabeth Vangioni-Flam, and Stan Woosley for their comments.

This research was based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This research has made use of NASA's Astrophysics Data System Abstract Service.

CPD gratefully acknowledges support provided by the University of Hawaii Foundation, and subsequently by NASA through grant HF-1042.01-93A from the Space Telescope Science Institute.

References

Bloemen, H., Wijnands, R., Bennett, K., Diehl, R., Hermsen, W., Lichti, G., Morris, D., Ryan, J., Schönfelder, V., Strong, A. W., Swanenburg, B. N., de Vries, C., & Winkler, C. 1994, A&A, 281, L5

Bykov, A., & Bloemen, H. 1994, A&A, 283, L1

Cassé, M., Lehoucq, R., Vangioni-Flam, E. 1995, Nature, 373, 318

Cayrel de Strobel, G., Soubiran, C., Friel, E.D., Ralite, N., Francois, P., 1997, A&AS, 124, 299

Duncan, D. K., Lambert, D. L., Lemke, M. 1992, ApJ, 401, 584

Duncan, D.K., Peterson, R.C., Thorburn, J.A., Pinsonneault, M.H., & Deliyannis, C.P. 1998, ApJ, in press

Duncan, D.K., Primas, F., Rebull, L.M., Boesgaard, A.M., Deliyannis, C.P., Hobbs, L.M., King, J.R., Ryan, S. 1997, ApJ, 488, 338

Edvardsson, B., Gustafsson, B., Johansson, S.G., Kiselman, D., Lambert, D.L., Nissen, P.E., & Gilmore, G. 1994, A&A, 290, 176
Edvardsson, B., Gustafsson, B., Kiselman, D., Lambert, bD.L., Nissen, P., Gilmore, G. 1993, A&A, 290, 176
Gustafsson, B., Bell, R.A., Eriksson, K., Nordlund, A. 1975, A&A, 42, 407
Kiselman, D. 1994, A&A, 286, 169
Kiselman, D., & Carlsson, M., 1996, A&A, 311, 680
Kurucz, R.L. 1993, CD-ROM # 1,13,18
Magain, P. 1989, A&A, 209, 211
Lemoine, M., Vangioni-Flam, E, & Cassé, M., 1998, ApJ, in press
McWilliam, A., Preston, G.W., Sneden, C., Searle, L. 1995, AJ, 109, 2757
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337 (MAR)
Murphy, R.J., Share, G.H., Grove, J.E., Johnson, W.N., Kurfess, J.D., Purcell, W.R., McNaron-Brown, K., & Ramaty, R. 1996, ApJ, 473, 990
O'Brian, T.R. & Lawler, J.E. 1992, A&A, 255, 420
Prantzos, N., Cassé, M., & Vangioni-Flam, E. 1993, ApJ, 403, 630 (PCV)
Ramaty, R., Kozlovsky, B., & Lingenfelter, R.E. 1996, ApJ, 456, 525
Ramaty, R., Kozlovsky, B., Lingenfelter, R.E., & Reeves, H. 1997, ApJ, 488, 730
Reeves, H., Audouze, J., Fowler, W.A., & Schramm, D.N. 1973, ApJ, 179, 909
Reeves, H., Fowler, W.A., & Hoyle, F. 1970, Nature, 226, 727
Reeves, H., & Meyer, J.-P. 1978, ApJ, 226, 613
Ryan, S. G., Norris, J. E., Bessell, M. S., & Deliyannis, C. P. 1991, ApJ, 388, 184
Vangioni-Flam, E., Audouze, J., Oberto, Y., & Cassé, M. 1990, ApJ, 364, 568
Vangioni-Flam, E., Cassé, M., Fields, B.D., Olive, K.A., 1996, ApJ, 468, 199
Walker, T.P., Steigman, G., Schramm, D.N., Olive, K.A., & Fields, B.D. 1993, ApJ, 413, 562
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272