THE ASTROPHYSICAL JOURNAL, 194:L143–L146, 1974 December 15


# THE ABUNDANCE OF BORON AND BERYLLIUM IN ALPHA LYRAE

ANN MERCHANT BOESGAARD* AND FRANÇOISE PRADERIE
Institut d'Astrophysique, Paris

DAVID S. LECKRONE†
Goddard Space Flight Center, Greenbelt, Maryland

AND

R. FARAGGIANA AND M. HACK†
Astronomical Observatory, Trieste
*Received 1974 July 29; revised 1974 September 13*

## ABSTRACT

*Copernicus* satellite observations have been used to measure the equivalent width of the B II resonance line λ1362 in α Lyr. Bonsack has determined the equivalent width for a Be II resonance line λ3130. Model atmosphere analyses of α Lyr result in LTE abundances of B/H = 1–2 × $10^{-10}$ and Be/H = 1 × $10^{-11}$. The maximum possible LTE abundance of B, obtained by taking extreme values of all the atmospheric and atomic parameters, is B/H ≤ 7 × $10^{-10}$, an extreme upper limit. An estimate of the non-LTE effects on these resonance lines indicates that Be is formed in LTE conditions and that the B/H ratio is 70 percent or more of the LTE value. The final abundances are B/H ≃ 1 × $10^{-10}$, Be/H = 1 × $10^{-11}$, and B/Be ≃ 10. It is argued that these represent the true cosmic abundances of B and Be within a factor of 3, and that both elements are produced by galactic cosmic-ray bombardment of heavier elements.

*Subject headings:* abundances, stellar — stars, individual

## I. INTRODUCTION

Studies of the rare light elements (Li, Be, B) have concentrated on Li I and Be II since their resonance lines lie in spectral regions accessible from the ground. The resonance lines of both B I λ2498 and B II λ1362 are in the rocket or satellite ultraviolet. The only stellar B abundance known is for the Mn Ap star κ Cnc from a very weak, high-excitation line of B II (Boesgaard and Heacox 1973). Underhill (1974) suggests B II as a possible contributor—along with Si III—to a weak feature at λ1362.4 in η CMa (B5 Ia). We report here the results of *Copernicus* satellite observations of the B II resonance line in the A0 V star, α Lyrae (Vega). In addition we have redetermined the Be abundance in Vega based on observations of the Be II resonance line by Bonsack (1961). Thus we find B/H, Be/H, and B/Be for a seemingly normal main-sequence star.

## II. OBSERVATIONS

Two scans covering the region of the B II line were made with the *Copernicus* satellite 1973 August 28–September 19, with the intermediate-resolution U2 phototube. The instrumental line width is ~0.2 Å. The equipment is described by Rogerson *et al.* (1973).

The B II line at λ1362.460 is indicated on a reproduction of one of the scans in figure 1. The scans have been corrected by one of us (D. S. L.) for background particles, stray light, and scattered light following a routine set up by R. Bohlin. Complete line identifications have been done independently by Leckrone and by Faraggiana and Hack from scans covering several hundred angstroms. We conclude that B II is by far the major contributor to the feature at 1362.46. A

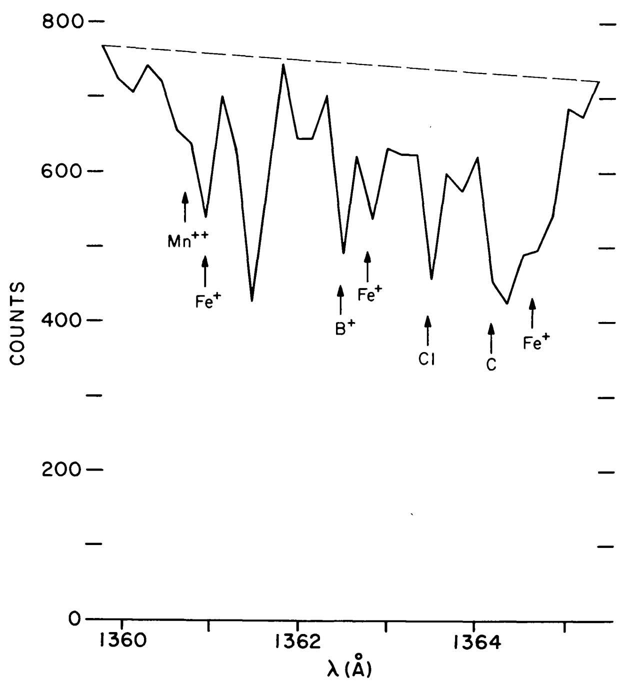


FIG. 1.—*Copernicus* U2 scan #70.01 of the B II region in α Lyr, corrected for stray light and scattered light. The wavelengths of the B II line and some other features are indicated. The dashed line represents the local continuum.

* On leave from Institute for Astronomy, University of Hawaii.

† Guest Investigators with the Princeton University Telescope on the *Copernicus* satellite, which is sponsored and operated by the National Aeronautics and Space Administration.

Si III line from multiplet 38 at λ1362.366 may contribute 4–9 mÅ to the equivalent width, and very weak nearby lines of Cu II, V III, and Zn I may contribute a few milliangstroms together. None of the other lines listed by Kelly and Palumbo (1973) within ±0.3 Å are present in α Lyr. Since α Lyr is only 8 pc away, we expect little or no contribution from interstellar B II.

The continuum was positioned as an upper envelope of the observed spectrum over a region of about 25 Å centered near the B II line. A line profile (approximately triangular) has been drawn for the B II feature. The measured equivalent width of B II, corrected for a small contribution of possible, weak blending lines is 0.070 Å on one scan and 0.073 Å on the other.

Bonsack (1961) measured a blended line at λ3130 of total equivalent width $W_{3130} = 0.026$ Å on spectrograms of 1.0 and 2.9 Å $mm^{-1}$ from the 100-inch telescope at Mount Wilson. He estimates that $W$(Be/$W$(3130) = 0.3 so that $W$(Be) = 0.008 Å.

## III. ANALYSIS

### *a) LTE Analysis*

Independent LTE estimates of the B/H ratio in Vega were derived at the Institut d'Astrophysique and at the Goddard Space Flight Center. Although different in approach with regard to choice of model atmospheres, to the treatment of blends, and to the choice of observed line strength criteria, the two analyses yielded identical results in those cases where identical microturbulent parameters, ξ, and line $gf$-values were adopted. The Paris analysis also treated the Be II λ3130 feature. Details of the analyses are given in table 1.

In the Paris analysis, theoretical equivalent widths were matched to the observed values, corrected for blending as outlined in § II. Two model atmospheres for Vega were tested—that of Schild, Peterson, and Oke (1971) and that of Peterson (1968)—with the former preferred by virtue of a better agreement between its predicted flux distribution and TD1 satellite observations (Malaise, Gros, and Macau 1974; Beeckmans, Malaise, and Macau 1974). Two values of the microturbulence parameter ξ were tested, 1 and 3 km $s^{-1}$, where 3 km $s^{-1}$ is the preferred value following analyses of Vega by Hunger (1955) and Gehlich (1969). The usual sources of continuous opacity were used plus Lα with natural broadening, resonance broadening after Sando (Praderie and Stecher 1973), and Stark broadening (Vidal, Cooper, and Smith 1973). Radiation damping and van der Waals broadening were assumed for the B II and Be II lines. The Paris analysis used the theoretical $gf$-value 1.1 for B II λ1362 (Wiese, Smith, and Glennon 1966; Burke, Hibbert, and Robb, 1972; Nicholaides, Beck, and Sinanoglu 1973) in preference to beam-foil and other experimental determinations for this resonance line. (The value preferred by Smith and Wiese 1971 from comparisons along isoelectronic sequences is 0.94, not significantly different from the theoretical value adopted here.)

The GSFC analysis utilized the heavily line-blanketed model atmospheres of Fowler (1972, 1974) with assumptions about continuous opacities as described in these

TABLE 1

ABUNDANCE RESULTS

| Feature | Observed* Strength | Assumptions† | Derived‡ $N$(Element)/$N$(H) | Adopted LTE Abundance | Non-LTE Abundance |
|---|---|---|---|---|---|
| | | | Paris Analysis | | |
| Be II λ3130..... | −5.66±0.24 | *a* | $1(+1, -0.5)\times10^{-11}$ | $1\times10^{-11}$ | $1\times10^{-11}$ |
| | | *b* | $1(+1, -0.5)\times10^{-11}$ | | |
| | | *c* | $6(+6, -3)\times10^{-12}$ | | |
| | | *d* | $6(+6, -3)\times10^{-12}$ | | |
| B II λ1362...... | −4.28±0.16 | *a* | $1.9(+1, -0.7)\times10^{-10}$ | $1\text{–}2\times10^{-10}$ | $\sim1\times10^{-10}$ |
| | | *b* | $1.1(+0.7, -0.4)\times10^{-10}$ | | |
| | | *c* | $1.9(+1, -0.7)\times10^{-10}$ | | |
| | | *d* | $1.1(+0.7, -0.4)\times10^{-10}$ | | |
| | | | GSFC Analysis | | |
| B II λ1362...... | 0.63±0.04 | *e* | $4(+4, -2)\times10^{-10}$ | $1\text{–}2\times10^{-10}$ | |
| | | *f* | $1.1(+0.7, -0.4)\times10^{-10}$ | | |
| | | | B/Be | 10–20 | ~10 |

* Paris analysis, log $W/\lambda$ corrected for blends. GSFC analysis, estimated residual flux at 1362.428 Å, the nearest data point to B II line center.

† Paris analysis: *a*, *b*, Schild *et al.* (1971) model with ξ = 1 and 3 km $s^{-1}$, respectively, B II $gf$ = 1.1 (Wiese *et al.* 1966), Be II $gf$ = 0.70 (Allen 1963); *c*, *d*, same as *a*, *b* except with Peterson's (1968) model. GSFC analysis: *e*, Fowler's (1972, 1974) models 9375°– 9750° K, log $g$ = 4.0, ξ = 0, B II $gf$ = 0.821 (Morton and Smith 1973), blended with Si III λ1362.37, Si III $gf$ = 0.30 (Wiese *et al.* 1966), $N$(Si)/$N$(H) = $3.55 \times 10^{-5}$ (Withbroe 1971); *f*, same as *e* except with ξ = 3 km $s^{-1}$, B II $gf$ = 1.1, $N$(Si)/$N$(H) = $8.71 \times 10^{-5}$ (Strom *et al.* 1966).

‡ Uncertainty ranges in Paris abundances correspond to uncertainties in measured equivalent widths and in $gf$-values. Uncertainty ranges in GSFC abundances correspond to uncertainty in measured residual flux and in choice of model effective temperature.

references and line damping constants approximated by $3gf\gamma$ (classical). It was assumed that the only lines contributing significant opacity at *Copernicus* data point 1362.428 Å were Si III λ1362.366 and B II λ1362.461. Theoretical profiles of this blend were convolved with the trapezoidal slit function appropriate for the spectrometer and matched to the observed residual flux at the data point in question. Calculations were made for three log $g = 4.0$ models, $T_{\rm eff} = 9375°$, 9500°, and 9750°—models which bracket Vega in terms of its Balmer jump and Paschen slope (Oke and Schild 1970). The derived B/H ratio proved far less sensitive to model $T_{\rm eff}$ than to other parameters of the computation, and no attempt was made to derive an optimized model within this $T_{\rm eff}$ range.

Cases *e* and *f* in table 1 represent two extremes, the former with $\xi$, B II *gf*-value, and Si/H ratio chosen to maximize the derived B/H ratio, the latter with these parameters chosen to minimize B/H. Assuming the parameters of case *e* and at the same time assuming the B II line to be stronger than we have estimated from the observations by a plausible amount, one can force the derived B/H ratio to values as high as (7–8) × $10^{10}$. Similarly, one can force it to values as low as (7–8) × $10^{-11}$ with case *f*. We consider both extremes unlikely (the former more so than the latter), and we adopt an LTE value in the range $N(\text{B})/N(\text{H}) = (1\text{–}2) \times 10^{-10}$.

The Be/H value adopted in the Paris analysis, together with the value of B/H determined in both analyses (cases *b* and *f*), yields a B/Be ratio in the range 10–20 for Vega.

### *b) Estimate of Departures from LTE*

For each of the lines studied we use the model by Schild *et al.* (1971) to compare the source function at the line center, $S_L$, to the Planck function $B_\nu$. We assume that the continuum source function is $B_\nu$, which may be doubtful for B II λ1362 (the continuum there is due mainly to C I photoionization). We approximate $B_\nu$ by a linear function of $\tau_c$.

At various depths around $\tau_0$(at line center) = 1 we found that the line source function for both the B II and Be II lines was collision rather than photoionization dominated (Thomas 1957), approximating $S_L$ by its explicit expression for a two-level atom plus continuum (e.g., Jefferies 1968). We then showed that around $\tau_0 = 1$ the ratio $r_0 = d\tau_c/d\tau_0$ is much larger than $\epsilon$, the ratio of collisional to spontaneous de-excitation rates. In that case the *total* source function in the line is controlled by the radiation in the neighboring continuum rather than by electronic collisions within the atom itself.

Following Athay (1972), we define $\delta$ as a mean average probability that a line photon will be absorbed in a continuum transition, and compare $S_L$ to $B_\nu$ between $\tau_0 \simeq 1$ and $\tau_c \simeq 1$ for each of the studied lines. (*a*) For Be II, the line is very weak, $\delta \simeq 1$, $S_L \simeq B_\nu$, whatever $\tau_c$; i.e., LTE holds. (*b*) For B II, the line is near the shoulder of the curve of growth. From $\tau_0 \simeq 1$ to $\tau_c \simeq 1$, $\delta$ varies from 0.5 to 0.9. The largest departure of $S_L$ relative to $B_\nu$ occurs close to the surface:

$$S_L(0) \simeq \sqrt{\delta}\, B_\nu(\tau_0 \simeq \tau_{\rm th})\ ,$$

where $\tau_{\rm th}$ is the thermalization length. Taking into account that $B_\nu^{-1}(dB_\nu/d\tau_c) \simeq 6$ around $\tau_0 \simeq 1$, which leads to $B_\nu(\tau_0 \simeq \tau_{\rm th}) \simeq B_\nu(0)$, we have $S_L(0)/B_\nu(0) = 0.7$ at the line center. Therefore, $0.7(\text{B/H})_{\rm LTE} \leq (\text{B/H})_{\rm non-LTE} \leq (\text{B/H})_{\rm LTE}$. We conclude that $(\text{B/H})_{\rm non-LTE}$ could range from $0.84 \times 10^{-10}$ to the LTE value (the best estimate of which is taken to be $1.2 \times 10^{-10}$), and take B/H = $1 \times 10^{-10}$ as the abundance in round numbers.

## IV. DISCUSSION

The final results for Vega (corrected for non-LTE effects) are presented in table 2 with data on B and Be abundances in the Sun, meteorites, and the interstellar medium. The ratios B/H, Be/H, and B/Be predicted by Meneguzzi, Audouze, and Reeves (1971) for spallation of C, N, O nuclei by high-energy galactic cosmic rays are also given in the column labeled G.C.R.

General abundance determinations for $\alpha$ Lyr show it to have normal solar abundances, but with Na and Ni perhaps enhanced by an order of magnitude and Y underabundant by a similar amount (Hunger 1960; Strom, Gingerich, and Strom 1966; Gehlich 1969). We submit that the B and Be abundances in $\alpha$ Lyr also represent true cosmic abundances based on the following arguments:

1. Theory predicts that there will be no pre–main-sequence convective depletion by ($p$, $\alpha$) reactions of B or Be in a star as hot as $\alpha$ Lyr. Only stars arriving on the main sequence at spectral type K2 or cooler will deplete any Be in pre–main-sequence contraction (Bodenheimer 1966). The cross-section of B for ($p$, $\alpha$) reactions is less than that for Be (Salpeter 1955), so B is even less susceptible to pre–main-sequence deple-

TABLE 2

BERYLLIUM AND BORON ABUNDANCES

| Ratio | Vega | G.C.R. | Interstellar | Ref. | Sun | Ref. | Meteorites | Ref. |
|---|---|---|---|---|---|---|---|---|
| Be/H...... | $1\times10^{-11}$ | $2\times10^{-11}$ | $<5 \times10^{-11}$ | a | $1\times10^{-11}$ | c | $1.5\times10^{-11}$ | e |
| B/H....... | $1\times10^{-10}$ | $3\times10^{-10}$ | $\leq7.6\times10^{-11}$ | b | $<3\times10^{-10}$ | d | 4–6 $\times10^{-9}$ | f1 |
| | | | | | | | 2–24 $\times10^{-10}$ | f2 |
| B/Be...... | ~10 | 15 | ... | | <30 | | 330 | |
| | | | | | | | 13–160 | |

REFERENCES.—[a] Boesgaard 1974; [b] Morton *et al.* 1974; [c] Ross and Aller 1974; [d] Engvold 1970; [e] Sill and Willis 1962; [f1] Baedecker 1971, carbonaceous chondrites; [f2] Baedecker 1971, ordinary chondrites.

tion. Since an A0 V star has such a small outer convection zone (the temperature at the bottom is no higher than $\approx 50,000°$ K), the B and Be atoms on the surface will not be transported to regions where the temperature is the $(2-3) \times 10^6$ °K necessary for the destructive reactions to take place. Even if $\alpha$ Lyr is slightly evolved off the main sequence as Strom *et al.* (1966) suggest, it will not have undergone any post-main-sequence convective dilution.

2. The B and Be abundances in $\alpha$ Lyr are consistent with the upper limits for interstellar B and Be. Field (1974) estimates that atomic B should be depleted by a factor of 2 and atomic Be by a factor of 20 in the interstellar medium due to concentration in molecules and grains. Thus the interstellar matter could in fact have the same abundances of Be and B as $\alpha$ Lyr, even though the recent determination by Morton, Smith, and Stecher (1974) of an upper limit of B/H in front of $\zeta$ Oph is slightly less than B/H in $\alpha$ Lyr.

3. The only serious conflict between $\alpha$ Lyr and the solar system abundances is the meteoritic B abundance. Since B is volatile as a gas and very refractory as a metal, we concur with the statement by Morton *et al.* (1974) that "it is necessary to assume either that no type of meteorite is acceptable as a boron standard, or that the analyses are in error." For $\alpha$ Lyr no reasonable combination of computational assumptions and observational errors can force the B/H ratio derived to values as high as those typical of carbonaceous chondrites. Furthermore, there are other inconsistencies with the "cosmic" abundance of $B/H = 10^{-8}$ that has been suggested by Cameron, Colgate, and Grossman (1973); some of those contradictions have been discussed by Audouze, Lequeux, and Reeves (1973).

The ratios Be/H, B/H, and B/Be are close to the predictions of the galactic cosmic-ray spallation theory. The Be/H and B/H are a factor of 2–3 below the predictions, but this is certainly within the errors of our determination and the intrinsic cosmic scatter. Zappala (1972) has found that the true initial Li abundances show a spread of a factor of 4 ($Li_0/H = 5-20 \times 10^{-10}$); by analogy one expects a similar spread for Be and B.

In summary, we conclude that the abundances determined for $\alpha$ Lyr of B and Be are within a factor of 3 of the true cosmic abundances. These cosmic abundances can be well accounted for by creation from galactic cosmic-ray bombardment of heavier interstellar atoms.

We wish to express our appreciation to Dr. Andrew Skumanich, Dr. Hubert Reeves, and Dr. William A. Fowler for their helpful comments and encouragement. We are indebted to members of the Princeton University Observatory for assistance with the *Copernicus* observations. A. M. B. is grateful to the Institut d'Astrophysique for support during her sabbatical stay there.

## REFERENCES


Allen, C. W. 1963, *Astrophysical Quantities* (2d ed.; London: Athlone Press), p. 67.
Athay, R. G. 1972, *Radiation Transport in Spectral Lines* (Dordrecht: Reidel).
Audouze, J., Lequeux, J., and Reeves, H. 1973, *Astr. and Ap.*, **28**, 85.
Baedecker, P. A. 1971, *Handbook of Elemental Abundances in Meteorites*, ed. B. Mason (New York: Gordon & Breach), p. 77.
Beeckmans, F., Macau, D., and Malaise, D. 1974, *Astr. and Ap.*, **33**, 93.
Bodenheimer, P. 1966, *Ap. J.*, **144**, 103.
Boesgaard, A. M. 1974, *Astr. and Ap.*, **34**, 9.
Boesgaard, A. M., and Heacox, W. D. 1973, *Ap. J.* (*Letters*), **185**, L25.
Bonsack, W. K. 1961, *Ap. J.*, **133**, 551.
Burke, P. G., Hibbert, A., and Robb, W. D. 1972, *J. Phys. B*, **5**, 37.
Cameron, A. G. W., Colgate, S. A., and Grossman, L. 1973, *Nature*, **243**, 204.
Engvold, O. 1970, *Solar Phys.*, **11**, 183.
Field, G. B. 1974, *Ap. J.*, **187**, 453.
Fowler, J. W. 1972, Ph.D. thesis, University of Maryland.
———. 1974, *Ap. J.*, **188**, 295.
Gehlich, U. K. 1969, *Astr. and Ap.*, **3**, 169.
Hunger, K. 1955, *Zs. f. Ap.*, **36**, 42.
———. 1960, *ibid.*, **49**, 129.
Jefferies, J. T. 1968, *Spectral Line Formation* (Waltham: Blaisdell).
Kelly, R. L., and Palumbo, L. J. 1973, *NRL Report*, No. 7599.
Malaise, D., Gros, M., and Macau, D. 1974, *Astr. and Ap.*, **33**, 79.
Meneguzzi, M., Audouze, J., and Reeves, H. 1971, *Astr. and Ap.*, **15**, 337.
Morton, D. C., and Smith, W. H. 1973, *Ap. J. Suppl.*, **26**, 333.
Morton, D. C., Smith, A. M., and Stecher, J. P. 1974, *Ap. J.* (*Letters*), **189**, L109.
Nicolaides, C. A., Beck, D. R., and Sinanoglu, O. 1973, *J. Phys. B.*, **6**, 62.
Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.
Peterson, D. M. 1968, *Smithsonian Ap. Obs. Spec. Report*, No. 293.
Praderie, F., and Stecher, T. P. 1973, *Astr. and Ap.*, **23**, 49.
Rogerson, J. B., Spitzer, L., Drake, J. F., Dressler, K., Jenkins, E. B., Morton, D. C., and York, D. G. 1973, *Ap. J.* (*Letters*), **181**, L97.
Ross, J. E., and Aller, L. H. 1974, *Solar Phys.*, **36**, 11.
Salpeter, E. E. 1955, *Phys. Rev.*, **97**, 1237.
Schild, R., Peterson, D. M., and Oke, J. B. 1971, *Ap. J.*, **166**, 95.
Sill, C. W., and Willis, C. P. 1962, *Geochim. Cosmochim. Acta*, **26**, 1209.
Smith, M. W., and Wiese, W. L. 1971, *Ap. J. Suppl.*, **23**, 103.
Strom, S. E. Gingerich, O., and Strom, K. M. 1966, *Ap. J.*, **146**, 880.
Thomas, R. N. 1957, *Ap. J.*, **125**, 260.
Underhill, A. B. 1974, *Ap. J. Suppl.*, **27**, 359.
Vidal, C. R., Cooper, J., and Smith, E. W. 1973, *Ap. J. Suppl.*, **25**, 37.
Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, NSRDS-NBS 4, Vol. 1.
Withbroe, G. L. 1971, in *The Menzel Symposium*, ed. K. Gebbie (*NBS Spec. Publ.*, No. 353), p. 127.
Zappala, R. R. 1972, *Ap. J.*, **172**, 57.



ANN MERCHANT BOESGAARD: Institute for Astronomy, 2840 Kolowalu Street, Honolulu, HI 96822

R. FARAGGIANA and M. HACK: Astronomical Observatory, Trieste, Italy

DAVID S. LECKRONE: Code 671, Goddard Space Flight Center, Greenbelt, MD 20771

FRANÇOISE PRADERIE: Institut d'Astrophysique, 98 bis. Bd Arago, 75014 Paris, France