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THE ABUNDANCE OF BORON IN VEGA AND SIRIUS

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ABSTRACT

High-resolution (0.05 Å) observations of the region of the B II resonance line (1362 Å) have been made of Vega (A0 V) and Sirius (A1 V) with the *Copernicus* satellite. A strong B II feature is present in Vega, but only a weak line, due primarily to V III, is present in Sirius. An upper limit of $B/H < 5 \times 10^{-12}$ is derived for Sirius from line-profile fitting. A local thermodynamic equilibrium (LTE) synthesis of the B II blend in Vega results in an abundance ratio $B/H = 1 \times 10^{-10}$. Calculations of the effects of non–LTE on the line profile show that the LTE abundance would not be increased by more than 50% ($B/H = 1.5 \times 10^{-10}$) to account for departures from LTE. The B content of Vega probably represents the cosmic B abundance. The B deficiency in Sirius could result from interaction with the white-dwarf companion at an earlier stage in its evolution or from diffusion processes in the Sirius atmosphere.

Difficult observations at 0.10 Å resolution of subordinate lines from multiplet (3) of B II at 1624 Å show that those lines are *not* present in Sirius; but the identification of B in Vega appears to be confirmed by the presence of weak lines at 1624 Å in this star.

Subject headings: nucleosynthesis — stars: abundances — stars: individual

I. INTRODUCTION

It is important to determine the cosmic or universal abundance of boron to understand the origin of the light elements (cf. Reeves 1974). It is a difficult project spectroscopically, however, since B is a trace element best observed in the resonance lines, but the resonance lines of B I are at 2498 Å and of B II at 1362 Å. The chemical properties of B make the abundance in meteorites unreliable as an indicator of the cosmic B abundance. Molecular lines and higher transitions in the solar spectrum have given only an upper-limit B abundance for the Sun.

Ultraviolet spectroscopy appears necessary to derive a reliable cosmic abundance. *Copernicus* spectra of Vega at a resolution of 0.2 Å showed that the resonance line of B II was present; Boesgaard *et al.* (1974) derived a B/H abundance ratio[1] of 1×10^{-10}. More recently, solar rocket observations (center and limb) at 0.028 Å resolution of the B I resonance line at λ2496 by Kohl, Parkinson, and Withbroe (1977) give $B/H \approx 4(+4, -2) \times 10^{-10}$ for the Sun. Boron abundance determinations or upper limits are given in Table 1.

The B II resonance line can be usefully searched for only in stars where the region near 1300 Å is not of chromospheric origin, i.e., not in solar-type stars. Since B II is an abundant ion in the photospheric layers of stars with T_{eff} between 9000 and 14,000 K, we decided to study the 1362.46 Å line in Sirius (A1 V) and Vega (A0 V).[2] Observations of this feature have been made in both stars at a resolution of 0.05 Å with the *Copernicus* satellite (Rogerson *et al.* 1973).

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[1] Throughout the paper, the notation element/hydrogen, e.g., B/H, indicates the abundance ratio by number of atoms.

[2] Sirius = α CMa = HR 2491; Vega = α Lyr = HR 7001.

TABLE 1

SUMMARY OF BORON ABUNDANCES

Object	B/H	Spectral Features or Sample Studied	Reference
Sun	$< 6 \times 10^{-10}$	Absence of IR lines of B I	Grevesse 1968
	$< 3 \times 10^{-10}$	No BH lines in sunspots	Engvold 1970
	$< 1.2 \times 10^{-10}$	No B I line at λ = 16240 Å	Hall and Engvold 1975
	4×10^{-10}	Line λ2496.8 (B I)	Kohl *et al.* 1977
Meteorites	$3\text{–}6 \times 10^{-9}$	Carbonaceous chondrites	Baedecker 1971
	$2\text{–}5 \times 10^{-10}$	Enstatites	Baedecker 1971
Interstellar matter	$< 2 \times 10^{-9}$	λ1362.46 (B II)	Audouze *et al.* 1973
	$< 0.76 \times 10^{-11}$	λ1362.46 (B II)	Morton *et al.* 1974
Stars:			
κ Cancri	2×10^{-7}	λ3451.29 (B II)	Boesgaard and Heacox 1973
α Lyrae	1.0×10^{-10}	λ1362.46 (B II)	Boesgaard *et al.* 1974

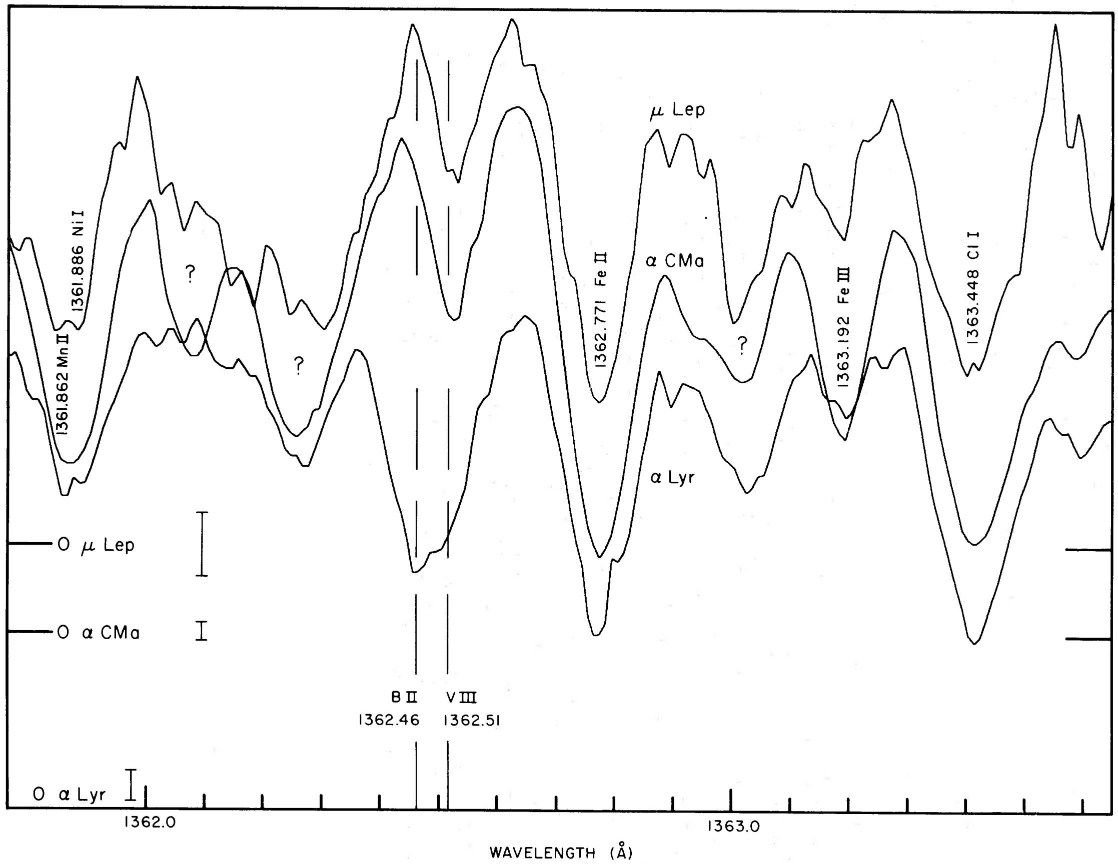

FIG. 1.—U1 scans in the B II 1362 Å region of Vega (A0 V), Sirius (A1 V), and μ Lep (Hg–Mn Ap star). In this figure, the intensity scale has been corrected for particle background but not for diffuse light, and normalized to a 0–100 scale. The zero level for each star is given at the left. The error bar shown represents $\pm 1\ \sigma$ from the photon counting statistics. Note that only V III appears present in Sirius and μ Lep, and the B II feature in Vega is asymmetric owing to the blend with V III. Identifications for several other lines are given. Question marks indicate that the line cannot be identified.

II. OBSERVATIONS OF B II LINES IN VEGA AND SIRIUS

a) *Resonance Line*

High-resolution spectra were obtained with the U1 phototube on the *Copernicus* satellite in the region of the B II λ1362.46 ($2s^2\ ^1S$–$2p\ ^1P^o$) line. Figure 1 shows the observations for Vega (HR 7001, A0 V), Sirius (HR 2491, A1 V), and μ Lep (HR 1702, Ap Mn). The original intensity scale in number of counts per 14 s has been corrected for the background due to cosmic-ray particles and is presented on a normalized, 0–100 scale; we give the absolute values for the location of the continuum later. The lines have been identified with the help of laboratory wavelengths by Kelly and Palumbo (1973) and the table of predicted wavelengths by Kurucz and Peytremann (1975).

Note first, on Figure 1, the general similarity of the spectra. (A line at 1362.09 Å is present only in Sirius, though, and is unidentified, as are several other lines.) Also note that the strong feature around λ1362.46 in Vega is broad and asymmetric: The B II resonance line at λ1362.46 is present but is blended with another line. Surprisingly, *only* the companion line in the blend is present in Sirius and μ Lep. The wavelength scale has been adjusted independent of the "B II blend." This scale rests on three lines: λ1361.862 (Mn II), λ1362.771 (Fe II), and the Cl I line around λ1363.5. The published value for the wavelength of this Cl I line is λ1363.449, but here, the central wavelength has to be displaced shortward by 0.05 Å; we find the same shift in all three stars of Figure 1. The necessity of systematically shifting lines in analyzing *Copernicus* spectra is not unusual (Morton 1975).

Two problems are immediately apparent from this first look at the data: (1) the line in Vega at 1362.46 Å is asymmetric; for this the Sirius spectrum will be our guide; and (2) the spectral features are all broadened—the width at half-intensity is 21 km s^{-1} for the "B II blend" in Sirius, 36 km s^{-1} in Vega—although the instrumental width is only 11 km s^{-1}; Sirius and Vega have been reported to be nonrotators (Slettebak 1954; see detailed references given in Uesugi and Fukuda 1970).

There are three scans each for Vega and Sirius, so we can determine whether the observed asymmetry of

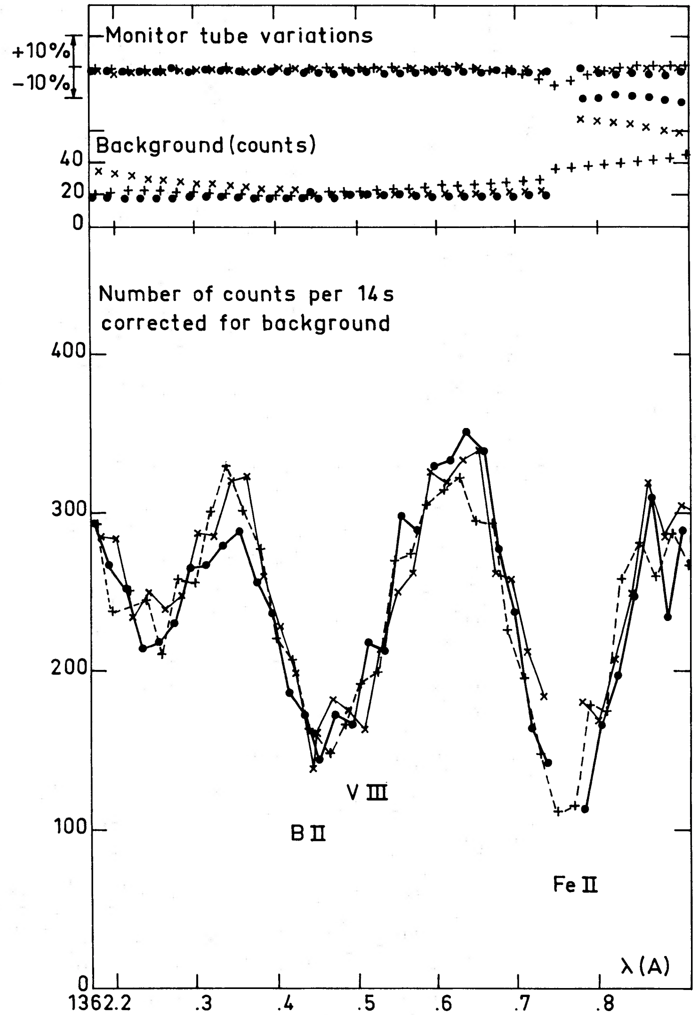

FIG. 2.—The three individual U1 scans for Vega are shown. The monitor tube and the background counts are plotted and show no irregularities across the B II profile. The asymmetry in the feature is real and not an artifact of the observations.

the "B II blend" in Vega could be instrumental. Figure 2 shows the three individual scans, a plot of the background count, and a plot of the monitor tube (V3) counts; in the region of B II, no instrumental irregularities occurred. Therefore, we can work with the averaged spectrum, corrected for the background and for the diffuse light in the spectrometer (9% of the energy over 40 Å is removed as contribution of the diffuse light in U1). Since we worked with only a few Å of spectral range for U1, the location of the continuum was settled proportionally from U2 (0.2 Å resolution) spectra[3] after a degradation of U1 to U2 resolution. The continuum on U2 spectra was taken as the envelope of the brightest windows around 1362 Å. Fortunately, one of these windows is precisely in our small spectral range for U1; the method we use fits it better than ±5% for Sirius and ±10% for Vega. The zero was carefully determined on both U2 and U1 spectra by the removal, first of particle background, then of diffuse plus stray light in the first case, of diffuse light in the second. The diffuse light correction for U1 was done by a procedure due to Bohlin (1975) after we had the conversion ratio between U2 and U1.

If we assume the uncertainty in the diffuse light is less than 50% of the diffuse light itself, we get the maximum relative uncertainties on the depression in the lines: for Vega, 15% at the line center and 10% in the wings; and for Sirius, 10% at the center, 5% in the wings.

Table 2 gives the count rates per 14 seconds in the continuum for both U1 and U2, Sirius and Vega, all referred to the same orbit. Although these values do not influence the profiles in relative flux units ($1 - F_c/F_R$) that we finally analyzed, we stress that the ratio U2/U1 differs by 30% between Vega and

[3] The U2 spectrum of Vega was kindly communicated by D. Leckrone; for Sirius, our U2 spectrum of 10 Å was supplemented by more extensive scans of R. Bell, which he kindly lent us.

TABLE 2

U1 AND U2 CONTINUA COUNTS

Star	U1 Continuum	U2 Continuum	Slope for U1 Δ Counts (counts Å^{-1})
	(at λ = 1362.65 Å in counts per 14 s)		(Δλ)
Vega:			
Number of counts*	332	645	−5.6
Diffuse light counts	24	...	...
Efficiency	0.96	1.00	...
Number of counts* corrected for efficiency†	346	645	...
Sirius:			
Number of counts*	1351	1165	−22.8
Diffuse light counts	98	...	...
Efficiency‡	0.95	0.85	...
Number of counts corrected for efficiency†	1422	2081	...

* Corrected for diffuse light, not for time variations in efficiency.

† All counts here referred to orbit No. 630.

‡ Response relative to orbit No. 630, from T. P. Snow, private communication (1975).

Sirius, a value which is hardly compatible with the guidance errors of the satellite.

The same relative spectral gradient for the continuum is assumed in Vega and Sirius in the narrow range surrounding the B II feature.

Intrinsic line widths were determined from two symmetric and most likely unblended lines. These lines were identified with Fe II λ1362.771 and Cl I λ1363.449 after a successful search for the other lines in the multiplets. There has been no report of line asymmetries or of line variability in Vega or Sirius; we therefore do not consider the presence of velocity fields to be the primary cause of the observed line widths. We suggest that these line widths are due to broadening by rotation.

The projected rotational velocity $v \sin i$ has been determined by two independent means: (1) we used the classical method of an *a posteriori* convolution of a theoretical profile by the rotation profile, and we adjusted the convoluted profile to match the observed one; and (2) Milliard, Pitois, and Praderie (1977) described the second method, which is based on Fourier transforms. In both approaches, the theoretical profile must be convoluted by the instrumental profile. The latter is taken from Rogerson (1973, private communication). The theoretical profiles for Fe II λ1362.771 and Cl I λ1363.449 have been computed in LTE with the Schild, Peterson, and Oke (1971) model for Vega and the Fowler (1974) model for Sirius. The microturbulence parameter is adopted from other studies: 3 km s^{-1} for Vega (Hunger 1955), and 2 km s^{-1} for Sirius (Kohl 1964). For the Cl line, we take $gf = 0.0836$ (Wiese, Smith, and Glennon 1966). The Cl abundance has been adjusted so that the computed equivalent width, W, equals the observed one (103 mÅ in Vega, 138 mÅ in Sirius). For Fe II, no gf-value was found, but from knowledge of the Fe abundance in Sirius (Gehlich 1969), we derived $gf = 0.30$ for λ1362.771 with the same constraint as above (W computed = W observed = 128 mÅ in Sirius); Fe II was not computed in Vega because of the lower-quality profile (see Fig. 2). As a by-product, and from the single Cl line analyzed, we obtain Cl/H = 3.6×10^{-6} = 8 times the solar value in Vega, Cl/H = 3.0×10^{-5} = 70 times the solar value in Sirius. Let us stress that the computed Cl I and Fe II lines are saturated, and therefore the abundance values are not well determined.

The classical method for determining rotation then leads to $v \sin i$ = 18–20 km s^{-1} for Vega, 10 km s^{-1} for Sirius. The error is ±2 km s^{-1}. By the method of Milliard *et al.*, we obtained $v \sin i$ = 18 km s^{-1} for Vega, 11 km s^{-1} for Sirius, with an error of ±2 km s^{-1}.

b) Subordinate Lines, λ1624 and λ3451

A search for subordinate lines of B II has been made to confirm the presence of B II in Vega and to check for its absence in Sirius. The laboratory spectrum of B II is discussed in Ölme (1970).

New *Copernicus* observations with the U1 tube in the *first* order (0.1 Å resolution) have been made of both Vega and Sirius in the 1624 Å region to search for the lowest-excitation triplet transition: $2s2p\ ^3P^o$–$2p^2\ ^3P$. The sensitivity of the far-ultraviolet phototubes is very low at this wavelength, so multiple scans for both Vega (150 scans) and Sirius (25 scans) were needed. Figure 3 shows these observations for both Sirius and Vega, with the wavelengths of the five lines in the multiplet marked. There are no B II features in the Sirius spectrum, but the two unblended lines, λ1624.018 and λ1624.34, may be weakly present in Vega. The B II lines in Vega have intensities of 5%–8% of the local continuum.

Ground-based observations with the 224 cm telescope at Mauna Kea have been used to search for the λ3451 line of B II ($2p\ ^1P^o$–$2p^2\ ^1D$) in Vega. The excitation potential of the lower level of this line is 9.06 eV. Two spectrograms at 6.7 Å mm^{-1} widened to 1.1 mm on the plate have been combined to give a single direct-intensity tracing. The resolution is about 0.1 Å. No line is present at 3451.29 Å. Measurements of the

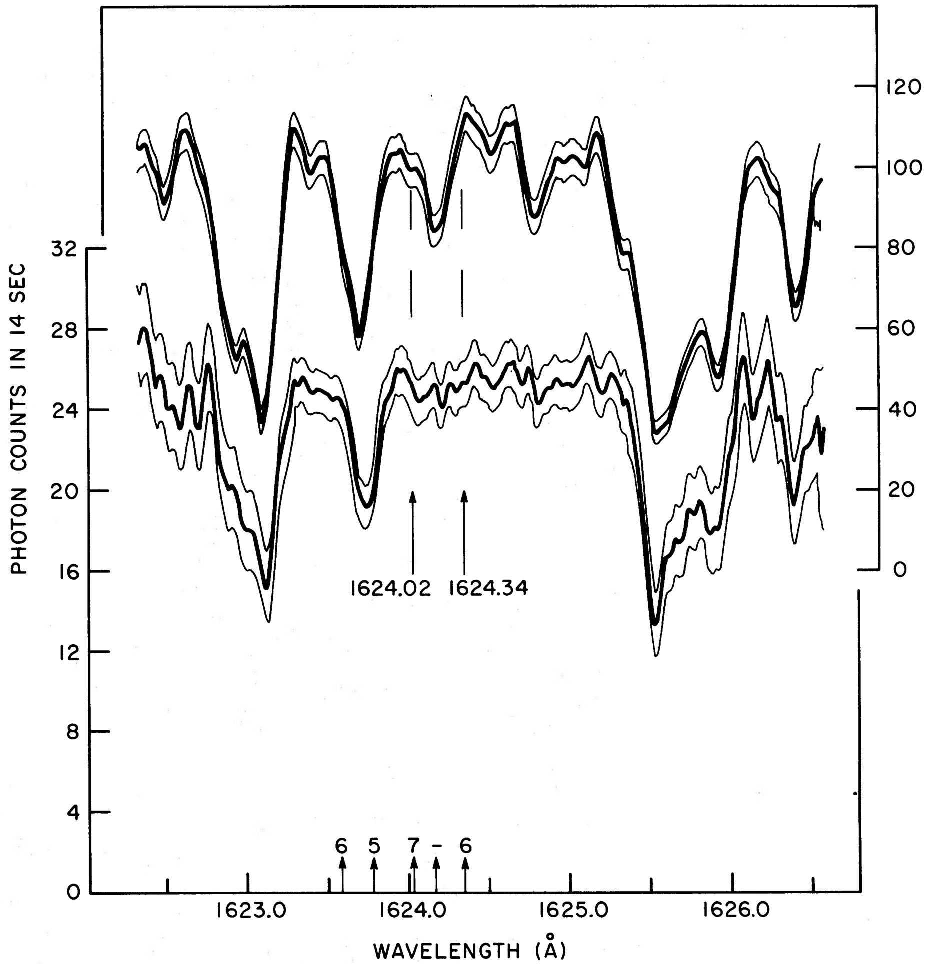

FIG. 3.—U1 scans in the B II 1624 Å region of both Vega (*lower curve, left-hand scale*) and Sirius (*upper curve, right-hand scale*). Arrows indicate the positions of the five lines in the multiplet. The laboratory relative intensities are given above the arrows (Ölme 1970). The features at 1624.02 and 1624.34 Å are absent in Sirius, but probably weakly present in Vega. The error envelopes are $\pm 2\ \sigma$.

nearby noise indicate that the minimum detectable line would have an equivalent width of 0.007 Å. Thus for Vega $W(3451) \leq 7$ mÅ.

III. THE CAUSE OF THE ASYMMETRY OF THE B II BLEND IN VEGA

According to the arguments above, we consider that the line *widths* are not due to the presence of velocity fields. Similarly, the velocity fields are not the cause of the line *asymmetry* of the 1362.46 Å line in Vega. We have tried to identify the contributors to the blend.

a) *Boron Isotopes*

We first asked if the asymmetry could be due to contributions from the two isotopes ^{10}B and ^{11}B; the measured isotopic ratio in meteorites is $^{11}\mathrm{B}/^{10}\mathrm{B} = 4$. The isotopic displacement is not measured or computed, to our best knowledge. This displacement is the sum of a normal term $\Delta\sigma_n = 366 \times 10^{-3}\ \mathrm{cm}^{-1}$, and a specific term, evaluated from Hartree-Fock wave functions by Bauche (1974, private communication), $\Delta\sigma_s = 268 \times 10^{-3}\ \mathrm{cm}^{-1}$. The total displacement amounts to $\Delta\lambda = 0.01176$ Å to $\pm 100\%$; the heaviest isotope has the shortest wavelength. We computed the blended line profile with the ratio $^{11}\mathrm{B}/^{10}\mathrm{B} = 4$ found in the meteorites, and with $\Delta\lambda$ values ranging from 0.012 to 0.025 Å. (Larger values than 0.012 were used, since Vinti [1940] found the computed displacement for the 3451 Å line of B II smaller than the observed value.) No noticeable asymmetry can be seen in the computed profiles, and we find no justification to try larger $\Delta\lambda$.

b) *Molecules*

At the line-center optical depth $\tau_0 = 1$ for B II λ1362.46, with the Schild, Peterson, and Oke (1971) model for Vega, and with $\mathrm{B/H} = 1 \times 10^{-10}$, the

TABLE 3

LINE LIST USED IN THE COMPUTATIONS, BLEND B II–V III

λ(Å)	Ion	α_{Sirius}	α_{Vega}	gf	Reference for gf
1362.460.......	B II	5.0×10^{-12}	...	1.096	Wiese *et al.* 1966
1362.477.......	Ni II	3.3×10^{-6}	1.9×10^{-6}	1.0×10^{-1}	KP* × 10
1362.508.......	V III	3.0×10^{-8}	1.0×10^{-7}	5.0×10^{-1}	KP × 10
1362.523.......	Fe III	2.0×10^{-4}	1.4×10^{-5}	2.0×10^{-3}	KP × 10
1362.528.......	Co II	2.3×10^{-7}	3.2×10^{-8}	4.9×10^{-6}	KP × 10
1362.547.......	Fe III	2.0×10^{-4}	1.4×10^{-5}	3.8×10^{-4}	KP × 10
1362.551.......	Mn II	1.2×10^{-6}	1.6×10^{-7}	1.6×10^{-4}	KP × 10
1362.553.......	Fe III	2.0×10^{-4}	1.4×10^{-5}	5.7×10^{-3}	KP × 10
1362.594.......	Cu II	2.0×10^{-7}	2.8×10^{-8}	2.2×10^{-1}	KP × 10

NOTE.—$\alpha = N_{\text{el}}/N_{\text{H}}$.

* KP is Kurucz and Peytremann 1975.

dominant molecule present is H_2 (Querci 1975, private communication). The Lyman system of H_2 has rotation lines located around 1362.5 Å in the (0, 4) and (2, 5) bands (Allison and Dalgarno 1969; Herzberg and Howe 1959). There are no candidate lines within ±0.04 Å of 1362.46. The blend is therefore not due to H_2.

c) *Atomic Lines*

A good candidate, V III 1362.508 Å, appears in the tables of Kelly and Palumbo (1973). This transition is $a\ ^2P_{3/2}$–$z\ ^2D_{5/2}$ (Iglesias 1962, 1969; Shadmi, Caspi, and Oreg 1969) with a gf-value of 0.05 (Kurucz and Peytremann 1975). The other two lines of the multiplet cannot be identified with certainty because of blends with strong lines, but a computation of these blends shows that the V III contribution is appreciable. In the following, the major contributor of the line at λ1362.508 is taken to be this line of V III. Other minor contributors are included in the computations (see below).

IV. LINE-PROFILE CALCULATION FOR SIRIUS

We computed a line profile for the feature at λ1362.51 in Sirius, assuming it is primarily due to V III at 1361.508 Å, but taking into account significant nearby minor contributors with gf-values given by Kurucz and Peytremann (1975). The Zn III line at λ1362.523 does not contribute, despite its large gf-value. The lines considered can be found in Table 3, together with the abundances, assumed equal to those derived from the visible spectrum (Gehlich 1969), with an adjustment of the reference solar values there to the scale of Withbroe (1971).

A first LTE computation of that group of blended lines, with Fowler's (1974) model and $\xi = 2$ km s^{-1}, shows that all gf-values are probably too small. We were forced to multiply them all by 10, to fit the observed line. For subordinate lines in ions, this factor is not impossible, for there is no means at present to estimate the accuracy of the Kurucz and Peytremann f-value computations. A difficulty arises for the V abundance. Various authors differ as to this value: $\log N = 6.11$ (Gehlich 1969), 4.4 to 4.6 (Strom, Gingerich, and Strom 1966), 6.02 (Kohl 1964), 4.35 (Latham 1970), in the scale $\log N_{\text{H}} = 12$. We adopted $\log N_{\text{V}} = 4.48$, again with the criterion that the equivalent width of the computed blend be equal to the observed value (43 mÅ). The resulting profile is shown in Figure 4, along with the observed one, and the theoretical profile convoluted by the instrumental and rotation profiles. We derive an upper limit for the B abundance in Sirius from the nonappearance of this line in the observed profile: B/H < 5×10^{-12}. This value, which is a maximum value, is 20 times smaller than that found in Vega from the previous

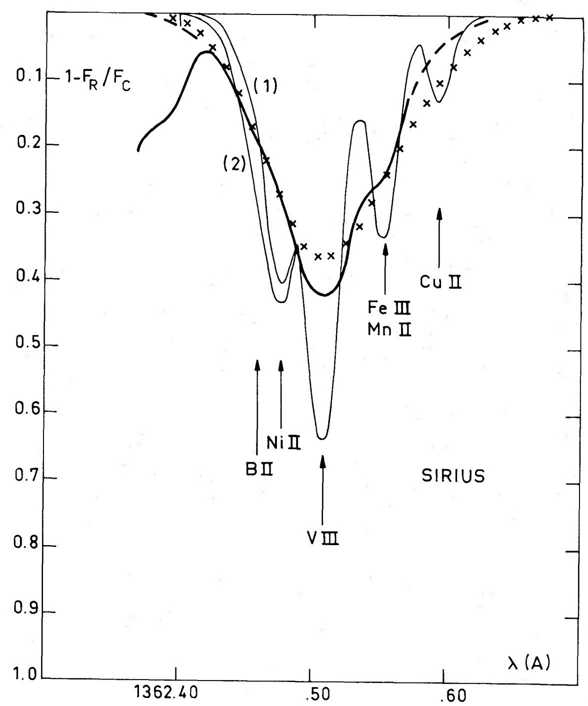

FIG. 4.—The observed and calculated profiles of the λ1362 feature in Sirius. The heavy solid line is the observed profile, the light solid lines are computed profiles, including contributions of B II and the elements listed in Table 3. Line 1 corresponds to B/H = 2.5×10^{-12}, line 2 to 5×10^{-12}. The computed profile (2) broadened by $v \sin i = 10$ km s^{-1} rotation is indicated by the crosses.

work (Boesgaard *et al.* 1974). We conclude that B is deficient in Sirius relative to Vega.

V. BORON ABUNDANCE IN VEGA

To determine the B content of Vega we have done an LTE synthesis of the B II blend, with the same constituents as in Sirius, and a non–LTE computation of the B II line alone.

We again stress that, for B II λ1362, there is a discrepancy between all *computed gf*-values, $gf \approx 1.1$, and the *experimental* values, $gf \approx 0.7$–0.8. Kernahan *et al.* (1975) attribute this to the possible influence of a B III line at λ1362.46 on the B II $2p^1\,P^o$ lifetime measurements. We therefore adopt the computed value, $gf = 1.096$ (Wiese, Smith, and Glennon 1966). The pressure broadening by electrons is taken from Griem (1974).

a) LTE Profile

The line list and abundances used are given in Table 3. When no determination of abundance for an element exists, we took the solar value (Withbroe 1971). Again a difficulty arises with V III, for no V abundance is published for Vega; and if we adopt the solar value, the V III line is much too weak. We compared computed line strengths of all three lines in multiplet (4) of V III with observed lines from U2 spectra and adopted $\mathrm{V/H} = 1 \times 10^{-7}$ for Vega, which is about 8 times the solar value. (If we use the Kurucz and Peytremann original *gf*-value, the V abundance would have to be 80 times the solar value to fit the B II blend in Vega, and the V abundance in Sirius would be about 100 times solar. The product *Ngf* is the unknown.)

The resulting profile is shown in Figure 5, with two values of B/H. The central intensity of the B II line is very close to zero, even in this LTE computation; this can be understood from two simultaneous effects: the continuum radiation at λ1362 is of photospheric origin, and the gradient of the Planck function with τ_c is large at ultraviolet wavelengths. The observed profile is also plotted, as well as the theoretical profile for $\mathrm{B/H} = 1 \times 10^{-10}$ convoluted by the instrumental and rotational profiles. For this fit, the value $v \sin i = 20\ \mathrm{km\ s^{-1}}$ is better than $18\ \mathrm{km\ s^{-1}}$. This fact, combined with the almost complete disappearance of the asymmetry in the profile corrected for rotation, suggests that we may have missed a contribution to the blend. A renewed search of the recent literature with the kind help of L. Brillet revealed no additional lines.

We conclude that the LTE analysis of the whole blend and the use of line profiles, not just equivalent widths, leads to the same boron abundance as given in our previous analysis (Boesgaard *et al.* 1974): $\mathrm{B/H} = 1 \times 10^{-10}$. The influence of the model and of the chosen ξ as well as that of the uncertainty in the *gf*-value was discussed in Boesgaard *et al.* (1974).

The computations of the blend showed that the short-wavelength side of the B II profile is hardly influenced by the contributions shortward of 1362.46 Å. This allows us first to be confident that the multiplicative factor we have imposed on Kurucz and Peytremann *gf*-values is not extremely critical (provided, for V III λ1362.51, N(V) *gf* is correct); when computing a non–LTE profile for the B II line *alone*, we can compare it with the symmetrized shortward half of the LTE B II profile.

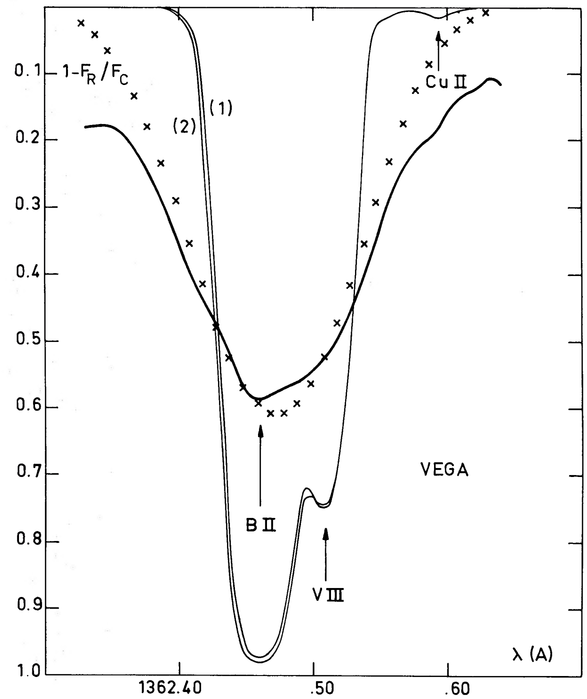

FIG. 5.—The observed and calculated profiles of the λ1362 feature in Vega. The heavy solid line is the observed profile, and the light solid lines are the computed profiles for two different B abundances ($\mathrm{B/H} = 8 \times 10^{-11}$ and 1×10^{-10}). *Crosses*, the computed profile, broadened by $v \sin i = 20\ \mathrm{km\ s^{-1}}$, which corresponds to $\mathrm{B/H} = 1 \times 10^{-10}$.

b) Non–LTE Profile

We reduced the B II model atom to four levels plus continuum (Fig. 6). The photoionization cross sections are assumed hydrogenic; the collision ionization rate is computed from Allen (1973); collisional excitation is computed following van Regemorter (1962).

The detailed calculations in the model atmosphere show that B II is the dominant ion throughout the atmosphere. This is an important point, since, as a consequence, the effects of departure from ionization equilibrium (due to poor knowledge of photoionizing radiation fields or of recombinations) are minimized. A consequence is that the population of the ground-level n_1 is practically identical to its LTE value everywhere in the atmosphere. Therefore the influence of departures from LTE on the derived abundance of boron will *not* come in via the line optical depth (which depends on n_1) but only via the line source function. The ratio of the departure coefficients b_2/b_1 is therefore critical. Consequently, an atom reduced to two levels plus continuum would be inadequate,

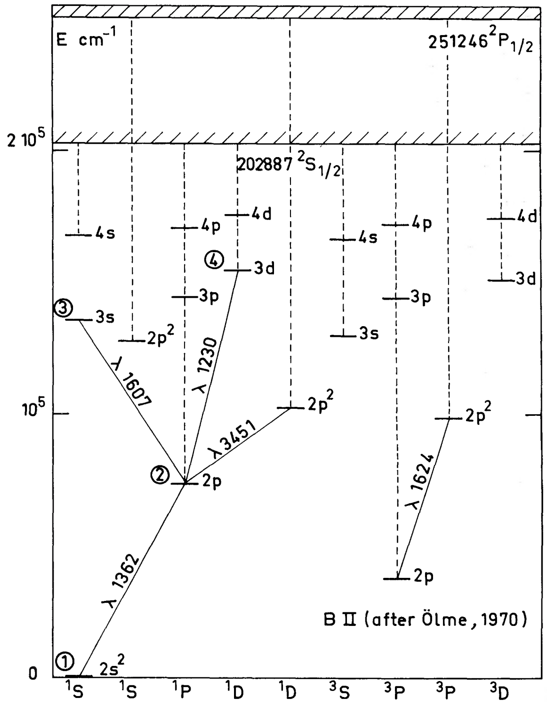

FIG. 6.—The energy level diagram of B II showing the four-level atom plus continuum used for the non-LTE calculations.

since the second level, labeled 2, would be artificially overpopulated in this case; we tried to check this.

The solution of the line transfer in the resonance line was performed with the help of S. Dumont's (1967) code, first for a two-level atom plus continuum, then with three and four levels, all singlets. (We do not consider the triplets in the present computation, since the upper levels of the transition λ3451 and λ1624 ionize toward the first excited state of B III, with ionization thresholds in the far-UV; we expect that the depopulation processes via the continuum are not strong for these levels [the lines themselves are weak], and their effect on $2p\ ^1P$, either directly for λ3451 or via the continuum for λ1624, is most likely small.) On the contrary, the computation shows that $3s\ ^1S$ and $3d\ ^1D$ are depopulated by photoionizations, and their coupling with $2p\ ^1P$ may influence the line source function for λ1362. In fact, it turns out that the resonance line is dominated by excitation from the neighboring continuum; $r = d\tau_c/d\tau_0$ is larger than $\epsilon = C_{21}A_{21}$, where C_{21} and A_{21} are the collisional and spontaneous de-excitation rates. Furthermore, the lines λ1607 and λ1230 are so weak (A_{ji}, taken from Kernahan *et al.* 1975) that they do not significantly perturb the ratio b_2/b_1, relative to the two-level plus continuum case. For λ1362 this ratio is of the order of 10 at $\tau_0 \approx 1$, and therefore a higher abundance than that in LTE is required to match the observed equivalent width ($W = 65$ mÅ) of the B II resonance line. For the computation, we symmetrized the shortward half of the profile and derived an abundance of 1.5×10^{-10} ($W_{\rm calc} = 64$ mÅ). Although the continuum radiation field at λ1362 (which photoexcites the resonance line) is computed in LTE, that fact appears to have little effect on the derived B/H abundance: departures from LTE in the dominant continuum contributor there (C I) have been shown by Snidjers (1977) to be very small.

The sense of the non-LTE effects on the B abundance differs from what we estimated earlier (Boesgaard *et al.* 1974); then we had assumed $b_2 = 1$, whereas the full computation shows that it is less than 1.

c) The Multiplet at λ1624

Figure 3 shows the region in Vega and Sirius of the five lines of the multiplet at λ1624. The clearest features are those at λ1624.018 and λ1624.340, from the transitions $2s2p\ ^3P_2{}^o$–$2p^2\ ^3P_2$ and $2s2p\ ^3P_2{}^o$–$2p^2\ ^3P_1$, respectively (Ölme 1970). (The two shortest-wavelength lines in the multiplet are masked by a strong absorption feature present in the spectra of both Vega and Sirius.) The laboratory relative intensities given are from Ölme. Neither the resonance line nor the subordinate lines are present in Sirius. For Vega with *gf*-values from Wiese, Smith, and Glennon (1966), the LTE calculations predict that the lines at 1624.018 and 1624.340 Å should have central absorptions of 7% and 5% of the continuum, respectively, with a B/H abundance ratio of 1×10^{-10}. The measured depths relative to the local continuum of the weak features at those positions in the spectrum of Vega are 8% and 5%, respectively, in agreement with the predictions. Note that $2s2p\ ^3P^o$ is a metastable level, so that it may be overpopulated relative to our LTE predictions. The observations in the λ1624 region are completely consistent with the presence of B in Vega and its absence in Sirius and provide additional support to our identification of the B II resonance line in Vega.

According to our LTE calculations (with *gf* from Wiese, Smith, and Glennon 1966), the high-excitation line at λ3451 will be completely absent ($W < 0.001$ Å) with $\mathrm{B/H} = 1 \times 10^{-10}$, in agreement with the observed absence of this feature.

VI. BERYLLIUM ABUNDANCE IN SIRIUS AND VEGA

Bonsack (1961) has measured the equivalent width of one of the Be II resonance lines, 3130.42 Å, in both Sirius and Vega and has determined the Be abundances. We have used his value of $W(\mathrm{Be}) < 0.004$ Å for Sirius and determined the upper-limit Be abundance with the Fowler (1974) model for Sirius. The *gf*-value used is 0.67 from Wiese, Smith, and Glennon (1966). For Sirius we find $\mathrm{Be/H} < 8 \times 10^{-12}$. (This upper limit is higher than that derived by Bonsack, but he assumed that Fe/H is the same in Sirius as in Vega, whereas Sirius has about 14 times more Fe than Vega [Gehlich 1969].)

The same spectrograms described earlier for our search for the B II line at 3451 Å in Vega are well exposed in the region of the Be II resonance lines. The total equivalent width of the feature at 3130 Å is

0.025 Å, of which about 0.007 Å can be attributed to Be II (the chief blending line is V II 3130.26 Å). The derived Be/H ratio is 1.0×10^{-11}.

The Be abundance has been determined in F and G main-sequence stars to be 1.3×10^{-11} (Boesgaard 1976*a*); arguments are given in that paper that this value represents the cosmic abundance for Be. The meteoritic and solar Be abundances are similar. Thus Vega shows the cosmic Be content, whereas Sirius is apparently deficient in Be.

VII. SUMMARY AND CONCLUSIONS

The LTE B abundance found from high-resolution observations of the B II resonance line (λ1362) in Vega confirms the results of the lower-resolution observations of Boesgaard *et al.* (1974), i.e., $B/H = 1 \times 10^{-10}$. Effects due to non-LTE increase this number, but not by more than 50%, i.e., $B/H \approx 1.5 \times 10^{-10}$. The agreement of the measured and predicted central depths of the weak subordinate B II lines at λ1624 in Vega is consistent with the identification of B II as the major contributor to the blend at λ1362. In Sirius neither the resonance line nor the subordinate lines are present, and Sirius is deficient in B relative to Vega by a factor of at least 20.

Table 4 gives the B and Be abundances found in Sirius and Vega and compares them with the abundances predicted by the production of the light elements by spallation reactions on C, N, O atoms in the interstellar gas by galactic cosmic rays (GCR) (Meneguzzi, Audouze, and Reeves 1971, as modified by Reeves 1974—see Boesgaard 1976*b*). The derived abundances are not in error by more than a factor of 2; this error estimate includes uncertainties in the models, the *gf*-values, the continuum location, etc. Within the errors, the B and Be abundances in Vega agree very well with the predictions of the GCR theory for the origin of the light elements. (For more detailed discussions on the origin of the light elements, see review papers by Reeves 1974 and Boesgaard 1976*b*.) Arguments have been presented by Boesgaard *et al.* (1974) that Vega shows the cosmic or universal abundance of B and Be; those arguments are still valid and will not be repeated here. We conclude that the cosmic B/H ratio is 1.5×10^{-10} within a factor of less than 2, and that B is created by bombardment of heavier atoms in the interstellar gas by energetic galactic cosmic rays.

The atmosphere of Sirius has apparently been modified and no longer shows the cosmic amounts of B and Be: it is deficient in B by at least a factor of 20 and in Be by at least a small factor. We see at least two possible ways by which the atmospheric composition could have been altered: (1) interaction with the white-dwarf companion; and (2) diffusion.

Bonsack (1961) has suggested that the atmosphere of Sirius A was influenced by Sirius B during its evolution as an M supergiant through mass transfer when Sirius B was much closer to A than it is now. If atoms of Li, Be, and B are transported below the surface of a star to regions where the temperatures are a few million kelvins, they will be destroyed through fusion with protons. The surface abundance of light elements can also be reduced by effects of convective dilution, wherein the deepening of the outer convection zone during post–main-sequence evolution causes material that contains the light elements to be mixed with material in the interior where the temperatures were too high for Li, Be, and B to exist. It is not relevant here whether destruction or dilution is primarily responsible for the light-element deficiency in an evolved star with the mass that Sirius B must have had originally; observations of M giants and supergiants do show that they are deficient in Li by factors of 10–2,000 relative to the cosmic abundance (see Boesgaard 1976*b*). During the M supergiant phase of the evolution of Sirius B, mass transfer to Sirius A could have taken place.[4] In such a picture, the outer layers transferred from Sirius B to A would then be deficient in Li, Be and B. It is likely that a star of the mass of Sirius A would not mix this new surface deposit if, as predicted by the mixing length theory, no surface convection zone is expected. Thus we can qualitatively account for the absence of B and Be in Sirius A if the atmospheric material of Sirius A originally belonged to Sirius B.

If a stellar atmosphere is sufficiently stable, diffusion or element separation can take place because of the effects of radiation pressure, gravity, a temperature gradient, etc. This theory was applied originally to Ap stars by Michaud (1970). Whether an element will be enhanced or depleted depends on many factors, like formation of an ionization barrier or mixing by turbulent convection. Without detailed calculations, it is not possible to determine whether diffusion could be responsible for the deficiency of B and Be.

Both of these suggested explanations are equally ad hoc and qualitative at present. The first explanation —interaction with the binary companion, Sirius B— is probably the more likely, as there is ample evidence that mass transfer does take place in binary systems.

TABLE 4

BORON AND BERYLLIUM ABUNDANCES

Abundance Ratio	Sirius	Vega	GCR
B/H..........	$< 5 \times 10^{-12}$	1.5×10^{-10}	1.8×10^{-10}
Be/H.........	$< 8 \times 10^{-12}$	1×10^{-11}	1.3×10^{-11}
B/Be..........	...	10	14

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[4] No system of the total mass ($\sim 3\ M_\odot$) and eccentricity of Sirius has been studied through these phases of evolution, although Lauterborn (1970) discusses Sirius at the end of a paper devoted to the evolution of a 7 $M_\odot$ binary system.

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