IDENTIFICATION OF LINES IN THE
SPECTRA OF B STARS

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ABSTRACT

Identifications of lines in the spectra of B stars are given. About fifty lines for which no previous identifications had been made are interpreted.

Within recent years three important lists of absorption lines in B stars have been published[1] by O. Struve;[2] by O. Struve and T. Dunham, Jr.;[3] and by Roy K. Marshall.[4] The first list deals with spectra extending from $\lambda\,3850$ to $\lambda\,4923$;[5] the ten stars investigated are of spectral types O9, B0, B1, B2, B3, B5, B8. The plates were taken either with the Coudé spectrograph of the Mount Wilson Observatory or with the Bruce spectrograph of the Yerkes Observatory, on Eastman Process emulsion, which gives excellent contrast. Of the total number of lines measured, 73 remained unidentified. The list by O. Struve and T. Dunham, Jr., deals only with the spectrum of the B0 star 23 τ Scorpii. The spectrogram was obtained with the Coudé spectrograph and the 100-inch Mount Wilson reflector, on Eastman Process emulsion, and extends from about $\lambda\,3945$ to $\lambda\,4713$. Several new identifications for C III, N III, and O III were added to the first list of Struve, while 53 lines remained unidentified. The study of class B stellar spectra made by R. K. Marshall is based on spectra taken with the single-prism spectrograph attached to the $37\frac{1}{2}$-inch reflector of the University of Michigan. Owing to the unusually high transmission of that optical system, Marshall's list begins at $\lambda\,3587.19$ A. Most of the plates were taken on Eastman Process emulsion. Of the 534 lines tabulated, almost exactly one-half have not been identified.

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[1] The following abbreviations will be used: O. S. (O. Struve), S. D. (Struve-Dunham) and M (R. K. Marshall).

[2] *Ap. J.*, **74**, 225, 1931.   [3] *Ibid.*, **77**, 321, 1933.

[4] *Pub. of the Observatory of the University of Michigan*, **5**, No. 12, 137, 1934.

[5] The region $\lambda\lambda$ 3850–3950 is given only for γ Pegasi (B2); for wave-lengths longer than 4700, only the stronger lines could be measured.

Marshall's list of ultra-violet lines is certainly excellent, but in the ordinary photographic region it is inferior to those of Struve and of Struve and Dunham.

In the following paper we give a few additional identifications. Attention should be drawn toward the following points:

1. In each multiplet the relative intensities of the stellar lines must be compatible with the laboratory intensities.

2. The absolute laboratory intensities have to be considered.

3. The spectral type corresponding to maximum intensity of the stellar line and the behavior of intensity as a function of spectral type must be reasonable.

4. The gradient effect makes all weak absorption lines in dwarfs of type B relatively stronger than the laboratory intensities might indicate.

5. The atomic weight of the elements and their normal abundances have to be considered.

6. It may happen that for two different spectral types—for example, B0 and B8—lines of the same measured wave-length may have different origins.

7. The difference λ obs. $-\lambda$ lab., which is allowed for an identification, depends upon the dispersion in that region and upon the structure of the line (intensity, sharpness).

8. It may happen that a faint line has been omitted in the measures of one particular star.

In this paper none of the lines recently identified by R. K. Marshall (O III),[6] O. Struve (C III),[7] J. E. Mack, P. Swings, and O. Struve (C IV),[8] O. Struve and H. Pillans (Si IV),[9] D. H. Menzel and R. K. Marshall (Ne II);[10] and E. Mac Cormack (Ne I)[11] has been listed. When a line of one of the three lists considered here has been identified in one of the other lists, it has been omitted here. When components of a multiplet have been identified by O. S., S. D., or M, the identification of other lines in the same multiplet is comparatively easy; only the new identifications are then given, the symbol of the multiplet being written in brackets.

[6] *Ap. J.*, **76**, 317, 1932.

[7] Included in list S. D.

[8] *Ap. J.*, **75**, 77, 1932.

[9] *Observatory*, **57**, 133, 1934.

[10] *Proc. Nat. Acad.*, **19**, 879, 1933.

[11] *Pub. A.S.P.*, **46**, 64, 1934.

The authors believe that an investigation of the ultra-violet region of $\lambda < 3600$ A (by using an aluminized telescope and a quartz or U.V spectrograph) would be fruitful.

TABLE I

C II

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identifi-cation
2p″²P—3p′²S.......	3868.84	2	8.81	M	B2	XXX
	3871.62	1	1.89	M	....	Bl. *He* I
(3d′⁴F—4f⁴G).......	3878.22	1	8.10	M	B2	Bl. *He* I
	79.60	1⎱	0.38	M	B1, 2	XXX?
	80.59	1⎰				
(3d′⁴D—4f′⁴F)......	4076.00	7	5.88	O.S.	Bo, 1, 2	Bl. *O* II
3d′²D—4f′²D.......	4285.96	1	6.24	O.S.	B2	XXX
	96.11	1	6.54	O.S.	Bo, 2	XXX
3p′⁴P—4s′⁴P........	4313.50	2	3.32	O.S.	Bo, 1, 2	Bl. *O* II
	17.42	4	7.21	O.S.	Bo, 1, 2	Bl. *S* II
	18.92	2	8.45	O.S.	Bo, 2	Bl. *O* II
	25.88	2	5.64	O.S.	Bo, 1, 2	Bl. *O* II
Absent...........	4630.52	1	0.55	O.S.	Bo, 1, 2	Bl. *O* II

Less probable identifications ($\Delta\lambda$ seems too large):

No designation.....	⎧4292.00	1	2.55	S.D.	Bo	Bl. *O* II
	⎨4376.78	1	6.23	M	Bo	Bl. *O* III
	⎩4625.71	1	5.16	O.S.	B1, 2	XXX

TABLE II

N II

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identifi-cation
(3d³D—4f³D).......	4160.8	0	0.62	M	B1, 3	XXX
	73.51	0	⎧3.59⎱	O.S.	B2, 3	Bl. *S* II
	73.75	0	⎨4.12⎰			
			⎩4.06	M	B2, 3	Bl. *S* II
3d′D—4f′D........	4044.75	1	5.00	O.S.	B2	XXX

C II, N II, N III, and O II.—The identifications are given in Tables I, II, III, and IV.[12]

TABLE III

N III

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$(3s'^2P - 3p'^2D)$..	4215.69	3	5.79	S.D.	Bo	Bl. [*N* II]
$4p^2P - 5s^2S$.....	4544.80	o	4.90	S.D.	Bo	XXX

Less probable identifications (Δλ seems too large)

$3p'^2D - 3d'^2D$..	3934.41	3	3.62	M	Bo	Bl. *Ca* II, *S* II
	38.52	4	9.12	M	Bo	XXX?
	42.78	1	3.46	M	Bo	XXX?

TABLE IV

O II

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$4p^2P - \overline{4d}^2D$...	3785.01	o	5.36	M	B1, 2	XXX
$4s^2P - \overline{4p}^2D$....	3838.41	o	8.30	M	B1, 2	Bl. *He* I, *N* II
$(3d^4F - 4f^4F)$....	4026.40	o	6.31	S.D.	Bo	Bl. *He* I, *N* II
	33.18	o	2.90	O.S.	B2	XXX
	44.96	o	5.00	O.S.	B2	XXX
	46.15	o	5.80	M	Bo	XXX
$e^4P^o - z^4D$.....	4103.01	5	3.40	O.S. and M	O9, Bo, 2	Bl. *N* III
$\overline{3d}^2D - \overline{4f}^2D$...	4342.83	1	2.90	O.S.	Bo, 1	Bl. *O* II
$(3d^2D - 4f^4D)$...	4482.85	o	2.98	S.D.	Bo	Bl. *O* III
$(3d^2D - 4f^2D)$...	4613.67	1	3.84	S.D.	Bo	Bl. *N* II
	21.28	o	1.49	S.D.	Bo	Bl. *N* II
$(3d^2D - 4f^2D)$...	4707.80	o	7.98	O.S.	Bo, 1, 2	XXX

[12] In these tables the symbol xxx means that no identification existed previously for the line; in case of blending, the blending line is indicated.

Ne II.—A few remarks may be made concerning the identification of *Ne* II lines by D. H. Menzel and R. K. Marshall.[10]

1. In $3s^4P - 3p^4P^o$ it does not seem possible that the strong *Ne* II line λ 3766.29 which is at a distance of 4 *A* from *H*ι could have been masked by *H*ι.

2. In $3p^2P^o - 3d^2D$ the identifications are rather doubtful, as the strongest line λ 3829.77 does not appear in 10 Lacertae (an O9 spectrum with very numerous and sharp lines), although the region from λ 3820 to λ 3835 in 10 Lacertae is completely free from lines.

3. In $3d^4D - 4f^4D^o$ three lines by O. S. and S. D. are identified by Menzel and Marshall; it is also possible to identify λ 4217.22 (τ Scorpii, Bo, int. 2) with λ lab. 4217.15 (int. 3).

4. In $3d^4F - 4f^4G^o$ two identifications may be added to the two made previously by Menzel-Marshall:

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$(3d^4F-4f^4G^o)$...	4290.40	6	{0.53 {0.47	S.D. M	Bo} Bo}	Bl. *N* III
	4428.54	6	{8.53 {8.44	S.D. M	Bo} Bo}	Bl. [*N* II]

5. In $3d^4F - 4f^4F^o$ other identifications in τ Scorpii (S.D.) are allowed:

$(3d^4F-4f^4F^o)$...	4369.77	5	9.33	S.D.	Bo	Bl. *O* II
	4397.94	6	8.01	S.D.	Bo	XXX
	4430.90	4	0.99	S.D.	Bo	Bl. [*S* II]
	42.67	3	2.95	S.D.	Bo	Bl. *O* II
	46.46	3	6.97	S.D.	Bo	Bl. *N* II, *O* II

6. An identification may be made in $3d^2P - 4f^2D^o$:

$3d^2P-4f^2D^o$...	4511.29	2}	11.13	M	Bo }	Bl. *N* III
	11.37	4}	10.88	S.D. and O.S.	O9, Bo}	

Na II.[13]—The *Na* II absorption lines having a wave-length greater than 3580 A require an excitation potential of more than 32 volts; thus they should be strong only in the hottest stars. λ 3631.37 (int. 8) of *Na* II may tentatively account for λ 3631.67 (class O9). An examination of the ultra-violet parts of a few O5–O8 spectra would be interesting.

Na III and Mg III.—The lower excitation potentials of the visible lines are:

$$\text{For } Na \text{ III} \quad : \quad \geq 57 \text{ volts},$$

$$\text{For } Mg \text{ III} \quad : \quad \geq 65 \text{ volts}. [14]$$

Thus it seems impossible to expect these lines in B-type spectra.

Al II and III.—Marshall casts suspicion upon the identification of *Al* II and *Al* III. The identification of *Al* III is absolutely safe and some of the lines are actually strong (e.g., $\lambda\lambda$ 4150, 4480, 4512.5, and 4529), as may be seen on the illustrations of the spectrum of γ Pegasi given in Struve's complete paper.[15]

Besides $\lambda\lambda$ 3601.73 (int. 4) and 3612.26 (int. 2) observed by Marshall in α Pegasi and β Canis Majoris and which are certainly due to *Al* III, two lines in the visible part of Marshall's list, $\lambda\lambda$ 4150.05 and 4529.45, have their origin in *Al* III.

Al II seems also to be definitely present. Several lines in Marshall's list may be attributed to *Al* II by comparison with Struve's complete list. In addition to those lines a few more identifications are indicated in Table V.

Table V shows that *Al* II is certainly present in B stars. It may be recalled that in the Sun the abundances of *Al* and *Si* are of the same order ($\mu_{Al} \sim 10^{-1}\mu_{Si}$). The three first ionization potentials are similar:

$$Al \text{ I } 5.96 ; \quad Al \text{ II } 18.73 ; \quad Al \text{ III } 28.31 ;$$

$$Si \text{ I } 8.12 ; \quad Si \text{ II } 16.27 ; \quad Si \text{ III } 33.30 .$$

P III and IV.—For *P* III the identifications are indicated in Table VI.

[13] Questioned by Marshall, *op. cit.*, p. 153.

[14] Kindly communicated by Dr. B. Edlén and Dr. J. Söderqvist.

[15] *Op. cit.*, p. 248, Pl. XI.

TABLE V

Al II

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$(4^3P^0 - 5^3D)$......	3649.20	1.5	9.58	M	B2	XXX
	51.06	6	1.14	M	B2	XXX
$4^1P^0 - 6^1D$......	3703.22	4	3.38	M	B2	XXX
$4^3D - 12^3F$......	3734.7	1	4.33	M	....	Bl. H_λ
$4^3P - 6^3S$.......	3731.95	1	2.04	M	B2, 3	XXX
	3.91	2	4.33	M	....	Bl. H_λ
	8.00	3	$\{$7.87	L*	B3	XXX
			$\{$7.35	M	B5	XXX
$5^1S - 12^1P$......	3753.10	1	3.44	M	B2, 8	XXX
$5^3S - 8^3P$.......	3774.3	0	3.73	M	B2, 3, 5	XXX?
$4^3D - 11^3F$......	3842.2	3	2.74	M	B5	Bl. O II, N II?
$(4^3D - 10^3F^0)$....	3996.08	1				
	.16	4	6.66	M	B5	XXX
	.32	0.5				
	.38	3				
$5^1S - 10^1P$......	4009.58	1	9.32	M	B2, 3, 5, 8	Bl. He I

* Measured by H. M. Losh, in ζ Tauri (*Pub. Obs. U. of Michigan*, 4, 1, Table 10, 1931).

TABLE VI

P III

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$4s^4P^0 - 4p^4P$....	3895.03	6	5.56	M	B1, 2	XXX
	3904.79	6	4.88	M	B0, 1	XXX
	22.72	4	2.79	M	B0, 1	XXX
	33.38	4	3.62	M	B0, 1	Bl. Ca II, S II
	51.51*	5	2.75	M	B1	XXX
	57.64	6	7.54	M	B0,·1, 2	XXX
	97.17	5	6.66	M	B0, 1	XXX

* This line is quoted by Marshall as being of poor quality; the wave-length was not measured in the B1 star β Cephei, but in the B5p star 67 Ophiuchi; the lines in β Cephei and in 67 Ophiuchi have probably different origin.

P behaves similarly to Si, as is shown by the ionization potentials:

$$P \text{ I } 11.11 \; ; \quad P \text{ II } 19.81 \; ; \quad P \text{ III } 30.23 \; ; \quad P \text{ IV } 51.1 \; ;$$

$$Si \text{ I } \; 8.12 \; ; \quad Si \text{ II } 16.27 \; ; \quad Si \text{ III } 33.30 \; ; \quad Si \text{ IV } 44.91 \; .$$

Bowen[16] has found a line of P IV at λ 4249.57 (int. 6) having the designation $4^1S - 4^1P^o$ (lower E.P.-28.9 volts), which could possibly

TABLE VII

S II

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$4p'^2D^o - 4s^2P$....	3669.03	4	9.23	M	B2	XXX
$4p^2S^o - 5s^2P$.....	3783.13	3	2.78	M	B2	XXX
$4p^4P^o - 4d^4P$....	3792.46	5	2.63	M	B2, 3	XXX
	3802.68	1	3.12	M	B2	Bl. O II
	60.66	3	0.58	M	B2, 3, 5	XXX
	92.32	5	2.21	M	B2, 3, 5	XXX
$(4p^4D^o - 4d^4D)$...	3939.52	0	9.12	M	B1, 2, 3	XXX?
	47.02	2	7.28	M	B0, 1, 2	XXX?
	50.45	0	9.67	M	B0, 1, 2, 3	XXX?
	63.14	3	2.64	M	B0, 5	Bl. O II
	70.68	2	0.10	M	....	Bl. $H\epsilon$?
	90.94	8	0.98	M	B1, 2, 5	XXX
	4003.90	3	3.58	S.D.	B0	Bl. N III
$(4p^2D - 4d^2F)$....	4009.41	2	9.28	O.S.	....	Bl. He I $[C$ II$]$
$(3d^2F - 4p'^2F^o)$...	3993.49	6	3.61	M	B2	XXX

explain the unidentified λ 4250.10 (int. 1) of 10 Lacertae (class O9) and λ 4249.89 (int. 1) of τ Scorpii (class B0).

S II and III.—According to Marshall,[17] Gilles's tables are untrustworthy, but the investigations of O. Bartelt and L. Eckstein[18] have brought new material which has allowed the identifications listed in Tables VII and VIII.

[16] *Phys. Rev.*, **39**, 8, 1932.

[17] *Op. cit.*, p. 152.

[18] *Zs. für Phys.*, **86**, 77, 1933; *Zs. für Astroph.*, **7**, 272, 1933.

TABLE VIII

S III

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$(4s^3P^o - 4p^3P)$	3837.79	5	7.33	M	B1, 2	XXX
	60.64	4	0.58	M	B1, 2, 3	XXX
$(3d^3D^o - 4p^3D)$	4499.29	0	9.40	S.D.	B0	XXX?
	4527.96	0	7.18	M	B0	XXX??

Ca III.—There are two laboratory lines in the astrophysical region:

	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$4s_3 - 4p_{10}$	3761.62	6	1.27	M	O9	XXX
$4s_2 - 4p_{10}$*	4081.74	5	1.83	M	O9–B0	XXX

* This second identification is somewhat doubtful, as there exists some incompatibility between the measures of S.D. and M near λ 4081 A.

Ti II.—Possible identifications are indicated in Table IX.

TABLE IX

Multiplet Designation	Laboratory Wave-Length	Laboratory Intensity	Stellar Wave-Length	Author	Spectral Types	Identification
$b^2D - y^2D^o$	3741.68	(50)	1.85	M	B3	XXX
	57.69	(30)	7.70	M	B8	XXX
	76.06	(6)	5.97	M	B5–B8	XXX

A II.—When comparing all the multiplets of *A* II given by De Bruin[19] with the absorption lines of classes B0, B1. and B2, we find a percentage of coincidences as large as in the case of *Ne* II. The number of coincidences observed is obviously greater than the number of chance coincidences calculated by the Russell-Bowen formula; in addition, the intensities observed agree quite well with the laboratory intensities. If the presence of *A* II could be verified with certainty, an important number of lines of B stars would be identified;[20] these lines appear where they ought to (maximum at B1–B2), owing

[19] *Zs. für Phys.*, **48**, 62, 1928; **51**, 108, 1928; **61**, 307, 1930.

[20] More than twelve, which had heretofore no other suggested identification.

to their ionization and excitation potentials, which are lower than for *Ne* II.

Ionization potentials:

$$Ne \text{ I } 21.47 \text{ volts} ; \quad Ne \text{ II } 40.9 \text{ volts} ;$$

$$A \text{ I } 15.69 \text{ volts} ; \quad A \text{ II } 27.72 \text{ volts} .$$

Excitation potential of lower level:

$$Ne \text{ II} : \text{between } 27 \text{ and } 28 \text{ volts} ;$$

$$A \text{ II} : \text{between } 17 \text{ and } 22 \text{ volts} .$$

Arguments against these identifications are the atomic weight of argon (39.94) and the fact that it has never been observed in stellar or nebular spectra. These arguments do not seem convincing. The discovery of *A* II in B stars would be of interest, in connection with a recent paper by H. N. Russell and D. H. Menzel.[21]

The question of *A* II is being investigated here; the results will appear later.

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[21] *Proc. Nat. Acad.*, **19,** 997, 1933.