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NEW IDENTIFICATIONS OF *Fe* III IN THE SPECTRA OF EARLY B STARS

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ABSTRACT

Starting from their laboratory measurements, the authors are able to show that about one hundred lines observed in the spectra of early B-type stars are due to *Fe* III. The ionization potential of *Fe* III is 30.48 volts.

1. In a previous paper[1] several *Fe* III lines of the astronomical region were computed, beginning with a term analysis of the *Fe* III spectrum in the far ultraviolet region: these lines were found to be prominent in early B-type stars. We have now investigated the vacuum-spark spectrum of iron, with a large quartz spectrograph (Hilger E.1), from λ 2000 through the visible region. The spark was obtained by discharging 0.4 μF at about 60,000 volts through a spark gap of 1 mm, a few sparks being sufficient for an exposure. The spectrum is extremely rich in lines. After removing *Fe* I and *Fe* II from the measurements, some three thousand lines remain in the region above λ 2975. The very high stages of ionization were suppressed by means of a large induction coil, but *Fe* IV and, probably, *Fe* V are also excited in the spark. Considering the spectral structure of the various ions, however, it is not likely that stages higher than *Fe* III will be prominent in this region, and most of the lines measured in the astronomical region are certainly of *Fe* III origin.

Although the term analysis is not yet quite complete, the measured wave lengths enable us to identify with certainty many unexplained lines of early B-type stars. This identification work constitutes the main subject of the present paper.

We shall examine successively the identifications of absorption lines in the ultraviolet, the ordinary photographic, and the visual regions of the early B-type spectra. Next we shall consider the spectra of Be and P Cygni stars.

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[1] Swings and Edlén, *Ap. J.*, **88,** 618, 1938.

2. *Ultraviolet region of the early B-type stars.*—A good list has been published by W. S. Adams and Theodore Dunham, Jr.,[2] covering the region between λ 3000 and λ 3600. It happens that strong *Fe* III lines appear in this region and give reliable identifications of fairly strong absorption lines, namely, the group of prominent unidentified lines at λλ 3266.9, 3276.2, and 3288.9; Adams and Dunham had actually suggested that these three lines are probably due to the same element. The identifications are summarized in Table 1. No very strong line of *Fe* III appears in the region λλ 3604–3964.

TABLE 1

Laboratory Wave Length and Intensity		Mean Stellar Wave Length	Intensity in—				Previous Identification	Notes
			βC Ma (cB1)	εC Ma (B1)	χ^2 Ori (cB1)	γ Peg (B2)		
3086.31	(6)	86.4	5	5	8	6	86.3 *Si* III	1
3136.43	(10)	36.5	1	2	......	......	....	4
3174.09	(10)	74.1	1	2	......	......	....	5
3176.00	(10)	76.0	2	1	2	......	....	5
3178.03	(10)	78.05	1	1	......	......	....	5
3198.81	(5)	98.9	1	......	1	......	98.6 *Ne* II	
3218.34	(6)	18.2	1	......	......	......	18.2 *Ne* II	
3266.88	(20)	66.95	3	2	4	3	....	2, 3
3276.08	(15)	76.25	3	2	2	2	....	2, 3
3280.58	(6)	80.5	......	......	1	......	....	3
3288.81	(15)	88.9	2	......	2	......	....	2, 3
3305.22	(10)	05.2	2	2	2	......	05.2 O II	3
3339.36	(10)	39.4	1	......	1	......	....	3
3360.84	(6)	60.6	1	......	......	......	60.7 *Ne* II	
3367.02	(6)	67.2	2	......	1	......	67.2 *S* III	
3586.12	(9)	86.05	1	......	......	1	....	6
3600.93	(10)	00.9	1	......	......	......	....	6
3603.88	(9)	03.95	2	......	1	......	....	6

1. *Fe* III minor contributor.
2. Group of prominent unidentified lines suggested, by W. S. Adams and Th. Dunham, to be due to the same element.
3. Multiplet $a^5F - z^5G^o$; low excitation potential, 10.3 volts.
4. Multiplet $a^3F - z^3D^o$; low excitation potential 11.2 volts.
5. Multiplet $a^3F - z^3G^o$.
6. Multiplet $a^3F - z^3F^o$.

3. *Photographic region of the early B-type stars.*—For the region λ 3900 to λ 4700 we possess very good lists of wave lengths by O. Struve,[3] O. Struve and Theodore Dunham, Jr.[4] (τ Sco), R. K. Mar-

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[2] *Ap. J.*, **87**, 102, 1938.

[3] *Ap. J.*, **74**, 225, 1931.

[4] *Ap. J.*, **77**, 321, 1933.

shall,[5] and, recently, H. Kühlborn.[6] The comparison of the laboratory data with the stellar wave lengths and intensities is based essentially on Kühlborn's extensive and excellent table. Of course, there appear many wave-length coincidences, several of which have a physical meaning. But for the weak laboratory lines the chance coincidences are very numerous. A detailed and complete discussion is not feasible before a more advanced term classification is performed. In fact, the general procedure here has been:

a) To examine first the lines of laboratory intensity greater than 5 (on our arbitrary scale). The corresponding identifications are probably certain.

b) Next, to examine the lines of laboratory intensity 5. It seems possible that a few identifications are somewhat doubtful. Within the region concerned, no vacuum-spark line of intensity greater than 5, and hardly any of intensity 5, are missing in Kühlborn's list.

c) To examine, finally, the lines of laboratory intensity 4 in γ Pegasi only (except when observed by Struve in γ Peg and not by Kühlborn in that star), in order to reduce the number of chance coincidences. Even so, there may still be a few purely chance coincidences.

No line of intensity weaker than 4 has been considered, although there seem to be good reasons to believe that several lines of laboratory intensity 3 or 2 are present in γ Peg. This part of the investigation will be performed later, when a more advanced term classification will be available.

Table 2 summarizes the results. The notations used are: column 3: K_1, from the list of lines in ζ Persei by Kühlborn; K_2, from the list of lines in γ Orionis; K_3, from the list of lines in ζ Cassiopeiae; S, from the list by Struve; SD, from the list by Struve and Dunham; M, from the list by Marshall; B, from the list by Baxandall;[7] column 4 (notations used by Kühlborn): a, major contributor (50–100 per cent); b, contributor from 20–50 per cent; c, contributor from 5–20 per cent; a?, major contributor unknown. The intensities are from γ Peg. References to the tables by H. H. Plaskett,[8] Pillans,[9] and

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[5] *Pub. U. of Michigan Obs.*, **5**, 137, 1934.

[6] *Veröff. Babelsberg*, **12**, Heft 1, 1938.

[7] Solar Physics Committee, 1914.

[8] *Dom. Ap. Obs.*, **1**, 325, 1922.

[9] *Ap. J.*, **80**, 51, 1934.

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TABLE 2

Laboratory Wave Length and Intensity	λ and Intensity in γ Peg, According to Kühlborn	Other Observations	Previous Identifications (in Kühlborn's Table)	Notes
3964.11 (5) 3964.44 (3)	64.24 (1–2)	....	a?	
3968.78 (8)	68.78 (1–2)	M 68.41 (3)	a?; ? *C* II 8.63 (00);	
3975.13 (4)	75.17 (2–3)	K_1 75.29; ? M 74.58 (1)	a?; ? *Fe* II 5.03 (1)	
3978.43 (4)	....	K_1 78.39; S 78.30 (1)	*P* III 8.27 (9)	
3979.42 (5)	....	K_1 and K_2 79.58	*Ar* II 9.36 (7); *S* II 9.86 (3)	
3993.15 (5)	93.16 (1)	S 93.33 (1); M 93.61 (2 in δ Cet)	a?	
4000.83 (4)	00.86 (2–3)	K_1 and K_2 00.83	a?	
4002.36 (4)	02.40 (1)	K_2 02.38	a?; ? *Fe* II 2.55 (3)	
4003.41 (4)	03.51 (1–2)	K_2 03.40	a *Ca* III ? 3.35 (5); a *N* III 3.64 (4)	
4008.81 (5)	08.76 (2–3)	....	a?	
4022.36 (4)	22.24 (3–4)	K_1 and K_2 22.35	a?	1
4035.54 (4)	35.384 (3–4)	K_1 35.52; S 35.12 (2)	a?; b *Ar* II 5.47 (6)	1, 2
4039.12 (3s)	39.03 (1–2)	K_1 and K_2 39.02; S 9.24 (1)	a?	3
4044.05 (4)	44.05 (3–4)	K_2 43.94	a?	1
4053.28 (5)	53.12 (4–5)	S 53.08 (1)	a?	1, 2
4057.51 (4)	57.46 (2)	....	a *P* III 7.39 (4)	
4066.11 (4)	66.10 (1–2)	....	a?	
4081.19 (7)	81.29 (1)	S 81.01 (1); SD 1.1 (1); M 1.38 (2 in δ Cet)	a?	2
4085.53 (4)	85.47 (3)	M 85.24	a?; ? *P* 5.55 (1)	
4103.15 (4)	03.02 (6)	....	a *O* II; etc.	4
4109.95 (5?)	09.86 (2)	K_2 10.06	a *Ca* II 9.83 (1); a *N* I 9.98 (12)	
4113.23 (7) 4113.45 (7)	13.26 (1–2)	....	a?	
4115.74 (4)	15.63 (2)	....	a?	
4118.57 (8)	18.72 (3)	....	a?; ? *P* II 8.96 (2)	
4120.02 (4)	20.18 (4–5)	K_1 and K_3 20.15	a *O* II 0.28 (5); b?	
4120.97 (8)	20.84 (34)	....	*He* I	4, 9
4121.31 (6)	21.51 (3)	....	a *O* II 1.47 (4)	
4122.06 (8)	22.01 (2–3)	K_1 21.99	a *B* II 1.95 (7); a *C* III 2.05 (3)	5, 9
4122.98 (8)	22.84 (3–4)	S 22.75 (1); M 22.68 (2 in δ Cet)	a?	9
4136.95 (4) 4137.30 (2)	37.10 (1–2)	....	a?	
4137.93 (8)	37.81 (4)	S 37.72 (2); M 37.50 (2 in δ Cet)	a?; ? *N* I 7.63 (7)	9
4139.37 (7)	39.37 (2–3)	? S 39.79 (1)	a?	9

TABLE 2—*Continued*

Laboratory Wave Length and Intensity	λ and Intensity in γ Peg, According to Kühlborn	Other Observations	Previous Identifications (in Kühlborn's Table)	Notes
4140.51 (6)	40.45 (1–2)	S 40.82 (1); M 40.48 (2 in βC Ma); SD 0.6 (1)	a?	9
4145.74 (5)	45.48 (1–2)	K_1 45.47; M 45.90 (2 in β Cep)	....	
4146.82 (4)	46.94 (1)	K_1 and K_2 46.90	a *S* II 6.94 (3)	
4154.98 (8)	54.83 (1)	S 55.09 (1); B 4.8 (1)	a *N* II 5.0 (00*n*)	5
4161.39 (4)	61.28 (1–2)	....	a?	
4164.79 (20)	64.76 (7)	K_1, K_2, and K_3 64.80; S 64.78 (3); SD 64.81 (3); M 64.71 (3 in δ Cet); B 64.8	a?; ? *S* III 4.96 (0)	6, 9
4166.86 (9)	66.82 (5–6)	S 66.90 (1); SD 6.70 (1); M 6.93 (1); etc.	a?; c *P* II 6.73 (3)	9
4168.41 (4)	68.43 (3)	K_1 68.30	a *S* II 8.41 (5); b *Al* II 8.42 (1); c *Al* II 8.51 (0.5)	9
4174.27 (10)	74.26 (2)	S 74.12 (1); M 74.06 (2 in δ Cet)	a *S* II 4.30 (6)	5
4176.79 (4)	76.80 (2)	K_1, K_2, and K_3 76.84	a?	
4179.25 (5)	....	K_2 79.21 (1)	*Ar* II 9.31 (5)	
4182.02 (4)	82.11 (2)	K_1 and K_2 82.18; M 82.09 (1 in ·δ Cet)	a *S* III 2.14 (00); a?	
4184.09 (4)	84.23 (2)	K_1 and K_2 84.27	a *Ca* III ? 4.29 (8)	
4186.50 (4)	86.46 (1–2)	K_2 and K_3 86.46; S 86.83 (1); M 86.85	a?; b *K* II 6.23 (9)	
4189.10 (7)	89.21 (2)	S 88.74 (1)	a *P* III 9.08 (3); b?	
4193.98 (4)	93.96 (1–2)	K_1 93.95	a?	
4200.06 (6)	99.98 (2–3)	K_1 and K_3 99.86; M 00.21 (1 in β Cep)	a *N* III 0.02 (6); ? *He* II, *Ar* II, *Ti* III ?	
4200.38 (6)	00.37 (2)	K_2 00.47	a?	
4203.91 (5)	03.86 (1)	K_3 03.89	a?	
4210.87 (10)	10.74 (1–2)	K_2 10.77; ? S 11.36 (1)	a?; ? *P* 0.8 (0)	
4220.32 (5)	20.22 (3)	S 20.07 (1 in δ Cet); M 20.08 (1 in δ Cet)	a?; b *Ca* II 0.13	
4222.39 (8)	22.27 (2–3)	K_2 and K_3 22.19; S 22.36 (2); SD 22.04 (1)	a *P* III 2.15 (7); b?	
4230.52 (4)	30.62 (1)	S 30.76 (1)	a?	
4235.54 (10)	35.67 (2.3)	K_2 35.48	....	
4238.78 (5)	38.55 (3)	K_2 38.46; S 38.83 (1)	a?	
4243.85 (8)	43.92 (1)	K_2 43.9; S 43.84 (1); M 44.09	a?; ? *Ne* II 4.17 (0)	

TABLE 2—*Continued*

Laboratory Wave Length and Intensity	λ and Intensity in γ Peg, According to Kühlborn	Other Observations	Previous Identification (in Kühlborn's Table)	Notes
4249.95 (7)	....	K_1 and K_2 50.00; SD 9.83 (1)	*S* II 9.92; ?	
4253.62 (4)	53.63 (3–4)	S 53.66 (3); M 53.88 (2)	a *S* III 3.59 (9); a *O* II 3.74 (4)	4
4255.20 (5)	....	K_1 and K_2 54.96	a?; *S* II 5.01 (0)	
4261.46 (4)	61.41 (2–3)	M 61.56	a?	
4263.52 (4)} 4263.94 (4)}	63.52 (1)	S 63.81 (1 in δ Cet); M 63.67 (2)	a?; ? *K* II 3.31 (7)	
4271.47 (6)	71.63 (1–2)	S 71.78 (1); M 71.74 (2 in δ Cet)	a?; ? *P* III 1.85 (1); ? *Ca* III ? 1.87 (7)	
4273.43 (5)	....	K_3 73.44 (3); S 73.35 (1 in γ Peg); M 73.19 (1 in γ Peg)	a?	
4286.13 (10)	86.2 (2)	S 86.24 (1)	a?; ? *C* II 5.96 (1)	
4291.11 (4)	91.26 (2)	? S 91.48 (2 in βC Ma)	a *O* II 1.22 (2); c *S* II 1.45 (1); c *P* III 1.1 (1)	
4296.86 (—)*	96.93 (3)	K_2 97.04; S 96.54 (1)	a?; b *Ne* II 6.96 (0)	
4304.81 (10)	04.79 (2–3)	K_1 and K_2 04.83	a?; a *K* II 4.94 (3)	5
4310.37 (12)	10.31 (1–2)	K_3 10.22; SD 10.39 (1); S 10.54 (1)	a?	
4352.70 (4)	52.48 (1–2)	S 52.47 (1)	a?; ? *Ar* II 2.23	8
4365.56 (3)	65.66 (1)	K_1 65.6	a *Ne* II 5.72 (2)	8
4372.41 (20)	72.404 (5)	K_1, K_2, and K_3 72.33; S 72.30 (2); SD 2.69 (1); M 2.30 (2)	a?; b *C* II 2.49 (4); ? *Si* 2.33	6
4372.88 (—)	72.85 (1–2)	....	a?	
4395.78 (6)	95.80 (4)	K_2 95.85; S 95.88 (2); M 95.86 (2)	a *O* II 5.94 (4); a?	8
4419.59 (10)	19.601 (3)	K_2 19.55; S 19.62 ( ); M 19.67 (1 in βC Ma); SD 19.97 (1); B 9.4 (1–2); etc.	a?	8
4422.5 (5 bl.)†	22.33 (2)	K_2 22.31; M 22.53 (2 in δ Cet)	a?	
4430.95 (7)	31.08 (2)	S 31.03 (2); SD 30.99 (2)	a *Ar* II 1.02 (8); b *S* II 1.02 (1)	8
4447.86 (5 bl.)†	47.78 (2)	....	a *Al* II 7.8 (3)	
4483.48 (4)	83.43 (2)	K_1 and K_2 83.38; S 83.24 (2)	a *S* II 3.42 (6); c *P* II 3.66 (4)	
4483.91 (4)	84.07 (2–3)	K_2 84.10; SD 83.93 (1)	a?	

* Part of blending with *Fe* II of total intensity 12.

† Part of blending with *Fe* I of intensity 5.

TABLE 2—*Continued*

Laboratory Wave Length and Intensity	λ and Intensity in γ Peg, According to Kühlborn	Other Observations	Previous Identifications (in Kühlborn's Table)	Notes
4535.50 (5)	35.88 (1–2)	....	a?; a *S* IV 5.69 (4); ? *S* II 5.7 (00)	7
4545.16 (4)	45.21 (1)	SD 44.9 (1)	a *Ar* II 5.08 (10); b *P* III 4.97 (3)	
4559.09 (6)	59.25 (1–2)	K_2 59.3; B 59.3 (2); M 58.77 (2 in βC Ma)	a?	
4570.34 (4)	70.24 (2)	....	a?	
4573.14 (5)	72.84 (3–4)	K_2 73.0 (1); SD 73.05 (1)	a?	
4581.58 (4)	81.66 (3)	K_2 81.7 (2)	a *P* II 1.76 (5); b?	
4591.84 (4)	91.98 (2)	K_2 91.9 (1); SD 92.19 (1); S 92.27 (2)	a?	
4694.57 (4)	94.67 (1–2)	K_2 94.4; S 94.67 (1)	a *N* II 4.55 (3)	

1. *Fe* III is probably not the only contributor.
2. Multiplet $5p\,^7P^\circ - 6s\,^7S$; low excitation potential, 20.5 volts.
3. Sharp line (impurity?).
4. *Fe* III minor contributor.
5. *Fe* III important contributor.
6. The two strongest unidentified lines in the early B-type stars.
7. Doubtful identification.
8. Previously published; predicted $a\,^5P - 4p\,^5P^\circ$ multiplet; low excitation potential, 8.2 volts.
9. Multiplet $5p\,^7P^\circ - 5d\,^7D$.

Losh[10] seemed superfluous in connection with the present work and have therefore been omitted.

4. *Visual region of the early B-type stars.*—The lists of stellar absorption lines in the visual region of the early B-type stars[11] are still of a rather preliminary character. It is not impossible that the two lines measured by Marshall in γ Ori at 5001.36 (5) and 5127.51 (4) are actually the *Fe* III lines at 5002.02 (8) and 5127.32 (6), but these identifications are only provisional. In the vacuum spark a large number of fairly strong *Fe* III lines appear from λ 5000 to λ 6200, including the multiplets $a\,^5D - 4p\,^5P^\circ$, $4d\,^7D - 5p\,^7P^\circ$, $5s\,^7S - 5p\,^7P^\circ$, and, probably also, $4d\,^5D - 5p\,^5P^\circ$ and $5s\,^5S - 5p\,^5P^\circ$, which should all be found in suitable stellar spectra.

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[10] *Pub. U. of Michigan Obs.*, **4**, 1, 1932.

[11] Marshall, *Ap. J.*, **82**, 97, 1935.

TABLE 3

Be STARS

LABORATORY WAVE LENGTH AND INTENSITY	WAVE LENGTH AND INTENSITY IN—		PREVIOUS IDENTIFICATIONS	NOTES
	γ Cass (Baldwin)	BD+11°4673 (Merrill)		
4352.7 (4)	....	52.7 (0)	52.80 [*Fe* II]	1
4372.40 (20)	72.55 (0.3)	72.1 (0)	? 72.46 [*Fe* II]	
4382.5 (comp.)	82.63 (0.3)	....	....	1, 2
4395.78 (6)	95.60 (0)	96.0 (0)	....	2
4419.59 (10)	19.57 (1)	19.8	....	2
4430.95 (7)	....	30.94 (0)	....	
5157.85 (4)	....	58.1 (0)	? 58.05 [*Fe* II]	1

1. Identification rather doubtful.
2. Previously published.

TABLE 4

P CYGNI

Laboratory Wave Length and Intensity	Absorption Line	Emission Line	Notes
3600.93 (10)	99.56 (3)	00.88 (3)	
3603.88 (9)	02.51	03.49 (2)	
4039.12 (3 s)	37.13 (2)	38.74 (1)	
4164.79 (20)	....	64.07 (3)	
4352.7 (4)	....	52.07 (2)	2
4372.41 (20)	72.66 (1)	....	
4382.5 (comp.)	82 (1)	83.07 (3)	2
4419.59 (10)	17.42 (7)	19.24 (5)	2
4430.95 (7)	29.04 (4)	30.91 (3)	2
4940.46 (4)	38.01	....	1
5073.78 (3)	71 (1)	....	2
5100.7 (10)	97 (1)	....	
5127.32 (6)	25 (2)	27 (2)	2
5155.97 (4)	54 (3)	56 (3)	1
5193.90 (4) 5194.43 (4)	92.3 (1–2)	....	3

1. Identification rather doubtful.
2. Previously published.
3. Observed by E. K. Kharadse, *Zs. f. Ap.*, 11, 304, 1936.

5. *Fe* III *lines in the spectra of Be and P Cygni stars.*—The lists of wave lengths considered are due to P. W. Merrill (BD+11°4673)[12] and R. B. Baldwin (γ Cass)[13] for Be stars and to O. Struve[14] (for P Cygni). Our results are summarized in Tables 3 and 4.

In connection with this question it may be noticed that *Fe* III offers a typical example of absorption lines starting from both metastable and non-metastable lower levels. This may be of interest in discussions concerning extended atmospheres.[15]

6. *The ionization potential of Fe* III.—The septet and quintet systems are now connected by intercombination lines. From three members of the ns^{7}S series a Ritz formula gives the ionization potential of *Fe* III as 30.48 volts, which is in close agreement with our previous estimate,[1] 30.3 volts.

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[12] *Ap. J.*, **69**, 330, 1929.

[13] *Ap. J.*, **87**, 573, 1938.

[14] *Ap. J.*, **81**, 73, 1935.

[15] See Struve, *Astronomical Symposium of Western Reserve Academy*, p. 52, Hudson, Ohio, 1938.