STUDIES OF THE PECULIAR A STARS. IV. THE RELATIVE ABUNDANCES OF FOUR IRON-PEAK ELEMENTS

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Received November 26, 1965; revised January 17, 1966

ABSTRACT

Equivalent widths are given for twenty-nine unblended lines of Fe II, Cr II, Mn II, and Ti II measured in the wavelength interval λλ 3200–3520 on 10 Å/mm spectrograms of each of twenty-one normal and peculiar A and B stars. These include four λ 4200 Si stars, seven Mn stars, five Eu-Cr-Sr stars, one Am star, and four normal stars. The relative strengths of the measured lines of these four elements are very insensitive to changing excitation conditions and are used to determine relative abundances by coarse curve-of-growth techniques. The main results of the analyses are as follows: (*a*) The excitation temperatures obtained for the peculiar stars are similar to those of normal stars of the same color. (*b*) All the Ap stars, with the exception of the Mn stars, have abnormally high microturbulent velocities. (*c*) The Mn stars have an abnormal distribution of abundances among the four elements studied. The Mn stars have a ratio of Mn : Fe which is from 6 to 60 times higher than normal. In the Mn stars the ratios Cr : Fe and Ti : Fe are also abnormal, but these ratios differ from star to star. (*d*) In the case of the Si-rich and O-poor varieties of Ap stars the relative abundances of the four elements studied are entirely normal. In particular, the Cr/Fe abundance ratio is normal in Ap stars of the Eu-Cr and Sr-Eu-Cr types. In these stars the enhancement of the Cr lines seen at low dispersion is real, but the lines of Fe, Ti, and Mn are also enhanced.

I. INTRODUCTION AND MEASUREMENTS

Earlier papers in this series have dealt with the behavior in a large variety of peculiar A stars of ions whose excitation and ionization potentials resemble those of hydrogen. Since the photo-ionization of hydrogen is the main source of continuous opacity in the atmospheres of A- and B-type stars, the strengths of well-chosen lines of such ions are insensitive to the excitation conditions and can be used to determine abundances which are nearly independent of our knowledge of the stars' atmospheric structures. In Paper I (Sargent and Searle 1962) we considered the behavior of the infrared lines of O I and Mg II, while in Paper II (Searle and Sargent 1964) we considered Si II and Mg II, in each case deriving abundances by crude single-layer atmosphere techniques. In Paper III (Mihalas and Henshaw 1966) our results were confirmed by a model-atmosphere analysis of the data published in Papers I and II. However, in their paper Mihalas and Henshaw were not able to reproduce the observed strengths of the O I and Mg II infrared lines and they suggested that this was due to a high value of the microturbulent velocity in the upper levels of the stars' atmospheres in both the normal and peculiar stars. Mihalas and Henshaw pointed out that this difficulty was overcome completely in Paper I, despite the cruder techniques therein employed, by the device of carrying out analyses relative to normal stars and by the careful choice of the lines studied.

The difficulties encountered in Mihalas and Henshaw's model-atmosphere approach emphasize that we cannot hope at the present time to obtain *absolute* abundances for

* We regret to report the tragic death of Mr. Lungershausen, a graduate student in the Department of Astronomy.

many elements in studies of Ap star spectra because we have inadequate knowledge of their atmospheric structures, particularly in the upper layers where the magnetic fields dominate. This is because the models do not properly represent these upper layers. (On the other hand, there is now ample evidence from the first three papers in these series that the Ap star atmospheres behave normally in the deeper layers where the wings of the Balmer lines are formed.)

The iron-peak elements play an important role in the understanding of the physical nature of the Ap stars. A large fraction of the stars are classified as Mn or Eu-Cr stars, and the implication is often drawn that Mn and Cr are overabundant. Moreover, in a recent theory of abundance anomalies in Ap stars by Fowler, Burbidge, Burbidge, and Hoyle (1965), it was suggested that the Fe-peak elements have been produced by a process of rapid neutron addition in stellar interiors; this suggestion may be open to verification if accurate abundances can be obtained. Unfortunately, the available lines of the iron-peak elements in A and B stars arise predominantly from low-lying levels of the singly ionized state and may be expected on grounds of excitation and ionization to be formed in the upper levels of the atmospheres where the structure is not well known.

TABLE 1

IONIZATION POTENTIALS (eV)

Element	Ionization Stage		
	I	II	III
Ti ...	6 83	13 57	27 47
Cr ..	6 76	16 49	30 95
Mn..	7.43	15 64	33 69
Fe ...	7 89	16 18	30 63

However, as can be seen from Table 1, the iron-peak elements have similar ionization potentials for all ions of interest and, also, lines of similar excitation potential in each ionization stage. Hence, although we cannot expect to obtain accurate *absolute* abundances for these elements, even using the best current model-atmosphere techniques, we can determine their *relative* abundances. As we shall see in the third section, the results are very insensitive to the adopted atmospheric parameters.

In order to make such a relative analysis, we must use lines which are present in measurable strength in both normal and peculiar stars. This condition is relatively easy to satisfy for Fe, Cr, and Ti, but the only suitable lines of Mn to be found in the accessible regions of the spectra of normal B stars are those of multiplet 3 of Mn II around λ 3450. In order to avoid unnecessary assumptions regarding atmospheric structure, we have chosen lines between the Balmer discontinuity λ 3646 and λ 3100 where the atmospheric cutoff occurs. In this region it is possible to find a number of unblended lines of Ti II, Cr II, and Fe II as well as Mn II in a wide variety of peculiar and normal A and B stars. In this region, in addition to the lines of the ions mentioned, a few lines of Sc II, Co II, Ni I, and Fe I were found to be present and unblended in some of the stars observed. These were thought to be inadequate for analysis and will not be discussed further.

During 1961–1963 we obtained spectrograms at the coudé focus of the Mount Wilson 100-inch reflector of the eighteen Ap stars and three normal stars listed in Table 2. These spectrograms had a dispersion of 10 Å/mm and were obtained on baked Kodak IIaO emulsion. They were well exposed in some part of the wavelength interval λλ 3120–3500 and were 0.5 mm wide. To obtain this entire wavelength region on well-exposed plates,

usually several spectrograms had to be taken for each star. Any one equivalent width listed in Table 3 is, however, in most cases based upon measurements of only one spectrogram. Table 2 is self-explanatory; the peculiarity types in the fourth column were taken mostly from Jaschek and Jaschek (1958). Of the stars in Table 2, one (μ Ori) is a metallic-line star and three stars (ι CrB, 21 Aql, and HR 8216) have been earlier classified as peculiar but may well be normal. HR 8216 has been classified as an Eu-Cr star but a line-identification study of 1500 lines in its spectrum by one of us (Sargent, unpublished) did not reveal a single line of Eu! The star has exceedingly sharp lines, as does ι CrB, which has been classified as an Mn star although Maestre and Deutsch (1961), in a high-dispersion study, did not find the Mn lines particularly strong. We have already

TABLE 2

THE STARS OBSERVED AND ATMOSPHERIC PARAMETERS

BS No	Star	HD or MK Sp Type	Pec Type	$B-V$	log ξ	θ_{exc}	θ_{eff}	log g
710	HD 15144	A2	Sr	+0 17	0 88	0 74	0 60	4 0
873	21 Per	A0p	λ 4200	00	68	0 80	45	3 0
1268	41 Tau	A0p	λ 4200	− 12	58	0 45	34	3 5
1339	53 Tau	B8	Mn	− 05	38	0 85	.41	4 0
1638	11 Ori	B9	λ 4200	− 07	68*	. . .	.	.
2124	μ Ori	A2	Am	+ 15	73	0 89		
2657	γ CMa	B5	Mn	− 11	18	. . .	. .	
3465	49 Cnc	A0p	λ 4200	− 12	48	0 89		.
3500	14 Hya	B9	Mn	− 08	28*		. . .	. . . .
3623	κ Cnc	B8	Mn	− 11	.20	. . .	.35	3 5
4752	17 Com A	A0p	Eu-Cr	− 07	98	0 80	.43	4 0
5475	π^1 Boo	A0	Mn	− 02	48	0 71	45	3 75
5971	ι CrB	A0	Mn:†	− 05	48	0 80	42	3 75
7113	112 Her	B9	Mn	− 10	18	0 91	36	3 75
7287	21 Aql	B8	Si†	− 07	48*	.	38	3 0
8097	γ Equ	F0p	Eu-Cr-Sr	+ 27	88	0 99	67	3 5
8216	HD 204411	A3	Eu-Cr†	+ 09	73	1 10	55	3 0
8911	κ Psc	A2p	Eu-Cr	+ 03	88	1 17	49	3.75
2421	γ Gem	A0 IV	Normal	00	68	0 95	47	4 0
7773	ν Cap	B9 V	Normal	− 05	48	1 00	41	4 0
8641	o Peg	A1 V	Normal	−0 02	0 38	1 00	0 45	4 0

* Assumed.

† Perhaps normal stars; see text.

found in Papers I and II that 21 Aql, although classified as an Si star, has normal abundances of the light elements, including silicon. Thirteen of the peculiar stars in Table 2 and all of the three normal stars were studied also in Papers I or II or, in some cases, in both. In the last two columns of Table 2 we list the values of θ_{eff} and log g obtained for these stars from our data by Mihalas and Henshaw.

Tracings of the spectrograms were intercompared so as to discover as many unblended lines of iron-peak elements as possible common to all, or nearly all, of the stars. Table 3 gives the equivalent widths in milliangstroms for the measured lines. The fourth column lists, where available, the log gf-value given by Corliss and Bozman (1962) for each line.

II. CURVES OF GROWTH AND RELATIVE IONIC CONCENTRATIONS

In this section we first determine the microturbulent velocity, ξ, and the reciprocal excitation temperature, θ_{exc}, for each star using the Corliss and Bozman gf-values for the lines of Cr II and Ti II. We then determine the concentrations of Fe II, Cr II, Mn II,

TABLE 3

EQUIVALENT WIDTHS (MÅ) AND *gf*-VALUES

λ (Å)	MULT.	E.P. (eV)	LOG *gf*	STAR (BS)																				
				710	873	1268	1339	1638	2124	2657	3465	3500	3623	4752	5475	5971	7113	7287	8097	8216	8911	2421	7773	8641
Ti II:																								
3236.12...	24	1.08	−0.05	78	35	15	51	....	158	30	57	121	...	47	20	36	31	<10	122	96	188	56	70	39
3236.57...	2	0.03	0.29	133	100	40	97	27	192	36	161		36	124	30	55	65	29	202	185		113		100
3271.65. .	66	1.24	0.24	95	46	< 30	53	....	104	.....	50	123	...	. .	< 30	40	34	<20	89	73	.....	86	56	53
3272.08...	66	1.22	0.22	109	66	< 38	60	. .	168	.....	91		..	89	< 30	49	36	<25	110	87	.....	99		75
3282.33. .	66	1.22	0.05	90	< 30	32	53	< 30	170	. ...	105	65	....	81	< 35	53	36	<30	126	102	.....	100	36	63
3282.66...	89	1.88	1.10	119	84	55	59	. .	155	.... .	109	55	.. .	. .	< 35	46	41	22	87	87	... .	77	41	70
3332.11...	65	1.24	0.44	138	83	59	49	< 30	88	< 30	86	33	46	126	49	45	25	17	114	101	84	71	46	75
3346.72...	7	0.13	−0.88	124	45	20	33	41	76	22	93	42	....	93	34	30	15	<15	104	117	103	61	33	65
3491.05...	6	0.11	−0.84	69	50	< 25	47	< 20	100	.... .	46	< 25	. ..	57	< 20	29	20	. ...	65	73	64	47	26	36
3504.89 ..	88	1.88	1.18	104	65	89	61	15	103	.. ..	129	65	16	71	34	37	21	... .	100	92	108	59	36	48
3510.84...	88	1.88	1.00	79	66	31	65	.... .	84	.....	50	82	20	66	30	32	29	. ...	69	75	43	43	29	44
Cr II:																								
3209.21...	9	2.53	0.58	138	88	68	63	.. . .	175	.... .	122	63	40	223	51	45	44	14	119	138	. . .	111	33	108
3347.84. .	4	2.42	0.21	122	43	42	37	35	97	26	78	34	17	107	47	47	22	19	112	87	59	59	44	47
3368.05...	4	2.47	0.90	189	100	108	56	.... .	140	38	88	45	35	274	60	69	36	... .	. . .	158	208	103	55	84
3378.34...	21	3.09	0.31	105	40	69	31	37	83	23	52	40	14	137	37	38	< 15	22	88	80	85	43	30	40
3382.68...	3	2.44	0.39	119	57	57	46	... .	99	27	67	35	24	207	42	43	17	13	99	126	120	73	65	51
3408.77...	3	2.47	0.80	250	102	83	71	108	164	47	100	98	34	211	71	81	27	22	146	167	173	86	79	87
3422.74. .	3	2.44	0.65	224	109	104	59	50	155	34	102	70	38	246	72	70	21	17	156	150	155	81	72	74
3457.62...	135	4.92	. . .	72	28	.. . .	21	< 30	54	< 20	40	42	....	67	47	29	< 15	<15	61	63	< 35	13	25	23
3511.84...	2	2.47	−0.20	78	66	48	29	43	86	. ....	69	73	. .	102	19	20	< 15	. ...	60	75	69	29	<25	46
3603.8....	13	2.69	.....	192	111	74	70	146	.. .	.....	139	88	19	.....	63	65	.....	.....	131	173	190	84	55	98
Mn II:																								
3474.1....	3	1.81	0.51	262	155	109	153	130	201	109	192	166	154	222	198	131	141	.....	230	199	169	109	96	125
3482.91...	3	1.82	0.43	158	117	64	95	.... .	126	85	91	105	103	219	116	69	82	.....	118	131	110	71	53	93
3488.68...	3	1.84	0.24	163	108	54	99	46	138	48	87	110	82	176	98	67	81	. ...	94	138	89	61	53	54
Fe II:																								
3277.35...	1	0.98	.....	121	87	52	29	. . .	172	.....	122	... .	.. .	90	47	49	76	55	118	84	.....	112	... .	74
3281.29 ..	1	1.04	.....	89	76	105	....	< 30	163	.. .	111	39	34	80	< 30	54	67	<40	102	82	... .	107	42	53
3302.86...	1	1.04	... ..	.	39	31	. .	< 25	138	< 20	56	90	15	71	.....	32	51	22	. . .	50	42	45	88	42
3303.47...	1	1.09	.....	103	45	29	17	< 25	96	< 20	71		24	62	.....	42	50	19	76	54	35	60		44
3493.46...	114	4.13	. .	38	62	75	23	< 20	90	. ..	. .	20	27	17	.	26	82	. .	30	41	14	38	<25	40

and Ti II in each star relative to one of the standard stars, *o* Peg. We adopt this procedure partly for the reasons given in § I and partly because the *gf*-values available for Fe II and Mn II appear to be unreliable. (In a model-atmosphere analysis of the Mn abundance in 53 Tau, Auer, Mihalas, Aller, and Ross [1966] found that lines of Mn I and Mn II give results which differ by a factor of about 10^3.)

Although the Cr II lines listed in Table 3 have a small range in excitation potential and are hence suitable for determining log ξ, unfortunately they do not cover a large range in the horizontal coordinate of the curve of growth, log η. To aid in fixing the vertical shift in the curve of growth for each star, the three lines of Ti II arising from levels at 1.8-eV excitation were also plotted and were added to the curves of growth for Cr II by arbitrary horizontal shifts to obtain the best continuations of the Cr II curves. It was then possible to define reasonable curves of growth for each star, and these were fitted to theoretical ones published by Wrubel (1949) for log $a = -1.8$ and $B^0/B^1 = \frac{4}{3}$ so as to obtain values of log ξ. These are given in the sixth column of Table 2. We chose the theoretical curve with log $a = -1.8$ because the work of Papers II and III shows that the Ap stars have atmospheric parameters characteristic of stars near the main sequence and our material is insufficient to determine log a for each star. Trials with log $a = -2.2$ showed that its adoption did not appreciably alter the results to be given later.

The average line strengths for each of the four elements studied are roughly the same in a given star so that the adopted value of log ξ does not have a large influence on the derived relative abundances. However, it is of physical interest that, as Table 2 clearly shows, there is a correlation between the derived log ξ and the kind of spectroscopic peculiarity. The Mn stars have systematically small values of ξ, and the other Ap stars have systematically large ones. The average values are, for five Sr-Eu-Cr stars, $\langle \log \xi \rangle = 0.83$, for four λ 4200 Si stars $\langle \log \xi \rangle = 0.61$, and for six Mn stars $\langle \log \xi \rangle = 0.33$. In compiling these averages we have omitted two of the suspected normal stars, ι CrB (Mn) and 21 Aql. The three normal stars in Table 2 have $\langle \log \xi \rangle = 0.51$. It should be noted that the luminosity class IV star, γ Gem, has a higher value of log ξ than the two normal class V stars. The error in log ξ for an individual star, arising partly from the scatter of the plotted points and partly from the short base line in log η, is about ± 0.15. On this basis the differences in $\langle \log \xi \rangle$ for the four categories of star given about are all statistically significant. It should be noted that the derived "microturbulent velocity" is simply a parameter which describes the vertical shift of the curve of growth; it can arise from a variety of physical causes in addition to mass motions in the line-forming layers. In particular, Zeeman splitting of the lines and hyperfine structure can both influence the line strengths. However, we can minimize the influence of such effects on the derived abundances by analyzing each peculiar star relative to normal stars having roughly the same line strengths for the four elements considered.

Having determined log ξ, the values of $\theta_{\rm exc}$ listed in the seventh column of Table 2 were obtained using the lines of Ti II. We see that both the normal and peculiar stars have surprisingly high (almost solar) values of $\theta_{\rm exc}$ for their values of $\theta_{\rm eff}$. This effect was first discovered in α Lyrae (A0 V) by Wright (1962) and has not been satisfactorily explained. Computations of the contribution functions for various levels of Ti II made by J. Jugaku (personal communication) using Hunger's (1955) model of α Lyrae show that these lines are formed in the outer layers of the atmosphere and that current model atmospheres fail to explain the large difference between $\theta_{\rm eff}$ and $\theta_{\rm exc}$ that is observed. This is a reason additional to those presented in § I for not trusting values of absolute abundances of the iron-peak elements derived from such lines, even when model atmospheres are used. The data in Table 2 do not clearly show whether there is a relationship between $\theta_{\rm exc}$ and color for our stars. In any case, the derived value of $\theta_{\rm exc}$ does not vary markedly from star to star; thus, in view of the small range in excitation potential of the lines in Table 3, we feel justified in adopting for all the stars $\theta_{\rm exc} = 0.85$. This value is used in deriving the relative ionic concentrations of our four elements by the following procedure.

The abscissa of the curve of growth is given by

$$\eta = \text{const.}\ n_{r,s} gf\lambda/k\xi\ , \tag{1}$$

where the symbols have their usual meanings. For each line in each star we obtained log η by reading log $Wc/\lambda\xi$, into the Wrubel curve of growth using the appropriate value of ξ. We then corrected these values of log η to find these values, log η_c, which would be obtained if all the lines were at a standard wavelength $\lambda_0 = 3400$ Å and if they had a standard excitation potential $\chi = 2$ eV. In doing this we assume that the wavelength dependence of the continuous opacity is the same for all stars, so that the ratio κ/κ_0 (where κ_0 is the continuous opacity at λ_0) is the same for any one line in all stars. The value of log η_c is given by

$$\log \eta_c = \log \eta + F(\lambda) + \theta_{\text{exc}}(\chi - \chi_0)\ . \tag{2}$$

Here $F(\lambda)$ is a function of wavelength alone, which is the same for all stars. We now wish to obtain the relative ionic concentrations n_{r*} for our four elements (n_{r*} is the concentration of singly ionized atoms in a hypothetical 2-eV excitation level per unit statistical weight). From equation (1) we have

$$\log n_{r*} = \log \eta_c - \log gf\lambda_0 + \log \kappa_0 + \log \xi\ . \tag{3}$$

In order to eliminate the gf-values we calculate for each line the mean value of log η_c in the three standard stars, o Peg, γ Gem, and ν Cap. Denote such averages by $\langle \log \eta_c \rangle_{\text{st}}$. Then, if we use the usual logarithmic notation $[X] = \log X_{\text{star}} - \langle \log X \rangle_{\text{st}}$, we may write from equation (3)

$$[n_{r*}] = [\eta_c] + [\kappa_0] + [\xi]\ . \tag{4}$$

The quantity $[\eta_c] + [\xi]$ was computed for each line of each ion for all the stars. It should be the same for all lines of a given ion in a given star because it represents the value of $[n_{r*}/\kappa_0]$. We then form for each ion in each star the mean value of $\langle [\eta_c] \rangle + [\xi]$ and subtract from it the value for the same quantity for o Peg. This gives us a quantity

$$\Gamma = [n_{r*}] - [n_{r*}]_{o\ \text{Peg}} - [\kappa_0] + [\kappa_0]_{o\ \text{Peg}}\ ,$$

which is given for each ion and each star in Table 4. We do not know the values of $-[\kappa_0] + [\kappa_0]_{o\ \text{Peg}}$, but these are the same for all ions in a given star so that Γ represents for each star the relative concentrations of the ions Fe II, Cr II, Mn II, and Ti II taking their concentrations to be equal in o Peg.

III. RELATIVE ABUNDANCES

According to the parameters obtained by Mihalas and Henshaw which are listed in Table 1 (see above), the reciprocal effective temperatures of the stars studied in the paper range from $\theta_{\text{eff}} = 0.34$ for 41 Tau to $\theta_{\text{eff}} = 0.67$ for γ Equ. Baschek and Oke (1965) have shown that β CrB, which has very similar colors and spectrum to γ Equ, has $\theta_{\text{eff}} = 0.58$ when excessive line blanketing is allowed for, so that a range in θ_{eff} of 0.34–0.58 seems more reasonable. Using Mihalas' (1964) models, we can estimate roughly that the ionization temperature should vary between $\theta_{\text{ion}} = 0.41$ and $\theta_{\text{ion}} = 0.65$ in the layers where our lines are formed. The standard star, o Peg, has $\theta_{\text{ion}} = 0.52$. Since the measured lines have only a small range in excitation potential, we shall not make serious errors in estimating relative abundances when the four elements studied are slightly ionized. However, for stars having $\theta_{\text{ion}} \lesssim 0.5$ we may expect that these elements will become doubly ionized. In the case of Fe, Cr, and Mn, the maximum differential corrections to the ionic concentrations obtained in the last section necessary to obtain true relative

abundances will not be large. These corrections will be of order $[\theta_{\text{ion}}^{(\text{star})} - \theta_{\text{ion}}^{(o\ \text{Peg})}]$ times the range in second ionization potential which is, approximately, $0.1 \times 0.9 \approx 0.1$, a negligible amount. In the case of Ti and Fe the maximum correction will be $\sim 0.1 \times 2.5 \sim 0.25$. Thus the ionization corrections to Table 4 necessary in order to obtain relative abundances should nowhere be larger than 0.25, and in view of our lack of knowledge of the conditions in the region of line formation we feel justified in making no corrections at all.

The situation is shown precisely in Table 5 which contains results of a series of computations of relative ionic concentrations over an extremely wide range of atmospheric parameters. We computed n_{r*}, the concentration of once-ionized species in a hypothetical 2-eV excitation level per unit statistical weight. The relative abundance of the

TABLE 4

RELATIVE IONIC CONCENTRATIONS

Star	Ti II	Cr II	Mn II	Fe II
HR 710	+0 01	+0 31	+0 19	+0 03
21 Per	−0 21	−0 15	+0 04	− 12
41 Tau	−0 52	−0 11	−0 43	− 15
53 Tau	+0 10	−0 17	+0 63	− 71
11 Ori	−0 98	−0 24	−0 51	− 34
μ Ori	+0 44	+0 31	+0 20	+ 76
γ CMa	−0 39	−0 37	+0 57	− 24
49 Cnc	+0 46	+0 37	+0 41	+ 65
14 Hya	+0 34	+0 27	+1 04	− 27
κ Cnc	−0 38	−0 64	+0 93	− 25
17 Com A	−0 24	+0 35	+0 08	− 11
π^1 Boo	−0 71	−0 26	+0 62	− 64
ι CrB	−0 39	−0 27	−0 03	− 18
112 Her	−0 25	−0 70	+0 93	+ 85
21 Aql	−1 14	−1 18	. .	− 41
γ Equ	+0 04	+0 09	−0 17	− 01
HR 8216	+0 15	+0 32	+0 22	− 07
κ Psc	−0 06	+0 10	−0 33	− 18
γ Gem	−0 08	−0 26	−0 50	+ 05
ν Cap	−0 34	−0 17	−0 21	. . . .
o Peg	0 00	0 00	0 00	0 00

elements that was assumed does not affect our final results but it was, of course, held constant. At each θ and $\log P_e$ the ratio of the n_{r*} was formed for each element relative to Fe and these ratios were (arbitrarily) normalized to unity at $\theta = 0.70$ and $\log P_e = 2.0$. The logarithms of these normalized ratios are the entries in Table 5. These computations show that nowhere do the relative concentrations of Mn II and Fe II (or Cr II and Fe II) vary by much more than a factor of 2. This means that the strikingly abnormal ratios of Mn II and Fe II observed in several peculiar A stars (as shown in the results of Table 4) must be interpreted as abundance effects. Similarly the failure to find abnormal ratios of Cr II:Fe II in many stars of Table 4 implies that these elements must have a normal abundance ratio.

In view of Table 5 and the arguments presented in this section, we interpret Table 4 as giving relative abundances which should be correct to a factor of 2 in the case of Cr:Fe and Mn:Fe and correct to a somewhat larger factor in the case of Ti:Fe. In Table 6 we give the three ratios [Ti/Fe], [Mn/Fe], and [Cr/Fe] obtained from Table 4. In each case this table gives the abundance ratio by number of atoms of an element to iron, divided by the same ratio in a normal star.

TABLE 5

RELATIVE IONIC CONCENTRATIONS AS A FUNCTION OF θ AND LOG P_e

LOG P_e	θ								
	0 45	0 50	0 55	0 60	0.65	0 70	0 75	0 80	0 85
	Mn II:Fe II								
0 00 . .	−0 24	−0 27	−0 06	0 23	0 07	−0 01	0 00	0 00	0 00
1 00 .	− 24	− 24	− 04	31	11	00	.00	00	01
2 00	− 21	− 12	+ 12	38	14	00	07	03	06
3 00 . .	−0 09	−0 19	+0 15	0.44	0 17	+0 02	0 07	0 15	0 26
	Cr II:Fe II								
0 00. .	0 14	0 15	0 11	−0 01	0 00	0 00	0 00	0 00	0 00
1 00 .	.14	.13	07	+ 11	04	00	.00	.00	01
2 00	11	05	08	+ 23	08	00	01	03	10
3 00 . .	0 04	0 01	0 10	+0 35	0 14	0 04	0 11	0 25	0 47
	Ti II:Fe II								
0 00 .	−1 19	−1 30	−1 28	−0 85	−0 59	−0 28	−0 07	−0 01	0 00
1 00 .	−1 17	−1 24	−0 90	− 53	− 25	− 04	− 01	00	+ 01
2 00 .	−1 10	−0 89	−0 35	− 25	− 11	00	+ 01	+ 04	+ 10
3 00 .	−0 73	−0 30	−0 09	−0 04	−0 01	+0 04	+0 11	+0 25	+0 46

TABLE 6

RELATIVE ABUNDANCES

Star	[Ti/Fe]	[Cr/Fe]	[Mn/Fe]
HR 710	−0 02	+0 28	+0 16
21 Per	− 09	−0 03	+0 16
41 Tau	− 37	+0 04	−0 28
53 Tau	+ 81	+0 54	+1 34
11 Ori	− 64	+0 10	−0 17
μ Ori.	− 32	−0 45	−0 56
γ CMa	− 15	−0 13	+0 81
49 Cnc	− 19	−0 28	−0 24
14 Hya	+ 61	+0 54	+1 31
κ Cnc	− 13	−0 39	+1 18
17 Com A	− 13	+0 46	+0 19
π^1 Boo	− 07	+0 38	+1.26
ι CrB	− 21	−0 03	+0 15
112 Her	− .60	−1 55	+0 08
21 Aql . .	− .73	−0 77	. . . . .
γ Equ	+ 05	+0 10	−0 16
HR 8216 .	+ 22	+0 39	+0 29
κ Psc . . .	+0.12	+0 28	−0 15

IV. THE ABUNDANCE RESULTS

It may be seen by examining Table 4 or Table 6 that, of the eighteen supposed peculiar stars, no less than ten have normal relative abundances of the four iron-peak elements within ± 0.4, which we consider to be an estimate of the random and systematic errors in our analysis (cf. the interagreement of the results for the standard stars). These are HR 710 (Sr), 21 Per (λ 4200 Si), 41 Tau (λ 4200 Si), μ Ori (Am), 49 Cnc (λ 4200 Si), 17 Com A (Eu-Cr), ι CrB (Mn), γ Equ (Eu-Cr-Sr), HR 8216 (Eu-Cr:), and κ Psc (Eu-Cr). Of the remaining stars one, 11 Ori (λ 4200 Si), has a marginally significant deficiency of Ti. Judged from its color 11 Ori is one of the hottest stars in Table 2, and the Ti deficiency may well be due to Ti being partially doubly ionized while the other three elements are not. For this reason we conclude that 11 Ori may well be normal. One star, 21 Aql, had deficiencies of Ti and Cr relative to Fe. Although the deficiency of Ti again may be an ionization effect, that of Cr cannot be explained in this way. The earlier papers in this series have shown that 21 Aql has normal He, C, O, Mg, and Si. Very few lines could be measured in this star, and the apparent chromium deficiency that we have found in this work needs to be confirmed.

TABLE 7

ABUNDANCES OBTAINED BY OTHER AUTHORS

Star	Peculiarity Type	[Ti/Fe]	[Cr/Fe]	[Mn/Fe]
α^2 CVn....	Si-Eu-Cr	−0 1	−0.2	+0 7
HD 133029	λ 4200 Si	−0 2	+0 4	+0 6
HD 151199	Sr	....	+0 3	+1 0
β CrB..	Sr-Eu-Cr	+0 1	+0 7	+0 8
γ Equ	Sr	−0 4	+0 7	+1 2
3 Cen A .	P, Ga	<−0 4	<−1 6	0 0
53 Tau (a)	Mn	+0 9	−0 65	+2 0
53 Tau (b) .	Mn	+1 56	0 00	+2 22
κ Cnc.	Mn	0 0	+0 3	+1 7
10 Aql	Sr	+0 1	+0 4	+0 6

The remaining six stars—53 Tau, γ CMa, 14 Hya, κ Cnc, π^1 Boo, and 112 Her—are all classified as Mn stars, and all except 112 Her reveal abundance excesses in the Mn/Fe ratio. These range from a factor of 6 to a factor of about 60. In 112 Her the abundance ratio Mn/Fe appears normal, but both Mn and Fe are in excess over Ti and Cr. The structure of the iron peak in this star closely resembles that in 3 Cen A as is shown in Table 7, where we give the results found by Jugaku, Sargent, and Greenstein (1961) for the relative abundance of the iron-peak elements in the latter star. The stars are similar in other respects, both having extremely sharp lines and abnormally strong lines of P II and Ga II (Bidelman 1960, 1962).

Of the remaining five Mn stars, γ CMa, κ Cnc, and π^1 Boo are similar in having normal ratios of Cr/Fe and Ti/Fe. In the last two stars, 14 Hya and 53 Tau, all the ratios Cr/Fe, Ti/Fe, and Mn/Fe are abnormally high. There thus appear, on close examination, to be at least two kinds of Mn star. These differences among the Mn stars do not appear to be correlated with the color of the star, the microturbulent velocity, the size of the Mn/Fe abnormality, or with other known abundance peculiarities such as the presence of Be, Ga, or P.

We may summarize the abundance results by stating that the ten λ 4200 Si, Eu-Cr, Eu-Cr-Sr, and Sr stars in our sample and the single Am star do not have abnormal abundance ratios. On the other hand, the five Mn stars and 112 Her all have abnormal iron

peaks. In addition we have found that the Mn stars are distinguished by having abnormally low values of the microturbulent velocity in the outer layers; in the other Ap stars the microturbulent velocity is abnormally high. This work thus emphasizes the distinction found in Papers I and II between the Mn stars and other Ap stars. In the Mn stars the elements He, C, O, Mg, and Si are normal; in the other types of Ap star one or more of these elements is always abnormal.

V. COMPARISON WITH THE RESULTS OF OTHERS

For comparison with our results of Table 6 we show in Table 7 the iron-peak abundance ratios obtained by the authors cited for the nine stars α^2 CVn (Burbidge and Burbidge 1955*a*), HD 133029 (Burbidge and Burbidge 1955*b*), HD 151199 (Burbidge and Burbidge 1956), β CrB (Hack 1958), γ Equ (Hack 1960), 10 Aql (Auer 1964), 3 Cen A (Jugaku *et al.* 1961), 53 Tau (two analyses: [*a*] Aller and Bidelman 1964, and [*b*] Auer *et al.* 1966) and κ Cnc (Jugaku and Sargent, unpublished). Table 7 summarizes the entire hitherto existing information on the iron-peak abundances in peculiar A stars. Three stars are common to Tables 6 and 7. For κ Cnc there is reasonable agreement, but for γ Equ and 53 Tau there is not. Other authors all agree that peculiar A stars of all types have anomalous relative iron-peak abundances. This result is in qualitative disagreement with our own result that such anomalies are confined to the Mn stars. This disagreement is serious and requires discussion.

The abundance ratios given in Table 7 for α^2 CVn are relative to the standard star γ Gem. The serious disagreement with our work concerns the Mn/Fe ratio (the other listed ratios being normal within a factor of 2), for in stars of the Si-rich, O-poor type to which α^2 CVn belongs (see Papers I–III) we find that Mn/Fe is normal. The abundances of Fe, Ti, and Cr in the α^2 CVn analysis by Burbidge and Burbidge are derived from lines of ions, but the Mn abundance is derived from lines of the neutral atom. In this star nearly all Mn is in the form Mn^+ so that the derived Mn abundance stands or falls with the accuracy of the ionization and excitation conditions used in the analysis. The parameters adopted by Burbidge and Burbidge entirely fail to account for the presence of Si III in the spectrum of this star (we have shown previously in Papers II and III that the temperature scale used in these early analyses was grossly in error), and consequently the Mn excess in α^2 CVn cannot be considered well founded. Similar remarks apply to the analyses of HD 133029 and HD 151199.

Auer's recent careful analysis of 10 Aql shows similar effects but to a much smaller degree. He finds a marginally significant excess in the Mn/Fe ratio when comparison is made to solar abundances while the other iron-peak ratios are normal. Again the Mn abundance is based on Mn I lines, and again there are grounds for doubting the validity of the ionization and excitation conditions assumed. From the infrared lines of Mg II we have concluded (Paper I) that the Mg/H ratio is normal in 10 Aql. From lines of Mg I Auer finds Mg to be apparently overabundant by a factor of 40. Auer himself emphasizes that this result is probably a consequence of errors in the assumed ionization conditions.

The results in Table 7 for γ Equ and β CrB are the final abundances given by Hack and are relative to solar abundances. In the case of γ Equ Hack derived abundances relative to the Sun in two ways: first, by direct comparison and, second, by obtaining abundances in γ Equ relative to β CrB, in β CrB relative to α^2 CVn, and in α^2 CVn relative to the Sun. She finds the Mn/Fe ratio in γ Equ is enhanced relative to its value in the Sun by a factor which by direct comparison is 3 but which by a chain of intercomparisons is 30. Hack finally adopted a mean value of 16. The difference between these numbers is a guide to the accuracy of the analysis. We conclude that previous studies, despite their unanimity, offer no serious challenge to our conclusion that Ap stars of the Si-rich and O-poor varieties have entirely normal relative abundances of the iron-peak elements that we have studied in this work.

We next examine the disagreement between our results for 53 Tau and those obtained by Aller and Bidelman in a curve-of-growth discussion of this star and by Auer *et al.* in a model stellar atmosphere reanalysis of Aller and Bidelman's data. Our results for the Ti/Cr and Mn/Cr ratios differ from those obtained by Aller and his co-workers by a factor of about 20. We are unable to explain this serious discrepancy. The star 53 Tau closely resembles the standard B8 V star ν Cap in its continuous energy distribution and hydrogen-line profiles. Mere inspection of our measured equivalent widths for 53 Tau and ν Cap establishes that, if the abundances are normal in the stars that we have adopted as standards, then the Ti/Cr ratio cannot be enhanced in 53 Tau by a factor of $\sim$40 and the Mn/Cr ratio enhanced by the factor of $\sim$200 that were found by Auer *et al.* It is noteworthy that in their analysis Auer *et al.* found that their model did not account for the observed Mn II/Mn I ratio. The f-values for Mn I are well determined, but those for Mn II are not. The overabundance of Mn by a factor of 165 which they found from the strength of the Mn I lines is, however, clearly incompatible with our result (based on Mn II) from a differential study. Our conclusion is that the model atmosphere adopted by Auer *et al.* fails to represent the atmosphere of 53 Tau. As this model gave the Fe II/Fe I ratio observed (as well as fitting continua, hydrogen-line profiles, Si II/Si I) this failure is extremely hard to understand. However, the difficulty is presumably connected with the value of the ionization at very small optical depths and with systematic errors in the f-value scales for the singly ionized metals.

Until this confused situation is cleared up—and it is most important that it should be—we believe that abundance analyses (whether "coarse" or "fine") based upon differential studies of lines of the dominant ions are the only reliable guides to the composition differences between the Ap and normal stars.

VI. CONCLUDING REMARKS

The most remarkable (and unexpected) result of this work is that all the Ap stars with the exception of the Mn stars have normal relative abundances among the iron-peak elements. This is particularly surprising because many stars are classed as Eu-Cr stars with the implication that the Cr/Fe ratio is high. An examination of Table 2 (see above) shows that in the Eu-Cr stars—κ Psc, HR 8216, 17 Com A, HR 710, and γ Equ—the lines of Cr II do indeed have larger equivalent widths than in the normal stars and most of the peculiar stars. However, *this is also true of Ti, Mn, and Fe.* The implication is, clearly, that the high microturbulent velocities in the outer atmospheres of these stars enhance all lines on the flat portion of the curve of growth and that, by chance, this is more noticeable for Cr than for the other elements.[1]

The discovery that the iron peaks are normal in most of the Ap stars has serious implications for nuclear theories of these stars, for example, that recently proposed by Fowler *et al.* (1965). In this theory the rare-earth elements are supposed to be formed by subjecting the iron peak to a rapid flux of neutrons under conditions of high density and temperature. During this process the iron peak undergoes radical changes which, however, are very sensitive to the precise combination of neutron flux, density, and temperature (Clifford and Tayler 1965). It appears from our work that, unless there is a special combination of physical circumstances that bring the iron peak back to its original shape, then the theory of Fowler *et al.* is incorrect. It may be noted that, in having normal relative iron-peak abundances and overabundances among the rare-earth elements, the Ap stars of the Sr-Eu-Cr class resemble the S stars and Ba stars even more closely than has previously been recognized. However, the fact that Ba is not overabundant in the Ap stars is a fatal objection to the idea that they, like the S stars, have undergone nuclear transformation induced by neutron capture on a slow time scale. We conclude from this that it may well be impossible to fit the observed compositions of

[1] It should be noted, however, that the increased microturbulence cannot possibly account for the enormous strengthening of, for example, the rare-earth lines in such stars as α^2 CVn.

the Ap stars into a purely nuclear theory and that perhaps other possibilities, for example, the stratification of material at the stellar surface or in the pre-stellar nebula, should be seriously considered.

This work was begun at Mount Wilson and Palomar Observatories and the Astronomy Department, California Institute of Technology, and was supported by the U.S. Air Force under Contract AF 49(638)-21. It is a pleasure to thank Dr. J. L. Greenstein for the opportunity of working in his department. The work was completed at the Mount Stromlo Observatory; one of us (W. L. W. S.) wishes to thank Professor Bart J. Bok for his hospitality and the National Science Foundation and the Australian National University for support.

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