AN ABUNDANCE ANALYSIS OF 3 CENTAURI A*

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ABSTRACT

Abundances in 3 Centauri A (B4 IV or Vp) are derived, using γ Pegasi (B2 IV) as a standard comparison star and the approximation of a single-layer atmosphere. The abundances of certain elements (P, Ca, Ga, and Kr) not observed or observed only weakly in γ Pegasi are derived relative to Si in 3 Centauri A. We find that C, Ne, Si, A, and Ca have normal abundances. He and O are underabundant by a factor of 6 in 3 Centauri A; N is overabundant by a factor of 5; P by a factor of 100; Fe by a factor of 4; and Kr by a factor of about 1300. An identification of Ga II which is not yet certain leads to an overabundance of about 8000 for Ga. We derive upper limits for the abundances of Al, S, Cl, Zn, Ge, As, Se, Br, Rb, and Sr. Of these, S is deficient by a factor of more than about 10. It is likely that Ga and Kr are local abundance peaks but that other elements in the same region of the periodic table could be almost as overabundant without being detected spectroscopically. It is conjectured that these abundance anomalies, together with the large concentration of He^3 reported previously, have been produced by the acceleration of particles on the surface of 3 Cen A. H W. Babcock has not detected a regular magnetic field in the star, although it is probably related to the "manganese" stars which have magnetic fields.

I. INTRODUCTION

The star 3 Centauri A[1] has a spectral type of about B5 (Bertiau 1958; Mme de Vaucouleurs 1957) and is the brighter member of a visual double system. The companion, which is 8″ distant, has a spectral class of B8 V and has $m_v = 6.1$. It is reasonable to suppose that the stars form a physical binary system. According to Bertiau (1958), both are members of the Scorpio-Centaurus association.

Recently, Bidelman (1960) discovered that the spectrum of 3 Cen A contains unusually strong lines of P II and P III. On comparing visually the strengths of the lines, Bidelman estimated that the abundance ratio P:Si might be as high as 1:10. This is very much larger than the "cosmic" value of P:Si $\simeq$ 1:100 quoted by Suess and Urey (1956). Several lines in 3 Cen A were, for a time, unidentified. Recently Bidelman informed us that he has identified several of these lines with Kr II and Ga II. Lines of these ions have never been reported as occurring in stellar spectra, although Bidelman finds lines of Ga II in the spectrum of the "manganese" star κ Cancri (B8p) which, like 3 Cen A, has abnormally strong phosphorus lines.

While measuring the plates in preparation for the present work, the writers found longward shifts in certain of the He I lines which were interpreted as isotope shifts (Sargent and Jugaku 1961). In addition, we derived an upper limit for the abundance of deuterium. In the present paper we give details of our abundance analysis and, in the final section, conjecture how the abundance anomalies might be related to the large He^3 abundance.

II. THE SPECTRUM

Table 1 contains details of the material on which the work is based. All the spectrograms were obtained at the coudé focus of the 200-inch telescope, trailed in declination to reduce contamination from 3 Cen B. About 200 lines were found in the region λλ 3600–

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[1] HD 120709; $\alpha_{1950} = 13^{\rm h}48\overset{\rm m}{.}9$, $\delta = -32°45'$; $m_v = 4.72$.

8600. The following ions have been identified: H, He I, C II, N II, O I, O II(?), Ne I, Mg II, Si II, Si III, P II, P III, S II(?), A II, Ca II, Ni II, Fe II, Fe III, Ga II, and Kr II. The lines of P II and Fe III were identified with the aid of wavelengths and intensities published by Martin (1959) and by Glad (1956), respectively. Table 2 contains a list of the identified lines and mean equivalent widths.

On our plates, the lines of the Balmer and Paschen series may be distinguished up to $n = 16$ or 17. The correlation of Unsöld and Struve (1940), together with the fact that 3 Cen A is a sharp-lined star, implies a luminosity class of IV or V. The ratio of the equivalent widths of Si II λ 4131 : Si III λ 4553 indicates a spectral type intermediate between B5 and B3, using the relation of Underhill (1957). Aller has kindly supplied us with a photoelectric scan of the combined continuous spectrum of 3 Cen A and B. From it we obtain a value for the Balmer discontinuity of $D = 0.17$, in good agreement with the value for a main-sequence star of spectral type about B4 (Barbier, Chalonge, and Canavaggia 1947). At the Balmer jump, 3 Cen B is $1^{\mathrm{m}}8$ fainter than 3 Cen A and so does not appreciably effect the value of D just derived. From all the available evidence we conclude that 3 Cen A has a temperature and luminosity equivalent to those of a normal B4 IV or V star.

TABLE 1

OBSERVATIONAL MATERIAL

Plate	Dispersion (A/mm)	Date	Emulsion	Observer
Pc 4976 .	9	Feb. 16, 1960	Bkd IIa-O	J. L. G.
Pb 5067 ...	4 5	May 5, 1960	Bkd IIa-O	J. L. G.
Pb 5068.. .	4 5	May 5, 1960	Bkd IIa-O	J. L. G.
Pc 5071 .	13 5	May 6, 1960	IIa-F	J. L. G.
Pc 5072...	13 5	May 6, 1960	I N	J. L. G.
Pc 5088....	13 5	May 12, 1960	103a-F	G. M.

* J L G. = Jesse L Greenstein; G. M = Guido Münch.

In Figures 1 and 2 we compare the profiles of two representative He I lines with those in γ Pegasi (B2 IV). The singlet series lines have broad wings with sharp central cores. The forbidden line is quite clearly visible in the blue wing of λ 4472; this is normal for a star which is on or near the main sequence. The triplet series lines have normal broad profiles with no pronounced central core. Thus the He line profiles are not unusual except that certain of the lines are shifted longward of their normal positions. We attribute these shifts to the presence of a substantial fraction of He^3. As was observed by Bidelman (1960), the He I lines in 3 Cen A are a little weak for the spectral type—the equivalent widths are typical of B6 rather than B4. Those lines, such as λ 5016, that arise from metastable lower levels are not enhanced, nor do they have unusual profiles. Thus from the He I lines there is no evidence that 3 Cen A is a shell star.

No certain lines of O II are identified in the spectrum, and the infrared plate was obtained in order to examine the O I triplet at λ 7774. The lines were found to be weakly present, having a combined equivalent width of $W = 159$ mA. Keenan and Hynek (1950) have shown that W increases as we go from early to late B; at A0, W has a maximum value of about 800 mA. In the standard B2 IV star γ Peg we have measured $W = 290$ mA, so that the O I lines in 3 Cen A are definitely abnormally weak. In this respect 3 Cen A resembles many of the peculiar A stars (Slettebak 1950).

The H and K lines are present in moderate strength, and it is not easy to sort out the stellar and interstellar contributions. Stellar H and K lines may be found as early as B3; in 3 Cen A the lines have the same radial velocity as lines of other elements. The D lines are not present on plates of the visual region; we estimate that the equivalent

TABLE 2

EQUIVALENT WIDTHS

λ	Multiplet	E P. (volts)	W (mA)	log gf	log $Wc/\lambda v$	log $\eta/N_{r,s}$	Remarks (Blends)
H:							
3721 94	3	10 15	800				
3734 37	3	10 15	1680				
3750 15	2	10 15	2500				
3770 63	2	10 15	3410				
3797 90	2	10 15	4800				
3835 39	2	10 15	5230				
3889 05	2	10 15	5000				
3970 07	1	10 15	5100				
4101 74	1	10 15	5640				
4340 47	1	10 15	5770				
4861 33	1	10 15	5030				
6562 82	1	10 15	5180				
8598 39	9	12 04	1900				
8665 04	9	12 04	2100				
He I:							
3819 61	22	20 87	433				
3867 63	20	20 87	82				
3964 73	5	20 53	68	−1 29	−0 18	−13 43	17 per cent Hϵ
4009 27	55	21 13	250				
4026 19	18	20 87	783				
4120 82	16	20 87	88	−1 44	−0 08	−13 73	2 per cent Hδ
4143 76	53	21 13	251				
4168 97	52	21 13	47				
4387 93	51	21 13	352				
4437 55	50	21 13	50	−2 04	−0 36	−14 51	
4471 48	14	20 87	576				
4713 14	12	20 87	118	−0 98	−0 01	−13 43	
4921 93	48	21 13	313				
5015 68	4	20 53	118	−0 80	−0 04	−13 20	
5047 74	47	21 13	30	−1 61	−0 64	−14 22	
5875 63	11	20 87	340				
6678 15	46	21 13	306				
7065 19	10	20 87	195				
C II:							
3918 98	4	16 26	38	−0 57	−0 19	−13 09	
3920 68	4	16 26	41	−0 26	−0 16	−12 78	
4267 15	6	17 97	110	+0 98	+0 23	−12 22	
5889 97	5	17 97	71	−0 17	−0 10	−13 73	
5891 65	5	17 97	71	−0 43	−0 10	−13 99	
6578 03	2	14 39	44	+0 03	−0 35	−12 41	4 per cent Hα
6582 85	2	14 39	46	−0 27	−0 33	−12 71	3 per cent Hα
N II:							
3995 00	12	18 42	60	+0 20	+0 04	−11 68	
4041 32	39	23 04	10	+0 86	−0 75	−12 62	
4447 03	15	20 32	21	+0 27	−0 47	−12 38	
4601 48	5	18 39	21	−0 40	−0 48	−12 43	
4607 15	5	18 38	19	−0 49	−0 53	−12 52	
4613 87	5	18 39	15	−0 62	−0 63	−12 65	
4621 39	5	18 39	25	−0 49	−0 41	−12 52	
4630 54	5	18 40	45	+0 08	−0 15	−11 95	
4643 07	5	18 40	21	−0 40	−0 48	−12 44	
5001 47	19	20 56	34	+0 68	−0 31	−12 18	
5679 56	3	18 40	34	+0 25	−0 36	−12 02	
5931 79	28	21 06	30	+0 01	−0 44	−13 22	Atmospheric blend
5941 67	28	21 07	49	+0 29	−0 22	−12 95	Atmospheric blend
6630 5	41	23 10	15	−0 01	−0 79	−14 04	Doubtful
O I:							
7771 96	1	9 11	60	+0 37	−0 21	−12 16	
7774 18	1	9 11	50	+0 22	−0 30	−12 32	
7775 40	1	9 11	49	0 00	−0 31	−12 54	

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TABLE 2—*Continued*

λ	Multi-plet	E P (volts)	W (mA)	log gf	log $Wc/\lambda v$	log $\eta/N_{r,s}$	Remarks (Blends)
O II:							
4649 14	1	22 90	9	+0 49	−0 82	−11 52	
Ne I:							
5881 90	1	16 55	17	−0 47	−0 60	−12 68	
5944 83	1	16 55	20	...	...		
6143 06	1	16 55	49	−0 03	−0 16	−12 29	
6266 50	5	16 64	44	−0 17	−0 21	−12 47	
6334 43	1	16 55	54	−0 20	−0 13	−12 49	
6382 99	3	16 60	38	−0 11	−0 29	−12 43	
6402 25	1	16 55	73	+0 40	0 00	−11 89	
6506 53	3	16 60	55	+0 04	−0 13	−12 30	
6598 95	6	16 78	30	−0 07	−0 40	−12 48	
8082 46	6	16 78	33				
8654 38	33	18 62	69				
Mg II:							
4481 13 4481 37	4	8 83	141	+1 00	+0 47	−10 88	
Si II:							
3853 66	1	10 03	55	−1 70	+0 16	−13 38	
3856 02	1	10 03	96	−0 74	+0 41	−12 42	
3862 59	1	10 02	88	−0 97	+0 37	−12 65	
4128 05	3	9 79	64	+0 22	+0 20	−12 55	
4130 88	3	9 80	74	+0 40	+0 26	−12 37	
5041 06	5	10 02	83	+0 13	+0 23	−12 95	
5056 02	5	10 03	100	+0 60	+0 31	−12 48	
5957 61	4	10 02	39	−0 39	−0 17	−13 64	
5978 97	4	10 03	39	−0 08	−0 18	−13 33	
6347 09	2	8 09	116	+0 25	+0 27	−12 41	
6371 36	2	8 09	100	−0 06	+0 21	−12 72	
Si III:							
3806 56	5	21 63	28	+0 70	−0 12	−11 90	10 per cent H10
4552 65	2	18 92	53	+0 31	+0 08	−11 55	
4567 87	2	18 92	42	+0 09	−0 03	−11 77	
4574 78 .	2	18 92	24	−0 38	−0 27	−12 25	
P II:							
3827 43	26	13 08	23				7 per cent H9
4019 53	30	13 25	8				
4044 61	30	13 25	47	...	...	...	
4062 15	17	12 76	9	−1 87	−0 62	−14 29	
4064 73	16	12 76	8	−0 91	−0 68	−13 33	
4109 28	30	13 25	12	...	...	...	11 per cent Hδ
4127 57	16	12 80	27	−0 90	−0 15	−13 36	
4187 48	*		44				
4420 71	*	...	38				
4452 46	31	13 38	26	...	...	...	
4463 00	25	13 03	18	−0 03	−0 36	−12 65	
4466 13	24	13 03	4	−1 43	−1 02	−14 05	
4467 98	25	12 99	24	−0 61	−0 24	−13 22	2 per cent He I
4475 26	24	13 03	30	−0 26	−0 14	−12 88	
4499 24	11	10 97	39	−0 34	−0 03	−12 27	
4530 81	25	13 00	23	−0 61	−0 26	−13 23	
4554 83	28	13 09	37	+0 20	−0 06	−12 46	
4558 07	29	13 09	25				
4565 27	36	13 64	16	...	...	...	
4588 04	15	12 75	47	+0 78	+0 04	−11 78	
4589 86	24	13 03	38	+0 49	−0 05	−12 16	
4602 08	15	12 80	44	+0 71	+0 01	−11 87	
4626 70	15	12 76	12	−0 35	−0 56	−12 91	
4658 31	15	12 80	14	−0 35	−0 49	−12 94	
4943 53	13	12 80	31	+0 05	−0 17	−12 62	
4969 71	*	...	30	...	...	...	
5191 41	7	10 71	45	−0 40	−0 03	−12 40	
5253 52 .	10	10 97	67	+0 29	+0 14	−11 82	

* Not in R M T or not classified into multiplets

TABLE 2—*Continued*

λ	Multi-plet	E P (volts)	W (mA)	log gf	log $Wc/\lambda v$	log $\eta/N_{r,s}$	Remarks (Blends)
P II:							
5296 13	7	10 76	60	−0 18	+0 08	−12 22	
5316 07	6	10 71	74	−0 32	+0 17	−12 34	
5344 75	6	10 69	46	−0 42	−0 03	−12 44	
5386 88	6	10 71	59	−0 54	+0 07	−12 59	
5409 72	6	10 71	43	−0 42	−0 07	−12 47	
5425 91	6	10 76	78	+0 16	+0 19	−11 90	
5499 73	6	10 76	38	−0 32	−0 13	−12 39	
6024 18	5	10 71	96	+0 11	+0 23	−12 04	
6034 04	5	10 69	72	−0 25	+0 11	−12 40	
6043 12	5	10 76	111	+0 38	+0 29	−11 79	
6087 82	5	10 71	61	−0 37	+0 03	−12 55	
6165 59	5	10 76	41	−0 37	−0 15	−12 56	
6459 99	32	13 38	47				
6503 46	*		42				
6507 97	*		57				
7845 63	*		89				
P III:							
4057 44	1	14 43	17	−1 00	−0 35	−12 71	
4059 34	1	14 43	51	−0 04	+0 13	−11 76	
4080 11	1	14 43	35	−0 30	−0 04	−12 02	2 per cent Hδ
4222 22	3	14 55	72	+0 18	+0 26	−11 62	
4246 75	3	14 55	53	−0 12	+0 13	−11 93	
S II:							
7967 43	12	13 94	66				Doubtful
A II:							
4426 01	7	16 68	9	+0 18	−0 60	−11 69	
Ca II:							
3933 66	1	0 00	77	+0 12	+0 38	−11 50	
3968 47	1	0 00	37	−0 18	+0 06	−11 80	41 per cent Hε
Ni II:							
3769 46	4	3 09					
4067 05	11	4 01	14				
Fe II:							
3757 46	154	4 72					
3906 04	173	5 54	8				
4173 45	27	2 57	15				
4178 89	42	2 88	18				
4233 17	27	2 57	38				
4296 57	28	2 69	7				
4303 17	27	2 69	15				
4351 76	27	2 69	17				6 per cent Hγ
4385 38	27	2 77	32				2 per cent He I
4416 82	27	2 77	18				
4508 28	38	2 84	19				
4515 34	37	2 83	17				
4520 23	37	2 79	15				
4522 59	38	2 83	25				
4534 17	37	2 84	5				
4549 47	38	2 82	34				
4555 89	37	2 82	18				
4583 83	38	2 79	31				
4629 34	37	2 79	16				
4635 33	186	5 93	16				
4923 92	42	2 88	49				
5018 43	42	2 88	49				
5169 03	42	2 88	58				
5197 57	49	3 22	27				
5316 61	49	3 14	59				
6493 05	*	. . . .	36				
6516 05	40	2 88	79				

TABLE 2—*Continued*

λ	Multi-plet	E P (volts)	W (mA)	log *gf*	log $Wc/\lambda v$	log $\eta/N_{r,s}$	Remarks (Blends)
Fe III:							
4352 70	4	8 21	13		−0 36	− 0 07†	4 per cent Hγ
4371 10	4	8 21	16		−0 28	− 0 07	
4395 78 .	4	8 22	19		−0 20	− 0 08	
4419 59 .	4	8 21	30		−0 01	− 0 08	
4430 95	4	8 21	21		−0 16	− 0 08	
5127 32 .	5	8 62	40		+0 05	− 0 13	
5156 0..	5	8 60	28		−0 11	− 0 12	
5260 25 .	*		41			. .	
5291 78 .	*		36			. .	
Ga II:							
4250 9 .	*	14 10	13	+0 46	−0 30	−11 13	
4253 7.	*	. ..	.	.. .	. .	.. .	
4255 5	*	14 10	34	+0 68	+0 11	−10 91	
4261 8 .	*	14 11	29	+0 83	+0 04	−10 76	
6334 2 .	*						Blend: Ne I
6419 4.	*					..	
Kr II:							
4355 48 .	*	13 98	25	+0 48	+0 01	−11 10	3 per cent Hγ
4615 28	*	14 26	11		..		
4619 15..	*	14 68	13	.			
4658 87	*	13 98	15	. . .			
4739 00	*	13 98	20				
4765 74	*	14 26	17				

† Values in this column for Fe III are differences between the 3 Cen A and γ Peg values of log $\eta/N_{r,s}$ E P of the reference state is 8 21 ev

width of D2 is less than 20 mA. The interstellar D2 line normally has an equivalent width about twice that of the K line (Binnendijk 1952), so that the interstellar K line in 3 Cen A must have an equivalent width less than about 10 mA. The measured equivalent width of K in 3 Cen A is 77 mA; it is, therefore, reasonable to suppose that this is mostly contributed by the star. No interstellar lines were found on a 20 A/mm plate of the photographic region of 3 Cen B.

Several lines remained unidentified until Bidelman discovered that it is likely that most of them are produced by Ga II and Kr II. We have found six lines which may be attributed to Ga II and six which are produced by Kr II. The presence of Kr II is beyond doubt, since the measured wavelengths agree very well with the laboratory ones and, moreover, only lines with the strongest laboratory intensities have been found. The presence of Ga II is less certain because there is some disagreement in the laboratory wavelengths published by different authors (Bidelman 1961). However, as in the case of Kr II, we observe only those lines of Ga II with the largest laboratory intensities. Only two lines which are certainly of stellar origin now remain unidentified. These are λ 6716.7, for which $W = 41$ mA, and λ 5106.0, for which $W = 20$ mA.

Although the spectrum of 3 Cen A contains unusually strong lines of certain elements, there is no evidence that this is brought about by the star having an unusual atmospheric structure. Thus there are no emission lines and no obvious metastability effects. The star does not have a detectable magnetic field (Babcock, unpublished). The profiles of the He I and H lines are normal, and those of other elements do not vary from element to element. We therefore conclude that 3 Cen A is a B4 IV or V star which has a normal atmospheric structure in which certain elements have abnormal abundances.

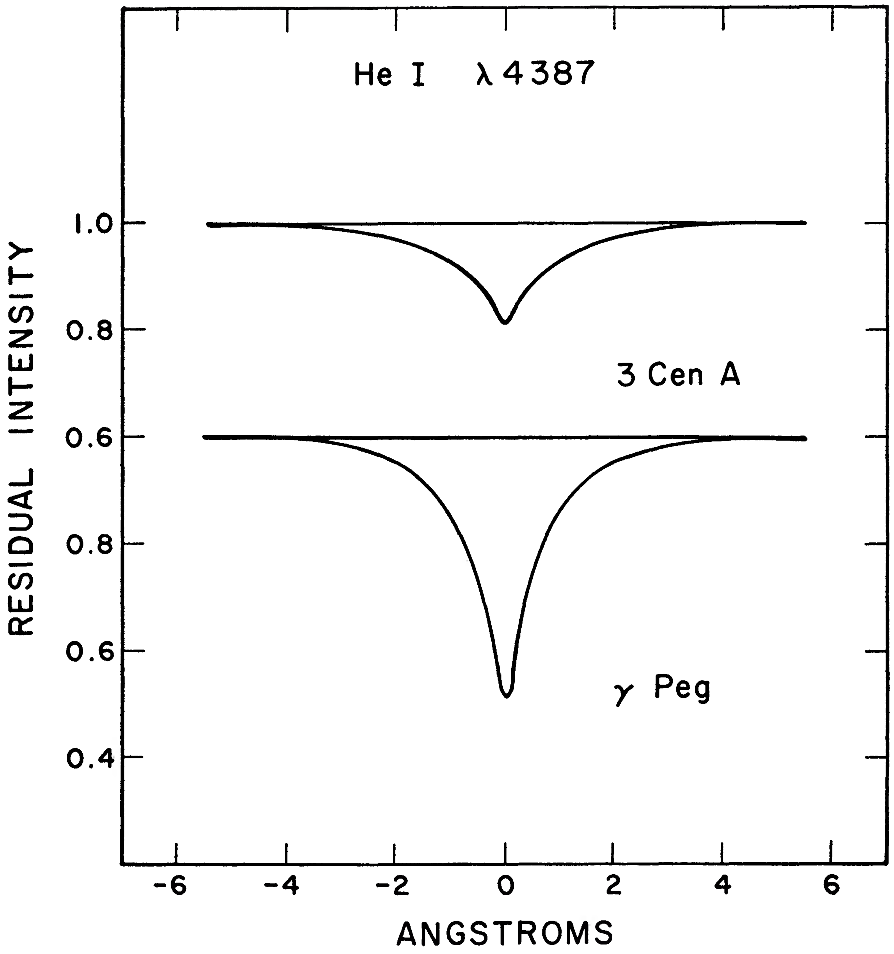

FIG. 1.—Profile of the singlet series line λ 4387 of He I in 3 Cen A and in γ Peg (taken from data tabulated by Aller 1956).

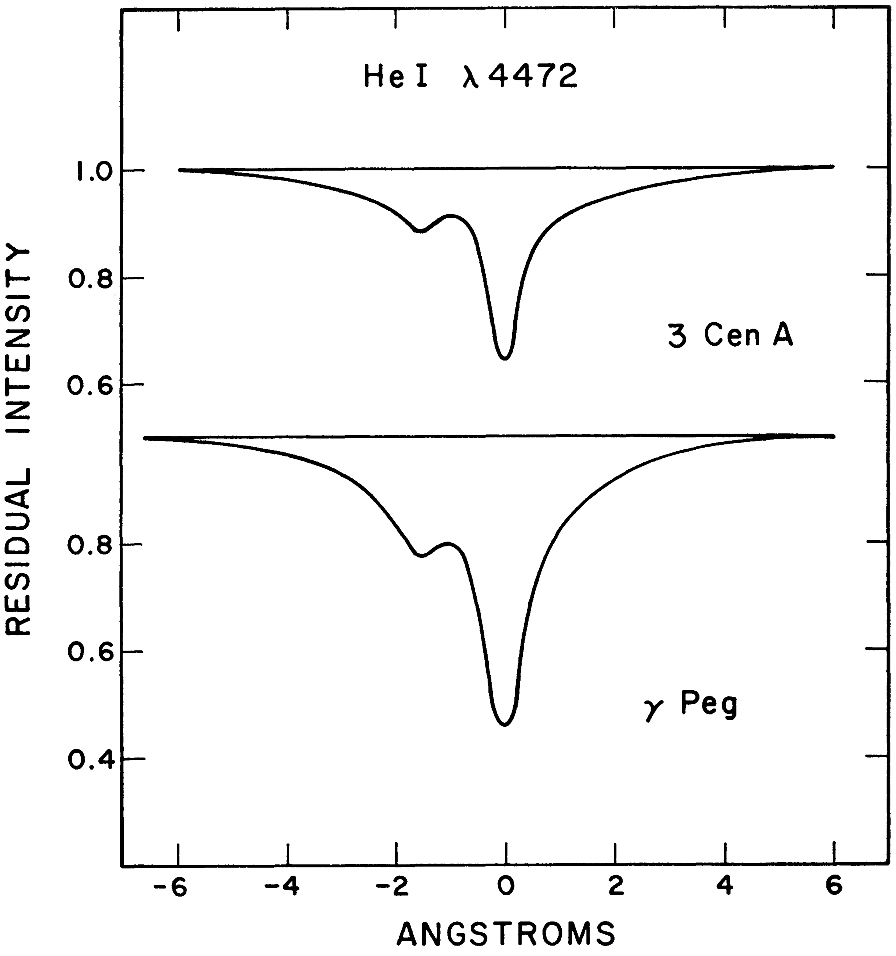

FIG. 2.—Profile of the triplet series line λ 4472 of He I in 3 Cen A and in γ Peg (taken from the data of Aller 1956). The forbidden component, λ 4469, is present in the shortward wing in both stars.

III. ABUNDANCE ANALYSIS

In determining the abundances in 3 Cen A, we are handicapped by the lack of good theoretical model atmospheres for B4–B5 stars and by the extreme rareness of sharp-lined comparison stars of this spectral type. The only other very sharp-lined B4 star of which we are aware is *α* Sculptoris. This star is, however, in some respects peculiar itself (Jugaku and Sargent 1961), in that the He I and O I lines are abnormally weak, while lines of Cr II, Ti II, and Sr II are abnormally strong. The only detailed model atmospheres for hot stars relatively close in temperature to 3 Cen A correspond to spectral types earlier than B3 (McDonald 1953, improved by Milligan 1955; Underhill 1957). There are no good model atmospheres for later stars until we come to A0 (Hunger 1955; Osawa 1961).

We have, therefore, compared 3 Cen A with γ Pegasi (B2 IV), using a single-layer atmosphere approximation (coarse analysis) for both stars. Aller and Jugaku (1959) have made a detailed analysis for γ Peg, using the model atmospheres computed by Underhill and McDonald. As we shall show, several of the abundance anomalies in 3 Cen A are so well marked that they could not possibly be introduced by the inaccuracy of the monolayer atmosphere approximation. The use of γ Peg as a comparison star has the additional advantage that equivalent widths are available for more elements than are normally found in a B4 or B5 star.

The electron pressure, P_e, and the ionization temperature, T_{ion}, characterizing the atmospheres of 3 Cen A and γ Peg were found in the following way: In 3 Cen A, the Balmer lines can be detected up to $n = 16$ or 17. On inserting $n = 17$ into the Inglis-Teller formula, we find an electron density of $\log n_e = 13.96$ (Traving 1960). We take the effective temperature of a B4 V star to be 17000° K (Arp 1959). Using the formula for the temperature distribution in a gray atmosphere, the temperature at an optical depth in the continuum of $\tau = 0.3$ is 15500° K. Combining this temperature with the electron density already derived, we find an electron pressure of $\log P_e = 2.3$. These preliminary values of T_{ion} and P_e were used to plot curves of growth for the lines of P II, P III, Si II, and Si III. Throughout this work we used Wrubel's (1949) curve of growth (based on a Milne-Eddington approximation and pure scattering) with $B_1/B_0 = 4/3$ and (except in the case of helium) $a = 0.01$. In plotting the curves of growth we used the procedure described by Aller (1953). Using the Saha equation, the Si II:Si III equilibrium gave $\theta_{\text{ion}}(\text{Si}) = 0.335 \pm 0.018$ while the P II:P III equilibrium gave $\theta_{\text{ion}}(\text{P}) = 0.352 \pm 0.018$. The mean of these two determinations is $\theta_{\text{ion}} = 0.344$. Using this temperature, the electron pressure was recalculated from the original value of the electron density; the new value was $\log P_e = 2.27$. It should be noted that it was not possible to derive an excitation temperature for 3 Cen A, since no element has lines arising from widely spaced levels of excitation. Therefore, in this analysis, we have assumed equality of ionization and excitation temperatures.

A similar procedure was used to derive a mean electron pressure and ionization temperature for γ Peg, using the data published by Aller (1956) and Aller and Jugaku (1958). We found $\theta_{\text{ion}} = 0.278$ and $\log P_e = 2.34$.

Curves of growth were then plotted in the usual way for both stars, in order to derive the abundance difference for each element. Experimental *f*-values were used wherever possible; however, in most cases we had to use the Bates-Damgaard tables (1949). In the case of Fe II, Fe III, and Ni II it is not possible to use the Bates-Damgaard procedure. Therefore, the iron abundance was obtained by using the Fe III lines in γ Peg to determine empirical *f*-values by assuming that the abundance ratio Fe:H in γ Peg is the same as that in the sun. In the case of the single line of Ni II we assumed $gf = 1$. Since lines of Kr II are not observed in γ Peg or any other star, we had to use the Bates-Damgaard *f*-values for this element.

In Table 2, for each line used in the analysis, we have listed the *gf*-value, the ordinate log $(Wc/\lambda v)$ of the curve of growth, and the abscissa log $\eta/N_{r,s}$, where $N_{r,s}$ is the number of atoms per gram in the reference state s (unit statistical weight) of the stage of ionization r, and the quantity η is defined by Aller (1953, p. 296). This quantity includes, for each line, a correction allowing for the wavelength dependence of the continuous opacity. In computing the correction term we used the opacity table compiled by Allen (1955) from the work of Miss Vitense (1951).

In determining the helium abundance, six moderately weak lines were chosen for which it was assumed that the profiles of the wings were determined by quadratic Stark effect. Values of the damping constants were evaluated for each line, using the collisional damping constants tabulated by Aller and Jugaku (1959). The line λ 3965 lies in the wing of Hϵ, and Unsöld's (1955) theory of line blending was applied to correct the measured equivalent width. For γ Peg we adopted the values of log a published by Aller and Jugaku (1959). The values of log a for 3 Cen A are given in Table 3. This table also contains the values of log $N_{r,s}$ calculated for a reference level of 20.53 ev. The standard deviation of the mean of the six values of log $N_{r,s}$ is 0.1.

In the spectrum of 3 Cen A, oxygen is represented only by the three lines of the O I triplet and by one weak line, λ 4649, of O II. In the case of 3 Cen A there is a good agreement between the values of the oxygen abundance determined by using O I and O II, but in γ Peg the agreement is very poor. This is probably a result of stratification in the atmosphere of γ Peg. Since the O II lines arise from highly excited levels and since most of the oxygen is O II, we consider that the results derived from the O I lines are more accurate. Accordingly, the O II result has been ignored in deriving the values of the abundances presented in Table 5.

TABLE 3

DATA FOR THE HE I LINES

(Reference State 20.53 ev)

λ	log a	log $N_{r,s}$	λ	log a	log $N_{r,s}$
3965	−1 75	13 94	4713	−1 65	13 91
4121	−1 16	14 03	5016	−1 69	13 62
4438	−0 95	14 42	5048	−1 43	13 78

In Table 4 we give the values of log $N_{r,s}$ for each ion. The second column contains the excitation potential of the reference level used. Table 5 contains the values of log N, the total number of atoms per gram in all stages of ionization, for each element. For those elements with lines in both 3 Cen A and γ Peg, we give, in the fourth column, the values of $\Delta \log N = \log N_{3\,\mathrm{Cen}} - \log N_{\gamma\,\mathrm{Peg}}$. The fifth column contains the abundances in γ Peg derived by Aller and Jugaku (1959, p. 143) on a scale such that log $N(\mathrm{H}) = 12.00$. In order to derive our adopted abundances in 3 Cen A on the same scale, we have added algebraically the fourth and fifth columns; the results are given in the sixth column. For those elements (Ca, P, Ni, Ga, and Kr) whose abundances have not been derived accurately or at all in γ Peg, the values of log N in the sixth column were obtained by finding the difference between the abundance of each element and that of silicon in 3 Cen A. The difference was then added algebraically to the Si abundance in the sixth column.

We now consider the accuracy of the abundances derived in this section. We find that the abundance of He in 3 Cen A is low compared with that in γ Peg. The evidence given in Section II indicates that this result is in the correct sense, although the actual value should be treated with caution. This is because, while there are approximately equal amounts of He I and He II in 3 Cen A, the observable lines of He I arise from a very high

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level (21 volts), so that we are liable to an error of $\Delta \log N = 21\Delta\theta$ for an error $\Delta\theta$ in θ. We earlier estimated that $\Delta\theta$ is about 0.02, so that $\Delta \log N(\mathrm{He}) \approx 0.4$. For a similar reason, the abundances of C and N may also be inaccurate. The errors in the values of $\log N$ for the elements O and Ne should be lower because the observable lines arise from levels that are within a few volts of the ground level of the most predominant stage of ionization. Our most accurately determined quantity should be the ratio of $N(\mathrm{Si}) : N(\mathrm{P}) = 3:2$, since the effects of stratification on the two elements should be similar and, moreover, lines are observable in both from two stages of ionization. The abun-

TABLE 4

POPULATION OF REFERENCE STATES

ION	E P. (ev)	LOG $N_{r,s}$	
		3 Cen A	γ Peg
He I	20.53	13 84	14 68
C II	14 39	13 26	13 54
N II	18 38	12 20	12 48
O I	9 11	12.40	12 67
O II	22 87	10.87	12 35
Ne I	16 55	12 51	12.08
Mg II	8 83	12 66	12 72
Si II	6 83	13.73	12 75
Si III	18 92	12 20	12 95
P II	10 69	12 82	......
P III	14 43	12 59	11 58
A II	16 34	11 1:	11 3:
Ca II	0 00	12 96	......
Ga II	14 11	11.34	......
Kr II	13 98	11 61	......

TABLE 5

ABUNDANCES IN 3 CEN A

ELEMENT	LOG N		Δ LOG N	γ PEG (ALLER, JUGAKU 1959)	3 CEN A (ADOPTED)	SOLAR SYSTEM (ALLER, 1959*)
	3 Cen	γ Peg				
H	....	......	......	12.00	12 0	12 0
He	21 22	21 99	−0 77	11 17	10 4	11 2
C	19 03	19 05	−0 02	8 54	8 5	8 6
N	19 52	18 78	+0 74	8 03	8 8	8 1
O	18 66	19 47	−0 81	8 70	7 9	9 0
Ne	19 55	19 59	−0 04	8 67	8 6	8 7
Mg	18 50	19 13	−0 63	7 88	7 3	7 4
Si	18 60	18 31	+0 29	7 23	7 5	7 5
P	18 45	(16 42)	+2 03	5.50	7 4	5 4
A	17 52	17 45	+0 07	6 9	7 0	6 9
Ca	16 85		. .	. . .	5 8	6.2
Fe	......	. .	+0 63	......	7 2	6 6
Ni	16 5	. ..	.....	.....	5 4	6 0
Ga	17 41	. . .	.	.....	6 3	2.5
Kr	17 39	. .	....	....	6 3	3 2

* Based on the analysis by Goldberg, Müller, and Aller (1960)

dance of Mg is extremely inaccurate because we could use only the two partially resolved components of λ 4481 which fall on the damping portion of the curve of growth. Likewise, the abundance of Ca is inaccurate because we had to compare resonance lines of this element with high-excitation lines of other elements; stratification effects must therefore be important. The abundances of Ga and Kr should not be in error by more than a factor of 5; the enormous excesses of these elements cannot possibly be due to the crude method of analysis.

IV. UPPER LIMITS

We have derived upper limits for the abundances of certain elements which, although not observed in 3 Cen A, are of special interest. These fall into two groups—first, elements such as Al, Cl, and S which are found in γ Peg and, second, elements which are in the same region of the periodic table as Ga and Kr. Several elements in this latter group (such as As, Se, and Br) are not observed in the stellar spectra at all. In Table 6 we give details of the lines used in estimating the upper limits. The maximum detectable equivalent width was estimated to be 10 mA for lines in the photographic region and 20 mA in the visual and infrared regions. In several cases, f-values were estimated by using the Bates-Damgaard tables; in the rest we assumed $gf = 1$ for the strongest line observable.

TABLE 6

DATA FOR UPPER LIMITS

Element	Predicted Strongest Line		Source*	E P (ev)	Maximum E W. (mA)	log gf	Abundance (log N(H) = 12)
	Ionization Stage	λ					
Al .	Al III	4529 2	a	15 6	10	0 89†	<6 0
S.	S II	5453 8	a	13 6	20	0 44†	<6 4
Cl..	Cl II	3860 8	a	15 9	10	0 29†	<7 3
Zn ...	Zn II	4911 7	b	12 0	10	0 76†	<5 6
Ge.. ..	Ge II	5893 4	b	9 8	20	0 23†	<5 7
As....	As III	3922 6	c	13 4	10	0 12†	<5 7
Se .. .	Se II	6056 0	d	10 6	20	0 00‡	<6 2
Br... .	Br II	Several lines at 4800	e	11 6	10	0 00‡	<6 0
Rb	Rb II	4244 4	f	16 6	10	0 00‡	<6 1
Sr.	Sr II	4077 7		0 0	10	0 10	<4 4

* a = Aller and Jugaku (1959); b = Moore (1945); c = Rao (1931); d = Martin (1935); e = Ramanadham and Rao (1944); f = Laporte, Miller, and Sawyer (1931).

† Assuming $gf = 1$

‡ Calculated using Bates-Damgaard (1949) tables

V. CONCLUSIONS

Our over-all conclusions concerning the abundances in 3 Centauri A may be summarized as follows:

a) The ratio deuterium:hydrogen is less than about 0.01 (Sargent and Jugaku 1961).

b) Helium is deficient by a factor of about 6; moreover, most of it is in the form of He^3 (Sargent and Jugaku 1961).

c) The elements C, Ne, Mg, Si, Ca, and A have abundances that are about normal.

d) Oxygen is deficient by a factor of about 6.

e) Nitrogen is overabundant by a factor of about 5, P by a factor of 100, Fe by a factor of 4, Ga by a factor of about 8000, and Kr by a factor of about 1300.

f) The fact that Al and Cl are not observed is consistent with their having normal abundances. Sulfur is deficient by a factor greater than about 10. The elements in the same region of the periodic table as Ga and Kr could be almost as overabundant without this being detected.

VI. DISCUSSION

It seems most probable that the abundance anomalies summarized above have been produced by nuclear reactions resulting from the acceleration of particles on the surface of 3 Cen A, since it is almost certainly a main-sequence (and, therefore, unevolved) member of the relatively young Scorpio-Centaurus association (Bertiau 1958), most of whose members have normal spectra. One member of the association, τ Scorpii, has been extensively studied (Traving 1955) and has abundances similar to those in the sun. Our conclusion is somewhat at odds with the fact that H. W. Babcock (unpublished) has not yet detected a magnetic field in 3 Cen A. (Such fields have been found in all the sharp-lined peculiar A stars, which are also thought to have undergone surface nuclear reactions.) There are two possibilities—either 3 Cen A had a large field at some time in the past, or it has at present an incoherent field which may be strong in localized regions (perhaps similar to the sunspots). The remarkable sharpness of the lines and lack of rotation compared with other association members and with 3 Cen B may indicate very efficient conversion of the star's rotational energy into magnetic energy and fast particles. It is, however, unlikely that this could have occurred while the star remained on the main sequence. Such an explanation would therefore demand that the star is in an advanced evolutionary phase and happens to have returned to the vicinity of the main sequence.

The main abundance peculiarities in 3 Cen A which any theory must broadly explain are (*a*) the anomalously high concentration of He^3, (*b*) the fact that the even-odd effect no longer appears to influence the abundances, and (*c*) the huge overabundances of the medium-heavy elements. (We have direct evidence only for Ga and Kr, but it seems inconceivable that these elements should be so much enhanced without neighboring elements also being enhanced.)

We have already pointed out (Sargent and Jugaku 1961) that the He^3 must have been produced from H and He^4, since these are the only isotopes that are sufficiently abundant in normal stars. For similar reasons, if we assume that 3 Cen A condensed out of material of normal (that is, solar) composition, the excesses of Ga and Kr must have been produced by build-up from lighter elements rather than by the fission or spallation of heavy elements. There are several possible processes by which medium-heavy nuclei could be built up.

a) Collisons of the abundant ions of the C, N, O group could occur at high energies. Taking O^{16} as the most abundant isotope, we have competing exoergic reactions, $O^{16}(O^{16}, \gamma)S^{32}$ and $O^{16}(O^{16}, p)P^{31}$, of which the latter is by far the more probable. Whether resonances play any role in heavy-ion reactions is not clear; because of the high barrier, such fusion reactions are less likely than ones in which the nuclei are partly shattered. It is interesting to note that the other fusion reactions involving C^{12}, N^{14}, and O^{16} would then transfer elements from the O group to Na, Al, Mg, and Si, where, in general, given the high abundance of such nuclei and the difficulty of observing Na, the effects would not be as easily detectable as in the case of P. The major effect would be to smooth the isotopic abundances in the neighborhood of masses 23–29.

b) Processes involving neutrons might be a reasonable consequence of high-energy electromagnetic acceleration in flarelike events involving hydrogen. If the neutrons produced are not thermalized, are not consumed in $H^1(n, \gamma)D^2$, and have relatively high energy, a group of n, np reactions may occur. For example, $S^{32}(n, np)P^{31}$ (first suggested by Bidelman 1960) would directly reverse the odd-even effect and account for the P excess and the S deficiency. The reaction requires neutrons of 9 Mev energy. If this is the upper limit to the neutron energy and if considerations of possible high-energy resonances are omitted, the other *n*, *np* reactions are $Al^{27} \rightarrow Mg^{26}$, $Na^{23} \rightarrow Ne^{22}$, $N^{14} \rightarrow C^{13}$, of which only the latter would have observable consequences. The $He^4(n, np)T^3(\beta^-, \nu)He^3$ reaction, which would be very important for the He^3 anomaly, requires 28 Mev, unfortunately. At such high energies, almost all reactions would occur, and other radical changes in the abundances might be expected. It is difficult to relate the P/S anomaly with the He^3/He^4 anomaly, because of the stability of He^4. Destruction of O^{16} by $O^{16}(n, pn)N^{15}$, requiring 12 Mev, is relatively easier and may be connected with the generally observed oxygen deficiency in the magnetic stars. However, low-energy neutrons would not affect O^{16} at all because of the small capture cross-section.

c) By reactions involving collisions at several hundred Mev between ions in the CNO group and the Fe peak. Such a reaction would be

$$_{28}Fe^{56} + {}_{8}O^{16} \rightarrow {}_{31}Ga^{69} + \text{light fragments}\,.$$

In fact, such reactions are inherently improbable. It is more likely that, without special resonance effects, at low energies there will be an interchange of a single nucleon or that at high energies both nuclei will lose mass by spallation.

d) Fowler has suggested that the medium-heavy elements would most likely be produced by the addition of neutrons on a fast time scale to the iron peak elements. On this theory it is envisaged that the neutrons are produced (probably in flarelike activity) from hydrogen by (p, n) reactions involving the more abundant nuclei. Deuterium and He^3 would be produced by the reactions $H^1(n, \gamma)D^2$ and $D^2(p, \gamma)He^3$. A large flux of neutrons would also tend to remove the odd-even effect, so that, broadly speaking, the mechanism proposed by Fowler seems capable of explaining the observed facts in general outline, although it is not clear why the ratio He^3:D (which is greater than about 3:1) is so high. (It is hoped that Fowler will publish a more elaborate form of this hypothesis at a later date.)

Although it seems likely that the comparison star, 3 Cen B, has nothing to do with the abnormal abundances on the surface of 3 Cen A, it would nevertheless be of interest to know whether 3 Cen B is normal. A 20 A/mm plate of the photographic region of 3 Cen B secured at Palomar shows that the star is rapidly rotating. Apart from the Balmer series, only three broad lines—namely the K line, λ 4472 of He I, and λ 4481 of Mg II—are visible. This is quite consistent with Mme de Vaucouleurs' (1957) spectral classification of B8 V, as is the difference in apparent magnitude between 3 Cen A and 3 Cen B. Probably the only way in which a possible peculiarity in 3 Cen B could be detected is by an examination of the infrared O I triplet.

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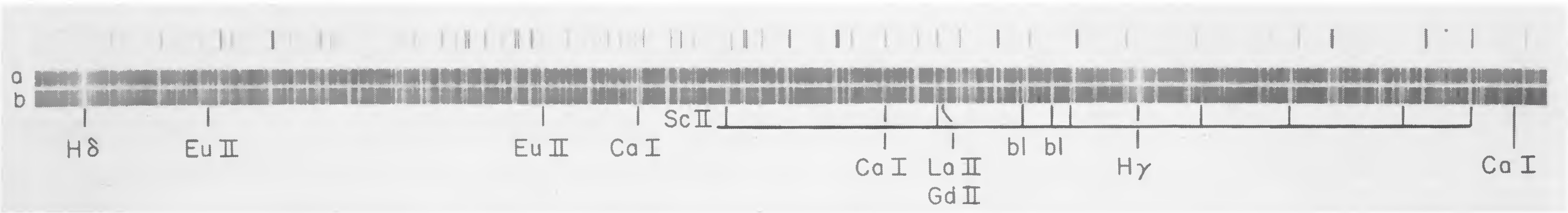

Fig. 1.—Reproduction of spectrograms of (*a*) HD 174704 and (*b*) 35 Cygni (F5 I*b*). All lines of Sc II are greatly weakened in HD 174704. Features at λ 4314 and λ 4320 indicated by the abbreviation "bl" are blends containing Sc II lines. Note the modest weakening of Ca I lines and the enhancement of λ 4129 and λ 4205 of Eu II in HD 174704 relative to 35 Cygni. The latter line of Eu II is blended with a line of V II.