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THE EXISTENCE OF He^3 IN 3 CENTAURI A*

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ABSTRACT

The positions of 10 He I lines have been measured on 5 high-dispersion plates of 3 Centauri A (B4p). Some of the lines are displaced longward of their normal wavelengths by up to 0.39 A. There is a good correlation between the observed shifts and the isotope shifts for He^3. On comparing the displacements in 3 Centauri with those measured in other B stars, we conclude that the Stark effect cannot produce shifts of the magnitude observed in 3 Centauri. Using the simple approximation that the observed displacements are proportional to the ratio $He^3/(He^3 + He^4)$, we find that this ratio in 3 Centauri is 0 84 ± 0 10. From a study of the profile of $H\gamma$ measured on 3 plates, we find that the ratio deuterium: hydrogen is less than about 0.01. We consider some possible ways in which He^3 could be produced in large quantities in the atmosphere of 3 Centauri.

I. INTRODUCTION AND MEASUREMENTS

Bidelman (1960*a*) has pointed out that the sharp-lined B5 star 3 Centauri A[1] has anomalously strong lines of phosphorus. While measuring microphotometer tracings of the spectrum in preparation for an abundance analysis, we found that the wavelengths of some of the He I lines (notably λ 6678) were a few tenths of an angstrom greater than would be expected from other lines of He I and lines of other elements. The lines with anomalous positions are all lines which Fred, Tomkins, Brody, and Hamermesh (1951) have found to have large isotope shifts. In order to check the existence of substantial helium isotope shifts in 3 Centauri, we have measured the displacements of several He I lines on five spectrograms.

Table 1 contains the results of the measurements. The first column gives the laboratory wavelength of the line in angstroms. The wavelengths quoted for the triplet series lines have been obtained by weighting the wavelengths of the individual components according to the values of $2J + 1$ for the lower levels. The letters S and T indicate that a line is a member of the singlet or triplet series, respectively. The next five columns give the difference between the observed wavelength and that to be expected on the basis of the positions of stellar lines of other elements measured on the same plate. (In Tables 1 and 2 a negative sign indicates a shorter wavelength than expected.) Plates Pb 5067, Pb 5068, and Pc 5088 were obtained by using the coudé spectrograph of the 200-inch telescope. The first two have a dispersion of 4.5 A/mm in the photographic region, while Pc 5088 has a dispersion of 13.5 A/mm in the visual region. Two He I lines were not measured on Pc 5088, since the iron comparison arc was not sufficiently well exposed in their vicinity. Ce 14229 and Ce 14240 were obtained with the coudé spectrograph of the 100-inch telescope. They have a dispersion of 15 A/mm in the visual region.

The standard deviation of measurements on a single spectrogram of stellar lines (other than the broad helium and hydrogen lines) was ±0.02 A on the higher-dispersion plates and 0.05 A on the lower-dispersion plates. From the relative scatter in the sums of the forward and backward measurements, we conclude that the error of the wavelengths of hydrogen and helium lines is about twice that of other stellar lines. This estimate is

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[1] HD 120709; $\alpha_{1950} = 13^h48^m.9$, $\delta_{1950} = -32°45'$; $m_v = 4.72$.

consistent with the scatter of the measurements on different plates in Table 1. The seventh column of Table 1 gives the weighted mean displacement and the eighth column the estimated error in the weighted mean.

Table 2 contains the measured displacements for several He I lines in the spectra of γ Pegasi (B2 IV) and HR 2154 (B5 IV). For γ Peg we have taken the arithmetic mean of the displacements measured by Miss Underhill (1948*a*, *b*) and by Aller and Jugaku (1958). In computing the shifts from their measurements we have used the wavelengths in Table 1. The discrepancies between the two sets of measurements indicate that the displacements for γ Peg have an accuracy of ± 0.02 A. Star HR 2154 was selected for measurement (on one plate of dispersion 15 A/mm) because it is one of the few known sharp-lined B5 stars. (It has $v \sin i = 10$ km/sec, according to Slettebak and Howard 1955.) The fourth column of Table 2 gives the difference in the mean displacements measured for 3 Centauri and γ Peg, while the fifth column contains the isotope shift for pure He^3 measured by Fred *et al.* (1951). It is obvious that the lines $\lambda\lambda$ 6678, 5016, 4922, and 4388, which have large isotope shifts, are displaced considerably in 3 Centauri and not in the other two stars. This would appear to rule out the possibility that the shifts in 3 Centauri are produced by the Stark effect. We have attempted to eliminate small shifts due to the Stark effect by subtracting γ Peg displacements from those of 3 Centauri.

The large redward displacements of the singlet series lines in 3 Centauri may be seen

TABLE 1

3 CENTAURI—SHIFTS OF He I LINES (ANGSTROMS)

λ	Pb 5067 May 5, 1960	Pb 5068 May 5, 1960	Pc 5088 May 12, 1960	Ce 14229 Feb 7, 1961	Ce 14240 Feb 9, 1961	Weighted Mean	Estimated Error
3867 49 (T)	0 12	0 17				0 15	±0 04
4026 21 (T)	15	11				13	± 04
4120 83 (T)	06	05				05	± 04
4387 93 (S)	26	31				28	± 04
4471 50 (T)	05	06				05	± 04
4713 17 (T)	04	08		.	. . .	06	± 04
4921 93 (S)	0 28	0 30		0 44	0 32	33	± 04
5015 68 (S)			. . .	21	29	25	± 10
5875 67 (T)			0 10	11	10	10	± 07
6678 15 (S)			0 53	0 37	0 29	0.39	±0 07

TABLE 2

COMPARISON WITH ISOTOPE SHIFT (ANGSTROMS)

λ	γ Peg	HR 2154	3 Cen $-\gamma$ Peg	Isotope Shift
3867	+0 03		0 12	0 08
4026.	+ 03		10	08
4121	+ 05		01	07
4388	+ 05		23	.28
4472	+ 03		02	.07
4713	+ 03	. .	03	.07
4922	+ 04	+0 06	29	.33
5016 .	− 03	+ 00	28	21
5876 .	+ 05	− 02	05	04
6678..	0 00	+0 01	0 39	0 50

quite clearly when its spectrum is examined in a comparator with that of other B stars. However the "manganese" star, κ Cancri (B8p), which Bidelman (1960*b*) has found to have a phosphorus anomaly similar to that of 3 Centauri, shows no detectable displacement when compared with normal B stars in this manner. (The He I lines in κ Cancri are too weak to be measured with any precision in the normal way.)

E. M. and G. R. Burbidge (1956) have found marginal evidence for the existence of helium isotope shifts in the magnetic star 21 Aquilae (B8p). Struve, Wallerstein, and Zebergs (1961) have recently made measurements on plates of the visual region of 21 Aql. They find that λ 6678 has a displacement of 0.06 ± 0.05 A, so that the presence of He^3 in 21 Aql is not established. Subsequent measurements by the writers on two 15 A/mm plates of the visual region of 21 Aql have confirmed the result of Struve *et al.* It should be noted that the Burbidges did not have access to red plates of 21 Aql on which the lines with the largest isotope shifts are found. Thus 3 Centauri appears at present to be the best authenticated case of a star in which there is a measurable concentration of He^3.

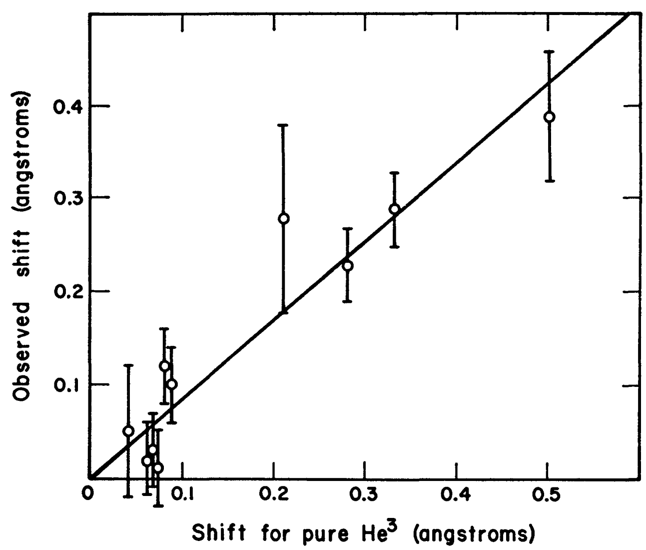

FIG. 1.—Observed shift plotted against isotope shift for the lines in Table 2

In Figure 1 we have plotted the net shifts in 3 Centauri given in Table 2 against the isotope shifts. The vertical bars represent the errors given in Table 1. We assume that the ratio $He^3/(He^3 + He^4)$ may be obtained by determining the slope of the best straight line through the points. This is strictly true only in the case of weak lines when self-absorption and saturation effects are unimportant. A consideration of special cases shows that these effects should not produce a large departure from a linear relation, and in any case it is our principal result that in 3 Centauri the He^3/He^4 ratio is abnormally large. Hence we have fitted a straight line by least squares to the points in Figure 1. The points were weighted according to the reciprocals of the squares of the errors in Table 1. The ratio $He^3/(He^3 + He^4)$ given by the slope is 0.84 ± 0.10 (standard deviation). The intercept on the ordinate is 0.00 ± 0.02.

Thus we conclude that in 3 Centauri the He^3/He^4 ratio has the abnormally large value of between 5:1 and 16:1. This is supported by the following facts:

a) There is a good correlation between the observed displacement and the measured isotope shift for He^3.

b) The displacements are very unlikely to have been caused by the Stark effect, since they have not been found in other B stars such as γ Peg, HR 2154, κ Cancri, and 21

Aquilae. In the abundance analysis, details of which will be given in a later paper, we have found that the mean electron pressure in the atmosphere of 3 Centauri is given by $\log P_e = 2.27$, while in γ Peg the corresponding value is $\log P_e = 2.34$.

c) The displacements cannot have been produced by instrumental effects because no anomalies were found in the positions of lines of other elements on plates obtained with either telescope.

d) No evidence has been found to suggest that 3 Centauri is a shell star or has peculiar motions in its atmosphere. In particular, λ 5016—one of the singlet lines which arises from a metastable level—has a shift which fits reasonably well into the correlation obtained from non-metastable lines.

e) An examination of the whole spectrum shows that blending by lines of other elements cannot seriously effect the positions of the He I lines.

II. SEARCH FOR DEUTERIUM

In order to put an upper limit on the abundance of deuterium in 3 Centauri, we have examined the profile of Hγ on three plates of the photographic region. This line has an isotope shift of $\Delta\lambda_I = -1.18$ A (Merrill 1958) and was chosen because Hα is contaminated by atmospheric features, while Hβ lies at a wavelength where the sensitivity of the II*a*-O plate is varying too rapidly. Table 3 contains details of the mean profile of Hγ measured on three plates. We have given *D*, the depth of the line as a fraction of the height of the continuum, as a function of Δλ, the distance in angstroms from the line center. Within the accuracy of measurement (about 1 per cent), equivalent points on either side of the line center have exactly the same value of *D;* therefore, in Table 3 we have combined the measurements made on opposite wings.

TABLE 3

PROFILE OF Hγ

Δλ (A)	D	Δλ (A)	D	Δλ (A)	D
0 0	0 63	4	0 24	10	0 09
0 5	50	5	20	12	06
1 0	43	6	17	14	04
1 5	39	7	14	16	03
2 0	35	8	12	18	02
3 0	0 29	9	0 10	20	0 02

Münch (1958) has derived the following formula to express the line depth as a function of distance from the line center for early-type stars:

$$D(\Delta\lambda) = D_0 \bar{\eta}(1+\bar{\eta})^{-1}, \tag{1}$$

where D_0 is the depth at the center of the line and η is the ratio of the line-absorption coefficient to that in the continuum:

$$\eta(\Delta\lambda, \tau) = \frac{l(\Delta\lambda, \tau)}{\kappa_\lambda(\tau)}. \tag{2}$$

The quantity $\bar{\eta}$ is the mean value of η with respect to optical depth τ. Although $\bar{\eta}$ can be computed theoretically from a model atmosphere, we have preferred to do so empirically by applying equation (1) to the data in Table 3. We now consider a blended hydrogen and deuterium line. In both cases the dependence of $\bar{\eta}$ on Δλ will be the same, since it is determined by the Stark effect. Let $X_{\rm H}$ denote the fraction by number of atoms of hydrogen and X_D the fraction of deuterium. Then we assume that $\bar{\eta}$ for a blended line (which we denote by $\bar{\eta}'$) is given by

$$\bar{\eta}'(\Delta\lambda) = X_H\bar{\eta}(\Delta\lambda) + X_D\bar{\eta}(\Delta\lambda - \Delta\lambda_I) . \quad (3)$$

By substituting $\bar{\eta}'$ instead of $\bar{\eta}$ in equation (1) we have computed the profile of the blended hydrogen and deuterium line for several values of X_D ranging from 0.1 to 0.001. For all these values there is very little asymmetry in the wings of the blended profile. Instead, deuterium manifests itself by the presence of a core displaced by $\Delta\lambda_I = 1.18$ A shortward of the center of Hγ. In Table 4 we give the equivalent width of the displaced deuterium line (calculated by using the wing of the hydrogen line as a continuum) as a function of X_D. We estimate that we could detect a line of equivalent width about 20 mA on our plates. This implies that the upper limit for the deuterium abundance is about 1 per cent. It should be noted that, by using fine-grain emulsions and the highest dispersion, it should be possible to lower this limit by a factor of 10.

III. DISCUSSION

The ratio of He^3:He^4 of about 10:1 which we have derived for 3 Centauri in this paper is very large when compared with the terrestrial value of 10^{-4}–10^{-5} (Strominger,

TABLE 4

EQUIVALENT WIDTH OF Dγ

X_D	W (mA)	X_D	W (mA)	X_D	W (mA)
0 001	2 3	0 01	21	0 03	48
0 005	11	0 02	36	0 10	110

Hollander, and Seaborg 1958) and with the solar upper limit of 0.02 ± 0.03 determined by Greenstein (1951) from the displacements of the chromospheric emission lines.

We now consider some possible ways in which a large He^3:He^4 ratio could be produced in 3 Centauri, on the supposition that we begin with material of normal (that is, solar) composition.

a) It is due to the *p–p* chain not being completed in the normal manner by the reactions $He^3(He^3, 2p)He^4$ or $He^3(\alpha, \gamma)Be^7$. (The chain terminates with the production of He^3 at temperatures below 8×10^6 ° K.) By this means we can produce, at most, one He^3 nucleus for every three protons initially present. The normal He^4:H ratio is about 1:10 by number, so that, even if all the hydrogen were consumed, it would not be possible to have a He^3:He^4 ratio greater than 10:3. Since at the surface of 3 Centauri the abundance of hydrogen appears to be normal, it is apparent that this suggestion must be incorrect.[2] Moreover, as has been pointed out by a referee, it is hard to understand how the products of incomplete hydrogen burning could be observed at the surface unless the outer layers of the star had been stripped off or unusually violent mixing had occurred. This would again be in contradiction with the normal hydrogen abundance.

b) The He^3 has been produced by the spallation of medium-weight nuclei following the acceleration of protons and ions to energies of several hundred Mev at the surface of the star. In a normal star the abundance of elements heavier than He is so small as to make this suggestion impossible.

c) W. A. Fowler has suggested to us that the surface of the star has been subjected

[2] We wish to thank J. L. Greenstein for suggesting this argument

to a flux of neutrons probably produced by high-energy particles accelerated during flare activity. Deuterium would be produced by $H^1(n,\gamma)D^2$ in the quiescent material surrounding the flares. The deuterium would in turn produce He^3 through $D^2(p,\gamma)He^3$ upon circulation by surface convection currents down to regions having a temperature of about 10^6 ° K. It will be expected that $He^3/D^2 \approx T/\tau$, where τ is the mean circulation time and T is the total duration of the processes under discussion. It is not unreasonable to assume that $T \gg \tau$. In this case, practically all the deuterium will have been converted to He^3 as the observations probably indicate. This hypothesis has the same drawback as *b*, namely, it is difficult to envisage a neutron source sufficiently abundant to change such a large fraction of the material.

d) From the foregoing arguments, it seems reasonable that if we are to produce He^3 in the observed quantities from stellar material of normal composition, it must be made by reactions which deplete He^4. In this connection, the recent discovery by Appa Rao (1961), that in the low-energy (200–400 Mev) cosmic rays the $He^3:He^4$ ratio has the high value of 0.41 ± 0.09, is of great interest. Appa Rao discusses the possibility that the He^3 is formed as a result of collisions of He^4 nuclei in the primary cosmic rays with protons in the interstellar gas. It may be that such collisions can take place as a result of non-thermal acceleration processes on the surfaces of certain stars. It is not clear whether such a mechanism would be consistent either with the small amount of deuterium which must be present on the surface of 3 Centauri or with the other abundance anomalies which we shall describe in a further paper (Jugaku, Sargent, and Greenstein 1961). When one considers possible acceleration mechanisms, however, it should be noted that H. W. Babcock (unpublished) has not been able to detect a magnetic field in 3 Centauri, although its sharp, unblended lines make it a favorable object.

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REFERENCES

Aller, L. H., and Jugaku, J. 1958, *Ap. J*, **127**, 125.
Appa Rao, M. K. V. 1961, *Phys. Rev.*, **123**, 295.
Bidelman, W. P. 1960*a*, *Pub. A.S.P.*, **72**, 24.
———. 1960*b*, *ibid.*, p. 471.
Burbidge, E. M., and Burbidge, G. R. 1956, *Ap. J.*, **124**, 655
Fred, M., Tomkins, F. S., Brody, J. K., and Hamermesh, M 1951, *Phys. Rev*, **82**, 406.
Greenstein, J. L. 1951, *Ap. J.*, **113**, 531.
Jugaku, J., Sargent, W. L. W., and Greenstein, J. L., *Ap. J.*, **134**
Merrill, P. W. 1958, *Lines of the Chemical Elements in Astronomical Spectra* ("Publications of the Carnegie Institution of Washington," No. 610).
Münch, G. 1958, *Ap J.*, **127**, 642.
Slettebak, A., and Howard, R. F. 1955, *Ap. J.*, **121**, 202.
Struve, O., Wallerstein, G., and Zebergs, V. 1961, *Pub. A.S P*, **73**, 220.
Strominger, D., Hollander, J. M., and Seaborg, G. T. 1958, *Rev. Mod. Phys*, **30**, 585.
Underhill, A. B., 1948*a*, *Ap. J*, **107**, 337.
———. 1948*b*, *ibid.*, **108**, 472.