NO. 20. THE COMPOSITION ANOMALIES OF 3 CENTAURI A

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1. Introduction

CAUSES of abundance anomalies in stellar atmospheres may include one or more of the following: (*a*) mass loss resulting in exposure of regions usually masked by the atmosphere; (*b*) accretion; (*c*) mixing; (*d*) special conditions at the surface, past or present; (*e*) prestellar environmental anomalies. These are discussed with particular reference to 3 Cen A, and the conclusion drawn that, in spite of some objections, fluctuations in the composition of the prestellar matter may be a major cause in determining that star's present anomalous atmospheric chemical composition.

2. Characteristics of 3 Cen A

The star has been classified as B5 III by Bertiau (1958), B5 IV by Mrs. de Vaucouleurs (1957), and B4 IV or V by Jugaku, Sargent, and Greenstein (1961). It is the brighter component of the visual double 3 Centauri; the apparent visual magnitudes of the two stars are 4.6 and 6.1, the separation being about 8″. The pair is thus not a close binary, and interaction between the components is unlikely. The star 3 Cen A, located near the edge of the Scorpio-Centaurus Association, appears to be a member of this rather loose aggregate of B stars. The radial velocity and proper motion measures for 3 Cen A are in good accord with the mean values for the association (Blaauw, 1956; Bertiau, 1958; Buscombe and Morris, 1960; Morris, 1961). The age of the cluster, given as 2×10^7 years by Bertiau (1958), may be reasonably assumed to be that of the individual stars, and particularly of 3 Cen A. Such evidence as exists (see Bertiau, 1958) indicates that 3 Cen A is a main sequence star. Of other stars in the association, τ Scorpii (near the opposite edge of the association) has normal chemical abundances (Traving, 1955), and it has been suggested (Searle, 1962) that 3 Cen B is also normal. It should be noted, however, that the spectrum of 3 Cen B shows broad lines, and it is thus not clear that the apparent normality is established.

The lines of the spectrum of 3 Cen A are sharp, indicating the *absence* of turbulence, rotation (except possibly pole-on), and excessive ordered magnetic fields ($>$ 200 gauss; see below, Sec. [*d*]); no emission lines have been detected, so that shells or streams of gas, at least on an observable scale, must also be missing. Convincing quantitative evidence of abundance and isotopic anomalies as compared with the sun (Goldberg, Müller, and Aller, 1960; Aller, 1961) has been given by Sargent and Jugaku (1961) and Jugaku, Sargent, and Greenstein (1961), following Bidelman's earlier (1960) identification of unusual components in the spectrum, particularly lines of phosphorus. The main anomalies are included in Table 1, taken from Jugaku, Sargent, and Greenstein (1961).

3. Possible Causes of Composition Anomalies in Stars

(a) Mass Loss

Loss of an appreciable fraction of a star's mass

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TABLE 1

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).

by the removal of the outer layers would expose material containing greater amounts of helium, certainly, and carbon, possibly, etc. The anomalies of 3 Cen A, such as the overabundance of Ga and Kr, do not seem to have any simple connection with such mass loss. In addition, the helium content is low rather than high. Hence mass loss is rejected as a cause of the anomalies in 3 Cen A.

(b) Accretion

There is no specific evidence for the infall of matter on a star, and arguments have been given that stars, especially hot stars or stars with magnetic fields, cannot accrete matter from the interstellar medium (Menzel, 1955; Schatzman, 1955). The acquisition of a large amount of matter from the other member of the binary seems unlikely here because of the wide separation of the pair. Thus, accretion is also rejected.

(c) Mixing

The radiative temperature gradient in early main sequence stars is stable (according to discussions of model star evolution; Mestel, 1959; Sweet, 1961), and early main sequence stars have no hydrogen convection zone. The earliest type for which mixing in the outer layers is important is probably A0, and if this is so, surface convection may be ruled out of consideration in the case of the B stars. Spiegel (1960) has invoked surface convection currents in a helium convection zone near the surface of the sharp line star 10 Lacertae (O9.5) to account for the "Trumpler red shift" (Trumpler, 1935). Such currents, if they existed, would be superficial and could not be responsible for creating the observed anomalies. Since He^3 has an extremely short life in the interior of a hot star, deep currents cannot bring He^3 to the surface. Therefore, mixing is rejected as a source of the anomalies.

(d) Special Conditions at the Surface in the Star's Past or Present History

Various authors have discussed the abundances of Table 1 on the assumption that the element abundances were initially normal but have been altered by nuclear reactions involving energetic protons ($Ep \geqq 20$ Mev), the protons being accelerated in changing magnetic fields. The mechanism of surface spallation, suggested by Wallerstein (1962), was earlier treated by Fowler, Burbidge, and Burbidge (1955), who pointed out that its effective operation requires magnetic fields as high as 10^7 gauss. The highest general field so far observed in any star is 3.4×10^4 gauss (Babcock, 1960) in HD 215441. Although this seems a likely star to show abundance anomalies, they are actually minor. There is, in fact, no clear causal correlation of magnetic fields with abundance peculiarities, although they are present simultaneously in magnetic A stars. Even if there were such a connection, Dr. Babcock (1962) states that the spectrum of 3 Cen A is consistent with the presence of a field of 85 gauss ± 75 (p.e.) gauss. Since the measured intensity is of the same order of magnitude as the probable error, it is by no means certain that an ordered field is present, but a field of the order of 200 gauss is not ruled out; neither are isolated magnetic spots of $\sim 10^3$ gauss (Searle, 1962). These fields are too small to produce measurable anomalies in the integrated spectrum.

Suppose, however, that abundance peculiarities *are* caused by magnetically-induced surface reactions taking place in discrete spots. The present magnetic fields in 3 Cen A could not produce effects of the order observed; the requisite fields must have existed at some past time. Since essentially all of the surface He^4 atoms (10% of the atoms of the photosphere if this had been originally of normal composition) are supposed (e.g., Wallerstein, 1962) to have undergone conversion, the scale of the reactions involved implies that the *entire surface layer* has been bombarded by energetic protons. The necessary magnetic fields could thus hardly have been confined to *small* spots. Very large surface currents must have flowed, and the present sharpness of the lines of the spectrum requires that such currents, if formerly present, have now ceased. A magnetic origin of the anomalies thus requires that 3 Cen A formerly had large fields and large surface disturbances which subsequently vanished. There is no specific evidence that B stars evolve in this way. Comparison with later type stars (e.g., A pec and magnetic A stars; Wallerstein, 1962) should take into account the relative ages and frequency of occurrence. 3 Cen A, which is so far observationally unique, is of earlier spectral type and is therefore probably younger than the magnetic stars. Moreover, the abundance anomalies, apart possibly from that of oxygen, are not the same as in the latter (Sargent and Searle, 1962), so that the connection between 3 Cen A and the A stars is scarcely well established.

Further, consider the hypothesis that suprathermal protons have actually decimated the He^4, but somehow not the He^3, in the highly endothermic spallation reactions discussed, for example, by Wallerstein. Possible reactions are:

$$He^4 + p \rightarrow H^3 + 2p - 19.8\text{ Mev}, \qquad (1)$$

$$He^4 + p \rightarrow He^3 + p + n - 20.6\text{ Mev}, \qquad (2)$$

$$He^4 + p \rightarrow He^3 + d - 18.4\text{ Mev}, \qquad (3)$$

$$He^4 + p \rightarrow 2p + n + d - 26.1\text{ Mev}, \qquad (4)$$

$$He^4 + p \rightarrow p + 2d - 23.9\text{ Mev}, \qquad (5)$$

$$He^4 + p \rightarrow 3p + 2n - 28.3\text{ Mev}. \qquad (6)$$

Wallerstein (1962) favors reaction (3), but Fowler, Greenstein, and Hoyle (1962) consider that (1), (2), and (6) are the most probable. Data on this point are discussed below. The existence of these alternative reactions means a reduced probability of creating He^3; the most likely result is the liberation of neutrons and protons. In further consideration of equations (1)-(6), the fast protons would also promote reactions such as the energetically favored:

$$C^{12} + p \rightarrow He^4 + p - 7.4\text{ Mev}, \qquad (7)$$

$$N^{14} + p \rightarrow C^{11} + He^4 - 2.9\text{ Mev}, \qquad (8)$$

$$\rightarrow C^{12} + He^3 - 4.8\text{ Mev}, \qquad (9)$$

$$O^{16} + p \rightarrow N^{13} + He^4 - 5.2\text{ Mev}. \qquad (10)$$

The magnitude of the required effect means, as we have remarked, that *all* the surface matter must have undergone a collision with an energetic proton. It thus appears that the C, N, and O should be almost completely destroyed by the large flux of protons. The data on 3 Cen A show normal C, excess N, and somewhat deficient O, whereas the result of irradiating the surface of 3 Cen A with energetic protons should be to reduce the original elements to protons and those with masses greater than 30 or so.

One could also argue that the He^3 ought to be accelerated by the same mechanism which energizes the protons. At the surface temperature of 3 Cen A much of the helium must be ionized. However, even were the temperature low enough to preclude general ionization of the helium, but to allow ionization of H, the He^3 emerging from the proposed reactions would still be charged, so that the extensive magnetic fields would accelerate these He^3 nuclei. Numerous He^3 reactions with C, N, O targets are exothermic, have large cross-sections at energies well below 20 Mev, and would rapidly deplete the star of any He^3 which had been generated. Neutrons, which would be plentiful if a previously existing normal quantity of He^4 had been fragmented, would help destroy the He^3 by the rapid exothermic reaction

$$He^3 + n \rightarrow H^3 + p$$

followed by prolific H^3-induced reactions using up any H^3 which did not revert to He^3.

The above arguments can be put on a somewhat quantitative basis by consideration of measured cross-sections. For example, the bombardment of He^4 by protons has been studied by Eisberg (1956) and Wickersham (1957) for proton energies of 40 Mev and 28 Mev, respectively, while the bombardment of O^{16} has been examined over the proton energy range from 20 Mev to 150 Mev by Albouy, Cohen, Gusakow, Poffe, Sergolle, and Valentin (1962). $C^{12}(p,pn)C^{11}$ data come from Crandall, Millburn, Pyle, and Birnbaum (1956). Data on He^3 reactions in carbon have been obtained by Cochran and Knight (1962) for 6 Mev $< E_{He^3} <$ 24 Mev. The principal results are summarized in Table 2 and discussed below.

TABLE 2

CROSS-SECTIONS FOR NUCLEAR REACTIONS

Reaction	Cross-section	Reference
$He^4(p,d)He^3$	$\frac{d\sigma}{d\omega} = 1.0$ mb/ster at 30° (lab.)	Eisberg (1956)
$He^4(p,d)He^3$	$\frac{d\sigma}{d\omega} \simeq 3$ mb/ster	Wickersham (1957)
$He^4(p,2p)H^3$	8.9 mb	Wickersham (1957)
$He^4(p,pn)He^3$	4.8 mb	Wickersham (1957)
$C^{12}(p,pn)C^{11}$	90 mb at 45 Mev	Crandall *et al.* (1956)
$O^{16}(p,pn)$	70 mb at 50 Mev	Albouy *et al.* (1962)
$C^{12}(He^3,He^4)C^{11}$	340 mb at 9 Mev	Cochran and Knight (1962)
$C^{12}(He^3,pn)N^{13}$	130 mb at 13 Mev	Cochran and Knight (1962)
$C^{12}(He^3,2\alpha)Be^7$	100 mb at 18 Mev	Cochran and Knight (1962)

The measurement on $He^4(p,d)He^3$ by Eisberg (1956) was carried out at a single angle, while Wickersham (1957) studied a number of angles, and an average differential cross-section is listed in Table 2. One sees that reaction (3) does have a larger cross-section than reactions (1) and (2). However, it is also clear that (7) and (10) have comparable cross-sections, as have the He^3-induced reactions. Thus we argue that, even in the *unlikely* circumstance that the direct destruction of He^3 by protons is down by an order of magnitude relative to the $He^4 + p$ reactions, it is still impossible for the He^3 to escape being consumed in processes involving other light nuclei like carbon. Indeed, if the concentration of He^3 ever approached that of C, N, O, there would also be the exothermic reaction $He^3 + He^3 \rightarrow He^4 + 2p$ to prevent any further growth of the He^3 concentration.

The production of tritium (Fireman, DeFelice, and Tilles, 1961) and He^3 (Schaeffer and Zähringer, 1962) in solar flares has been established by satellite measurements and is one basis for the 3 Cen A analysis by Wallerstein (1962). The present authors argue that these nuclei would be rapidly destroyed after production *if they remained in the star*.

The possibility (Wallerstein, 1962) that the cross-section for $S^{32}(p,d)S^{31}(\beta^+)P^{31}$ might lead to an enhanced P/S ratio does not justify overlooking the other consequences, mentioned above, of the generation of fast protons. Bidelman (1960) had previously suggested that the P/S ratio in 3 Cen A might be due to $S^{32}(n,p)P^{32}$. This mechanism, which is energetically forbidden for the *thermal* neutrons proposed by Bidelman, simply leads again to S^{32}, since P^{32} is beta-active with a 14.3 day half-life. Thus the P/S ratio is unaffected. The $S^{32}(n,np)P^{31} - 9$ Mev reactions discussed by Jugaku, Sargent, and Greenstein (1961) require energetic neutrons, the source of which is unclear. Also, since 3 Cen A has normal hydrogen, any fast neutrons, however made, would be rapidly thermalized.

We conclude that the surface acceleration mechanism is inconsistent with the data on light elements in 3 Cen A. In addition, that mechanism would be badly strained were it held responsible for the observed Ga and Kr anomalies.

(e) Prestellar Environmental Anomalies

Consider the suggestion that 3 Cen A formed out of abnormal matter. Aller (1961) and Bidelman (1962) have discussed prestellar abundance anomalies. This approach implies local fluctuations in interstellar composition. These undoubtedly exist, though observations (in special regions only, e.g., Orion Nebula, Mathis, 1957; Crab Nebula, Woltjer, 1958) are still meager. Aller (1961) discusses this point. Although τ Scorpii[1] is a normal (B0V) star

[1] τ Scorpii is stated by Buscombe and Morris (1960) to be an irregular velocity-variable with small amplitude.

(Traving, 1955; Aller, Elste, and Jugaku, 1957) belonging (Bertiau, 1958) to the Scorpio-Centaurus Association, it is now at least spatially far removed from 3 Cen A, the two stars being virtually at opposite edges of the association. Hence a local fluctuation of the chemical composition of the prestellar matter might have affected 3 Cen A and not the other stars. The normality of the τ Sco spectrum cannot be used to argue that 3 Cen A must initially have been normal. One could just as well urge that τ Sco should have experienced the same evolution as 3 Cen A since τ Sco is only slightly different in spectral class. There are also other sharp-line stars of the same class as 3 Cen A, but without the 3 Cen A composition (e.g., HR 2154; see Sargent and Jugaku, 1961).

For the particular case of 3 Cen A, we point out that the He^3/He^4 and He/H anomalies in 3 Cen A may mean that the *p-p* and CNO sequences had not reached their termination points in the star(s) which produced the pre-3 Cen A matter. This hypothesis, shown by Sargent and Jugaku (1961) to be unlikely when applied to 3 Cen A itself, has the merits of simplicity and of explaining qualitatively the excess of N and deficiency of O in the star. An abbreviated operation of normal stellar nuclear reactions, and these include neutron processes, might also account for the overabundance of the other (heavier) anomalous elements; for example, if the *s*-process in the predecessor star(s) had not reached equilibrium, the medium-weight elements would not have suffered destruction after their creation.

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