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THE SYNTHESIS AND DESTRUCTION OF ELEMENTS IN PECULIAR STARS OF TYPES A AND B*

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ABSTRACT

A discussion is given of the properties of the peculiar A and B stars and especially their anomalous abundances and positions in the H-R diagram. It is known that the compositions can only be explained if it is supposed that (i) the high abundances of heavy elements, particularly in the rare-earth region, and the abundances in the vicinity of the iron peak have been produced in a region in which a process of rapid neutron addition has occurred; it is shown here that the conditions are suitable for this when the star has reached a degenerate core configuration, the key reaction being $C^{13}(\alpha,n)$. This implies that either the peculiar A and B stars are at an advanced phase of evolution, i.e., they have passed through a giant phase and have returned to the vicinity of the unevolved main sequence, or else that such a process has gone on in a close binary companion and mass has been transferred to the surface of the peculiar star. This latter possibility is open to observational test since, if this were true, all stars of this type should have close evolved companions. In addition to an r-process of this type, it is also shown (ii) that to produce the underabundance of the light elements, especially helium, and also to obtain the high He^3:He^4 ratio seen in 3 Centauri A a vast amount of surface spallation followed by shallow mixing must have occurred The stars have therefore had a very complicated evolutionary history, with surface spallation and then interior nucleosynthesis followed by rapid mixing It appears that the properties of degenerate cores and the possibility of rapid heating and energy generation and release at this phase are of the utmost importance in explaining these stars. The theory described here for explaining the observed phenomena cannot be explored in more detail until evolutionary tracks for stars in this mass range have been developed in detail. On the observational side some discussion is given of stars that may be at different parts of the evolutionary track that these stars are traversing.

One conclusion derived from our considerations of neutron capture processes merits special notice. We believe that the excess phosphorus concentration found in κ Cnc and 3 Cen, for example, is produced in a Si-P-S cycle, and we predict an excess concentration of Si^{30} in such stars.

I. INTRODUCTION

The stars with strong surface magnetic fields have some physical properties for which no adequate explanation has been given. The characteristics which single them out as a group are (1) atmospheric magnetic fields, which are in general $\geq$ 1000 gauss; (2) pecul-

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iar spectral characteristics that often indicate that their surface regions contain anomalous abundances of many elements. A review article giving a discussion of the properties of the atmospheres of the magnetic stars, in which details and full references can be found, has recently been published by Sargent (1964). An earlier review by Babcock (1960) concentrates particularly on a discussion of the magnetic fields.

In general the two distinct properties of magnetic fields and spectral peculiarities go together. The large proportion of stars with strong magnetic fields are the peculiar A stars (Ap) all of which show spectral anomalies reflecting peculiar compositions that we shall discuss further in § II. In addition to these there are a few stars with peculiar compositions that suggest strongly that they are allied genetically to the peculiar A stars, although they do not have strong magnetic fields. These also will be discussed in § II. On the other hand, Babcock (1958) has shown that there are some stars (e.g., RR Lyrae) which have strong surface magnetic fields but whose compositions appear to be normal within their population characteristics. We shall not be concerned with such stars in this paper.

In their spectral peculiarities and in the presence of magnetic fields in some of them, the metallic-line (Am) stars show similarities to the Ap stars and there may be an evolutionary or genetic relationship, although the magnetic fields, where they have been detected, are much smaller than in the Ap stars. Abt (1961) has discovered that there is a very high proportion of spectroscopic binaries among the Am stars, a considerable fraction of these being with short periods. The observed proportion of binaries is high enough for the tentative conclusion to be drawn that *all* Am stars are close binaries. On the other hand, in his compilation of results on magnetic stars, Babcock (1958, p. 252) has noted that only ten out of eighty-nine stars are binaries—an unusually low proportion. This is a question which needs more observational work; we return to its significance for evolutionary considerations in § VI.

Another property of the peculiar A and B stars is that they may all show some small variability in light and color (Abt and Golson 1962) and much larger variability in magnetic field (Babcock 1958). No theoretical interpretation of their variability in light has been attempted as far as we are aware. The problem must presumably be related to the evolutionary character of these stars.

Much attention has been paid to the variable magnetic fields, but no satisfactory models have emerged. The most severe problem is encountered when trying to explain how a field of many kilogauss in the atmosphere can reverse its polarity in a regular fashion in a period of a few days. Cowling (1952) showed how exceedingly difficult this problem is, and, although non-radial oscillations have been proposed, there have been no further suggestions as to how field reversal can take place. The alternative explanation for the field variations is that the magnetic field observed is concentrated in two large spot regions, one of positive and one of negative polarity, which have an axis that is inclined to the axis of rotation of the star (cf. Deutsch 1958). This oblique rotator model also is unsatisfactory in some respects, and it is clear that any model that is used to explain the magnetic-field characteristics must take account of the evolutionary history of these stars.

Our emphasis here is on the composition of the stars. We shall accept as correct that the stars have atmospheres of anomalous composition. The recent critical survey of the observation material by Sargent (1964) supports this view, and the abundance analyses that have been carried out in the period since the first work on α^2 CVn (Burbidge and Burbidge 1955) have shown the same effect in other stars of this type, as well as finding anomalies involving other elements.

It has been suggested by Babcock (1947, 1963) and Jensen (1962) that selective stratification or migration of paramagnetic atoms resulting from the force exerted on the atomic magnetic moments by the gradient of the magnetic field may take place. If this were an efficient process it might have the effect of concentrating elements in spot regions, and it is then not inconceivable that for appropriate contributions to the spectra from the spot regions, as compared with the remainder of the photosphere, spurious anomalous overabundances of some elements might be found. However, as soon as the quantitative aspects of this suggestion are investigated it appears untenable. It is required that an optical pumping mechanism due to the irradiation by polarized light operate to align the magnetic moments to give a net paramagnetic moment. The elements that are most strongly affected have been listed by Babock (1963). While some of the elements that show the greatest anomalies—Cr, Mn, Eu—are included, many that also show very large anomalous abundances, particularly the rare earths other than Eu (see § II), are not. Moreover, the magnetic-field gradients required for even a modest concentration of some elements—by a factor of 10 over 10^{11} cm—are $\sim 10^2$ gauss/km which is 10^2 times higher than that found in sun spots. It appears to us that this effect might be responsible for some part of the variation in line intensities that is seen in some magnetic stars through their magnetic cycles—there must be some small degree of vertical or horizontal stratification. However, it cannot account for the anomalous compositions with which we shall be concerned in the remainder of the paper.

II. OBSERVED ANOMALOUS ABUNDANCES

Detailed curve-of-growth analyses have been carried out for twelve Ap stars, and it is largely from the compositions determined in these studies that our theoretical investigation has begun. The stars can be divided into groups corresponding to the spectral features that are most prominent. This nomenclature is used in the list that follows. The stars are:

α^2 CVn (A0p; Si, Cr, rare earths)	γ Equ (F0p; Cr, Sr, rare earths)
HD 133029 (A0p; Si, rare earths)	α Scl (B5p; weak helium)
HD 151199 (A2p; Sr, rare earths)	3 Cen A (B5p; P)
HD 34452 (A0p; Si)	73 Dra (A2p; Si, Cr, rare earths)
ϵ UMa (A0p; rare earths)	53 Tau (B9p; Mn)
β CrB (F0p; Cr, Sr, rare earths)	κ Cnc (B8p; Mn)

A critical discussion of the reliability of the abundance determinations in these stars has been given by Sargent (1964), and we shall accept the numbers in the majority of cases as correct, though it should be borne in mind that uncertainties of the order of $10^{1/2}$ are normally to be expected with analyses of this kind. Logarithmic overabundance ratios for all of the elements for which such ratios could be determined are given in Table 1, which has been taken from Sargent's survey.

In addition to these analyses of all observable elements in individual stars, we now have information from a few studies of the abundances of particular elements in many stars; also we have a few cases in which spectral lines attributed to very rare elements have been identified; in such cases, although abundances have not been determined, the very presence of lines of these elements means that they must be greatly overabundant. While this latter material is very preliminary it will be used in what follows.

We now consider the abundance anomalies as they appear, going systematically through the periodic table for elements for which information is available.

H.—These stars appear to have normal hydrogen content; all other abundances are determined relative to hydrogen.

He.—In the majority of the cases in which conclusions can be drawn it is found that helium is very considerably depleted. This applies particularly to the stars in which the silicon abundance anomaly is most pronounced, and in the remarkable star 3 Cen A. The work of Searle and Sargent (1964) suggests that the helium abundance is depleted by factors of from 10 to 100 in the Ap stars of higher temperature, where He I lines could be looked for. In 3 Cen A the reduction is by a factor of about 10, and 80 per cent of the helium present is He^3. The low abundance of helium is particularly important when we consider possible theories for the abundance anomalies. However, in the cooler Ap stars we have no information as to the helium abundance.

Li, Be, B.—These elements are considered together since they all have the property that they are very easily destroyed by mixing into a stellar interior. In the hotter Ap stars only Be can be looked for; Li can be looked for in the cooler stars. In a selection of the brighter Ap stars it has been shown (Sargent, Searle, and Jugaku 1962) that, while some of these stars show no evidence of abnormal abundance of Be, in a few cases this element is overabundant with respect to the Sun by factors of the order of 100. By measurement of the wavelength of the Li line in two magnetic stars and six normal stars, Wallerstein and Merchant (1965) have shown that the magnetic stars seem to have a higher content of the isotope Li^6, relative to Li^7, than the normal stars. Li^6 and Li^7 should be produced in the ratio $\sim 1:2$ by spallation, but usually the Li^7 abundance is observed to be greater than implied by this ratio.

TABLE 1

ABUNDANCE RESULTS FOR PECULIAR A STARS

Element	α^2 CVn	HD 133029	HD 151199	β CrB	γ Equ	3 Cen A	73 Dra	53 Tau	κ Cnc
He						−0 8			−1 2
Be	+1 2					<+0 4			+2 0
C						0 0		+0 4	
N						+0 7			
O	−1 0			<−1 8	<−1 7	−0 8			+0 3
Ne						0 0			
Na					0 0				
Mg	−0 4	+0 1	+0 1	+0 2	+1 2	−0 6:	+2 7	−0 3	−0 8
Al	0 0	+0 3				<−0 2			
Si	+1 0	+1 4	+0 1		+0 5	+0 3	+0 7	+0 1	
P						+2 0			+2 0
S						<−1 0			
Ar						+0 1			
Ca	−1 7	−1 3	+0 4	+0 1	+0 7	−0 4:	−2 0	−1 5	
Sc	−0 2			+0 4	+0 7	<+0 6			
Ti	+0 4	+0 4		+0 9	+0 2	<+0 2	+0 3	+0 6	−0 2
V	+0 1	+0 5		+0 4	+0 8	<+0 7			
Cr	+0 7	+1 0	+0 3	+1 5	+1 3	<−1 0	+1 6	−0 9	+0 1
Mn	+1 2	+1 2	+1 0	(+1 6)	+1 8	+1 6	+1 5	+1 8	+1 5
Fe	+0 5	+0 6	+0 0	+0 8	+0 6	+0 6	+0 6	−0 3	−0 3
Co				(+1 0)	+1 7				
Ni	+0 5	+0 4		+0 3	+1 6	−0 2			
Ga						+3 8		+2 4	
Kr						+3 1			
Sr	+1 1	+1 2	+1 8	+1 6	+2 6	<+1 7	+0 9	+1 5	
Y	+1 3				+0 6				
Zr	+1 5	+1 6		+2 0	+0 8				
Xe									(+3 0)
Ba	≤0 0		−0 2	+0 7	+1 2				
La	+3 0	+2 3		+2 8	+2 3				
Ce	+2 6	+2 4		+2 9	+2 0		+1 3		
Pr	+3 0	+2 8		+2 7	+2 4				
Nd	+2 4	+2 1		+2 2	+2 3				
Sm	+2 6	+2 4		+2 3	+1 7				
Eu	+3 3	+2 9	+2 1	+3 2	+2 6		+3 3		
Gd	+2 9	+2 5		+2 9	+2 2		+2 8		
Dy	+2 9	+2 7		+3 6	+2 5				
Hg									(+4 6)
Pb	(+3 2)								

C.—In a majority of the Si stars evidence from the C II lines suggests that C is underabundant by factors of 10–100.

N.—It is possible that nitrogen is underabundant in some Ap stars (Sargent *et al.* 1962).

O.—Studies by Sargent and Searle (1962) show that oxygen is underabundant throughout the whole range of Ap stars except in the Mn stars. The abundance of this element is estimated to be reduced by 10–100 throughout all other classes of these stars.

Mg.—Magnesium does not show large abundance anomalies. Sargent and Searle have reported that abundance variations by a factor of ~2 in either direction about the solar abundance are probably present.

Si.—In the hotter stars, the Si stars, this element is found to be overabundant by a rather large factor of about 100. The Si-Eu-Cr stars also show similar but not so large overabundances, but the Mn stars show a normal abundance of Si.

P.—This element is known to be overabundant in 3 Cen A and κ Cnc by a factor of about 100. In other stars we have no information about this element.

Ca.—In a few cases this element is found to be underabundant by factors of 10–100. In many cases, however, it is normal.

Fe-peak elements.—From all the information available at present, the elements that show anomalies among the iron-peak group are Cr, Fe, and Mn. In the hotter stars of the group, the Si stars and the Mn stars, Cr is either normal or can be slightly over- or underabundant (in the Mn stars). However, in the other groups it is always overabundant by about 1 order of magnitude. Mn is apparently normal in the Si stars, but it is overabundant in all of the other stars, by factors ~100 in the Mn stars and rare-earth stars and by factors ~10 in the other cases. Fe shows a much smaller anomalous effect. Sargent has argued that it has normal abundance in all of these stars, but we have concluded that it is probably overabundant in many cases, though only by factors of 2 or 3.

Ga.—Lines of this element were identified in two stars, 3 Cen A and 53 Tau (Bidelman 1960*a*, 1961, 1962*a*). This element has then been found to be overabundant by a factor of 6000 in 3 Cen A, and by 250 in 53 Tau.

Kr.—This element has been found in 3 Cen A (Bidelman 1961, 1962*a*). It is overabundant by a factor of about 1000.

Sr, Y, Zr.—These elements are found to be overabundant over the whole range of Ap stars with overabundance factors in general of between 10 and 100.

Xe.—This element has been identified in κ Cnc by Bidelman (1961, 1962*b*). While no abundance analysis has been carried out, it is clear that its detection means that it is overabundant by a large factor ~30–300.

Ba.—This element is found only to have normal abundance in the majority of Ap stars in which it has been studied. In two cases (β CrB and γ Equ, which are rare-earth stars) it is found to be overabundant by factors of 5–10.

La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho.—These rare earths show the greatest degree of overabundance of any group of elements in the Ap stars. In the five stars in which they have been investigated in detail, the average overabundance factors are about 500. Sargent has given reasons for believing that these factors have in some cases been *under*-estimated. The investigations largely stem from the first study of α^2 CVn by Burbidge and Burbidge (1955). We have recently reinvestigated the validity of the identifications of some of the lines that were used in that study, and now believe that blending is serious for many of the La lines used and hence the evidence for the large overabundance of La is weak. We therefore shall suppose in what follows that this element is more nearly of normal abundance than the other rare earths. In addition to the stars studied in detail, HD 101065, investigated so far only in a qualitative and preliminary fashion by Przybylski (1963), shows very prominent lines of Ho and Dy as well as other rare earths. This is a remarkable star, whose spectrum shows nothing but H, Ca (which appears deficient), and the rare earths. According to Przybylski, the presence of Ca is based only on the

K-line; the H-line is masked by a strong Dy-line! This star is probably cooler than most Ap stars; it is obvious that it has an anomalous composition very rich in rare earths, but an analysis has not yet been made.

Hg.—Recent Bidelman (1962*b*) has tentatively identified one line in κ Cnc as being due to Hg. If this is the case, then Sargent has shown that it is overabundant relative to the Sun by factors $\sim$40000 if no blending is present. Bidelman has identified what he believes to be this line in other Ap stars of the Mn group, but the measured wavelengths vary slightly and he has pointed out that this might mean that different isotopes of Hg are dominant in different stars. As has been pointed out by Sargent, this may also be due to blending.

Pb.—The problem of determining the abundances of the very heavy elements is first that of making good identifications and then taking account of the serious problems of line blending. Burbidge and Burbidge (1955) identified Pb in the spectrum of α^2 CVn. It was then found to be overabundant with respect to the Sun by a factor of about 1500. This is the only star in the Ap group in which the element has been identified.

This concludes our summary of the types of abundance anomalies which are present in the Ap stars. The stars cover a range in effective temperature, and the same anomalies are not found throughout. In some cases the differences between the stars are real, but in many cases the spectroscopic method does not allow us to tell whether anomalous abundances in one group are present in others. (For example, how overabundant are the rare earths in the hotter Ap stars?) In Figure 1 we have plotted the relevant part of the zero-age main sequence (Sandage 1957), the Pleiades main sequence (Johnson and Morgan 1953; Sandage 1957), which is somewhat evolved, and the Ap and Am sequence as defined by Eggen (1959). Eggen considered the straight line to represent the Ap stars only for $B - V > 0$, and found that the Ap sequence turned up, roughly parallel to the evolved main sequence, for $B - V < 0$. We have plotted large open circles to represent the mean values for the various types of Ap star given by Jaschek and Jaschek (1958, 1962). The Si point further to the left represents the Si λ 4200 stars (since the λ 4200 feature is simply due to Si II at high excitation, this merely means these stars are hotter than the Si stars). We have extended Eggen's sequence as a straight line to $B - V = -0.1$ and have indicated on this sequence the spans in $B - V$ occupied by the various types of Ap stars and the Am stars, as given by the groupings of the Jascheks. The overlap between the Si and Mn groups gives a clear-cut indication of a real difference in the Mn/Si abundance ratio among different Ap stars. We return to a discussion of Figure 1 in § III.

Finally, the abundances in the metallic-line stars and in another, perhaps related, group of stars should be mentioned. The abundance determinations in the few metallic-line stars so far analyzed in detail have been briefly reviewed by Sargent (1964). The similarity between the Am and Ap stars lies in the fact that (i) Ca, deficient in some of the Ap stars, tends to appear underabundant also in the Am stars; (ii) Ni and Zn appear to be overabundant in the Am stars while the element Ga, just past these in the periodic table, is overabundant in Ap stars; (iii) the heavy elements Ba, La, Ce, and Sm are overabundant in one Am star. It is known that the atmospheres of Am stars are structurally peculiar, with large turbulent velocities and low effective gravity, and there is still considerable controversy about whether these apparent abundance anomalies are real. In any case, they are much less pronounced than the anomalies in the Ap stars. Babcock (1958) found that six out of twenty-six Am stars had small magnetic fields, less than 500 gauss.

Recently, Sargent (1965) has discussed a group of stars—the λ Boo stars—that have long been known to be anomalous in having at the same time spectral types A and metal deficiencies similar to those in the old population II stars. The λ Boo stars also have small space velocities, as far as is known, and so do not appear to belong to an old stellar population. As will be seen in the following sections, on our present viewpoint for the theory of the abundance anomalies in Ap stars, we predict that there should be seen a class of stars similar to main-sequence A-type stars but having a low abundance of all elements relative to hydrogen. These would then be stars in which violent spallation, initiated by flare activity, would have occurred, wiping the slate clean, so to speak, prior to the contamination of the surface by the products of nuclear reactions in the interior. It is an interesting possibility, to which we return in the concluding § VIII, that the λ Boo stars are, in fact, these objects.

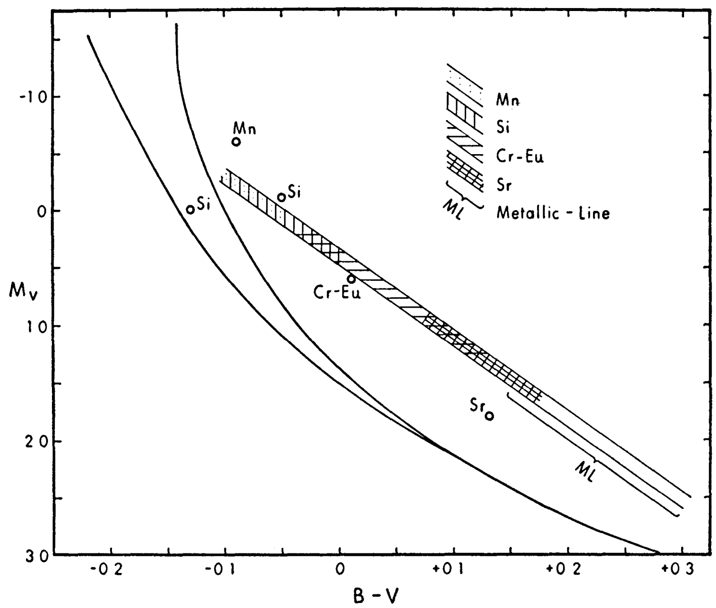

FIG 1—Schematic color-magnitude diagram, showing the Ap and Am stars. The left-hand curve represents Sandage's zero-age main sequence, and the right-hand curve, the Pleiades sequence. The band to the right of these is centered on Eggen's straight-line relation for the Ap and Am stars, but has been extended to the left of his termination at $B - V = 0$. No significance is to be attributed to the width of this sequence; there is actually a great scatter in the observations. The color limits of the different types of peculiarity marked on this sequence are taken from the Jascheks' work, as are also the open circles representing mean locations of the different types of peculiar stars. The left-hand Si point is their Si λ 4200 group, and the right-hand, their Si group. The colors of the Mn and Si stars obviously extend to the blue side of the termination of Eggen's sequence, but the sequence may diverge here, the Mn stars extending upward parallel to the normal main sequence, and the Si λ 4200 stars lying on the blue side of the normal main sequence.

In the following sections we shall be considering the abundance anomalies in detail. As an illustration of these, we have plotted in Figure 2 a schematic "normal" abundance-curve taken from the data compiled by Aller (1961), normalized to 10^{12} atoms of hydrogen. We have also marked on the curve the anomalous abundances in the Ap stars, normalized also to 10^{12} atoms of hydrogen, taking average values for the over- or under-abundance factors from the review by Sargent (1964). The lengths of the lines plotted for the various anomalous elements are meant to indicate a combination of the range of the anomaly and uncertainty in the determinations, but we emphasize that this plot is only schematic and should not be taken literally. For example, Ca, plotted as *under*-abundant by factors of 3–30, is probably normal in some Ap stars.

III. EVOLUTIONARY STAGE OF Ap STARS

There are many manifestations of nucleosynthesis in stars. We have shown (Burbidge, Burbidge, Fowler, and Hoyle 1957) that two different types of evidence for nucleosynthesis are present in stars: (1) evidence that nucleosynthesis has taken place in different degrees in the material out of which the stars condensed. The different abundances of the iron-peak elements in stars of old and young populations provide the best evidence of this kind; (2) evidence that element synthesis has gone on within individual stars since they were formed. The best evidence for this type of process is given by the compositions of the Ba II stars, the S stars, and the carbon stars, which show large overabundances of elements with isotopes which were synthesized through the *s*-process and the products of the He burning. It is obvious that a process of type (2) must be responsible for the compositions seen in the Ap stars, since, if (1) applied, other stars in galactic clusters containing Ap stars would have the same abnormal compositions.

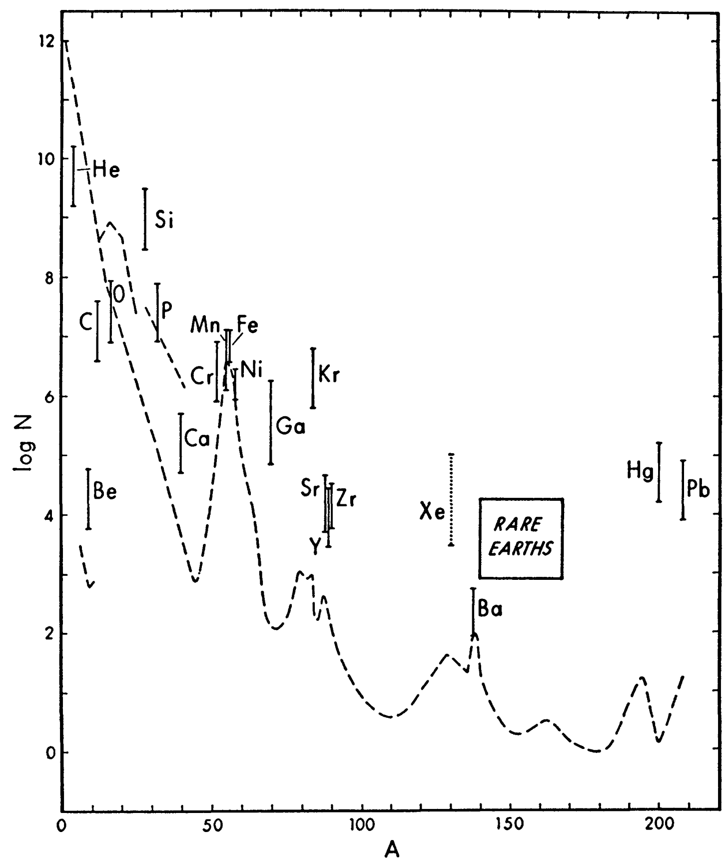

FIG. 2.—Schematic abundance-curve, indicating the elements that are anomalous in the Ap stars. The dashed lines represent the normal abundances, plotted against the atomic weight A, and the full vertical lines represent the anomalous abundances *in those types of Ap stars where those particular elements are in fact anomalous* (not all occur in all stars). The dashed line at Xe represents a guessed overabundance from the identification of this element in κ Cnc.

In earlier theoretical work on the nuclear physics of the production of anomalous abundances in magnetic stars (Burbidge and Burbidge 1955; Fowler, Burbidge, and Burbidge 1955; Burbidge, Burbidge, and Fowler 1958), we assumed that the Ap stars are somewhat evolved main-sequence stars lying in the region of the turnoff from the main sequence, with masses in the range 2–3 $M_\odot$. We then developed a theory for the production of anomalous abundances in a thin atmospheric layer by surface nuclear reactions, the energy for which came from the star's magnetic field. We postulated that large fluxes of protons were accelerated in spot regions in the surface and gave rise both to spallation in the highest levels and to a neutron flux through (p,n)-reactions lower in the atmosphere, and that these neutrons were captured to produce the overabundances of the heavy elements.

During this period, it was several times suggested to us by Bidelman that the Ap stars might, in fact, be at a much later evolutionary stage, subsequent to a red-giant phase (see, e.g., Bidelman 1960*b*). We maintained that the position of the Ap stars in the color-magnitude diagram and the differences in heavy-element anomalies between the S-type red-giant stars and the Ap stars (Ba overabundant in the former, Eu and Gd in the latter) were strong arguments against this possibility.

The recent observational work on overabundances of Ga, Kr, and Xe, and the enormous strength of Dy and Ho in HD 101065 (Przbylski 1963), while all other elements normally strong are vanishingly weak, have led us to reconsider the nuclear physics of the problem. Before we discuss this, we shall first consider the position of the Ap stars in the color-magnitude diagram and the bearing of this on their possible evolutionary stage.

There have been many papers discussing the location of the Ap stars in the color-magnitude diagram, and their magnitudes and colors as compared with those of stars of the same spectral type (see, e.g., Meadows 1962 and references given therein). The Ap stars are population I objects, and it has long been known that, when they are found in galactic clusters or moving groups, they tend to be the brightest members, lying in the region where the cluster main sequence departs a magnitude or so from the zero-age main sequence. This is not always so; two Ap stars in M39 lie to the right of the M39 main sequence but some way below the top of it, and of the two Ap stars in the Coma Berenices Cluster, both lie well to the left of the line defined by Eggen (Mendoza 1962). Jaschek and Jaschek (1958, 1962) have shown that, according to present evidence, the Ap stars are found in only those clusters whose main-sequence turnoff point is in the range of spectral type from mid-A to late B, i.e., in a narrow range of age, and, further, that the class of spectral peculiarity depends upon the age, so that the Si anomaly occurs in the youngest and hence most massive Ap stars and the Sr anomaly, at the other end of the sequence in Figure 1, in the oldest stars of this type. However, as mentioned in § II, the grouping of stars qualitatively according to the obvious anomalies may in some cases represent only temperature differences, and the same abundance anomalies are often present in more than one group.

We shall develop in the subsequent sections the theory that the Ap stars are indeed at a late evolutionary stage, having started as main-sequence A or B stars in the mass range 2–3 $M_{\odot}$, that they have evolved through a red-giant phase, and that they have returned to the general neighborhood of the main sequence following massive structural change and mixing according to the scheme described in § VI.

It becomes very important, therefore, to know the position of the Ap stars in the log L–log T_{eff} plane. That these stars have higher temperatures than indicated by their spectral types has been noted by many workers. Because of the large overabundances of the rare earths and the richness in lines of the rare-earth spectra, the Ap stars will suffer a greater blanketing effect than stars of normal composition in the same temperature range. The fact that, in Strömgren's *uvby* photometry, the Ap and Am stars can be picked out readily by their high m_1 indices (Strömgren 1963; Cameron 1964) shows that blanketing has an important effect. The blanketing effect, being greater in the blue than in the visual spectral regions, always shifts stars to the right in the color-magnitude diagram with respect to the line-free theoretical position. Since elements in the iron peak also are in general overabundant, they will also cause increased blanketing. The Ap sequence in Figure 1 is inclined at an angle to the observed main sequence; the point giving the Jascheks' mean value for the hottest Si stars lies just to the left of the observed main sequence. Blanketing corrections will be largest for the coolest stars, so that the tendency will be to change the slope of the Ap sequence.

Since we are arguing that the Ap stars are actually in a post–red-giant stage, and are the analogue among population I stars in this mass range of the population II horizontal branch stars, it will be important to know whether these stars with $B - V > 0$ will be moved, when blanketing corrections are applied, to the left of the main sequence. Baschek and Oke (1965) have determined the increase in blanketing in the Am stars in the Hyades, due to their spectral peculiarities, over the blanketing appropriate to that in the normal Hyades stars of the same temperature, and have found that they move to the left of the Hyades main sequence. In view of the possible connection between the Am and Ap stars, this is noteworthy. They also measured two magnetic stars. Sargent has pointed out to us that one of these, β CrB, may belong to the Hyades moving group, according to Eggen, and, if so, it lies at the top and slightly to the left of the Hyades evolved main sequence when its value of $B - V$ is corrected by Baschek and Oke for the difference in line blanketing between it and normal stars. The position of the A0p star 17 Com A in the color-magnitude diagram of Weaver (1952) lies already, with no blanketing corrections, to the left of the evolved main sequence. There is evidently considerable scatter in the positions of the Ap stars.

In the following sections we discuss the evolution of stars of 2–3 $M_\odot$ and the nuclear physics of processes which could produce the abundance anomalies in the Ap stars. We find it necessary for the stars to have had a very complicated evolutionary history so that (*a*) a vast amount of nuclear activity has occurred to subject the original material to spallation on a large scale; and (*b*) nuclear processes normally associated with rather advanced evolutionary phases have taken place in the interior and neutrons have been added at rates ranging up to a modified *r*-process.

The reasons for arguing that (*a*) has occurred stem from the abundances of the light elements and particularly helium. These are deficient, though the hydrogen content is normal. In stars in which a low helium abundance is seen we might suppose either that the material out of which the star condensed contained only the presently observed amounts of helium, or that the star is highly evolved so that the bulk of the helium and perhaps the C and O also have been burned. The argument against the first suggestion is that the He/H ratio is found in all normal stars where it can be determined to be approximately the same, ~ 0.1 and not ~ 0.01 or 0.001 as is found in these stars, and other stars presumably of the same genetic origin, e.g., the Sco-Cen stars in the case of 3 Cen, have this normal abundance of He. The argument against the second suggestion is that a highly evolved star will have burned its hydrogen also, and these stars are quite distinct from hydrogen-poor stars, such as υ Sgr, which have evolved in this way. The only possible explanation seems to be that the whole of the surface material seen now has been broken down and that at a later stage heavy elements that have been built in the interior have mixed to the surface.

To develop a complete theory we should proceed first by working out the astrophysical evolution of the stars, i.e., the variations in temperature, density, and geometrical distribution. This information, combined with the nuclear data, would solve the problem as far as the internal nucleosynthesis is concerned, but detailed stellar evolutionary computations have not been made for the post–red-giant stage. As far as the surface nuclear reactions are concerned the astrophysical conditions still remain unclear, since there is as yet no proper understanding of the mechanism by which very large fluxes of particles can be accelerated and we have not been able to make progress in this aspect in the present investigation.

Thus our emphasis throughout the present paper will be on the nuclear physics. We shall discuss first the nuclear processes required to account for the anomalies in the heavy-element regions and in the region of Si and the iron peak. We shall then turn to the astrophysical conditions required if this mechanism is to work. We shall next discuss the requirements for the surface spallation processes and then return again to the less certain astrophysics.

IV. NUCLEAR CONSIDERATIONS: THE *r*-PROCESS

In the following discussion we shall quote nuclear-reaction rates from the papers of Caughlan and Fowler (1962, 1964) and Fowler and Hoyle (1964). We begin with the following inferences: (i) the large abundance excesses of the rare earths demand a process of neutron addition; (ii) the process cannot be entirely slow; otherwise Ba would be in excess, which it is not, and Eu, Gd, Dy, and Ho would not be overabundant. This leads immediately to the further important inference that short time scales must be involved, and this suggests a connection with the "flash" of some nuclear fuel, the simplest possibility being the helium flash. Two serious questions immediately arise. The Ap stars lie close to the main sequence. How is this possible if evolution has become sufficiently advanced for the helium to be fired? What is the neutron source? Following our policy of dealing first with problems of nuclear urgency, we shall concentrate in this section on the second question and on its implications, returning to astrophysical problems in the next part of the paper. However, we shall make use of a new astrophysical concept at the present stage: that there may be several flashes, not just one. We shall also take account of a different view of the manner in which the flash occurs in a degenerate core. In the past it has been tacitly assumed that the flash begins at the center. Our view is that the first firing may occur *on the outside,* and that the core can simply peel away at its surface —in the sense of changing from degeneracy to non-degeneracy. We think it probable that convective motions accompany the transition from degeneracy to non-degeneracy, and that mixing, at any rate on a limited scale, of different samples of material can occur.

The possibility exists that C^{12}, produced in the flash itself, becomes mixed with a limited supply of protons. With $C^{12}(p,\gamma)$ $N^{13}(\beta^+)$ C^{13} occurring, a neutron source becomes established. There is no necessity for $C^{13}(\alpha, n)$ to occur at this stage, however. Since we are contemplating a series of temperature oscillations, the C^{13} may well be burned in a subsequent higher-temperature phase. By separating the building of the neutron source from its actual burning we acquire an extra degree of freedom in the problem.

In order to build heavy elements by neutron addition it is essential that the number of "seed nuclei" be much less than the number of neutrons—in fact we require of the order of 10^2 neutrons per seed nucleus. Since the number of neutrons cannot exceed the number of light nuclei, C, O, N, etc., it is clear that the latter must have very small neutron-capture cross-sections. This allows the iron-group elements to take over as the main seed nuclei. However, not all of the light nuclei have small capture cross-sections. Hence we require those light nuclei which do not have small capture cross-sections to be largely absent, or to become converted into nuclei that do have very small cross-sections.

So long as the temperature is not too high ($T_8 < \sim 4$), O^{16} is a "safe" nucleus from the present point of view, as are C^{12}, C^{13}, and C^{14}. The "dangerous" nucleus is N^{14}, because of $N^{14}(n,p)C^{14}$ with its very large cross-section. Provided C^{13} is in excess concentration above N^{14}, and provided the proton released in the (n,p)-reaction does not itself generate some further "dangerous" nucleus, neutron addition to appropriate heavy-seed nuclei occurs. At high temperatures the latter condition is difficult to meet—for example, one could have

$$C^{12}(p,\gamma)N^{13}(\alpha,\ p)O^{16}(n,\gamma)O^{17}(p,\alpha)N^{14}\ ,$$

regenerating N^{14}. By keeping the temperature down such a sequence is avoided; as already noted $O^{16}(n,\gamma)$ O^{17} is slow for $T_8 < \sim 4$, while for $T_8 < \sim 2$ the N^{13} decays to C^{13} instead of undergoing an (α,p)-reaction. Now for $N^{13}(\alpha,p)O^{16}$,

$$\log\ \tau_\alpha(N^{13}) = -16.6 - \log\ \rho x_\alpha + \tfrac{2}{3}\log T_9 + \frac{15.55}{T_9^{1/3}}\ . \qquad (1)$$

Under "flash conditions" we expect $\rho x_\alpha \simeq 10^5$ gm cm^{-3}, and for this particular helium density $\tau_\alpha(N^{13}) \simeq \tau_\beta(N^{13}) \simeq 10^3$ sec at $T_9 \simeq 0.22$. It seems then that for neutron addition to heavy seed nuclei the best conditions are (1) that proton addition to C^{12} should produce as much C^{13} as possible and as little N^{14}; (2) that neutron addition should take place before the temperature rises above $T_8 \sim 3$. We comment in turn on these requirements.

It is inevitable that, if C^{12} is mixed with an excess of protons, more N^{14} than C^{13} will be produced. The $C^{13}:N^{14}$ increases as $p:C^{12}$ decreases, and in fact the former ratio $\to \infty$ as the latter $\to 0$. But when $p:C^{12}$ is small the ratio $C^{13}:C^{12} \simeq p:C^{12}$ is also small. A consideration of this problem by Caughlan and Fowler (1962) and Caughlan (1965) has shown that, *provided the time scale for proton addition is long compared to* $\tau_\beta(N^{13})$, the ratio $C^{13}:C^{12}$ cannot exceed about 0.1 if $C^{13}:N^{14}$ is to exceed unity. In the present case, however, we can readily contemplate a short time scale, $<\tau_\beta(N^{13})$, since we are dealing with a flash situation. The rate of $N^{13}(p,\gamma)\,O^{14}$ is then slower than $C^{12}(p,\gamma)\,N^{13}$, because of the higher Coulomb barrier of the N^{13} nucleus. A considerably improved value of $C^{13}:C^{12}$ is thereby obtained, since N^{13} does eventually decay to C^{13}, but in this case after the process of proton addition is completed.

In a flash situation we expect the time scale of proton addition to be of the order of the radius of the degenerate core, $\sim 10^9$ cm, divided by the speed of the dynamic motions generated by the energy released in the flash. The latter could become comparable with the speed of sound in the material, $\sim 10^8$ cm sec^{-1}, so that time scales as short as 10 to 10^2 sec can certainly be contemplated. This is shorter than $\tau_\beta(N^{13}) \simeq 10^3$ sec.

Although there is nothing impossible in the conditions we are postulating, it is true that the conditions are special ones. There does not appear to us to be anything objectionable in this, because we are looking for a highly special nuclear situation. Only a modest fraction of the material of a star need experience a conversion of its iron-group elements to the rare earths in order that the abundances of the latter be increased by factors of $\sim 10^3$. We are therefore seeking a restricted subclass of all the conditions that occur in a highly complex situation. We are untroubled, for instance, by the requirement that the protons shall not be mixed in excess with C^{12}. Our point of view is that mixtures will be variable, that $p:C^{12}$ may be quite different in different samples of material—or indeed in different flashes—and that our interest lies in cases where this ratio happens to be not too large.

Two problems arise concerning condition (2). First, can we be sure that $C^{13}(\alpha,n)$ occurs fast enough for an r-process if the temperature is not permitted to rise above $T_8 \simeq 3$? The answer is plainly affirmative since $\tau_\alpha(N^{13}) \sim 10^3$ sec at $T_8 \simeq 2$, and $\tau_\alpha(C^{13})$ must certainly be less than $\tau_\alpha(N^{13})$ because the Coulomb barrier for C^{13} is lower than for N^{13}. In fact

$$\log \tau_\alpha(C^{13}) = 15.7 - \log \rho x_\alpha + \tfrac{2}{3} \log T_9 + \frac{14.0}{T_9^{1/3}}, \tag{2}$$

so that

$$\log \frac{\tau_\alpha(C^{13})}{\tau_\alpha(N^{13})} = +0.9 - \frac{1.55}{T_9^{1/3}}, \tag{3}$$

and C^{13} burns nearly 10^2 times faster than N^{13} at $T_8 \simeq 2$. The time scale for $C^{13}(\alpha,n)$ is only ~ 1 sec at $T_8 \simeq 3$.

On such a short time scale it is unlikely that the energy released by $C^{13}(\alpha,n)$ can be transported away, the energy remains *in situ* and raises the temperature. How much C^{13} can be burned before the temperature rises above 3×10^8 ° K? The answer to this question sets a limit to the number of neutrons that can be used in the building of the rare earths, since the N^{14} difficulty comes into operation if the temperature rises higher than this. With the temperature rising as the flash proceeds the r-process must be confined to the stages at which the temperature is less than $T_8 \sim 3$.

It is easily shown that, when C^{13} is present, flash conditions are triggered by the C^{13}, rather than by $3\alpha \rightarrow C^{12}$. For the latter reaction we have that

$$\log \tau_{3\alpha}(\mathrm{He}) = 9.25 - 2 \log \rho x_{\alpha} + 3 \log T_9 + \frac{1.875}{T_9} . \quad (4)$$

Thus for $T_9 = 0.1$, $\rho x_{\alpha} = 10^5$ gm cm^{-3}, and equation (2) gives $\tau_{\alpha}(C^{13}) \simeq 5 \times 10^7$ sec, whereas equation (4) gives $\tau_{3\alpha}(\mathrm{He}) \simeq 10^{15}$ sec. In addition to the energy released by $C^{13}(\alpha,n)\,O^{16}$, $+2.214$ MeV, we must remember that the subsequent capture of the neutron released in this reaction yelds $\sim$8 MeV. Evidently, each C^{13} nucleus gives a net energy yield of $\sim$10 MeV. To raise the temperature from $T_8 \sim 1$ to $\sim$3 requires every particle to increase its kinetic energy by $\sim$25 keV. Most particles in the thermal assembly are electrons, and there is an electron:nucleon ratio of about 0.5. The nucleons are of course almost entirely bound in such nuclei as He^4, C^{12}, C^{13}, . . . , the heavy particles contributing little to the thermal energy. It follows that some 15 keV per nucleon is required to lift the temperature by the above amount. One C^{13} reaction per 700 nucleons gives $\sim$15 keV per nucleon. Hence we expect about 1 neutron per 10^3 nucleons to be produced by C^{13} burning before the temperature rises too high for the operation of an *r*-process. We proceed next to investigate the consequences of this important conclusion.

Recalling that in the abundance scale with Si $= 10^6$ the total number of nucleons $\sim 6 \times 10^{10}$, a neutron production of 1 per 10^3 nucleons corresponds to $\sim 6 \times 10^7$ neutrons, or 60 neutrons per Si. Since the silicon abundance is about twice that of the iron group we have $\sim 10^2$ neutrons per iron-group nucleus, correct for building to atomic weights of 150–160. We actually need 100–150 neutrons per iron-group nucleus in order to build Dy, Ho, Hg, and Pb. Then neutron production will be sufficient for

$$\mathrm{Mg, Si} \rightarrow \mathrm{Ga, Kr}\ ;$$

$$\mathrm{Fe} \rightarrow \text{Rare earths, Hg, Pb}\ .$$

Calculations of the heavy-element abundances for different time scales and supplies of neutrons have been made by Seeger, Fowler, and Clayton (1965). It may be noted that the calculations made by using a mass law containing deformation terms lead to a hump between $A = 145$ and $A = 180$.

For each of the elements Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy, we have taken the mean of the overabundances listed in Table 1 for the stars α^2 CVn, HD 133029, β CrB, and γ Equ, which have nearly complete lists of values for these elements. The overabundances have been multiplied by the standard abundances of Aller (1961) to give the mean absolute abundance on the hydrogen $= 10^{12}$ abundance scale. We have then divided the mean abundance of each element by the number of isotopes for that particular element that can be made by a process of fast neutron addition, according to Burbidge *et al.* (1957). The resulting values of the logarithm of the abundance per isotope are plotted against the atomic weight A in Figure 3. The smoothness of the plot from Nd to Dy is striking.

In addition to this fast buildup, we expect an appreciable number of neutrons to be acquired by seed nuclei *under rather slow conditions*. It is true that the final stages, as the temperature rises above $T_8 = 2$, are rapid, but $\tau_{\alpha}(C^{13})$ is very temperature-sensitive. A quarter of the neutrons are released below $T_8 = 1.5$ and at this temperature $\tau_{\alpha}(C^{13}) \simeq 10^5$ sec. Plainly, we have a curious combination of the *s*-process and the *r*-process. A considerable number of neutrons are captured under conditions that approximate to the *s*-process. It is only in the last stages that neutrons are made available under the conditions of the *r*-process. The *s*-process builds the well-known peaks at Sr, Ba. Then, exposed to a rapid flux of neutrons, these peaks are displaced to higher atomic weights. This process meets with two major successes. It explains the general dominance of the rare earths, and it explains the absence of a Ba overabundance. There are also the observed overabundances in the Sr, Y, Zr peak to be explained. It is possible that for some samples of material the C^{13} abundance is too low to give as many as 1 neutron per 10^3 nucleons. With, say, $\sim$30 neutrons per Fe nucleus the Sr peak would be reached, but the energy released would not be sufficient to bring on the *r*-process. We would remain in the *s*-process. The essential difference between Sr, Y, Zr, and Ba could well be that building the Sr peak does not release sufficient heat to bring on the *r*-process, whereas building the Ba peak does.

The possibility that the release of neutrons may not be sufficient to bring on the *r*-process has a further very interesting consequence. Neutron addition to Si^{28} follows the sequence,

$$Si^{28}(n,\gamma)Si^{29}(n,\gamma)Si^{30}(n,\gamma)Si^{31}(\beta^-, 4\text{ sec})P^{31}(n,\gamma)P^{32}$$

$$(\beta^-, 21\text{ days})S^{32}(n,\gamma)S^{33}(n,\alpha)\,Si^{30}\,.$$

Not all material will pass through the extreme conditions of a flash; there will be some material lagging behind, and in this a Si-P-S cycle can be established. *We think the excess P concentration found in κ Cnc, for example, could be produced in this way, and we would predict an excess concentration of* Si^{30} *in such stars.*

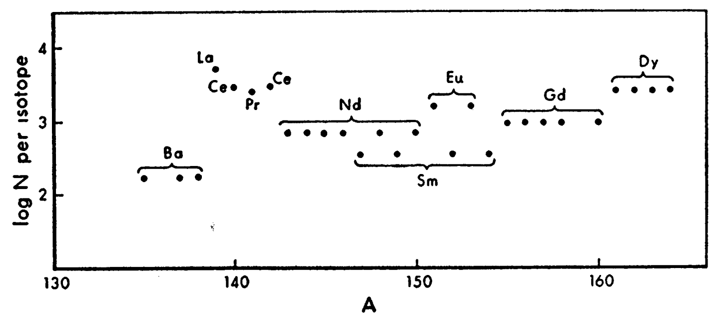

FIG. 3.—The mean of the individual values for the stars α^2 CVn, HD 133029, β CrB, and γ Equ, of the logarithm of the abundances of Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy, divided by the number of isotopes produced by a process of rapid neutron addition, plotted against atomic weight A. For each element, the number of dots is the number of such isotopes.

In the opposite direction, the C^{13} could be sufficient to give far more than 1 neutron per 10^3 nucleons. For an equal mixture of helium and carbon it is possible to contemplate ratios such as $He^4:C^{12}:C^{13} \simeq 3:1:0.2$, in which case we have one C^{13} to $\sim 10^2$ nucleons, yielding 1 neutron per $\sim 10^2$ nucleons. The first 10 per cent would then be burned in the manner considered above, but the burning of the remaining C^{13} would lift the temperature to $T_9 \simeq 1$. Neutrons would be made available extremely rapidly but would be mainly captured by light nuclei. Other processes come into operation at $T_9 \simeq 1$, which we consider in the next section.

V. FURTHER NUCLEAR CONSIDERATIONS: SILICON AND THE IRON-GROUP ELEMENTS

We now consider the effect of the release from $C^{13}(\alpha,n)\,O^{16}$ of one neutron per 10^2 nucleons. In § IV we saw that a release of 1 neutron per 10^3 nucleons was sufficient to increase the temperature by $\sim 10^8$ degrees. Now, however, the temperature rises catastrophically by $\sim 10^9$ degrees. At such temperatures the light elements are converted rapidly (<1 sec) by α-particle addition to heavier elements, for example:

$$C^{12}(\alpha,\gamma)O^{16}(\alpha,\gamma)Ne^{20}(\alpha,\gamma)Mg^{24}(\alpha,\gamma)Si^{28}\ldots .$$

The total energy release in material with approximately equal concentrations by mass of helium and carbon is $\sim 10^{18}$ ergs gm^{-1}. Thus, since

$$\frac{\Re T}{\mu}+\frac{aT^4}{\rho}\simeq 10^{18},$$

it is easily shown that when $\rho = 10^5$ gm cm^{-3}, $\mu = 2$, the temperature is raised to $T_9 \simeq 2$. Hence a high C^{13} concentration, yielding 1 neutron per $\sim 10^2$ nucleons, can bring on a catastrophic situation in which the light elements are entirely scoured out and in which the temperature is raised so high that photonuclear effects become important. For T_9 somewhat above 2, all nuclei except Si^{28} become unstable to photonuclear effects. It is of interest to consider what happens in such a situation. We consider two cases: (i) There are insufficient α-particles to convert all the light elements to Si^{28}; (ii) the He:C ratio is such that (α,γ)-reactions convert the whole of the light elements to Si^{28}, some helium being left over.

In case (i) more α-particles are simply made available by the photodisintegration of C^{12}, until the whole of the material is built to Si^{28}. Case (i) leads to Si production alone. In case (ii) we have to consider the fate of the excess helium. The α-particles certainly do not remain free. They attach themselves to silicon nuclei, but, with nuclei heavier than Si^{28} also subject to photodisintegration, the attachment is not permanent. Clearly, we expect the system to shuffle itself into a lowest energy state, and this does not consist of adding an α-particle to every Si^{28}. Instead it is preferable, from an energy point of view, to add a number of α-particles to a fraction of the silicon nuclei, so that a mixture of Si^{28} and of iron-group nuclei are produced. What ratio of silicon to iron group do we expect?

Write r for the mass ratio of He^4 to C^{12}, assuming for simplicity that initially the whole of the material is helium and carbon. Then *by number* $He^4:C^{12}$ is initially $3r:1$. In order that we have case (ii), r must exceed $\frac{4}{3}$. Suppose further that the outcome of the (α,γ)-reactions is a simple mixture of Si^{28} and Ni^{56}. Then it is easy to see that $4\ Si^{28} + 11\ Ni^{56}:Si^{28} + Ni^{56} = 3r:1$, so that $Ni^{56}:Si^{28} = 3r-4:11-3r$. We are concerned here with values of r not much greater than unity. For example, for $r \sim 1.5$, iron group:silicon $\simeq 1:10$.

These considerations are evidently of interest in relation to Ap stars with excess Si, and with abnormal distributions of the iron-peak elements. In the latter connection, we note that the presence of the neutrons affects the details of the abundances in the iron peak. Because the neutrons are more strongly bound in the iron peak than they are in $Si^{28}(n,\gamma)\ Si^{29}(n,\gamma)\ Si^{30}\ldots$, by ~ 1 MeV per neutron, we expect the neutrons to join the iron-peak nuclei and not the silicon. With 1 neutron to 10^2 nucleons, and with Si:Fe group $= 10:1$, say, we have about 3 neutrons per iron-peak nucleus. The parameter R used by Clifford and Tayler (1965), which determines the details of the abundances of the iron-group nuclei, is then about 0.94, and the abundance details are substantially different from those found in solar-system material, with Fe^{54} and Ni^{58} the most abundant nuclei. After a flash in which these nuclei are produced it is possible that mixing with protons could lead to $Fe^{54}(p,\gamma)\ Co^{55}(\beta^+)\ Fe^{55}(\beta^+)\ Mn^{55}$. It is plausible that excess Mn could be produced in this way. The old suggestion of a *surface* spallation of Fe^{56} to give Mn^{55} (Burbidge and Burbidge 1958) now seems less likely to us, partly for reasons that will be given in the last section, and partly because spallation would produce a spreading of the width of the iron peak, as well as a reduction of the mean atomic weight. It is then difficult to see why V should not be greatly enhanced, since the normal vanadium abundance is very low compared to that of Cr and Fe.

VI. ASTROPHYSICAL CONSIDERATIONS: DEGENERATE CORES

The necessity for short time scales points toward the importance of degenerate cores. At this stage we wish only to discuss the properties of such cores, without prejudice to the precise way that they may enter the problem of the Ap stars.

It is known that, if a degenerate core grows to a certain mass, typically about 0.5 $M_\odot$, it becomes almost catastrophically unstable; of the order of the gravitational energy, $\sim 5 \times 10^{16}$ ergs/gm or $\sim 10^{50}$ ergs in total, is released quickly by nuclear processes, and the core becomes wholly, or partially, non-degenerate. In view of this nuclear energy release, it would be surprising if considerable mixing of elements of material from different parts, core and envelope particularly, did not take place in some degree. It does not seem at all unreasonable that in some cases mixing might be violent enough for material from the inner regions to arrive at the extreme surface of the star.

Following the exhaustion of hydrogen at their centers, stars of solar mass develop degenerate cores. It is also known that much more massive stars do not develop such cores. The difference is due to the shape of the $X(M)$-curve at the moment of exhaustion of the central hydrogen. In Figure 4 we show the two characteristically different forms of this curve. The difference is caused by the convective cores of massive stars that persist through a considerable inner region until the central hydrogen falls almost exactly to zero. This causes the helium core of a massive star to grow very rapidly, releasing so much gravitational energy that the helium is fired before degeneracy can set in.

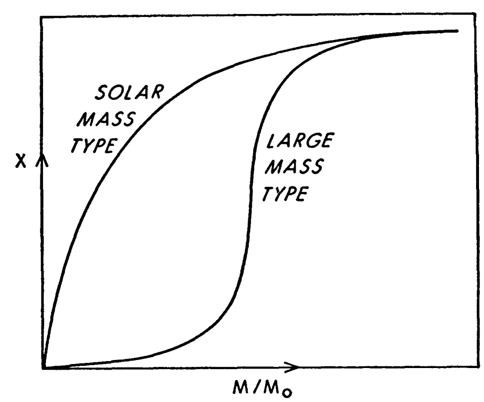

FIG. 4.—Schematic representation of the shape of the $X(M)$-curve at the moment of exhaustion of the central hydrogen, for stars of solar mass and for stars of large mass (M_0 = mass of star).

Stars of type A are intermediate between these cases. We shall *postulate* that degenerate cores arise in them. In principle, it is possible to decide this question by computing a sequence of evolutionary models. Great care is necessary, however, in treating the very last stages of exhaustion of the hydrogen. We are not convinced that sufficiently reliable results are available at the present time to decide whether degeneracy arises in A stars or not. Our postulation is that the Ap stars are the largest masses for which degeneracy occurs (immediately after hydrogen exhaustion, not at more advanced phases of evolution).

A star with a degenerate core of appreciable mass ($>0.3\ M_\odot$, say) surrounded by a hydrogen-burning shell must take up a giant structure, unless the core is passing through a transient phase, defined by the condition that the rate of generation of energy by nuclear processes is large (or small) compared to the luminosity, so that the rate of storage of gravitational energy is large in magnitude compared to the luminosity. So long as the rate of energy generation is closely equal to the luminosity, the giant structure has the following properties:

a) The radius of the core is $\sim 10^9$ cm. Degeneracy ceases when $\rho \approx 3 \times 10^{-8}\ T^{3/2}$ gm cm^{-3}, a relation which, for $T \approx 5 \times 10^7$ degrees, gives $\rho \approx 10^4$ gm cm^{-3}.

b) Nuclear energy comes from hydrogen burning. It does not seem as if giant models can exist for cores surrounded by energy-producing shells except in the case where the nuclear fuel is hydrogen.

c) The hydrogen does not begin at the place where the material first becomes non-degenerate in the outer parts of the core. The density at the commencement of the hydrogen burning is ~ 10 gm cm^{-3}, so that nearly 10 scale heights of core material surround the degenerate portion of the core. Since the scale height $\sim 10^8$ cm, this non-degenerate exterior also has a radial extent of $\sim 10^9$ cm. Although the non-degenerate exterior has dimensions comparable to the degenerate portion, it has considerably less mass, $\sim 4\pi r_c^2 H \rho_1$, where H is the scale height and ρ_1 is the density, $\sim 10^4$ gm cm^{-3}, defining the cessation of degeneracy. This is $\sim 10^{31}$ gm ($10^{-2} M_\odot$). In spite of this comparatively small mass the non-degenerate portion of the core plays a critical role in providing a high opacity. Gravitational energy released in the degenerate part of the core makes its way through the non-degenerate region of high opacity, causing a temperature difference to exist between the degenerate part of the core and the outer hydrogen-burning zone. The temperature of the latter is $\sim 4 \times 10^7$ degrees, and hence the core temperature always exceeds this.

d) The outer hydrogen zone can also be divided into two parts, an inner part in which $T \propto r^{-1}$ approximately and $\rho \propto T^3$, which extends out to $r \approx 10^{11}$ cm, and an outer convective zone extending essentially to the photosphere of the star. Hydrogen burning takes place in the inner part, in a shell of thickness $\sim 10^9$ cm immediately surrounding the core.

e) The inner part of the hydrogen zone contains comparatively little mass, $\ll M_c$ in a typical giant. The remaining mass of the star, $\sim(M - M_c)$, is stored in the outer convective part.

f) The star evolves by passing hydrogen from the outer convection zone through the inner zone—the hot bubble region—to the core. As the hydrogen moves through the extreme inner part of the bubble, hydrogen burning takes place and it is as helium that material arrives at the core.

g) The luminosity L is determined essentially by M_c, with $L \propto M_c^{\sim 8}$. There is only a slight dependence on the remaining mass, $(M - M_c)$.

h) The radius R is also mainly determined by M_c. There is, however, some dependence on $M - M_c$. The giant sequence for $M = 3\, M_\odot$ lies to the left of that for $M = M_\odot$, but not greatly so, not more than the difference, say, between the Hyades giants and a typical M giant.

It must be emphasized that all these conclusions are dependent on the carbon-nitrogen cycle being operative in the hydrogen-burning zone. If the CN cycle became suppressed, for example, due to a sequence of events in which the elements C, N, O were converted to heavier nuclei, the structure would be entirely changed. Indeed the interior would probably behave like a helium star in such a case. However, the exterior envelope of hydrogen, with mass $\sim 2\, M_\odot$, would cause the star to lie considerably further to the right in the H-R diagram than the region occupied by pure helium stars (which is appreciably to the *lejt* of the usual main sequence). Probably the star would take up a position not far from the usual main sequence.

It is important to understand how it comes about that in the case of hydrogen burning on the CN cycle, degenerate cores become unstable. Write F for the flux out of the degenerate portion of the core. We have

$$\tfrac{1}{3} a c \frac{dT^4}{dr} = -\kappa \rho \frac{F}{4\pi r^2} \quad \text{and} \tag{5}$$

$$\frac{\mathfrak{R}}{\mu} \frac{d}{dr}(\rho T) = -g\rho \tag{6}$$

contribution to F as well as a nuclear contribution. Suppose *initially* that the nuclear contribution from the core is small and can be neglected. We have

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scattering, and M_c in solar units, we find

$$[T^4] = 8.87 \times 10^{-41} \frac{F}{M_c} [\rho T] ,$$

where square brackets represent the difference of values between the inner and outer boundaries of the non-degenerate portion of the core. Evidently ρ is small at the outer boundary, so that ρT may be taken at the inner boundary, denoted by subscript unity. We have

$$T_1^4 - T_H^4 = 8.87 \times 10^{-41} \frac{F}{M_c} \rho_1 T_1 , \quad (8)$$

in which T_H is the temperature at the outer boundary, i.e., at the beginning of the hydrogen. Also $\rho_1 \approx 3 \times 10^4 T_1^{3/2}$, this being just the defining condition for degeneracy (N.B. $\mu_e = 2$ for helium). So

$$T_1^4 - T_H^4 = 2.66 \times 10^{-36} \frac{F}{M_c} T_1^{5/2} . \quad (9)$$

Suppose for the moment that F is determined by nuclear processes within the degenerate material. Then F is given by

$$F_{nuc} = \int_0^{M_c} \epsilon(\rho, T) \, dM , \quad (10)$$

$\epsilon(\rho,T)$ being the energy generation per unit mass. Also, with M_c fixed, ρ is a known function of M. And because of electron conductivity the temperature is approximately uniform, so long as conditions are steady, i.e., the time scale long. So $T \approx T_1$ and F_{nuc} is evidently a function of M_c and T_1. Substituting $F_{nuc}(M_c,T_1)$ in equation (9), it is clear that with M_c specified this equation can be solved for T_1. There is only one such solution, because F_{nuc} increases monotonically with T_1. Hence we see that for a core of given mass there is just one core temperature that gives steady conditions, $T_1 = T_1^*$, say. Should T_1 be less than T_1^*, the core cools down; should T_1 be greater than T_1^*, the core heats up. In the latter case the right-hand side of equation (9) is greater than the left-hand side (with F given by eq. [10]). Since F_{nuc} increases far more steeply with T_1 than T_1^4 it is clear that the imbalance increases. Evidently the core continues to heat up, *and this will go on so long as degeneracy persists.* For energy production in helium burning the critical temperature turns out to be $T_1^* \approx 8 \times 10^7$ degrees. For carbon burning the temperature would be approximately ten times higher.

So far we have not included the contribution to F of the gravitational energy of core formation. Because helium is constantly being added to the core, i.e., because material is flowing from an outer convective region of small gravitational potential to the core where the gravitational potential is high, $\sim 10^{17}$ ergs gm^{-1}, there must be a gravitational contribution to F as well as a nuclear contribution. Suppose *initially* that the nuclear

$6 \times 10^{18} X$ ergs gm^{-1} is the energy release in hydrogen burning, so that $L/(6 \times 10^{18} X)$ is the mass added to the core per second, L being in ergs sec^{-1}. Neglecting F_{nuc} and substituting F_{grav} for F in equation (9) gives

$$T_1^4 - T_H^4 = 4.44 \times 10^{-38} \frac{L}{XM_c} T_1^{5/2}. \quad (12)$$

Since $L \propto M_c^{\sim 8}$, it is clear that the right-hand side increases steeply with M_c. For sufficiently large M_c the solution of equation (12) for T_1 increases to T_1^*, at which nuclear processes take control. The core temperature rises until non-degeneracy occurs. For X of order unity the value of M_c giving $T_1 = T_1^*$ turns out to be $\sim 0.5\ M_\odot$. If we substitute $T_1 = T_1^* \approx 0.8$, $XM_c = 0.5$, equation (12) gives $L \approx 8 \times 10^{36}$ ergs sec^{-1} $\approx 2 \times 10^3\ L_\odot$, which corresponds to a bolometric magnitude of -3.5, about that at the tip of the observed giant sequences.

Having now understood why gravitational energy serves as a trigger that can cause a nuclear fuel to "flash," we find that an interesting problem of stability arises. To expand the core to a non-degenerate state, essentially the whole of the gravitational energy must be supplied by the nuclear processes, $\sim 10^{17}$ ergs gm^{-1} for 0.5 $M_\odot$, or about 10^{50} ergs, requiring the burning of $\sim 10^{32}$ gm of He. Plainly, a slight excess of energy production would be sufficient to shatter the star. The question therefore arises as to whether the nuclear reactions remain in control at the moment of expansion, i.e., at the moment that density and temperature are related by $\rho \approx 3 \times 10^4\ T_8^{3/2}$. This latter equation should be read as an equation for T_8, the temperature that material of specified ρ must rise to in order to become non-degenerate. For $M_c \approx 0.5\ M_\odot$ the central density $\sim 10^6$ gm cm^{-3}, so that the corresponding $T_8 \approx 10$, and at this density and temperature helium burning is quite out of control. Thus the time scale for expansion of heated, non-degenerate material is given by dividing the core radius $\sim 10^9$ cm by the speed of sound, which for $T_8 \approx 10$ is $\sim 3 \times 10^8$ cm sec^{-1}; the time scale is thus ~ 1 sec, and this is close to the lifetime of the helium. Hence complete instability is to be expected if the "flash" starts at the center. Stability would seem to require that the flash begin in the outer part of the degenerate core. For example, if the flash began with $\rho \approx 10^5$ gm cm^{-3}, the corresponding value of T_8 would be only ~ 2, and at this temperature the lifetime of the helium is much greater than the time scale for expansion. This situation is very sensitive to the density of the material in which the flash first begins.

There are indeed good reasons why the flash begins in the *outer part* of the core. The argument is not elementary, and we begin by considering the adiabatic relation for *non-relativistically* degenerate material. Accurately, $P = 2\ U\rho/3$, and since $dU + PdV = dQ = 0$,

$$\frac{dU}{U} = \frac{2}{3} \frac{d\rho}{\rho}, \qquad \text{i.e.,} \qquad U = \rho^{2/3}, \qquad P \propto \rho^{5/3},$$

for adiabatic changes. Now for non-relativistic degeneracy P can be expressed in the form

$$P = A \rho^{5/3} \left[1 + \frac{5\pi^2}{12} (\log \Lambda)^{-2} + \ldots \right], \quad (13)$$

where A is a constant ($K_1\ \mu_e^{-5/3}$) and $\log \Lambda$ is given by

$$\log \Lambda = \frac{mc^2}{kT} [(1 + x^2)^{1/2} - 1] \approx \frac{mc^2 x^2}{2kT} \qquad \text{if} \qquad x^2 \ll 1. \quad (14)$$

Here $\log \Lambda$ must be $\gg 1$ for degeneracy to apply, and x is defined by

$$\frac{\rho}{m_H \mu_e} = \frac{8\pi}{3} \left(\frac{mc}{h} \right)^3 x^3 \approx 6 \times 10^{29} x^3. \quad (15)$$

At the highest density in question, $\rho \approx 10^6$ gm cm^{-3}, $\rho/m_H\mu_e = 3 \times 10^{29}$, so that $x^3 \approx \frac{1}{2}$. At the lowest density, $\rho \approx 10^5$ gm cm^{-3} and $x^3 \approx \frac{1}{20}$. Cessation of degeneracy corresponds to $\log \Lambda \approx 1$.

Evidently $\log \Lambda$ remains constant for adiabatic changes, so that the temperature varies with density according to

$$T \propto (1 + x^2)^{1/2} - 1 , \qquad (16)$$

with x related to the density by equation (15). In the case $x \ll 1$, $T \propto x^2 \propto \rho^{2/3}$, which is the same as the adiabatic relation for a non-degenerate gas consisting of mass points. In the case $x \gg 1$, $T \propto x \propto \rho^{1/3}$. Clearly then, T increases under adiabatic compression only slowly with density.

Consider the situation at the center of the degenerate core. The temperature is close to T_1. This could not be the case if adiabatic compression were the only agency whereby the central temperature could be raised. The central density behaves as about M_c^2 so that adiabatic compression could not lift the temperature, as M_c increased, faster than $M_c^{4/3}$. Yet T_1 increases much faster than this as T_1 approaches T_1^*. With $T_H^4 \ll T_1^4$ in equation (12) we have

$$T_1^{3/2} \approx 4.44 \times 10^{-38} \frac{L}{XM_c} \qquad (17)$$

and with $L \propto M_c^{\sim 8}$ it is clear that $T_1 \propto M_c^{\sim 5}$. The center can keep step with the temperature in the outer part of the degenerate core only *through an inward flow of heat*. The gravitational energy is very largely released in the outer part of the core. Heat flows inward as well as outward. To promote the inward heat flow it is necessary that the central temperature be lower than the temperature further out. The amount by which it is lower depends on the electron conductivity. Although the conductivity may be high, there is always a temperature lag at the center, and this becomes especially pronounced as the heating process speeds up toward the flash. Because the nuclear reactions are very sensitive to temperature for $T_8 \approx 1$, it seems possible that the flash will not occur at the center, even though the higher density at the center would certainly favor the central material if the core were accurately isothermal. The central temperature lag may well be sufficient to overcome this density advantage. The fact that stars near the tip of the giant branch are not observed to explode catastrophically suggests that flash conditions do not occur first at the center. (*Note added in proof.*—Recent computations by Mr. P. Eggleton have shown that the heat released through adiabatic compression of the positive ions is sufficient to make the helium flash occur at the center of a degenerate core of mass $\sim 0.5\, M_\odot$, rather than in the outer parts of the core. However, these computations did not include the cooling effect of neutrino emission, which is strongest at the center. Preliminary estimates suggest that inclusion of neutrino losses may well lead to the situation envisioned in the text, with the flash at the outside, not at the center.)

If the flash occurs at the outside, say, in the outer 10 per cent of the mass of the core, this outer part will simply peel away, leaving the inner 90 per cent still degenerate. The whole core will not pass from degeneracy to non-degeneracy in the short time scale of the actual flash. Instead the outer 10 per cent or so will be impelled outward and will join the hydrogen-burning shell. It is at this stage that mixing of C^{12} with protons could occur, *and in the proper ratio of about 1 proton per C^{12} nucleus.* To see this we note that the total mass of hydrogen in the shell is quite small, and the density ρ depends on central distance about as $1/r^3$, $\rho \approx 10\,(2 \times 10^9/r)^3$ gm cm^{-3}, so that the mass of the shell between r_c and r ($r > r_c$) is $\sim 10^{30} \ln (r/r_c)$ gm. Even for r much greater than the radius of the core, $r_c \sim 2 \times 10^9$ cm, the mass of hydrogen is not much greater than 10^{30} gm. This must be compared with the mass of C^{12}. To expand the degenerate material against the gravitational field of the core a release of $\sim 10^{17}$ ergs gm^{-1} is needed, which requires a 10 per cent conversion of helium to carbon. Hence if the mass expanded is 10 per cent of the whole core, viz., 0.05 $M_{\odot} = 10^{32}$ gm, the mass of C^{12} is $\sim 10^{31}$ gm. This C^{12} mixed with $\sim 10^{30}$ gm of hydrogen corresponds to ~ 1 proton per C^{12} nucleus. The time scale for the mixing is just that of the expansion of the core material, which could be as short as 10–10^2 sec, i.e., short compared to $\tau_\beta(N^{13})$. Hence it is possible that conditions of the kind described in the previous section as the most appropriate for the building of C^{13} do indeed occur at this stage of the star's evolution.

During the early stages of the flash, when T_1 is not much above T_1^*, the energy generation rate in the helium is only 10–10^2 ergs gm^{-1} sec^{-1}, and the time scale for the early stages is 10^{12}–10^{13} sec. In the late stages of the flash, on the other hand, the temperature rises well above $T_8 = 1$, even for a flash not at the center of the core. A reasonable value for a flash in the outer part of the core would be $T_8 \simeq 2$, and at this temperature the energy generation rate is $\sim 10^{12}$ ergs gm^{-1} sec^{-1}, so that the final stages develop in a time scale of less than a day. The degeneracy criterion $\rho \approx 3 \times 10^4\, T_8^{3/2}$ gm cm^{-3} contains the same proportionality $\rho \propto T^{3/2}$ as does the adiabatic condition both for degenerate material (in the case $x^2 \ll 1$) and non-degenerate material. Since passage from degeneracy to non-degeneracy is likely to take place at densities not much higher than 10^5 gm cm^{-3}, when x^2 is indeed $\ll 1$, it follows that passage from degeneracy to non-degeneracy is likely to be accompanied by rapid convection, which can well be associated with the mixing described in the preceding paragraph.

We next are concerned with conditions after the flash. Does the region outside the remaining part of the core settle back to a steady-state condition with the luminosity balanced by nuclear-energy generation? Or does the flash penetrate deeper into the degenerate material causing the core eventually to become wholly non-degenerate? A decision between these alternatives must await detailed computations. Our suspicion is that time scales favor the first possibility. Thus the time scale required for setting up the steady-state exterior condition is given by E/L, where E is the energy released in the flash. With $L \simeq 10^{37}$ ergs sec^{-1}, and $\sim 10^{49}$ ergs as the energy released in the flash, we obtain $\sim 10^{12}$ sec, which is probably rather less than the time scale for the development of a flash in the remaining portion of the core.

In the former case the core will simply reform by adding again the material which left it at the time of the flash. A second flash must then inevitably occur, but with C^{13} as nuclear fuel. The conditions would indeed be close to those considered in § IV. In the latter case the core dissipates itself through repeated flashes. These have somewhat similar properties to the requirements described in § IV, but the physical conditions are not as close as we would like, since the C^{13} would not rejoin the degenerate material. Because the time scales for the two cases are rather comparable, it is possible that in some stars one possibility arises and in other stars the other possibility. If the C^{13} does not rejoin the degenerate material, neutrons from C^{13} (α,n) would very likely be released under s-process conditions only, in which case we would expect an enhancement of Ba along with the rare earths (Caughlan and Fowler 1964). It is an interesting suggestion that the difference between the evolution of the Ap stars and the Ba II and S stars may turn on this question, on whether C^{13} rejoins the degenerate material or not.

VII. SPALLATION AT THE SURFACE

In the original investigations of the compositions of these stars we argued that all of the abundance anomalies were produced by nuclear reactions on the surface. We have in the previous sections given a schematic account of the way in which the overabundances of the heavier elements can be produced by neutron addition in the interior. However, we have not been able to find any internal nuclear processes that will account for the underabundances of He, C, and O, and conclude that these must have come about through surface spallation. The most stringent conditions on the extent of the spallation are derived from the observational result that the helium is generally underabundant (Sargent and Searle 1964) and that in the case of 3 Centauri, as well as the abundance of

He being low, the ratio of He^3:He^4 is $\sim$4:1. We shall therefore discuss in this section the conditions which are necessary to attain this helium composition.

We suppose that a flux of energetic protons is accelerated and that the He^4 is broken up. Neutrons that are captured combine almost entirely with H to give D. A small fraction of these neutrons would be captured by heavier elements provided that these heavier elements could survive the intense activity that is required to spall the He^4. Such a mechanism of neutron capture with neutrons arising following (p,n)-reactions at the light abundant elements was originally proposed (Burbidge and Burbidge 1955; Fowler *et al.* 1955) to explain the overabundances of Sr, Y, and Zr, and the rare earths. A weakness of this scheme was that it did not appear possible to avoid building an overabundance of Ba. In fact, the amount of spallation which we now believe must occur to give rise to the helium anomalies precludes this mechanism because the heavy elements will also be completely spalled.

We therefore have a surface region containing the spallation products, largely protons and neutrons, and D. To build He^3 the simplest reactions are $D(p,\gamma)\ He^3$, $D(d,n)\ He^3$ and $D(d,p)\ T(\beta^-)\ He^3$. However, the following difficulty is encountered when we try to estimate the importance of these reactions. Conditions must be non-thermodynamic and particle energies corresponding to very high effective temperatures are required ($kT \sim 1$ MeV) and at such high temperatures He^3 is a very unstable nucleus. Thus while He^3 can be built under such conditions through $D(p,\gamma)\ He^3$, etc., it will be destroyed through $He^3(d,p)\ He^4$ and $He^3(n,p)\ T(p,\gamma)\ He^4$. The only conditions under which it appears to us that He^3 can be built are the conditions under which the normal thermonuclear process, $D(p,\gamma)\ He^3$, occurs, i.e., at temperatures $\sim 10^6$ degrees. Thus we require that the D must be mixed from the surface layers to deeper regions for He^3 to be synthesized.

However, an enormous breakup of He^4 is then required. The mass of material cooler than 10^6 degrees is $\sim 4\pi R^2\, P(T = 10^6)\, g^{-1}$, where R is the radius, $P(T = 10^6)$ is the pressure at 10^6 degrees, and g is the gravity (the material forms a thin layer and can therefore be treated as having everywhere the same g). Since $g = GM/R^2$, the total mass is then $4\pi R^4 P/GM$. Typical values might be $M = 3\ M_\odot$, $R = 1.5 \times 10^{11}$ cm, $P = 3 \times 10^{11}$ dynes cm^{-2}, giving 5×10^{30} gm, of which about one-third was initially He^4. Remembering that $\sim 6 \times 10^{18}$ ergs is required to disrupt 1 gm of He^4, the total energy requirement is $\sim 10^{49}$ ergs. If $D(p,\gamma)$ could be operated at temperatures less than 10^6 degrees, the energy requirement would be reduced; if a temperature of only 5×10^5 degrees were needed the energy needed could be reduced to $\sim 10^{48}$ ergs. The necessary energy could hardly be much less than this. For comparison, the total magnetic energy of a field of intensity 10^8 gauss existing throughout the star is $\sim 10^{48}$ ergs, so that the total dissipation of the whole of such a field would be needed, if the energy of the spallating particles were derived directly from the field.

Since we have supposed here that all of the material has been broken down, the only helium which is present at this epoch will be the He^3 and He^4 which is produced by the mixing to lower levels. If the concentration of D is low following the spallation, it must be mainly destroyed by $D(p,\gamma)\ He^3$, after mixing down to temperatures of $\sim 10^6$ degrees; the helium content will then be $\lesssim 10^{-2}$ of the normal value and will be wholly He^3. If the concentration of D was higher it will be destroyed by $D(d,p)\ T$ and $D(d,n)\ He^3$, reactions which have a $\langle \sigma v \rangle$ value about 10^3 times that of $D(p,\gamma)\ He^3$. In this case the final He^3:He^4 ratio is determined by the ratio of the lifetimes for $T(p,\gamma)\ He^4$ and $T(\beta^-)\ He^3$. To obtain a ratio He^3:$He^4 \approx 10:1$ we require $\tau_p(T) \approx 100$ years.

The presence of light elements, though they are underabundant on the surfaces of these stars, suggests at first sight that the material that we see has not undergone complete breakdown by spallation, though as we have shown a very high degree of spallation is required to produce He^3 and the general depletion of helium. The possibility should be borne in mind, therefore, that the underabundant light elements that appear on the surface have come from the deep interior after the surface material has been completely spalled.

The problem remains of the source of the high-energy particles that give rise to this immense amount of surface activity. The energy required is of the order of that released in a degenerate core. Shock waves propagated from the core to the surface might be able to supply this energy. It is also possible that such phenomena amplify the magnetic field, which then transfers energy to the particles in an acceleration process. The problem is a very difficult one, and the acceleration processes are not very efficient (cf. the discussion of acceleration in spots by Fowler *et al.* 1955). However, we believe that such processes are essential to explain the underabundances of the light elements and especially helium.

VIII. ASTROPHYSICAL DISCUSSION AND CONCLUSIONS

We have described possible mechanisms by which the anomalous overabundances can be built in the interior of a star that has had a degenerate core, and we have discussed the very extensive spallation activity that must have taken place in the surface layers to give rise to the underabundances of He, C, and O. In this concluding section we direct our attention successively to (*a*) the sequence of events that has given rise to these over- and underabundances; (*b*) the reasons why the stars in question are found in the vicinity of the main sequence; (*c*) the mixing processes that have brought the processed material from the deep interior to the surface; (*d*) the reasons why these stars have such strong surface magnetic fields; (*e*) the possibility that the evolution of a binary companion has been in large part responsible for the anomalies seen—this is to be taken as an alternative to our main thesis, that these stars are single stars which have moved back from the giant branch. Finally, we discuss (*f*) observations that suggest that other types of stars may be related in an evolutionary sequence to the peculiar A and B stars.

a) The theory developed in this paper for producing anomalous abundances of Si, the iron-peak elements, Ga, Kr, Sr, Y, Zr, and the heavy elements requires that the Ap stars possessed (or perhaps still do) degenerate cores. We shall, later in this section, put forward an alternative evolutionary scheme whereby the Ap stars could be members of binary systems in which the companion star is highly evolved, but first we outline the sequence of events through which an Ap star, if single, should have evolved.

Since these stars occur in galactic clusters with ages in the range 8×10^7 to 6×10^8 years, they started with masses of 2–3 $M_\odot$. Since they now lie in the vicinity of the main sequence, and since their spectra show them to have normal surface gravities for their luminosities, they should not have lost a great deal of mass. For them to have possessed degenerate cores means that they must have passed through a stage of being giants and then have moved back rapidly to the vicinity of the main sequence. The flashes that we have been describing occur in the giant phase, not in the Ap phase. During the flashing and the return to the main sequence, a magnetic field would have to be brought to the surface, and the spallation reactions described in § VII should take place. A stabilizing readjustment having occurred, the stars settle down, with interior material having been brought to the surface, to a lifetime of a further 10^7 years, according to the known frequency of Ap stars, which is 10 per cent of normal A stars.

b) The question then arises as to what mechanism drove the stars back toward the main sequence. A flash based on the energy released by $C^{13}(\alpha,n)\,O^{16}$ is far more unstable than a flash in pure helium because of the much greater rate of this reaction. We expect a complete burning of C^{13}. To produce non-degeneracy, a temperature of $T_8 \simeq 2$ is required even for a flash in the outer part of the core, and at this temperature the C^{13} burns in a time scale that is less than the expansion time of the material. If the C^{13} content is sufficiently high, the energy released will be much greater than is required by the criterion for non-degeneracy, $\rho \approx 3.10^4\, T_8^{3/2}$. As was shown in § V, a C^{13} content of 1 nucleus per 10^2 nucleons drives the temperature above $T_8 = 10$, and the whole of the light elements C, N, O are then scoured out. It is possible that a subsequent suppression of the carbon-nitrogen cycle in hydrogen burning then produces a major structural change in which the star is moved back toward the main sequence. This should be a promising line of exploration, but detailed computations are evidently needed.

c) We have already remarked that the energy necessary to expand a degenerate core, $\sim 10^{50}$ ergs, is not much less than the total binding energy of the star, and that when this happens some mixing of material throughout the star is to be expected. A star with a giant structure can readily move interior material to its surface since most of the mass of the outer hydrogen envelope is already convective; hot bubbles would carry the highly evolved material of very peculiar composition to the surface. There is, however, a question whether under conditions in which 10^{18} ergs gm^{-1} are released at temperatures in excess of 10^9 ° K the interior situation might not be sufficiently violent to remove the hydrogen envelope entirely. The potential energy in the envelope is $\sim 10^{15}$ ergs gm^{-1}, so the total gravitational potential of an envelope of mass, say, 2 $M_\odot$ is $\sim 3 \times 10^{48}$ ergs. This would be supplied by the high-temperature burning of $\sim 3 \times 10^{30}$ gm of core material. However, we cannot immediately conclude that the violent burning of this quantity of material must strip away the whole envelope of a star, because the material will not lie at the extreme edge of the degenerate core but will be tamped by perhaps 10^{32} gm of material lying above it. The energy required to lift this latter quantity of material, at $\sim 10^{17}$ ergs gm^{-1}, is $\sim 10^{49}$ ergs, a somewhat greater requirement for ejection of the envelope than is set by the potential energy of the envelope itself.

These considerations enable us to estimate a rough order-of-magnitude limit to the Si and anomalous Fe-group concentration we could expect at the surface, in those stars where reactions have proceeded beyond the neutron production and capture to the scheme described in § V. The production of Si must be less than $\sim 10^{31}$ gm. The violent burning of 10^{31} gm at 10^{18} ergs gm^{-1} gives $\sim 10^{49}$ ergs, and this would remove the envelope, in which case we would be left with an evolved core, not an Ap star. The mixing of up to $\sim 10^{31}$ gm of Si throughout an envelope of mass 2 $M_\odot$ gives a Si concentration up to $\sim 3 \times 10^{-3}$ by mass, or an upper limit of 1 Si per 10^4 nucleons. Since the normal Si concentration is 1 Si per 6×10^4 nucleons, we deduce a possible increase of Si at the surface by a factor of order 10. Further, we found in § V that Si:Fe $\sim$ 10:1, so we expect an upper limit to the augmentation of iron of 1 Fe per $\sim 10^5$ nucleons. This is comparable with the normal iron abundance, which requires that the iron abundance be not increased by a factor of more than 2 or 3, a result in interesting agreement with observation.

If He is found to be appreciably underabundant in all Ap stars, we must conclude that spallation has been so severe that essentially none of the heavy elements originally present in the surface can be expected to have survived. Hence the observed heavy elements must be those brought up subsequently from the interior. Nothing of the original abundances should therefore be left. The great bulk of the material produced by spallation will be hydrogen. In order that the whole of the material down to a depth where $T = 10^6$ degrees be affected by spallation, the amount affected per unit surface area must be 10^6–10^7 gm cm^{-2}. It can be questioned whether surface reactions can affect so large a quantity of material, in view of the fact that the spallating particles cannot penetrate more than 10^2–10^3 gm cm^{-2}. However, our estimate refers to the Ap star. In a preceding giant phase the amount of material that must be affected per unit surface area is substantially less. Thus in a transition from a giant structure to an Ap star the surface area is contracted by a factor of order 10^3, so that 10^6–10^7 gm cm^{-2} in the Ap star would correspond to 10^3–10^4 gm cm^{-2} in the giant.

d) So far we have said little about the magnetic fields associated with the Ap stars. An explanation of the large surface fields of these stars could be that the fields have simply been carried outward from the interior to the surface. In this way we have a rather obvious connection between composition anomalies and the magnetic field. Both arise because interior material reaches the surface.

The usual formula for the time scale of decay of a magnetic field in material of conductivity σ is $\sigma L^2/c^2$, where L is the length scale. Now σ is temperature-dependent, $\sigma \simeq 10^7 T^{3/2}$ sec^{-1}, with T in degrees Kelvin. At the surface $T \simeq 10^4$ degrees, and, since $L \simeq 10^{11}$ cm, decay takes place in $\sim 10^{14}$ sec. Thus a surface field decays in a time scale much shorter than the age of an A star, $\sim 3 \times 10^{15}$ sec, even if the length scale is set as high as the radius of the star. The situation is different in the interior. For $T = 10^7$ degrees, $L \simeq 10^{10}$ cm, the decay time is increased to 3×10^{16} sec. Hence an original interior field is preserved, whereas an original surface field due to electric currents flowing at the surface is not preserved. But a stirring of interior material to the surface can renew the surface field for a time scale of order 10^{13} to 10^{14} sec.

e) The strongest argument against the model we have described in this paper arises from the fact that not all Ap stars are single; about one in six is a member of a spectroscopic binary. In a few cases the components are too close for the Ap star to have once been a giant without its surface spilling over the critical Lagrangian surface. The star HR 710, with period $\sim$3 days (Babcock 1960), is such a special case.

This argument is supported in some degree by the Am stars, which possess analogous (although not identical) anomalies to the Ap stars (cf. § II). According to Abt (1961), essentially all Am stars are members of spectroscopic binaries, a considerable fraction with short periods. The unusually *low* fraction of Ap stars in spectroscopic pairs and the unusually *high* fraction of Am stars in such pairs, combined with the analogy between these two classes, suggests that their binary nature may be an important factor in the problems before us. Thus we shall now consider an alternative evolutionary picture in which a binary character for the Ap stars is all-important.

First we notice an important point of principle that does not seem to have received the attention it deserves. We noted in § VI that both the luminosity and radius of a giant depend mainly on the mass of the core, M_c, and very little on the mass $\sim(M - M_c)$ of the outer envelope. This remains true so long as M_c does not become close to the total mass, M. Clearly, as the mass in the envelope tends to zero the envelope collapses on to the core and the star becomes a cooling white dwarf. The latter situation can arise in a binary with separation less than the radius which a giant component would have if it were a single star. Matter spills over the critical Lagrangian surface and is probably expelled to infinity—it cannot simply drain into the other component because of angular momentum considerations, although a fraction of it will very likely do so. The final effect must be to produce a cooling white dwarf.

These considerations have several important effects in our problem. First, as already described, an expanded degenerate core is a potentially powerful object. Flashes similar to those described in the preceding sections can then readily expel material. A very strong magnetic field probably emerges from the core surface. The stripping away of the outer envelope of a star provides a simple and direct way of gaining access to interior material which may have been processed in the manner described in §§ IV and V. It is attractive to suggest that material of anomalous composition arrives at the surface of an Ap star from the deep interior of a companion star, and that it carries a magnetic field, so that the magnetic field then links the two stars.

Several results follow very simply. The star that receives must evidently evolve more slowly than its companion. It must lie near the main sequence, since evolution to a giant phase would involve a similar stripping process. The receiving star must also be quite closely limited in spectral type. It must not be of such early type that the evolving companion was so massive that no degenerate core developed in its interior. It must not be of such late type that a deep convection zone exists in the subphotospheric layers; otherwise the material of anomalous composition received from the companion would be mixed throughout a substantial envelope, thereby masking the anomalies. The fact that anomalies are stronger in the Ap stars than in the Am stars could be due to the later types of the latter.

We are attracted by the simplicity of this second alternative. However, it is necessary in this second picture that all Ap stars possess companions of a white-dwarf character, probably with masses of $\sim 0.5\ M_{\odot}$. In the absence of observational confirmation of this requirement we can only regard this possibility as a tentative speculation. Also we might add that the apparent correlation of the type of abundance anomaly with luminosity (Mn stars, Si stars, Eu-Cr-Sr stars, and Am stars in order of decreasing luminosity) is a difficulty, perhaps a fatal one, in this second picture.

f) In § II we mentioned the λ Boo stars, which are population I A-type stars having metal deficiencies similar to those in old population II stars (Burbidge and Burbidge 1956). In § VII we discussed spallation reactions as a means of causing large-scale breakup of all elements heavier than H, including He^4, in the outer parts of a star on its way to becoming an Ap star. Suppose that in a particular case no interior material managed to reach the surface. Then we should have a star showing a normal hydrogen abundance, weak helium, and underabundant metals, i.e., a star showing the characteristics of λ Boo. The possibility that this is, in fact, what the λ Boo stars are is discussed by Sargent (1965); according to him, they form 1 per cent of the normal A-type stars, in comparison with the Ap stars which form 10 per cent.

A striking difference between the Ap stars and the λ Boo stars is that the former have sharp-lined and the latter have broad-lined spectra. We have not discussed the question of rotation in considering the evolution of Ap stars. Several workers (e.g., Babcock 1960) contend that the Ap stars are rapid rotators seen pole-on; others, however, believe that they are intrinsically slow rotators (e.g., Cameron 1964; Strömgren 1963, from the *uvby* photometry). We should entertain the possibility, according to the single-star hypothesis and not the binary hypothesis, that, in view of the difference between the Ap and the λ Boo stars, the appearance or otherwise of interior material and a magnetic field on the surface could depend upon the stellar rotation.

According to the sequence of events outlined in (*a*) and in § VII, there is a stage, after the onset of the flashes, when widespread spallation has to occur, initiated either by electromagnetic processes (flare-like activity) or by shock waves which steepen in the low-density surface layers. According to (*c*), it would be most logical if this occurred while the star still had a giant structure. Presumably this phase would be short-lived, but we may still ask whether we could observe any stars where this may be occurring. The requirements are that (i) the stars should be red giants; (ii) there should be a variable blue continuum superposed on the red-giant spectrum, with emission lines that could be of high excitation; (iii) the stars, being in an unstable state of rapid evolutionary change, would be expected to vary in light; (iv) there might be a magnetic field in evidence. Stars that appear to fulfil these conditions are the so-called symbiotic stars (e.g., Merrill 1932*a*) such as BF Cyg, CI Cyg, AX Mon, R Aqr, and others. XX Oph (the "iron star" of Merrill 1932*b*, 1946) might fall into this category also. We note further that one of these stars, AG Peg, has a magnetic field measured in the emission lines (Babcock and Cowling 1953).

In this paper we have attempted to account for the chemical compositions of the peculiar A stars. Our approach is quite different from previous discussions in that we have concluded that the nuclear physics demands that the stars are long past their main-sequence evolution and have passed through a phase at which a degenerate core was developed, and a modified *r*-process has occurred. We also conclude either that a powerful mixing process has been at work so that the products of the interior nucleosynthesis have been brought to the surface, or that the stars must be members of binary systems and that such processes occurred in the companions and material was moved to the surfaces of the peculiar A stars. To account for the underabundances of the light elements, particularly helium, a vast amount of spallation of surface material and mixing to comparatively shallow layers must have taken place. The sequence of events has been such that the surface processes occurred before the deep interior products were brought to the surface.

All the abundance anomalies described in § II are not seen in all the stars in the peculiar star sequence shown in Figure 1. While in many cases the atmospheric conditions may be such that anomalies cannot be detected, it is almost certainly true that not all anomalies are present throughout the sequence. Thus there may be a continuous range in the kinds of interior and surface nuclear activity that occur.

Our model is only schematic because of the limitation of our knowledge of the detailed evolutionary tracks of stars in this part of the H-R diagram, and the lack of understanding of the physical processes of mixing. However, our conclusion that these abundances can only have been produced in a star that is highly evolved means that a new approach should be made to the problems of the strong magnetic fields, their variations, often periodic, and small light variations. At present we do not understand these phenomena, and apart from our comments concerning the possibility that the strong magnetic fields are in evidence because they have been exposed or brought to the surface, we have nothing further to add in this direction.

The suggestion that an r-process can take place in a situation in which the star is not shattered is new, since we have supposed previously (cf. Burbidge *et al.* 1957) and still do believe that the bulk of the r-process isotopes in the cosmos were made in supernova or massive star outbursts.

It is obvious that a vast amount of work remains to be done in this field on both the theoretical and observational sides. We hope that this paper will provoke such studies.

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