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THE SUBGIANT CH STARS*

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ABSTRACT

A new class of peculiar stars has been discovered on objective-prism plates. These objects have G-type spectra with weak metallic lines but enhanced features of CH and the *s*-process elements, and most of these stars have high space velocities. Photometrically they show the high violet opacity seen in other carbon-rich stars of similar temperature. Several lines of evidence indicate visual absolute magnitudes near $M_v = +2$. These stars are similar in composition to, and much more common per unit volume of space than, the better-known CH stars. It is proposed that these objects acquire their unusual surface compositions in events that partially mix Population II red giants, and that later, as they evolve back up the red-giant branch, they become CH stars. These "subgiant CH stars" are probably present in several globular clusters.

Subject headings: carbon stars — high-velocity stars — Population II stars — spectral classification — stellar evolution

I. INTRODUCTION

Among the late-type stars there are several classes of spectroscopically peculiar objects whose atmospheres are now regarded as containing the products of nuclear reactions that have occurred in the stars' interiors. These stars have gradually become known as spectroscopic surveys have been extended to fainter objects and higher spectral resolution, allowing the detection of spectral peculiarities of increasing subtlety. Thus the carbon stars have such strong molecular bands that they were discovered with visual spectroscopes over a century ago. With the advent of large-scale objective-prism surveys at Harvard around the beginning of the present century, enough spectroscopic data were obtained to permit the recognition of two classes of carbon stars, the R- and N-type stars, and of a new, small group of late-type stars with peculiar banded spectra, the S-type stars. More detailed spectroscopic study of the carbon and other peculiar late-type stars led to the discoveries of the classes of CH stars (Keenan 1942) and Ba II stars (Bidelman and Keenan 1951).

The present paper deals with a new class of peculiar stars found on objective-prism survey plates of relatively high spectral resolution, obtained with the Curtis Schmidt telescope of the University of Michigan. These objects appear to be Population II G-type subgiant stars showing enhanced abundances of carbon and the elements produced in the *s*-process. For conciseness, it is proposed that these objects be called the "subgiant CH stars," a name this paper will attempt to justify. We will call the previously known class of CH stars with strong C_2 bands the "giant CH stars," and will refer to both groups together simply as "CH stars" or "Population II carbon stars."

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II. THE SUBGIANT CH STARS

The stars of this new class were all recognized initially on Curtis Schmidt plates obtained at various times over the last 20 years with the 10° objective-prism combination. The relatively high dispersion of the resulting spectrograms, 108 Å mm^{-1} at Hγ, is adequate to permit accurate spectral classification and the recognition of various spectral peculiarities of stars down to about the tenth magnitude (Bidelman 1966; Bond 1970*a*). The first members of the subgiant CH class were noted by several persons working with the Michigan plates under the direction of W. P. Bidelman; these stars were found to have G-type spectra with somewhat weak metallic lines, very strong CH features, and strong lines of Sr II at 4077 and 4215 Å. Two stars showing these characteristics, HD 176021 and HD 204613, were announced a few years ago by the writer (Bond 1970*b*). Several members of this class also showed a strong Ba II line at 4554 Å, and were classified as "weak-lined Ba II stars" by MacConnell, Frye, and Upgren (1972); these authors gave an illustration of the objective-prism spectrum of one such star, HD 50264. In a few extreme cases, the metallic lines were so weak that the Sr II lines, CH features, the hydrogen Balmer lines, and sometimes λ4554 were the *only* features strong enough to be seen in the objective-prism spectra longward of the Ca II H and K lines. The discovery of the subgiant CH stars was delayed until now because these stars are relatively faint and lack the strong wide molecular bands of cooler stars of the same chemical composition. A large-scale survey at relatively high spectral resolution, but at the same time reaching sufficiently faint stars, was necessary for their discovery.

The search for subgiant CH stars has been carried out on Curtis Schmidt plates obtained while the

TABLE 1

THE SUBGIANT CH STARS

Star	α (1900)	δ (1900)	V (mag)	$b - y$ (mag)	m_1 (mag)	c_1 (mag)	n	μ (yr^{-1})	R.V. (km s^{-1})	Notes
HD 50264..........	6^h47^m3	$-29°28'$	9.02	0.38	0.22	0.18	1	0".108	+ 80	1
HD 55496..........	7 08.0	−22 48	8.40	0.59	0.31	0.39	1	0.023	+324	1
HD 76225..........	8 49.7	−26 33	10.3	...	...	...	...	...	+ 32	2
HD 89948..........	10 17.7	−29 04	7.7	...	...	...	...	0.079	+ 23	3
HD 123585.........	14 03.4	−43 53	9.28	0.34	0.19	0.26	1	0.048	+ 21	1, 4
HD 127392.........	14 26.0	−30 47	9.67	...	...	...	...	0.031	− 61	1, 5
HD 176021.........	18 53.0	−65 03	7.58	0.38	0.17	0.22	3	0.345	+106.2	6, 7
CPD−62°6195......	20 58.0	−61 57	9.79	...	...	...	...	...	+119	8
HD 204613.........	21 24.7	+56 54	8.24	0.40	0.21	0.29	1	0.225	−112	6, 9
HD 216219.........	22 46.0	+17 28	7.49	0.41	0.22	0.27	2	0.052	+ 14	10
HD 224621.........	23 54.2	−36 36	9.59	0.36	0.22	0.19	1	0.138	...	

NOTES TO TABLE 1.—(1) Classified as Ba II star by MacConnell *et al.* 1972. (2) Classified as marginal Ba II star by MacConnell *et al.* 1972. (3) Spectral peculiarities first noted, and classified as marginal Ba II star, by MacConnell *et al.* 1972. (4) $B - V = 0.51$, $U - B = -0.03$ according to A. U. Landolt (unpublished). (5) $B - V = 0.68$, $U - B = 0.07$ according to A. U. Landolt (unpublished). (6) Spectral peculiarities first noted by Bond 1970*b*. (7) Radial velocity from two Cerro Tololo 9 Å mm^{-1} coudé spectra, mean error ± 0.4 km s^{-1}; $B - V = 0.58$, $U - B = -0.07$ according to Eggen 1972. (8) Spectral peculiarities first noted by Bond 1970*a*; radial velocity kindly provided by N. G. Roman, who also found $B - V = 0.72$, $U - B = 0.13$. (9) $B - V = 0.61$, $U - B = 0.06$ according to Eggen 1972. (10) Spectral peculiarities first noted by Bond 1970*c*; four-color photometry by Warren 1973.

telescope was located in Michigan, by Michigan spectral survey observers after the telescope was moved to Cerro Tololo Inter-American Observatory in 1967, and by the writer at Cerro Tololo in 1971. It is difficult to estimate the completeness of the search for stars of the new class in question, because their spectral peculiarities are somewhat subtle in certain cases, and of course the entire sky, particularly in the northern hemisphere, has not yet been searched. Taking these factors into account, the writer estimates that about one-fifth to one-fourth of the objects of this type brighter than the tenth magnitude are now known.

The writer presently considers the 11 stars listed in table 1 as definite members of this class; additional candidates undoubtedly exist in the material published by MacConnell *et al.* (1972). The four-color Strömgren photometry listed in table 1 was obtained (with the exception noted) by the writer, using 16-inch (41-cm) and 36-inch (91-cm) telescopes at Kitt Peak and Cerro Tololo; n denotes the number of photometric observations of each star. The proper motions were taken from the Smithsonian Astrophysical Observatory *Star Catalog*. Except as noted, the radial velocities were measured by the writer on Kitt Peak, Cerro Tololo, or Michigan slit spectrograms of moderate dispersion and have mean errors of about ± 10 km s^{-1}.

In view of the existence of several large proper motions and radial velocities in table 1, it is emphasized that all of the subgiant CH stars were originally selected purely on the basis of their objective-prism spectra.

III. SPECTROSCOPIC PECULIARITIES

Figure 1 compares the spectra of several representative subgiant CH stars with those of normal stars at classification dispersion (125 Å mm^{-1}). The strengths of the hydrogen Balmer lines indicate spectral types ranging from late F or G0 to late G, but other features in the spectra are definitely abnormal. The most obvious peculiarity is the extraordinary enhancement of the Sr II λ4077 line: in every case, this line and Hδ are by far the most conspicuous features between Ca II H and K and Ca I λ4226. Another Sr II line, λ4215, is also much stronger than in normal stars. The strontium enhancement clearly is not a luminosity effect, since the remainder of each spectrum definitely is not characteristic of high-luminosity stars. The Ba II line at λ4554 is visible in several of the spectra, although in normal stars this line generally is not easily seen at all at this dispersion.

All of the stars (except HD 76225, which may have a composite spectrum) show enhanced features of the CH molecule. Although relatively prominent CH is seen in the spectra of some high-velocity stars (Keenan and Keller 1953; Bond 1970*a*, fig. 1), the strong Sr II and Ba II lines of the subgiant CH stars clearly distinguish them from the majority of high-velocity stars.

Although the spectra of the subgiant CH stars show enhanced Sr II, Ba II, and CH, most of the remaining spectral lines are weaker than in normal stars. This effect is particularly noticeable at λλ4030–4071 (Mn I, Fe I), λ4226 (Ca I), and λ4383 (Fe I). The line weakening is most extreme in the spectra of HD 76225, HD 50264, and HD 55496, but all of the stars of this group have at least slightly weak lines. There is some tendency for Ba II to be strongest in the stars with the weakest metallic lines.

The only subgiant CH star yet studied at high dispersion is HD 176021, for which the writer has obtained two 9 Å mm^{-1} coudé spectrograms with the 60-inch reflector at Cerro Tololo. Figure 2 compares two sections of one of these spectrograms with sections of the solar spectrum. The overall general line weakening seen at classification dispersion is shown more clearly, as is the enhancement of a few lines. The Fe I

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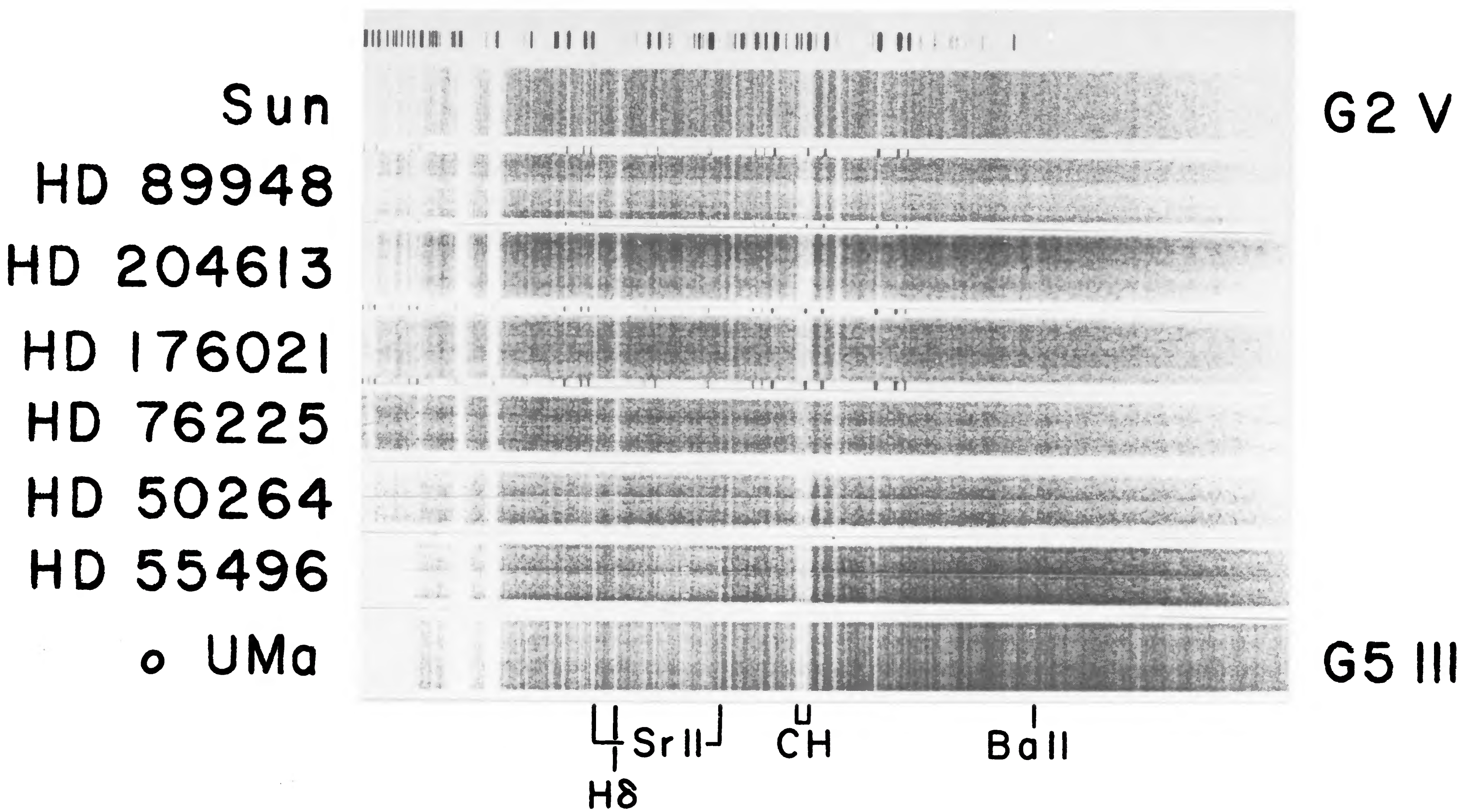

FIG. 1.—125 Å mm^{-1} Kitt Peak and Cerro Tololo slit spectrograms of subgiant CH stars compared with spectra of two normal stars, the Sun (spectrum of daylight sky) and o UMa. In the spectra of the subgiant CH stars, note the enhancement of Sr II λλ4077–4215, the G-band of CH, and Ba II λ4554, and the general weakening of other metallic lines.

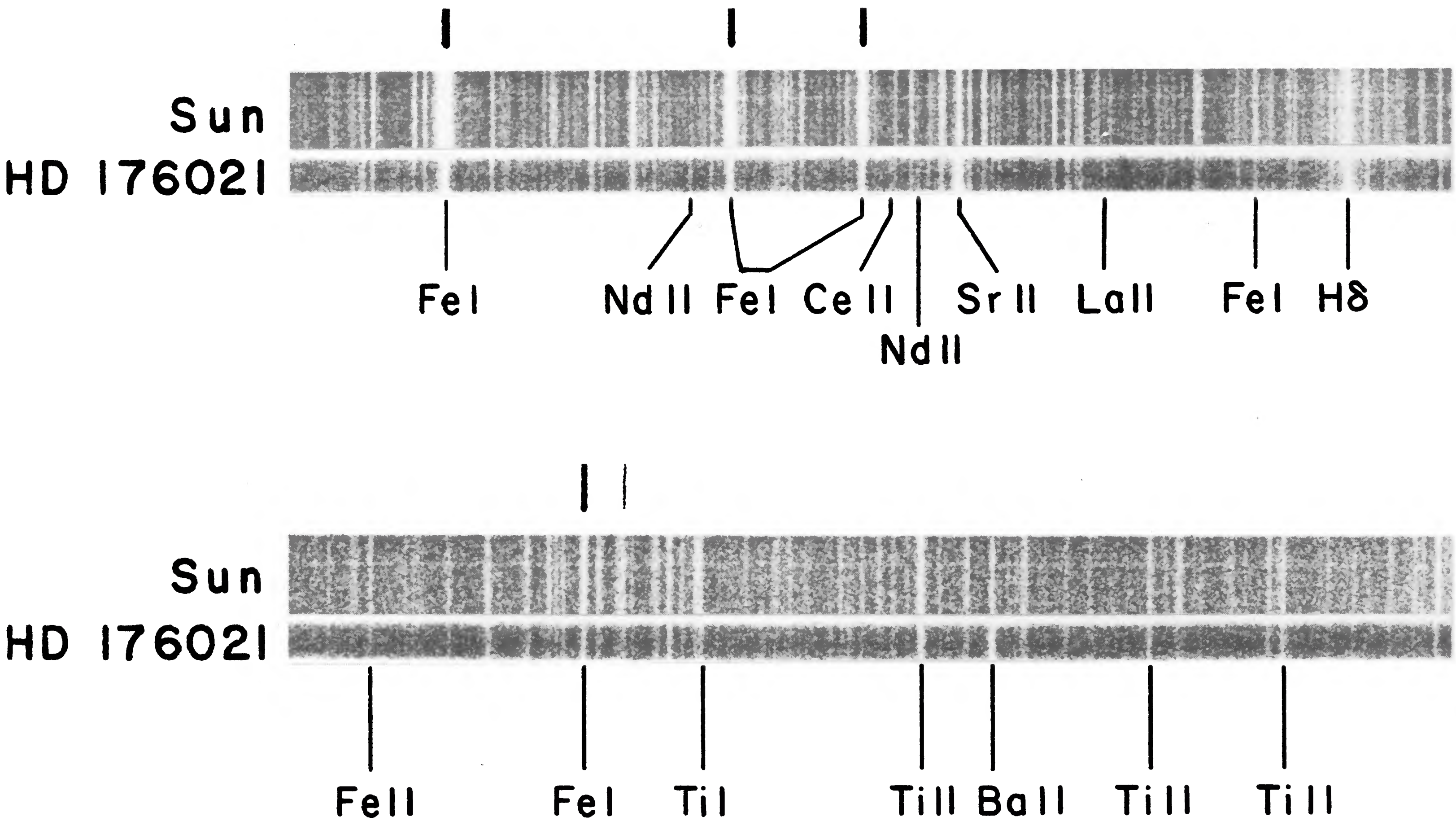

FIG. 2.—Sections of 9 Å mm⁻¹ Cerro Tololo spectrograms of HD 176021 and the Sun (spectrum of daylight sky). Note the general weakening of lines of the iron group of elements and the enhancement of lines of strontium, barium, and rare-earth elements in the spectrum of HD 176021. Lines of Ti II are relatively strong in HD 176021 because of a somewhat lower-than-solar surface gravity. *Top sections*, 4036–4108 Å; *bottom sections*, 4510–4582 Å.

lines show very noticeable weakening in HD 176021, and there is a considerable strengthening of Sr II and Ba II. In addition, figure 2 illustrates what could not be seen at lower dispersion, namely, the enhancement of certain normally very weak lines of certain heavy elements. Those shown in the figure include lanthanum, cerium, and neodymium; elsewhere in the spectrum of HD 176021, enhanced lines of zirconium, yttrium, possibly praseodymium and samarium, and of course CH have also been found. It is clear that HD 176021 is a somewhat metal-deficient star with enhanced abundances of carbon and the heavy elements produced in the well-known *s*-process of nucleosynthesis by neutron-capture reactions. A detailed abundance analysis of HD 176021 will be published at a later date.

Lines of atomic carbon and of atomic and ionized technetium are not present in the spectrum of HD 176021 at this dispersion. The absence of C I is not surprising because the available lines in the photographic region are of fairly high excitation. The absence of Tc I and Tc II suggests that the enrichment of this year's atmosphere with heavy elements occurred so long ago that this radioactive element has decayed (see § VI).

The main point the writer wishes to establish in this section is that the subgiant CH stars show just the spectral peculiarities to be expected in stars of the same composition as, but hotter than, the giant CH stars. The weakness of most metallic lines and the enhancement of CH and the *s*-process elements in giant CH stars have been described by several authors (e.g., Keenan 1942; Bidelman 1956; Wallerstein and Greenstein 1964). The spectra in figure 1 are arranged in order of decreasing temperature, and it can be seen that there is a smooth progression from objects of about type G0 (HD 89948 and HD 204613) to the cooler star HD 55496. The spectrum of HD 55496 bears a very close resemblance to that of the bluest CH star, HD 26 (illustrated by Keenan and Keller 1951 and Roman 1965). The only significant differences between these two stars' spectra are that HD 26 is slightly cooler and hence shows weak C_2 bands, and HD 55496 has somewhat weaker metallic lines than HD 26. In view of the close similarities of the spectral peculiarities of the two groups, we propose that the subgiant and giant CH stars form a continuous sequence of stars of the same abnormal chemical composition, differing only in temperature and, probably, luminosity.

In figure 2, the strengths of lines from ionized iron and titanium in the spectrum of HD 176021 suggest a surface gravity slightly lower than the Sun's. This is a consequence of a luminosity somewhat higher than the Sun's. The luminosities of the subgiant CH stars will now be considered in detail.

IV. LUMINOSITIES

a) *Space Motions*

It is clear from table 1 that the class of subgiant CH stars comprises stars of differing kinematic characteristics. In addition, the number of stars presently known to belong to this class is still small. Hence an accurate determination of secular parallax is not possible at the present time.

A crude estimate of the luminosities of these stars can be made by using their reduced proper motions (defined by $H = m_v + 5 \log \mu + 5$). The absolute magnitude is related to H by $M_v = H + 3.38 - 5 \log V_T$, where the transverse velocity V_T is expressed in km s^{-1}. For the subgiant CH stars, $\langle H \rangle = +8.5$, and the mean radial velocity without regard to sign is $\langle |V_R| \rangle = 63$ km s^{-1}. (HD 55496 was excluded from this calculation since it appears to be an atypical object of very high velocity moving nearly directly away from the Sun.) We assume that the space velocities have random directions, so that $\langle V_T \rangle \simeq \frac{1}{2}\pi \langle |V_R| \rangle$, and find $M_v \simeq +1.9$. Using the same method for the giant CH stars known to the writer, we find $\langle H \rangle = +7.4$, $\langle |V_R| \rangle = 143$ km s^{-1}, and $M_v \simeq -1.0$. Although the giant CH stars in particular undoubtedly have a considerable range of visual absolute magnitudes (a range of at least -2.5 to $+0.2$ is found in § VI), we nevertheless have an indication that the subgiant CH stars as a group are less luminous than the giant CH stars.

Several of the subgiant CH stars have relatively large proper motions that allow useful limits to be placed on their luminosities. If they are to have velocities less than the escape velocity of 380 km s^{-1} in Schmidt's (1965) model of the Galaxy, then HD 50264, HD 176021, HD 204613, and HD 224621 must have visual absolute magnitudes fainter than about $+0.5$, 0.0, $+0.7$, and 0.0, respectively. (This limit for HD 224621 happens to be practically independent of its as yet unmeasured radial velocity.) HD 176021 and HD 224621 have retrograde galactic orbits unless they are fainter than $M_v = +1.6$ and $+0.8$, respectively. Retrograde orbits are relatively infrequent even among such high-velocity objects as large-proper-motion subdwarfs (see, for example, Sandage 1969, fig. 3). Because there is already another subgiant CH star, HD 55496, that has a retrograde orbit for any choice of M_v, it seems unlikely (though not impossible) that two more out of the 11 known members of this class would also have such orbits.

In table 2 are listed the U, V, W components of the space velocities with respect to the Sun for the subgiant CH stars (U is directed away from the galactic center, V is in the direction of galactic rotation, and W is toward the north galactic pole). The motions were computed assuming both $M_v = +2$ and $+4$. Several stars show the large negative V velocities typical of the high-velocity stars, and similar to those of most giant CH stars. The presence of some fairly low velocities need not be of concern, since similar cases were found earlier in the writer's survey of metal-deficient stars selected using spectroscopic criteria only (Bond 1970*a*). The $M_v = +4$ velocities are unusual in that the transverse velocities (not tabulated) are much smaller than the radial velocities; hence, as already noted, these objects are probably somewhat brighter than this.

TABLE 2

SPACE MOTIONS FOR $M_V = +2$ (*top rows*) AND $M_V = +4$ (*bottom rows*)

Star	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})
HD 50264.......	125	−42	76
	74	−57	19
HD 55496.......	165	−278	−30
	175	−271	−32
HD 89948.......	41	−8	37
	17	−16	20
HD 123585......	−46	−4	−51
	−27	−10	−17
HD 127392......	75	−10	−21
	57	14	−25
HD 176021......	−42	−227	61
	−67	−118	−3
HD 204613......	52	−105	−192
	11	−108	−82
HD 216219......	29	7	−16
	11	10	−11
HD 224621*.....	−148	−150	...
	−59	−60	...

* Note.—Motions for HD 224621 were computed assuming a radial velocity of 0 km s^{-1}. U and V are nearly independent of the radial velocity.

We conclude from their motions that these objects *cannot* be brighter than about $M_v \simeq +0.5$, and that a reasonable estimate is $M_v \simeq +2$. Thus the luminosities appear to be intermediate between those of ordinary giants and of main-sequence stars, and the term "subgiant" is justified.

b) *Trigonometric Parallaxes*

The large proper motion of HD 176021 attracted the attention of southern parallax observers some decades ago. The parallax catalog (Jenkins 1963) lists two measurements of 0".015 and 0".025 determined at the Yale-Columbia Southern Station and at the Cape, respectively, from which a weighted mean absolute parallax of 0".017 ± 0".008 was obtained. Taken at face value, this indicates an absolute magnitude $M_v \simeq +3.7$; but in view of the well-known uncertainties in small parallaxes, this should be considered only weak evidence for a relatively low luminosity.

c) *Interstellar Reddening*

As the writer has pointed out previously (Bond 1970*b*), HD 204613 lies at a galactic latitude of only +5°, but appears to be essentially unreddened on the basis of a comparison of its estimated spectral type with its measured colors. A conservative upper limit on the reddening of $E(B - V) < 0.10$ mag can be set. Hiltner (1956) has obtained photometry of early-type stars near the location of HD 204613, and FitzGerald (1968) has studied the (color excess, distance)-relation in this region. From these data, we find an upper limit $m - M < 8$ for HD 204613 if $E(B - V) < 0.10$ mag. Since $m_v = 8.2$ for this star, we have $M_v > +0.2$, another indication that the subgiant CH stars are less luminous than at least some of the giant CH stars.

d) *Moving Groups*

Eggen (1972) found visual absolute magnitudes of +3.7 for HD 176021 and +3.25 for HD 204613 by assuming them to be members, respectively, of the "Arcturus" and "η Cephei" moving groups. A star is considered to be a member of a moving group primarily on the basis of the V-component of its space velocity relative to the Sun, with a range of 20–30 km s^{-1} allowed among the U-components of the group members' velocities. For the Arcturus and η Cep groups, $V = -116$ and -97 km s^{-1}, respectively.

Eggen used the writer's preliminary radial velocity of HD 176021 (Bond 1970*b*) in his calculations. Using the more accurate coudé radial velocity given in table 1, we find that HD 176021 could still be regarded as a member of the Arcturus group if we adopt $M_v = +4.1$; in this case, $(U, V, W) = (-67, -116, -4)$ km s^{-1}. On the other hand, any desired value of V between -500 and -65 km s^{-1} could have been obtained by assuming an appropriate value of M_v between 0.0 and +7.0. One is therefore justified in regarding this determination of M_v with skepticism.

In the case of HD 204613, the moving-group method unfortunately gives no useful information even if the technique's validity is accepted, since the V velocity of this particular star happens to change by less than 2 km s^{-1} per magnitude change in the assumed M_v. The deduced absolute magnitude for this star is thus too sensitive to errors in proper motion and radial velocity to be useful for our purposes.

e) *Summary*

The discussion of the space motions of the subgiant CH stars appears to give the most compelling evidence for luminosities lower than those of ordinary giants and of most, if not all, giant CH stars. The trigonometric parallaxes and interstellar-reddening evidence corroborate this conclusion. The moving-group method, although it also leads to the same conclusion, appears to deserve low weight. The best estimate for this group of stars is probably $M_v \simeq +2$.

V. PHOTOMETRIC PROPERTIES

In figure 3 is shown the $(U - B, B - V)$-diagram for the subgiant CH stars (data from table 1) and for the giant CH stars (data from Mannery and Wallerstein 1970). Figure 4 shows the $(c_1, b - y)$-diagram for the same groups of stars; here the photometry for the giant CH stars is from Bond and Neff (1969), with the addition of data for a new giant CH star, CD −28°1082. (This star's peculiarities were discovered recently on a Curtis Schmidt objective-prism plate by the writer. From one observation with the Cerro Tololo 36-inch reflector, $V = 10.50$, $b - y = 0.70$, $m_1 = 0.29$, and $c_1 = -0.27$.)

The line in figure 3 represents the $(U - B, B - V)$-relation for normal dwarf stars (Johnson 1966), and the crosses in figure 4 represent the Strömgren indices for a collection of well-observed normal late-type stars (data taken from Crawford and Barnes 1970). Both

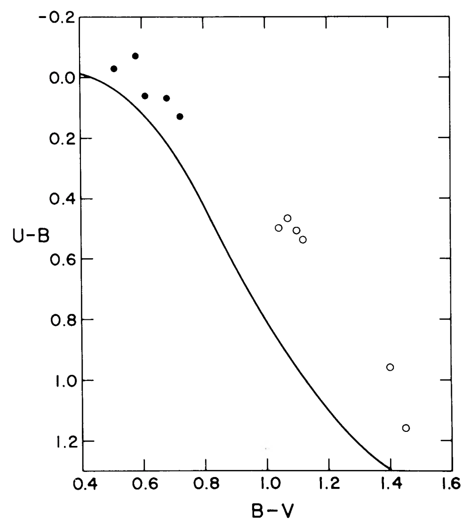

FIG. 3.—($U - B$, $B - V$)-diagram for subgiant CH stars (*filled circles*), giant CH stars (*open circles*), and normal dwarf stars (*line*). Data are from table 1, Mannery and Wallerstein (1970), and Johnson (1966), respectively. Note that both subgiant and giant CH stars show an "ultraviolet excess" actually attributable to a "violet deficiency."

figures reveal the fact that CH stars do not have normal colors (with the possible exception of HD 55496, which, as shown in figure 4, has a normal value of c_1; this single observation should be rechecked).

The giant CH stars, as shown in figure 3, have considerable "ultraviolet excesses," already noted by several authors (e.g., Wallerstein and Greenstein 1964; Mannery and Wallerstein 1970). In addition, the giant

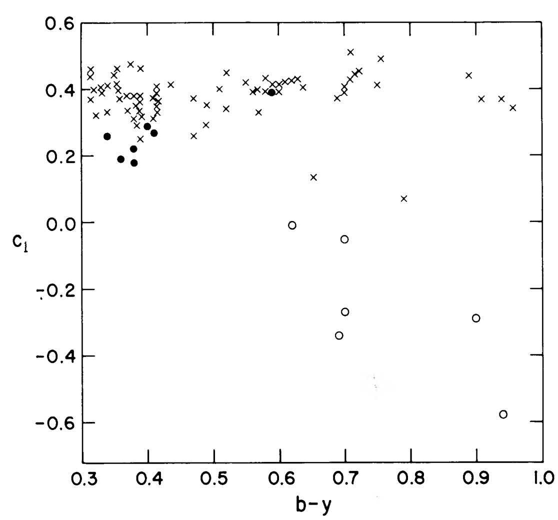

FIG. 4.—(c_1, $b - y$)-diagram for subgiant CH stars (*filled circles*), giant CH stars (*open circles*), and normal late-type stars (*crosses*). Data are from table 1, Bond and Neff (1969), and Crawford and Barnes (1970, table 2), respectively. Two normal late-type dwarfs have low c_1 indices, a luminosity effect already pointed out by the writer (Bond 1970*a*). The CH stars of both types have very low c_1 indices, again attributable to the violet deficiency described in the text.

CH stars have extraordinarily low c_1 indices, as shown in figure 4. The Ba II stars (low-velocity, strong-lined stars with enhanced carbon and *s*-process elements) also show these photometric effects (Warner 1965; Bond and Neff 1969). Bond and Neff showed that these effects are in fact not due to the usual ultraviolet excess found in weak-lined stars, but instead to a wide, continuous absorption centered near 4000 Å. Thus the giant CH stars actually show a "deficiency" in the B and v bands that is the primary cause for their anomalous colors. The point we wish to emphasize here is that figures 3 and 4 demonstrate the presence of the same effect, to a somewhat lesser degree, in the subgiant CH stars. The metalic-line index, m_1, is also affected by this absorption and therefore is not a reliable indicator of line weakening for these stars. In fact, the subgiant CH stars have normal or even high values of m_1 in spite of their weak metallic lines.

The source of this absorption has not yet been identified with certainty, but it must satisfy several constraints. The absorption is continuous, since no additional lines near 4000 Å of the requisite strengths are seen on high-dispersion spectrograms of the CH and Ba II stars that show the absorption. It is unlikely to be due to a negative ion, since the absorption increases with decreasing temperature, but the negative-ion concentration should decrease as the electron pressure in the stellar atmosphere decreases. The additional absorption also appears to be unrelated to the heavy-element enhancement in these stars, in view of unpublished photometry by the writer indicating the presence of the absorption in R-type carbon stars that do not show strong *s*-process elements. (The writer thanks T. D. Faÿ for discussions of these points.)

Warner (1965) attributed the absorption in the Ba II stars to the CN molecule. However, CN is very weak in the spectra of most of the subgiant CH stars, which nevertheless show the effect. A more plausible explanation of the additional absorption is one due to D. L. Lambert (private communication), who suggests that it is produced by absorption from the $X\,^2\Pi$ ground state of the CH molecule to the continuum of the low-lying $B\,^2\Sigma^-$ state. CH is indeed enhanced in the spectra of all classes of stars yet found to show the absorption near 4000 Å, and of course should strengthen with decreasing temperature as observed.

If Lambert's attribution to CH is correct, the violet absorption in these stars is distinct in origin from the well-known absorption that virtually obliterates the violet spectra of the N-type carbon stars; the latter absorption probably is produced in a circumstellar dust cloud (Gilra and Code 1971).

VI. THE EVOLUTION OF POPULATION II CARBON STARS

The subgiant CH stars appear to show the same abundance anomalies, high space velocities, and photometric properties as the well-known giant CH stars. These new objects differ only in having earlier spectral types and lower luminosities than the giant CH stars. An understanding of the evolution of Population II carbon stars probably requires only an explanation of the origin of the *subgiant* CH stars, because once a subgiant CH star exists, it would naturally evolve across the H-R diagram and become a giant CH star. We propose that *the subgiant* CH *stars are the progenitors of the giant* CH *stars*.

It is suggested that the origin of subgiant CH stars can be attributed to events of violent mixing occurring in Population II red giants. This mixing not only brings processed material to the stellar surface, but also mixes enough unprocessed material into the stellar core to permit the star to begin a new phase of hydrogen burning in the subgiant region of the H-R diagram. This hypothesis of a considerable degree of mixing, and its consequences, will be explored in this section.

a) *Mixing in Evolved Population II Stars*

There are at least two stages in the evolution of Population II stars when extensive mixing conceivably could occur: during the helium flash when the star is at the tip of the hydrogen-burning red-giant branch in the H-R diagram; or later, during the helium-shell-flashing stage when the star lies on the asymptotic giant branch.

i) *The Helium Flash*

Some years ago, Woolf (1964) proposed that the ignition of helium burning in the core of a Population II red giant induces a complete mixing of the star, followed by the horizontal-branch phase of its evolution. This idea has fallen into disfavor since models of completely mixed stars failed to predict observed properties of horizontal-branch stars (Larson 1965), but unmixed helium-burning models were much more successful (e.g., Faulkner 1966 and many subsequent authors). Furthermore, theoretical studies of the helium flash (Härm and Schwarzschild 1966) indicated that mixing does not occur during this event.

However, the earlier studies of the helium flash were based on quasi-static models. When Edwards (1969) investigated dynamic models of the helium flash in a 1 $\mathfrak{M}_{\odot}$ Population II star, he found that the ignition is actually quite violent and leads to an "explosion" of the stellar core. Edwards speculated that a substantial degree of mixing of the core material with the stellar envelope might occur subsequently. Conceivably the carbon and heavy elements produced during the flash could make their way up to the stellar surface, as was already suggested by Woolf (1964). Although Woolf's proposal does not appear to be valid for horizontal-branch stars, the writer believes that some modification of it might be applicable to the rarer subgiant CH stars.

Of course, these are considerable theoretical difficulties to be overcome before this proposal could be accepted. For example, Molnar's (1971) study indicated that the elements synthesized during the helium flash in Edwards' model would likely be those of the *r*-process. Furthermore, other recent authors (e.g., Tomasko 1970; Demarque and Mengel 1971), using somewhat different theoretical treatments, have found that the helium flash has less drastic consequences than found by Edwards, so that the star is expected to proceed fairly smoothly into the horizontal-branch phase.

Nevertheless, the writer suggests that such evidence as the apparent mass loss between the red-giant and horizontal-branch stages indicates that the helium flash may indeed be more violent than generally supposed. It does not seem impossible that in some rare cases significant mixing of the star does occur during this event.

ii) *Helium Shell Flashes*

As a horizontal-branch star exhausts helium in its core, it once again ascends the red-giant branch, this time as an asymptotic-giant-branch star. Theoretical calculations (Schwarzschild and Härm 1967) show that the helium-burning shell does not generate energy at a constant rate, but instead produces energy primarily during short flashes. During a helium shell flash, the region just outside the helium-burning shell becomes unstable to convection. The resulting mixing, if it extends upward into the unprocessed regions of the star, leads to the *s*-process as well as the upward movement of carbon produced by helium burning (Sanders 1967). It was proposed by Cameron and Fowler (1971) that the additional energy released by mixing-induced nuclear reactions might enlarge the convective zone until it joins the base of the outer convective envelope of the star, thereby mixing the processed material all the way up to the surface. This mechanism has been studied in more detail by Sackmann, Smith, and Despain (1974), who found that in a star of solar mass the first helium shell flash alone generates enough carbon to produce a Population II carbon star upon mixing to the surface.

It thus appears well established that element synthesis can occur at this stage. The ultimate fate of a helium-shell-flashing star is not yet known. It seems not unlikely that, in some cases, the flashes might become violent enough to mix the star in a manner somewhat similar to that suggested by Edwards for the helium core flash.

b) *Consequences of the Substantial-Mixing Hypothesis*

Let us assume that the subgiant CH stars have gone through a stage of considerable mixing, during one of the phases just mentioned. We ask how the star will evolve following the mixing that produces the surface abundance anomalies.

It seems unlikely that the subgiant CH stars have been *completely* mixed. This would move the star all the way back to the main sequence appropriate to its composition. There is no strong evidence that the subgiant CH stars are this faint, or that there is the clump of such stars expected at the relatively long-lived main-sequence phase. We therefore consider only partially mixed stars.

Rood (1970) has studied the evolution of low-mass Population II stars following mixing of some envelope material into the stellar core at the helium core flash. As a result of the mixing, a star moves part way from

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the giant-branch tip down toward the main sequence (the exact new location in the H-R diagram depending on the assumed degree of mixing and other parameters), and enters a second phase of core *hydrogen burning*. The star's subsequent evolution is along a track parallel to, but at a somewhat higher luminosity than, its original hydrogen-burning evolution; but because of its smaller fuel supply, the star now evolves on a much shorter time scale. After a few times 10^8 years, the star once again begins to ascend the giant branch; there is ample time for any technetium mixed up to the surface to decay, as was already concluded in § III.

If the mixing into the core occurs later in the star's evolution, for example at the helium-shell-flashing stage, its subsequent evolution should be qualitatively similar to that described by Rood. This is because one again would have a model with a hydrogen-burning core composed of essentially inert material plus an admixture of hydrogen. The evolutionary time scale in this case would be even shorter than for the post-helium-flash model.

Figure 5 shows schematically the evolution proposed for Population II carbon stars. Partial mixing gives rise to the subgiant CH stars, which then evolve as described by Rood and, as they ascend the giant branch, become giant CH stars. This hypothesis, if correct, should have several observable consequences, which will now be examined.

i) *Distribution of Colors*

If the CH stars evolve as indicated in figure 5, their color distribution should show a blue cutoff, a group of slowly evolving subgiants, a Hertzsprung gap across

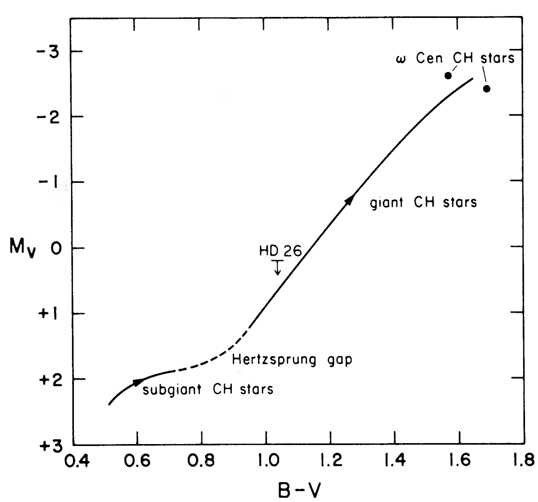

FIG. 5.—Proposed evolutionary scheme for Population II carbon stars. Following the mixing event that brings processed material to the surface, the star evolves as a subgiant CH star, moves rapidly across the Hertzsprung gap, and then climbs the giant branch as a giant CH star with strong C_2 bands. Except for the positions of the CH stars in the globular cluster ω Centauri (Wing and Stock 1973) and the upper limit for HD 26 assuming it is gravitationally bound to the galaxy, the evolutionary track is intended to be schematic only.

which evolution is rapid, and finally a group of cool stars that are evolving up the giant branch.

Inspection of figures 3 and 4 shows the expected behavior: the subgiant CH stars first appear at $B - V \simeq 0.5$; there is a Hertzsprung gap from about $B - V = 0.7$ to 1.0; and then there is the reddest subgiant CH star, HD 55496, followed by a sequence of giant CH stars. (A gap in the giant CH star colors at $B - V = 1.2$ to 1.4, if real, is not explained.) The blue cutoff and Hertzsprung gap are not likely to be due to observational selection, since stars with the abundance anomalies of the subgiant CH stars could easily be recognized on the objective-prism survey plates if they existed in either unpopulated region.

ii) *Relative Numbers per Unit Volume*

Under the partial-mixing assumption, the subgiant CH stars are in a longer-lived evolutionary phase than the giant CH stars. Therefore, the former should be more common per unit volume of space.

The number of giant CH stars brighter than the tenth visual magnitude known to the writer is 13. Although new giant CH stars continue to be discovered at a low rate (e.g., Bond 1970*c* and § V of this paper), the sample now known must be very nearly complete, in view of the ease of detecting C_2 bands at low spectral resolution.

Table 1 lists eleven subgiant CH stars; as described in § II, this sample is still incomplete, and the total number brighter than tenth magnitude is probably 40–50. To compare the numbers per unit volume, the ratio of ~ 3.5 must be multiplied by $10^{0.6\Delta M}$, where ΔM is the difference in absolute magnitude between the two groups of stars. It is difficult to choose ΔM, since M_v is not known accurately for either group; and if our evolutionary scheme is correct, there is a large range of luminosities among the giant CH stars. As a crude estimate, we adopt $\Delta M \simeq 2$–3 mag from § IV, with the result that the subgiant CH stars are ~ 50–200 times more common per unit volume than giant CH stars. Our expectation of a higher space density for the subgiant CH stars is thus borne out.

iii) *Dependence of Absolute Magnitude on Color*

It is expected under our hypothesis that the subgiant CH stars will have a small range of absolute magnitudes, with the bluest CH stars being slightly brighter, and the remaining, redder CH stars showing progressively higher luminosities. In § IV we already showed that the subgiant CH stars are fainter as a group than the giant CH stars. Among the giant CH stars, the only ones with well-determined absolute magnitudes are the two in the globular cluster ω Centauri, which are rather luminous at $M_v \simeq -2.5$ (Wing and Stock 1973). These objects do have moderately red colors, in agreement with our hypothesis. The expected substantial range in the luminosities of giant CH stars is definitely established by the large proper motion of HD 26. This star, the bluest of the giant CH stars, is escaping from the galaxy if it is brighter than $M_v = +0.2$.

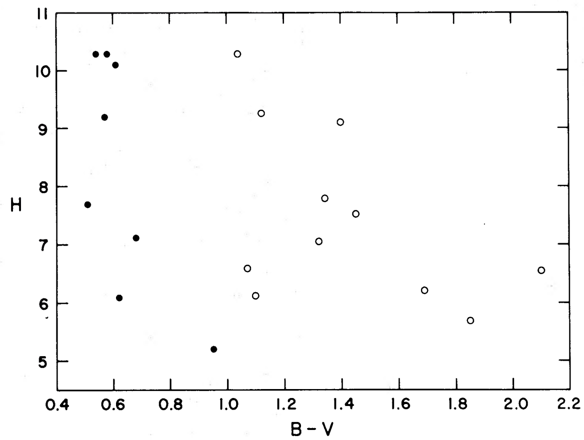

FIG. 6.—Plot of reduced proper motion, $H = m_v + 5 \log \mu + 5 = M_v + 5 \log V_T - 3.38$, versus $B - V$ color index for subgiant CH stars (*filled circles*) and giant CH stars (*open circles*). In agreement with the scheme of fig. 5, the subgiant CH stars and the bluest giant CH stars have similar values of H, but the redder giant CH stars have smaller values of H.

An indirect check has been made in figure 6, where the reduced proper motion H is plotted against $B - V$ for the subgiant and giant CH stars. The figure is at least not inconsistent with an expected upper envelope starting at the highest values of H for the bluest stars and declining thereafter slowly at first, then rapidly among the giant CH stars.

iv) *Existence of Subgiant* CH *Stars in Globular Clusters*

If the CH stars evolve as suggested, they should be recognizable in the color-magnitude diagrams of globular clusters. Unfortunately, the giant CH stars probably mingle with the numerous hydrogen-burning giants, so we should expect to see only a subgiant sequence starting at $B - V \simeq 0.5$ to 0.6 and $M_v \simeq +2$, and merging redward into the giant branch. Since the subgiant CH star stage probably lasts at most a few percent of the hydrogen-burning lifetime, these stars will be quite rare and would be seen only in the most thoroughly studied clusters.

Inspection of White's (1970) atlas of globular-cluster color-magnitude diagrams shows that few globular clusters have yet been studied to the required degree of thoroughness. Nevertheless, almost all clusters that have been observed down to the requisite absolute magnitudes show stars lying to the blue of the subgiant branch. Perhaps with some imagination, sequences of stars showing the behavior expected of subgiant CH stars can be discerned in the diagrams for NGC 4147, ω Cen, NGC 5466, and NGC 6397. Although these stars are generally quite faint, spectra could be obtained with modern techniques to ascertain whether they in fact show the peculiarities illustrated in figure 1. One logically might start with ω Cen, which already is known to contain two giant CH stars and should therefore contain many subgiant CH stars.

c) *Do all Low-Mass Stars Become Subgiant Carbon Stars?*

i) *Population II*

If the mixing hypothesized to explain the CH stars occurs at the helium core flash, we can be sure that the vast majority of Population II stars do not become CH stars. Since the horizontal-branch lifetime is comparable to the lifetimes found by Rood (1970) for the partially mixed stars, these two groups of stars should be present in globular clusters in the proportions that stars choose one path or the other. It is clear from globular-cluster color-magnitude diagrams that the horizontal-branch stars greatly outnumber the subgiant CH stars. (The possibility that all stars become CH stars *first*, and later horizontal-branch stars, can be ruled out because horizontal-branch stars are not known to show the abundance anomalies of CH stars.) We therefore agree with most other authors that most—if not all—Population II red giants become horizontal-branch stars subsequent to the helium flash.

If the mixing occurs at the helium shell flash, CH stars are post–horizontal-branch stars. Their subgiant phases, as mentioned earlier, would then be briefer; and even if all Population II stars become CH stars, the horizontal-branch stars would still greatly outnumber them in a cluster. Without a better idea of the subgiant lifetime, we cannot decide whether all horizontal-branch stars become CH stars or not.

ii) *Population I*

It is significant that all of the early G-type stars found by the writer to show enhanced CH and *s*-process elements show metallic-line weakening to some extent; this is not an observational selection effect, since the writer found large numbers of somewhat cooler Ba II stars with metallic lines of normal strength on the same objective-prism plates. Therefore, it probably can be concluded that Population I stars do not pass through a subgiant-carbon-star phase, presumably because they never undergo a substantial degree of mixing. A theoretical explanation of this difference between the two populations would be of considerable interest.

There is evidence that at least in some Population I carbon stars the mixing of processed material to the surface occurred while the star was on the giant branch. This is shown by the presence of lines of technetium in the spectra of several luminous N-type stars (see Wallerstein 1973); because of the short half-life of technetium, these stars can hardly have had time to undergo any significant evolutionary changes since the mixing event.

VII. SUMMARY

The discovery of a new class of peculiar G-type stars has led to a new interpretation of the evolution of Population II carbon stars. These new objects show all the spectroscopic, kinematic, and photometric properties expected of stars of the same composition as, but hotter and less luminous than, the well-known CH stars. It is proposed that these objects acquire their surface abundance anomalies in mixing so extensive that the star moves part way back toward the main sequence in the H-R diagram. The star then evolves initially as a "subgiant CH star" of the new class described here. Later, during its second—or third—ascent of the giant branch, the star is a (giant) CH star cool enough to show strong C_2 bands. All of the available evidence is consistent with this hypothesis. Observations of faint subgiants in globular clusters are suggested as a check on these ideas.

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