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# SOME INTRINSIC PROPERTIES OF CARBON STARS

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## ABSTRACT

Near-infrared spectrograms of moderate dispersion have been employed to establish a new two-dimensional classification scheme for carbon stars which involves temperature and luminosity. Intrinsic colors of the spectral subtypes were determined, and these were employed to construct a color-color diagram which clearly separated out the early- and late-type stars. A galactic-rotation solution, using radial velocities and intrinsic colors, yielded a mean absolute magnitude of −2.7 for the middle carbon stars. This value was employed to construct the ($M_{\rm bol}$, log $T_e$)-diagram for these stars which were found to form an extension of the normal giant branch to cooler temperature.

## I. INTRODUCTION

Stars exhibiting strong bands of $C_2$ and CN were arranged into two classes, R and N, by Cannon (1918) in the Henry Draper Catalog. Shane (1928), working in the blue and ultraviolet spectral regions at low dispersion, extended the classification scheme developed at Harvard.

In 1941, Keenan and Morgan proposed a two-dimensional classification scheme for these stars which involved temperature and carbon abundance. Their criteria were equivalent blue spectral types, the strength of the D-lines of Na (λλ5890, 5896), the relative intensities of stretches of continuum, and ratios of band strengths. Stars on their system were classified $C0_x$–$C9_x$, where the temperature ranged from 4500° K at C0 to about 2500° K at C9, and where the carbon-abundance parameter $x$ ranged from 1 through 5.

The Keenan-Morgan C system is open to a number of serious objections. The D-lines can be contaminated by the strong interstellar lines of sodium if one attempts to extend the scheme to the more distant carbon stars. The usefulness of the D-lines is restricted to the later carbon stars because in the earlier ones a broad region of absorption extending from λ5750 to λ6050 nearly obliterates these lines. The most serious objection, however, is the poor correlation between C class and the temperatures of carbon stars derived from multicolor photometry. This point will be discussed in § II.

The major impetus for a new classification scheme comes from the recent multicolor photometry of carbon stars carried out by Mendoza V. and Johnson (1965) and Mendoza V. (1967). The observations are on the wide-band *UBVRIJKLMN* system of Johnson (1966), and extend from 0.36 to 10.2 $\mu$. From their data these authors calculated bolometric corrections (B.C.) and effective temperatures for a number of carbon stars. The effective temperatures discussed below were derived from the calibration of the $(I - L)$ index (Johnson 1966). It should be kept in mind that although these are referred to as effective temperatures, they are in actuality color temperatures and may systematically differ from effective temperatures by an additive constant.

These temperatures have been used as a zero point to establish a new classification

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scheme in the near-infrared region (λλ7500–8900) for carbon stars. The intrinsic redness of these stars, coupled with the decrease in interstellar absorption with longer wavelength, results in greatly increased efficiency in this spectral region over the blue region.

Slit spectra having a dispersion of 124 Å $mm^{-1}$ were employed. These were obtained by using the 36-inch telescope at Cerro Tololo. A spectrum of a star of visual magnitude 7.5 with $V - I = 3.5$ (a typical carbon-star value) could be obtained in about 30 minutes with a slit width projected on the sky of 2″.0. All spectra were photographed on hypersensitized I-N plates.

The photoelectric observations discussed in § V were obtained with the 16-inch telescopes on Cerro Tololo within four weeks of the spectroscopic observations.

## II. RESULTS FROM MULTICOLOR PHOTOMETRY

Johnson (1966) has determined that the photometric index $(I - L)$ is well correlated with effective temperature for stars hotter than about 3000° K. For stars cooler than this he has fitted blackbody curves to his multicolor data to determine effective temperatures. This raises the serious question of whether these cool stars do, in fact, radiate as blackbodies.

Bahng (1966) has shown that carbon stars in the wavelength region 1.2–2.1 $\mu$ radiate more nearly as blackbodies than do the M stars. However, if there is an opacity caused by graphite surrounding carbon stars (Hoyle and Wickramasinghe 1962), this may redistribute the continuum radiation to such an extent that the observed energy distribution gives little or no information about the true temperature. This objection is important and in the final analysis must be answered. However, until more data are available on radii and opacities in cool stars, Johnson's method of determining effective temperatures must be considered the best presently available for carbon stars.

Hence, by using Johnson's (1966) technique together with the data of Mendoza V. and Johnson (1965) and Mendoza V. (1967), the bolometric corrections and effective temperatures of carbon stars listed in Table 1 can be derived.

These effective temperatures can be used to make a detailed comparison with the C system of Keenan and Morgan. Figure 1 plots the effective temperatures of the stars in Table 1 against their Keenan-Morgan types, when known.

Clearly there is no linear correlation between the two. The lowest temperatures occur from classes C4–C6, with the exception of one C9 star (U Cyg). The scatter is large. Hence it must be concluded that the C system, at least for C4–C9, is not a temperature sequence.

## III. INFRARED SPECTRAL CLASSIFICATION

It was shown by Sharpless (1956) that the infrared triplet of Ca II (λλ8498, 8543, 8662) behaves consistently with the temperature in M-type stars; the cooler the temperature, the weaker the lines. In the cooler carbon stars the two Ca II lines farthest to the blue are blended with nearby CN features and are difficult to use. However, the line at λ8662 is in a relatively clear region and in carbon stars is a sensitive indicator of the temperature.

A description of the infrared spectral classes follows. The C notation has been maintained throughout, although the class to which a star belongs on this infrared scheme is generally not the same as its Keenan-Morgan type. Even though the classes have been numbered continuously (C0–C9), this does not necessarily imply a continuous range of physical parameters.

*C0–C2.*—The hottest carbon stars are characterized in the near-infrared by very weak CN bands in the region λλ7895–8100 and by extremely strong Ca II lines. The spectra of these stars are, in fact, rather featureless except for the Ca II lines. At C0 the Ca II lines are the strongest observed in any carbon star, and their absolute intensity can be used to classify them at this type. The continuum features (which appear as

TABLE 1

BOLOMETRIC CORRECTIONS AND EFFECTIVE TEMPERATURES OF CARBON STARS

| Star | B.C. | $T_e$ (° K) |
|---|---|---|
| HD 156074 | −0.35 | 4400 |
| HD 182040 | −0.21 | 4300 |
| HD 188934 | −1.54 | 3800 |
| 8°2654 | −0.89 | 3200 |
| HD 113801 | −0.46 | 3000 |
| 17°3325 | −0.60 | 3000 |
| 2°3336 | −1.69 | 2700 |
| HD 189711 | −1.81 | 2600 |
| 19 Psc | −2.74 | 2530 |
| U Hya | −2.52 | 2500 |
| HD 133332 | −2.17 | 2500 |
| WZ Cas | −3.53 | 2420 |
| HD 166097 | −1.37 | 2400 |
| RS Cyg | −3.36 | 2400 |
| DS Peg | −2.73 | 2400 |
| HD 92839 | −2.60 | 2375 |
| HD 180953 | −2.83 | 2375 |
| HD 168227 | −2.87 | 2300 |
| RY Dra | −3.24 | 2175 |
| SV Cyg | −3.83 | 2100 |
| LW Cyg | −4.13 | 2090 |
| RX Sct | −4.21 | 2085 |
| T Cnc | −4.67 | 2050 |
| T Lyr | −4.77 | 2000 |
| V CrB | −4.63 | 1975 |
| U Cyg | −4.34 | 1775 |

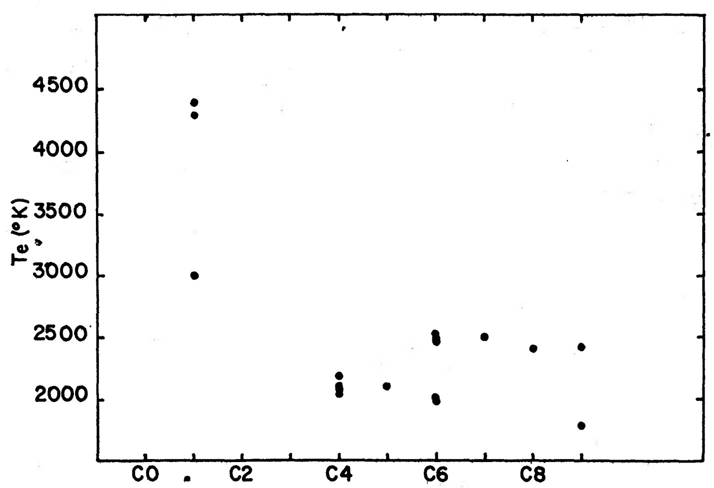


FIG. 1.—Comparison of the effective temperatures of carbon stars determined from the calibration of the index $(I - L)$ with their Keenan-Morgan C types.

emission lines at λλ8452, 8462, 8474, and 8508) are present but very weak. By class C2 the Ca II has noticeably weakened.

C3.—By the time a star reaches this class, the CN features have become very conspicuous and dominate the spectra from this type onward. The band heads at λλ7852, 7876, and 7899 are first well marked at this type. The Ca II lines are weaker than in class C2, but at C3 the lines at λλ8498 and 8543 still show clearly above the CN blends. An unidentified sharp absorption line at λ8582 is first seen at this class.

C4.—At C4 the Ca II line at λ8498 is just barely visible above the CN blend, while the line at λ8582 remains conspicuous. From this type onward the best criterion is the ratio of the Ca II line at λ8662 to the nearby line at λ8648 (probably due to CN) which remains relatively constant. At C4 this ratio is about 5.

C5.—The ratio of Ca II at λ8662 to λ8648 is about 3 at this class. The Ca II line at λ8498 has ceased to be visible above the CN blend, and the line at λ8582 disappears at this type and never reappears at later classes.

C6.—At this type Ca II λ8662/λ8648 is slightly greater than unity. The Ca II line at λ8543 is completely blended here with CN features.

C7.—At C7 the spectra undergo a marked change from the previous class. The ratio of Ca II λ8662/λ8648 is about unity, but some of the continuum features have changed. In classes C3–C6 all the features have remained relatively constant in strength, but at C7 the feature at λ8462 has completely disappeared while the one at λ8508 has greatly weakened relative to the ones at λ8452 and λ8474.

C8.—At C8 the weakened continuum features persist. The one at λ8452 becomes weaker than at C7. All Ca II lines have totally disappeared. In fact, the entire spectrum has a veiled appearance. The CN throughout this spectral region has decreased in intensity to the extent that this type resembles classes C0–C2 except for the Ca II lines. The K I line at λ7699 becomes weakly apparent at this type.

C9.—At this class the K I doublet (λλ7665, 7699) appears very strongly, easily separating this type from the others. The Ca II line at λ8662 is very weak, if present at all.

Figure 2 (Plate 4) illustrates the infrared temperature sequence for carbon stars. On the basis of the strength of the Ca II triplet, the continuum features, and the K I doublet, temperature classification can be made easily to $\pm 1$ subdivision.

Table 2 lists the approximate effective temperatures corresponding to each class. These were derived exclusively from the $(I - L)$ data. The temperatures for classes C1 and C2 are interpolated values and are enclosed in parentheses. A complete listing of all the stars classified will be found in the Appendix.

With the data presently available it is not possible to estimate the variations with phase in either temperature or C class. For this purpose we would require spectra throughout the cycle of variation of a star, and this is generally not available.

TABLE 2

APPROXIMATE EFFECTIVE TEMPERATURES OF C CLASSES

| C Type | $T_e$ (° K) | C Type | $T_e$ (° K) |
|---|---|---|---|
| C0.......... | 4400 | C5........... | 2450 |
| C1.......... | (3800) | C6........... | 2300 |
| C2.......... | (3200) | C7........... | 2200 |
| C3.......... | 2700 | C8........... | 2000 |
| C4.......... | 2600 | C9........... | 1800 |

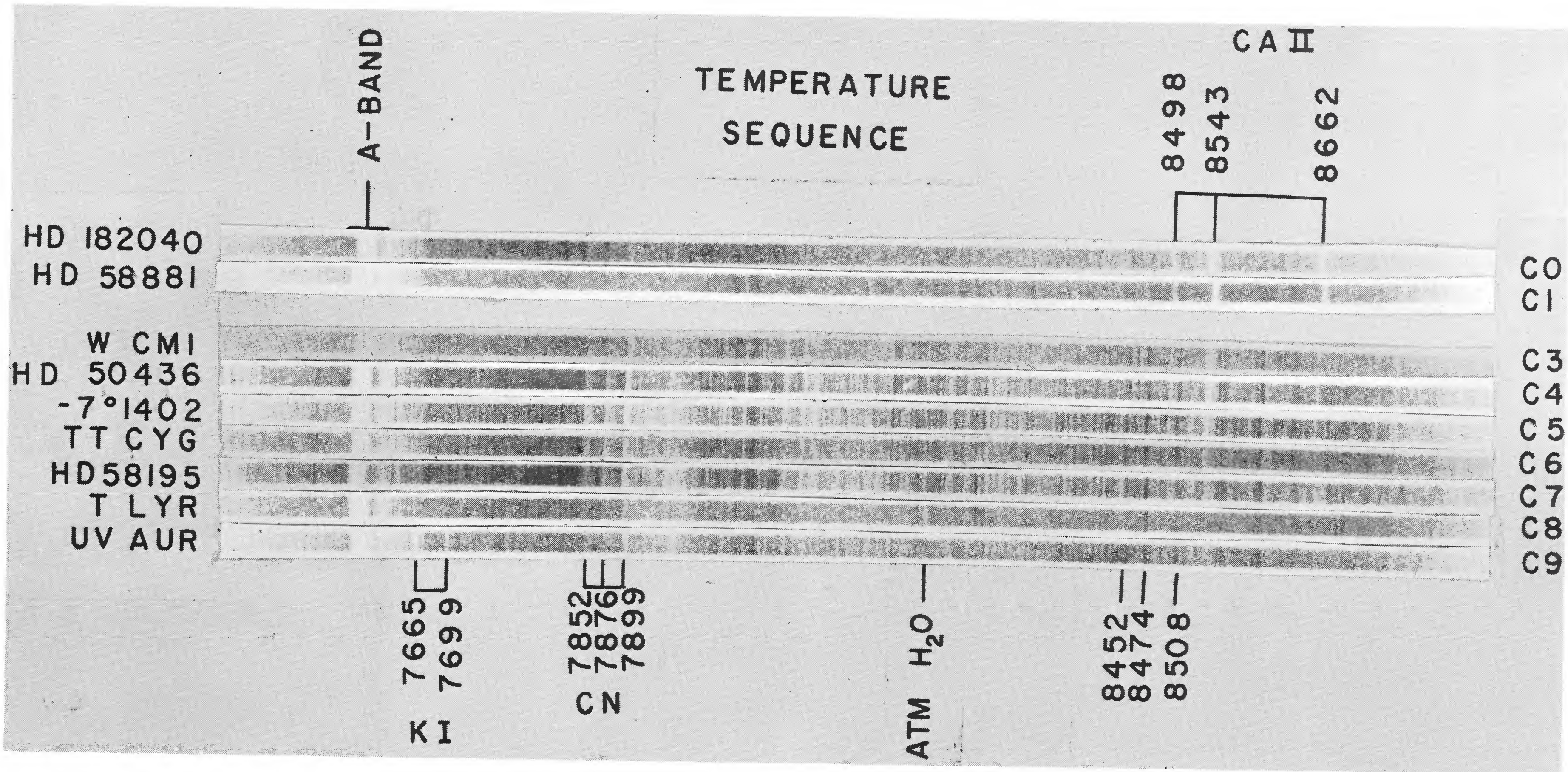


FIG. 2.—A sequence of carbon star spectra showing the change in spectral features in the near infrared with temperature. Original dispersion 124 Å $mm^{-1}$.

RICHER (*see* page 524)

## IV. PECULIAR STARS

There are several stars whose spectral features do not allow them to be placed in any of the above classes. Two of these, U Cyg (phase = 0.06) and RZ Peg (phase = 0.15), exhibit emission in the Ca II triplet just after maximum light. Near minimum light, U Cyg is spectroscopically identical to UV Aur, which would place it in class C9 at this phase. The spectrum of RZ Peg is illustrated in Figure 3 together with the C5 star RS Cyg.

The carbon star WZ Cas also exhibits a peculiar spectrum in the near-infrared region. According to the strength of the Ca II lines and the continuum features it is placed at class C5 (in agreement with the effective temperature of 2420° K derived by Mendoza V. 1967). However, it exhibits very strong K I lines. This star has other peculiarities. In the red spectral region it has extremely strong Na I D-lines and the strongest Li I (λ6708) line of any star known. Figure 3 (Plate 5) shows a spectrum of WZ Cas together with the normal C5 star HD 92839.

## V. INTRINSIC COLORS OF CARBON STARS

Within four weeks of the spectroscopic observations, photometric $UBV$ magnitudes were determined for thirty-three late-type carbon stars. The mean errors are listed in Table 3. The large errors in the $U$-magnitude are due to the faintness of these stars in this spectral region.

In Figure 4, which consists only of C5 stars, we have plotted $[(U - B) - (B - V)]$ versus $(U - B)$. On a diagram of this sort the reddening trajectory will have slope $1 - E_y/E_u$. A least-squares solution of the data in Figure 4 yields $E_u/E_y = 8.3$. This unacceptably large number must be due, in the main, to intrinsic ultraviolet opacity which is clearly not a constant at a particular spectral type.

TABLE 3

ERRORS IN PHOTOMETRIC OBSERVATIONS

| | |
|---|---|
| Error in $V$ .................... | ±0.05 mag |
| Error in $(B-V)$ ............... | ±0.03 mag |
| Error in $(U-B)$ ............... | ±0.19 mag |

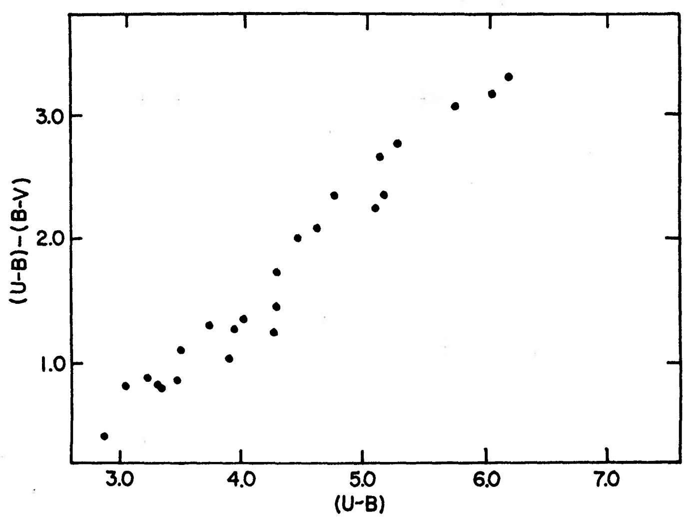


FIG. 4.—$[(U - B) - (B - V)]$ plotted against $(U - B)$ for C5 stars only

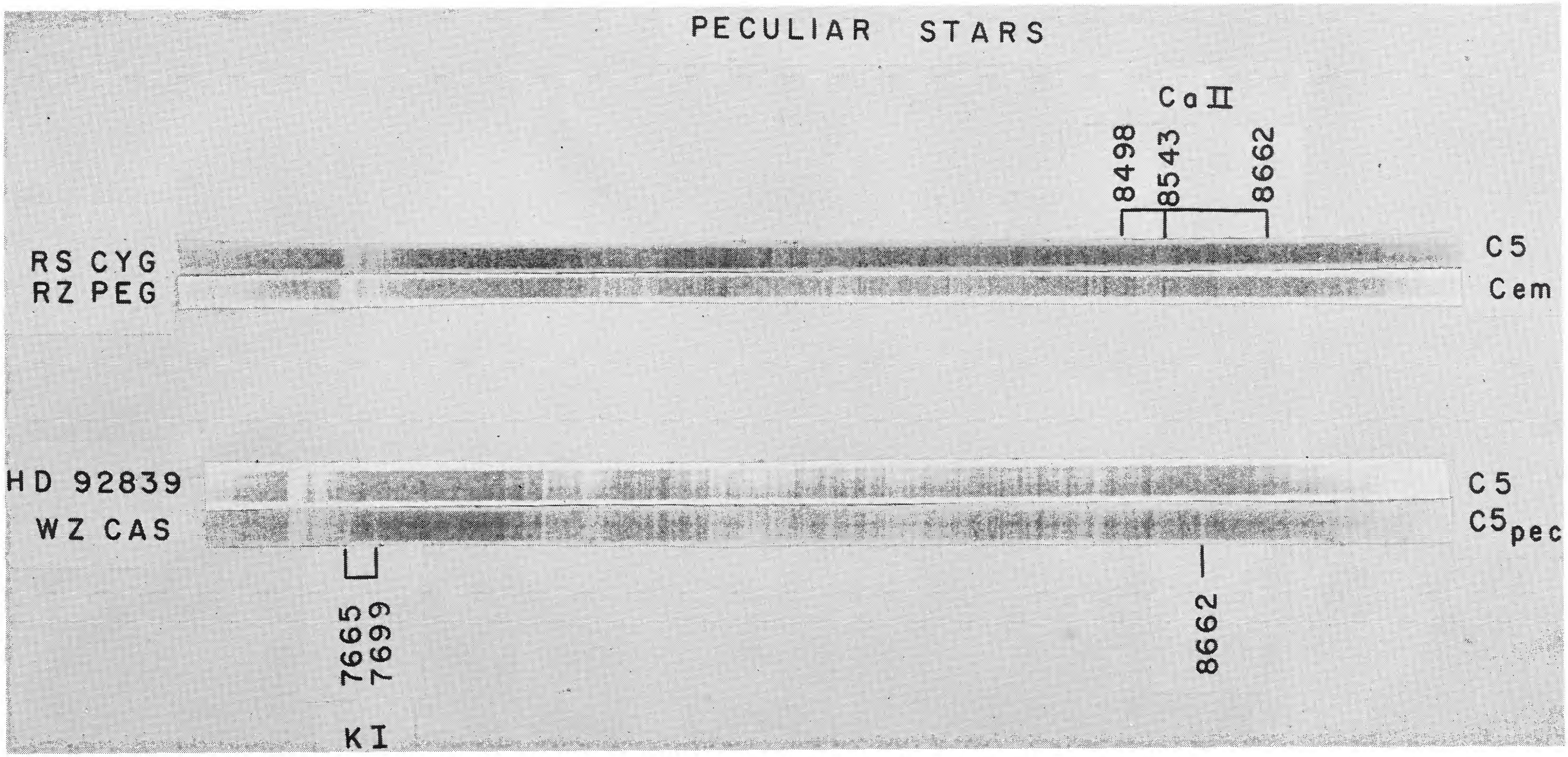


FIG. 3.—Carbon stars exhibiting peculiar spectra in the near-infrared. *Upper two spectra*, original dispersion 124 Å mm$^{-1}$. *Lower two spectra*, original dispersion 114 Å mm$^{-1}$.

RICHER (*see* page 525)

To determine the reddening, we plotted $[(U - B) - (B - V)]$ versus $(U - B)$ for the thirty-three stars observed here, together with twenty stars observed by Mendoza V. and Johnson (1965) (Fig. 5). All C0–C2 stars are plotted with open circles while the C3–C7 stars are indicated by closed circles. Two points about this figure are immediately obvious: (*a*) the C0–C2 stars form a well-separated group from the C3–C7 stars; (b) both groups follow compact loci in this plane with well-defined upper envelopes.

We shall consider the C3–C7 stars first. The five stars of this class that form an upper envelope are listed in Table 4.

Note especially that these stars are well removed from the galactic plane (and hence less reddened), and are all quite bright (and hence relatively close to the Sun). We assume, then, that these five stars are all reddened by the same amount, and we take this amount to be zero. All other C3–C7 stars plotted fall off the straight line defined by these stars because they are reddened. The amount of reddening was found to be rather insensitive to the slope of the reddening trajectory chosen. The use of values of $E_u/E_y$

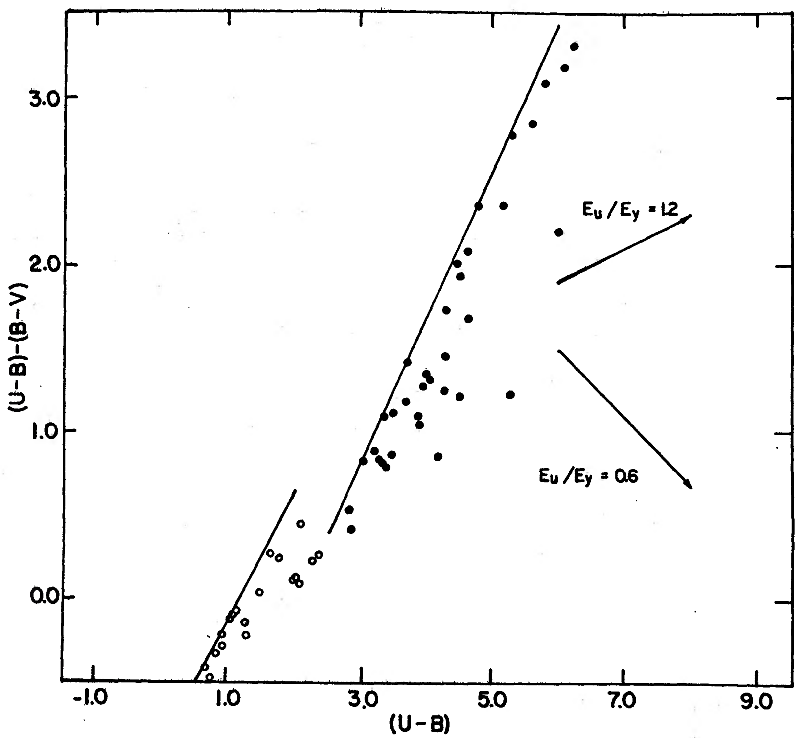


FIG. 5.—$[(U - B) - (B - V)]$ plotted against $(U - B)$ for 53 carbon stars. *Open circles*, C0–C2; *closed circles*, C3–C7.

TABLE 4

UPPER ENVELOPE FOR C3–C7 STARS

| Star | $b$ | $(U-B)-(B-V)$ | $(U-B)$ | $V$ |
|---|---|---|---|---|
| HD 88539...... | +18° | 0.82 | 3.04 | 6.63 |
| HD 37212...... | −26° | 1.08 | 3.37 | 7.82 |
| T Ind.......... | −46° | 1.41 | 3.72 | 5.96 |
| HD 92839...... | +46° | 2.36 | 4.77 | 6.00 |
| DS Peg......... | −14° | 2.78 | 5.30 | 6.05 |

from 0.60 to 1.20 never changed the reddening by more than 0.06 magnitudes for any star. For the actual calculation of the intrinsic colors and the reddening, $E_u/E_y = 0.70$ was used, a smoothed value for early-type stars. As long as the real value of $E_u/E_y$ for carbon stars lies within $\pm 0.3$ of 0.70, these intrinsic colors and color excesses should be accurate to $\pm 0.05$ mag.

Table 5 lists the C3–C7 stars, together with their observed and intrinsic colors and their color excesses. The stars are arranged in order of increasing galactic longitude.

With the understanding that there are large variations in the intrinsic colors at a given spectral type, we may calculate the mean colors for each type. These are tabulated in Table 6, together with the standard error in the mean. These colors certainly lend credence to the reality of the spectral classification scheme proposed in § III.

The intrinsic colors of the C0–C2 stars were derived in a similar manner. In their case, however, we have spectra of only five stars in the sample as most of these data have been taken from Mendoza V. and Johnson (1965). The assignment of these stars to the classes C0–C2 is in general based on their colors; they are all too blue to be C3 or later. For these stars, the upper envelope in the $[(U - B) - (B - V)]$ versus $(U - B)$ plane consists of the seven stars listed in Table 7. Again, if we adopt $E_u/E_y = 0.70$, we can derive the intrinsic colors and color excesses of Table 8. The mean intrinsic colors of C0 and C1 subtypes are listed in Table 9.

TABLE 5

COLORS OF C3–C7 STARS

| Star | Spectral Type | $V$ | $(U-B)_{obs}$ | $(U-B)_0$ | $(B-V)_{obs}$ | $(B-V)_0$ | $E_y$ |
|---|---|---|---|---|---|---|---|
| V Oph | C5 | 7.35 | 4.65 | 4.22 | 2.97 | 2.37 | 0.60 |
| HD 180953 | C5 | 7.02 | 4.47 | 4.42 | 2.46 | 2.39 | 0.07 |
| UW Sgr | C3 | 9.29 | 3.70 | 3.52 | 2.52 | 2.28 | 0.24 |
| AQ Sgr | C5 | 7.31 | 4.19 | 3.41 | 3.34 | 2.27 | 1.07 |
| RX Sct | C5 | 7.97 | 5.11 | 4.80 | 2.86 | 2.44 | 0.42 |
| S Sct | C5 | 6.69 | 6.22 | 5.98 | 2.91 | 2.58 | 0.33 |
| RS Cyg | C5 | 7.48 | 3.90 | 3.48 | 2.86 | 2.28 | 0.58 |
| DS Peg | C5 | 6.05 | 5.30 | 5.30 | 2.52 | 2.52 | 0.00 |
| 19 Psc | C5 | 4.90 | 3.31 | 3.12 | 2.48 | 2.23 | 0.25 |
| SU And | C5 | 8.19 | 4.30 | 4.15 | 2.57 | 2.36 | 0.21 |
| WZ Cas | C5 pec | 7.16 | 4.29 | 3.92 | 2.84 | 2.33 | 0.51 |
| Y CVn | C7 | 5.43 | 5.59 | 5.41 | 2.75 | 2.51 | 0.24 |
| Z Psc | C5 | 6.85 | 3.40 | 3.12 | 2.61 | 2.23 | 0.38 |
| HD 92839 | C5 | 6.00 | 4.77 | 4.77 | 2.41 | 2.41 | 0.00 |
| UU Aur | C5 | 5.60 | 5.15 | 4.81 | 2.91 | 2.44 | 0.47 |
| HD 38572 | C4 | 8.26 | 4.01 | 3.75 | 2.67 | 2.31 | 0.36 |
| HD 30710 | C4 | 9.40 | 4.07 | 3.74 | 2.76 | 2.31 | 0.45 |
| Y Tau | C5 | 6.54 | 6.07 | 5.83 | 2.89 | 2.56 | 0.33 |
| BL Ori | C5 | 6.40 | 3.50 | 3.42 | 2.39 | 2.27 | 0.12 |
| RT Ori | C6 | 7.99 | 5.18 | 4.90 | 2.82 | 2.45 | 0.37 |
| MSB 17 | C5 | 9.92 | 3.94 | 3.67 | 2.67 | 2.30 | 0.37 |
| −7°1402 | C5 | 9.96 | 3.34 | 3.12 | 2.53 | 2.23 | 0.30 |
| W CMa | C5 | 6.77 | 4.63 | 4.52 | 2.54 | 2.40 | 0.14 |
| HD 37212 | C4 | 7.82 | 3.37 | 3.37 | 2.29 | 2.29 | 0.00 |
| T Cae | C5 | 7.77 | 3.22 | 3.14 | 2.34 | 2.24 | 0.10 |
| HD 51208 | C3 | 6.34 | 2.84 | 2.75 | 2.31 | 2.19 | 0.12 |
| U Hya | C5 | 4.82 | 5.78 | 5.66 | 2.69 | 2.54 | 0.15 |
| HD 65424 | C5 | 7.85 | 4.27 | 3.75 | 3.02 | 2.31 | 0.71 |
| HD 88539 | C5 | 6.63 | 3.04 | 3.04 | 2.22 | 2.22 | 0.00 |
| HD 20234 | C5 | 5.78 | 2.88 | 2.67 | 2.47 | 2.18 | 0.31 |
| HD 203133 | C5 | 6.21 | 3.48 | 3.21 | 2.62 | 2.25 | 0.37 |
| HD 206652 | C6 | 8.95 | 4.51 | 4.37 | 2.58 | 2.38 | 0.20 |
| T Ind | C5 | 5.96 | 3.72 | 3.72 | 2.31 | 2.31 | 0.00 |

TABLE 6

MEAN INTRINSIC COLORS OF C SUBTYPES

| Spectral Type | $(B-V)_0$ | $(U-B)_0$ | $n$ |
|---|---|---|---|
| C3 | 2.24±0.06 | 3.14±0.54 | 2 |
| C4 | 2.30±0.01 | 3.62±0.15 | 3 |
| C5 | 2.34±0.02 | 4.05±0.19 | 25 |
| C6 | 2.42±0.04 | 4.64±0.27 | 2 |
| C7 | 2.51 | 5.41 | 1 |

TABLE 7

UPPER ENVELOPE FOR C0–C2 STARS

| Star | $b$ | $(U-B)-(B-V)$ | $(U-B)$ | $V$ |
|---|---|---|---|---|
| −13°3407 | +45° | −0.49 | 0.56 | 8.80 |
| HD 182040 | −13° | −0.41 | 0.67 | 6.96 |
| HD 156074 | +34° | −0.22 | 0.92 | 7.61 |
| HD 113801 | +42° | −0.12 | 1.05 | 8.52 |
| HD 223392 | −53° | −0.10 | 1.07 | 8.17 |
| 23°2998 | +38° | −0.07 | 1.13 | 9.80 |
| 17°3325 | +19° | −0.05 | 1.13 | 8.72 |

TABLE 8

COLORS OF C0–C2 STARS

| Star | $V$ | $(U-B)_{obs}$ | $(U-B)_0$ | $(B-V)_{obs}$ | $(B-V)_0$ | $E_y$ |
|---|---|---|---|---|---|---|
| HD 16115 | 8.12 | 0.76 | 0.63 | 1.23 | 1.07 | 0.16 |
| −13°3407 | 8.80 | 0.56 | 0.56 | 1.05 | 1.05 | 0.00 |
| 8°2654 | 9.43 | 1.65 | 1.58 | 1.38 | 1.30 | 0.08 |
| HD 113801 | 8.52 | 1.05 | 1.05 | 1.17 | 1.17 | 0.00 |
| HD 122547 | 9.54 | 0.95 | 0.87 | 1.23 | 1.13 | 0.10 |
| HD 133332 | 10.46 | 1.28 | 1.10 | 1.42 | 1.18 | 0.24 |
| HD 137613 | 7.55 | 0.85 | 0.78 | 1.17 | 1.11 | 0.06 |
| 65°1055 | 10.34 | 1.50 | 1.33 | 1.46 | 1.24 | 0.22 |
| 19°3109 | 10.38 | 1.28 | 1.04 | 1.50 | 1.17 | 0.33 |
| 23°2998 | 9.80 | 1.13 | 1.13 | 1.20 | 1.20 | 0.00 |
| HD 156074 | 7.61 | 0.92 | 0.92 | 1.14 | 1.14 | 0.00 |
| 2°3336 | 9.40 | 2.03 | 1.59 | 1.91 | 1.30 | 0.61 |
| 17°3325 | 8.72 | 1.13 | 1.13 | 1.18 | 1.18 | 0.00 |
| HD 166097 | 10.03 | 1.77 | 1.62 | 1.53 | 1.31 | 0.22 |
| HD 168227 | 8.66 | 2.00 | 1.57 | 1.89 | 1.30 | 0.59 |
| HD 182040 | 6.96 | 0.67 | 0.67 | 1.08 | 1.08 | 0.00 |
| HD 188934 | 9.37 | 2.10 | 1.59 | 2.01 | 1.30 | 0.71 |
| HD 189711* | 8.37 | 2.28 | 1.77 | 2.06 | 1.34 | 0.72 |
| V Ari* | 8.83 | 2.39 | 1.84 | 2.13 | 1.36 | 0.77 |
| HD 223392 | 8.17 | 1.07 | 1.07 | 1.17 | 1.17 | 0.00 |

* CH star.

TABLE 9

MEAN INTRINSIC COLORS OF C0 AND C1 SUBTYPES

| Spectral Type | $(B-V)_0$ | $(U-B)_0$ | $n$ |
|---|---|---|---|
| C0.............. | $1.10 \pm 0.02$ | $0.74 \pm 0.09$ | 3 |
| C1.............. | 1.17 | 1.07 | 1 |

### VI. COLOR-COLOR DIAGRAM

From the intrinsic colors derived in § V, a color-color diagram can be constructed for carbon stars which is freed from interstellar absorption. This is illustrated in Figure 6. Individual points have not been plotted, because the previous analysis has already constrained the data to lie along straight lines. The locus of G and K giants in this plane is plotted by individual points. The mean colors for each spectral type are indicated.

Figure 6 sharply separates the C0–C2 stars from the later carbon stars by about 0.80 mag in $(B - V)$ and 0.75 mag in $(U - B)$. Neither the early nor the late carbon stars radiate as blackbodies in the *UBV* region.

### VII. ABSOLUTE MAGNITUDES OF CARBON STARS

#### *a*) *Statistical Study*

The existing data on the absolute magnitudes of carbon stars are, in general, sketchy and unreliable. Gordon (1968) has given a good summary of the subject.

The first-order conditional equation of differential galactic rotation, with a *K*-term included, was used to determine the mean absolute magnitude of the thirty-three C3–C7 stars of Table 5. The radial velocities of Sanford (1944) were used, together with the Standard Solar Motion. The ratio of total to selective absorption was assumed to be 3.0, and the value of *A* (Oort's constant) was taken to be 14 km sec$^{-1}$ kpc$^{-1}$ (Humphreys 1970).

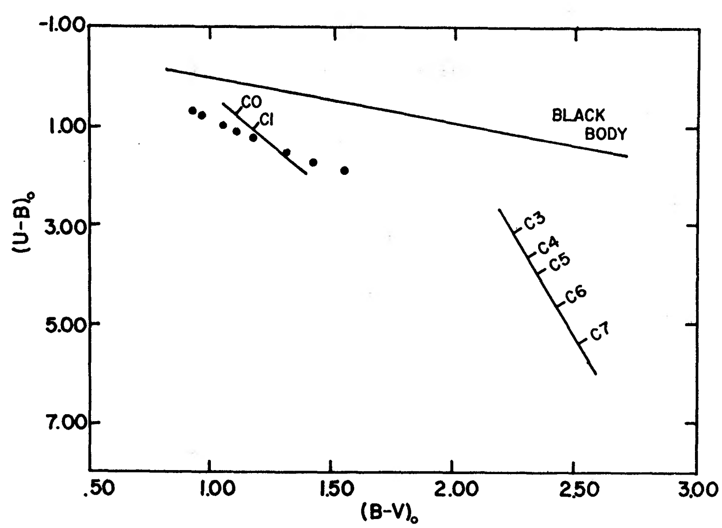


FIG. 6.—Color-color diagram for carbon stars. The intrinsic colors at each spectral type are marked. Locus of G and K giants is indicated by individual points.

The least-squares solution for $M_v$ and $K$ resulted in

$$M_v = -2.7 \pm 0.7 \quad \text{and} \quad K = 0.8 \pm 2.6 \,.$$

The $K$-term is consistent with zero. The result for the mean absolute magnitude is encouraging as Westerlund (1964) noted in his surveys of the Large Magellanic Cloud that the the carbon stars appeared at visual magnitude $15.7 \pm 0.5$. A distance modulus of 18.7 (Bok 1966) yields $M_v = -3.0 \pm 0.5$, in good agreement with the present result.

### b) *Spectroscopic Study*

In the near-infrared region Keenan and Hynek (1945) found numerous luminosity-sensitive lines in late-type stars (K0–M7). The most sensitive were those from low-level transitions of Ti I and Fe I. Many of these lines are not visible in the spectra of carbon stars, for they are often heavily blended with CN features.

However, several coincidences with low-level lines of Fe I and Ti I are seen. It is not surprising that Ti in atomic form is more abundant in carbon stars than in M stars, because the depletion of O relative to C in carbon stars makes it difficult to form TiO. The width of the observed coincidences with Fe I and Ti I lines indicates that these lines are probably blended with or are due entirely to CN. In any case, since it is well known that CN is sensitive to luminosity (Sharpless 1956), this will just tend to enhance any luminosity effects.

In spectral types C3–C7 two distinct groups have been isolated spectroscopically. In the first group (type I), all the lines coincident with low-level transitions of Fe I and Ti I are significantly stronger than in the second group (type II). This will be interpreted as a luminosity difference between the two groups in the sense that type I stars are intrinsically brighter than type II. It must be kept in mind, however, that this suggestion is only tentative. The correctness of the proposed scheme will have to wait until individual absolute magnitudes of a number of carbon stars are accurately derived.

Table 10 lists the wavelengths and possible identifications of the features used in the proposed luminosity classification for stars of type C3–C7. All CN identifications are from Davis and Phillips (1963).

TABLE 10

LUMINOSITY-SENSITIVE FEATURES IN CLASSES C3–C7

| λ (Å) | Possible Identification | Multiplet (Atomic) or Band Sequence (Molecular) |
|---|---|---|
| 8311 | Fe I 8311.0 | 12 |
| | CN 8311.1 | (3,1) |
| 8328 | CN 8328.3 | (4,2) |
| | CN 8328.6 | (4,2) |
| 8382 | Fe I 8382.2 | 12 |
| | Ti I 8382.5 | 33 |
| | Ti I 8382.8 | 33 |
| | CN 8382.8 | (3,1) |
| 8426 | Fe I 8425.9 | 12 |
| | Ti I 8426.5 | 33 |
| | CN 8247.1 | (2,0) |
| | CN 8427.0 | (3,1) |
| | CN 8427.0 | (4,2) |
| 8447 | Fe I 8447.6 | 12 |
| | CN 8447.8 | (3,1) |
| | CN 8446.3 | (4,2) |

Figure 7 (Plate 6) illustrates a sequence of C3–C7 stars classified provisionally according to luminosity. The strengthening of all the features of Table 10 can easily be seen.

Of the thirty-three stars used in the analysis of § VII*a*, thirty-two were of type II. Hence, for this group we may assign a mean visual absolute magnitude of $-2.7$. It is not possible with the data presently available to assign a mean visual absolute magnitude to type I. It does seem likely, though, that they are supergiants.

The stars UV Aur and V Hya have both been classified C9 on our new infrared scheme. The former is almost definitely a double star, and the latter is strongly suspected of being one (Gordon 1968). A spectrum of UV Aur has been obtained near minimum light (phase = 0.45) where its visual absolute magnitude is $-1.7$, while the spectrum of V Hya has been photographed close to maximum light (phase = 0.18). New photometry was obtained for V Hya and its companion, and these data indicate that V Hya at maximum light has $M_v = -3.9$. These spectra are illustrated in Figure 7.

The most striking differences in their spectra are the strengths of the CN band heads at λλ7852, 7876, and 7899. They are very weak in UV Aur and quite prominent in V Hya. Other CN lines, like the one at λ8487, are significantly stronger in the more luminous V Hya.

The visual absolute magnitudes of the later carbon stars are summarized in Table 11. Phases have been specified for the luminosities at C9, but none have been indicated for those of classes C3–C7. The reason for this is that the absolute magnitude of type II C3–C7 stars was determined from a sample of thirty-three stars in which it was assumed that the phases were randomly distributed. Hence the value for this group should represent their mean absolute magnitude during the light cycle. The visual absolute magnitude of V Hya must be considered tentative until it is firmly established that it is a binary star.

## VIII. ($M_{\rm bol}$, log $T_e$)-DIAGRAM

The absolute magnitudes derived in § VII can be combined with the effective temperatures and bolometric corrections of Table 1 to construct the ($M_{\rm bol}$, log $T_e$)-diagram for carbon stars. This diagram is illustrated in Figure 8, and includes only those stars from Table 5 or 8 that are also in Table 1. A smoothed giant and supergiant branch has been included by using the data of Johnson (1966), and the red end of the zero-age main sequence is indicated. Both the giant and supergiant sequences terminate at type M5.

Mendoza V. and Johnson (1965), using the $(R + I) - (J + K)$ temperature calibration of Johnson (1964) and a mean absolute magnitude for the later carbon stars of $-1.1$, found that these stars lie along the normal giant branch from spectral types M1 onward. The $(R + I) - (J + K)$ color index yields a higher temperature than the $(I - L)$ index, and their underestimate of the absolute magnitude exactly compensated for this to make the carbon stars appear as normal giants. Figure 8, however, clearly shows that the later carbon stars (*closed circles*) are well separated from the early giant

TABLE 11

VISUAL ABSOLUTE MAGNITUDES OF CARBON STARS

| Spectral Type | Luminosity Class I | Luminosity Class II | Standards I | Standards II |
|---|---|---|---|---|
| C3–C7.......... | ... | −2.7 | Y CVn<br>HD 52432<br>HD 148173 | DS Peg<br>W Ori<br>U Hya |
| C9.............. | −3.9 | −1.7 | V Hya (max) | UV Aur (min) |

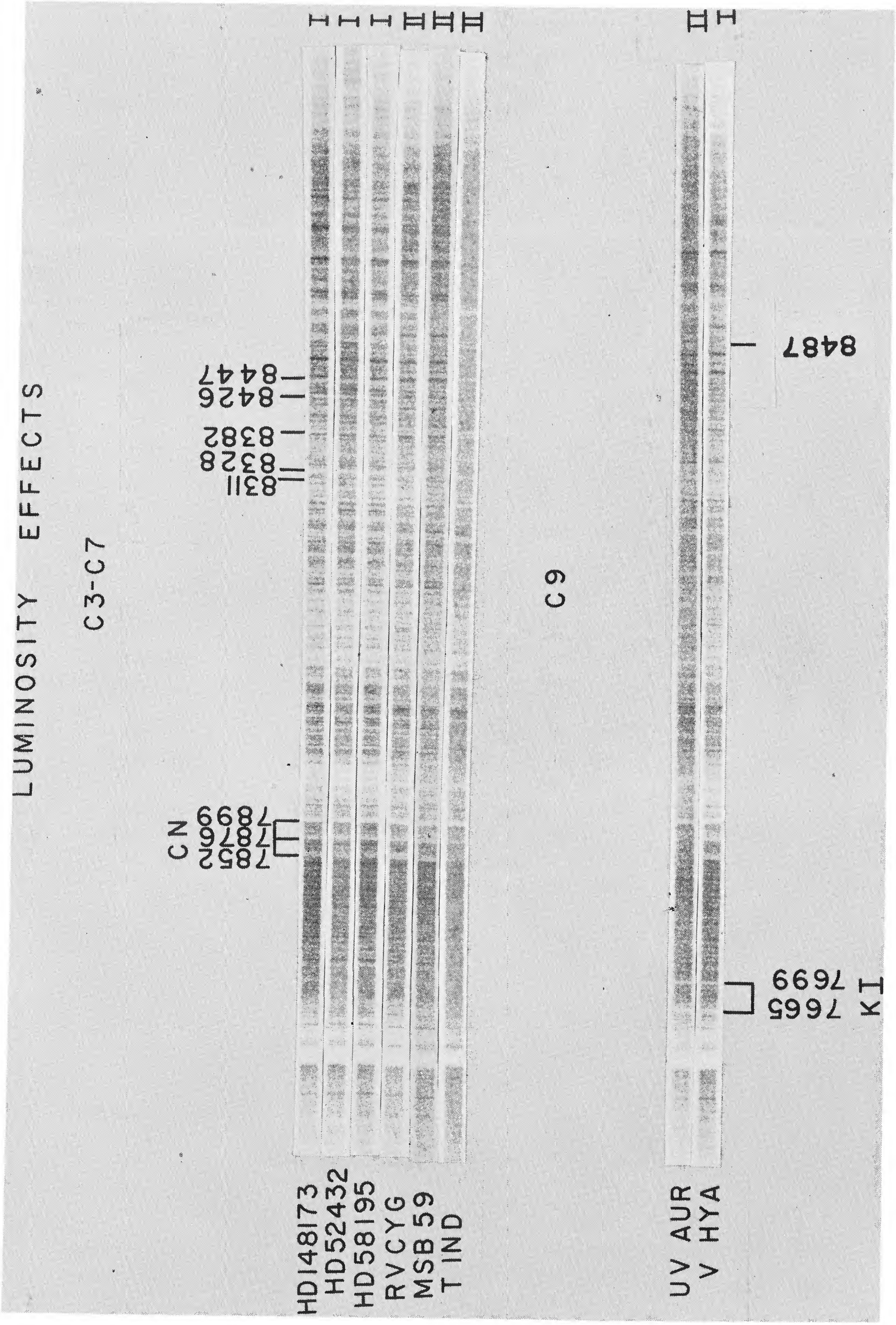


FIG. 7.—Sequence of carbon-star spectra showing the change in spectral features interpreted as luminosity effects. Original dispersion 124 Å $mm^{-1}$.

RICHER (*see* page 531)

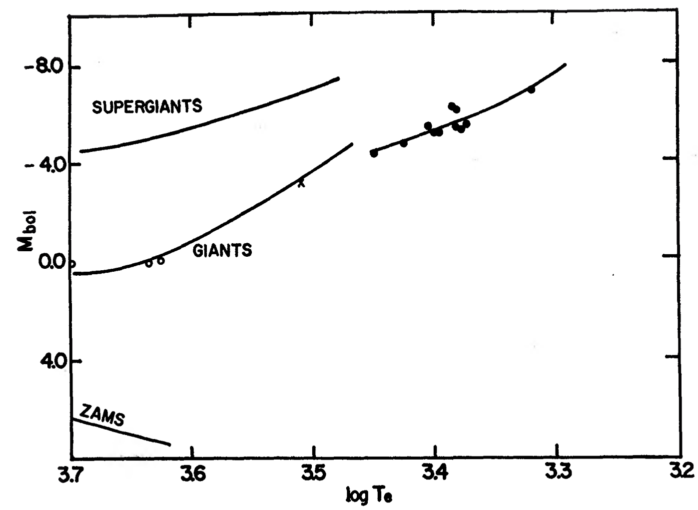


FIG. 8.—($M_{\rm bol}$, log $T_e$)-diagram for carbon stars. *Open circles*, C0–C2 stars; *closed circles*, C3–C7 stars; ×, CH star.

branch, and appear to form an extension to lower temperature. It appears that they may occupy the same general region of the ($M_{\rm bol}$, log $T_e$)-plane as the extreme giants of types M6–M9 (Mendoza V. and Johnson 1965).

Three C0–C2 stars are included in this diagram (*open circles*) by using Vandervort's (1958) absolute magnitude of +0.5. These stars lie along the blue edge of the giant branch. One CH star (HD 112869) is included and plotted as a cross. An absolute magnitude of −1.8 was used for this star in accordance with Warner's (1965) value found for the CH star in $\omega$ Cen. If this CH star is typical, then it appears that these stars are intermediate between the early and late carbon stars in the ($M_{\rm bol}$, log $T_e$)-plane.

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## APPENDIX

A catalog of data on carbon stars has been compiled from the observations discussed in the previous sections and is presented in Table 12. Column (1) contains the star name as it appears in Sanford's (1944) catalog, and column (2) lists some other identification which is in general an HD number or a variable-star designation. Stellar coordinates and radial velocities can, in general, be found in Sanford's catalog. Column (3) contains the spectral type on our new infrared scheme, and column (4) indicates the date on which the spectrum was obtained. All spectra were secured in 1969. Those without brackets refer to the date in 1969 September; those with brackets are 1969 October. Other dates are indicated. Columns (5)–(7) contain the photometric observations. These will usually be different from those of Tables 5 and 8 wherein a mean of all the observations was used. Column (8) indicates the date in 1969 October on which the photometry was obtained. If no date is given, the photometry is due either to Mendoza V. and Johnson (1965) or Mendoza V. (1967).

TABLE 12

CATALOG OF CARBON STARS

| Star (1) | HD or Other (2) | Spectral Type (3) | Date of Spectral Type (4) | $V$ (5) | $U-B$ (6) | $B-V$ (7) | Date of Photometry (8) |
|---|---|---|---|---|---|---|---|
| SU And | 225217 | C5 II | 30 | 8.22 | 4.13 | 2.58 | 15 |
| VX And | 1546 | C8 | 30 | 8.51 | ... | 4.43 | 15 |
| AQ And | 2432 | C6 II | 30 | 7.92 | ... | 3.79 | 15 |
| Z Psc | 7561 | C5 II | 21 | 6.84 | 3.39 | 2.62 | 15 |
| R Scl | 8879 | C6 II | 21 | 6.44 | ... | 4.81 | 15 |
| V Ari | 13826 | C5 II | 26 | 8.80 | 2.43 | 2.12 | 15 |
| R For | ... | C8 | 31 | 10.59 | ... | 4.87 | 15 |
| HD 16115 | ... | C0 | 27 | 8.19 | 0.73 | 1.23 | 17 |
| HD 20234 | ... | C5 II | 21 | 5.79 | 2.83 | 2.47 | 15 |
| T Cae | 30593 | C5 II | 25 | 7.73 | 3.22 | 2.32 | 13 |
| HD 30710 | ... | C4 II | (7) | 9.43 | 4.27 | 2.75 | 17 |
| TT Tau | 30755 | C5 II | 24 | 8.02 | ... | 2.93 | 17 |
| 38°955 | ... | C3 II | 30 | 8.64 | 2.66 | 2.85 | 13 |
| R Lep | 31996 | C6 II | 21 | 8.40 | ... | 5.29 | 15 |
| W Ori | 32736 | C6 II | 21 | 6.18 | ... | 3.86 | 15 |
| TX Aur | 33016 | C5 II | 31 | 9.09 | ... | 3.19 | 13 |
| SY Eri | 33404 | C5 II | 24 | 8.39 | 2.42 | 2.59 | 17 |
| 11°755 | V431 Ori | C6 II | (4) | 9.39 | ... | 3.61 | 22 |
| HD 34467 | ... | C4 II | (9) | 9.20 | ... | 2.75 | 17 |
| UV Aur | ADS 3934A | C9 II | (6) | ... | ... | ... | ... |
| RT Ori | 36602 | C6 II | 21 | 7.98 | 5.11 | 2.85 | 15 |
| HD 37212 | ... | C4 II | 22 | 7.84 | 3.33 | 2.27 | 15 |
| TU Tau* | 38218 | C5 II | 26 | 8.42 | ... | 2.95 | 17 |
| Y Tau | 38307 | C5 II | 24 | 6.54 | 5.81 | 2.82 | 15 |
| 15°921 | CP Tau | C5 II | 25 | ... | ... | ... | ... |
| HD 38572 | FU Aur | C4 II | (2) | 8.31 | 4.31 | 2.67 | 17 |
| TU Gem | 42272 | C6 II | 24 | 7.29 | ... | 2.77 | 13 |
| MSB 17 | ... | C5 II | (8) | 9.92 | 3.94 | 2.67 | 17 |
| −7°1402 | ... | C5 II | (6) | 9.96 | 3.34 | 2.53 | 17 |
| BL Ori | 44984 | C5 II | 24 | 6.40 | 3.44 | 2.40 | 15 |
| −26°2983† | ... | C6 II | 27 | 8.58 | 1.35 | 3.26 | 15 |
| UU Aur | 46687 | C5 II | 31 | 5.45 | ... | 2.87 | 22 |
| VW Gem | 47883 | C5 II | (2) | ... | ... | ... | ... |
| W Mon | ... | C6 II | (7) | ... | ... | ... | ... |
| HD 50436 | GY Mon | C4 II | 27 | 8.12 | ... | 2.25 | 22 |
| MSB 26 | CL Mon | C8 | 30 | 9.41 | ... | 4.27 | 22 |
| HD 51208 | ... | C3 II | 21 | 6.37 | 2.79 | 2.30 | 15 |
| RV Mon | 51620 | C5 II | 24 | 7.06 | ... | 2.65 | 15 |
| HD 52432† | ... | C7 I | 25 | 7.29 | 2.08 | 1.63 | 22 |
| RY Mon | ... | C6 II | 25 | 8.10 | ... | 4.15 | 22 |
| W CMa | 54361 | C5 II | 21 | 6.77 | 4.68 | 2.53 | 15 |
| −17°1866 | ... | C5 II | 26 | ... | ... | ... | ... |
| HD 58195 | BE CMa | C7 I | 27 | ... | ... | ... | ... |
| HD 58385 | ... | C5 II | (8) | ... | ... | ... | ... |
| HD 58881‡ | ... | C1 | (8) | ... | ... | ... | ... |
| W CMi | 54361 | C3 II | (7) | ... | ... | ... | ... |
| HD 63733‡ | ... | C2 | (2) | ... | ... | ... | ... |
| HD 65424 | ... | C5 II | 24 | 7.86 | 4.36 | 3.05 | 15 |
| X Cnc | 76221 | C6 II | April 13 | ... | ... | ... | ... |
| HD 88539 | ... | C5 II | 31 | 6.64 | 3.06 | 2.27 | 15 |
| U Hya | 92055 | C5 II | April 11 | 4.82 | 5.78 | 2.69 | ... |
| HD 92839 | VY UMa | C5 II | April 12 | 6.00 | 4.77 | 2.41 | ... |
| V Hya | ... | C9 I | (9) | 6.71 | ... | 4.91 | 22 |
| SS Vir | 108105 | C5 II | April 19 | ... | ... | ... | ... |

* Close double star.

† Photometry indicates previously unsuspected close double.

‡ S star according to Keenan (1954).

TABLE 12—*Continued*

| Star (1) | HD or Other (2) | Spectral Type (3) | Date of Spectral Type (4) | $V$ (5) | $U-B$ (6) | $B-V$ (7) | Date of Photometry (8) |
|---|---|---|---|---|---|---|---|
| Y CVn | 110914 | C7 I | May 14 | 5.43 | 5.59 | 2.75 | ... |
| RY Dra | 112559 | C7 I | April 11 | 6.35 | 8.90 | 3.26 | ... |
| Z Lup | 128033 | C5 II | (4) | ... | ... | ... | ... |
| X TrA | 134453 | C5 II | 23 | ... | ... | ... | ... |
| HD 148173 | ... | C7 I | (7) | ... | ... | ... | ... |
| V Oph | 148182 | C5 II | 26 | 7.35 | 4.65 | 2.97 | ... |
| SU Sco | ... | C6 II | 21 | 8.18 | ... | 4.33 | 14 |
| HD 156074 | ... | C0 | April 13 | 7.61 | 0.92 | 1.14 | ... |
| MSB 59 | ... | C6 II | (8) | 7.33 | ... | ... | 15 |
| MSB 60 | −29°13477 | C6 II | 26 | ... | ... | ... | ... |
| TW Oph | 158377 | C6 II | 22 | 8.20 | ... | 4.29 | 16 |
| TT Sco | 160205 | C6 II | 27 | 8.18 | ... | 3.76 | 16 |
| HD 160435 | V Pav | C5 II | 24 | 7.17 | ... | 3.70 | 16 |
| SZ Sgr* | 161208 | C5 II | 24 | ... | ... | ... | ... |
| SX Sco | 161511 | C5 II | (4) | 7.95 | ... | 2.85 | 15 |
| SS Sgr | 170495 | C5 II | (6) | ... | ... | ... | ... |
| T Lyr | ... | C8 | 29 | 8.18 | ... | 5.52 | ... |
| RX Sct | 171804 | C5 II | (2) | 9.03 | ... | 2.94 | 16 |
| HD 173291 | HK Lyr | C5 II | 30 | ... | ... | ... | ... |
| MSB 64 | DR Ser | C6 II | (7) | ... | ... | ... | .. |
| S Sct | 174325 | C5 II | 22 | 6.70 | ... | 2.93 | 14 |
| T Sct | 175377 | C5 II | 22 | 9.29 | ... | 2.59 | 16 |
| UV Aql | 176200 | C6 II | (6) | ... | ... | ... | ... |
| V Aql | 177336 | C5 II | 22 | 6.73 | ... | 3.99 | 14 |
| HD 180953 | ... | C5 II | 25 | 7.00 | 4.53 | 2.46 | 14 |
| U Lyr | ... | C8 | (9) | ... | ... | ... | ... |
| HD 182040 | ... | C0 | (9) | 7.03 | 0.65 | 1.07 | 14 |
| UX Dra | 183556 | C5 II | April 12 | ... | ... | ... | ... |
| AQ Sgr | 184283 | C5 II | 25 | 7.34 | 4.11 | 3.37 | 14 |
| TT Cyg | 186047 | C6 II | 30 | ... | ... | ... | ... |
| UW Sgr | 186665 | C3 II | 25 | 9.26 | 3.62 | 2.50 | 12 |
| AX Cyg | 189256 | C6 II | 30 | ... | ... | ... | ... |
| HD 190048 | BF Sge | C5 II | 27 | ... | ... | ... | ... |
| X Sge | 190606 | C6 II | 24 | 8.36 | ... | 3.29 | 16 |
| RS Cyg | 192443 | C5 II | 30 | 7.48 | 3.90 | 2.86 | ... |
| RT Cap | 192737 | C6 II | 25 | 7.41 | ... | 4.02 | 14 |
| U Cyg | 193680 | Cem | July 13 | 8.47 | 4.52 | 3.31 | ... |
| RV Aqr | ... | Cem | (4) | ... | ... | ... | ... |
| T Ind | 202874 | C5 II | 25 | 6.00 | 3.75 | 2.33 | 14 |
| HD 203133 | Y Pav | C5 II | 22 | 6.21 | 3.48 | 2.62 | 11 |
| S Cep | 206362 | C6 II | July 7 | ... | ... | ... | ... |
| DS Peg | V460 Cyg | C5 II | 30 | 6.05 | 5.30 | 2.52 | ... |
| HD 206652 | RR Ind | C6 II | 25 | 8.96 | 4.39 | 2.57 | 14 |
| RV Cyg | 206750 | C6 II | 30 | ... | ... | ... | ... |
| RX Peg | 208526 | Cem | 26 | ... | ... | ... | ... |
| HD 209621 | ... | C2 | (7) | ... | ... | ... | ... |
| RZ Peg | 209890 | Cem | 30 | ... | ... | ... | ... |
| ST And | 222241 | C2 | (9) | ... | ... | ... | ... |
| 19 Psc | TX Psc | C5 II | 21 | 4.92 | 3.28 | 2.49 | 14 |
| HD 223392 | ... | C1 | 30 | 8.24 | 1.01 | 1.17 | 16 |
| WZ Cas | 224855 | C5pec | July 9 | 7.16 | 4.29 | 2.84 | ... |

* Close double star.

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