

MULTICOLOR PHOTOMETRY OF CARBON STARS

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ABSTRACT

We have made multicolor photometric observations, over the range of wavelength from 0.35μ in the ultraviolet to nearly 10μ in the infrared, on thirty-nine carbon stars and six late-type long period variable stars. The bolometric corrections and effective temperatures of these stars have been computed, and have been used to construct the absolute bolometric-magnitude-effective-temperature diagram for carbon stars.

The effective temperatures of the carbon stars we have observed range from 5500°K downward to 2270°K . The bolometric corrections range from almost zero to nearly 5 mag.

The apparent angular diameters of some of the carbon stars are as large as $0.01''$ —large enough to be measurable by a Michelson interferometer with a 50-foot beam.

I. INTRODUCTION

We have made a multicolor photometric study of carbon stars as a part of the continuing multicolor photometric programs now under way at the Lunar and Planetary Laboratory. These stars have been studied rather extensively spectroscopically (cf. Keenan 1963) and photometrically by Vandervort (1958).

Our observations were made with the photometric apparatus described by Johnson and Mitchell (1962) and by Low and Johnson (1964). Some of the shorter wavelength observations were obtained with the 40-inch telescope of the Observatorio Astronómico Nacional, Universidad de México, during the spring of 1963. Most of the observations, however, were taken with the 21-inch and 28-inch photometric telescopes of the Lunar and Planetary Laboratory during the spring of 1964.

II. THE OBSERVATIONS

The observational data on the multicolor photometric system defined by Johnson (1964) are listed in Table 1. The columns of this table contain, first, the numbers of the stars in our program; second, the *Bonner Durchmusterung* designations; third, the constellation names or the *Henry Draper Catalogue* numbers of the stars; fourth through twelfth, the photometric data; and last, the spectral types by Keenan and Morgan (1941), Keenan (1954), Bidelman (1956), Vandervort (1958), or Merrill (1960). Observational data are given for thirty-nine carbon stars, and for several long-period variables of types M and S that were also observed on this program.

We had some difficulty in measuring the U magnitudes of carbon stars for which $B - V$ is redder than 2.5 mag., because most of the radiation coming through the U filter was infrared leak. In order to obtain information in this wavelength band for the reddest carbon stars, we found it necessary to use an ultraviolet filter consisting of 2-mm Schott UG 1 cemented to Corning 9780 (standard optical thickness); this filter defines an ultraviolet band narrower than the standard U , but it does not have an appreciable infrared leak. These different ultraviolet magnitudes were transformed to the standard U system by using only standard stars of Luminosity Class III later than A0. Four of these difficult carbon stars, identified in Table 1 by colons following the $U - V$ color-indices, have ultraviolet magnitudes fainter than 22. The limit of the $UBVRI$ photome-

TABLE 1
THE OBSERVATIONAL DATA

Star	BD	Name or HD	V	U-V	B-V	V-R	V-I	V-J	V-K	V-L	V-N	Sp
1	+07° 5128	26	8 25	1 55	1 04	0 76	1 22	1 63	2 22	.	.	CH
2a	-03° 353	o Cet	3 31	2 15	1 61	1 98	3 85	.....	.....	.	.	...
2b	-03° 353	o Cet	8 12	1 33	1 57	4 20	7 56	8 97	10 28	.	.	M7e
3	+14° 1283	BL Ori	6 18	5 80	2 32	1.76	3 06	4 02	5 47	.	.	C6,2
4.	-11° 1520	46407	6 26	1.77	1 11	0.77	1 24	1 68	2.23	..	.	Ba II
5.	-29° 6735	75021	7.17	5 17	1 85	1 55	2 85	3 83	5 37	.	...	R8
6	+20° 2243	T Cnc	9 05	13 3:	5 30	2 91	4 57	5.48	7 86	.	8 59	R5
7.	-12° 3218	U Hya	4 82	8 47	2 69	1 77	3 04	3 97	5 57	.	...	C7,3
8.	+68° 617	92839	6 00	7 18	2 41	1 74	3 01	3 96	5 58	6 07	.	C6, 3
9.	-13° 3407	.	8 80	1 61	1.05	0.74	1 20	1 48	3.18	4 45	.	R2
10 .	+07° 2561	R Vir	7 69	2 77	1 20	1 93	3 71	4 65	5 67	6 23	.	M4e
11	+61° 1313	S UMa	8 12	3.84	2 13	1 85	3 16	3.88	5 13	5 60	.	S2e
12	+08° 2654	.....	9 43	3 03	1 38	1 08	1 79	2 32	3 20	3 74	.	R0
13..	+66° 780	RY Dra	6 35	12 16	3.26	2 01	3 44	4 53	6 26	6 94	.	C4,4
14.	+38° 2389	112869	9 16	3 67	1.85	1 37	2 24	2 90	4 07	4 29	.	Cp,5;CH
15	-19° 3634	113801	8 52	2 22	1.17	0 75	1 29	1 89	2 63	3 59	...	C1,1
16 .	-22° 3601	R Hya	5 24	2.26	1 60	2 90	5 40	6 31	7.63	8 06	8 79	M6e
17.	+33° 2399	122547	9 54	2.18	1 23	0.84	1 47	2 12	2.79	.	...	R2
18.	-02° 3939	133332	10 46	2.70	1 42	1 50	2 71	3 64	5 00	5 56	.	R5
19 .	-24° 12084	137613	7 55	2.02	1 17	0 84	1 33	1.78	2.27	2 61	.	R2
20	+65° 1055	.....	10 34	2 96	1 46	1 12	2 03	2 39	2 79	.	...	R5
21	+40° 2929	V CrB	9 33	12 7:	4 41	2.64	4 09	5 63	7.73	8 62	.	N3e
22	+19° 3109	.....	10 38	2.78	1 50	0 96	1.60	2 38	2 88	.	...	R2
23.	+67° 950	R Dra	10 06	1 96	1 22	3.09	5.51	6 35	7.64	8 02	.	M6
24 .	+23° 2998	..	9.80	2.33	1 20	0 80	1.37	1.95	2.92	.	...	R0
25	+42° 2811	156074	7 61	2 06	1 14	0.72	1 19	1 58	2 32	2 53	.	C1,2
26	+02° 3336	.	9 40	3.94	1 91	1 28	2 26	3 16	4 28	4 84	.	R2
27.	+17° 3325	.....	8 72	2 31	1 18	0 83	1 40	1 94	2 68	3 65	.	R0
28..	+09° 3576	166097	10 03	3 30	1 53	1 20	2 03	2 77	3 73	5 07	.	R5
29..	-15° 4923	168227	8 66	3 89	1 89	1 70	3.13	4 24	5 77	6 56	.	R5
30.	+36° 3168	T Lyr	8 18	14 5:	5 52	2 94	4 65	5 63	7 95	8.71	8 48	C6,5
31.	-07° 4633	RX Sct	8 93	7 97	2 86	2 36	4 12	5 44	7 30	7.92	.	N
32..	-16° 5272	180953	6 86	6 67	2 34	1 81	3.19	4 21	5 80	6.31	.	R8
33.	-10° 5057	182040	7.01	1 72	1 09	0 81	1 26	1.49	1 90	1 70	...	C1,2
34a	+32° 3593	x Cyg	9.70	1 77	1 93	4.69	8 43	9 87	11 46	12 11	12 99	M8e;S10e
34b	+32° 3593	x Cyg	11.84	..	2 53	5.91	9 89	11 97	13 60	14 40	15 26	M9e;S10e
35.	-00° 3883	188934	9 37	4 11	2 01	1 40	2 37	3 16	4 22	4.11	.	R8
36.	+09° 4369	189711	8 37	4 34	2 06	1 35	2 41	3 32	4 53	5 18	.	N
37 .	+47° 3031	SV Cyg	8.80	9 77	3 27	2 26	3 79	4 96	6 97	7 59	.	R8
38	+38° 3957	RS Cyg	7 48	6 76	2 86	2 12	3 70	4 80	6 37	6 71	.	C8,2
39..	+47° 3077	U Cyg	8 47	7 83	3 31	2.15	3 93	5 26	7.42	8 42	.	C8,2
40..	+26° 4091	201626	8 16	1 57	1 10	0 82	1 34	1.77	2.29	.	...	CH
41	+34° 4500	DS Peg	6.05	7 82	2 52	1.83	3 21	4 11	5 71	6 32	6 30	C6,3
42.	+49° 3673	LW Cyg	8 82	13 2:	4 16	2 54	4 14	5 23	7 22	7 83	.	R2
43 .	+02° 4709	19 Psc	5 04	6 11	2 61	1.87	3.22	4 12	5 60	5 93	.	C6,2
44 .	+59° 2810	WZ Cas	7.16	7 13	2.84	2 14	3.81	4.97	6 56	6 82	.	C9,1

ter on the 21-inch telescope is about 22d U mag.; we were unable to record a significant ultraviolet measure for any of these four stars. For these four stars, the $U - V$ colors listed in Table 1 probably should be regarded as lower limits.

III. THE OBSERVED SPECTRAL ENERGY DISTRIBUTIONS

The observed spectral energy distributions for several stars selected from Table 1 have been plotted in Figure 1. There are also plotted, for comparison, the standard values for O stars, K0 III, K5 III, and M2 III stars, from Johnson (1964). We notice that the energy distributions of carbon stars differ relatively little from those of ordinary K and M giants for wavelengths longer than that of the V filter (0.55μ) but that they differ greatly for the shorter wavelengths.

These differences and similarities are better shown by Figure 2, in which are plotted the spectral energy distributions relative to that of an M2 III star (Johnson 1964; the reference type for Figure 1 is A0 V). The “ UV depression” in carbon stars, due to absorption by the polyatomic molecule, C_3 , shows plainly in a comparison of the dotted lines (K and M stars) and the solid lines (carbon stars). The “ UV depression” also carries over into the blue spectral region.

It is significant that the carbon stars do not differ greatly from the ordinary giants in the regions of the R , I , J , and K filters, for this means that we can apply the effective-temperature calibration of Johnson (1964), with the expectation that the temperatures so derived may be reasonably near to the true values. That effective-temperature calibration depends upon the measured total fluxes from a few stars (among the cooler stars, mostly ordinary giants) whose apparent angular diameters were measured interferometrically by Michelson and Pease (Pettit and Nicholson 1928).

IV. THE BOLOMETRIC CORRECTIONS AND EFFECTIVE TEMPERATURES

We have computed the bolometric corrections, BC , for the stars in Table 1, following the procedure outlined by Johnson (1964). This procedure consists primarily of a simple numerical integration under the spectral energy distribution, after conversion to absolute units. The results of this integration are then compared with the corresponding value for the Sun.

We have also computed the effective temperatures, T_e , by the procedure of Johnson (1964). This procedure, which uses a color index, $(R + I) - (J + K)$, centered around the wavelength of 1μ , was derived from the total fluxes, as computed above, and the measured angular diameters of ten stars. The effective temperature calibration depends, for the cooler stars, primarily upon K and M giants. Such stars have effective temperatures in the range around 3000° K, and the peak radiation of a black body of this temperature falls in the neighborhood of 1μ . The color index, $(R + I) - (J + K)$, was chosen to cover the wavelength range where most of the radiation of K and M stars comes out, in an effort to minimize errors in temperature determinations for stars (such as carbon stars) which were not represented in the original calibration.

These bolometric corrections and effective temperatures are listed in the second and third columns of Table 2; the first column lists the numbers of the stars, as in Table 1. The fourth column of Table 2 contains the angular diameters of the stars computed from the derived effective temperatures and the apparent bolometric magnitudes, $m_{bol} = V + BC$.

A comparison of our derived effective temperatures, T_e , with the vibrational temperatures which have been determined for some of these carbon stars is given in Table 3. The first column contains our star numbers; the second, third, and fourth, the vibrational temperatures by Bouigue (1954), Wyller (1960), and McKellar and Buscombe (1948); the last three columns give the differences between our effective temperatures and the

vibrational temperatures. In general, the vibrational temperatures appear to be lower than our effective temperatures, but the scatter in the differences is large.

We also compare, in Table 4, our effective temperatures with those of Keenan (1963), who derived them from his adopted temperatures of the "equivalent" normal K and M stars. The systematic difference between Keenan's temperatures and ours for carbon stars is essentially a reflection of the difference between Keenan's and Johnson's (1964) temperatures for the ordinary K and M giants.

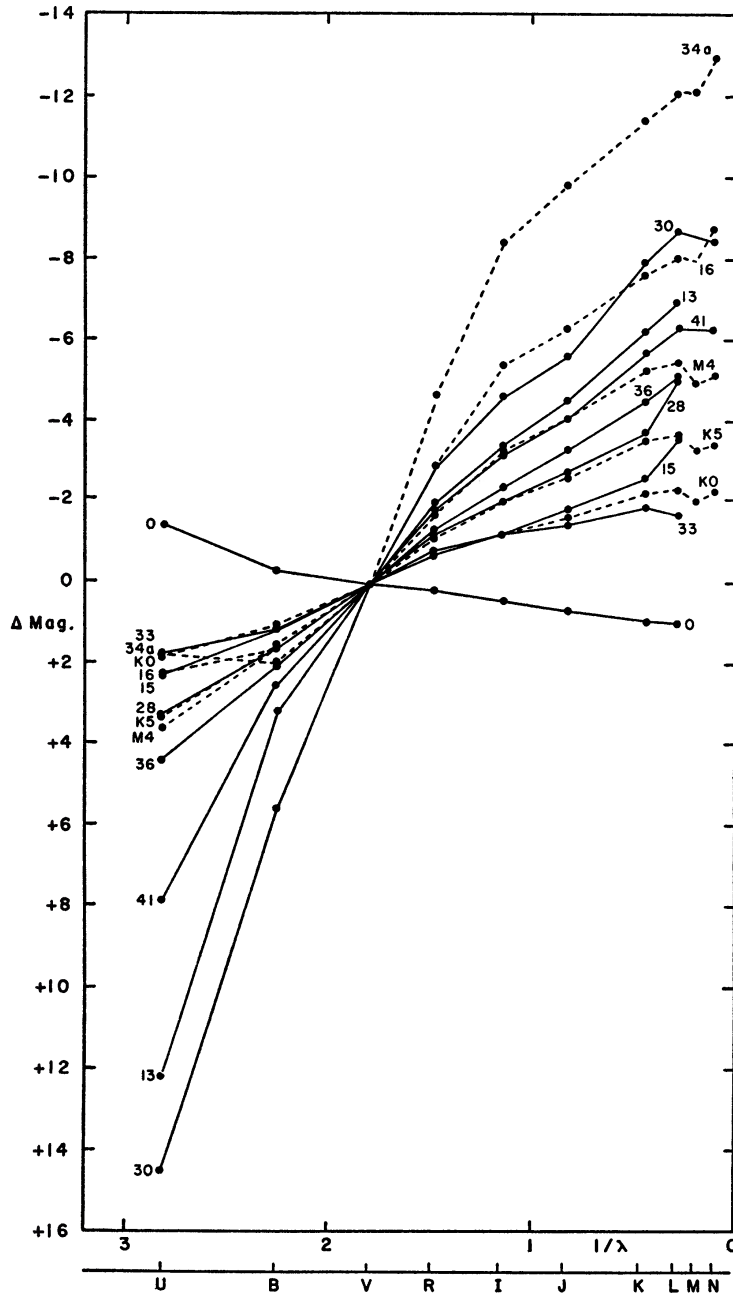


FIG. 1.—The spectral energy-curves for stars selected from Table 1, and for K0 III, K5 III, and M4 III from Johnson (1964). These data are relative to that for an A0 V star. The numbers of the curves correspond to the numbers of the stars in the first column of Table 1.

V. THE ABSOLUTE BOLOMETRIC-MAGNITUDE-EFFECTIVE-TEMPERATURE
DIAGRAM FOR THE CARBON STARS

The bolometric corrections and effective temperatures listed in Table 2, when combined with the absolute visual magnitudes derived for carbon stars by Vandervort (1958), permit us to construct the absolute bolometric-magnitude-effective-temperature diagram (hereafter called the "BT diagram") for these stars. This diagram is shown in Figure 3. The absolute visual magnitudes that were used in this computation are listed

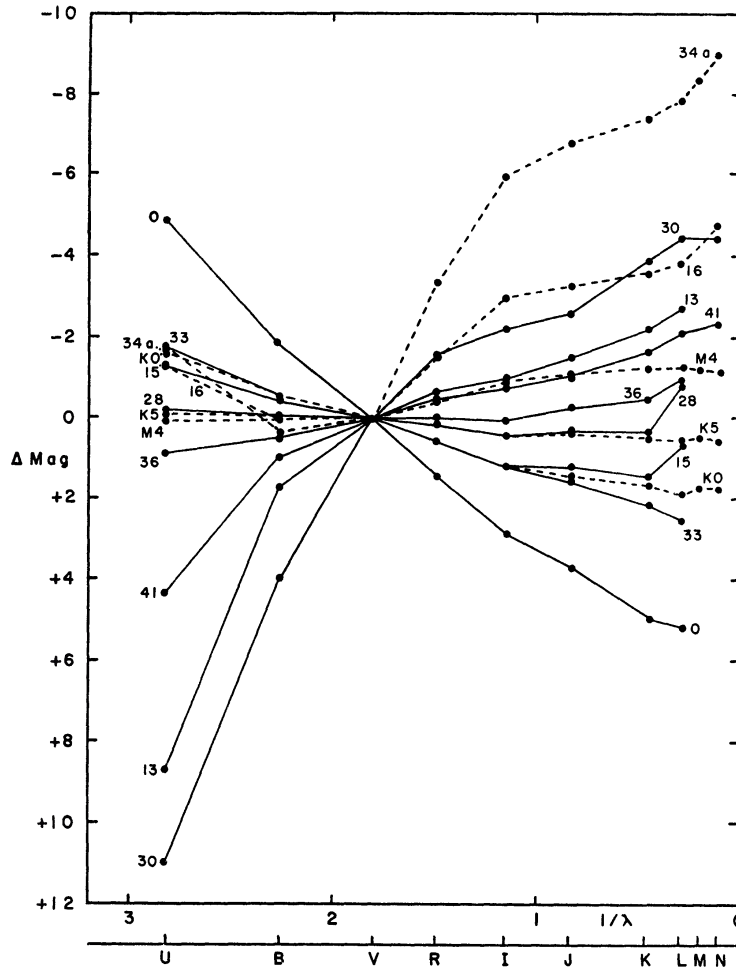


FIG 2.—The spectral energy-curves as in Fig. 1, except that the reference spectral type is M2 III

in Table 5; since Vandervort did not derive values for all of the types of stars we observed, it has been necessary to assume certain values as indicated in Table 5 by parentheses. The solid lines in Figure 3 are the zero-age main sequence (ZAMS) from Johnson (1964) and the Luminosity Class III sequence derived from the data of Johnson (1964, Table 2) and the absolute visual magnitudes of Keenan (1963). The line for Luminosity Class III also contains a slight smoothing of the data.

It is plain from Figure 3 that, in the BT diagram, the carbon stars are ordinary giant stars, very much like K and M giants of Luminosity Class III.

TABLE 2
THE BOLOMETRIC CORRECTIONS, EFFECTIVE TEMPERATURES, AND ANGULAR DIAMETERS

Star	BC	T_e (° K)	Diameter
1	-- 0 37	4780	0".0003
2b	-- 7 64	2070	".0544
3	-- 2 51	2890	".0064
4	-- 0 30	4750	".0008
5	-- 2 13	2830	".0035
6	-- 4 67	2480	".0063
7	-- 2 52	2860	".0123
8	-- 2 60	2840	".0075
9	-- 0 61	3970	".0004
10	-- 3 03	2880	".0041
11	-- 2 41	3180	".0021
12	-- 0 89	4020	".0003
13	-- 3 24	2640	".0100
14	-- 1 41	3530	".0006
15	-- 0 46	4170	".0004
16	-- 4 84	2540	".0375
17	-- 0 59	4070	".0003
18	-- 2 17	2990	".0007
19	-- 0 37	4770	".0004
20	-- 0 83	4600	".0002
21	-- 4 63	2270	".0065
22	-- 0 74	3980	".0002
23	-- 4 87	2620	".0039
24	-- 0 54	3980	".0002
25	-- 0 35	4650	".0004
26	-- 1 69	3230	".0008
27	-- 0 60	4250	".0003
28	-- 1 37	3590	".0004
29	-- 2 87	2700	".0028
30	-- 4 77	2440	".0097
31	-- 4 21	2360	".0059
32	-- 2 83	2760	".0059
33	-- 0 21	5520	".0004
34a	-- 8 65	1930	".0481
34b	--10 85	1680	".0653
35	-- 1 54	3390	".0007
36	-- 1 81	3140	".0014
37	-- 3 83	2470	".0048
38	-- 3 36	2640	".0057
39	-- 4 34	2270	".0084
40	-- 0 34	4750	".0003
41.	-- 2 73	2840	".0078
42.	-- 4 13	2500	".0054
43.	-- 2 74	2890	".0121
44.	-- 3 53	2560	0".0083

TABLE 3
VIBRATIONAL TEMPERATURES

Star	$T_v(B)$	$T_v(W)$	$T_v(M)$	$T_e - T_v(B)$	$T_e - T_v(W)$	$T_e - T_v(M)$
3	2200			+ 690		
6	2800			- 320		
7	2450	2390		+ 410	+ 470	
8	2500			+ 340		
13	3200			- 560		
14	3500			+ 30		
21	2200			+ 70		
25	3700	2170	4700	+ 950	+2480	- 50
29	2950			- 250		
30	3350			- 910		
31	2500			- 140		
32	2700			+ 60		
33	3000	2770	6200	+2520	+2750	-680
36	2350			+ 790		
37	2325			+ 145		
38	2250			+ 390		
39	2300			- 30		
41	2200			+ 640		
42	2950			- 450		
43	2400	2150		+ 490	+ 740	
44	2200			+ 360		
Means				+ 500	+1600	-365

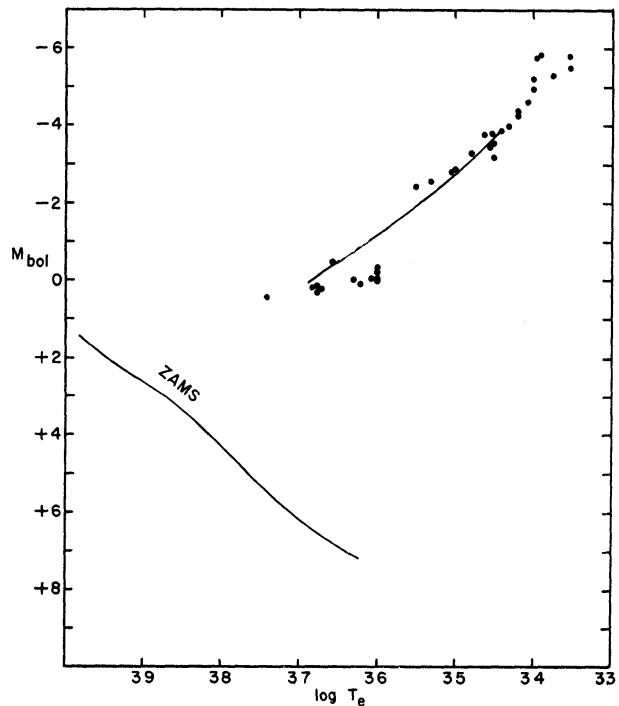


FIG. 3 —The BT diagram for carbon stars. The lines are the zero-age main sequence and the sequence of K and M giants of Luminosity Class III.

VI. THE COLORS OF LATE-TYPE M GIANT STARS

Our data in Table 1 contain a few observations of late-type M giants. We have α Cet near minimum (M7e), R Hya fairly near maximum (M6e), and χ Cyg at a point near minimum (estimated type M9e) and about halfway toward maximum (estimated type M8e). These few data allow us to derive tentative normal colors for M-type giants later than M5. These data are listed in Table 6; they may be considered to be an extension to the later spectral types of the Luminosity Class III table that was given by Johnson (1964, Table 2).

TABLE 4
TEMPERATURES FROM SPECTRAL TYPES

	T_{sp}	T_e	$T_e - T_{sp}$	n
R0	4600	4135	-465	2
C1	4450	4780	+330	3
R2	4300	4000	-300	6
C4, R4, R5	3600	3165	-435	6
C6	3100:	2780	-320	5

TABLE 5
ABSOLUTE MAGNITUDES OF CARBON STARS

M_v	Spectral Range
+0 4	C0-C2; (CH; Ba II)
-1 1	R5-R8; (C4-C9; N)

TABLE 6
THE COLORS, BOLOMETRIC CORRECTIONS, AND EFFECTIVE TEMPERATURES
FOR LATE-TYPE M GIANT STARS

Sp	$B-V$	$V-R$	$V-I$	$V-J$	$V-K$	$V-L$	BC	T_e ($^{\circ}$ K)
M6	1 70:	2 95	5 50	6 40	7 70	8 08	- 4 8	2550
M7	1 80:	3 95	7 00	8 30	9 85	10 38	- 7 7	2150
M8	1 93	4 95	8 51	10 25	11 92	12 60	- 8 6	1900
M9	2 53	5 95	10 02	12 20	14 05	14 88	-10 8	1650

VII. THE ANGULAR DIAMETERS OF THE CARBON STARS

The values of BC and T_e that were used to construct the BT diagram of Figure 3 were also used for the computation of the apparent angular diameters listed in the last column of Table 2. In addition, we have computed the angular diameters of the late M-type stars that we observed. We have made no attempt to account for the limb-darkening of these stars and we have, therefore, implicitly assumed that the limb-darkening of these stars is the same as that of the Sun. If this assumption is invalid, the computed diameters are systematically in error, but this error probably does not exceed 20 or 30 per cent.

It will be noticed that the angular diameters of some of the carbon stars are great enough that they should be measurable with a Michelson (Michelson and Pease 1921)

interferometer. In particular it should be possible to measure the angular diameters of Nos. 7(U Hya), 13(RY Dra), 30(T Lyr) and 43 (19 Psc) with an interferometer having a 50-foot beam.

VIII. CONCLUSION

We have presented multicolor data, over the range in wavelength from 0.3 to 9 μ , for a number of carbon stars. The effective temperatures and bolometric corrections which we have derived for these stars lead to the conclusion that they are ordinary giants in the BT diagram. All of our conclusions are, of course, dependent upon our implicit assumption that the carbon stars are not affected by interstellar extinction. A comparison of the positions of the carbon stars in the Galaxy with those of the B and A stars observed by Eggen (1963) indicates that few of the carbon stars are significantly affected by interstellar reddening. In the extreme case, the reddening in $B - V$, E_{B-V} , probably is not more than 0.1 mag.

The angular diameters that we have computed for σ Cet and χ Cyg are in excellent agreement with those of Pettit and Nicholson (1933), suggesting that the computed angular diameters for the carbon stars may be fairly close to the truth. We emphasize that many of these stars (and the long-period variables also) have diameters large enough to be measurable with a 50-foot beam Michelson interferometer.

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