OB STARS IN THE FIELD OF THE CARINA NEBULA

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ABSTRACT

We present the results of an objective-prism survey for OB stars in the field of the Carina Nebula (NGC 3372), as well as image-tube spectral classification of a sample of LS stars in the same area. These observations are used in the discussion of membership and distance modulus of the stellar association Carina OB1.

I. INTRODUCTION

The stellar population associated with the Carina Nebula (NGC 3372) shows one of the highest concentrations of OB stars in the Milky Way (see, for example, Bok, Hine, and Miller 1970). Several clusters are seen in the brightest region of the Nebula: Trumpler 14, 15, and 16 and Collinder 228.

Photoelectric observations are available for about 400 stars (Feinstein 1969; Graham 1970; Feinstein, Marraco, and Muzzio 1973; Feinstein, Marraco, and Forte 1976; Forte 1976; Turner and Moffat 1980) located in a circle 3° in diameter and centered in η Car. These numerous observations are extensive enough to allow the discussion of the luminosity and mass distribution functions of this very young stellar group. The large number of members provides a statistically significant sample. We first present a discussion of the early-type stars in the surrounding field, based on the results of an objective-prism survey as well as image-tube spectral classification for a number of "luminous stars" (Stephenson and Sanduleak 1971).

The main purpose of the objective-prism survey is to provide an estimation of the completeness of previous surveys in the same region (Graham and Lyngå 1965; Stephenson and Sanduleak 1971; Lodén *et al.* 1976) and also to increase the limiting magnitude of those works.

Spectral classifications are given for some early-type stars which, according to photometric criteria, seem to be associated with Car OB1 (Forte 1976). This classification provides an estimation of the expected number of outlying OB stars that may be physically related with the clusters that form the association's nucleus. Recent discussions of the distance moduli, reddening law, and ages have been published by Forte (1978), Turner and Moffat (1980), Feinstein, FitzGerald, and Moffat (1980), and Thé, Bakker, and Antalova (1980). All of these works point to the existence of a single group of clusters located at a distance of 2.5 kpc from the Sun. This last result, obtained through photometric methods, agrees with the spectroscopic determinations by Walborn (1973) and by Herbst (1976), even though the characteristics of the reddening law and the value of the ratio of total to selective absorption, R, are not completely settled (see Thé, Bakker, and Tjin A Djie 1980).

II. SEARCH FOR OB STARS

Spectroscopic surveys for OB stars in the Carina Nebula region were carried out by Graham and Lyngå (1965), Stephenson and Sanduleak (1971), and Lodén *et al.* (1976) (who also included later spectral types). The limiting magnitude of these works, as derived from the *UBV* photometry of some 70 stars (Forte 1976), is $V \cong 11.2$ mag. In order to increase this magnitude limit and to check the completeness of earlier surveys, a new search was undertaken using the "thin" objective prism (dispersion 1360 Å/mm at Hγ) mounted on the Curtis Schmidt telescope at Cerro Tololo Inter-American Observatory. All exposures were on baked IIIa-J plates.

This combination allows the classification of early-type stars in the natural groups OB$^-$, OB^0, and OB$^+$ defined by Sletteback and Stock (1957). Although these authors defined their system for a higher dispersion, the use of fine-grain plates and the very good seeing conditions at Cerro Tololo result in an almost equivalent system (see Muzzio and Orsatti 1977).

The selected exposure times represent a compromise between the limiting magnitude and the crowding produced by the very rich stellar field as well as the increase of the nebular background on the photographic plate. For the search, two plates (12 min and 30 min) were taken in February 1978. The prism was rotated 180° between exposures, and the images were widened by 0.1 mm.

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TABLE I. OB stars discovered in the field of NGC 3372.

Star	$\alpha(1950)$	$\delta(1950)$	V	$B-V$	$U-B$	Sp.
1	$10^h34\overset{m}{.}1$	$-59°34'$	11.74	0.54	−0.32	OB^-
2	10 35.4	−59 18	11.38	0.74	−0.31	OB^0
3	10 35.5	−59 27	12.43	0.65	−0.44	OB^0
4	10 35.6	−59 27	12.84	0.66	−0.18	OB^0
5	10 36.2	−58 52	11.70	—	—	OB^0
6	10 36.3	−59 04	11.18	0.82	−0.25	OB^0
7	10 36.8	−58 33	12.39	0.81	−0.17	OB^0
8	10 38.1	−59 45	12.03	0.37	−0.46	OB^-
9	10 38.3	−60 07	11.29	1.30	0.16	BI
10	10 39.6	−59 03	11.64	0.60	−0.32	OB^-
11	10 40.2	−58 42	12.48	0.55	−0.36	OB^-
12	10 41.4	−59 09	12.42	0.33	−0.46	OB^-
13	10 42.1	−58 34	12.47	0.37	−0.43	OB^-
14	10 42.9	−58 45	12.59	0.62	−0.22	OB^-
15	10 43.7	−59 33	12.05	0.86	−0.20	OB^+
16	10 43.8	−59 35	12.34	0.92	−0.12	OB^-
17	10 44.5	−58 23	11.62	1.09	0.04	OB^+
18	10 44.9	−59 04	11.83	0.79	−0.19	OB^0
19	10 45.9	−58 51	11.65	0.35	−0.51	OB^0
20	10 46.2	−59 29	12.36	0.57	−0.21	OB^-
21	10 47.0	−59 45	11.34	0.84	−0.02	OB^-
22	10 47.0	−60 12	12.37	0.64	−0.30	OB^0
23	10 48.3	−60 39	11.81	0.76	−0.28	OB^0
24	10 48.7	−59 02	12.67	0.51	−0.34	OB^0
25	10 49.5	−59 32	12.32	0.52	−0.06	BI
26	10 50.1	−60 23	11.80	0.64	−0.32	OB^0
27	10 50.9	−60 09	12.38	0.35	−0.44	OB^-
28	10 51.0	−59 33	11.09	1.02	0.14	OB^0
29	10 52.0	−59 21	12.07	0.63	−0.21	OB^-
30	10 52.1	−60 21	12.05	0.93	−0.17	OB^-
31	10 52.2	−60 01	12.06	0.86	−0.27	OB^+
32	10 53.0	−60 00	11.42	0.93	−0.14	OB^0
33	10 54.5	−59 11	11.61	0.66	−0.29	OB^0
LS 1800	10 41.3	−59 29	9.62	0.26	−0.72	OB^+
LS 1951	10 47.5	−59 17	10.59	0.24	−0.61	OB^0
LS 1955	10 48.1	−59 22	11.20	0.48	−0.40	OB^0
LS 1961	10 48.4	−59 25	11.54	0.32	−0.44	OB^-
LS 1973	10 49.3	−59 29	10.33	0.48	−0.52	OB^+
LS 1974	10 49.4	−59 38	10.41	0.31	−0.58	OB^0
LS 1976	10 47.6	−59 35	10.49	0.40	−0.57	OB^+

The discovered stars together with some luminous stars (denoted by LS) not previously observed in *UBV* are listed in Table I, where the running number, approximate positions for 1950.0, *UBV* photometry, and classification are given. Identification charts for these stars are provided in Figs. 1, where each field covers nearly $15' \times 15'$.

The photometry was performed with the Lowell 61-cm telescope at CTIO and shows that the limiting V magnitude of previous searches was exceeded by 1.5 mag. The observations were carried out by means of a standard photometer attached to a pulse-counting system and using the filter set CTIO No. 3. The accuracy was estimated as ±0.02 mag both for magnitudes and colors, and the transformation to the standard system was obtained through the standard stars given by Cousins (1973).

III. APPARENT MAGNITUDES, COLOR EXCESSES, AND DISTANCE MODULI

The corrected apparent magnitude $V_0 = V - RE_{B-V}$, color excesses E_{B-V}, and intrinsic colors $(U-B)_0$ were computed adopting the color calibration and reddening slopes given by FitzGerald (1970). Both the variable extinction method (Forte 1976) and the E_{V-I}/E_{B-V} color excess ratios (Forte 1978) support a normal reddening law in the outer regions of NGC 3372, and thus we adopted $R = 3.1$.

Figure 2 shows the color-magnitude diagram for the OB stars observed by Graham (1970) and by Forte (1976), and for the stars listed in Table I. Graham observed in the Walraven and Walraven (1960) system, and his colors were transformed to the Johnson $U-B$ color index by means of the following relation:

$$U - B = 1.99(B - U) + 0.67(V - B) - 0.81.$$

This transformation was derived from ten stars observed in common with Forte and gives an accuracy of ±0.25 mag in the $U-B$ color.

No evolutive sequence is detectable in Fig. 2, and the three groups of stars appear well mixed.

Graham (1970) obtained $H\beta$ indices and derived distance moduli which show a concentration around $V_0 - M_v = 12.3$. This concentration was identified with the Carina Nebula.

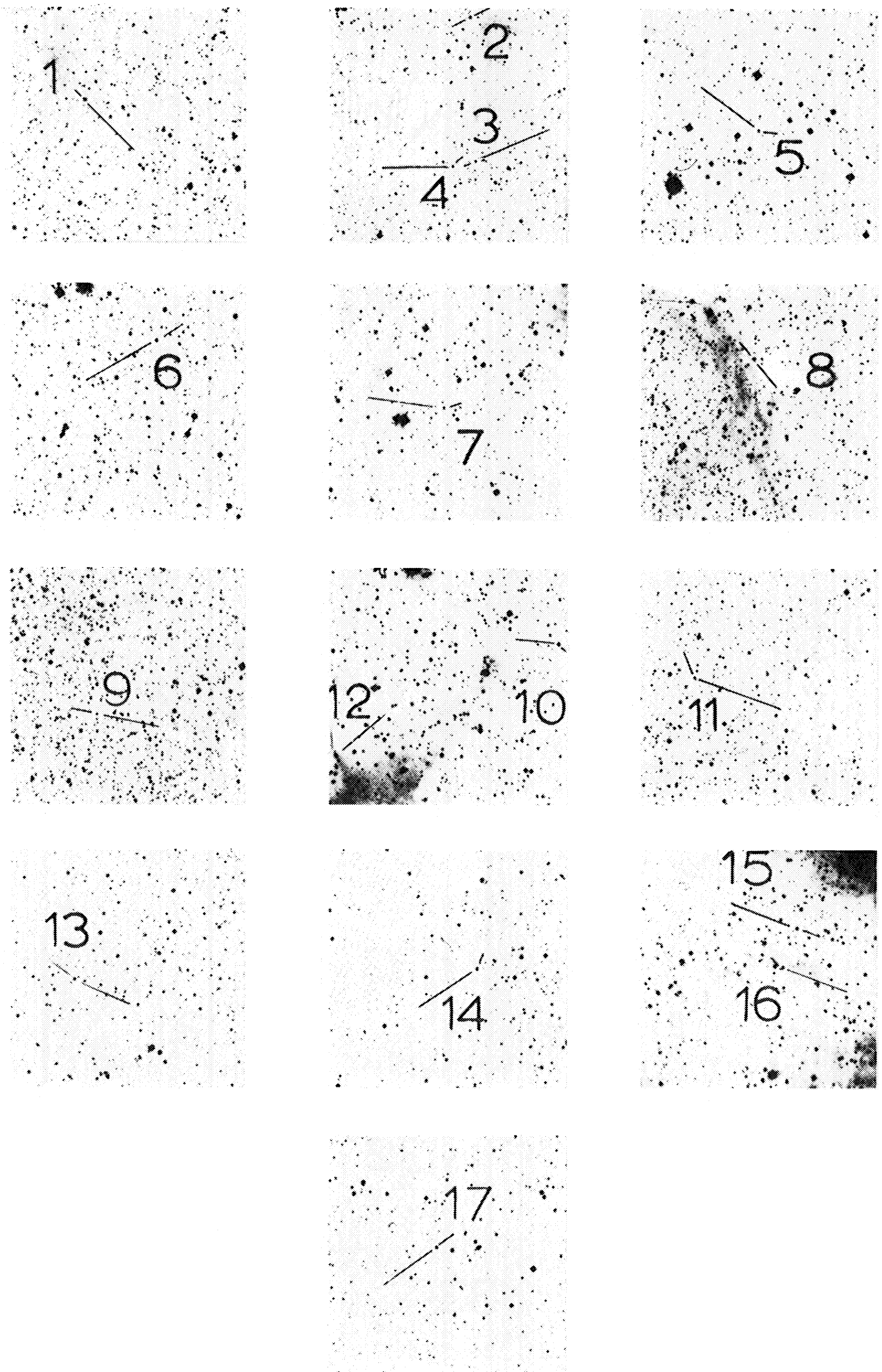

FIG. 1. Finding charts for the OB stars listed in Table I. North is up, east to the left.

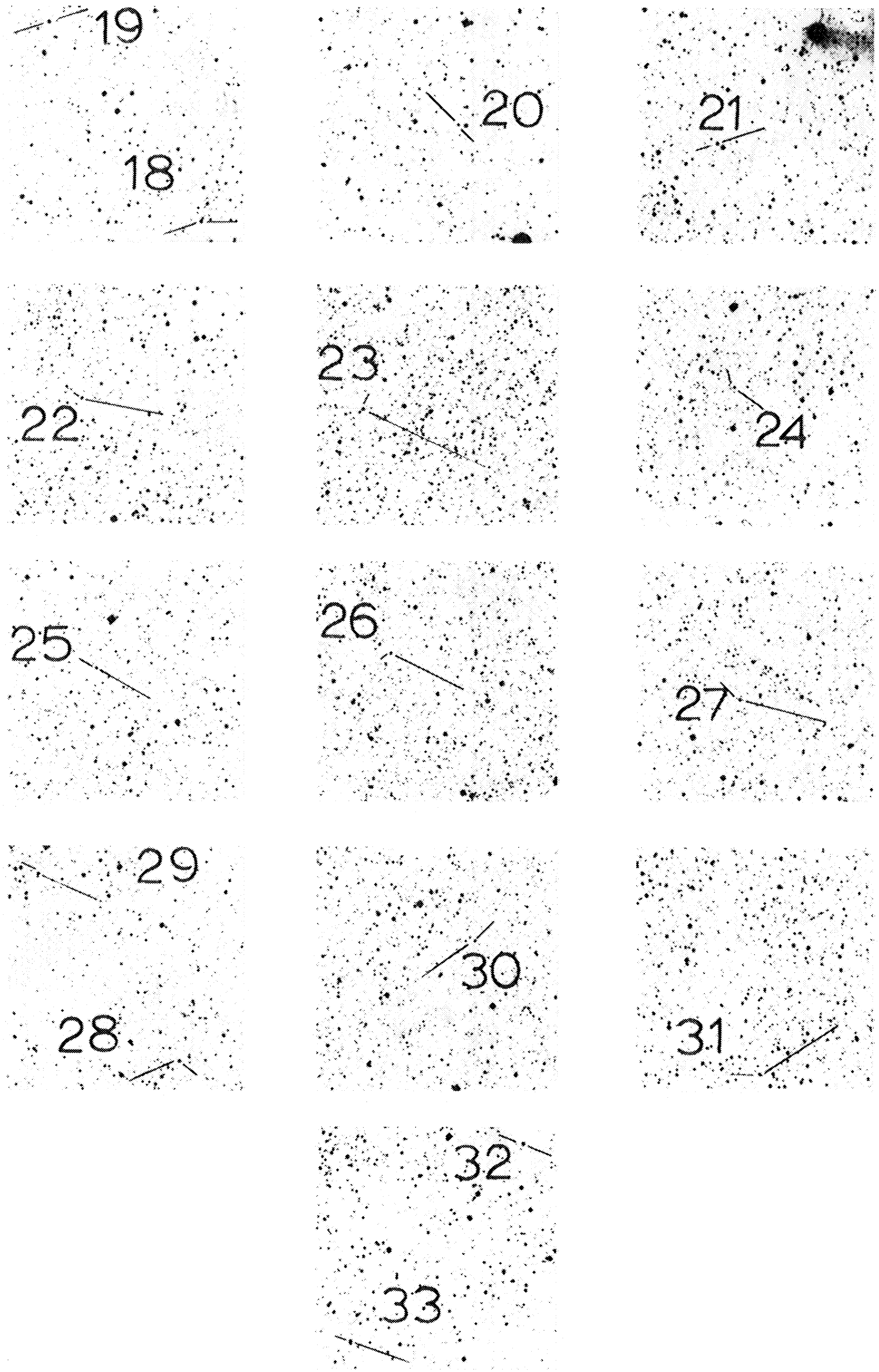

FIG. 1. (continued)

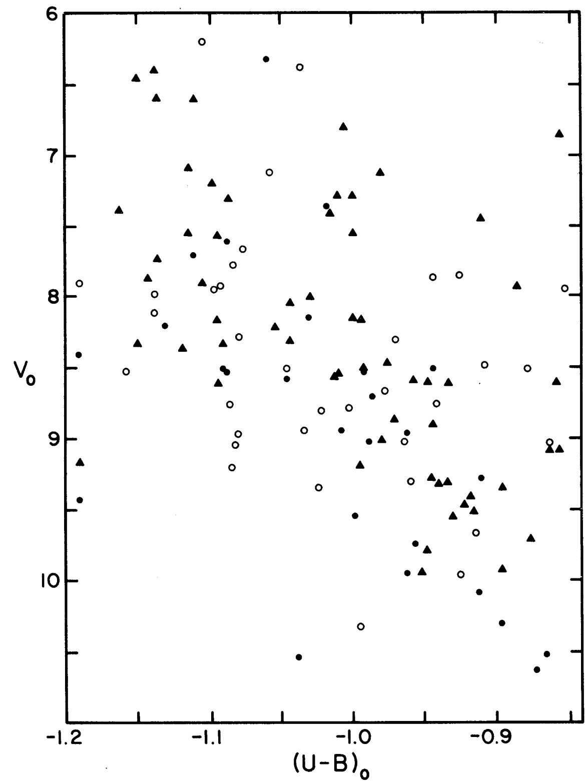

FIG. 2. Color-magnitude diagram for (a) OB stars discovered in this work (closed circles), (b) stars observed by Graham (1970) (triangles), and (c) luminous stars observed by Forte (1976) (open circles).

A number of stars observed by Forte (1976) were also tentatively identified as members on the basis of their positions in the color-magnitude diagram.

However, "well behaved" sequences can be obtained from a random spatial distribution of stars (see Maeder 1974). Further support for the physical existence of such sequences can be obtained only through spectroscopic observations.

The distribution of the stars in Fig. 2 suggests that the ZAMS calibration would be useless in an attempt to derive the distance moduli, because even though these stars are certainly young, they may represent an admixture of stars in different evolutionary stages. The distance moduli of the stars listed in Table I were obtained by means of the absolute magnitude calibration of the OB natural groups given by Herr (1969). A search for Hα-emission objects, made at CTIO with the Curtis Schmidt telescope and the 4° prism on 127-04 plates, showed that only OB stars 9 and 25 listed in Table I have Hα emission, and thus we adopted Herr's calibration for "non-emission-line stars." This calibration was derived for a different instrumental system, but its use is justified by the agreement between the mean intrinsic colors of the stars presented in this work and the values given by Herr in his Table I. For the stars listed in our Table I, we obtained $(U-B)_0 = -1.13 \pm 0.07$, -1.01 ± 0.10, and -0.88 ± 0.11 mag; and mean moduli $V_0 - M_v = 13.5 \pm 0.6$, 13.4 ± 0.9, and 13.4 ± 0.7 for the OB$^+$, OB^0, and OB$^-$ groups, respectively. These moduli show that the discovered stars are mostly background objects. This conclusion is also supported by Fig. 3, where the V_0 vs E_{B-V} values are depicted. While the stars observed by Graham (1970) and by Forte (1976) show a fairly uniform distribution between $E_{B-V} = 0.20$ and 0.70 (the same range of the color excesses observed for stars in the association's core), the stars presented in this work have appreciably larger reddenings.

Wrandemark (1976) studied the color excess versus distance distribution in a field close to the Carina Nebula. His Figs. 3 and 4 show that stars with color excess $E_{B-V} \geq 0.7$ should be located farther than $V_0 - M_v = 13.0$ from the Sun, in agreement with our previous result.

It can be mentioned that the faintest stars found in this search ($V_0 \geq 10.00$) could be related to the association according to their positions in Fig. 3, but they do not represent a major contribution to the total number of association members. With the adoption of $V_0 - M_v = 12.0$ for the association, the results presented in this section suggest that practically all of the stars brighter than $M_v = -2$ and in the color excess range character-

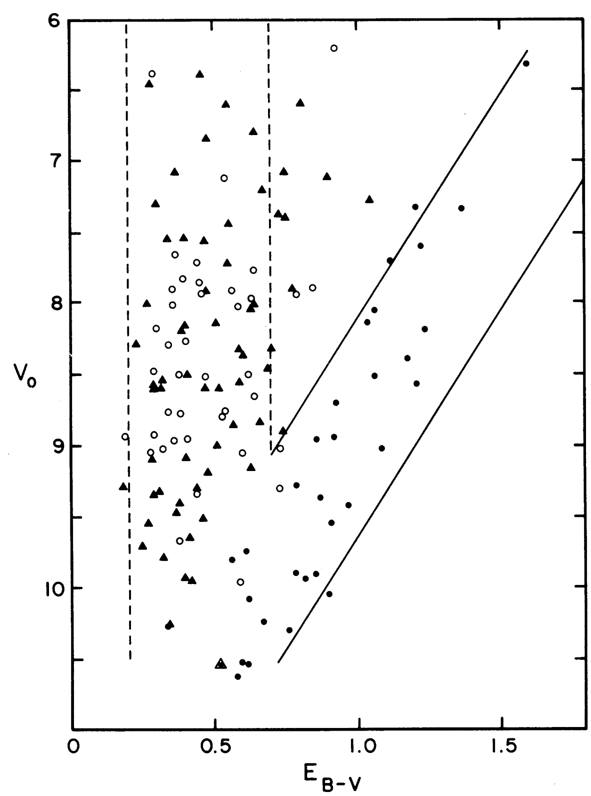

FIG. 3. Apparent corrected magnitude vs color excess diagram for the stars plotted in Fig. 2. The symbols have the same meanings as in Fig. 2. The completeness lines have a slope corresponding to $R = 3.1$. Dashed lines indicate the color excess range observed in Car OB1.

istic of Car OB1 have been detected by previous searches.

IV. IMAGE-TUBE SPECTRAL CLASSIFICATION

In order to get some information about the evolutionary stages and distance moduli of the OB stars in the association's periphery, we obtained spectrograms for a sample selected from Forte (1976, Fig. 5). The spectrograms were taken with the CIT image-tube spectrograph in combination with the Yale 1-m telescope at CTIO. The dispersion was 43 Å mm^{-1} with a widening of 0.6 mm. The plates were baked IIIa-J developed in D-19.

The classification was performed by comparing the program stars with a grid of standards in the range O5–B5 selected from Garrison, Hiltner, and Schild (1977). Although these classifications intend to reproduce the MK system, it must be kept in mind that important differences exist with the defining instrumental system (dispersion, emulsion, etc.).

Table II gives the resulting spectral types, color excesses, and distance moduli. Except for star 15, taken from Table I, the remaining identifications are from "Luminous Stars in the Southern Milky Way" (Stephenson and Sanduleak 1971). An inspection of Table II reveals that almost 70% of this sample are main-sequence stars. Among the O stars, four are located near the clusters and inside Stephenson and Sanduleak's "F" region.

The distribution of the stars in the color excess versus distance modulus plane is shown in Fig. 4. The spectroscopic moduli were computed adopting $R = 3.1$, since the reddening law seems to be normal outside the nebular

TABLE II. Spectral classification, color excesses, and distance moduli for OB stars in the field of NGC 3372.

Star	Sp.	E_{B-V}	$V_0 - M_v$(Sp)
15 (Table I)	O4V	1.20	14.0?
LS 1695	O9V	0.48	11.8
LS 1707	B0Ib	0.61	13.4
LS 1714	B1.5V	0.64	11.6
LS 1717	B1.5III	0.35	11.2
LS 1720	B0V	0.24	11.9
LS 1721	B1.5V	0.26	12.3
LS 1738	O8V	0.31	12.3
LS 1742	B2III	0.35	13.0
LS 1743	B1.5III	0.23	12.3
LS 1745	B2III	0.16	12.8
LS 1754	B1II	0.44	14.3
LS 1760	B2Ib	0.59	14.2
LS 1762	B2V	0.28	11.6
LS 1763	B2V	0.39	12.2
LS 1767	B1.5V	0.28	11.8
LS 1771	B1Ia	0.32	15.8
LS 1774	B2V	0.29	11.6
LS 1778	B2V	0.36	11.6
LS 1781	B1V	0.30	11.3
LS 1783	B1V	0.38	10.9
LS 1790	B2V	0.30	12.1
LS 1795	B1.5V	0.40	11.8
LS 1797	B1Ve	0.48	10.6?
LS 1798	B1.5V	0.28	11.3
LS 1800	O6V	0.58	12.8
LS 1801	B1.5V	0.35	12.9
LS 1807	O9V?	0.63	12.3
LS 1811	B0Ib	0.34	12.3
LS 1822	B1.5Ib	0.64	12.0
LS 1827	O9III	0.59	13.9
LS 1840	B1V?	0.45	12.2
LS 1842	B1V	0.44	12.0
LS 1879	B1.5Ib	0.92	13.1
LS 1897	O7V	0.74	12.4
LS 1914	B1V?	0.42	12.7
LS 1928	B0Ia	0.69	14.3
LS 1932	O5V	0.28	12.0
LS 1937	B1Ib	0.42	14.4
LS 1941	B2V	0.50	10.8
LS 1947	B0Ib	0.58	14.2
LS 1949	B2V	0.24	12.0

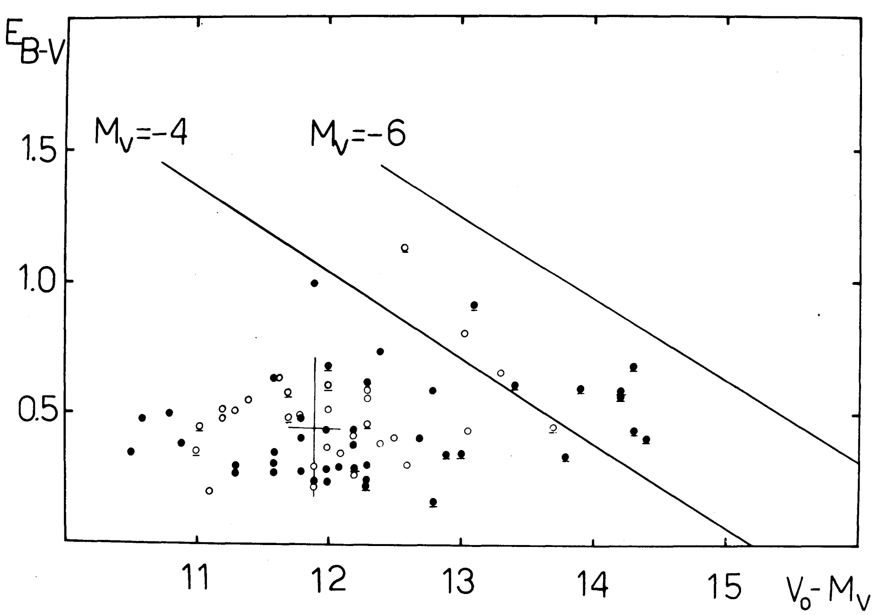

FIG. 4. Color excess vs spectroscopic distance modulus diagram for the luminous stars listed in Table II (closed circles) and stars observed by Herbst (1976) (open circles). Underlined circles are non-main-sequence stars. The completeness lines have a slope corresponding to $R = 3.1$. The cross represents the mean spectroscopic modulus, $V_0 - M_v = 11.9$, for 26 main-sequence stars. Star 15 was not included in this computation.

core, and using the absolute magnitude calibration given by Walborn (1972). The mean distance modulus for 26 main-sequence stars is $V_0 - M_v = 11.9 \pm 0.56$, in agreement with the photometric modulus. This mean value was derived by including five stars that belong to the group known as Bochum 10. For these stars, the mean modulus is $V_0 - M_v = 11.6 \pm 0.3$, and they probably belong to a foreground structure nearer to the Sun than the association nucleus. This modulus agrees with the conclusions given by Turner and Moffat (1980).

Figure 4 also includes cluster stars taken from Herbst (1976, Table 5). Their moduli were computed by adopting the reddening parameters of Forte (1978). These stars appear well mixed with the luminous stars and do not show a clear separation in distance or reddening.

The spectral types presented in Table II are consistent with an analysis of their positions in the $U - B$ vs $B - V$ diagram. However, the stars classified as B2V have colors not appreciably different from those corresponding to stars classified as B1.5V. Perhaps the former ones are the "bluest" B2V, and in this case a brighter absolute magnitude should be used in the computation of the distance modulus. The adoption of the B1.5V absolute magnitude for the stars classified as B2V would increase the mean modulus by 0.1 mag.

V. STAR 15

This star is found in the darkest region of the Nebula and has the largest known color excess in the region ($E_{B-V} \cong 1.2$ mag). The photometric values given in Table I show some variability when compared with observations made during February 1977 with the 90-cm telescope at CTIO ($V = 12.18$, $B - V = 0.90$, $U - B = -0.31$). A spectrogram obtained with the CIT spectrograph shows broad H and He II lines, while He I is barely seen at λ4541. The star was classified as O4V and is probably even earlier by comparison with O3V stars observed by J. C. Muzzio with the same instrument and dispersion.

If the star is associated with Car OB1, and if we adopt $R = 3.1$, its position would be about 1.4 mag below the main sequence defined by Trumpler 14 and 16. This discrepancy could be solved by using a larger value of R, and gives some support to previous results pointing to the existence of an abnormal ratio of total to selective absorption in the nebular core.

Other possible explanations of this star's position in the color-magnitude diagram are that it is a hot, underluminous object or a background object. This last possibility seems improbable, since O4 stars are uncommon objects and the probability of finding one superposed on the line of sight with a group of O3 stars is negligible. As a reference, only two stars were designated as this type among the 1113 early-type stars classified by Garrison, Hiltner, and Schild (1977).

VI. CONCLUSION

The spectroscopic search presented in this work shows that previous surveys had discovered practically all the OB stars brighter than $V = 11.2$ mag in a region 3° in diameter around η Car. The newly found OB stars have a mean color excess appreciably larger than the color excesses characteristic of the Car OB1 nucleus, and their distance moduli suggest that they are mostly background objects. Neither clustering nor concentration toward the nebular nucleus is seen for these stars. Even though the plates used for this search could have revealed O stars at the association's distance with visual absorptions as large as 6 mag, only two OB stars were detected behind the dark lanes that cross the nebula. One of these stars (No. 15) is seen through the region of maximum OH optical depth found by Dickel (1974). The visual absorption for this object (3.7 to 4.9, depending on the value of R) agrees with the estimation made by Dickel (1974) by comparing radio continuum and Hα fluxes.

On the other hand, the image-tube spectral classification for a sample of stars considered as "probably associated" according to photometric criteria suggests that 60% of them are actually related to the association. If this percentage is representative for the whole OB population inside the surveyed region, then one would expect about 100 member stars earlier than B2 within 60 pc from the association's core. This population would be comparable with the main-sequence population of the main clusters. Interestingly, inspection of Table II shows a lack of O stars (except in the innermost region), which suggests a difference in the mass distribution function between the stars formed in the clusters and those formed in the periphery of the association.

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