

RED SUPERGIANTS IN OPEN CLUSTERS*

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ABSTRACT

New spectral types and some new *UBV* photometry are presented for three southern open clusters containing M supergiants, and data for a fourth are rediscussed. It is concluded that the red supergiant near the cluster IC 2944 is probably not a member. The remaining three clusters which have red supergiants, NGC 3766, NGC 3293, and NGC 4755, have stellar populations similar to that of χ Per. Very young clusters such as h Per, M29, and NGC 6231 apparently do not have red supergiants. It is concluded that most red supergiants are associated with stellar populations of intermediate age ($[10-25] \times 10^6$ years). This conclusion is found to be consistent with the presence of α Ori and α Sco in subgroups of the associations I Ori and II Sco.

These results suggest that supergiants up to a mass limit of approximately $16 M_{\odot}$ spend an appreciable fraction of their helium-burning lifetimes, immediately after helium ignition, as red supergiants, and that neutrino emission dominates the luminosities of supergiants in post-helium-burning stages.

I. INTRODUCTION

In a recent study of the effects of neutrino emission on stellar evolution, Stothers (1969*a*) showed that the relative proportion of blue to red supergiants in young clusters provides a sensitive test for the occurrence in nature of neutrino emission according to the theory of direct electron-neutrino interaction. Stothers and Chin (1968) and Stothers (1969*b*) have shown that neutrino production by pair annihilation and the photoneutrino process accelerates evolution of the supergiants which are burning heavy elements and thereby increases the predicted ratio of the number of blue to red supergiants, n_b/n_r , by about an order of magnitude. The values for this ratio have not yet been precisely predicted because, as Stothers and Chin have shown, they depend on the amount of time spent as red supergiants immediately after the onset of helium burning, which in turn is very sensitive to the opacity and chemical inhomogeneity (treatment of semiconvection). An analysis of data for clusters and associations containing red supergiants (Stothers 1969*a*) suggested that the ratio is large for the most massive stars and is near unity for the less massive supergiants.

The present investigation is concerned with stellar populations of young clusters containing red supergiants, with the specific aim of establishing the spectral types and luminosity classes of blue supergiants associated with the M supergiants. Determination of spectral types provides the most sensitive data for the definition of stellar populations of the very young clusters because large differences in mass and age are reflected by only small differences in color among stars whose radiation is principally in the ultraviolet. Accordingly, spectral types based on new spectrograms for classification and on some new photometry were obtained in the spring of 1968 with the 36-inch and 60-inch reflectors of the Cerro Tololo Inter-American Observatory. The spectrograph used has been described by Hiltner, Garrison, and Schild (1969). Primary standards used in the classification were the Orion and Canis Majoris supergiants and the less luminous stars of the II Sco association.

II. CLUSTER DATA

The clusters observed are NGC 3766, NGC 4755, and IC 2944. In addition, Feast's (1958) observations of NGC 3293 are rediscussed with reddening and distance modulus

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reevaluated. Basic calibrations of magnitude and color versus spectral type, as well as bolometric corrections, are from Blaauw (1963) and Johnson (1966). A value of $R = 3.0$ has been used throughout to correct observed magnitudes for interstellar extinction.

a) NGC 3766

In many respects, NGC 3766 appears to be a condensation in a large association of supergiants analogous to the region of χ Per. Stars were observed to a magnitude limit

TABLE 1
OBSERVATIONAL DATA FOR NGC 3766

No.*	Sp	V	B-V	E_{B-V}	V_0	$m-M$	Notes
1.....	B2 IV p(e)	8.58	+0.01	0.25	7.83	11.1	1
5.....	B1.5 III	7.97	-0.18	0.07	7.76	11.8	
7.....	B2 V	10.11	+0.01	0.25	9.36	11.9	
8.....	B4 V	10.69	-0.03	0.15	10.24	11.6	
15.....	B2 III	8.56	+0.07	0.31	7.63	11.2	
20.....	B2 IV-V n	9.43	+0.05	0.29	8.56	11.5	
22.....	B2.5 V	9.99	-0.02	0.20	9.39	11.5	
23.....	B2 IV-V	10.42	+0.04	0.28	9.58	12.5	
26.....	B2 IV ne	9.06	-0.07	0.17	8.55	11.9	2
27.....	B2 IV-V	8.46	-0.04	0.20	7.86	10.8	
36.....	B4 V ne	10.33	+0.03	0.21	9.70	11.1	3
48.....	M0 Ib	7.38	+1.85	0.22	6.73	...	4
52.....	B1.5 V	10.29	+0.02	0.27	9.48	12.5	
63.....	B1.5 V n	9.26	+0.01	0.26	8.48	11.5	
67.....	B2 V p	9.85	-0.12	0.12	9.49	12.0	5
70.....	B2 IV-V	9.07	+0.01	0.25	8.32	11.2	6
81.....	B2 V npe	10.00	-0.15	0.09	9.73	12.2	7
88.....	B3 npe	10.00	+0.04	0.24	9.28	...	8
97.....	B2 V	9.62	-0.01	0.23	8.93	11.4	6
232.....	B4 Ia	7.16	+0.13	0.26	6.38	13.3	6, 9
3.....	B2 IV n	8.57	-0.04	0.20	7.97	11.3	6
13.....	B2 III	8.16	0.00	0.24	7.44	11.0	6
14.....	M0 Iab	7.18	+2.02	0.21	6.55	12.1	6
20.....	B2 IV	7.19	-0.04	0.20	6.59	9.9	6
21.....	A0 Ib	6.29	+0.09	0.08	6.05	11.2	6

* Numbers from Ahmed (1962). Italicized numbers from Plate 1 of Ahmed.

NOTES:

1. Sharp $H\gamma$ line and incipient emission at $H\beta$.
2. Moderate emission at $H\beta$.
3. Emission at $H\beta$, sharp absorption core in $H\delta$.
4. Reddening taken to be the cluster mean.
5. Weak He I lines.
6. Not within the cluster center of 5' diameter, and shown as small points in Fig. 1.
7. Faint emission at $H\beta$. Very broad hydrogen lines but moderately sharp helium spectrum.
8. Well developed shell star. $H\beta$ filled in with emission, sharp absorption cores in higher series members, strong Fe II absorption spectrum.
9. Assumed to be a background star.

of $B = 10.6$ in a field 5' in diameter and centered on the cluster. A few stars outside this limit, noted in Table 1, were sampled in a search for outlying supergiant members. New photometry was obtained for a few stars lacking published photometry and is listed in Table 1. Photometry for the remaining stars is from Sher (1965) or Ahmed (1962).

The H-R diagram for NGC 3766 is shown in Figure 1, *a*, where it is seen that the cluster turnup occurs principally at spectral type B2. The mean reddening found is $E_{B-V} = 0.22$ mag, and the true distance modulus is 11.6 ± 0.2 (rms) corresponding to a distance of 2.2 kpc. Two outlying stars, not plotted in Figure 1, *a*, are considered to be nonmembers because their distance moduli differ from the cluster mean by more than 1.5 mag. The outlying A0 Ib supergiant No. 21 should be investigated from motion data for member-

ship since it appears to define the luminosity of evolving supergiants in a cluster somewhat older than χ Per.

Four Be stars were found and are explicitly labeled in Figure 1, *a*. One of these, No. 26, had previously been discovered by Henize (reported in Sher 1965). A second star determined by Henize to be a Be star, No. 63, was found, in the present classification, to have only broad lines.

b) NGC 4755

New spectral types and photometry were obtained for some of the brightest stars in NGC 4755, primarily to provide overlap with previous work and to take advantage of the excellent seeing at Cerro Tololo for observing a crowded area. New spectral types are

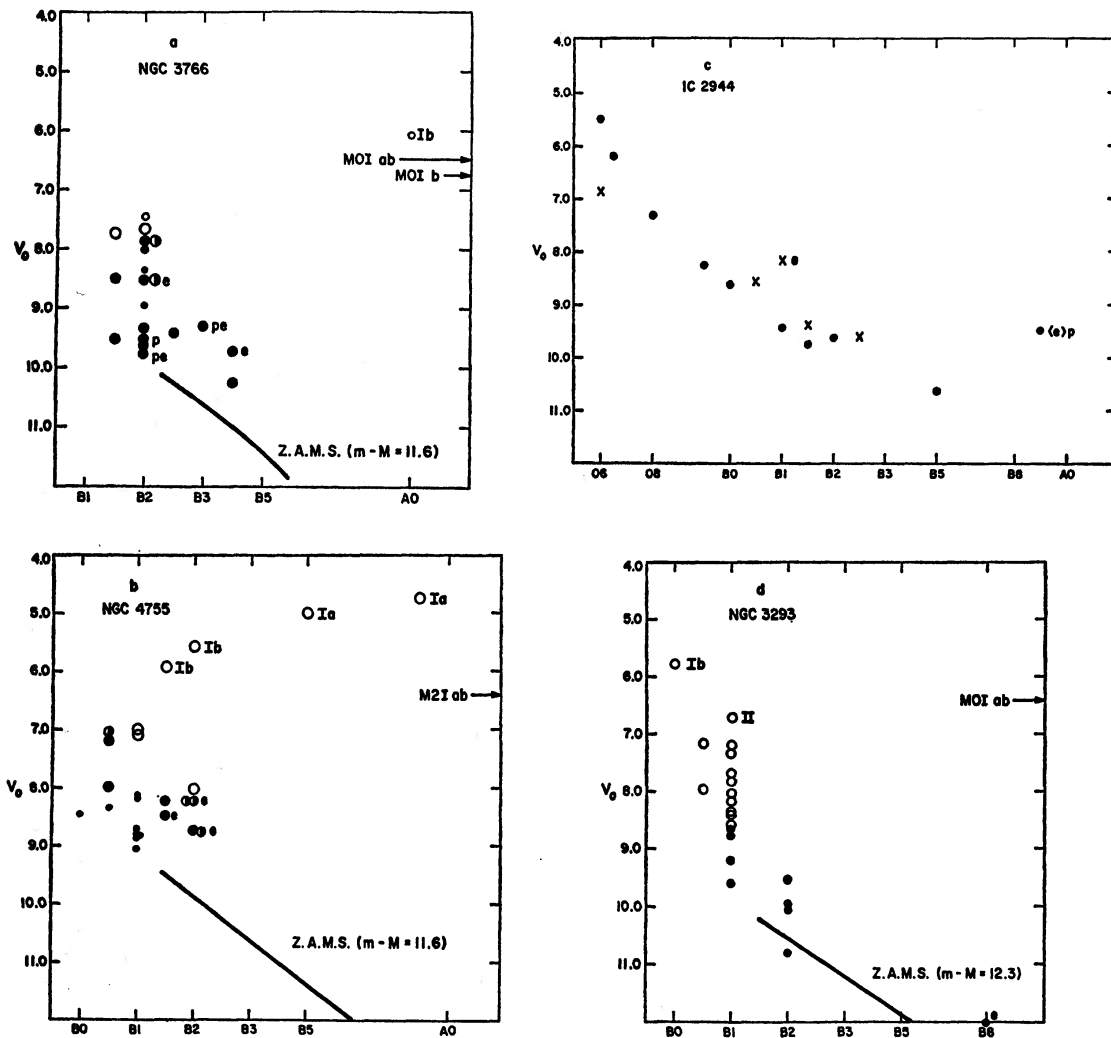


FIG. 1.—H-R diagrams for four young open clusters. *Filled circles*, luminosity class V or IV–V stars; *half-filled circles*, IV subgiants; *open circles*, III giants, or as noted. The zero-age main sequence (Z.A.M.S.) lines are shown for the cluster distance moduli given in the text. Arrows at the right-hand edges show the magnitudes of red supergiants. (*a*) NGC 3766; *small circles*, stars not included in the 5' cluster boundary. (*b*) NGC 4755; *small circles*, stars classified by Feast (1963) and not reobserved here. (*c*) IC 2944; *filled circles*, stars in the small stellar ring, as described in the text; *crosses*, stars in the 6' diameter field centered on HD 101265, but not lying on the small stellar ring. (*d*) NGC 3293; spectral types and photometry are from Feast (1958).

reported for all stars within $4'$ of the cluster center and to limiting magnitude $B = 10.0$; the new types are in excellent agreement with those reported by Feast (1963).

New photometry for seven stars is also reported in Table 2. Stars for which photometry from Arp and Van Sant (1958) was used do not have entries in the columns headed $U - B$ and n . Three stars measured show excellent agreement with the photoelectrically measured cluster standards of Arp and Van Sant, except in the case of star F. Of the two stars in common with Arp and Van Sant's list of photographically determined magnitudes and colors, one shows agreement whereas the other does not. No systematic differences between the new photometry and that of Arp and Van Sant are evident, and published photometry has been used for the ten stars not measured in the current program.

TABLE 2
OBSERVATIONAL DATA FOR NGC 4755

Star*	Sp	V	$B - V$	$U - B$	n	E_{B-V}	V_0	$m - M$	Notes
A.....	B9 Ia	5.75	0.33	...	...	0.33	4.76	11.9	
B.....	B5 Ia	5.94	0.22	...	...	0.31	5.03	12.0	
C.....	B2 Ib	6.80	0.24	...	...	0.41	5.57	11.3	
I-6.....	B1.5 Ib	7.00	0.18	...	...	0.36	5.92	11.6	
D.....	M2 Iab	7.66	2.16	+2.20	2	0.42	6.40	12.0	
II-23.....	B0.5 V n	7.93	0.20	...	...	0.48	7.2	11.2	1
E.....	B1 III	8.35	0.13	-0.69	2	0.39	7.18	11.6	
III-5.....	B0.5 IV n	8.43	0.18	...	...	0.46	7.05	11.6	2
I-5.....	B1 III	8.59	0.21	...	...	0.47	7.18	11.6	
F.....	B2 III	9.07	0.08	-0.70	2	0.32	8.11	11.7	
II-1.....	B0.5 V	9.37	0.18	...	...	0.46	7.99	12.0	
S(f).....	B1.5 V pne	9.56	0.13	-0.61	2	0.38	8.42	11.4	3
S(pr).....	B2 IV	9.63	0.23	...	2	0.47	8.22	11.5	
III-7.....	B1.5 V	9.66	0.23	...	...	0.48	8.22	11.2	
IV-17.....	B2 IV ne	9.76	0.26	-0.73	1	0.50	8.26	11.6	4
II-10.....	B2 V n	10.07	0.21	...	...	0.45	8.72	11.2	
III-6.....	B2 IV ne	10.19	0.24	-0.67	2	0.48	8.75	12.0	5
Mean.....	...	...	...	...	...	0.42	...	11.6	...

* Identifications from Arp and Van Sant (1958).

NOTES:

1. Two-lined spectroscopic binary, according to Feast (1963). V_0 has been corrected.
2. Variable radial velocity reported by Feast (1963).
3. $H\beta$ is in emission with a blue absorption component. The higher hydrogen lines show very strong, sharp absorption cores. He lines are very broad. Identification is from Feast (1963).
4. Emission cores in $H\beta$, $H\gamma$, and $H\delta$. He lines are broadened. No Fe II emission.
5. Emission cores in $H\beta$ and $H\gamma$ only. Faint Fe II emission.

The new H-R diagram for the cluster is shown in Figure 1, *b*. Luminosity classes are shown for the supergiants, and the three Be stars are identified. The double-lined spectroscopic binary II-23 has been corrected by 0.7 mag. Also included as small points in Figure 1, *b*, are stars classified by Feast (1963). The presence of two Ib supergiants at spectral types B1.5 and B2 is reminiscent of χ Per. Although χ Per does not itself have supergiants of spectral types B5 to A2, several have been identified with the stellar population similar to χ Per which immediately surrounds the double cluster (Schild 1967). The presence of Be stars at spectral types B1-B2 is also characteristic of the χ Per stellar population. Values of 0.42 and 11.6 are found for the mean reddening and distance modulus, respectively.

c) IC 2944

The cluster associated with the emission nebula IC 2944 has been carefully studied by Thackeray and Wesselink (1965) and has been more recently mentioned by Schmidt-Kaler (1968), who considers the cluster to be in the form of a large stellar ring that

includes the M supergiant HD 101712. Photographs of a small clustering around HD 101205 have been published by Thackeray and Wesselink (1965) and by Lynds (1968). The latter photograph shows better a moderate clustering of faint stars near one edge of an elliptical stellar ring 5' across, with HD 101205 near its southern end. These groups lack the star density of clusters like NGC 3766 and NGC 4755 and are more similar to NGC 2244 and IC 1805. The ring discussed by Schmidt-Kaler is approximately a factor of 5 larger and incorporates, near one end, the ring 5' in diameter mentioned above. The large ring can be seen as a chain of stars below and to the left of the small ring, which is 5.8 cm from the left and 6.5 cm from the bottom edge of the beautiful red plate of the greater region obtained by Bok (1969). The red supergiant HD 101712 is usually considered to be a member of the IC 2944 cluster, although it is 25' away from the small

TABLE 3
OBSERVATIONAL DATA FOR IC 2944

Star*	Sp	V	B-V	U-B	n	E_{B-V}	V_0	Notes
-62°2151.....	B1 V e	9.21	0.08	...	...	0.34	8.19	1
-62°2153.....	B1 V	10.21	0.00	-0.81	2	0.26	9.43	2
-62°2154.....	O6.5	7.16	0.01	-0.90	2	0.33	6.17	2
-62°2156.....	B0 V	9.63	0.04	...	...	0.34	8.61	2
-62°2157.....	B1.5 V	10.69	0.06	-0.67	2	0.31	9.76	2
-62°2158.....	O9.5 V	9.28	0.04	...	...	0.34	8.26	2
-62°2160.....	B9 p(e)	10.08	0.14	...	...	0.20	9.48	2,3
-62°2164.....	O8 V	8.48	0.08	...	...	0.39	7.31	2
-62°2166.....	B5 V:	10.83	0.08	-0.57	2	0.24	10.11	2
-62°2167.....	B2 V	10.66	0.11	-0.57	3	0.35	9.61	2
-62°2168.....	O6	6.5 var	0.01	-0.88	3	0.33	5.5	2,4
-62°2179.....	B2.5 V	10.76	0.17	...	...	0.39	9.59	
-62°2186.....	O6	8.07	0.09	...	...	0.41	6.84	
-62°2189.....	B1.5 V n	10.58	0.15	...	...	0.40	9.38	
-62°2194.....	B0.5 V	9.58	0.06	-0.75	3	0.34	8.56	
308811.....	...	11.11	0.34	+0.30	3	...	...
308822.....	...	10.64	0.37	+0.30	2	...	...
308828.....	...	10.61	0.73	+0.29	3	...	...

* CPD or HDE number.

NOTES:

1. Variable radial velocity noted by Thackeray and Wesselink (1965).
2. Member of small stellar ring.
3. Nearly featureless spectrum, apart from H absorption with poorly developed wings. Incipient emission at H β .
4. Brightness variable over a range of 0.12 mag in V. Variable radial velocity noted by Thackeray and Wesselink (1965).

stellar ring. It is seen to be at the edge of the nebular emission, in a location 2.5 cm from the left and 6.1 cm from the bottom edge of Bok's photograph.

A sample of the IC 2944 population was obtained by observing all stars brighter than $V = 10.8$ located within a circle 6' in diameter centered on HD 101205. This limit includes the weak clustering and the small ring mentioned above, as well as a few other stars. The region studied by Thackeray and Wesselink and the ring discussed by Schmidt-Kaler are very much larger. Photoelectric photometry was obtained for many stars observed spectroscopically, as well as for a sample of the fainter stars near HD 101205. To minimize the effects of nebular emission, the sky brightness in the vicinity of each program star was measured. Multiple observations, available for each star, are in excellent agreement even for the faintest stars measured. Star -62°2168 has variable magnitude with an observed range of 0.13 mag; it has also been reported by Thackeray and Wesselink (1965) to have variable radial velocity and is probably an eclipsing spectroscopic binary of spectral type O.

The H-R diagram for IC 2944, based on the data of Table 3, is shown in Figure 1, *c*.

Members of the small stellar ring are shown as filled circles, and are seen to define an extremely narrow main sequence reminiscent of NGC 2244 (Morgan *et al.* 1965). Stars appear to be above the main sequence at B5. Inclusion of stars not in the ring (*crosses* in Fig. 1, *c*) seems to increase the scatter, although the B1e star has variable radial velocity. These observations thus suggest that the population of the stellar ring is extremely young and homogeneous, and this may support its identification as a physical structure.

The larger ring discussed by Schmidt-Kaler (1968) incorporates the small stellar ring discussed above with several O stars and the M supergiant HD 101712. One of the few stars in the larger ring but not in the smaller is the O9.5 III giant HD 101413. It will be shown in a later section that this star is characteristic of an older stellar population. Since it has also been found that the M supergiants are characteristic of older stellar populations, confirmation of the identity of the larger ring as a physical entity must await observation of fainter members separate from the small ring. For the present, there is probably insufficient justification for associating the M supergiant with the stellar population exemplified by the very youthful stars in the small ring.

d) NGC 3293

Cluster NGC 3293 contains a single red supergiant of type M0 Iab. Because Feast's (1958) data for NGC 4755 indicate no systematic differences in spectral types from those estimated in the present work, the stars in NGC 3293 have not been reobserved and the spectral classifications of Feast (1963) have been adopted. The H-R diagram for stars within 2' of the cluster center is shown in Figure 1, *d*, in a format similar to that for the other clusters.

The H-R diagram has a turnup very similar to that in χ Per except in one important respect. Whereas the luminosity class I supergiants in the young clusters are all of later spectral types than stars at the turnup, NGC 3293 contains a supergiant of earlier spectral type. Moreover, a second B supergiant of similar very early type is very near the cluster and is usually considered to be a member. Although membership seems probable on the basis of positions projected on the plane of the sky and on the basis of distance moduli, radial velocities of the two supergiants are significantly more positive than the cluster mean. The possibility of systematic errors in the determination of the radial velocities of the supergiants has been considered and rejected by Feast. It is felt here that the question of membership of the two B supergiants must remain open until further data on motions become available.

An inspection of objective-prism plates by Sanduleak (1969) yielded no Be stars within the 4' cluster limits, but the B1 V star (Feast No. 12), a possible outlying member, was noted to have strong H α emission. Because of crowding in the cluster center, the presence of additional Be stars could not be definitely ruled out. A faint B8 Ve star has been listed by Feast (1958). The scarcity of Be stars is surprising since the stellar population defined by the turnup is similar to that of χ Per and NGC 4755, both of which have many Be stars of early B spectral type.

III. OB SUPERGIANT POPULATIONS IN YOUNG CLUSTERS

The H-R diagrams of the southern clusters containing supergiants show a striking result, namely, that all clusters containing M supergiants also have H-R diagrams with turnups at spectral types B0.5–B2. Clusters having only a slightly earlier turnup, such as h Per and M29, seem to be devoid of red supergiants. Because of the significance of this result in the theory of stellar structure and neutrino emission, it is important to ask why it differs from the current belief that M supergiants are associated with younger stellar populations as well. We emphasize that the present result is based on observations of central parts of well-defined clusters, where membership is highly probable. Previous results included observations of large associations such as I Ori, I Gem, and II Sco, where membership is less well established and where population differences and sub-

grouping are thought to exist (Blaauw 1964). It must now be shown that scarcity of red supergiants in clusters with stars of spectral type earlier than B0.5 is consistent with the presence of M supergiants in I Ori, II Sco, and I Gem.

At this stage it will be useful to define the several population types that are empirically found in the study of young clusters containing supergiants. In this discussion, we follow Keenan (1963) in naming stars of luminosity classes III, II, and I, respectively, as giants, bright giants, and supergiants. We also follow ordinary usage in describing the location in the H-R diagram at which a cluster H-R diagram is vertical as the *turnup*. This is not to be confused with the point at which departures from the line of the zero-age main sequence are first apparent; the latter is usually referred to as the *turnoff*. The cluster turnup has been found to be a useful measure of relative ages of clusters and is easy to determine for clusters having giants and supergiants. The position of the turnoff is more

TABLE 4

EMPIRICAL SUPERGIANT POPULATIONS

- A. Old Population ($-5.9, 10 M_{\odot}, 20$)
 - 1. Turnup at spectral type B2-3
 - 2. Supergiants of luminosity classes Ib and II at B6-A0
 - 3. Supergiants of luminosity classes Ib and II at K5-M0
 - 4. Prototypes: NGC 3766 and, possibly, NGC 457
- B. Intermediate Population ($-7.0, 13 M_{\odot}, 13$)
 - 1. Turnup at B1-B2
 - 2. Ib supergiants at B2, Iab and Ia supergiants at B5-A5
 - 3. Ia, Iab, and Ib supergiants at M0-M5
 - 4. Numerous Be stars at spectral types B1-2, III-V
 - 5. Prototypes: χ Per, NGC 4755
- C. Young Population ($-8.3, 20 M_{\odot}, 7$)
 - 1. Turnup at B0-B1
 - 2. Iab supergiants at B0.5, Ia supergiants at B2-3
 - 3. Few, or no, M supergiants
 - 4. Prototypes: h Per, M29
- D. Very Young Population ($-9.1, 30 M_{\odot}, 5.4$)
 - 1. Turnup at O9-O9.5
 - 2. Ia supergiants at B0-B0.5
 - 3. Few, or no, M supergiants
 - 4. Prototypes: Sco OB 1 (NGC 6231), Orion's Belt
- E. Early O-Star Population ($-10.0, > 40 M_{\odot}, 3.7$)
 - 1. Spectral types O4-O7
 - 2. Ia supergiants at O8-O9, scattered Ia+supergiants
 - 3. Few, or no, M supergiants
 - 4. Prototypes: Sco OB 1 blue branch, Per OB 1 O stars

difficult to determine because of the presence of spectroscopic binaries and, possibly, rotation and other effects which increase the vertical scatter in the H-R or color-magnitude diagrams.

In the context of the present discussion of clusters containing supergiants, the Pleiades are regarded as a very old cluster, even though the association of stars with dust in the Pleiades is well known. The H-R diagram of the Pleiades shows stars of late B and early K spectral types evolving horizontally as giants of luminosity class III. Somewhat younger clusters are characterized by the presence of luminosity class II B stars and Cepheids in their H-R diagrams. We shall be concerned here primarily with still younger clusters that contain stars of spectral type B2 and earlier. It will be useful to classify such clusters according to empirically established characteristics in order to clarify the discussion of M supergiants in associations. A classification scheme is outlined in Table 4.

It will be noticed that the populations are defined in terms of spectral types with luminosity classes. This is necessary because all the early-type stars discussed have similar colors, and most of the clusters containing these stars are highly and differentially reddened. Thus, the difference in population type between χ and h Per is fairly easily

detected from spectrograms (Schild 1965, 1967), although it is difficult to distinguish from photometric data alone. The supergiants within the empirically defined sequences are found to have constant bolometric luminosity in accordance with the prediction of Stothers and Chin (1968).

The empirical classification suggests that *old* clusters have red supergiants as late K and M0 stars, while the *intermediate* population clusters have M supergiants at slightly later spectral types. As noted above, still younger clusters ordinarily do not have red supergiants, although YZ Per is an outstandingly bright M2.5 Iab star seen in projection against the association Per OB 1 (Fig. 1 of Schild 1967) and may be a member of the more luminous *young* population found in the association. Although they must be rare, M supergiants with absolute magnitudes of -8.0 have been recognized in external galaxies (Tammann and Sandage 1968).

Physical parameters corresponding to the empirically derived populations of Table 4 have been obtained by applying the bolometric-correction data of Johnson (1966) to the absolute visual magnitudes associated with the spectral types according to the data of Blaauw (1963). Values of the absolute magnitudes for some of the earliest supergiants had to be modified slightly to obtain consistency with data for Sco OB 1. The bolometric magnitudes obtained were used to derive the masses and ages of the blue supergiants in the population groups, according to the calibrations of Stothers (1969*a*). These data are enclosed in parentheses in Table 4 in the form (M_{bol} , mass, age), where the reported ages are in units of millions of years.

IV. RED SUPERGIANTS IN ASSOCIATIONS

The principal finding of § II is that M supergiants are rare in clusters having *young* and *very young* supergiant populations. Can this be reconciled with the obvious presence of M supergiants in Orion and the Scorpius-Centaurus association, as well as in I Gem?

Because associations are often less homogeneous than the clusters in which the supergiant populations have been identified, a phenomenon that Blaauw (1964) has discussed and called subgrouping, it is necessary to identify the subgroups of the associations to which the supergiants belong. We discuss, in turn, the associations I Ori, II Sco, and I Gem.

a) I Orionis

Structure in I Ori has been discussed by Blaauw (1964), who attributes the youngest O stars to an *O-star* population in the sword region (Ic Ori). The well-known early B supergiants of the belt region of Orion define a *very young* population (Ib Ori); and an older population in the shoulder region, characterized by stars above the main sequence at spectral type B0.5–B3, has been identified (Ia Ori).

This subdivision into groups has been reexamined and supported in a recent study of distances and motions by Lesh (1968). On the basis of her new spectral types and recent photometry, Mrs. Lesh finds Ia Ori to be significantly closer than Ib and Ic Ori; respective distance moduli found are 7.9, 8.3, and 8.5, each with a probable error of 0.1; these are in agreement with the photometric results of Crawford and Barnes (1966). The stellar population of Ia Ori, as discussed by Mrs. Lesh, is found to be of the type defined here as *intermediate*.

The relationship of α Ori (M2 Iab) to any of the Orion subgroups remains uncertain. As noted by Mrs. Lesh, position in the sky and direction of motion suggest an origin in the *intermediate* population Ia Ori, but the amount of the motion is much too large. If α Ori is taken to be at the distance of Ia Ori, its absolute magnitude is about -7.6 , which is considerably brighter than the mean for the supergiants in southern clusters. Stothers (1969*b*) has shown that a much lower absolute magnitude is implied by its uncertain trigonometric parallax, by the strength of its K-line emission, and by its pulsational characteristics. Many discrepancies are removed if α Ori is considered a runaway member, as suggested by Stothers.

For the present, it is sufficient to note that the I Ori association contains several stellar populations, one of which is typical of clusters containing M supergiants, although the membership of α Ori in any of these populations remains uncertain.

b) II Scorpii

Structure in the association II Sco has been discussed by Blaauw (1964), who recognizes the Upper Scorpius and the older "Upper Centaurus-Lupus" populations. The association has been rediscussed by Garrison (1967) on the basis of new spectrograms and new photometry of the B and A stars. Garrison recognizes an *inner region* within "Upper Scorpius" (Garrison's Fig. 2), which contains the M supergiant α Sco. The H-R diagram of the inner region, shown in Garrison's Figure 5, contains an A0 II bright giant, a B1 giant, and a B2 subgiant. Such stars are characteristic of the *old* and *intermediate* supergiant populations that are found in the southern clusters containing M supergiants, studied in § II. It is probably incorrect to assign α Sco to the younger populations of τ Sco (B0 V) and ζ Oph (O9 V runaway star). Thus, although available data are only suggestive, it is reasonable to assign α Sco to an *intermediate-to-old* population.

c) I Geminorum

Stothers (1969b) lists ten supergiants as defining the I Gem association. These supergiants were found to have common distances, proper motions, and radial velocities (data on radial velocities available for some stars). One of the B supergiants in I Gem has a discrepant proper motion. Of the ten blue supergiants, two are judged to be *old* supergiant population, two are *young*, and six are *intermediate*, on the basis of their spectral classifications. Thus, the data for the loose, poorly defined association are inconclusive.

We conclude that the connection between red supergiants and very young stars, such as the supergiants in Orion's belt and the stars on the upper main sequence in II Sco, is not established, and there is no inconsistency in attributing the red supergiants to *intermediate* and *old* populations within the associations.

V. THE RATIO OF BLUE TO RED SUPERGIANTS

An important empirical number in the theory of stellar structure is n_b/n_r , the ratio of blue to red supergiants. Earliest models of supergiants, with neutrino emission neglected, predicted $n_b/n_r \approx 1$ (Hayashi, Hōshi, and Sugimoto 1962). More recently, however, Stothers and Chin (1968) have shown that a correct treatment of opacity brings some helium-burning models to the M region of the H-R diagram, so that relatively more M supergiants are expected. On the other hand, the near absence of M supergiants in the youngest clusters seems to show that neutrino emission is important for the youngest supergiants.

Stothers (1969b) has analyzed clusters and associations containing M supergiants and concluded that for the most luminous stars (15–60 M_\odot) $n_b/n_r \approx 5$, whereas for stars of lower mass (10–15 M_\odot) $n_b/n_r \approx 1$. Because selection effects may severely affect this conclusion in that only clusters containing red supergiants were considered, the ratio is redetermined here in light of new results.

In what follows we attempt to derive n_b/n_r for a fixed volume of space with the assumption that all M supergiants are associated with the *old* and *intermediate* supergiant populations. The calculation is done separately for stars within 2 kpc of the Sun and for the shell from 2 to 3 kpc. Blue supergiants and bright giants of spectral types B2 and later, corresponding to the range $-6.0 \leq M_{bol} \leq -7.6$, were counted from the OB star catalog of Hiltner (1956) where distance moduli were also available. Identifications of M supergiants for the same northern hemisphere area of the sky were taken from Nassau, Blanco, and Morgan (1954) and Blanco and Nassau (1957). Since photometry for the red supergiants is unavailable, reddening was allowed for statistically, with use of

$A_v = 0.8 \text{ mag kpc}^{-1}$, which is applicable to stars selected to limiting magnitude (Allen 1955). Following Sharpless (1966), we assumed that 70 percent of the identifications were supergiants rather than reddened giants.

Results are given in Table 5, where the numbers of supergiants counted as well as the ratio n_b/n_r are given for a volume of space 2 kpc in diameter, for the next outward shell of thickness 1 kpc, and for the region of Per OB 1 (the h and χ Per association). It can be seen from Table 5 that if the data for $r < 2$ kpc are considered to be complete, data for $2 \leq r \leq 3$ kpc are approximately 80 percent complete. Agreement among the three determinations is excellent though fortuitous, since large systematic errors may affect the first two determinations. The two statistically derived values of n_r , for example, are very sensitive to the assumed proportion of supergiants in the survey of the group at Case Institute and to assumptions about the mean value of reddening. The result for h and χ Per appears to be least susceptible to systematic error since the region of the double cluster has been very carefully surveyed for supergiants to faint magnitudes, and adoption of $n_b/n_r = 1.5$ is recommended.¹

The value of n_b/n_r for the *young* and *very young* supergiant populations cannot be directly determined because the association of a red supergiant with a group of such luminous blue stars has not yet been made. There is some evidence from the absolute

TABLE 5
RATIO OF BLUE TO RED SUPERGIANTS
(Intermediate and Old Populations)

Region	n_b	n_r	n_b/n_r
$r < 2$ kpc.....	44	27	1.6
$2 \leq r \leq 3$ kpc.....	40	27	1.6
h and χ Per.....	26	18	1.5

magnitude of YZ Per that it is associated with the *young* population of I Per, if association membership can be assumed. From the number of clusters containing *young* and *very young* supergiants, we may infer that the ratio is large. For example, if the uncertain case of I Per is excluded, then fourteen blue and no red supergiants are to be counted in the *young* or *very young* clusters M29 and NGC 6231 (Sco OB 1). In the statistics of small numbers, this is consistent with the upper limit of $n_b/n_r = 17$ predicted by Stothers for evolution of $22 M_{\odot}$ stars with neutrino emission. It is likely that final evaluation of this ratio for the luminous stars will have to come from a study of the Large Magellanic Cloud, where absolute magnitudes can be inferred to sufficient accuracy from a knowledge of apparent magnitude and distance modulus.

VI. SUMMARY AND CONCLUSIONS

Present findings confirm and extend the general picture proposed in the concluding section of Stothers (1969*b*) for the late evolutionary stages of massive supergiants. The available observational evidence from young clusters suggests that the oldest clusters containing B supergiants are typified by NGC 3766 and NGC 457. These clusters have helium-burning stars as late B supergiants and bright giants. Helium ignition and very advanced burning are probably taking place in the K–M supergiants of this population. NGC 4755 and χ Per represent a more youthful population in which helium burning

¹ A recently received manuscript from Humphreys (*Ap. J.*, in press) shows that, on the basis of more complete data for Perseus, $n_b/n_r = 1.1$. I thank Miss Humphreys for making her data available to me in advance of publication.

occurs in B stars of earlier spectral type and greater bolometric luminosity. Helium ignition and very late evolutionary stages are again thought to yield M supergiants; however, although these are of somewhat higher bolometric luminosity, they do not appear appreciably brighter, because they are generally of slightly later spectral type. Among the supergiants of yet younger clusters such as h Per and NGC 6231, red supergiants are very rare. This is evidence that the very massive stars spend very little time as red supergiants at the onset of helium burning, and also that supergiants burning carbon and heavier elements are extremely short-lived.

The new data suggest some modification of Stothers's (1969*a*) discussion of the "funneling effect" for OB stars into the M supergiant region. The apparent upper limit to M supergiant luminosities at $M_{\text{bol}} \approx -8$ ($M_v \approx -6$) is probably a result of the scarcity of the more luminous objects, which evidently evolve very quickly owing to neutrino emission. Data for open clusters suggest that the supergiants evolve at nearly constant bolometric luminosity, but since the more massive M supergiants have later spectral types (Table 4) and larger bolometric corrections, there is some apparent funneling toward $M_v = -6$. On the other hand, the most massive supergiants appear to occur at intermediate M spectral types, and $M_v \approx -8$ ($M_{\text{bol}} \approx -10$). M supergiants have been observed in NGC 2403 (Tammann and Sandage 1968), where the volume of space sampled is very much larger.

The picture of supergiant evolution presented here is consistent with theoretical and observational results found previously (Stothers 1969*a*; Stothers and Chin 1968, 1969). The abundances of M supergiants in the *old* and *intermediate* populations are a result of helium ignition in the M supergiant region. The scarcity of red supergiants among the *young* and *very young* populations apparently reflects a changeover to helium ignition as B supergiants and very short lifetimes in heavy-element-burning evolutionary stages due to neutrino emission. Effects of rotation and mass loss are not yet contained in models referred to above, and it is hoped that future theoretical work can be somewhat guided by the present observations.

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REFERENCES

- Ahmed, F. 1962, *Pub. Roy. Obs., Edinburgh*, **3**, 59.
 Allen, C. W. 1955, *Astrophysical Quantities* (London: Athlone Press), p. 251.
 Arp, H., and Van Sant, C. 1958, *A.J.*, **63**, 341.
 Blaauw, A. 1963, in *Basic Astronomical Data*, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 383.
 ———. 1964, *Ann. Rev. Astr. and Ap.*, **2**, 213.
 Blanco, V. M., and Nassau, J. J. 1957, *Ap. J.*, **125**, 408.
 Bok, B. 1969, *A.A.S. Photo-Bulletin*, No. 1 (cover photograph).
 Crawford, D. L., and Barnes, J. V. 1966, *A.J.*, **71**, 610.
 Feast, M. W. 1958, *M.N.R.A.S.*, **118**, 618.
 ———. 1963, *ibid.*, **126**, 11.
 Garrison, R. F. 1967, *Ap. J.*, **147**, 1003.
 Hayashi, C., Hoshi, R., and Sugimoto, D. 1962, *Progr. Theoret. Phys. Suppl.*, No. 22.
 Hiltner, W. A. 1956, *Ap. J. Suppl.*, **2**, 389.
 Hiltner, W. A., Garrison, R. F., and Schild, R. E. 1969, *Ap. J.*, **157**, 313.
 Johnson, H. L. 1966, *Ann. Rev. Astr. and Ap.*, **4**, 193.
 Keenan, P. C. 1963, in *Basic Astronomical Data*, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 89.
 Lesh, J. R. 1968, *Ap. J.*, **152**, 905.
 Lynds, B. T. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 119.
 Morgan, W. W., Hiltner, W. A., Neff, J. S., Garrison, R., and Osterbrock, D. E. 1965, *Ap. J.*, **142**, 974.
 Nassau, J. J., Blanco, V. M., and Morgan, W. W. 1954, *Ap. J.*, **120**, 478.
 Sanduleak, N. 1969, private communication.

Schild, R. 1965, *Ap. J.*, **142**, 979.

———. 1967, *ibid.*, **148**, 449.

Schmidt-Kaler, T. 1968, *Veröff. Astr. Inst. Ruhr-Universität, Bochum*, No. 1, p. 114.

Sharpless, S. 1966, *I.A.U. Symp. No. 24*, p. 345.

Sher, D. 1965, *M.N.R.A.S.*, **129**, 237.

Stothers, R. 1969a, *Ap. J.*, **155**, 935.

———. 1969b, *ibid.*, **156**, 541.

Stothers, R., and Chin, C. 1968, *Ap. J.*, **152**, 225.

Tammann, G., and Sandage, A. 1968, *Ap. J.*, **151**, 825.

Thackeray, A. D., and Wesselink, A. J. 1965, *M.N.R.A.S.*, **131**, 121.