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SPECTROSCOPIC STUDIES OF O-TYPE STARS. I. CLASSIFICATION AND ABSOLUTE MAGNITUDES*

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ABSTRACT

Spectrograms with dispersions of 16 Å mm^{-1} have been used to determine the spectral classification of 130 O-type stars. We are able to introduce intermediate MK types, e.g., O7.5, by *measures* of the He I and He II line strengths. We introduce a luminosity classification for the later O-type stars which involves measures of the ratio of Si IV to (singlet) He I. About fifty O-type stars have absolute magnitudes obtainable from membership in clusters and associations which have "well established" distances. These stars enable us to calibrate the luminosity criteria in terms of M_v.

We define Of stars as those in which the N III multiplet at λλ4634, 4640, 4641 is in emission above the continuum. Using only those O stars with known distances, we then find that the Of stars are *exclusively* in the hotter and brighter part of the H-R diagram. Although all O6 stars and earlier are Of, only the brighter later type O stars show these emission lines. Calibration of M_v with the spectral type and Of characteristics is provided for the O stars.

The presence of these lines in emission is suggested to be due to extended, possibly expanding, envelopes around these luminous stars. The He II 4686 line also appears in emission in some Of stars; there is a general tendency for the strength of this emission to be dependent on luminosity and effective temperature.

I. INTRODUCTION

The stars whose spectra are classified as type O in the MK system are among the hottest, youngest, and most massive stars in the Galaxy. Type O spectra are distinguished from type B by the appearance, at MK dispersion, of λ4541 of He II in absorption. A nice monograph on OB stars by Underhill (1966) reviews the state of our knowledge of these stars at that time.

According to the most recent models of, say, Mihalas and Auer (1970), the changeover from type B to type O occurs at a surface temperature of about 30,000° K. According to these authors, this is also roughly the temperature at which non-LTE effects begin to dominate line formation in stellar atmospheres. The spectra of stars of this temperature and hotter can be theoretically described only by a completely consistent non-LTE treatment, upon which some progress is now being made (Mihalas and Auer 1970).

A subgroup of O-type stars are called Of (Plaskett and Pearce 1931) which are defined by the presence, in emission, of N III λλ4634, 4640 and/or He II λ4686. Occasionally, other emission lines of Si IV, N IV, and C III have been reported as being present in some Of stars (e.g., Underhill 1966). There appear to be variations in the emission line strengths in several Of stars (Swings and Struve 1941; Oke 1954; Slettebak 1969), but aside from changes in He II λ4686, such variations have not been generally found for the absorption lines. These variations do not seem to be periodic but can occur in a few hours. One O star has been reported to have variations in the absorption line strengths (van Helden 1966), but this result has not been confirmed.

A number of bright O stars have been studied in the rocket ultraviolet (Morton 1967), and P Cygni profiles (i.e. redward shifted emission and violetward shifted absorption) have been found for several resonance lines. One Of star, ζ Pup, also has P Cygni line profiles in the rocket-ultraviolet spectral region (Smith 1970). Hutchings (1968) has

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studied the spectra of two very luminous Of stars which show P Cygni profiles in some subordinate lines in the blue. These observations suggest that at least some O and Of stars, possibly only the most luminous, have extended and expanding envelopes. The expansion of the atmosphere comes about because of radiation pressure in the ultraviolet resonance lines according to Lucy and Solomon (1970). The rates of mass loss due to the expansion may not be large enough to affect the evolution of the individual stars, but the expansion will have a profound effect on the problem of line formation. These aspects have been discussed by Lucy and Solomon (1970) and Lucy (1971), but a complete dynamical treatment of line formation for all lines has not yet been attempted.

An additional complication in the atmospheres of O stars is the effect of spherical symmetry. Their extended atmospheres may be large compared with the radius of the star, and the plane-parallel approximation will no longer be a suitable physical description. Cassenelli (1971) has discussed the continuous energy distribution in hot stars with extended envelopes. Line-formation problems in these types of atmospheres have not yet been fully solved.

We see that there are three major physical complications in understanding the atmospheres of O-type stars: non-LTE, extended and expanding envelopes, and effects of spherical symmetry. Theoretical work is presently underway on all of these problems.

Somewhat surprisingly, there has never been a systematic survey at relatively high dispersion of many O-star spectra. At the time of Underhill's review (1966), complete line-identification lists were available only for two O stars, of types O9 and O7. Since that time a detailed spectroscopic study of six O stars has been completed by Peterson and Scholz (1970). A few other O-star atmospheres have been studied by other authors, e.g., Buscombe (1969) and Hutchings (1968).

It is our intention in this series of papers to offer a homogeneous set of spectra of many O and Of stars to describe the classification, derive the absolute-magnitude scale, and discuss the absorption and emission line strengths. Particular long-standing problems we would like to solve include the relation between the O and Of stars, the definition of a normal O star, and the isolation of those stars with anomalous spectra. This paper will discuss the spectral classification and absolute magnitude scale. Later papers in this series will consider other topics, including questions of the temperature scale, and measures of the radial velocities of O stars.

The spectral classification of O stars depends primarily on the ratio of the strength of He I $\lambda4471$ to He II $\lambda4541$ (Morgan, Keenan, and Kellman 1943; Abt *et al.* 1968). In the O9 stars the former line is much stronger; the ratio changes gradually so that the latter line dominates in type O5. Luminosity criteria involving such lines as Si IV $\lambda4089$, C III $\lambda4068$, and He I $\lambda4143$ have been used at type O9 to define main-sequence and supergiant stars, but these have not been used for earlier types because of difficulties in consistency. We shall measure these lines to make more precise the MK classification, and demonstrate a luminosity criterion that is accurate for most O-type stars.

Of particular importance is the absolute magnitudes of the Of stars. It has been suggested (e.g., Roman 1951; Slettebak 1956) that they are generally the more luminous O stars, but this has not been universally accepted (e.g., Underhill 1966). We shall derive absolute magnitudes for a number of O and Of stars that are members of clusters and associations for which the distances are known independent of the spectra of O stars. In this way we can show what spectral features are shared by the more luminous, compared with less luminous, O stars. It will be conclusively demonstrated that indeed the Of stars are the more luminous types.

II. OBSERVATIONAL MATERIAL

We obtained all our spectra at the coudé focus of the Lick Observatory 120-inch telescope, using a grating-camera combination that gave 16 Å mm^{-1} in the blue. Most of the spectra were widened, on baked IIa-O plates, to 0.8 mm. A few were wider, and a few were narrower. The list of stars observed included all the stars classified as type O in the catalog of Jaschek, Conde, and de Sierra (1964) that are brighter than 8.0 visual and north of $-20°$ declination. A number of stars fainter than this limit or further south were also studied if they were in associations or of particular interest. The 130 O stars observed are listed in Table 1.

The V and $B - V$ colors in Table 1 were found in the literature, mostly from Hiltner and Johnson (1956). The MK spectral types were taken from the Jaschek catalog; where several MK types were given, the "most common" type was adopted. The spectral types listed in column (5) are newly derived in § III. The association membership in column (6) is taken directly from the IAU list (Ruprecht 1966) or from location within the boundaries of the association. Association or cluster membership and the absolute magnitudes in column (7) are more fully discussed in § IV.

Equivalent widths were derived for most lines visible in the spectra of these O stars from direct intensity tracings. Most of the tracings were obtained with a "computer assisted" method using a PDP 8 to derive the output. The plate calibration was derived by a computer-fitting procedure, and the direct intensity was computed point by point; the system is described by Robinson (1971). A few of the first plates traced used a "curve follower" method for the D–I transformation. A check of two plates by both methods revealed no systematic difference between the reduction procedures.

The equivalent widths were derived from the tracings by a numerical integration of the line profile. For a few stars two spectra were available. The equivalent widths in these cases were compared and were used to estimate a probable error for a single line: the result was ± 0.07 in log W. This number should be borne in mind in the results presented here since most stars had only one spectrogram each.

Equivalent widths expressed as log W, of He I λλ4471, 4120, 4143; He II λλ4541, 4686; and Si IV λλ4089, 4116 are presented in Table 2. Other lines will be discussed in subsequent papers.

III. SPECTRAL CLASSIFICATION

We shall adopt the classification criteria of Morgan *et al.* (1943) and Abt *et al.* (1968) for the O stars, namely, that the type is defined solely by the ratio of λ4471 to λ4541. An eye-estimate ratio is roughly equivalent to an equivalent-width ratio, here called W', if the latter is expressed logarithmically. Rather than adopt standard stars as in the MK system, we correlated all the MK types of all the stars in Table 1 with the average ratio of the line strengths of He I and He II. There is, of course, a spread in log W' for a given MK type. For example, the stars classified as O8 in the MK system had log W' ratios averaging around $+0.15$ and ranging from between ~ 0 to $\sim +0.30$.

Though the values of log W' vary continuously, we feel the observational errors are small enough to allow the assignment of intermediate types (e.g., O8.5) with confidence. In the mean, at each type, the new classification agrees with the MK one, but with occasional disagreement of up to three subclasses in individual cases. We made the spacing in log W' a smooth function of spectral type but stretched it at the hotter and cooler ends. This is necessary because the He I line disappears near O5 and the He II line near O9.5, so the ratio changes rapidly.

The types and the associated log W' values are given in Table 3. Our estimated probable error is a little less than one (new) subclass. We have defined a type O4 because this has been introduced by Abt *et al.* (1968) and because we observe stars which show log W' decidedly more negative than those at O5. Interestingly, the star Abt *et al.* defined as O4, HD 46223, is O5 on our system.

Stars were classified as Of if N III λλ4634, 4640 appeared in emission *above* the continuum. Emission at N III was never accompanied by an absorption component as far as could be seen on our spectra; i.e., there was no P Cygni structure in these lines. In a few stars the emission was so weak that it would not have been noticed on lower-disper-

TABLE 1

Catalog of O Stars

NAME HD OR BD	V	B-V	SP TYPE MK	SP TYPE REVISED	ASSOC.	$-M_V$	REMARKS
108	7.48	-.18	O8fp	O7If			
1337	6.05	+.03	O9III	O9.5I			SB2
5005	7.76	+.09	O6	O5.5f			
5005C			O9	O9V			
12323	8.90	-.12	O9V	ON9V	Per 1	3.6	H+χ
12993	8.95	+.20	O5	O6.5V	Per 1	4.5	H+χ
13268	8.18	+.13	O8V	O7:	Per 1	5.0	H+χ
14434	8.50	+.16	O6	O6.5:	Per 1	4.8	H+χ
14442	9.21	+.41	O5.5	O6f	Cam 1	4.9	H+χ
14633	7.47	-.21	O8	ON8.5V			
14947	7.98	+.46	O6f	O5.5f	Cam 1	6.3	H+χ
15137			O9.5V	O9.5III			
+60498	9.92	+.54	O9V	O9.5V	Cas 6	4.5	H+χ, IC 1805
+60501	9.60	+.46	O6.5	O6.5V	Cas 6	4.6	H+χ, IC 1805
15558	7.81	+.52	O6	O5f	Cas 6	6.6	H+χ, IC 1805
15570	8.10	+.70	O5f	O4f	Cas 6	6.9	H+χ, IC 1805
15629	8.43	+.42	O5	O5f	Cas 6	5.7	H+χ, IC 1805
+60512	9.41	+.50	O6	O7.5:	Cas 6	5.0	H+χ, IC 1805
16429	7.67	+.62	O9.5III	O9.5I	Cas 6	7.0	H+χ, IC 1805
16691	8.70	+.48	O5f	O5f	Cas 6	5.6	H+χ
17505	7.06	+.40	O7	O6f	Cas 6	6.6*	SB2, H+χ, IC 1848
17520	8.27	+.32	O8V	O9V	Cas 6	4.8*	VB, H+χ, IC 1848
17603	8.45	+.64	O7f	O8.5If	Cam 1	6.3	H+χ, IC 1848
+60586	8.48	+.30	O7	O8III	Cas 6	5.3	H+χ, IC 1848
+60594	9.30	+.36	O9V	O9V	Cas 6	4.6	H+χ, IC 1848
18326	7.82	+.38	O8				
19820	7.10	+.51	O9IV	O9III	Cam 1		SB2
24431	6.88	+.38	O9IV	O9V			
X Per	6.07	+.31	Ope	Bpe	Per 2	3.4	
ξ Per	4.02	+.04	O7	O7.5I	Per 2	5.0	
α Cam	4.29	+.04	O9.5Ia	O9.5I			
AE Aur	5.81	+.46	O9.5V	O9.5V	Ori 1	3.9	"Runaway"
34656	6.81	+.02	O7	O7If	Aur 1		
35921	6.81	+.20	O9.5III	O9.5:	Aur 1		Double Lines
δ Ori	2.20	-.21	O9.5II	O9.5I	Ori 1	6.3	
λ Ori A	3.66	-.19	O8f	O8IIIf	Ori 1	5.5	
λ Ori B	5.6		B0.5V	B0.5V	Ori 1	3.6	
36879	7.56	+.22	O6	O7.5III			
θ^1 Ori C	5.16	+.06	O6p	O7:	Ori 1	4.2	Trapezium
θ^2 Ori A	5.08	-.11	O9.5Vp	O9V	Ori 1	4.1	
ι Ori	2.74	-.25	O9III	O8.5III	Ori 1	5.7*	SB2
σ Ori	3.75	-.24	O9.5V	O9.5V	Ori 1	4.7	
ζ Ori	2.20	-.26	O9.5Ib	O9.5I	Ori 1	6.8	
μ Col	5.16	-.29	O9.5V	O9V	Ori 1	3.7	"Runaway"
41161			O9	O8V			
42088	7.55	+.07	O6	O6.5V	Gem 1	4.3	
45314	6.64	+.15	O9pe	Ope			
46056	8.19	+.18	O8	O8V	Mon 2	4.1	NGC 2244
48149	7.61	+.19	O8	O8.5V	Mon 2	4.7	NGC 2244
46150	6.72	+.13	O6f	O6f	Mon 2	5.5	NGC 2244
46202	8.17	+.17	O9V	O9V	Mon 2	4.1	NGC 2244
46223	7.25	+.22	O4	O5f	Mon 2	5.2	NGC 2244
46485	8.26	+.33	O8	O7.5:	Mon 2		
46573	7.95	+.33	O7	O7.5Vf	Mon 2		
46966	6.88	-.04	O8	O8.5V	Mon 2		"Ring"
47129	6.08	+.06	O8f	O7.5IIIf	Mon 2		"Ring"
47432			O9.5II	O9.5I			
15 Mon	4.65	-.25	O7	O8IIIf	Mon 1	5.1	NGC 2264
48099	6.38	-.05	O6	O6.5V	Mon 2		"Ring"
48279	7.97	+.11	O8	ON8V			

TABLE 1—*Continued*

NAME HD OR BD	V	B-V	SP TYPE MK	SP TYPE REVISED	ASSOC.	$-M_V$	REMARKS
52266	7.23	-.01	O9V	O9.5V			
52533	7.70	-.09	O9V	O8.5V			
53667	6.97	+.44	B0.5III	B0.5III	CMa 1		NGC 2353
53975	6.47	-.10	O8	O7.5V			
53662	6.21	+.03	O6	O7III	CMa 1		
29CMa	4.90	+.14	O7f	O8.5If			SB2, NGC 2362
τ CMa	4.39	-.14	O9III	O9I			NGC 2362
57682	6.42	-.20	O9V	O9V			
ζ Pup	2.25	-.26	O5f	O4f		6.6	"Gum" Nebula
ζ Oph	2.56	+.02	O9.5V	O9:			
151804	5.22	+.07	O8f	O8If	Sco 1	7.4	NGC 6231
152233	6.56	+.14	O6	O6f	Sco 1	6.3	NGC 6231
152249	6.44	+.20	O9I	O9.5I	Sco 1	6.5	NGC 6231
152408	5.77	+.16	O8f	O8If	Sco 1	7.1	NGC 6231
157857	7.78	+.18	O7f	O7:f			
162978	6.20	+.04	O8	O8.5IIIf			
163800	7.04	+.31	O8	O7If			
163892	7.44	+.09	O9IV	O9III			
164402	5.73	+.23	B0Ib	B0Ib	Sgr 1		M20
164438	7.48	+.34	O9IV	O9III			
164492	7.63	+.32	O7	O7.5III	Sgr 1		M20
9 Sgr	5.97	+.03	O5	O4f	Sgr 1	6.1	M8, NGC 6530
165052	6.87	+.09	O7	O7:	Sgr 1	5.4	M8, NGC 6530
165921			O7.5	O7:			Double Lines
166546	7.25	+.05	O9.5III	O9III			
166734	8.42	+1.09	O8f	O7.5If			
16 Sgr	5.98	+.04	O9II	O9III			NGC 6526
167659	7.39	+.22	O8	O7:f	Sgr 4	5.9	
167771	6.52	+.11	O8	O7If	Sgr 4	6.4	
167971	7.50	+.77	O8f	O7.5If	Ser 2		NGC 6604
168112	7.83	+.69	O5	O5.5f	Ser 2		NGC 6604
168075	8.77	+.44	O7	O6.5IIIf	Ser 1		NGC 6611
168076	8.24	+.44	O5f	O4f	Ser 1		NGC 6611
169582	8.70	+.56	O5f	O5.5f			
171589	8.28	+.32	O8f	O7.5Vf			
175754	7.04	-.07	O8f	O8IIIf			
175876			O6	O7:			
+223782	9.34	+.88	O7	O7IIIf	Vul 1		NGC 6823
186980	7.48	+.08	O7.5	O8IIIf	Vul 1		NGC 6823
9 Sge	6.20	+.01	O8f	O8If			
188209	5.60	-.06	O9.5III	O9.5I			
190429A			O5f	O4f	Cyg 3		NGC 6871
190429B			O9.5Ib	O9.5III	Cyg 3		NGC 6871
190864	7.76	+.20	O6	O7IIIf	Cyg 3		NGC 6871
191201			O9.5III	O9III	Cyg 3		SB2, NGC 6871
192281	7.55	+.38	O5f	O5.5f			
192639	7.11	+.35	O8f	O7.5IIIf	Cyg 1		NGC 6913
193322	5.84	+.11	O8	O8.5III			
193443	7.24	+.41	O9III	O9III	Cyg 1		NGC 6913
193514	7.40	+.45	O7f	O7.5IIIf	Cyg 1		NGC 6913
195592	7.08	+.87	O9.5Ia	O9.5I			
198846			B0IV	B0V			SB2
199579	5.96	+.05	O6	O6.5III			NGC 7000
201345			O9p	ON9.5V			
202124	7.80	+.22	O9.5Ib	O9.5I			
68 Cyg	4.99	.00	O8	O8V			
206267	5.62	+.21	O6	O6	Cep 2		Double Lines
207198	5.96	+.31	O9II	O9I	Cep 2		
207538	7.31	+.33	B0V	O9.5V	Cep 2		
14 Cep	5.54	+.07	O9V	O8.5III	Cep 2		SB2

TABLE 1—*Continued*

NAME HD OR BD	V	B-V	SP TYPE MK	SP TYPE REVISED	ASSOC.	$-M_v$	REMARKS
19 Cep	5.10	+.09	09.5Ib	09I	Cep 2		
210809	7.54	+.05	09Ib	09I	Cep 1		NGC 7380
λ Cep	5.08	+.25	06f	06f	Cep 2		
10 Lac	4.87	-.20	09V	08III	Lac 1	4.0	
215835	8.59	+.65	06	05.5	Cep 1		SB2, NGC 7380
216532	8.00	+.54	08	09.5V	Cep 3	3.8	
216898	8.00	+.53	08	09V	Cep 3	3.9	
217086	7.64	+.63	05	06.5:	Cep 3	4.6	
218915	7.20	+.02	09I	09.5I			
+602522	8.67	+.41	07f	06.5IIIf	Cas 2		

Note: A semi-colon following spectral types indicates that the luminosity type could not be determined, usually because of large line widths.

*Absolute magnitude discussed in notes to table.

NOTES TO TABLE 1

HD 108 (MWC 1). P Cygni profiles are seen in the hydrogen lines up to H10; emission is present at He I λ4471, He II λ4686. Other lines of He I appear filled in on the redward edge. This star is very unusual in that Si III λλ4552, 4563 appear in emission. Nitrogen III λλ4634, 4640, and C III λλ4647, 4650 are also in emission. The spectrum is overall similar to HD 152408 as described by Hutchings (1968), and can be considered an "extreme" Of star.

HD 1337. SB2 with orbit (Batten 1967): AO Cas. The spectral type of the secondary is earlier than the primary, which is a giant or supergiant. This result follows from the fact that He I/He II is smaller in the secondary than in the primary. Additionally, 4089/4143 is clearly larger in the primary than in the secondary. We derive $\Delta m = 0.6$ from the He I lines, which is a minimum difference if the secondary is appreciably earlier.

HD 5005 C. ADS 719C, visual companion to HD 5005.

HD 12323. This star is newly identified as belonging to the group with strong N III. Its absolute magnitude of -3.6 is of considerable interest in this connection since it is indistinguishable from a normal main-sequence star.

HD 14633. Called N III strong by Walborn (1970); our spectrogram agrees with this designation.

BD+60512. According to Vasilevskis *et al.* (1965) the proper motion of this star is very different from the other members of IC 1805. However, it is not impossible that the star has been ejected from the cluster, for its motion is directly away from the center (Vasilevskis 1971). In any case the modulus should not be very different from that of IC 1805 across the Perseus arm direction, as discussed in § IV.

HD 17505. Double lines appear on the two spectrograms we have of this star, which was not previously known as a binary. The spectral type of the secondary is an average of O7 from the two tracings; we derive $\Delta m = 0.7$ from the He I and He II lines. M_v is reduced by 0.4 mag for the primary star.

HD 17520. ADS 2165. This star is a close visual binary with equal components. M_v is reduced by 0.7 mag for the primary star. Only single lines are visible.

HD 18326. Our spectrogram shows a B-type shell spectrum. It is not impossible that the wrong star was observed, although there is no obvious candidate in the near vicinity. Confirmation of the spectral type of this star is needed.

HD 19820. SB2 with orbit (Batten 1967): CC Cas. Only single lines are visible on our spectrogram. According to Petrie (1950) $\Delta m = 1.6$.

X Per (MWC 78). The spectrum of this star is indeed very peculiar; broad emission lines are seen in the Balmer series up to Hδ; from the Hϵ to H10 they are filled in; beyond this the series is very faintly present in absorption. A few other O-star lines are very faintly present as broad shallow absorption, but He II is not present. The star is thereby classified as type B. Merrill and Burwell (1933) report bright Hα, and we note here emission at He I λ4471. An earlier description of this star has been given by Fleming (1912).

α Cam (MWC 92). Merrill and Burwell (1933) noted bright Hα. This line is undoubtedly in emission because the star is a supergiant with an extended envelope.

HD 35921 (LY Aur). Double lines appear on our spectrogram. Slettebak (1956) noted that this star is a binary, but no orbit has been obtained. Mayer (1968) has announced eclipses, and a preliminary light curve has been published by Wood (1971). The spectral type of the secondary is also O9.5 and $\Delta m = 0.6$ from the He I lines. The luminosity types are not determinable because the line broadening is large.

λ Ori B. Although listed as type Oe5 in the *Bright Star Catalogue*, it was classified as B0.5 V by Kopylov (Jaschek *et al.* 1964). Our spectrogram also suggests B0.5 V.

θ^1 Ori C. This star is called "p" by Slettebak (1956), who notes broad wings in the Balmer lines. There is some confusion with the nebular emission, and there is some filling in of hydrogen lines by emission. The wings of the lower members and the strengths of the upper Balmer lines appear normal for the type.

Silicon IV is strangely absent in the spectrum. There is an *inverse* P Cygni profile in He II λ4686 which has not been noted before in O-type stars.

θ^2 Ori. This star is called "p" by Slettebak (1956), who notes broad wings in the Balmer lines. Aside from the confusion with nebular emission, the hydrogen lines do not appear broad on our spectrogram compared with other O stars of similar spectral type. Interestingly, the Si IV lines are very weak for the spectral type, as in θ^1 Ori C.

ι Ori. SB2 with orbit (Batten 1967). The spectral type of the secondary is B0 or later as He II λ4541 does not appear on our spectrogram. We derive $\Delta m = 1.5$ from the He I lines. The M_v of the primary is reduced by 0.2.

HD 45314 (MWC 140). The hydrogen lines appear to be filled in up to H9; although He II λ4541 is absent, λ4686 is present in some strength, suggesting that the star may be a subdwarf according to the criterion of Sargent and Searle (1968). Other O-star lines such as Si IV and C III appear as broad features; He I is present.

HD 46966. This star, along with HD 47129 and HD 48099, belongs to an extended emission "ring" associated with Mon 2 (Morgan *et al.* 1965). See discussion in § IV.

HD 48279. Called N III strong by Walborn (1970); our spectrogram agrees with this designation.

HD 53667. Hiltner (1951) classified this star as Oe5. It was classified by Morgan, Code, and Whitford (1955) as B0.5 III. Our spectrogram also suggests this B type.

29 CMa. SB2 with orbit (Batten 1967). Only single lines appear on our spectrogram. There is some question about the detection of the secondary according to Batten.

HD 151804. A P Cygni profile is seen at Hβ, and emission is present in other lines. This star has been discussed by Hutchings (1968) and is a case of an "extreme" Of.

HD 152408. An "extreme" Of star, discussed by Hutchings (1968). Hydrogen lines are mostly filled in with emission.

HD 164402. Hiltner (1951) classified this star as O9.5. It was classified by Morgan *et al.* (1955) as a B supergiant. Our spectrogram agrees with this B type.

HD 165921. Double lines appear on the spectrogram we have of this star which was not previously known as a binary. The spectral type of the secondary is O9 or later since λ4541 He II is not seen (although the large line width makes detection difficult), but λ4686 He II is present. We derive $\Delta m = 0.4$ from the He I lines.

HD 167659. The Si IV lines are very weak for the spectral type.

HD 191201. SB2 with orbit (Batten 1967). The spectral type of the secondary is O9 V. We derive $\Delta m = 0.8$ from the He I lines—in good agreement with the luminosity classifications.

HD 198846. SB2 with orbit (Batten 1967): Y Cyg. The two components are nearly identical in their spectral types and line strengths. We formally derive $\Delta m = 0.1$ from He I λ4471, but the uncertainty also includes $\Delta m = 0$.

HD 201345. Called N III strong by Walborn (1970). Our spectrogram agrees with this designation.

HD 206267. Double lines of He II appear on our spectrogram. This star is a single-line SB with orbit (Batten 1967). Slettebak (1949) has already suggested that the extreme line width he found in HD 206267 might be due to two spectra. Classification of the secondary is difficult since He I cannot be seen, possibly because of the large line width. We derive $\Delta m = 0.8$ from the He II lines.

14 Cep. SB2 with orbit (Batten 1967). The spectral type of the secondary is O9.5 V. We derive $\Delta m =$ 0.6 from the He I lines, which agrees nicely with the luminosity classifications.

HD 215835. SB2 with orbit (Batten 1967). The spectral type of the secondary is O6.5, and we derive $\Delta m = 0.2$ from the He I and He II lines.

EXPLANATION OF SYMBOLS

* Log W are average of two spectrograms
E, emission (above the continuum).
P, line present but could not be measured because of line blend or width, or plate fault.
NP, line not present whereas it normally should be.

sion spectra, so some of these classifications are newly "f." There were only a very few stars that had emission lines reported in the literature which were not detected here. It is possible, when one considers the fact that emission lines vary in intensity (e.g., Slettebak 1969), that they also disappear. It is also possible that the report of emission lines was optimistic in the first place.

Many Of stars also had other lines in emission, but in all cases except one (θ^1 Ori C) N III was also seen. As far as classification in the blue region is concerned, N III in emission is a sufficient condition for a star to be classified Of. We did not so classify a star if N III appeared only in absorption but "weaker" than expected. Although this approach has been taken by other authors (e.g. Peterson and Scholz 1970), we consider it

TABLE 2

EQUIVALENT WIDTHS LOG W

NAME		He I			He II		Si IV	
HD OR BD	4120	4143	4471		4541	4686	4089	4116
108		P?	2.72		2.95	2.20	2.39	E
1337	2.25	2.14	2.81		2.12	2.27	2.60	P
5005			2.44		2.91	2.87		
5005C	2.22	2.26	2.95		2.63	2.65	2.38	2.21
12323	2.42	2.74	3.04		2.60	2.99	2.60	2.38
12993	2.07	2.26	2.83		3.02	2.98	2.30	1.98
13268			2.66		2.70	2.59	2.15	
14434			2.70		2.87	2.56		
14442			2.65		2.92	2.59E		
14633	2.29	2.51	2.94		2.65	2.78	2.60	2.30
14947			2.37		2.86	3.36E	2.09E	2.45E
15137	P	2.54	3.02		2.50	2.73	2.73	P
+60498	2.66	2.75	3.10		2.25	2.72	2.54	P
+60501		P	2.71		2.86	2.98	2.43	
15558			2.31		2.86	E		
15570			<1.68		2.88	3.45E	2.39E	2.29E
15629			2.41		2.97	2.72		
+60512			2.90		2.90	3.04		
16429	2.19	2.31	2.99		2.38	2.53	2.73	2.39
16691			2.43		2.94	3.78E	2.63E	2.53E
17505			2.62		2.84	2.36		
17520	2.11	2.53	3.00		2.67	2.94	2.53	2.20
17603		1.85	2.88		2.68	E?	2.56	2.08
+60586		2.38	2.93		2.82	3.02	2.52	2.20
+60594			3.02		2.72	2.95	2.64	
19820	2.23	2.36	2.92		2.51	2.43	2.53	2.23
24431	2.22	2.49	2.91		2.58	2.66	2.50	2.36
ξ Per		2.12	2.87		2.82	2.79	2.48	1.95
α Cam	2.22	2.43	3.03		2.40	2.13E	2.87	2.65
AE Aur	2.29	2.64	2.99		2.27	2.85	2.52	2.30
34656	2.00	2.05	2.89		2.90	2.58	2.42	2.25
35921			2.74		2.25	2.99	P	
δ Ori	2.23	2.31	2.91		2.33	2.47	2.69	2.59
λ Ori A	2.14	2.31	2.92		2.79	2.80	2.60	2.38
λ Ori B	2.71	2.78	3.03		<1.90	2.06	2.29	2.16
36879		1.97	2.87		2.83	2.83	2.28	
θ^1 Ori C	2.20	NP	2.75		2.72	2.54	NP	
θ^2 Ori A	2.20	2.52	2.93		2.51	2.65	2.32	1.86
ι Ori	2.19	2.29	2.88		2.62	2.65	2.53	2.27
σ Ori	2.46	2.69	3.07		2.38	2.57	2.49	2.26
ζ Ori	2.23	2.43	2.87		2.27	2.48	2.78	2.58
μ Col	2.43	2.52	3.00		2.60	2.84	2.58	2.39
41161	P	2.38	2.96		2.77	3.00	2.44	P
42088	2.14	2.18	2.73		2.89	2.97	2.24	2.11
46056			2.94		2.79	2.92	2.31	
*46149	2.25	2.34	2.96		2.69	2.92	2.45	2.19
46150			2.53		2.84	2.99	1.88	
46202	2.39	2.50	2.98		2.60	2.74	2.57	2.35
46223			2.36		2.91	2.93	1.64	
46485			2.89		2.82	2.97	2.33	
46573	1.95	2.35	2.92		2.86	2.94	2.22	1.94
*46966	2.25	2.45	2.91		2.68	2.76	2.38	1.90
*47129	2.30	2.27	2.85		2.72	NP		
47432	2.27	2.54	3.01		2.45	2.44	2.78	2.60
15 Mon	2.10	2.12	2.84		2.72	2.80	2.30	1.89
48099	1.94	2.19	2.73		2.89	2.79	2.12	
48279	2.24	2.51	2.97		2.80	2.96	2.50	2.22
52266	P	2.56	2.97		2.50	2.73	2.64	P
52533	P	2.25	3.00		2.76	2.73	2.38	P
53667	2.48	2.58	2.96			1.14	2.59	2.28
53975	1.90	2.40	2.89		2.80	2.92	2.44	2.04
54662	1.57	1.97	2.75		2.84	2.95	2.18	1.90
29 CMa		2.17	2.99		2.77	2.91	2.51	
τ CMa	2.00	1.96	2.93		2.50	2.47	2.67	2.36
57682	2.38	2.40	2.95		2.52	2.78	2.49	2.32

TABLE 2—*Continued*

NAME	He I			He II		Si IV	
HD OR BD	4120	4143	4471	4541	4686	4089	4116
*ζ Pup			2.05	2.96	3.35E		E?
ζ Oph	P	2.40	2.99	2.55	2.75	P	P
151804	1.81	<1.70	2.96	2.82	2.78E	2.76	2.41
152233			2.51	2.78	2.21	2.02	
152249	2.24	2.24	2.92	2.44	2.21	2.85	2.60
152408	NP	NP	2.98	2.81	3.52E	2.52	2.70E
*157857			2.89	2.94	2.33	2.29	
162978	2.02	2.07	2.99	2.78	2.67	2.34	2.01
163800	2.00	2.12	2.85	2.91	2.76	2.53	2.15
163892	2.41	2.43	3.04	2.71	2.82	2.59	2.34
164402	2.50	2.50	2.94		2.44	2.76	2.60
164438	2.21	2.39	2.90	2.53	2.75	2.66	2.43
164492	1.90	1.97	2.68	2.63	2.89	2.26	1.88
*9 Sgr			2.11	2.93	2.87		
165052			2.80	2.86	2.92	2.30	
165921			2.51	2.54	2.61		
166546	2.26	2.25	2.81	2.40	2.71	2.52	2.35
166734			2.86	2.84	2.56E	2.63	2.14
16 Sgr	2.23	2.22	2.91	2.42	2.64	2.48	2.21
167659			2.60	2.60	2.35	1.88	
167771	1.75	1.99	2.74	2.76	2.60	2.34	1.94
167971			2.71	2.67	2.51	2.70	2.36
168112			2.50	2.89	2.58		
168075	P	2.15	2.72	2.87	2.92	2.41	P
168076			2.15	2.90	2.42		
169582			2.65	2.98	E	2.00	
171589	1.89	2.34	2.91	2.91	2.54	2.35	1.81
175754	1.76	P	2.92	2.76	2.55	2.52	2.09
175876			2.76	2.85	2.53	2.12	
+223782	1.97	2.10	2.75	2.79	2.83	2.25	
186980	1.97	2.13	2.81	2.64	2.58	2.40	2.16
9 Sge	2.04	1.98	3.01	2.85	2.26E	2.68	2.07
188209	2.31	2.36	3.00	2.44	2.39	2.82	2.69
190429A			2.20	2.83	3.57E	2.36E	2.33E
190429B	2.32	2.40	2.89	2.44	2.59	2.58	2.47
190864	P	P	2.92	2.98	2.73	2.19	P
191201		2.36	2.79	2.36	2.48	2.61	
192281			2.41	2.90	2.74		
192639	1.84	2.12	2.81	2.79	1.84E	2.38	P
193322	2.19	2.30	2.95	2.73	2.82	2.46	2.26
*193443	2.17	2.30	3.00	2.58	2.79	2.54	2.31
193514	2.11	P	2.86	2.81	NP	2.34	
195592	2.35	2.50	3.00	2.35	NP	2.94	2.82
198846		2.39	2.74	NP	2.66	2.37	
*199579		1.97	2.76	2.88	2.96	2.17	
201345	2.25	2.64	2.96	2.30	2.71	2.64	2.48
202124	2.25	2.33	2.97	2.46	2.16	2.86	2.71
68 Cyg	P	P	2.95	2.81	2.65	2.31	P
206267			2.57	2.82	2.87		
207198	2.35	2.33	3.00	2.64	2.65	2.70	2.55
207538	2.47	2.58	3.00	2.50	2.73	2.59	2.40
14 Cep		2.04	2.79	2.53	2.69	2.35	
19 Cep	2.27	2.38	2.91	2.52	2.41	2.77	2.48
210809	2.02	2.33	2.92	2.62	2.33	2.69	2.49
λ Cep			2.64	2.88	2.86E	2.09	
10 Lac	2.37	2.26	2.87	2.70	2.82	2.50	2.40
215835			2.28	2.65	2.66		
216532		P	2.99	2.68	2.99	P	
216898	2.47	2.50	3.03	2.57	2.93	2.55	2.39
217086			2.71	2.87	2.81		
218915	2.30	P	3.00	2.49	2.44	2.81	2.63
+602522			2.72	2.83	2.88E	2.28	

NOTES TO TABLE 2

HD 108. P Cygni profiles: λ4471, 2.30E; λ4686, 2.82E; λ4116, P.
HD 1337. Secondary: λ4120, P; λ4143, 1.88; λ4471, 2.46; λ4541, 2.32; λ4686, 1.93.
HD 15629. P Cygni profile: λ4686, 2.49E.
HD 17505. Secondary: λ4471, 2.58; λ4541, 2.65; λ4686, 2.07.
X Per. Lines are too shallow to derive meaningful measures.
HD 35921. Secondary: λ4471, 2.53; λ4541, 2.02; λ4686, 1.99.
θ^1 Ori C. *Inverse* P Cygni profile: λ4686, 2.13E.
ι Ori. Secondary: λ4471, 2.23.
HD 45314. Lines are too shallow to derive meaningful measures.
HD 152408. P Cygni profiles: λ4471, 2.86E: λ4089, 2.24E.
HD 165921. Secondary: λ4471, 2.34; λ4686, 2.08.
HD 191201. Secondary: λ4143, 2.11; λ4471, 2.46; λ4541, 2.04; λ4686, 2.12; λ4089, 2.11.
HD 198846. Secondary: λ4143, 2.35; λ4471, 2.78; λ4686, 2.47; λ4089, P.
HD 206267. Secondary: λ4541, 2.43; λ4686, 2.43.
14 Cep. Secondary: λ4143, 2.18; λ4471, 2.49; λ4541, 2.02; λ4686, 2.14; λ4089, 2.11.
HD 215835. Secondary: λ4471, 2.30; λ4541, 2.47; λ4686, 2.73.

TABLE 3

SPECTRAL TYPES BASED ON 4471/4541 RATIO W'

Log W' Limit	Type	Limit	Log W' Limit	Type	Limit
	O9.5	$\geq +0.45$	0........	>O7	≥ -0.10
+0.45.....	>O9	$\geq +0.30$	−0.10.....	>O6.5	≥ -0.20
+0.30.....	>O8.5	$\geq +0.20$	−0.20.....	>O6	≥ -0.30
+0.20.....	>O8	$\geq +0.10$	−0.30.....	>O5.5	≥ -0.50
+0.10.....	>O7.5	$\geq$ 0	−0.50.....	>O5	≥ -0.70
			−0.70.....	>O4	...

NOTE.—The log W' limits for each type refer to the *difference* log $W(4471)$ − log $W(4541)$.

somewhat premature until we understand how these absorption lines vary in normal O stars. These points will be discussed in the next paper in this series.

Luminosity criteria in the MK system have been used only for O9 stars. One indicator of luminosity is the ratio of [4116 + 4120 (Si IV + He I)]/[4143 (He I)], according to Morgan *et al.* (1943). In supergiant stars this ratio is large whereas in main-sequence stars it is near unity. At MK dispersions λλ4116 and 4120 blend together, but at our dispersion these lines are often unblended. The line λ4120 is a triplet which is relatively insensitive to luminosity, whereas Si IV is sensitive. The line λ4143 is a singlet which is sensitive to luminosity. Because the strengths are similar, it seemed reasonable to use the other Si IV line, λ4089, to compare with the He I singlet feature. We therefore adopt (4089 Si IV)/(4143 He I) as the luminosity indicator. The ratio 4116/4120 is also a luminosity indicator, but not as sensitive since the triplet He I line does not vary strongly.

Other MK luminosity indicators for O9 stars have included the ratio of (4067, 4070 C III)/(4089 Si IV); (4387 He I)/(4541 He II); and (4647, 4650 C III)/(4686 He II) (Morgan *et al.* 1943). We shall discuss the equivalent-width dependencies of these lines, and others, in the next paper in this series. We can state here that these additional criteria generally agree with the luminosity calibration given above but with more scatter. Our calibration of the luminosity as a function of this ratio will be discussed in § VI.

A few O stars have previously been designated peculiar by a "p" following the designation; this sometimes indicated that certain absorption lines appear to be "abnormally" weak or strong. There appears to be good evidence that either the C or the N abundance, or both, is abnormal in a few O stars (Walborn 1970). Walborn (1971) has introduced a nomenclature analogous to that for the W-R stars for these cases. For example, HD

201345, O9 Vp in which the N III lines are strong, Walborn calls ON 9V. We adopt his nomenclature for the few O stars in which this anomaly is seen, because it is nicely descriptive.

A few other stars have been called peculiar for other reasons which are discussed in the notes to Table 1. We will reserve the designation "p" for only those stars whose spectra are completely dissimilar to normal O or Of stars. A few O stars have been included by Merrill and Burwell (1933) in their list of Be stars (MWC numbers) because of the presence of bright hydrogen lines, but without the presence of N III in emission. Not all of these Oe stars are analogs of Be stars, and we will comment on individual cases in the Notes to Table 1. The designation "e" will be reserved for those stars in which the emission is obviously of a different character and origin from the Of.

IV. CLUSTER AND ASSOCIATION DISTANCES

Most of the O stars of Table 1 appear to be members of clusters and associations, and about half have "well-established" distances (defined below). A few O stars do not seem to be associated with stellar groups. Distances have been given for all of these groups by Ruprecht (1966), but those values were derived from a very mixed assortment of methods and references and cannot be accepted without qualification. Often there is a large disagreement between the distances found from colors alone (e.g., Johnson *et al.* 1961) or from spectra of the O and B supergiants (e.g., Morgan, Whitford, and Code 1953). We will comment on a few associations where this problem is evident.

The absolute-magnitude system for early stars is based upon the zero-age main sequence (ZAMS) given by Blaauw (1963) or Johnson (1963) and depends on the Hyades, Pleiades, α Per, NGC 2362, and III Cep cluster fitting procedures. We did not adopt the age-zero portion for stars bluer than -0.30 in $B - V$ as this was based only on colors in NGC 6611. In fact, we will derive a new ZAMS for the O stars.

The cluster fitting used to define the ZAMS has itself depended on colors alone, but this does not lead to any difficulty in principle unless one is fitting mostly $B - V < -0.20$ where the (M_v, color)-relation is very steep. It is best to have spectral types to determine V_0 and use the colors only to determine A_v. Garrison (1967) has used both spectral types and colors to determine the distance to Sco-Cen. Fortunately, his (spectral type) main sequence agrees reasonably well with that of Johnson (1963). Garrison (1970) has also derived a new modulus for III Cep by comparing spectral types with those in Sco-Cen. This modulus agrees to within 0.2 mag with the modulus from colors alone. Probably the ZAMS has been well defined up to B0, at $B - V = -0.30$, from both colors and spectral types. It is important to realize that the ZAMS defined in this way for spectral types is not the same as an "average" (M_v, spectral type) relation (e.g., Blaauw 1963).

We will therefore define "well established" cluster distances as those for which both spectral types and colors have been used. For a few clusters Hβ indices are available for the B stars. In the case of III Cep, Crawford and Barnes (1970) obtained the same modulus as that from the *UBV* colors, so the Hβ calibration is consistent for B stars. We shall now discuss in turn each cluster/association with a well-established distance, following the order in Table 1.

a) *h and χ Persei*

These O stars are obtained from Wildey's (1964) study of this association. The stars are listed as belonging to three separate associations according to their position in the sky (Ruprecht 1966). They are also considered to be in several physical groupings, IC 1805, IC 1848, "inner," and "outer" according to Schild (1967). Schild suggests that not all of these groups are coeval. However, there is general agreement that the modulus is near 11.8 mag (Schild 1967) for all groups. This appears reasonable, for we are looking across the Perseus spiral arm in this region. We adopt this modulus.

Wildey (1964) has given "extrinsic" unreddened colors for these O stars based on unreddening one or more close faint companion stars. In some cases the $(B - V)_0$ are considerably bluer than -0.33, the normal limit for this color system. It is not impossible that some O stars do in fact have anomalous colors. However, Wildey's reddening method for some other stars in the h and χ Per Cluster led to results which have been criticized by Crawford, Glasbey, and Perry (1970). They suggest that the method is sound but the photographic photometry was probably inadequate for the fainter stars. We therefore adopt Wildey's reddened (photoelectric) colors for the O stars and unredden them in a normal manner to the $(B - V)_0$ of Johnson (1963). This usually made a difference of only a few tenths of a magnitude in M_v except for one star (HD 12993) which turned out to be 1 mag fainter.

b) Perseus 2

The distance modulus (8.0) of this association is derived by Lesh (1968) from spectral types of B stars. Lesh (1969) suggests that ξ Per may be behind the association, so our M_v for this star could be a lower limit.

c) AE Aurigae and μ Columbae

These stars are "runaways" from the Orion Association according to Blaauw and Morgan (1954), and we adopt their M_v.

d) Orion 1

The moduli of the subgroups Ib Ori and Ic Ori are taken from Lesh (1968). She does not list λ Ori as belonging to this association, but it appears in the same region of the sky and has the same reddening. We adopt the modulus of Ic Ori for this star.

e) Gemini 1

The modulus of 10.7 is taken from Crawford *et al.* (1955); the colors are from Hardie, Seyfert, and Gulledge (1960).

f) Monoceros 2 (NGC 2244)

There has been a long standing uncertainty about the distance of this association, NGC 2264, and the Rosette Nebula. It has been claimed by Johnson (1965) and Morgan *et al.* (1965) that the value of R in the region is nearer to 6 than its "normal" value of 3. Dufour and Lee (1970) have found a value of R near 4. If the reddening is reasonably uniform across a cluster, as it is here, then the value of R adopted does not affect the M_v derived for stars in that cluster.

Nevertheless, we decided to adopt the point of view that R was 3, and derive anew the cluster modulus, using the spectral types of the B stars. We used the age-zero main sequence of Johnson (1963), converted his (M_v, color)-relation to a (M_v, spectral type)-relation by using the standard (color, spectral type)-relation of Johnson (1963). The colors of the B stars in NGC 2244 are taken from Johnson (1962), and the spectral types from Morgan *et al.* (1965). The colors are used only for A_v; the spectral types define the M_v scale. The average modulus derived from the B stars was 10.9 ± 0.2, which can be compared with the initial determination of Johnson (1962), using colors only and $R = 3$, of 11.1. The M_v derived for the O stars are roughly consistent with those derived from Morgan *et al.* (1965), as they must be. That they are inconsistent with the modulus of 9.8 and the value for R of Dufour and Lee (1970) suggests that the latter paper is in error.

As we are looking along a spiral arm in the direction to Mon 2 it is important to be sure that all stars in the same direction are at the same distance. The five O stars in NGC 2244 do seem to be in close proximity to the Rosette Nebula. Three other stars, labeled "ring" in Table 1, have also been considered to be related to this cluster (Morgan *et al.* 1965). However, it is believed that the "ring" is somewhat nearer to us (Miller

1971), as the reddening is smaller for these stars than for NGC 2244. In the absence of spectral classification of other stars in the "ring" the distance cannot be determined without recourse to the O stars—something we are trying to derive independently. We are also uncertain of the relation between the two other O stars listed in Mon 2 and NGC 2244, as their reddening is appreciably larger.

g) Monoceros 1

The modulus of the cluster NGC 2264, if $R = 3$ is used, is given by Morgan *et al.* (1965) as 9.5, in agreement with Walker (1956). The reddening in NGC 2264 is much smaller than in the "ring" associated with NGC 2244. Unless the value of R is very different from 3 in this region, as claimed by Johnson (1965), these groups are all at different distances along this spiral arm according to Miller (1968, 1971).

h) ζ Puppis

The distance modulus of 8.3 is derived by Brandt *et al.* (1971) from Hβ observations of several B stars surrounding γ Vel. These two stars have commonly been presumed to be at about the same distance and associated with the Gum Nebula.

i) Scorpius 1

The distance modulus of 11.5 for NGC 6231 is given by Schild, Hiltner, and Sanduleak (1969). Only the brighter O stars in this cluster could be studied because of the declination of $-41°$.

j) Sagittarius 1

Hiltner, Morgan, and Neff (1965) derive a modulus of 11.0 from spectral classification and UBV observations of NGC 6530.

k) Sagittarius 4

The distance of this association has been discussed by Fernie (1962). He derived his modulus of 11.5 by using five B stars and two O stars. If we use only the B stars, we derive the modulus of 11.7 which is adopted here.

l) Serpens 1

Walker (1961) has given a modulus of 12.6 for the cluster NGC 6611, based on UBV colors of over 500 stars. Johnson *et al.* (1961) found a modulus of 12.0 using other UBV measures, while Morgan *et al.* (1953) found 11.8 for Ser 1 using spectra of the O stars and B supergiants. Other estimates for the distance range all the way down to a modulus of 11.1 (Becker 1963). Walker (1971) suggests that the colors of the cluster stars be reobserved from the southern hemisphere so as to be certain of the U observations; he suggests that part of the reason for the discrepancies between northern observers may be caused by bandwidth effects due to the large zenith distance of the southerly declination. Spectral classification along the main sequence should also be undertaken. We feel that the distance to this cluster/association is not well determined.

m) Cygnus 3

Johnson *et al.* (1961), using UBV colors, give a modulus of 11.2 for NGC 6871. The modulus of Cyg 3 is 11.7 according to Morgan *et al.* (1953). Neither of these determinations appears to be accurate enough for our purposes.

n) Cygnus 1

Johnson *et al.* (1961), using UBV colors, give a modulus of 10.3 for NGC 6913. The modulus of Cyg 1 is 10.9 according to Morgan *et al.* (1953). Neither determination appears to be accurate enough for our purposes.

o) *Cepheus 2*

Simonson (1968) has derived the distance and reddening for this association with spectral types and colors. He finds a modulus of 9.6 and no evidence of the large value of R that had been suggested by Johnson (1965). Unfortunately, there is a large dispersion (± 0.7 mag) in the individual distance moduli in Cep 2, and it has been suggested (Simonson 1968) that the stars may not all be at the same distance. This seems likely when one considers that the stars are not very compactly clustered in the sky and that the line-of-sight direction is nearly down a spiral arm. We consider the association to be spread out along the line of sight too much to derive individual moduli for the O stars.

p) *Cepheus 1*

Johnson *et al.* (1961), using *UBV* colors, give a modulus of 11.6 for NGC 7380. The modulus of Cep 1 is 12.5 according to Morgan *et al.* (1953). Neither determination appears to be accurate enough for our purposes.

q) *Lacerta 1*

A modulus of 8.3 is derived by Lesh (1968) and 8.9 derived by Crawford (1961) on the basis of Hβ photometry. Both results appear to be reasonable, and we adopt an average of 8.6.

r) *Cepheus 3*

Blaauw, Hiltner, and Johnson (1959) give a modulus of 9.3 derived from *UBV* colors. Crawford and Barnes (1970) also obtain a modulus of 9.3 from Hβ photometry. Although Johnson (1965) has suggested an anomalous value fo R for this association, this has not been confirmed by Becker (1966) or Garrison (1970).

V. ABSOLUTE MAGNITUDES OF O STARS

We can now readily derive the M_v for the O-star members by combining the modulus, V, and the A_v. The latter number is derived from the observed $B - V$ color and unreddening to the standard $(B - V)_0$ relation of Johnson (1963). In nearly all cases the O stars that define the cluster or association appear to be physically related to it, and questions of their membership should not arise. Only rarely are data on proper motion or radial velocity available for these groups.

Underhill (1967) has questioned the membership of several O stars in IC 1805, even though they are extremely close together in the sky and proper-motion data (Vasilevskis, Sanders, and van Altena 1965) show that all but one are moving together. But her criticism depended upon assuming an absolute magnitude for each O star and then deriving individual moduli. She showed that the moduli gave greatly discordant results. This is, of course, putting the cart before the horse, and we see no reason to discard membership in IC 1805 for these stars on this basis.

A few of our O stars either are known double-line spectroscopic binaries (SB 2) or were observed to have double lines in their spectra. In this case it is necessary to reduce the absolute magnitude of the combined light of the system to that of the primary. We found the luminosity difference by using Petrie's (1939) method. We took the ratio of the He I lines for the late O stars, or the He II lines for the early O stars, or a combination of the two, as an estimate of the difference. The Notes to Table 1 give our estimate of the magnitude difference between the components of double systems. The results are perhaps accurate to ± 0.2 mag. The correction of the total light to that of the primary follows in a straightforward manner.

The M_v and spectral types of Table 1 are combined in Figure 1. The different symbols distinguish between the different cluster/association stars. This figure is intended to demonstrate that there are some systematic differences between the various groups in

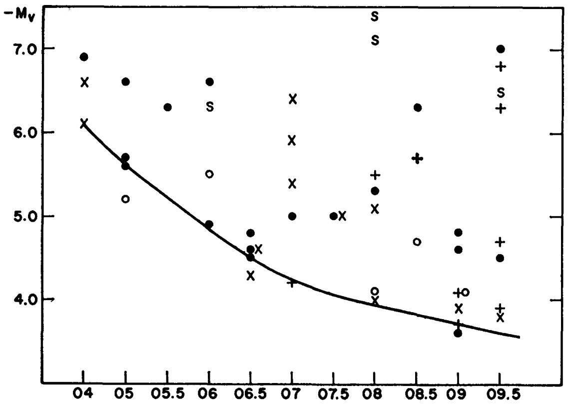

FIG. 1

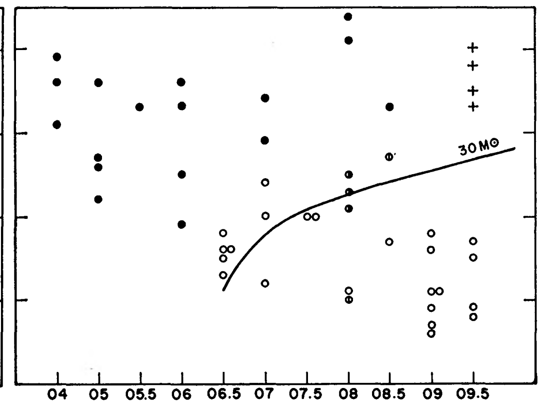

FIG. 2

FIG. 1.—H-R diagram for O stars that are members of clusters or associations with well-established distances (§ IV). *Filled circles*, stars in h and χ Per; *open circles*, stars in NGC 2244; *plus signs*, stars in Orion 1 association; letter *S*, stars in NGC 6231; *crosses*, stars in other associations. Classification is from Table 1 *Solid line*, empirical zero-age main sequence from these data.

FIG. 2.—H-R diagram for the stars of Fig. 1, showing the distinction between the O stars (*open circles*) and Of stars (*filled* or *partially filled circles*). Four O9 supergiants are shown as crosses. The circles with a vertical line are stars classified type III. Also shown is an evolutionary track of 30 $\mathfrak{M}_{\odot}$, adapted from Simpson (1971). The Of stars are concentrated in the brightest and hottest part of the diagram. The changeover from Of to type O occurs in the vicinity of the evolutionary track for a 30 $\mathfrak{M}_{\odot}$ star; all stars more massive than a somewhat higher value are Of.

luminosity. It should be noted that the stars in NGC 2244 generally fall along the lower main-sequence boundary of the (M_v spectral type)-diagram.

The stars in Per 1 are both at the lower and upper regions of the H-R diagram, consistent with the statement that they do not represent coeval groups. The ZAMS for O stars can be defined from the lower boundary of Figure 1.

Perhaps the most important result from this paper is shown in Figure 2 where we have segregated the O and Of stars. There is a very clear separation between these groups in the sense that the Of stars are the more luminous. We can assert that the presence of N III in emission is favored by a combination of increasing temperature and luminosity. We also show in Figure 2 the evolutionary track of a 30 $\mathfrak{M}_{\odot}$ star according to a model of Simpson (1971). We adopted the bolometric corrections and temperature scale of Morton (1969). It can be seen that the Of boundary roughly parallels the 30 $\mathfrak{M}_{\odot}$ evolutionary track. This suggests that *all* stars more massive than, say, 35 $\mathfrak{M}_{\odot}$ will be Of and that stars less massive than, say, 25 $\mathfrak{M}_{\odot}$ *never* will be. It also suggests that as Of stars evolve away from the main sequence, the basic mechanism causing the emission phenomenon remains.

VI. LUMINOSITY CRITERIA

For convenience in what follows we shall refer to the O4–O6 types as the early O stars; O6.5–O8.5 types as the middle O stars; and the O9 and O9.5 types as the late O stars.

From Figure 2 we see that N III in emission occurs in *all* the early O stars and *all* the brighter middle O stars. These lines do not appear in emission in any late O stars, even the very luminous ones. Our suspicion is that their absence is merely an ionization effect, as there are other emission lines present in the very luminous late-type supergiants (e.g., Underhill 1966). The exclusive occurrence of N III emission in a discrete region of the H-R diagram suggests that its formation is related directly to L and T_e.

It is important to note that the early O stars do not differ among themselves much in M_v. Here the ZAMS is only a magnitude fainter than the sequence of the most luminous O stars. It would be nice to find a spectral criterion that distinguishes the brighter from the fainter *early* O stars, but if we consider the small range available in M_v it will not be too surprising if we are disappointed. Among the middle O stars, the presence of N III emission is a good luminosity indicator; the range in M_v here is over 2 mag. Among the middle and late O stars, the luminosity criterion is given by the ratio (4089 Si IV)/(4143 He I).

We show in Figure 3 the H-R diagram with the (4089 Si IV)/(4143 He I) ratios indicated. There are fewer stars than in Figure 1 or 2 because of line-blending problems in the broadest-lined stars. In the early O stars, both λ4143 and λ4089 are either very weak or completely absent. This is an expected ionization effect. Silicon IV is seen in emission in three early Of stars spanning the range of M_v. Thus Si IV emission cannot be used as a luminosity indicator. The change of 4089/4143 very nicely correlates with M_v for the middle and late O stars. For this reason it can be defined as a luminosity indicator for these types. It is only possible to distinguish between three separate luminosity classes among these types with sufficiently different M_v. Type III is not too well determined for the middle O stars, but there are distinct differences between types I and V for these stars. The adopted M_v for the spectral types and the ZAMS of Figure 1 are given in Table 4. The estimated probable errors are ±0.5 mag for the mean relations. Although derived independently, the mean relations of Table 4 are similar to those obtained by Hack (1966).

Table 5 shows the 4089/4143 values adopted for the three luminosity classes. Table 5 is the basis for the luminosity classes assigned in Table 1. A diagram analogous to Figure 3 was constructed for the line ratio (4116 Si IV)/(4120 He I). In the brighter O stars this ratio was large, and in the fainter stars it was more nearly unity. This line

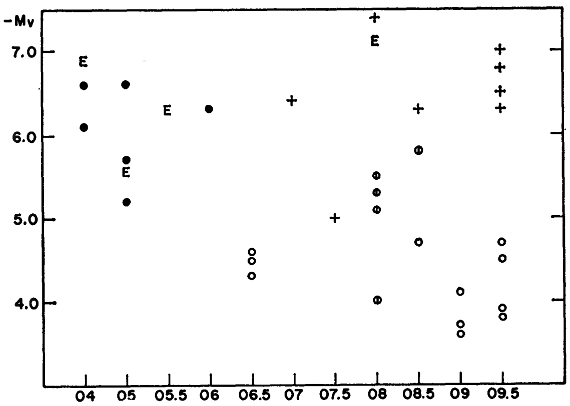

FIG. 3

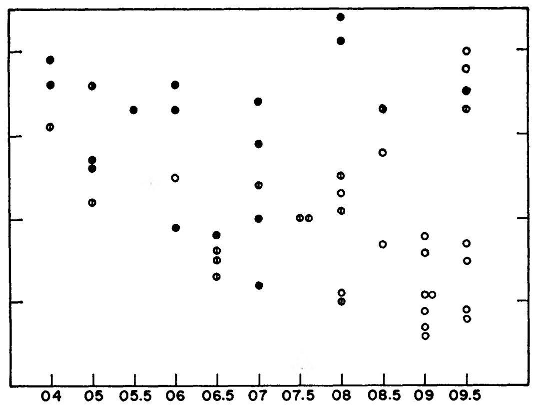

FIG. 4

FIG. 3.—H-R diagram for the stars of Fig. 1 with measured Si IV λ4089 and He I λ4143 equivalent widths: symbols represent measures of the line ratio W' as follows: *open circles*, $-0.20 < \log W' \leq +0.10$; *circles with vertical lines*, $+0.11 < \log W' \leq +0.30$; *plus signs*, $\log W' > +0.30$. For the filled circles, $\log W$ for Si IV λ4089 is less than 2.10, and He II λ4143 is not present. The letter *E* denotes emission, above the continuum, in λ4089. There is a general weakening of Si IV toward the hottest O stars and a strengthening of Si IV/He I with increasing luminosity. This figure is used to calibrate the 4089/4143 ratio with M_v, given in Table 5.

FIG. 4.—H-R diagram for the stars of Fig. 1 showing the He II 4686/4541 ratio. Symbols represent stars with measures as follows: for the open circles, λ4686 is greater than λ4541; for the circles with vertical lines, λ4686 is about equal to λ4541; for circles with plus signs, λ4686 is appreciably weaker than λ4541. The half-filled circles represent stars in which λ4686 is missing; the filled circles, stars with λ4686 in emission, above the continuum. There is a general weakening and tendency for emission to appear in He II λ4686 as one proceeds from the lower right corner to hotter and brighter regions of the H-R diagram. Unfortunately, there is not a clear-cut luminosity effect for this ratio.

TABLE 4

(M_v, SPECTRAL TYPE)-RELATIONS FOR O STARS

	MEAN RELATIONS			
S	ZAMS	V	III	Of and/ or I
O4	−6.1	...	...	−6.5
O5	−5.6	...	...	−6.4
O5.5	−5.2	...	...	−6.3
O6	−4.9	...	...	−6.3
O6.5	−4.5	−5.0	−5.5	−6.3
O7	−4.2	−4.8	−5.5	−6.3
O7.5	−4.1	−4.6	−5.5	−6.4
O8	−3.9	−4.5	−5.5	−6.5
O8.5	−3.8	−4.4	−5.5	−6.6
O9	−3.7	−4.3	−5.5	−6.7
O9.5	−3.6	−4.2	−5.5	−6.7

TABLE 5

LUMINOSITY CLASSES BASED ON 4089/4143 RATIO W'

Log W' Limit	Luminosity Class	Log W' Limit
+0.10	>V	≥−0.20
+0.30	>III	≥+0.11
	I	≥+0.31

ratio cannot be used for stars quite as early as 4089/4143 because the lines are intrinsically weaker and disappear sooner with increasing ionization. Both ratios give consistent luminosity results; 4089/4143 has a little less scatter.

Another line that appears in the blue region of the spectrum of most O stars is He II λ4686. This line exhibits a completely different behavior from the He II Pickering series of λλ4541, 4339, 4200, etc. Its upper level can be populated from an excited He II transition at λ1215 which may be pumped by the Lα of hydrogen. Emission at λ4686 is found in some O stars and may therefore be related to emission at Lα. Normally, if seen in absorption, λ4686 is stronger than λ4541 because of the higher transition probability. In Figure 4 we show the values of 4686/4541 for the stars of Figure 1. Helium II *emission* at λ4686 occurs mostly in the early O stars, but not in all of them.

There is a tendency for 4686/4541 to decrease with increasing luminosity and temperature, similar to the appearance in emission of N III. Presumably, the weakening of λ4686 relative to λ4541 is due to incipient emission in the former line. However, there is no clear-cut luminosity effect, neither is there a direct relation between the strength of λ4686 emission and that of N III. Helium II 4686 emission is only indirectly related to L and T_e.

VII. DISCUSSION AND CONCLUSION

We have introduced an improved classification scheme for the spectra of O-type stars by measuring the equivalent widths of He I and He II lines in large numbers of objects. This measurement has enabled us to introduce intermediate types—e.g., O8.5—to the MK system. By using stars with absolute magnitudes obtainable from membership in clusters and associations we have been able to show that a Si IV/He I line ratio (λ4089/4143) reproduces well the absolute magnitudes of types up to as early as O6. The luminosities of O-type stars can with confidence be separated into three groups, I, III, and V, and a calibration with M_v is given in Table 4.

If we define Of stars in a conservative manner, i.e., those with emission in N III λλ4634, 4640 above the continuum, we find that all stars of type O6 and earlier are Of, and all later type O stars brighter than about −5.8 are also Of. Hardly any stars outside these limits show emission at N III. In fact, the presence of emission is itself a good luminosity indicator. The N III lines do not evidence P Cygni structure. Emission in other lines appears in some Of stars, but there is not a one-to-one correspondence in strength among them. These points will be discussed at more length in the next paper in this series.

We suggest the following physical picture for the atmospheres of O-type stars. The presence of emission indicates an extended atmosphere. We suppose that the strength of the emission indicates the extent of the envelope in which the lines are formed. The P Cygni structure indicates expansion of the envelope, being more pronounced in proportion to the velocity gradient. Ionization and excitation conditions in some stars are such as to favor P Cygni emission only in resonance lines, visible in the rocket-ultraviolet region, even though extended envelopes with large expansion velocities may be present.

Direct evidence for the presence of expanding envelopes is provided by the observations of P Cygni line profiles by Morton (1967) in several O-type supergiants, and by Hutchings (1968) in two very luminous Of stars. In the former case, emission lines are not seen in the visible region, but we suppose that their absence is due to unfavorable ionization or excitation conditions—e.g., the stars are not quite hot enough to have sufficient N III present. We suggest that there is *indirect evidence* that Of also have extended envelopes, as emission lines are seen in the visible region. We note the observations of Smith (1970) of the early Of star ζ Pup shows P Cygni profiles in the rocket-ultraviolet region. We suggest that most, if not all, Of stars would also show such profiles in this region.

Stars in the hottest, most luminous regions of the H-R diagram have atmospheres in a delicate balance with radiative instability. In these stars radiation pressure in select resonance lines is likely to drive the atmosphere outward (Lucy and Solomon 1970). It is just these stars that we expect to have extended the expanding envelopes, and which we have found to be Of.

The least luminous O stars, with no emission lines in the visible region, probably do not have extended envelopes—two main-sequence B stars observed by Morton (1967) do not show P Cygni structure in the rocket-ultraviolet region. The relation between the O and Of stars is merely that the latter are more massive and thereby more luminous, and their atmospheres are in dynamical instability. There is no compelling evidence that O stars evolve into Of stars, nor that one group is younger or older than the other. (Theoretical studies do not indicate a steep dependence of evolution time on mass for the upper main sequence.) We see that there can be "age zero" Of stars, and evolved Of stars, just as for "normal" O stars.

We are indebted to Dr. Herbig for providing several of the spectrograms used in this investigation, and Dr. Kuhi for obtaining a spectrogram of HD 152408. We have profited from discussions with Dr. J. Miller and correspondence with Dr. Mihalas. Portions of this work were undertaken while one of us (P.S.C.) was Visiting Professor at the University of Utrecht; he would like particularly to thank Dr. Underhill for fruitful discussions concerning the spectra of O-type stars. W.R.A. was partly supported by a University of California Regents Fellowship.

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