THE ASTROPHYSICAL JOURNAL, 193:113–124, 1974 October 1

SPECTROSCOPIC OBSERVATIONS OF O-TYPE STARS. V. THE HYDROGEN LINES AND λ4686 He II

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Received 1974 January 25; revised 1974 April 8

ABSTRACT

We present data concerning the λ4686 He II and Hα lines, including selected profiles, in a number of O-type stars. We now find, in agreement with Walborn, that the emission-line behavior of λ4686 tends to correlate with luminosity. Both it and Hα come into emission if extended envelopes are present and it is this physical condition that is related to luminosity. Envelopes invariably appear in O-type stars if M_v is brighter than about −6. The observed emission strength of both lines and the extent of the envelope is relatively insensitive to luminosity. The scatter in the relation between these parameters is large and we feel one cannot predict M_v from the line strength more accurately than about ±0.5 mag. We also call attention to a group of stars that we classify as Oe and Oef (the latter group identical to the Onfp designation of Walborn) in which characteristic "double" emission lines are observed in either the hydrogen lines, or in λ4686, respectively. We believe the double emission is the result of a combination of roughly central emission and central absorption in the line profile. These profiles can be produced by stars having *envelopes with appreciable rotation.* The Oe and Oef stars share the characteristic of having rapid rotation, and luminosity somewhat near the main sequence. They do not follow the luminosity-envelope relationship observed for the Of stars. We believe the Oe and Oef stars are a continuation of the Be phenomenon to the earliest spectral types, or at least the manifestation of rapid rotation affecting the atmosphere.

Subject headings: early-type stars — emission-line stars — line profiles — spectral classification — Of-type stars

I. INTRODUCTION

This is the fifth in a series of papers concerned with the spectra of O-type stars. In Paper I, Conti and Alschuler (1971) introduced a revised classification of the O and Of-type stars, and showed that the Of stars, those with λλ4634, 4640 N III in emission, were exclusively in the hottest and brightest portion of the H-R diagram. In Papers II and IV, Conti (1973*a*, 1974) discussed the equivalent widths of several lines of hydrogen, He I, and He II and showed that they generally agreed with the non-LTE model predictions of Auer and Mihalas (1972). However, it was found that for some stars, generally the more luminous objects, both λ4686 He II and Hα were either weak or in emission, a result not predicted by the plane-parallel models. It appears that the behavior of these lines can be used as an indicator of the strength and extent of expanding envelopes around these stars.

In this paper we will discuss the relations between Hγ and Hα, as typical of the Balmer line behavior, and between Hα and λ4686. The observational material is based on 16 Å mm^{-1} spectrograms, obtained at the coudé focus of the Lick Observatory 120-inch (3-m) telescope, and discussed in Papers II and IV. These spectra were acquired during the years 1968–1970 and represent the most homogeneous collection of high-dispersion spectroscopic material presently available for the O stars.

In § II, we will reconsider the question of using λ4686 He II as a luminosity indicator, as proposed by Walborn (1971). Although in Paper I we felt the correlation was not firmly established, our recent recognition that two kinds of stars show emission at λ4686 leads us to reconsider Walborn's arguments. In this section and subsequently we adopt his usage of O((f)), O(f), and Of classification, as describing the behavior of λ4686. A reclassification of the stars in Papers I (and II) is given.

In § III, we introduce the classification type Oe and O(e) for those O stars showing characteristic double emission, or central emission in the hydrogen lines *alone*, by analogy with Be stars. We also introduce the classification Oef and O(ef) for those O stars showing characteristic double emission at λ4686, but not necessarily in the hydrogen lines. This latter group has been recognized by Walborn (1973) who used the nomenclature Onfp for these stars. We attempt to justify our different nomenclature in § III, where we give a brief discussion of the properties of the class.

In § IV, we present relations between the hydrogen lines and λ4686, and discuss their implications for the envelopes and the luminosities. In § V we present line profiles of Hα, λ5876 He I and λ4686 of He II for several representative O and Of stars. The implications of spherically symmetric and nonspherically symmetric

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extended envelopes as deduced from these profiles are discussed in § VI.

II. CLASSIFICATION

a) *Spectral Type*

In Paper I we adopted the point of view that the spectral type of an O star could best be determined by measuring and comparing the equivalent widths of λ4471 He I and λ4541 He II, alone. For this we used 16 Å mm^{-1} coudé dispersion spectra. The relation to existing MK spectral types was made simply by plotting the line ratio as a function of the types known *at the time* and deriving a smooth relation. This classification was later related to an effective temperature scale by calibration with the Auer-Mihalas (1972) model predictions (Conti 1973*b*, Paper III).

At about the same time, Walborn (1971) independently began classification of O-type stars based on 63 Å mm^{-1} cassegrain spectra obtained at Kitt Peak and Cerro Tololo observatories. His approach was to select "standards" at each spectral type for comparison of his various stars. Since his standards were also classified on the existing MK system, his results should, in principle, be similar to ours. Several stars which he adopts as standards have a different spectral type in our system and some worry has been expressed in the literature that our results are not compatible. Fortunately such fears are groundless.

Figure 1 gives a comparison between the spectral types of all stars classified in Papers I and II and by Walborn (1973, and references therein). The lower line is the least-squares relation for the points, which is closely parallel to and displaced by less than *one-half* a spectral subclass from the upper 45° line. The largest difference between the two systems for any star is two spectral subclasses and this occurs for only about 10 percent of the cases. Figure 1 clearly indicates the two classification schemes are compatible, although for a given star there might be a difference in spectral type. Although we have not used type O9.7 for several supergiants, Walborn's use of this subdivision appears to us to be reasonable.

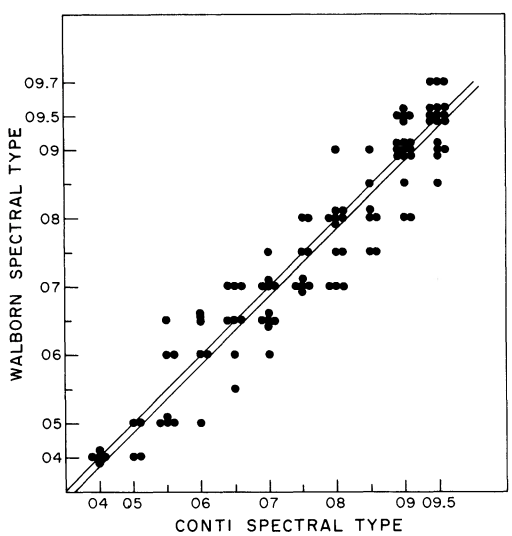

FIG. 1.—Comparison of Walborn spectral types (*ordinate*) with this paper (*abscissa*) from table 1. The upper line is the 45° relation; the lower line, the least-squares result. The two independent spectral classifications are closely similar.

b) *Luminosity Classification*

In Paper I we adopted as a luminosity indicator the ratio between the (absorption) lines of λ4089 Si IV and λ4143 He I. Unfortunately, these lines tend to weaken with earlier spectral class so that by type O6 or O6.5 they no longer can be used. We were able to calibrate this luminosity criterion by means of stars observed in clusters and associations with known distances derived independently of the O stars. Our calibration of the O7–O9.5 stars is found, overall, to be similar to that obtained by Walborn (1973). Walborn feels that he can further subdivide these later O types into classes Ia, Iab, and Ib, II, III, IV, and V, although in Paper I and here we will use only I, III, and V. We will return to this point in § IV.

For the earlier O stars there appeared to us to be no criteria that could safely be used to make a statement about the luminosity of a star, although it was recognized that there was a tendency for λ4686 to weaken and go into emission with increasing luminosity. The problem was that certain stars were found that were exceptions to this relation (fig. 4 of Paper I). Among these stars were θ^1 Ori C, HD 14442, HD 14434, HD 13268, HD 15629, HD 16691, HD 165052, and BD +60°513. With the exception of the last two stars named, all were discrepant to the proposed λ4686 line-strength–luminosity correlation in the sense that the line appeared to be either weak or in emission, yet the star appeared to be *relatively faint*.

It was certainly too much to expect that even a large fraction of these stars could have incorrect M_v, given the considerations that went into our choice of cluster moduli. However, subsequent results have led us to believe that for nearly all these stars, the *spectrum* is suspect. Let us now consider each of these stars in turn. In Paper IV it was found that both BD +60°513 and HD 165052 are double-line spectroscopic binaries with similar components, hence the values of M_v given in Paper I are overestimated. Careful reexamination of the apparent P Cyg profile found on the tracing of HD 15629 indicates that the emission is likely to be spurious. We became more certain of this conclusion after we had obtained two spectra of this star at Palomar, and found only absorption. It was realized in Paper II that the tracing of HD 13268 was defective, due to the plate being badly out of focus, and that the apparent absence of λ4686 might not be real. Conti (1972) has discussed the inverse P Cygni profile observed in θ^1 Ori C which indicates the emission mechanism is not similar to the other stars discussed here. HD 14442 and HD 14434 have been found by Walborn (1973) to show double emission at λ4686 and their status is different from the other stars (§ III). We have also found that although the reddening of

HD 16691 is similar to the other stars in the h and χ association, the strength of the interstellar K-line is 50 percent stronger. It might not be impossible for *this one star* to be behind the spiral arm that contains the association, although it must be admitted that we are now moving in a direction opposite from Paper I. If HD 16691 is, in fact, at the same distance as the h and χ association, then it is *very* discrepant in a (λ4686, luminosity)-correlation as it has a very strong λ4686 He II emission line, along with Hα, although M_v is only -5.6.

Nearly coincident with, and independently of Paper I, Walborn (1971) introduced the nomenclature ((f)) for those O stars showing N III emission, but with λ4686 strongly in *absorption*; (f) for those O stars showing N III emission but λ4686 *weakly in absorption or missing*; and f for those showing both N III and λ4686 *strongly in emission*. In view of the fact that we have subsequently found this notation useful (e.g., Mihalas, Hummer, and Conti 1972), we will adopt it in what follows. We make the additional criterion that if λ4686 is only *weakly* in emission, the star will be denoted as O(f).

It is then a simple matter to reclassify the stars from Papers I and II with respect to the ((f)), (f), and f of Walborn's system, although using our *measures* of λ4686. We consider the star to be O(f) if λ4686 is at least a factor of 2 weaker than predicted by Auer and Mihalas (1972) as shown by figure 7 of Paper II. Our revised classifications are found in table 1, which also include Walborn's (1973, and references therein) independent classifications.

As expected, there is nearly a one-to-one correspondence between our ((f)), (f), and f notation and Walborn's. Aside from our use of "e" and "ef," which we will discuss in § III, the only other major differences in classification are the use of ((n)), (n), and n by Walborn. Here he has made reference to the observed line widths, the stars with very large line widths being denoted by n without parentheses, and the single and double parentheses denoting proportionately narrower lines. Although such nomenclature is useful, we feel that it is too cumbersome and uses up too much space to describe a stellar spectrum. We therefore will not adopt it here.

Walborn also uses the lowercase letter "p" in some cases in which he finds the spectrum to be anomalous. This is almost always used for spectra in which P Cygni profiles are seen. As we feel that these stars are only more extreme examples of stars with extended envelopes, and do not represent a new physical situation, we prefer not to use this nomenclature. We will reserve the letter "p" in our classification for stars whose spectrum cannot be understood with "normal" or expanding envelopes; e.g., θ^1 Ori C will be classified as O7Vp (Conti 1972).

If we now take our spectral types of table 1, and the M_v derived in Paper I (one from Paper II) we find the H-R diagram for O, O((f)), O(f), and Of stars in figure 2 (we have omitted the stars referred to previously). Looking first at the Of and O(f) stars we see that indeed they are exclusively in the brighter portions of the H-R diagram. There is clearly an improvement over the results of figure 4 in Paper I, indicating that λ4686 is related to luminosity. Since there is a range of less than 2 mag among the early O stars, we will not use other luminosity indicators in the classification. Walborn's use of I, III, and V at these spectral types depends wholly on the appearance of λ4686 which is redundantly accounted for in the "f" classification.

For the later type O stars, it is possible to use luminosity classifications which depend only on absorption-line ratios and we will retain this scheme. There is similarly a tendency for the O(f) and Of stars to be the most luminous stars between O7 and O8.5, although by type O9 this nomenclature is dropped since N III is not observed in emission, and λ4686 is weaker because of the lower temperature.

III. Oe AND Oef STARS

a) Oe *Stars*

We will define the Oe class as those stars showing emission in the hydrogen lines, but *without* emission in N III or λ4686 He II (see also Conti 1973*c*). Some stars also show emission in λ5876 He I. The emission profile is roughly centered with respect to the velocity of the stellar photosphere and often has a central reversed absorption feature, giving the *appearance* of double emission lines. We believe the profile is physically a combination of central emission and absorption, rather than double emission, because frequently the absorption feature goes below the nearby continuum. The double emission often appears to have unequal components.

Typical line profiles for these and other stars to be discussed below have been taken from the tracings of 16 Å mm^{-1} spectrograms in the blue and red regions, obtained at the coudé focus of the Lick Observatory 120-inch telescope. The profiles have been normalized and converted to velocity units. It should be remembered that the blue and red regions of the spectrum were taken at different times, often separated by months.

In figure 3 we give the line profiles for HD 155806, an O7.5 IIIe star typical of its class: a relatively narrow emission line at Hβ, with a roughly central reversal; a very broad absorption line at Hγ, with a slight emission reversal near line center; and a relatively broad absorption at λ4686 without any emission. A coudé spectrogram taken very recently at Kitt Peak showed an intense emission feature at Hα, suggesting that the Balmer emission-line decrement is very steep in this star. The difference between Hβ and Hγ indicated by figure 3 is consistent with this observation.

The implications of the central emission with central absorption will be considered in § VI. Other Oe-type stars with similar features known to us at this time include HD 39680, HD 45314, He 60848, and HD 92714 (we are indebted to Dr. Nancy Houck for calling the latter star to our attention).

At least two O-type stars, HD 46056 (Paper IV) and ζ Oph (Niemelä and Mendez 1974), appear to

TABLE 1
O STAR CLASSIFICATION-REVISED

Star Name	Spectrum: This Paper	Spectrum: Walborn	Remarks	Star Name	Spectrum: This Paper	Spectrum: Walborn	Remarks
108	O7If	O6:f?pe		ζ Pup	O4ef	O4I(n)f	
1337	O9.5III	O9III:(n)	SB2	ζ Oph	O9V(e)		
5005	O5.5((f))	O6.5V((f))		151804	O8If	O8Iaf	
5005C	O9V	O8V(n)		152233	O6(f)	O6III:(f)p	
12323	ON9V	ON9V		152249	OC9.5I	OC9.5Iab	
12993	ON6.5V	O6.5V		152408	O8If	O8:Iafpe	
14434	O6.5(ef)	O5.5Vn((f))p		152424	OC9.5I	OC9.7Ia	
14442	O6ef	O5n(f)p		155806	O7.5IIIe	O7.5V[n]e	
14633	ON8.5V	ON8V		157857	O7:(f)	O6.5III(f)	
14947	O5.5f	O5If^{+}		162978	O8.5III((f))	O7.5II((f))	
15137	O9.5III	O9.5II-III(n)		163800	O7I((f))	O7III((f))	
+60 498	O9.5V	B0V		163892	O9III	O9IV((n))	
+60 501	O6.5V	O7V		164438	O9III		
15558	O5(f)	O5III(f)		164492	O7I	O7.5III((f))	
15570	O4f	O4If^{+}		9 Sgr	O4((f))	O4V((f))	
15629	O5((f))	O5V((f))		165052	O7:	O6.5V(n)((f))	SB2
+60 513*	O7.5:	O7Vn	SB2	165921	O7:		SB2:≥O9
16429	O9.5I	O9.5II((n))		166546	O9III	O9.5II-III	
16691	O5f	O4If^{+}		166734	O7.5If	O7Ib(f)+O8-9I	SB2:
17505	O6(f)	O6.5V((f))	SB2:O7V	16 Sgr	O9III	O9.5II-III((n))	
17520	O9V	O8V		167659	O7I((f))	O7II(f)	
17603	O8.5I(f)	O7.5Ib(f)		167771	O8I(f)	O7III:(n)((f))	
+60 586	O8III	O7V		167971	O7.5If	O8Ib(f)p	
+60 594	O9V			168075	O6.5III((f))		
18326†	O7V	O7V(n)		168076	O4((f))	O4V((f))	
19820	O9III	O8.5III((n))		168112	O5.5((f))	O5III(f)	
24431	O9V	O9III		168504	O8III		
X Per‡	OBe			169582	O5.5(f)	O6If	
ξ Per	O7.5I	O7.5III(n)((f))		171589	O7.5V((f))	O7II(f)	
α Cam	O9.5I	O9.5Ia		175754	O8III((f))	O8II((f))	
AE Aur	O9.5V	O9.5V		175876	O7:	O6.5III(n)(f)	
34656	O7I((f))	O7II(f)		+223782	O7III((f))	O7V((f))	
35921	O9.5:	O9.5III:n	SB2:O9.5	186980	O8III((f))	O7.5III((f))	
δ Ori	O9.5I	O9.5II		9 Sge	O8If	O7.5Iaf	
λ Ori A	O8III((f))	O8III((f))		188209	O9.5I	O9.5Iab	
36879	O7.5III	O7V(n)		227018	O6.5III		
θ^1 Ori C	O7Vp			190429A	O4f	O4If^{+}	
θ^2 Ori A	O9V			190429B	O9.5III		
ι Ori	O8.5III	O9III	SB2:≥B0	190864	O7III((f))	O6.5III(f)	
σ Ori	O9.5V			191201	O9III	O9.5IV((n))	SB2:O9V
ζ Ori	O9.5I	O9.7Ib		191612	O7.5III(f)	O6.5f?pe	
μ Col	O9V	O9.5V		192281	O5.5(ef)	O5Vn((f))p	
41161	O8V	O8Vn		192639	O7.5IIIf	O7Ib(f)	
42088	O6.5V	O6.5V		193322	O8.5III	O9V:((n))	
45314‡	OBe			193443	O9III	O9III	
46056	O8V(e)	O8Vn		193514	O7.5III(f)	O7Ib(f)	
46149	O8.5V	O8.5V		195592	O9.5I	O9.7Ia	
46150	O5.5((f))	O5V((f))		199579	O6.5III	O6V((f))	
46202	O9V	O9V		201345	ON9.5V	ON9V	
46223	O5((f))	O4V((f))		202124	O9.5I	O9.5Iab	
46485	O7.5:	O7Vn(e)		68 Cyg	O8V	O7.5III:n((f))	
46573	O7.5V((f))	O7III((f))		206267	O6	O6.5V((f))	SB2
46966	O8.5V	O8V		207198	O9I	O9Ib-II	
47129	O7.5III(f)	O8p		207538	O9.5V	B0IV	
47432	O9.5I	O9.7Ib		14 Cep	O8.5III	O9V:	
15 Mon	O8III((f))	O7V((f))		19 Cep	O9I	O9.5Ib	
48099	O6.5V	O7V		210809	O9I	O9Iab	
48279	ON8V	O8V		λ Cep	O6ef	O6I(n)fp	
52266	O9.5V	O9IV(n)		10 Lac	O8III	O9V	
52533	O8.5V			215835	O5.5	O6V(n)	SB2:O6.5
53975	O7.5V	O7.5V		216532	O9.5V	O8.5V((n))	
54662	O7III	O6.5V		216898	O9V	O9IV	
29 C Ma	O8.5If	O7Ia:fp		217086	O6.5:	O7Vn	
τ C Ma	O9I	O9II		218915	O9.5I	O9.5Iab	
57682	O9V	O9IV		+60 2522	O6.5IIIef	O6.5(n)(f)p	
				225160	O8I(f)	O8Ib(f)	

*This star has been mislabeled in Papers I, II and IV as BD +60 512, an error which has propagated from Hiltner (1956) and Wildey (1964). Our discussion in Paper I that the proper motion measured by Vasilevskis et al. (1965) was different from other members of IC 1805 is also erroneous. The proper motion of this star, VSA 232, agrees well with association membership. We are indebted to Dr. Walborn for calling this error to our attention.

†The description of the spectrum in Paper I as being a shell star really refers to the nearby star BD +60 606 (Cowley and Conti 1974).

‡Spectrum impossible to classify consistently between O or B: probably variable.

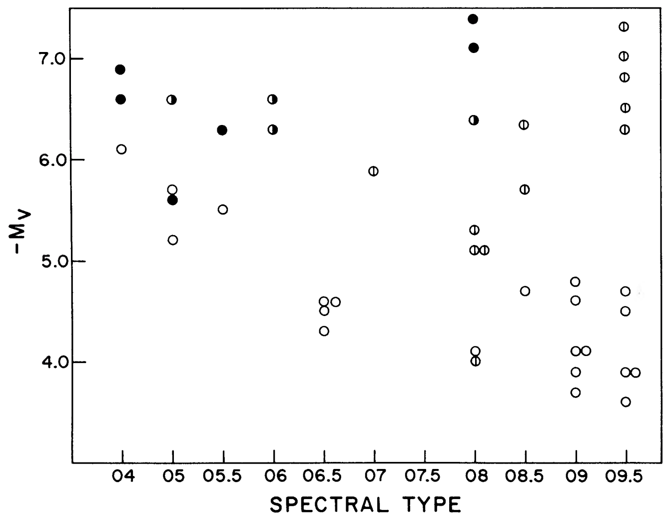

FIG. 2.—H-R diagram for O stars with M_v obtained from membership in associations with known distances (from Paper I). *Open circles*, stars classified as luminosity V; *circles with vertical lines*, luminosity III or I; *filled circles*, Of stars; *half-filled circles*, O(f) stars. Note that O((f)) stars are denoted by open circles. The Of and O(f) stars are generally the most luminous types, indicating that λ4686 He II emission is related to luminosity, although not in a strictly one-to-one manner.

have emission visible *only* at Hα, without any in the other Balmer lines. Following Walborn's (1971) concept of using parentheses to denote mild effects, we propose to classify these stars as O(e) types. The former has a slight emission reversal in the absorption core of Hα, but the latter has emission above the continuum in Hα, with an absorption core.

The Oe and O(e) stars share the additional characteristic of broad absorption in the other lines in the spectrum, suggesting large rotational velocities. Aside from the presence of λ4542 in absorption indicating the spectral type as O, the overall appearance is similar to Be stars. It is for this reason that the Oe nomenclature has been adopted.

The luminosity classes that have been assigned are either III (one star) or V indicating that the stars are near the main sequence. HD 46056 has an absolute magnitude of -4.1 from its membership in the cluster NGC 2244 (Paper I), which is on the main sequence. If these stars are physically similar to Be stars, then we expect that the large rotational velocities are in some manner responsible for creating an envelope (disk or ring?) of material around the star which produces the hydrogen emission. It is expected that changes in the emission line strengths and so-called *V/R* variations will be observed for these Oe stars also. Preliminary inspection of coudé spectra of several of these stars recently obtained at Kitt Peak supports this assertion.

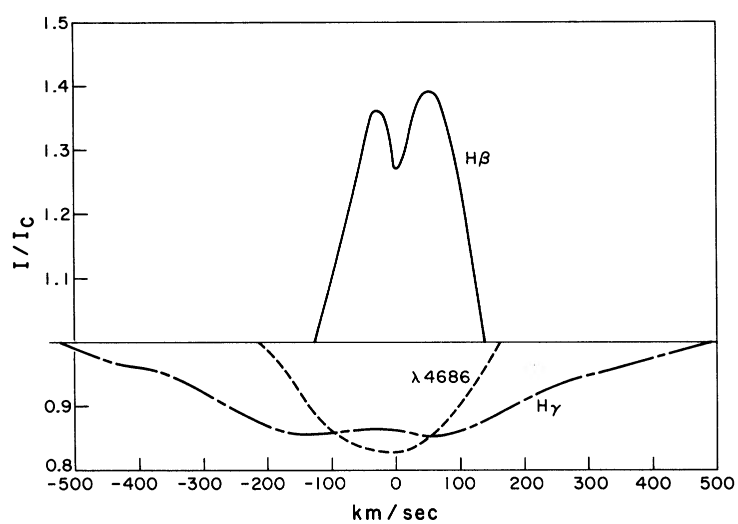

FIG. 3.—Line profiles of the O7.5 IIIe star HD 155806. Strong double emission is seen at Hβ, and a slight emission reversal is observed in the center of Hγ. The He II line at λ4686 is strongly in absorption. The Hα line (not shown) is extremely bright. The similarity of the emission profiles shown here to classical Be stars should be noted.

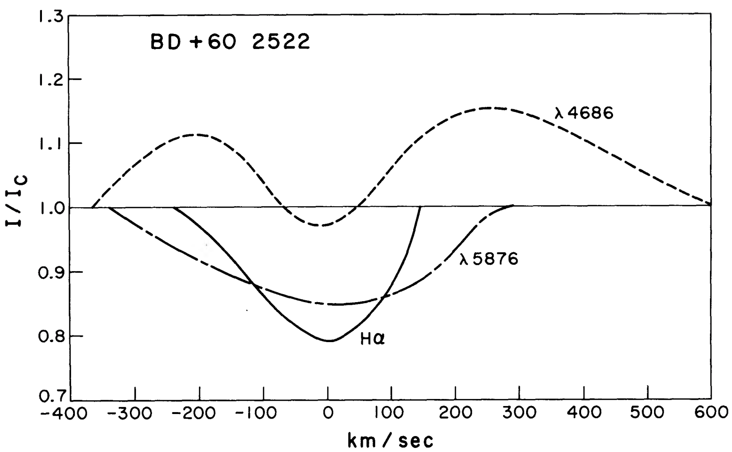

FIG. 4.—Line profiles of the O6.5 IIIef star BD+60°2522. Double emission is seen at λ4686 He II, although only absorption is observed at Hα and λ5876 He I. The broad emission and the roughly central absorption imply the envelope in which λ4686 is formed has appreciable rotation (see § VI). The broad λ5876 is also indicative of large rotational velocity of the star itself. Hα is weaker than predicted by plane-parallel non-LTE models.

b) Oef *Stars*

We will define the Oef class as those stars showing an emission structure in λ4686 similar to that in Oe stars; namely central emission with a central absorption reversal, giving the appearance of double emission in this line. Usually there is no emission in the Balmer lines. In two cases emission seen at Hα is quite dissimilar to that at λ4686. This class was recognized by Walborn (1973) who used a classification of "Onfp" with parentheses around the "n" of "f" in some cases.

Figure 4 gives line profiles for Hα, λλ5876 and 4686 for the O6.5 IIIef star, BD +60°2522. The typical spectroscopic features of this class of objects are broad emission at λ4686 with a central reversal, but *absorption* (only) at Hα and λ5876. The other Balmer lines are similar in appearance to Hα with no evidence of emission. Other Oef stars known to us at this time are HD 14442, ζ Pup, and λ Cep.

Parenthetically, it should be remarked that λ Cep was not recognized as having double emission in Paper I because the particular spectrogram available to us showed only a single emission feature. Subsequent coudé observations of this star indicates that the profile of this line changes drastically in appearance from night to night (Conti and Frost 1974; see also Slettebak 1969). In the case of HD 14442, the violet emission present on our spectrogram was noted as an "unidentified" emission and promptly forgotten until the appearance of Walborn's (1973) paper. The anomalous appearance of λ4686 in ζ Pup has been remarked elsewhere (Baschek and Scholtz 1971; Mihalas and Lockwood 1972).

In a few O-type stars, the emission at λ4686 is very weak, so much so that the central absorption dominates the profile. Analogous to O(e) stars we classify these stars as O(ef). Two examples of this class are HD 14434 and HD 192281. In the former case, the emission can barely be seen above the continuum, although it was noted in Paper II that λ4686 absorption was weak.

The Oef and O(ef) stars share the additional characteristics of broad absorption widths in the other lines in the spectrum, suggesting large rotational velocities. The stars are all of early spectral type, the latest being O6.5. This suggests a temperature distinction from the Oe stars which are generally of later spectral type. From cluster membership (Paper I) the M_v range from −6.6 for ζ Pup, to −4.9 and −4.8 for HD 14442 and HD 14434, respectively. This also puts them near the main sequence, although for the hottest stars, the limited range in M_v makes this statement less meaningful. Aside from the O6.5(ef) star HD 14434, the other stars show N III emission, consistent with their position in the H-R diagram (Paper I).

The implications of the peculiar emission-line structure at λ4686 for the Oef stars will be considered in § VI. Our introduction of the "e" and "ef" suffix to the classification of O stars is such that there is no danger of confusion between the two classes. We think that the similarities between the groups are so striking as to warrant their use in preference to the use of Onfp by Walborn (1973) for the latter group.

We have introduced the letter "e" in our classification because of the similarities of large rotational velocities and the typical appearance of "double" emission in the Balmer lines or λ4686 for certain stars. The implication of physical similarity to Be stars is deliberate but cannot yet be completely justified. We have noted with some surprise that BD +60°2522 appears to be an infrared source according to observations of Cohen and Barlow (1973). Their interpretation of this radiation as due to dust grains could corroborate the similarity to Be stars. Further detailed

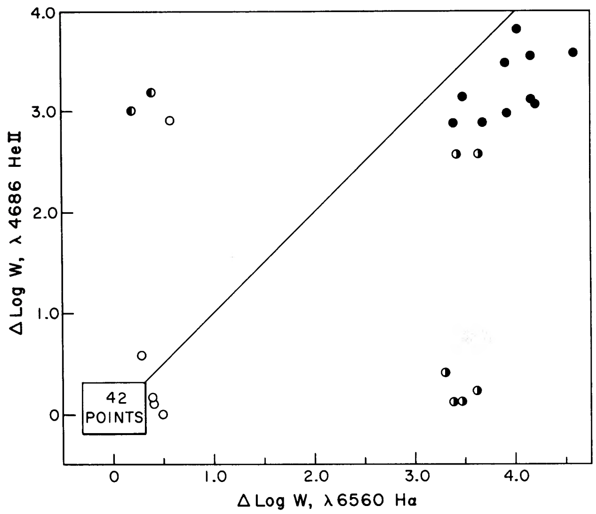

FIG. 5.—Relation between the deviation of λ4686 He II and Hα from the plane-parallel predictions. *Open circles*, no emission; *right-hand half-filled circles*, Hα in emission; *left-hand half-filled circles*, λ4686 in emission; *filled circles*, both lines in emission. Most O stars (42 points) have equivalent widths of these lines in agreement with the models. However, for a number of Of and OI stars, these lines are greatly weakened or in emission (large Δ log *W*). Usually, the Hα is more affected than the λ4686 (the 45° line is for equal effect in the two lines).

spectroscopic observations of Oe and Oef stars have been made and will be reported on in the next paper in this series.

IV. THE RELATION BETWEEN Hα, THE Of CLASSIFICATION, AND LUMINOSITY

We have previously observed that generally Hα and λ4686 are in emission, or absorption together in the same stars (Paper IV). To see this more graphically, we have plotted in figure 5 the *deviation* of Hα and λ4686 from the predictions of the non-LTE *plane-parallel* models of Auer and Mihalas (1972). These are expressed in terms of log *W* (equivalent width), which tends to push together the large values of the deviation, but spread out the smaller ones, enabling us to plot all stars on one diagram. These numbers have been adopted from Papers II and IV by first converting to equivalent width, taking the absorption-line or emission-line (i.e., with opposite sign) strength deviance from the predicted value, and then converting back to logarithms.

Over half of the stars are deviant by less than a factor of 2 (0.3 dex) from the plane-parallel models; we consider this as good agreement with the predictions. As the models do not predict emission in either of the lines under consideration, the position of the other stars in this diagram can be taken to be evidence of extended envelopes for the line-forming region. We see that for the stars in the upper right-hand portion of figure 5, both Hα and λ4686 are in emission, although Hα is somewhat stronger. These stars are clearly to be identified as stars with very extensive envelopes.

TABLE 2

STARS WITH ANOMALOUS Hα AND/OR λ4686 He II

Star	Sp	Δ log *W*	
		λ4686	Hα
108	O7 If	3.1	4.15
14947	O5.5f	3.45	3.9
15558	O5(f)	3.0	0.2
15570	O4f	3.55	4.15
15629	O5((f))	0.1	0.15
16429	O9.5 I	0	0.5
16691	O5f	3.8	4.05
ζ Ori	O9.5 I	0.1	3.4
151804	O8 If	3.05	4.2
152233	O6(f)	0.55	0.3
152249	O9.5 I	0.4	3.3
152408	O8 If	3.6	4.6
152424	O9.5 I	2.55	3.45
167771	O8 I((f))	0.15	0.4
167971	O7.5 If	2.95	3.90
168076*	O4((f))	0.1	3.45
9 Sge	O8 If	2.9	3.7
188209	O9.5 I	0.2	3.6
192639	O7.5 IIIf	2.9	3.4
193514	O7.5 III(f)	2.9	0.6
195592	O9.5 I	2.6	3.65
λ Cep	O6ef	3.15	3.5
218915	O9.5 I	0.1	0.4
+60°2522	O6.5 IIIef	3.2	0.4

* A reexamination of the equivalent width measured for λ4686 in Paper I indicates it was a factor of 2 too small. The corrected log W/λ is 2.69, based now on an average of two plates.

Two O9.5 supergiants with λ4686 *missing* also fall in the upper right portion of figure 5. Three other O9.5 supergiants have Hα emission, but λ4686 in absorption. It is probably a temperature effect that λ4686 is not present or is in absorption rather than being in emission. The one O9.5 supergiant with known λ4686 emission (α Cam) is not plotted because a red spectrogram is not available to us.

We have no ready explanation for the other star which has Hα but not λ4686 in emission, nor for three other stars with λ4686 emission, but Hα in absorption. A disturbing possibility is that the emission is sufficiently variable in time to provide this result. For the convenience of the reader, table 2 contains the list of the deviant stars with their Δ log *W* so they may be identified in figure 5.

With the possible exceptions noted above, either Hα or λ4686 could be used as an indicator of an extensive envelope around the star. Nearly all the discrepant stars in figure 5 are above the main sequence, according to the luminosity classification in table 2.

Let us now examine the relation between luminosity and the extended envelope, as disclosed by the emission-line strength of Hα (which can be used for O9 and O9.5 supergiants, whereas λ4686 cannot be). In figure 6 we have plotted the Hα/Hγ line ratio as a function of M_v for those stars for which this quantity

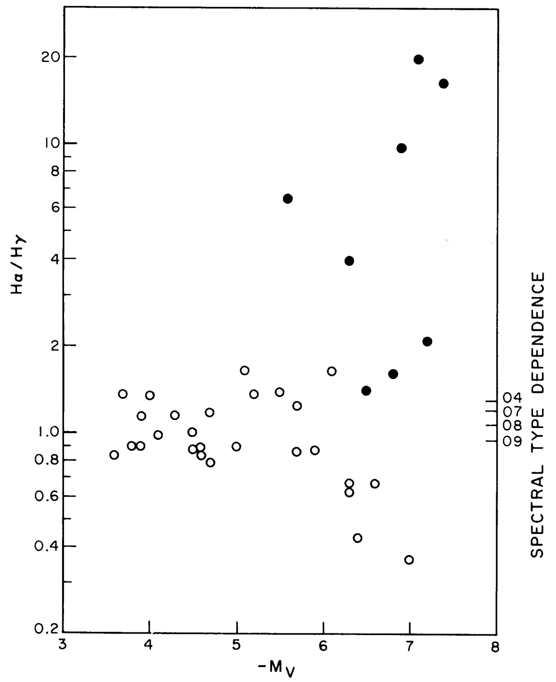

FIG. 6.—Relation between M_v and the observed ratio of Hα/Hγ, a measure of the extent of the envelope. *Open circles*, Hα in absorption; *filled circles*, Hα in emission. The predicted ratio is near unity according to the non-LTE plane-parallel models. The exact spectral-type dependence of this ratio for main-sequence stars is shown along the right-hand ordinate; that for lower-gravity models is about 1.3. For stars with M_v fainter than -6, the line ratio is near that predicted, and we expect that these lines are formed in plane-parallel geometry. For stars brighter than this, the Hα line weakens or goes into emission, implying a greater and greater extension to the envelope. There is a tendency for the envelope to be stronger with brighter M_v, but the scatter is such that the Hα strength cannot be used to predict M_v very accurately.

is available from cluster membership (Paper I). We have taken this ratio as a measure of the extent of the envelope. The ratio is predicted to be near unity according to the non-LTE plane-parallel models of Auer and Mihalas (1972) with a slight temperature and gravity dependence. We have indicated along the right-hand margin of figure 6 this dependence as a function of spectral type. For all lower-gravity models, the predicted number is near 1.3. The result is that for stars of all spectral types where M_v is fainter than -6, the line ratio is roughly in agreement with the plane-parallel predictions. For stars with M_v brighter than -6, either the Hα is considerably weaker than predicted, or else comes very strongly into emission. (In a few stars with Hα emission, Hγ is also weak.)

An important point is that for stars with M_v *brighter than* -6, *the extent of the envelope is nearly independent of luminosity*. This is so because there is very little difference in luminosity for gross differences in the Hα emission. The scatter in the relation is also large. We feel one could not safely predict the M_v of a star from this observed relation. Similar statements also hold for the behavior of λ4686 He II, suggesting that only a coarse grid of luminosity classification (e.g., I, III, and V) is physically meaningful, although finer subdivisions presumably say something about the envelope.

Since the effect of luminosity on the Balmer lines should be a maximum for Hα, luminosity criteria for O-type stars based on other Balmer lines are probably less sensitive. We have, in fact, investigated this point with attempts to correlate various measures of Hγ with M_v. We have tried using the equivalent width, the total width, and the half-width as a function of M_v. The best correlation, that of M_v with total width of Hγ, is shown in figure 7. There is a general relation between these two parameters in the sense that the line is *narrower* in the brighter stars. However, the spread in the relation is sufficiently large so that the width *cannot* be used to predict M_v quantitatively. In fact, a good deal of the correlation shown in figure 7 is a

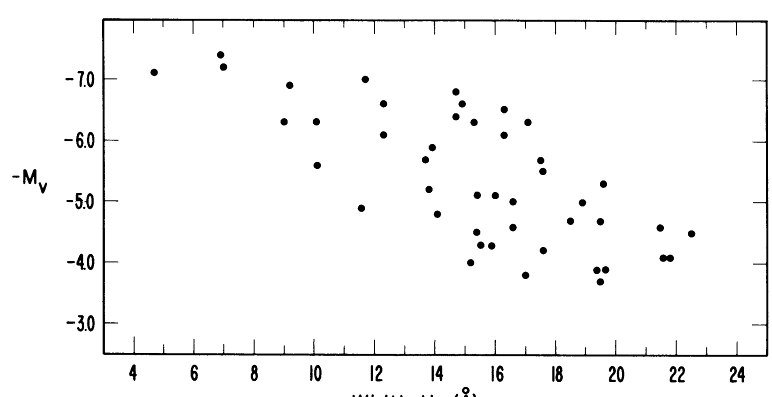

FIG. 7.—Relation between the total width of Hγ (*abscissa*) and M_v (*ordinate*). (The total width is the width where the line appears to merge with the continuum on the tracings; the accuracy in the continuum is about 5 percent.) Generally speaking, the brighter O stars have a narrower Hγ line, but the scatter is too large to permit one to predict M_v quantitatively from this relation. Much of the correlation shown is a spectral-type effect: the earlier-type stars have a narrower line because of a temperature dependence. These stars are generally brighter than the later O types.

spectral type effect: the line is narrower in the earlier O-type stars which are generally more luminous than the later types.

V. TYPICAL ENVELOPE PROFILES

In this section we will briefly discuss the line profiles observed for several representative luminous O and Of stars. This small sampling is based on the Lick Observatory spectroscopic data discussed in Papers I, II, and IV. The intensities have been normalized and the abscissa converted to velocity units. Line center is taken from observations of other lines but the inaccuracy in the microphotometer tracings is such that this is only accurate to about 50 km s^{-1}.

In figure 8 we see typical line profiles for δ and ζ Ori, two O9.5 supergiants with M_v of -6.3 and -6.8, respectively (Paper I). In the region of line formation of Hα in the latter star a wind velocity of about 200 km s^{-1} is indicated as we see a P Cygni profile. The Hα line is weak in δ Ori, but there is no indication of any velocity. It should be recalled that Morton (1967) has found strong P Cygni profiles in some resonance lines in the far-ultraviolet region of these same stars. The C IV and S IV lines show wind velocities of about 1900 km s^{-1} in ζ Ori and 1400 km s^{-1} for δ Ori. It is clear that both stars have extended expanding envelopes, although they are not exactly the same (see also Hutchings 1970). We note also that the profiles of λ4686 are nearly identical and those of λ5876 are generally similar in the two stars.

From the predicted line optical depths, we expect Hα to be formed further from the stellar surface than the other lines in the visible region, and the ultraviolet resonance lines to be formed even further out. The velocity information then implies that the atmospheres of these stars are being accelerated away from the surfaces. It may be possible to find a spherically extended flow model which will duplicate these observations, although there may be problems of uniqueness.

Figure 9 shows line profiles of two Of stars, HD 152408, O8 If, and HD 108, O7 If. The M_v of the former star is -7.1 from membership in NGC 6231; that of the latter is also probably similar but cannot be determined independent of the spectrum because the star is not a member of an association. Both stars have strong Hα emission, and a P Cygni profile at λ5876. HD 152408 shows emission at λ4686 and HD 108 shows a P Cygni profile for this line. (It should be kept in mind that the velocity axes are different in fig. 9.) The wind velocity for HD 152408 is 400–500 km s^{-1} for these lines, and about half that for HD 108 (see also discussion of HD 152408 by Hutchings 1968*a*.) Following the example of ζ Ori, a higher wind velocity should be observed for the resonance lines in the far-ultraviolet region. The expanding envelopes of these stars are similar but differ quantitatively.

The four stars we have discussed so far show evidence of roughly symmetrical outflow, since the profiles are classical P Cygni–type I profiles (Beals 1951). There is evidence that these profiles change and the flow and/or envelope varies but on time scales of years according to the discussion of these stars, and similar ones, by Beals (1951). As an example of a nonsteady, and/or nonsymmetrical flow, figure 10 shows the line profiles of 9 Sge, an O8 If star. Of particular interest here is the extended violet absorption wing of λ5876, which has two different "levels" at about -300 and -500 km s^{-1}. The lower velocity

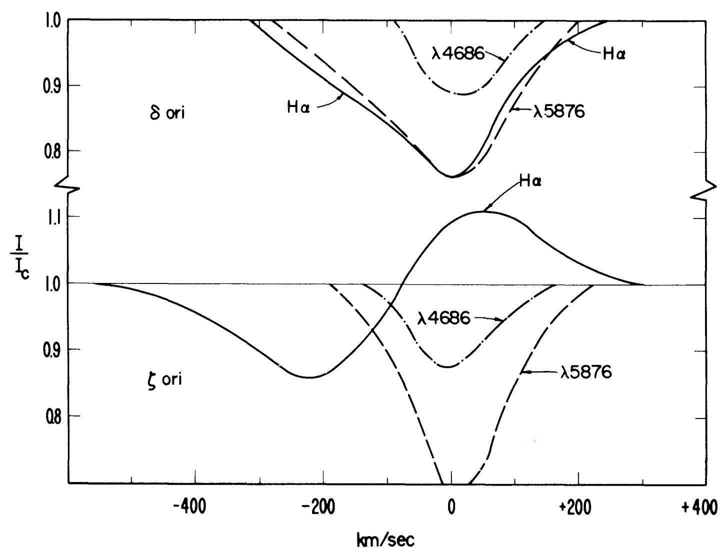

FIG. 8.—Normalized line profiles of Hα, λ5876 He I, and λ4686 He II for two O9.5 supergiant stars, δ Ori (*upper curve*) and ζ Ori (*lower curve*). These have been smoothed by hand from microphotometer tracings. The placement of the line center is accurate to perhaps 50 km s^{-1}. The He I and He II lines are similar in the two stars, but there is a P Cygni profile observed in ζ Ori for Hα. Both stars have large wind velocities associated with the resonance lines observed in the rocket ultraviolet region by Morton (1967).

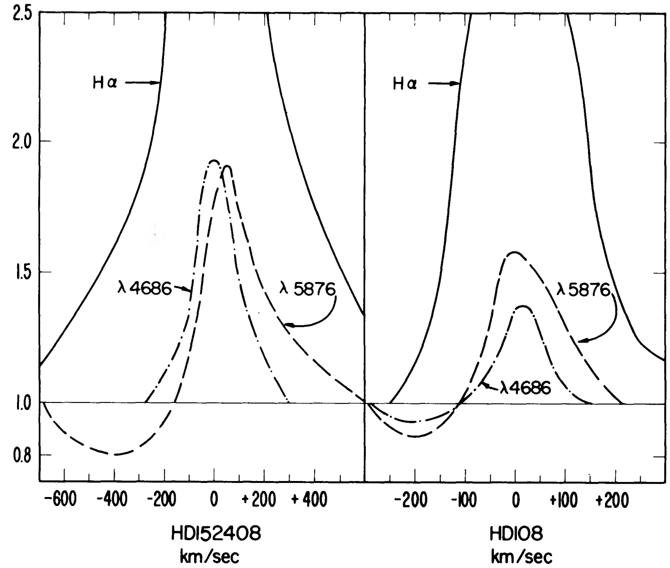

FIG. 9.—Normalized line profiles of Hα, λ5876 He II, and λ4686 He II for two Of supergiant stars, HD 152408 (*left*) and HD 108 (*right*). These have been smoothed by hand from microphotometer tracings. The placement of the line center is accurate to perhaps 50 km s^{-1}. P Cygni profiles and strong Hα emission are observed in both stars, indicating extensive envelopes and winds.

corresponds to the absorption part of the P Cygni profile of Hα, the higher velocity may correspond to the redward "tail" of emission at Hα. Clearly, the physical interpretation of such profiles will not be simple. On the other hand, the emission profile of λ4686 is sharp and symmetrical, and this line is presumably formed in a different region (the spectrum of this line was taken at a different time, however).

VI. INTERPRETATION

Detailed discussion of the Oef and Of stars will be presented at a later time when appropriate models have been constructed. We will here just give a simplified interpretation and point out the importance of rotation in this connection. Figure 11 is a schematic representation of two extreme situations for the

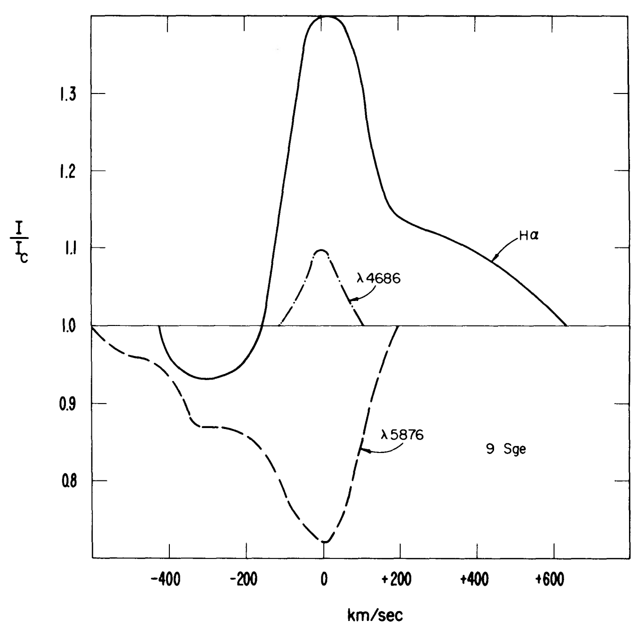

FIG. 10.—Normalized line profiles of Hα, λ5876 He I, and λ4686 He II for the Of supergiant star 9 Sge. The violet wing of λ5876 shows an anomalous structure. Unlike the four stars shown in figs. 8–9, there is evidence here for either a nonsymmetrical outflow, or a fluctuation in the flow velocity.

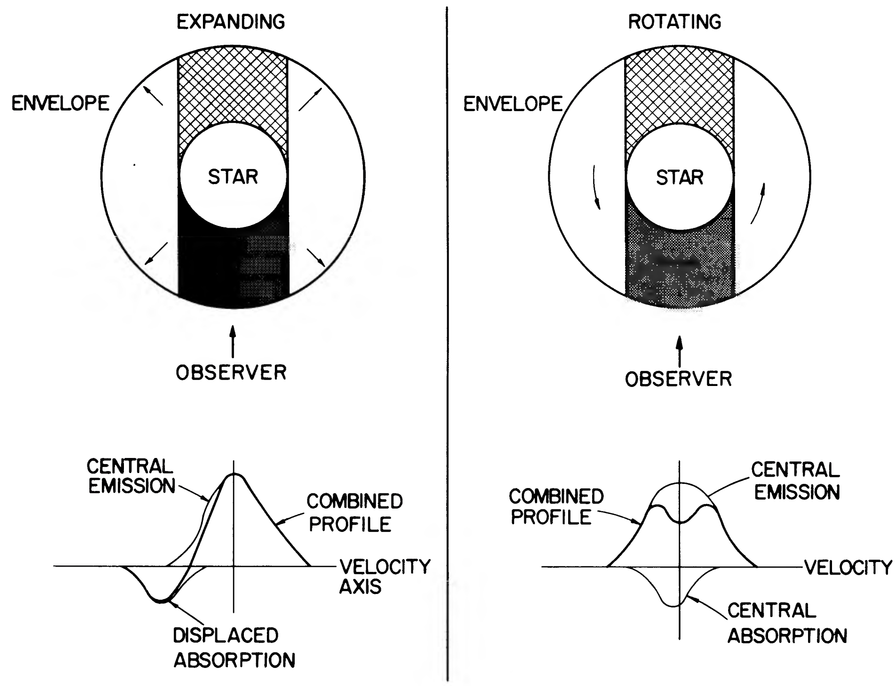

FIG. 11.—Idealized geometrical representations of a spherical envelope with expansion (*left*) or rotation (*right*). The crosshatched volume behind the star is not visible to the observer; the shaded volume in front produces the absorption line; and the volumes on either side of the star produce the emission part of the line. In the expanding case, the absorption component is violet displaced, although the emission is central. The combined profile is a P Cygni type. In the rotating case, both the absorption and the emission are central. The combined profile gives the characteristic double emission appearance. If there is a small net outflow (or inflow) in the rotating case, the absorption is similarly displaced and the emission peaks will be unequal. If the expansion and rotation velocities are comparable, a complicated profile will result where the absorption is shifted appreciably although not all the way toward the violet, although the emission remains roughly central. Although these profiles will be produced by the spherical geometry shown, other geometries, such as a ring, or doughnut, will also produce these profiles if the velocity is correctly specified.

velocity of an envelope; outflow and rotation. The crosshatched volume behind the star as seen by the observer is not observed. The shaded volume in front of the star produces the absorption lines; the envelope is thereby considered to be thin in optical depth. The envelope volumes to either side of the line of sight to the star produce the emission.

The left-hand part of figure 11 shows the typical P Cygni model, where the envelope is expanding, either uniformly or with acceleration. The important observational result is that the absorption part is displaced towards the violet, whereas the emission is central. The combination of emission and absorption gives the P Cygni profile. The resultant emission has a small redward displacement, due entirely to the suppression of its violet side by the absorption. The *width* of the emission, and the *displacement* of the absorption, are a measure of the *velocity dispersion and average velocity* in the envelope. The *strength* of the emission and of the absorption are a function of the *geometrical size* of the envelope compared with the stellar "photosphere."

Contrast this picture with the right-hand side of figure 11, where we sketch a rotating envelope. Here the absorption is roughly central, as in the emission. The combination produces the characteristic "double emission" profile that we see in the Oe and Oef stars. The *width* of the emission is a measure of the *average rotational velocity*, but we cannot distinguish between solid-body rotation or individual Keplerian orbits for the matter in the envelope just from the profile. The *strength* of the emission and absorption are a function of the *geometrical size* of the envelope. If the rotating envelope has a very small net outflow (or inflow) the placement of the absorption with respect to the emission will vary slightly, resulting in a profile which has the appearance of unequal emission peaks.

If the outflow velocity and the rotational velocity are comparable, a complicated combination of a P Cygni profile and the double emission profile will result; for example, the absorption could be appreciably displaced to the violet, but not be all the way at the end (e.g., ζ Pup). This type of profile is what Beals (1951) referred to as type III P Cygni lines. We should add that very complicated profiles can be produced by envelopes with spherical symmetry, but with a *combination* of expansion and rotation (Hutchings 1968*b*).

There is also a uniqueness problem for the geometry that must be considered. Certainly the sketched envelopes will uniquely produce the P Cygni or double emission profiles, but other *geometrical shapes* will also. For example, the material in the envelope could be concentrated in a shell, or a doughnut, and give either of these two profiles if the velocity is correctly specified. Then the envelope is not spherically symmetric, although it is azimuthally symmetric. We do not think this could be the case for stars having expanding envelopes but this possibility should be borne in mind for the rotating envelopes. To specify the geometry, other physical information must be at hand.

VII. DISCUSSION

We have seen that a number of Of and luminous type O stars have emission observed in λ4686 He II and/or Hα. This emission can be understood only if the lines are formed in an extended atmosphere regime, even though many other lines observed in the spectrum can be understood in terms of plane-parallel geometry. In many cases the extended atmospheres are expanding, often with large velocities, as P Cygni profiles are found. In a number of stars we have definite evidence that the expansion is accelerating outwards and we believe this is the case generally.

A number of other Oe and Oef stars also have extended atmospheres, but the profiles observed for λ4686 and/or Hα for these stars suggest there is appreciable rotation of the envelope. Other absorption lines show evidence of rapid rotation of the star itself. These stars are generally near the main sequence and there appears to be some physical similarity to Be stars. Our explanation of the Oe and Oef stars, at least, is that they have low gravity at the equator and only a small amount of radiation pressure there is needed to form an envelope. We do not think "rotationally forced ejection" is an applicable physical statement.

For neither Of, Oe, nor Oef stars is the geometry of the envelope certain, but we think that in the former case spherical symmetry applies. To a first approximation, we might expect the envelopes of Oe and Oef stars to be more in the form of a doughnut or ring around the equator, than to have spherical symmetry. For at least a few Oef stars, such as ζ Pup, both expansion and rotation must be important.

We are indebted to Drs. Mihalas and Walborn for comments on the manuscript. The timely receipt of preprints from Dr. Walborn and Sra. Niemelä was very stimulating to the results of this investigation. Mr. Brian Flannery assisted in early stages of this work. We are appreciative of financial support by NSF under grant GP-36465.

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