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NARROW COMPONENTS IN THE PROFILES OF ULTRAVIOLET RESONANCE LINES: EVIDENCE FOR A TWO-COMPONENT STELLAR WIND FOR O AND B STARS?

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ABSTRACT

The spectra of 26 early-type stars were studied for the presence of narrow shifted absorption features, superposed on the wide P Cygni profiles of the UV resonance lines. Seventeen out of the 26 stars show such narrow absorptions. The central velocity, v_s, of these features is almost the same for different ions within one star, with no evidence for a relation between v_s and the ionization potential. The velocities of the narrow absorptions for different stars are correlated with the terminal velocity, v_∞, of the stellar wind and have a typical value of $0.75v_\infty$. The width (FWHM) of the narrow absorptions is about $0.18v_\infty$. The column density of the narrow components is not correlated with $T_{\rm eff}$ nor with the mass loss rate, except for a few main-sequence stars which have a small mass loss rate and no narrow components. The narrow components have a hydrogen column density of about 10^{21} to 10^{22} cm^{-2}, and contribute about 10% to 60% of the total column density of the wind. The degree of ionization derived from the narrow components is higher than the mean ionization of the wind.

Several possible explanations are considered. The observations may be explained by assuming that the wind consists of a two-component gas: a "normal" component which is accelerated in the wind from $v \approx 0$ to v_∞, and which produces the general P Cygni profile, and a less dense component which occurs only at a distance $r \gtrsim 2R_*$ and has a smaller outward velocity than the normal component. The difference in velocity between the two components may generate shocks which are responsible for the production of the observed X-rays and for the superionization of the wind. This model is similar to the unstable wind model proposed by Lucy and White to explain the observed X-ray flux from OB supergiants.

Subject headings: stars: early-type — stars: winds — ultraviolet: spectra

I. INTRODUCTION

Observations of the ultraviolet spectrum of early-type stars have shown that these stars are losing mass at a considerable rate (10^{-5}–10^{-8} $M_\odot$ yr^{-1}) and that the ejected material is accelerated to velocities of the order of a few times 10^3 km s^{-1}. Despite the fact that the mechanism which produces the mass loss is still unknown, it is generally believed that the large velocities are due to radiation pressure in UV resonance lines. (For a review of the mechanisms of mass loss see Cassinelli, Castor, and Lamers 1978; Cassinelli 1979.)

In an attempt to understand the mechanism of mass loss and the dependence of the mass loss rate on luminosity, temperature, and gravity, the authors, using *Copernicus* data, have studied the profiles of UV resonance lines in 25 OB stars of various luminosities and temperatures (Gathier, Lamers, and Snow 1981; hereafter GLS). The profiles were compared with predicted profiles from the atlas of Castor and Lamers (1979). In the course of this study we realized that many of the observed resonance line profiles in most of the stars show narrow absorption features. These narrow features have a typical width of the order of about 300 km s^{-1} and are usually present in both components of a doublet.

Such narrow components have been detected before in the UV spectra of a few early-type stars by Morton (1976) and Snow and Morton (1979). The variability of these components was studied by Snow (1977) who compared two scans (taken about 4 yr apart) of the UV line profiles of 15 stars. He found that the narrow components do not change in velocity (except for the C III λ1175 line in ζ Pup) but that the strength of the components can change drastically. In some stars the narrow components were present in only one of the two spectra.

The narrow components in the spectrum of ζ Pup (O4 If) were explained by Hamann (1980) in terms of a plateau in the velocity law at 1600 km s^{-1}, which produces a large column density at that particular velocity.

In this paper we study the presence or absence of similar narrow components in the spectra of a large number of OB stars. The general characteristics of the narrow components in terms of velocity, width and ionization are studied in § IV. The components will be interpreted in § V in terms of ionization balance, velocity plateaus in the wind, shells or a two-component wind. The features will be called "narrow components," indicating that they are formed in the wind and are Doppler shifted, but that their width is considerably smaller than the full width of the P Cygni profiles, which is generally of the order of 1000 to 3000 km s^{-1}.

II. THE OBSERVATIONS

The spectra used for this study were taken from Snow and Jenkins (1977). The first 27 stars of this catalog, ranging in spectral type from O4f to B1 Ib, show mass loss effects by the presence of resonance lines with P Cygni profiles, shortward-shifted line cores or enhanced violet wings. The binary 29 CMa was excluded from this study. The remaining 26 program stars are listed in Table 1. In order to reduce the noise, all spectra were convoluted with a Gaussian profile with a full width at half maximum (FWHM) of 0.67 Å, corresponding to a velocity of about 150 km s^{-1}. The spectra from the catalog were consulted to identify the contributions from the interstellar lines. Similarly, the spectra of stars with a small mass loss rate, such as 15 Mon [O7 V (f)] and τ Sco (B0 V), were used to locate the position of strong photospheric components which should not be mistaken for narrow components.

The spectral lines studied are listed in Table 2. The list includes lines from two high-ionization stages (O VI and N V) and two low-ionization stages (Si IV and Si III). The presence of the first two ions show that the wind is superionized either by collisions in a warm wind ($T \approx 1 \times 10^5$ K) or by Auger photoionization by bremsstrahlung from a thin corona or from elsewhere in the wind (e.g., Cassinelli, Castor, and Lamers 1978). By studying both high- and low-ionization stages we may be able to find information on the nature of the observed narrow components.

TABLE 1

THE PROGRAM STARS

Name	HD	Type
ζ Pup	66811	O4 If
9 Sgr	164794	O4 V((f))
	199579	O6 V((f))
15 Mon	47839	O7 V((f))
θ^1 Ori C	37022	O7 Vp
ξ Per	24912	O7.5 III((f))
λ Ori A	36861	O8 III((f))
τ CMa	57061	O9 II
ι Ori	37043	O9 III
10 Lac	214680	O9 V
α Cam	30614	O9.5 Ia
δ Ori A	36486	O9.5 II
ζ Oph	149757	O9.5 V
μ Col	38666	O9.5 V
μ Nor	149038	O9.7 Iab
ζ Ori A	37742	O9.7 Ib
ϵ Ori	37128	B0 Ia
τ Sco	149438	B0 V
κ Ori	38771	B0.5 Ia
ϵ Per	24760	B0.5 III
δ Sco	143275	B0.5 IV
θ Car	93030	B0.5 Vp
ρ Leo	91316	B1 Iab
γ Ara	157246	B1 Ib
ζ Per	24398	B1 Ib
139 Tau	40111	B1 Ib

TABLE 2

THE UV RESONANCE LINES

Ion	I.P.[a] (eV)	λ(Å)	f
O VI	113.90	1031.928	0.130
		1037.619	0.065
N V	77.472	1238.808	0.152
		1242.796	0.076
Si IV	33.492	1393.755	0.528
		1402.770	0.262
Si III	16.345	1206.510	1.66

[a] Ionization potential of previous ionization stage.

III. THE NARROW COMPONENTS

a) *The Presence of Narrow Components*

The resonance lines were studied for the detection of narrow components in the absorption part of the profiles at negative velocity. The narrow components are superposed on the wider underlying P Cygni profiles or on the extended violet absorption wings.

The presence of such narrow components is assumed to be real and due to the stellar wind if the following criteria are satisfied:

1. The components should not be due to interstellar lines. This can be checked by looking at the original *Copernicus* spectra, and in most cases by the width and velocity shifts, which usually exceed that expected for interstellar lines.
2. The components should not be due to photospheric lines. This can be checked by looking at the spectra of slowly rotating stars and stars with very little mass loss.
3. The components should be present in both lines of a doublet at the same Doppler velocity. This last criterion cannot be applied to the singlet resonance line of Si III. For many stars it cannot be applied to the O VI lines either, since part of the wing of the λ1031.928 line is absorbed by the interstellar Lα line.

A few examples of line profiles with narrow components are shown in Figures 1 and 2.

All of the 26 program stars show evidence for mass loss in at least one of the lines studied. In 17 of the stars we found evidence for narrow components. The nine stars for which no narrow lines could be clearly identified have either very small mass loss rates and very weak P Cygni profiles [e.g., HD 199579, O4 V(f); τ Sco, B0 V; ϵ Per, B0.5 III; 139 Tau, B1 Ib); large mass loss rates and almost saturated profiles (e.g., ζ Pup, O4 If); or very strong interstellar H and H_2 lines superposed on the O VI and N V lines.

In almost all of the 17 stars which show narrow

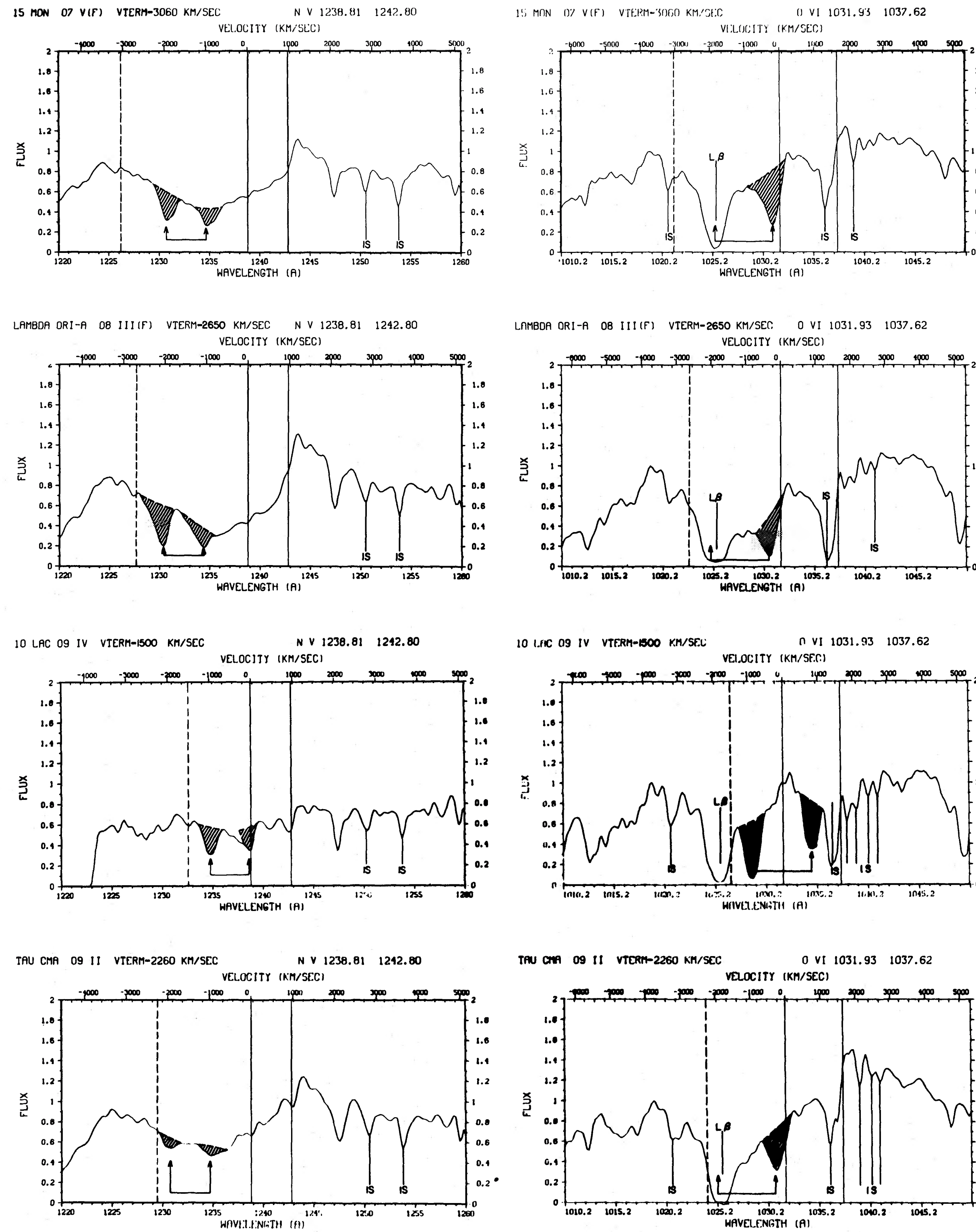

FIG. 1.—Narrow components in the UV resonance doublets of N V and O VI. The laboratory wavelengths of the components is indicated by full vertical lines. The wavelength corresponding to the terminal velocity for the short wavelength component of the doublet is indicated by a dashed vertical line. The interstellar lines, which are easily recognized in the original *Copernicus* spectra, are indicated by IS. The arrows indicate the wavelengths of the narrow components, if the Doppler shift of the O VI lines is the same as for the N V lines.

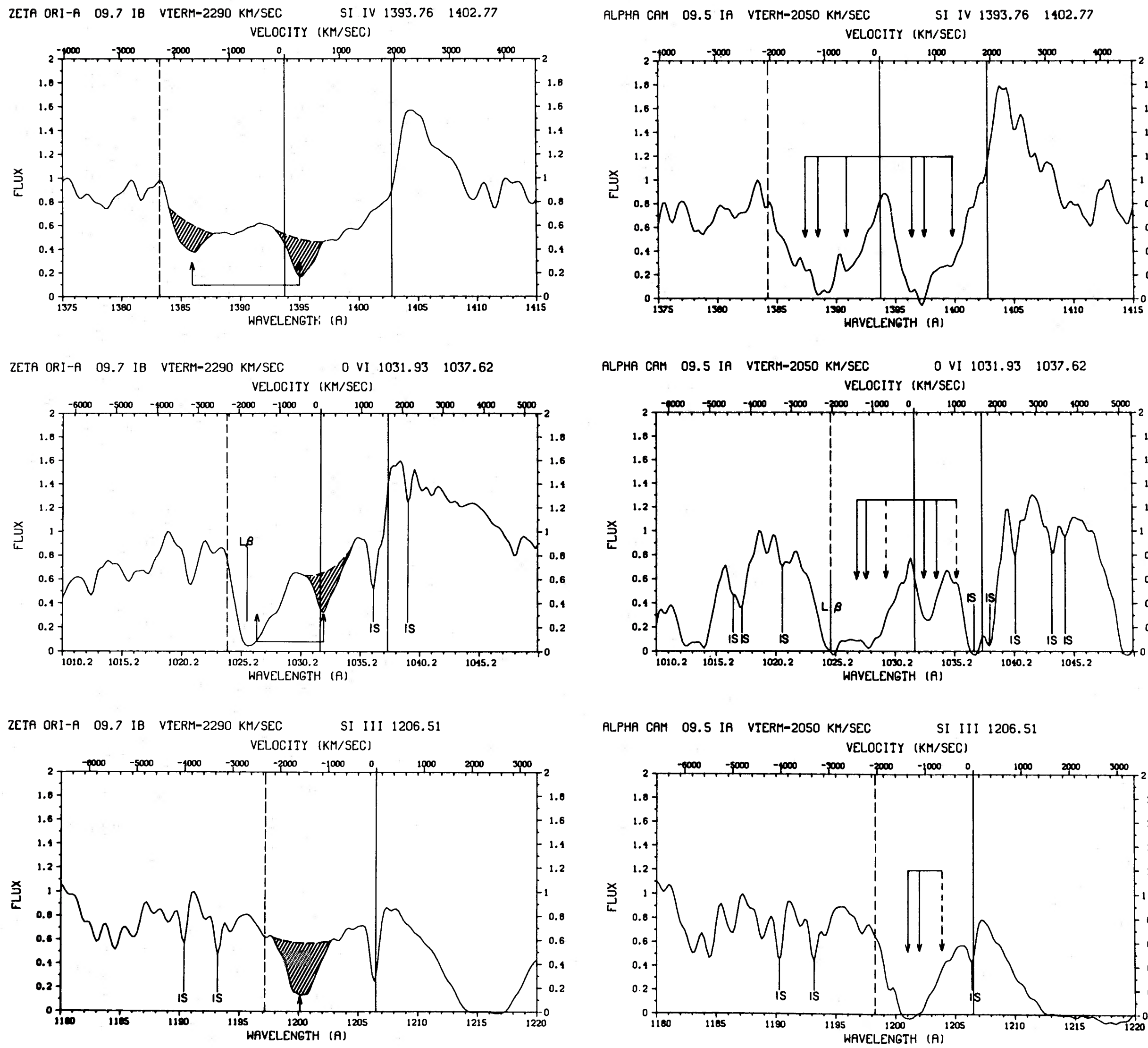

FIG. 2.—The presence of narrow components in the profiles of Si IV, O VI, and Si III lines in ζ Ori and α Cam. The Si IV lines of α Cam show the presence of possibly three components, indicated by arrows. The expected wavelengths of the corresponding components in the lines of O VI and Si III is also shown by arrows. *Full arrows*: narrow components possibly present; *dashed arrows*: narrow components possibly not present.

components, these components were detected in O VI and N V lines. The Si III lines do not show P Cygni profiles or violet wings in stars of type O9.5 or earlier, because this element is more highly ionized in the wind. Therefore, it is not surprising that we do not find narrow components for Si III lines in the earlier O stars. Similarly, the Si IV lines show only weak evidence for mass loss in stars of types O9 and earlier, except if the mass loss rate is very large, as in ζ Pup and ξ Per. Consequently, the lack of detected narrow components in the Si III and Si IV lines of many O stars should not be taken as evidence that such components occur in the highly ionized species only. In fact, the presence of narrow components in the Si IV lines of a few O stars with well developed Si IV P Cygni profiles suggests that they occur in both the high- and low-ionization species, similar to the situation for stars of types between O9.5 and B1.

b) The Velocities of the Narrow Components

The stars for which we clearly found narrow components are listed in Table 3. The terminal velocities of the winds are taken from GLS. For stars which do not show P Cygni profiles with steep edges, the value of v_∞ is uncertain. These are indicated by a colon.

The velocity, v_s, at the center of the narrow components and the FWHM, F_s, of the narrow components, are also listed in this table. The velocity, v_s, could be determined with an accuracy of about 50 km s^{-1} or better. The width F_s is more difficult to determine; its accuracy is estimated to be about 100 km s^{-1} in most cases, but

TABLE 3

VELOCITIES AND WIDTHS OF THE NARROW COMPONENTS

		Velocity of Narrow Components v_s (km s^{-1})									Width (FWHM) of Narrow Components F_s (km s^{-1})								
		O VI		N V		Si IV							N V		Si IV				
Name and Type (1)	v_∞ (km s^{-1}) (2)	1031.93 (3)	1037.62 (4)	1238.81 (5)	1242.80 (6)	1393.76 (7)	4102.77 (8)	Si III 1206.51 (9)	Mean ($\bar{v}_s$) (km s^{-1}) (10)	$\bar{v}_s/v_\infty$ (11)	1031.93 (12)	1037.62 (13)	1238.81 (14)	1242.80 (15)	1393.76 (16)	1402.77 (17)	Si III 1206.51 (18)	Mean ($\bar{F}_s$) (m s^{-1}) (19)	$\bar{F}_s/v_\infty$ (20)
15 Mon O7 V((f))	3060	...	2150	1920	1930	...	...	...	2000±130	0.65±0.04	...	640	340	360	...	...	...	430±140	0.14±0.05
θ^1 Ori C O7 Vp	1650	...	1860?	...	...	...	...	...	...	...	...	520	...	...	...	...	...	520:	0.32:
ξ Per O7.5 III((f))	3000	...	2290	2230	2270	2010	2170	...	2190±110	0.73±0.02	...	260	...	...	340	340	...	310± 50	0.10±0.02
				1790	1810	1920	1920	...	1860± 70	0.62±0.02	...	...	...	...	...	430:	...	430:	0.14:
λ Ori A O8 III((f))	2650	...	1970	2060	2030	...	...	...	2020± 50	0.76±0.02	...	490	390	...	...	...	...	440± 70	0.17±0.03
τ CMa O9 II	2260	...	1910	1960	1930	...	...	...	1930± 30	0.85±0.01	...	490	390	410	...	...	...	430± 60	0.19±0.02
ι Ori O9 III	2360	...	2090	2080	2080	...	...	...	2080± 10	0.88±0.00	...	490	360	480	...	...	...	440± 70	0.19±0.03
10 Lac O9 V	2000:	880	840	990	...	...	...	...	900± 80	0.45±0.04:	520	520	380	...	...	...	...	490± 60	0.25±0.03:
α Cam O9.5 Ia	2050	1140	...	...	...	1130	1170	...	1150± 20	0.56±0.01	...	...	...	...	430:	430:	...	430± 10:	0.21±0.01:
		...	1360	1410	1450	1410	1420	1370	1400± 40	0.68±0.02	...	490	480:	...	...	...	...	490± 10	0.24±0.01
δ Ori A O9.5 II	2410	1080	1130	...	...	1660	1620	...	...	...	470	460	...	...	...	...	...		
		...	1830	1820	1830	1840	1850	...	1830± 10	0.76±0.00	...	460	410	560	...	...	...	480± 60	0.20±0.03
ζ Oph O9.5 V	2000:	...	...	1410	1350	...	...	...	1380± 40	0.69±0.02:	...	...	290	390	...	...	...	340± 70	0.17±0.04:
μ Col O9.5 V	2000:	1000	...	...	...	...	...	...	1000:	0.50:	440	...	...	...	...	...	...	440:	0.22:
ζ Ori A O9.7 Ib	2290	...	1620	1580	1640	1660	1640	1570	1620± 40	0.71±0.02	...	...	410	480	510	510	650	510± 90	0.22∓0.04:
μ Mor O9.7 Iab	2190	...	1880	...	...	...	...	...	1880:	0.86:	...	550	...	...	...	...	...	550:	0.25:
ε Ori B0 Ia	2100	...	1480	...	...	...	...	...	1480:	0.70:	...	550	...	...	...	...	...	550:	0.26:
κ Ori B0.5 Ia	1870	1460	1400	...	...	1440	1410	...	1430± 30	0.76±0.02	...	460	...	...	...	...	...	460:	0.25:
ε Per B0.5 III	1500:	1080	1230	...	...	...	...	...	1160±110	0.77±0.07:	...	...	...	...	...	...	...	...	...
ρ Leo B1 Iab	1580	1030	990	...	1040	960	...	1080	1020± 50	0.65±0.03	320	...	...	260	260	...	...	280± 30	0.18±0.02
		...	...	...	...	1290	...	1400	1350± 80	0.85±0.05	...	...	...	...	...	...	...	...	...
Mean										0.74±0.10									0.18±0.04

NOTES.—(1): indicates uncertain value. (2) Underlined values could be measured relatively accurately. (3) The uncertain values in cols. (12) and (21) were not included in the calculation of the mean values of $\bar{v}_s/v_\infty$ and $\bar{F}_s/v_\infty$ for all stars.

depends strongly on the noise in the data and the strength of the lines. All velocities were measured with respect to the stellar center of mass, i.e., the wavelength scale of the Snow and Jenkins (1977) catalog was adopted with the correction described in their equations (1a) and (1b). In many of the O stars only one narrow component was found in the O VI doublet, at a wavelength between 1029 and 1031 Å. This component was attributed to the λ1037.62 line and not to the λ1031.93 line because first, if the component were due to the λ1032 line, one expects a similar but weaker narrow component to occur in the region between 1035 and 1037 Å due to the other doublet line, which is not observed; second, the narrow component velocity derived from the assumption that it is due to the λ1037.62 line agrees very well with the velocity of the N V narrow components. With such a velocity the expected narrow components of the λ1031.93 line is blended by the interstellar Lα line (see Fig. 1).

In several stars more than one narrow component can be observed, e.g., in ξ Per, α Cam, δ Ori A, and ρ Leo. In α Cam even a third component at -650 km s^{-1} may be present in the Si IV lines. This particular star is known to show short-time variations in its P Cygni profiles (de Jager *et al.* 1979), as are δ Ori A and ζ Pup (York *et al.* 1977).

A comparison between the values of v_s and F_s for lines of the same doublet gives an indication of the accuracy of the data. With a few exceptions, the values of v_s within a doublet agree to within 50 km s^{-1}, whereas much larger differences of up to about 100 km s^{-1} occur between the values of F_s within one doublet. The velocities of the narrow components of N V and Si IV, Si III are plotted against the velocity of the O VI narrow components in Figure 3. We notice that there is an excellent one-to-one correlation and that the velocities of the low ionization species such as Si III and Si IV agree very well with the velocities of the high ionization species O VI and N V. *There is no evidence for either an increase or a decrease of v_s with ionization potential.*

The mean velocity of the narrow components, v_s, for each star is given in Table 3, column (11) and the same value expressed in terms of v_∞ is given in column (12). Both values are plotted versus spectral type in Figure 4. The values of v_s/v_∞ occur in a strip around $v_s/v_\infty \approx 0.75$, whereas the values of v_s occur in a wide band with some evidence for a decrease toward later spectral types. It is important to notice that the data for various stars agree much better with another if plotted as v_s/v_∞ than as v_s. This indicates that the velocity of the narrow components is more or less proportional to the terminal velocity of the wind. The mean value of v_s/v_∞ averaged over all stars, omitting the uncertain values, is 0.74 ± 0.10. If stars with multiple narrow components are also omitted, the mean value is 0.78 ± 0.08.

The width of the narrow components, F_s, is less accurately determined than v_s. The mean values per star, F_s and F_s/v_∞, are listed in Table 3, columns (20) and (21). Omitting the uncertain values, we find the average value of F_s/v_∞ for all stars to be 0.18 ± 0.04. The data in Table 3 suggest that the width of the N V narrow components is

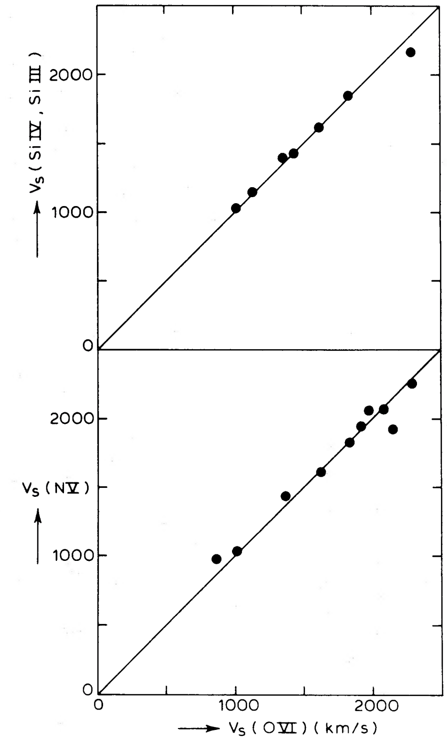

FIG. 3.—The radial velocity of the narrow components of Si IV and Si III (*upper graph*) and N V (*lower graph*) is plotted against the velocity of the narrow components of O VI.

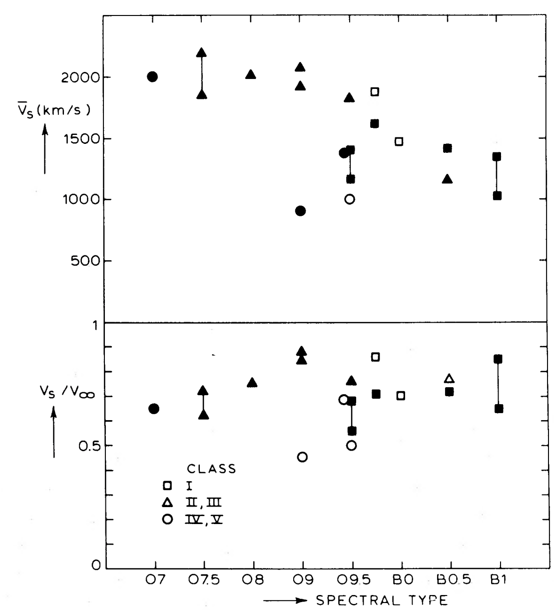

FIG. 4.—The mean central velocity of the narrow components in each star are plotted vs. spectral type. The upper graph shows the velocity of the narrow components (v_s), and the lower graph shows the normalized velocity (v_s/v_∞). Different symbols refer to different luminosity classes. If a star has multiple narrow components, both are indicated and connected by a vertical line. Open symbols refer to the less accurate values of Table 3. Notice that v_s/v_∞ is approximately independent of spectral type and luminosity.

systematically smaller than the width of the O VI narrow components, but the relevant data are scarce.

c) *The Optical Depth and Column Densities of the Narrow Components*

In order to determine the column densities of the narrow components we consider the fits of the observed profiles to the theoretical profiles (GLS). The theoretical profiles were described by a radial optical depth

$$\tau(w) = \tau_a(w) + \tau_s(w)\,, \tag{1}$$

where w is the normalized velocity, $w = v/v_\infty$, $\tau_a(w)$ is the optical depth law which fits the underlying (i.e., without narrow components) P Cygni profile (Castor and Lamers 1979) and $\tau_s(w)$ is the optical depth law which fits the additional narrow component. The opacity of the narrow component was assumed to have a Gaussian shape

$$\tau_s(w) = A_s \exp\left[-(w - v_s/v_\infty)^2/0.601(F_s/v_\infty)^2\right] \tag{2}$$

with a central velocity v_s, a FWHM of F_s, and an opacity A_s at the center of the narrow component. By comparing the optical depth in the narrow component with the one in the underlying P Cygni profile, we find that the optical depth $\tau_s(w)$ within the full half-width of the narrow component is about 4 times as large as the optical depth $\tau_a(w)$ of the underlying P Cygni profile at the same velocity.

The column density of the narrow components can be derived:

$$N_s = T_s v_\infty/(\pi e^2/mc)\lambda f \tag{3a}$$

with

$$T_s = \int_0^1 \tau_s(w)dw = 1.064 F_s A_s/v_\infty\,. \tag{4a}$$

The column density of the underlying P Cygni profile is given by

$$N_a = T_a(0.2, 1)/(\pi e^2/mc)\lambda f \tag{3b}$$

and

$$T_a(0.2, 1) = \int_{0.2}^1 \tau_a(w)dw\,. \tag{4b}$$

We use the optical depth and the column density in the region where $v = 0.2v_\infty$ to $v = v_\infty$, because of the uncertainty in the line fits at small velocities (see GLS).

In Table 4 we listed the column densities N_a and N_s for those lines for which we obtained a good fit between the observed and theoretical profiles (weight 2, 3, or 4 in GLS). We also list the ratio N_s/N_a between the column densities of the narrow components and the underlying P Cygni profile, which may provide information on the relation between the narrow components and the stellar wind. The values of log N_s/N_a are plotted against log N_a in Figure 5. The data suggest the presence of a strong anticorrelation, especially for the giants and the supergiants. Apart from the main sequence stars μ Col and τ Sco, which have very weak or no narrow components, and the star γ Ara, which has exceptionally wide narrow components of $F_s/v_\infty \approx 0.35$, the data seem to fit a relation of the type

$$\log N_s/N_a = c - \log N_a\,. \tag{5}$$

The least-squares fit relation of this type is shown in Figure 5 by dashed lines.

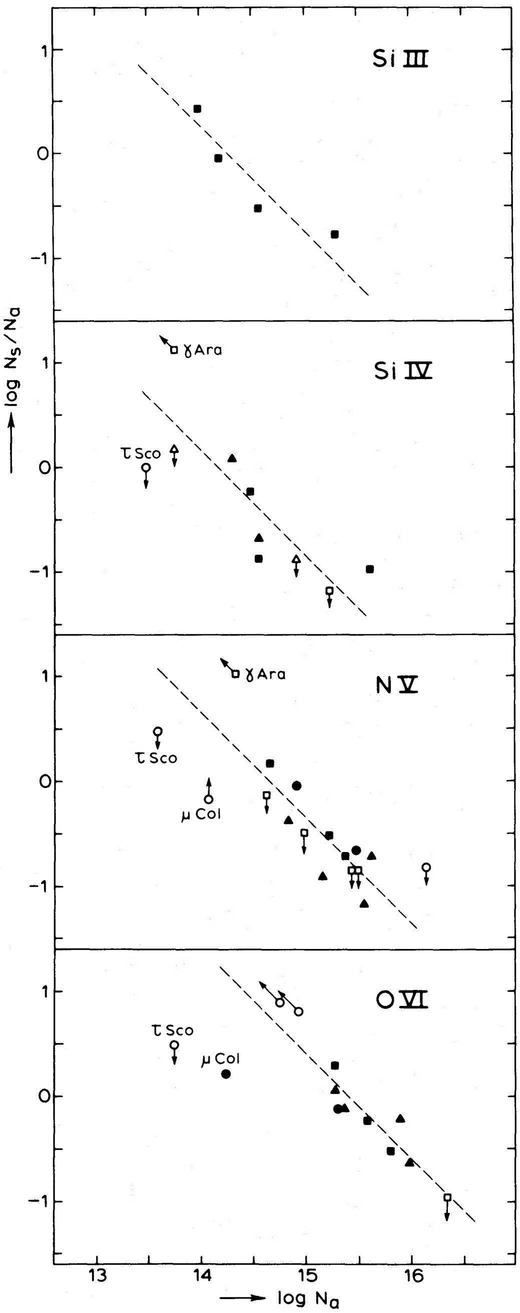

FIG. 5.—The ratio between the column density of the narrow components (N_s) and the column density of the underlying P Cygni profile (N_a) is plotted against N_a for different ions. Squares refer to supergiants and Of stars, triangles to giants, and circles to main-sequence stars. Open symbols refer to upper or lower limits. The majority of the data shows an anticorrelation of N_s/N_a against N_a. The mean empirical relations are indicated by dashed lines.

TABLE 4

COLUMN DENSITIES OF THE NARROW COMPONENTS

Star (1)	Type (2)	Log T_{eff} (3)	v_∞ (km s^{-1}) (4)	Ion (5)	Log N_a (6)	Log N_s (7)	Log N_s/N_a (8)	Log N_s^{min}(H) (9)	Log N_s(H) (10)
ζ Pup	O4 If	4.505	2660	O VI	16.33	<15.35	<−0.98	<19.52	<21.53
HD 199579 ..	O4 V((f))	4.580	3440	N V	16.15	<15.32	<−0.83	<19.96	<21.59
15 Mon	O7 V((f))	4.544	3060	O VI	<14.93	15.74	> 0.81	19.91	22.08
				N V	15.49	14.83	−0.66	19.47	21.39
ξ Per	O7.5 III((f))	4.531	3000	Si IV	14.30	14.39	0.09	19.54	20.75
λ Ori	O8 III((f))	4.544	2650	O VI	15.90	15.68	−0.22	19.85	21.94
				N V	15.61	14.90	−0.71	19.54	21.25
τ CMa	O9 II	4.491	2260	O VI	15.36	15.25	−0.11	19.42	21.79
				N V	15.16	14.26	−0.90	18.90	21.32
				Si IV	14.92	<14.06	<−0.86	<19.21	<21.41
ι Ori..........	O9 III	4.531	2360	O VI	15.98	15.34	−0.64	19.51	21.68
				N V	15.56	14.37	−1.19	19.01	20.93
10 Lac........	O9 V	4.544	2000:	O VI	<14.75	15.64	> 0.89	19.81	21.96
α Cam	O9.5 Ia	4.477	2050	Si IV	15.61	14.65	−0.96	19.80	21.46
				Si III	15.30	14.52	−0.78	18.97	21.33
δ Ori	O9.5 II	4.477	2410	O VI	15.29	15.35	0.06	19.52	21.89
				N V	14.83	14.46	−0.37	19.10	21.54
				Si IV	14.55	13.87	−0.68	19.02	21.24
ζ Oph	O9.5 V	4.505	2000:	O VI	15.31	15.20	−0.11	19.37	21.61
				N V	14.92	14.88	−0.04	19.52	21.62
μ Col	O9.5 V	4.544	2000:	O VI	14.23	14.45	0.22	18.62	21.03
				N V	<14.08	13.90	>−0.18	18.54	21.08
μ Nor	O9.7 Iab	4.477	2190	N V	15.50	<14.64	<−0.86	<19.28	<21.46
ζ Ori	O9.7 Ib	4.477	2290	O VI	15.27	15.56	0.29	19.73	21.98
				N V	15.22	14.70	−0.52	19.34	21.47
				Si III	14.19	14.14	−0.05	18.59	21.06
ε Ori	B0 Ia	4.398	2100	O VI	15.80	15.28	−0.52	19.45	21.73
				N V	15.38	14.66	−0.72	19.30	21.50
				Si IV	15.22	<14.03	<−1.19	<19.18	<21.17
				Si III	14.45	13.93	−0.52	18.38	20.88
τ Sco	B0 V	4.505	2000:	O VI	13.75	<14.23	< 0.48	<18.40	<20.85
				N V	13.60	<14.08	< 0.48	<18.72	<21.36
				Si IV	13.49	<13.49	< 0.00	<18.64	<21.05
κ Ori	B0.5 Ia	4.415	1870	O VI	15.58	15.35	−0.23	19.52	21.92
				N V	15.43	<14.57	<−0.86	<19.21	<21.73
				Si IV	14.54	13.68	−0.86	18.83	21.13
ε Per	B0.5 III	4.447	1500:	Si IV	13.73	<13.89	< 0.16	<19.04	<21.67
θ Car	B0.5 Vp	4.447	2000:	N V	<14.08	<14.60	...	<19.24	<21.83
ρ Leo	B1 Iab	4.322	1580	N V	14.65	14.82	0.17	19.46	22.00
				Si IV	14.46	14.23	−0.23	19.38	21.69
				Si III	13.99	14.40	0.41	18.85	21.48
γ Ara	B1 Ib	4.322	1050	N V	<14.32	15.37	> 1.05	20.01	22.38
				Si IV	<13.73	14.84	> 1.11	19.99	22.14
ζ Per	B1 Ib	4.322	1500	N V	14.62	<14.48	<−0.14	<19.12	<21.94
				Si IV	<13.37	<13.89		<19.04	<21.62
139 Tau	B1 Ib	4.322	1500:	N V	14.98	<14.48	<−0.50	<19.12	<21.72

NOTES.—(1) The star θ^1 Ori C is omitted, because this star was not included in the study by GLS. (2) The shell components of μ Nor and ε Per are very weak, so only upper limits for N_s are derived. (3) The star γ Ara is included in this list, although its narrow components are not superposed on underlying P Cygni profiles.

The deviations from these least-squares fit relations are rather large. In order to investigate the behavior of N_s more closely, we plotted the values of log N_s against log T_{eff} and log $\dot{M}$ (from GLS) in Figure 6. There is no evidence for a correlation between log N_s and T_{eff}. There is no clear evidence for a correlation between log N_s and $\dot{M}$. However, the stars with log $\dot{M} < -6.8$ also show the lowest values of N_s. If we exclude the stars μ Col, τ Sco, and γ Ara for the reasons mentioned above, we find the following mean values for the column densities of the narrow components:

$$\log N_s(\text{O VI}) = 15.4 \pm 0.2 \,,$$

$$\log N_s(\text{N V}) = 14.7 \pm 0.2 \,,$$

$$\log N_s(\text{Si IV}) = 14.2 \pm 0.4 \,,$$

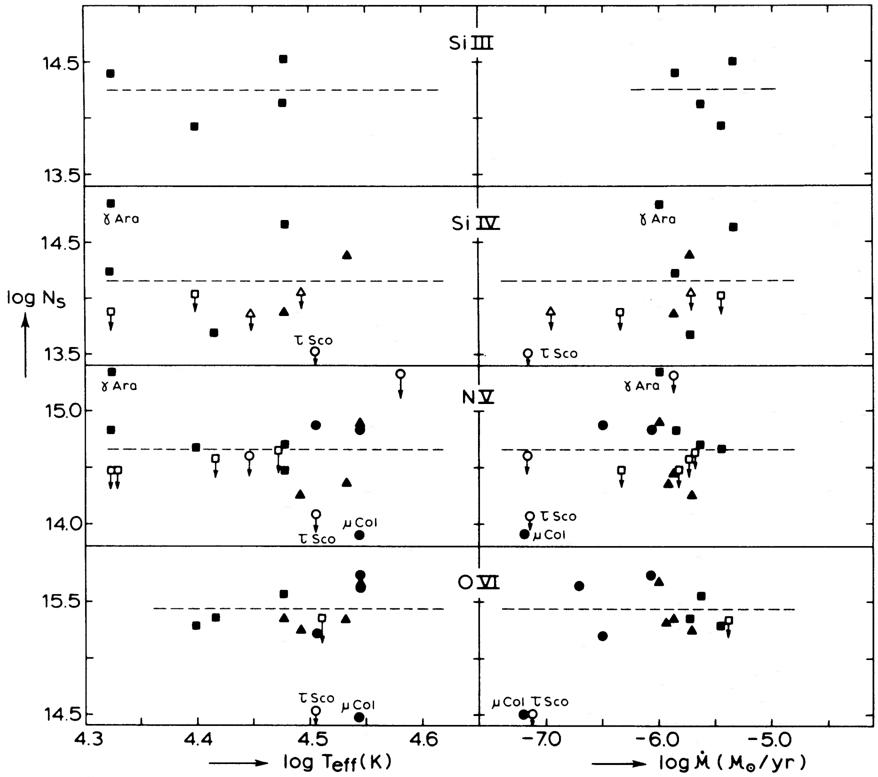

FIG. 6.—The column densities of the narrow components are plotted against T_{eff} (*left panels*) and $\dot{M}$ (*right panels*). Symbols are the same as in Fig. 5. There is no correlation between N_s and T_{eff}. There is no clear correlation between N_s and $\dot{M}$, except for stars with log $\dot{M} \lesssim -7$, which have small values of N_s. The mean values of N_s are indicated by dashed lines.

and

$$\log N_s(\text{Si III}) = 14.3 \pm 0.3 .$$

The individual stars deviate from these mean values within about a factor of 3.

The total hydrogen column density of the narrow components can be derived from the values of N_s by adopting abundances [O/H] = −3.17, [N/H] = −3.94, [Si/H] = −4.45, and ionization fractions. Minimum values for the column densities can be found by adopting maximum ionization fractions: O VI/O = 0.1, N V/N = 0.2, Si IV/Si = 0.2, Si III/Si = 1 (e.g., Jordan 1969). These minimum values of log N_s^{min}(H) are listed in Table 4, column (9). More realistic estimates can be obtained by adopting ionization fractions as derived for the wind of each star individually by Lamers, Gathier, and Snow (1980). These ionization fractions are typically of the order of O VI/O $\approx 6 \times 10^{-3}$, N V/N $\approx 2 \times 10^{-3}$, Si IV/Si $\approx 3 \times 10^{-3}$, Si III/Si $\approx 1 \times 10^{-3}$. The resulting values of log N_s(H) are listed in Table 4, column (10). The mean values of the column densities are given in Table 5. The maximum ionization fractions would give values of N_s^{min}(H) that are low by two orders of magnitude. The more reasonable values, however, yield log N_s^{min}(H) ≈ 21.5, in reasonable agreement with Table 4.

d) The Ionization Equilibrium of the Narrow Components

The ionization balance in the material which produces the narrow components can be compared with the ionization in the part of the wind which produces the P Cygni profiles. In Figure 7 we plotted the ratios of column densities N(O VI)/N(N V) and N(N V)/N(Si IV) of the narrow components against the same ratios derived from the underlying P Cygni profile. The line corresponding to a ratio of unity is also indicated. We notice that the ratio O VI/N V is higher in the narrow components than in the P Cygni profile by about a factor of 4. The same

TABLE 5

MEAN HYDROGEN COLUMN DENSITIES OF THE NARROW COMPONENTS

Column Density	O VI	N V	Si IV	Si III
Log N_s^{min}(H)	19.51 ± 0.35	19.29 ± 0.39	19.43 ± 0.45	18.70 ± 0.26
Log N_s(H)	21.78 ± 0.29	21.50 ± 0.41	21.40 ± 0.44	21.19 ± 0.27

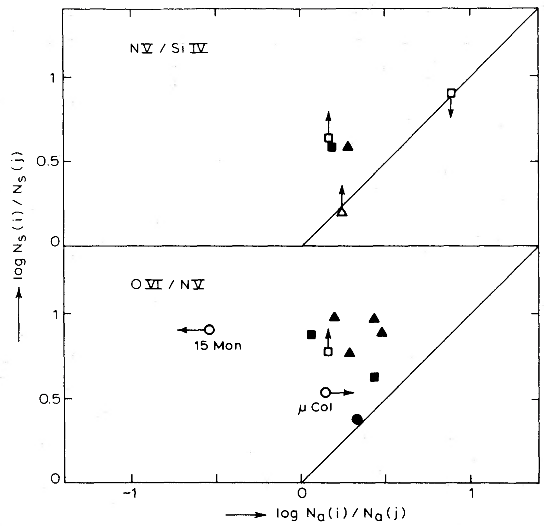

FIG. 7.—The ratios between the column densities (N_s) of the narrow components N V/Si IV and O VI/N V are plotted against the ratios between the column densities (N_a) of the underlying P Cygni profiles. The symbols are the same as in Fig. 5. The line corresponding to a ratio 1 is also shown. Most of the data points are on the left side of this unity relation, indicating that the narrow components have a higher degree of ionization than the P Cygni profiles.

behavior is found for the N V/Si IV ratio which is higher in the narrow components by about a factor of 3. The uncertainty in these numbers is large, especially for the main-sequence stars. The larger O VI/N V ratio of the narrow components is also reflected in Table 5 which showed higher values of log N_s(H) derived from O VI than from N V.

e) Summary of the Characteristics of the Narrow Components

The important characteristics which were derived from the observed narrow components are:

1. The narrow component velocity is the same for different ions within one star.
2. The narrow component velocity $\bar{v}_s/v_\infty$ is about 0.75 and independent of spectral type and luminosity class.
3. The mean FWHM of the narrow components, F_s, is about 0.18 v_∞.
4. The column densities, N_s, of the narrow components do not show a clear correlation with either $T_{\rm eff}$ or mass loss rate (Figs. 5 and 6). The exceptions are the main sequence stars τ Sco and μ Col which have a small mass loss rate, log $\dot{M} < -7$, and small column densities of the narrow components.
5. The hydrogen column density of the narrow components has a minimum value of about 3×10^{19} cm^{-2}, corresponding to maximum ionization fractions of the observed ions. Assuming a more realistic estimate of the ionization fractions, based on studies of the stellar winds, we find a mean hydrogen column density of about 3×10^{21} cm^{-2}, with a scatter of about a factor of 3. The stars τ Sco and μ Col have considerably weaker narrow components.
6. The O VI/N V ratio and the N V/Si IV ratio in the narrow components are about a factor of 4 larger than in the P Cygni profile.

IV. POSSIBLE EXPLANATION FOR THE NARROW COMPONENTS IN THE WIND

a) Peaks in the Degree of Ionization

The narrow components might be explained by peaks in the ionization fractions of the relevant ions. Such a peak could be caused by a changing ionization fraction, e.g., if silicon would change from Si III at low velocities to Si V at high velocities in the wind, the fraction of Si IV would show a maximum at the intermediate velocities. In this case, however, we would expect a systematic trend of the narrow component velocity with the ionization potential. If the degree of ionization increases outwards, we expect smaller velocities for the Si III and Si IV narrow components than for the N V and O VI lines, and a reverse situation if the degree of ionization decreases. The data in Table 3 do not show any sign of such a trend.

b) A Stationary Shell in the Wind

The presence of narrow components in the profiles can be due to two types of stationary phenomena: either a shell, i.e., a layer in which the density is higher than in the layers above or below, or an extended region of almost constant flow velocity, i.e., a plateau in the velocity law. Assuming spherical symmetry and mass continuity, i.e., $v(r) \cdot \rho(r) \cdot r^2$ is constant, the difference between these two types is in the velocity law: a shell requires a layer where the flow velocity is actually smaller than in the neighboring layers, whereas in the other case the velocity can be monotonically increasing outwards but with a smaller gradient near the shell velocity.

The presence of a stationary high-density shell is unlikely. If the acceleration of the wind is due to radiation pressure, as is generally accepted for all stellar wind models (e.g., Cassinelli 1979), a region of decreasing flow velocity requires a vanishing or very small radiation pressure. To estimate the maximum deceleration which may occur, we consider the kinetic and potential energy of the flow at a distance of the shell, r_s, where the flow velocity is v_s. The kinetic energy per unit mass is $0.5v_s^2$ and the potential energy is $0.5\ v_{\rm esc}^2 \cdot (R_*/r_s)$, where $v_{\rm esc}$ is the escape velocity at the stellar surface. If the radiation pressure was "switched-off" at a distance r_s, the flow would slow down due to the stellar gravity and reach a velocity v with

$$v^2 = v_s^2 - v_{\rm esc}^2(R_*/r_s) . \quad (7)$$

Adopting a value of $v_s \approx 0.75v_\infty$ and $v_\infty \approx 3v_{\rm esc}$ (Abbott 1978) and assuming that the shell is at a distance of $r_s \gtrsim 2R_*$, we find that the flow can slow down to $v \gtrsim 0.95v_s$, i.e., by only 5% at most. This would produce a density increase of only 5%. (In this estimate we neglected the effect of a possible steep temperature gradient near $r \approx r_s$. This is justified because the shell components in the lines are superposed on the P Cygni profiles of the same ions, which indicates that the degree of ionization in the shell is about the same as in the layers which move at smaller and at larger velocities.) Such a small increase in the density is insufficient to explain the fact that the optical depth at the narrow component velocity is about four times as large as at neighboring velocities.

c) *A Plateau in the Velocity Law of the Wind*

An extended region of almost constant flow velocity will produce a large column density and thus a large optical depth at that particular velocity. Such a plateau would produce narrow components for all ions at the same velocity and with the same width. Both facts may agree with the observed characteristics of the narrow components.

The radial optical depth is proportional to the ion density, n_i, and the inverse velocity gradient in the wind;

$$\tau(w) \propto n_i\left(\frac{dv}{dr}\right)^{-1} \propto q_i \cdot \rho \cdot \left(\frac{dv}{dr}\right)^{-1} \propto q_i\left(\frac{dv^2}{dr^{-1}}\right)^{-1} , \quad (8)$$

where q_i is the ionization fraction and ρ is the density. In a stationary wind the density is proportional to $r^{-2}v^{-1}$ because of the mass continuity equation. If the ionization balance in the velocity plateau is about the same as in the rest of the wind, the 4 times larger value of τ for the narrow component (§ III*c*) implies a 4 times smaller velocity gradient dv^2/dr^{-1} in the plateau than at the neighboring velocities.

In Figure 8 we have sketched a simple velocity law which would produce such narrow components. This velocity law is characterized by

$$dv^2/dr^{-1} = A \quad \text{for} \quad v \le 0.65v_\infty \quad \text{and} \quad v \ge 0.85v_\infty \quad (9)$$

and

$$dv^2/dr^{-1} = A/4 \quad \text{for} \quad 0.65 < v/v_\infty < 0.85 , \quad (10)$$

where $A = -1.90R_*v_\infty^2$. This law predicts $v = 0$ at $r = R_*$, $v = v_\infty$ at $r \to \infty$, and the optical depth between $v_s - 0.5F_s < v < v_s + 0.5F_s$ is 4 times larger than at the other velocities. In the same figure we have shown the velocity law which was derived for ζ Pup by Hamann (1980) from an analysis of the UV line profiles with the comoving frame method. The agreement between Hamann's velocity law and the one we estimated from fitting the mean narrow components in the profiles of our program stars is good. This figure shows the large extent of the plateau in the velocity law which is required to produce a sufficient optical depth for the narrow components.

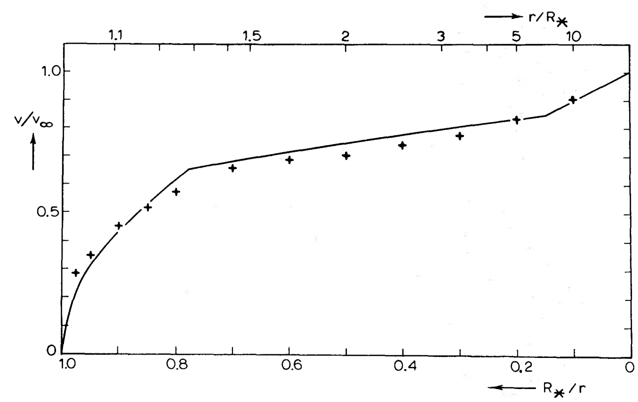

FIG. 8.—The normalized velocity law required to produce the narrow components by means of a velocity plateau is indicated by a full line (eqs. [9] and [10]). The velocity law for ζ Pup derived by Hamann 1980 on the basis of a detailed analysis of the line profiles is indicated by crosses.

The presence of such a velocity plateau requires an acceleration mechanism which is effective close to the star (large dv^2/dr^{-1}), decreases at intermediate distances (small dv/dr at $1.2 \lesssim r/R_* \lesssim 5$) and increases again at larger distances. It is not obvious how radiative acceleration could produce such a velocity law. In general, one expects the radiative force to decrease outwards as r^{-2}, because of the dilution of the radiative flux. Therefore, the velocity in the supersonic part of the wind is expected to vary according to $vdv/dr \propto r^{-2}$ which yields dv^2/dr^{-1} = constant. J. I. Castor (1979, private communications) has suggested that the velocity law for a radiatively accelerated wind may not follow such a simple relation if the effect of overlapping lines, a changing degree of ionization with distance, and the correct angle distribution of the radiation is taken into account. Recently Panagia and Macchetto (1982) have investigated the effect of multiple scattering in the UV lines on the velocity law and mass loss of early type stars. They showed that multiple scattering can occur and that it may increase the radiation pressure by a factor of up to about 10 compared to single scattering. The increase in radiation pressure becomes effective at a distance of about $r \gtrsim 2R_*$, because interception of photons by the stellar disc makes multiple scattering inefficient at $r < 2R_*$. Both effects will result in a velocity law which may differ drastically from the simple velocity law predicted by Castor, Abbott, and Klein (1975) in their radiation driven wind model.

Although improved calculations of the radiation pressure may modify the velocity law of Castor, Abbott, and Klein drastically, we do not think that such modifications could produce a velocity law as sketched in Figure 4, which is required to explain the narrow components. The very extended velocity plateau and the depth of the narrow components require a drastic decrease of the radiation pressure over a very extended region of the stellar wind. None of the suggested possibilities produces such a decrease.

In addition to these arguments, there are some observed characteristics of narrow components which suggest that they are not formed by a velocity plateau: the strong time variations in the strength of the narrow components (Snow 1977); the appearance of more than one narrow component in the spectra of, e.g., α Cam (§ III*b*), and the presence of very strong narrow components in the spectra of some stars which have a weak P Cygni profile (e.g., 10 Lac in Fig. 1). Moreover, the higher O VI/N V ratio in the narrow components compared to the underlying P Cygni profile would require an additional assumption to explain the change in the degree of ionization at the velocity plateau.

d) *A Decelerating Stellar Wind*

The narrow components might be due to a decelerating stellar wind if the wind velocity at large distances from the star decreases to about 0.75 times its maximum velocity. In that case the maximum velocity which is derived from the violet edge of the P Cygni profiles is larger than the true terminal velocity of the wind. In § IV*b* we have argued that the stellar gravity can decelerate the wind by only 5% of its maximum velocity if this maximum is reached at $r \gtrsim 2R_*$. Therefore, an alternative deceleration mechanism should be considered.

The stellar wind will slow down where it runs into the interstellar medium. Castor, McCray, and Weaver (1975) and Weaver *et al.* (1977) have studied the structure and evolution of the interstellar bubbles. They found that the wind of an early-type star blows a bubble in the interstellar medium with a radius of about 30 pc, a temperature of about 10^6 K, and a typical column density of 10^{18} cm^{-2}. This shocked wind region is too hot to explain the presence of the narrow components in the ions such as Si IV and Si III. Moreover, its predicted column density is a factor of 30 smaller than our minimum estimate of the observed column density.

The thin cold shell of swept-up interstellar gas which surrounds the shocked wind region has a predicted column density of 3×10^{19} cm^{-2} and a temperature of about 10^4 K. The velocity of this shell is only about 20 km s^{-1}, which is far too low compared to the observed narrow components which have a typical velocity of about 1500 km s^{-1}.

We conclude that the narrow components cannot be explained by a deceleration of the stellar wind due to gravity, nor by deceleration due to the interstellar medium.

e) *Narrow Components Due to a Variable Mass Loss Rate*

Suppose that the star has a variable mass loss rate and that, in addition to a stationary wind, shells (spherically symmetric) or puffs (not spherically symmetric) are ejected occasionally. The time during which such shells can be observed depends on the time scale for the decrease in column density and on the lifetime of the shells before they dissipate. In the density enhanced shells or puffs, the pressure difference between these regions and the ambient surroundings will lead to diffusion on a time scale roughly equivalent to the sound speed crossing time. At a height of 10 R_* and a velocity of 2000 km s^{-1}, the density of the wind is about 3×10^8 cm^{-3} for a star of 10 $R_\odot$ and a mass loss rate of 10^{-6} $M_\odot$ yr^{-1}. Hence a puff or shell with twice this density has a density $n \approx 6 \times 10^8$ cm^{-3}. If the puff has a column density of about 3×10^{21} cm^{-2} (§ III*c*), its geometrical thickness is about 5×10^{12} cm. For $T \approx 10^5$ K, the speed of sound in the puff is about 40 km s^{-1}, leading to an estimate of the sound speed crossing time of $\tau \approx 15$ d. This time is much longer than the time of about 10 hr needed by the shell to reach a distance of 10 R_*. At a shell distance of 10^2 R_*, the sound speed crossing time is 1.5×10^3 d, and this distance is reached in about 10^2 hr. So the shells or puffs are stable against dissipation, due to their large column densities and geometrical extent. We can estimate the column density and its decrease with time of an ejected shell.

Suppose the star has gone through a period of enhanced mass loss, during which time a shell was ejected. Assume that the shell ejection started at time $t = 0$ and lasted until $t = t_s$. The mass loss rate during the shell ejection phase is $\dot{M}_s$. For simplicity we assume that the shell is ejected at a constant velocity v_s. We adopt a typical value of $\dot{M}_s \approx 2 \times 10^{-6}$ $M_\odot$ yr^{-1}, which is twice the typical "quiet" rate of 10^{-6} $M_\odot$ yr^{-1}. (The observed variability of the Hα and UV lines show that the mass loss rate can vary within a factor of 2 for normal stars, e.g., Snow, Wegner, and Kunasz 1980.) At time, t, the outer and inner boundary of the shell have reached a distance above the stellar surface of $v_s t$ and $v_s(t - t_s)$ respectively. The hydrogen column density of the shell at time t is

$$N_{\rm H}(t) = 2.22 \times 10^{48} \dot{M}_s R_*^{-1} v_s^{-1} \times [(1 + (t - t_s)/t_*)^{-1} - (1 + t/t_*)^{-1}] \ {\rm cm}^{-2} \ , \quad (11)$$

with $\dot{M}_s$ in $\dot{M}_\odot$ yr^{-1}, R_* in cm, v_s in cm s^{-1}, and t in seconds.

The time

$$t_* = R_*/v_s \quad (12)$$

is the time in which the shell moves over one stellar radius. At a time $t \gg t_s$ and $t \gg t_*$, i.e., long after the shell has been ejected, the column density decreases proportional to the distance of the shell from the stellar center:

$$N_{\rm H}(t) \approx 2.22 \times 10^{48} \dot{M}_s R_*^{-2} t_s (t/t_*)^{-2} \ . \quad (13)$$

By comparing this expression with the observed column density of the shell we can obtain an estimate of the time elapsed since the shell ejection. For typical values of $\dot{M}_s \approx 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$, $R_* \approx 10R_*$, $v_s = 1.5 \times 10^8$ cm s^{-1}, $t_* = 4.8 \times 10^3$ s ≈ 1.3 hr and an observed column density of 3×10^{21} cm^{-2} (§ III*e*), we find that $t \lesssim 7 \times 10^4$ s ≈ 1 d. (We assumed $t_s < t$, i.e., the ejection phase already ended when the components are observed at -1500 km s^{-1}.) So the column density is as large as observed for only 1 d after the ejection of the shell. After that time the column density decrease rapidly proportional to $(t/t_*)^{-2}$. This time is too short to explain the presence of strong narrow components in a large fraction of the stars.

On the other hand, the presently observed narrow components might contain material which is accumulated from a large number of previously ejected shells. Suppose that N shells are ejected at time intervals Δt. The observed column density is then

$$N_{\rm H}(t) = 2.22 \times 10^{48} \dot{M}_s R_*^{-2} t_s \sum_{i=1}^{N} (t + i\Delta t/t_*)^{-2} . \quad (14)$$

Unless the interval between the shell ejections is very short and of the order of hours, the contribution of the terms with $i > 1$ in equation (14) becomes very small, and equation (14) approaches the expression in equation (13). This leaves us with the same discrepancy between the short time scale for the column density of the shells and the fact that narrow components are rather common phenomena in the UV spectra of early type stars.

So we conclude that the narrow components are probably not due to ejected shells, unless the shells are ejected in a rapid succession of about one per day, or unless the mass loss rate during the shell ejection phase is many times ($\gtrsim 10$) larger than the mass loss rate during the quiet phases. (The observations of normal Of stars and supergiants indicate that the fluctuations in mass loss are of the order of a factor of two or smaller.)

The arguments given are based on an assumed column density of the narrow components of 3×10^{21} cm^{-2} (see § III*e*). However, if we adopt the minimum values for the column density of 3×10^{19} cm^{-2}, corresponding to maximum ionization fractions, we find that the shells may have a sufficiently large column density during a period up to $t \approx 100$ d. This last value is probably seriously overestimated. First, it is unlikely that O VI, N V, and Si IV are all dominant stage of ionization. Secondly, the O VI/N V ratios of the narrow components are similar (but not exactly the same; see § III*d*) to those of the P Cygni profiles, indicating more or less normal ionization fractions.

f) *A Two-Component Stellar Wind*

The presence of narrow components which have a velocity smaller than v_∞ and a degree of ionization which is higher than in the rest of the wind may be explained by assuming that the wind consists of two coexisting components.

The material which produces the P Cygni profiles occurs at all velocities from $v = 0$ to $v = v_\infty$, so this material is evidently accelerated outwards. This will be called "normal material."

The material which produces the narrow components, called "low-velocity material," occurs mainly at a velocity of about $0.65 \lesssim v/v_\infty \lesssim 0.85$, suggesting that it only occurs at a considerable distance from the star, say $r \gtrsim 2R_*$. If the low-velocity material is not confined to a small distance range, but exists in an extended area, say $2 \lesssim r/R_* \lesssim 10^2$, where the "normal" material has already reached the terminal velocity, the low-velocity material is evidently moving slower than the "normal" material. If the low-velocity material and the "normal" material coexist in the same geometrical region of the wind, the "normal" material moves through the low-velocity material at a relative velocity of about 0.15 to $0.35 v_\infty$, corresponding to about 300 to 700 km s^{-1}.

The low-velocity material has a higher O VI/N V ratio than the "normal" material and possibly also a higher N V/Si IV ratio. From a study of the ionization in the winds of 25 OB stars Lamers, Gathier, and Snow (1980) showed that the mean O VI/N V ratio in the winds decreases with increasing mean density in the wind. If a similar relation also holds for the two components of the wind, the higher O VI/N V ratio suggests that the low-velocity material is less dense than the "normal" material.

In summary, the narrow components can be explained by a two-component wind, if the low-velocity material occurs at a distance $r \gtrsim 2R_*$; is less dense and moves slower than the "normal" material. The interaction between the "normal" material and the low-velocity material may be responsible for the observed X-rays. Such a two-component model can explain the presence of narrow components in a large fraction, and possibly in all, of the program stars. If the wind consists of an ensemble of regions of these two components, the observed short-time variations in the P Cygni profiles might be explained as statistical fluctuations of this ensemble.

This explanation does not account for the fact that the column density of the narrow components is independent of the mass loss rate. In a first approximation one might have expected that a certain fraction of the wind material occurs as "low-velocity component," in which case one would observe N_s/N_a to be about constant. However, the data in Figure 5 and in Figure 6 do not support this explanation.

V. SUMMARY AND DISCUSSION

From a study of the profiles of UV resonance lines in 26 OB stars we found that at least 17 stars have narrow components in their profiles. For each star, narrow components are found in high (O VI and N V) and low (Si IV and Si III) ions at about the same velocity. The velocity of the center of the narrow component is correlated with the terminal velocity of the wind and is approximately $0.74 \pm 0.10 v_\infty$. The width of the narrow components is about $0.18 v_\infty$. The optical depth at the center of the narrow components is about 2 to 10 times as large as the optical depth of the underlying P Cygni profile at the same velocity, with a mean value of about four. The column densities of the narrow components do not seem to be correlated with $T_{\rm eff}$ nor with the mass loss rate (Fig. 6), except for the main-sequence stars with $\log \dot{M} \lesssim -7$. The column densities of the narrow components are approximately: $\log N(\text{O VI}) \approx 15.4$; $\log N(\text{N V}) \approx 14.7$; $\log N(\text{Si IV}) \approx 14.2$; and $\log N(\text{Si III}) \approx 14.3$, with a scatter of about 0.5 to either side of these mean values. Assuming reasonable ionization rates and abundances, we found that the hydrogen column density of the narrow components is typically of the order of 10^{21} to 10^{22} cm^{-2}. The O VI/N V ratio of the narrow components is about 3 to 9 times larger than the ratio derived from the underlying P Cygni profiles. A few stars have multiple narrow components.

The relation between the velocity of the narrow components and the terminal velocity, although clearly suggested by the data in Figure 4, might partly be an artifact of the observations. The terminal velocity of stars is difficult to determine, except when the star shows lines of at least two different ions which have a steep violet edge at the same velocity. The best example of such a star is ζ Pup (Morton and Underhill 1977). If a star has strong narrow components and a weak underlying P Cygni profile, such as the N V lines of 15 Mon or the O VI lines of 10 Lac in Figure 1, the violet edge of these narrow components might easily be mistaken for terminal velocity. (For instance, in the line fitting procedure by Olson and Castor [1981] they assumed the narrow components of N V in 15 Mon to be P Cygni profiles with $v_\infty = 2200$ km s^{-1}.) This effect will result in a tendency to identify the terminal velocity of stars with strong narrow components with the violet edge velocity of the narrow components. This yields an estimate of $v_\infty \approx v_s + F_s$, if the distance from the center of the narrow component to the edge of the narrow component is about F_s. The best counterexample, which shows that the narrow components are really at a velocity smaller than v_∞, is ζ Pup. The value of v_∞ is 2660 ± 150 km s^{-1} according to Morton and Underhill (1977) or 2520 km s^{-1} according to Hamann (1980). The velocity of the narrow components of the unsaturated lines (e.g., Si IV, S IV, P V) is about 1700 km s^{-1}, which is $0.64 v_\infty$ or $0.68 v_\infty$ depending on the adopted value of v_∞. So one of the best observed and studied UV spectra (small noise, well developed P Cygni profiles for many ions) supports the suggestion of Figure 4 that the narrow component velocity is indeed about $0.74 \pm 0.10 v_\infty$.

We have considered several possible explanations for these narrow components. The fact that the narrow components are observed in a large fraction of our sample of stars shows that they cannot be due to short-lived phenomena. The fact that their velocity is correlated with the terminal velocity of the wind suggests that they are due to the wind. The narrow components are not due to peaks in the degree of ionization, since the velocities of the narrow components are the same for low ion stages (Si III and Si IV) as for the high stages (O VI and N V). The narrow components are not due to a stationary shell nor to a plateau in the velocity law, since the narrow components have a very large hydrogen column density and a higher degree of ionization than the underlying P Cygni profile. The narrow components are not due to a slowdown of the stellar wind at a distance of $r \gtrsim 2R_*$ from the star, because the stellar gravity can decelerate a flow with $v \simeq 3v_{\rm esc}$ by only 5% at most. A deceleration of the wind by the interstellar medium cannot explain the large column densities of the narrow components, nor their large velocities.

The narrow components could be due to the ejection of shells or puffs. However, the large column densities of the narrow components and the fact that they are observed in a large fraction of the program stars, requires either that the shells are ejected very frequently (approximately once a day) or that the ejected material has a density much larger ($\geqslant 10$ times) than the normal wind. These requirements are not supported by the observations of normal (non-Be) Of stars and supergiants.

The presence of narrow components might be explained by assuming a two-component stellar wind. The general P Cygni component is due to so-called "normal material" which is accelerated from $v \approx 0$ to v_∞ km s^{-1}. The narrow component may be due to so-called "low-velocity material," which is moving outward at a smaller velocity of about $0.75 v_\infty$. The higher degree of ionization of the low-velocity material suggests that its density is smaller than in the "normal" material. The relative velocity of about $0.25 v_\infty$, i.e., about 500 km s^{-1}, between "normal" material and the low-velocity material may generate shocks of a few million degrees, which may be responsible for the observed X-rays as well as for the formation of O VI via Auger ionization in the wind.

This two-component model, derived from the UV observations, shows a strong resemblance to the model for the unstable line-driven winds proposed by Lucy and White (1980) to explain the observed X-ray fluxes from hot stars. In their model the wind consists of blobs which are accelerated by radiation pressure to v_∞. These blobs move through an ambient gas which is not radiatively accelerated, because of the shadowing by the optically thick blobs. The blobs would correspond to our "normal material," which produces the P Cygni lines, whereas the ambient gas would correspond to our "low-velocity material." The velocity difference between the blobs and the ambient gas in Lucy and White's model for ζ Pup is about 350 km s^{-1}, and occurs near $v_{\rm blob} = 0.5 v_\infty$. This would produce narrow components at a velocity of about $0.35 v_\infty$. However, our observations show that the narrow components have a typical velocity of about $0.75 v_\infty$.

We have looked for one explanation which can account for all of the basic characteristics of the narrow components in all our program stars. We realize, however, that some of the stars do not follow the same general trends derived from the majority of the stars. For instance, the star γ Ara has exceptionally wide narrow components $F_s/v_\infty \approx 0.35$. Also, the stars 15 Mon, 10 Lac, and γ Ara have exceptionally strong narrow components of O VI, compared to their very weak P Cygni profiles. Such exceptions may be indicative of the possibility that more than one mechanism is responsible for the presence of narrow components in early-type stars.

The occurrence of more than one mechanism is the more likely, since detailed studies of a few stars showing narrow components in their spectra clearly required different explanations. We mention two examples, P Cygni and γ Cas. The visual and UV spectrum of P Cygni shows the presence of narrow components at three distinct velocities at -95, -160, and -210 km s^{-1}. The shell components at the first two velocities are constant over a period of about 60 yr, whereas the highest velocity component varies with a period of 114 d. The very long lifetime of these narrow components indicates that they are formed in stationary shells in the wind (de Groot 1969; Cassatella *et al.* 1979). The UV spectrum of γ Cas (B0.5 IV*e*) shows the occasional presence of narrow components in the C IV, Si IV, and N V lines. These components are observable over a period of a few weeks, during which time the velocity and profile changes are observed. A detailed study of the evolution of the profiles with time shows that these narrow components are due to shells ejected occasionally (about every few weeks) which are accelerated outward and can be observed during about two weeks (Henrichs, Hammerschlag-Hensberge, and Lamers 1980).

These two examples show that stationary shells do occur, at least in one star, and that shell ejection can explain the presence of narrow components, at least in some Be stars. With this in mind, we might speculate that the narrow components of the main-sequence stars such as 15 Mon and 10 Lac are possibly due to ejected shells, similar to the situation for γ Cas. The discrepancy between the very strong narrow components and the very weak underlying P Cygni profiles (contrary to the much smaller ratio observed in giants and supergiants) supports this explanation for these stars. The narrow components observed in the supergiants are possibly due to a two-component wind.

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