

THE EFFECTIVE TEMPERATURES OF HOT STARS. II. THE EARLY-O TYPES¹

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ABSTRACT

We derived the stellar parameters of a sample of Galactic early-O type stars by analyzing their UV and far-UV spectra from the *Far Ultraviolet Spectroscopic Explorer* (905–1187 Å), the *International Ultraviolet Explorer*, the *Hubble Space Telescope STIS*, and the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (1200–2000 Å). The data have been modeled with spherical, hydrodynamic, line-blanketed, non-LTE synthetic spectra computed with the WM-BASIC code. We obtain effective temperatures ranging from $T_{\text{eff}} = 41,000$ to 39,000 K for the O3–O4 dwarf stars and $T_{\text{eff}} = 37,500$ K for the only supergiant of the sample (O4 If⁺). Our values are lower than those from previous empirical calibrations for early-O types by up to 20%. The derived luminosities of the dwarf stars are also lower by 6%–12%; however, the luminosity of the supergiant is in agreement with previous calibrations within the error bars. Our results extend the trend found for later O types in a previous work by Bianchi & Garcia.

Subject headings: stars: early-type — stars: fundamental parameters — stars: mass loss — stars: winds, outflows — ultraviolet: stars

On-line material: color figures

1. INTRODUCTION

Hot massive stars have a great impact on the surrounding interstellar medium (ISM) and play a crucial role in the chemical evolution of galaxies. Their strong ultraviolet radiation is responsible for the ionization of nearby H II regions where their stellar winds blow vast bubbles. Their supersonic wind outflows and the supernova explosion at the end of their evolution transfer energy and momentum to the ISM and disperse the material processed in the stellar interiors, thus setting the conditions for the formation of subsequent generations of stars.

The determination of the physical parameters of massive stars is therefore of great interest, yet complicated. High-resolution spectroscopy is needed. Modeling the stellar atmosphere requires that we account for the expanding wind, the nonlocal thermodynamic equilibrium (non-LTE) conditions, and the so-called line-blanketing that modifies the flux distribution, especially at short wavelengths.

Spectroscopy in the ultraviolet and far ultraviolet ranges (hereafter UV and far-UV) is a powerful tool for studying the winds of massive stars since these spectral regions contain the resonance lines of the most abundant ions in the wind. In this work we analyze spectra from the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) (Moos et al. 2000), covering the 905–1187 Å region, in conjunction with spectra at longer wavelengths (1200–2000 Å) from the *International Ultraviolet Explorer* (*IUE*), the *Orbiting Retrievable Far and Extreme Ultraviolet Spectrometers* (*ORFEUS*), and the Space Telescope Imaging Spectrograph (*STIS*) on board

the *Hubble Space Telescope* (*HST*). The *FUSE* spectra allows us to uniquely constrain the stellar parameters by adding new ionization stages to those accessible to *IUE*, *ORFEUS*, and *HST/STIS* (e.g., Bianchi et al. 2000; Bianchi & Garcia 2002).

This is the second paper of a series devoted to providing accurate and consistent determination of the stellar parameters of Galactic massive stars with this method. Bianchi & Garcia (2002, hereafter Paper I) studied six mid-O type stars and found effective temperatures lower (by 15%–20%) than previously determined for the sample stars or calibrated for their spectral types. In this work we perform a similar analysis for early-O type stars. The paper is organized as follows. In § 2 we provide details about the data and the reduction. In § 3 we summarize the relevant information from the literature about the program stars. In § 4 we compare the spectral line characteristics. The stellar parameters are derived in § 5 by modeling the spectra. In § 6 the results are discussed.

2. DATA AND REDUCTION

For all the program stars we analyzed *FUSE* spectra (905–1187 Å) and UV archival spectra ($\lambda > 1200$ Å) from *IUE*. For a few objects we also used *ORFEUS* and *HST/STIS* archival data. The data sets used are listed in Table 1.

The *FUSE* data, taken through the LWRS aperture (30'' × 30''), have a resolution of $\lambda/\Delta\lambda \geq 20,000$. The data were processed with the pipeline (*CALFUSE*) version 2.0.5 (Dixon, Kruk, & Murphy 2001). All the LiF and SiC segments were examined to assure optimal centering of the spectra in the extraction window and to avoid data defects such as event bursts or the “worm” (Sahnou et al. 2000; Sahnou 2002). The good portions from different channels were combined, after the consistency of wavelength scale and flux level was checked, to achieve the maximum signal-to-noise ratio (S/N). The wavelength ranges 905–930 and 1181–1187 Å, at the ends of the *FUSE* range, have poor spectral quality and were not used in this work. The data in the 1082.5–1087 Å region

¹ Based on observations with the NASA-CNES-CSA *FUSE*, which is operated by The Johns Hopkins University under NASA contract NAS5-32985, on *IUE* observations from the MAST and INES archives and on MAST archival data from the *HST* and the *ORFEUS* mission.

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TABLE 1
DATA SETS USED IN THIS WORK

Star	<i>FUSE</i>	<i>IUE</i>	<i>HST/STIS</i>	<i>ORFEUS</i>
HD 190429A.....	P1028401	SWP 38994
HD 64568	P1221103	SWP 29337	...	...
HD 93250	P1023801	SWP 22106	...	...
HD 93205	P1023601	SWP 14747	O4QX 01010	...
HDE 303308.....	P1221602	SWP 07024	O4QX 04010	...
HD 96715	P1024301	SWP 43980, SWP 21999	...	tues5233_4
HD 168076	P1162201	SWP 28277	...	...

come entirely from the SiC channels; therefore the He II $\lambda 1084.9$ line was given a small weight in the analysis. The resulting combined spectra, normalized to the local continuum, are shown in Figure 1.

The *FUSE* wavelength range contains several absorption lines and bands of interstellar atomic and molecular hydrogen. In order to assess which features in the spectrum are purely stellar and to determine reliable continuum points for flux normalization, we calculated the H₂+H I absorption spectrum for the line of sight of each star. We used measurements of hydrogen column densities when available in the literature or, otherwise, we estimated the column density from color excesses using the relations from Bohlin, Savage, & Drake (1978): $N_{\text{H}}/E(B-V) = 5.8 \times 10^{21}$ atoms cm⁻² mag⁻¹, where $N_{\text{H}} = N_{\text{H I}} + 2N_{\text{H}_2}$, and $N_{\text{H I}}/E(B-V) = 4.8 \times 10^{21}$ atoms cm⁻² mag⁻¹. The hydrogen (H I+H₂) absorption models are plotted over the observed spectra in Figures 1, 3, 5, and 7.

We examined all the existing *IUE* observations of the program objects taken with the SWP camera (1150–1975 Å), using the on-line tools of the MAST archive, to check for variability and to exclude saturated portions, and chose the data with the best S/N. High-dispersion *IUE* spectra ($\Delta\lambda \approx 0.2$ Å) are available for all objects except for HD 64568, for which only a low-dispersion spectrum ($\Delta\lambda \approx 6$ Å) exists. We then downloaded the selected spectra from the INES archive (Wamsteker et al. 2000) because the data typically have a better background correction at wavelengths shorter than 1400 Å than the data in the MAST archive. We additionally used *HST/STIS* spectra (0'2 × 0'09 aperture and E140H grating, 1150–1700 Å, $\lambda/\Delta\lambda = 114,000$) for two objects and *ORFEUS/TUES* spectra (900–1400 Å, $\lambda/\Delta\lambda = 10,000$) for one program object. These data were downloaded from the MAST archive. The normalized spectra in the UV range that contains the strongest spectral lines (1200–1750 Å) are shown in Figure 2.

3. THE PROGRAM STARS

We performed an exhaustive literature search about the program stars and collected all data useful to this study. In particular, we searched for reliable spectral classifications and information about multiplicity and the environment of the stars. Table 2 compiles the spectral classification and other relevant data, including the hydrogen column densities in the line of sight of each object. A discussion on the individual objects is given in the following section.

3.1. HD 190429A

HD 190429 is a multiple system that belongs to the Cygnus OB3 association. HD 190429A has three companions (B, C, and D) located at 1'7, 42'5, and 29'0, respectively (Abt 1986); therefore only the B component is included in the *FUSE*

and *IUE* large apertures. The D component may be at the edge of the *FUSE*/LWRS slit, but it is considerably fainter than HD 190429A ($\Delta V \sim 4$; Abt 1986). Mason et al. (1998) report a companion of HD 190429A at a 0'09 distance, but we found no further information on this object.

For HD 190429A we adopt a spectral type of O4 If⁺ (Walborn 1972, 1973) and O9.5 II for the B component (Walborn & Howarth 2000). The luminosity class of the secondary varies in the literature from Ibp (Morgan, Code, & Whitford 1955) to III (Abt 1986; Conti & Leep 1974; Guetter 1968). In § 5.2 we estimate that its contribution to the total flux amounts to 15% at most. We examined the 16 large-aperture high-resolution *IUE* spectra of HD 190429A taken with the SWP camera. Since we found no significant variation in the flux levels and the line profiles, we include this object in our analysis. The study of HD 190429A is of particular interest, because it is the only supergiant star earlier than O5 observed with *FUSE* except for HD 93129A (O2If*), which also belongs to a binary system.

The *IUE* spectrum of HD 190429A shows characteristics intermediate between O3 If* and O5 If⁺ in the UV morphological sequence described by Walborn & Nichols-Bohlin (1987). Conti, Hanson, & Morris (1995) concur that the UV spectral morphology of HD 190429A is typical of an O4–O5 If⁺ star but found that its IR spectrum (*K* band) resembles that of a Wolf-Rayet star, indicating the presence of a strong wind. Morris et al. (1996) obtained similar results. Walborn & Howarth (2000) found that the emission of H α and He II $\lambda 4686$ in HD 190429A is stronger than in other O3–O5 If⁺ stars, again suggesting that HD 190429A is evolving to the WN stage. However, the mass-loss rate that we derive (§ 5) is consistent with that predicted by the radiation pressure–driven wind theory (§ 6).

3.2. HD 64568

HD 64568 belongs to NGC 2467/Puppis OB2 (Havlen 1972) and is one of the ionizing stars of the irregular H II region Sh 2-311 (Sharpless 1959). HD 64568 is a primary standard for the O3 V((f*)) type in the recent revision of the spectral classification of early-type objects by Walborn et al. (2002b), based on optical spectra. We adopt this spectral classification, although other works are discrepant: MacConnel & Bidelman (1976), Crampton (1971), Cruz-Gonzalez et al. (1974), and Lodén (1965) classify HD 64568 as O5; Houk & Smith-Moore (1988) as O5/6. None of these works provided luminosity class. Garrison, Hiltner, & Schild (1977) classified the star as O4 V((f)) and Peton-Jonas (1981) as O5 V. The UV and far-UV spectral morphology is consistent with the O3 V((f*)) classification.

We did not find conclusive reports about binarity. Solievella & Niemela (1986) analyzed medium dispersion CTIO spectra

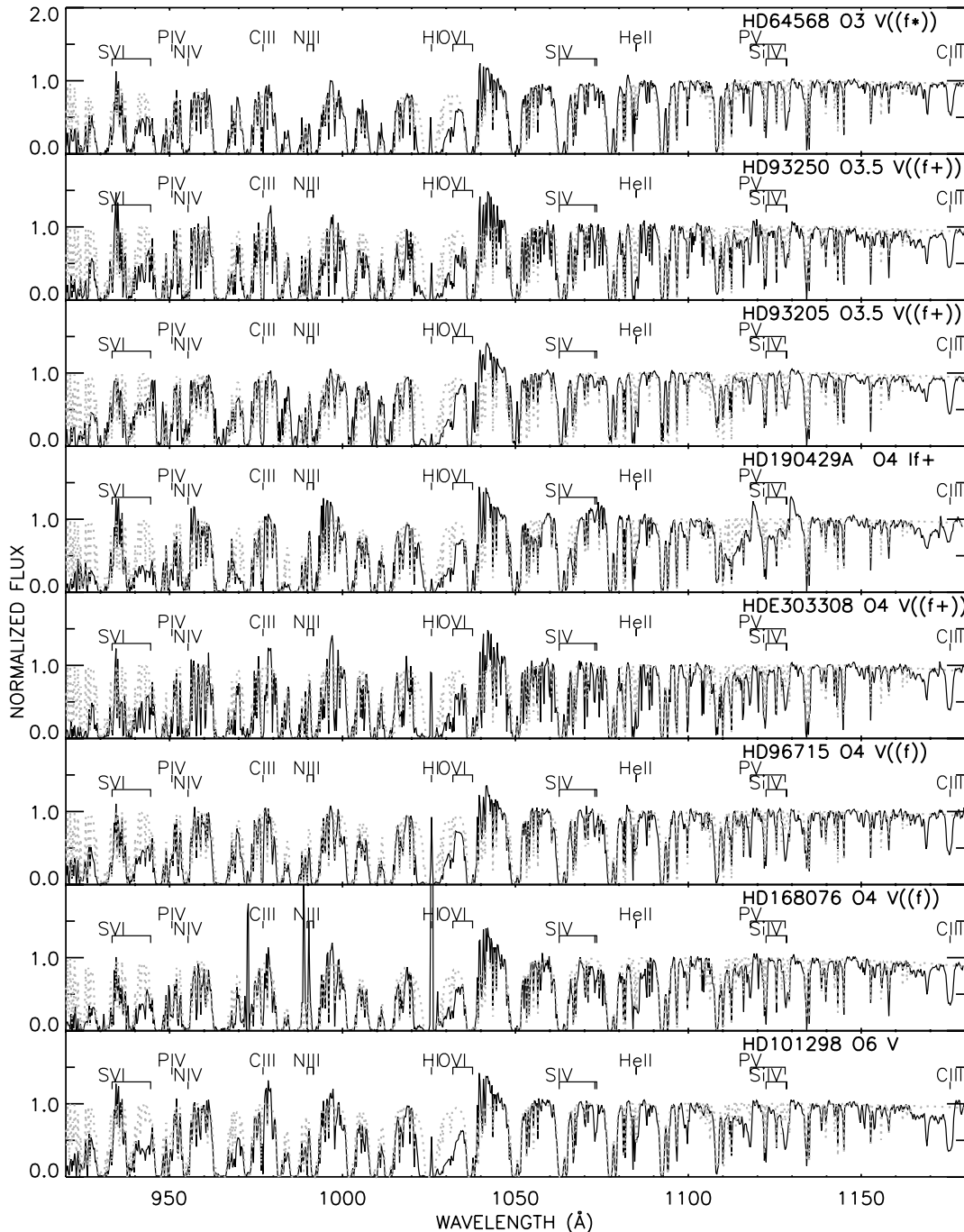


FIG. 1.—*FUSE* spectra of the O3–O4 type stars analyzed in this paper and HD 101298 (O6 V, analyzed in Paper I), arranged by spectral type. The spectra are rebinned to steps of 0.25 Å for clarity and normalized to the local continuum. The light-gray dotted lines are interstellar hydrogen ($H_2+H\ I$) absorption models, calculated for the line of sight of each star (see § 2), that aid us to identify the genuine stellar features against the interstellar ones. Note the stronger profiles that $P\ V\ \lambda\lambda 1118.0, 1128.0 + Si\ IV\ \lambda\lambda 1122.5, 1128.3, 1128.4$, and $C\ IV\ \lambda 1169 + C\ III\ \lambda 1176$ exhibit in the spectrum of the supergiant star. The dwarf stars have very similar spectral features, but there is a smooth increase of $C\ III\ \lambda 1176$ and $P\ V\ \lambda\lambda 1118.0, 1128.0 + Si\ IV\ \lambda\lambda 1122.5, 1128.3, 1128.4$ from O3 V to O6 V. [See the electronic edition of the *Journal* for a color version of this figure.]

and found radial velocity variations but could not determine whether they are due to binarity or to instabilities in the atmosphere. Crampton (1972) obtained several measurements of the radial velocity and found a maximum variation of 10 km s^{-1} .

3.3. HD 93250

HD 93250 is located in the Carina Nebula (NGC 3372), an $H\ II$ region consisting of four lobes ionized by several stellar

clusters, including Trumpler 14 and Trumpler 16 (Tr 14 and Tr 16). HD 93250 belongs to Tr 16. We adopt the spectral type O3.5 V((f+)) from Walborn et al. (2002b). Other authors agree that HD 93250 is a dwarf star (O3 V((f)) (Walborn 1971a, 1982), O3:V((f)) (Levato & Malaroda 1982), and O3 V(f) (Thackeray & Andrews 1974)). However, HD 93250 is one of the brightest stars in the Carina complex ($V = 7.37$; Feinstein 1982). Conti & Frost (1977) found evidence of a luminosity class higher than V and classified the star as

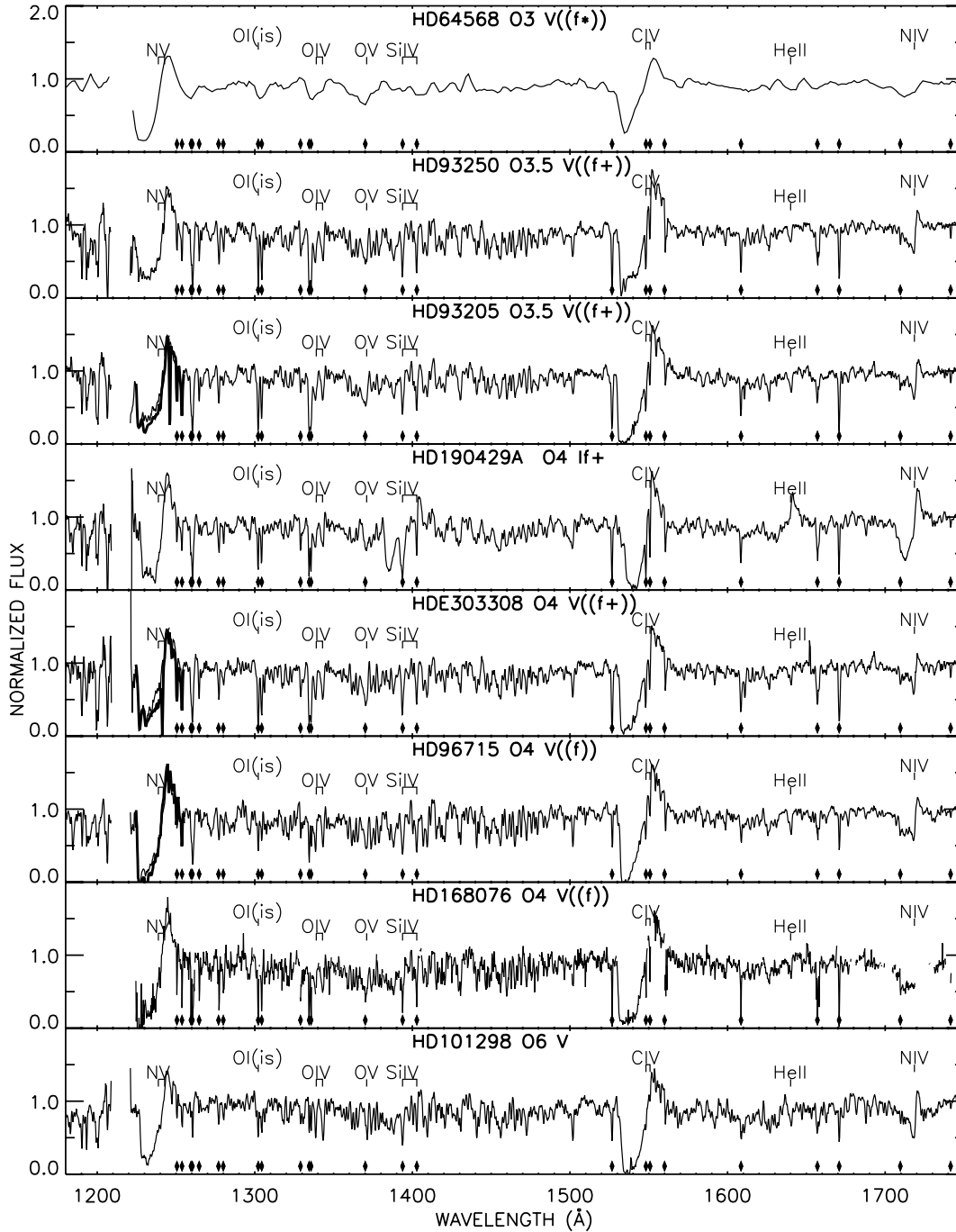


FIG. 2.—Normalized *IUE* spectra of the stars included in Fig. 1. The spectra are rebinned to 0.25 Å, except for the spectrum of HD 64568, which has low resolution (6 Å). The positions of the most important interstellar lines are marked with diamonds at the bottom of the spectra. The *IUE* data have very poor quality in the Ly α region, which has been removed for clarity. The saturated portions have been removed from the spectrum of HD 168076. The thick lines plotted over the spectra in the N v $\lambda\lambda$ 1238.8, 1242.8 region are *ORFEUS/TUES* data for HD 96715 and *HST/STIS* data for HDE 303308 and HD 93205. Note that the Si iv $\lambda\lambda$ 1393.8, 1402.8 absorption weakens toward earlier spectral types. N iv $\lambda\lambda$ 1718.0, 1718.5 and O v λ 1371.0, and to a lesser extent, C iv $\lambda\lambda$ 1548.2, 1550.8 increase from the O6 V to the O3.5 V stars. The most important luminosity effects are the stronger He II λ 1640.0, Si iv $\lambda\lambda$ 1393.8, 1402.8, and N iv $\lambda\lambda$ 1718.0, 1718.5 P Cygni profiles of the supergiant spectra.

O3 (providing no luminosity class). According to Mathys (1988), the star is a giant (O3 III(f)), and Penny, Gies, & Bagnuolo (1996) classified it as a supergiant (O3 I) on the basis of its UV spectrum. We find that the *FUSE* spectrum (see Fig. 1) does not display the characteristic signatures of supergiants, i.e., the S iv $\lambda\lambda$ 1062.7, 1073.0, 1073.5 and P v $\lambda\lambda$ 1118.0, 1128.0 P Cygni profiles (see Paper I and Figs. 1 and 3 of this paper), supporting the luminosity class V.

On the other hand, the radius that we derive from line fitting (see § 5.1.2) is larger than for the other O3.5 V((f+)) star of the sample, consistent with the higher luminosity of HD 93250.

Walborn & Panek (1984) studied the UV-morphology of the early-type dwarf stars and found no anomaly in the *IUE* spectrum of HD 93250, except for the unsaturated profile of C iv $\lambda\lambda$ 1548.2, 1550.8. They suggested that an unresolved

TABLE 2
THE PROGRAM STARS

Star	Spectral Type ^a	Spectral Type Reference	V	$B-V$	$E(B-V)^b$	$\log N_{\text{H I}}^c$ (cm^{-2})	$\log N_{\text{H}_2}^d$ (cm^{-2})	Distance (Kpc)
HD 190429A.....	O4 If⁺ ; O4 f; O4 I O5 If+O9.5 III+B1 IIIs O4f+O9.5III; O4If ⁺ +O9.5 II O5f+B0III; O5f+O9.5Ibp	1, 2, 3; 4; 5 8 9, 10; 11 12; 13	7.07 (6)	0.09 (6)	0.41	21.29	20.31	2.3 (7)
HD 64568	O3 V((f*)) ; O4 V ((f)); O5 V O5; O5/6	14, 1; 15; 16 19, 20, 21, 22; 23	9.39 (17) ...	0.11 (17) ...	0.44 ...	21.32 ...	20.34 ...	5.5 (18) ...
HD 93250	O3.5 V((f*)) ; O3 V((f)); O3:V((f)); O3 V(f) O3 I; O3 III(f); O3; O5	1; 2, 14, 21, 24; 25; 26 5; 29; 4; 13	7.37 (27) ...	0.17 (27) ...	0.50 ...	21.38 ...	19.92/19.94 ^e (28) ...	2.5 (25) ...
HD 93205	O3.5 V((f*)) ; O3 V; O3 O3 V+O8 V	1; 14, 21, 2, 25, 24, 26; 4 32, 33	7.75 (30) ...	0.05 (30) ...	0.38 ...	21.33 (31) ...	19.52 ...	2.5 (25) ...
HDE 303308.....	O4 V((f*)) ; O4 V((f)) O3 V; O3 V((f)); O3 V(f); O3	1; 29 24, 2; 3, 14, 21, 25; 26; 4	8.15 (27) ...	0.12 (27) ...	0.45 ...	21.45 (31) ...	19.99/19.81 ^e (28) ...	2.5 (25) ...
HD 96715	O4 V((f)) ; O4 V; O5:	3, 21; 2, 15; 26	8.27 (34)	0.10 (34)	0.43	21.31	20.33	2.9 (3)
HD 168076	O4 V((f)) ; O4 V((f ⁺)); O5 V((f*)) O4 ((f)); O4f; O5; O4 III(f)	3; 35; 36 10, 4; 9; 13, 23; 29	8.18 (36) ...	0.43 (36) ...	0.75 (36) ...	19.67/21.65 ^f (37) ...	20.32/20.43 ^f (37) ...	2.0 (36) ...

^a Adopted types in bold face; other values from the literature are compiled. For multiple systems we also list here the spectral type of the companion(s) (if known).

^b If no reference is provided, calculated from $B-V$ (this table) and $(B-V)_0$ (from Massey 1998).

^c If no reference is provided, $N_{\text{H I}}$ is derived from the relation of Bohlin et al. 1978, using $E(B-V)$ from this table.

^d If no reference provided, $N_{\text{H}_2} = 0.5(N_{\text{H}} - N_{\text{H I}})$ and $N_{\text{H}}/E(B-V) = 5.8 \times 10^{21}$ atoms cm^{-2} mag⁻¹ (Bohlin et al. 1978), $E(B-V)$ from this table.

^e Column densities of the foreground cloud (first value) and the Carina Nebula (second value).

^f Column densities of the translucent component of the hydrogen cloud (first value) and of the diffuse component (second value).

REFERENCES.—(1) Walborn et al. 2002b; (2) Walborn 1972; (3) Walborn 1973; (4) Conti & Frost 1977; (5) Penny et al. 1996; (6) ten Brummelaar et al. 2000; (7) Morgan, Whitford, & Code 1953; (8) Abt 1986; (9) Conti & Alschuler 1971; (10) Conti & Leep 1974; (11) Walborn & Howarth 2000; (12) Guetter 1968; (13) Morgan et al. 1955; (14) Walborn 1982; (15) Garrison et al. 1977; (16) Peton-Jonas 1981; (17) Havlen 1972; (18) Kaltecheva & Hilditch 2000; (19) MacConnel & Bidelman 1976; (20) Crampton 1971; (21) Cruz-Gonzalez et al. 1974; (22) Lodén 1965; (23) Houk & Smith-Moore 1988; (24) Walborn 1971a; (25) Levato & Malaroda 1982; (26) Thackeray & Andrews 1974; (27) Feinstein 1982; (28) Lee et al. 2000; (29) Mathys 1988; (30) Feinstein, Marraco, & Muzzio 1973; (31) Diplas & Savage 1994; (32) Conti & Walborn 1976; (33) Morrell et al. 2001; (34) Schild, Garrison, & Hiltner 1983; (35) Bosch, Morrell, & Niemelä 1999; (36) Hillenbrand et al. 1993; (37) Rachford et al. 2002.

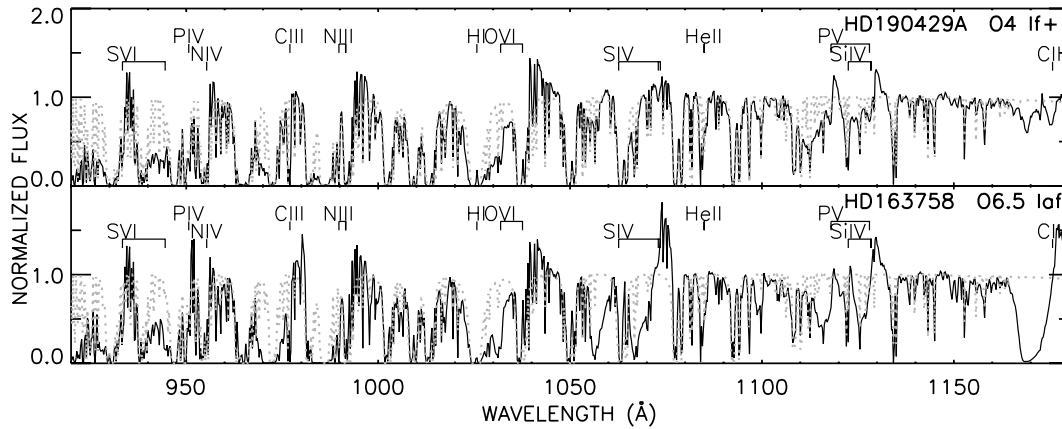


FIG. 3.—Temperature effects in luminosity class I: *FUSE* spectra of the supergiant stars HD 190429A (O4 If⁺) and HD 163758 (O6.5 Iaf, from Paper I) (lines are as in Fig. 1). The strength of S iv $\lambda\lambda$ 1062.7, 1073.0, 1073.5 and C iv λ 1169 + C iii λ 1176 severely decreases toward higher T_{eff} . Note also that the wind profile of the P v $\lambda\lambda$ 1118.0, 1128.0 + Si iv $\lambda\lambda$ 1122.5, 1128.3, 1128.4 blend changes in shape, whereas the O vi $\lambda\lambda$ 1031.9, 1037.6 P Cygni profile is almost identical in both spectra. [See the electronic edition of the *Journal* for a color version of this figure.]

later type companion could be a possible explanation. Levato et al. (1991) measured a constant heliocentric radial velocity and concluded that the star is not a binary; no companion was found in the speckle interferometric survey of Mason et al. (1998). We discuss this point further in § 5.1.2.

3.4. HD 93205

HD 93205 is part of a multiple system, again located in the Tr 16 cluster. HD 93205 is a spectroscopic binary with additionally a visual companion (HD 93204, O5 V) at a 18".7 distance (Mason et al. 1998), which may be included in the *FUSE*/LWRS aperture, but not in the *IUE* large aperture. The primary component of the HD 93205 system is consistently classified in the literature as O3 V (see Table 2) but has been revised to O3.5 V((f⁺)) by Walborn et al. (2002b), which we adopt. Conti & Walborn (1976) and Morrell et al. (2001) provided spectral classification for both components of the system: O3 V+O8 V.

The question whether HD 93205 is an eclipsing binary is not settled. From the inclination angle ($i \simeq 45^\circ - 53^\circ$; Conti & Walborn 1976) no eclipses are expected. Antokhina et al. (2000) found photometric variability in the system of a maximum of ~ 0.02 , which they explained with a nonuniform brightness distribution. The latest photometric study (van Genderen 2003) suggests instead that the light-curve variations (amplitude 0.02) are due to eclipses. The only large-aperture *IUE* spectra, SWP 14747 and SWP 07959, were taken at phases $\Phi = 0.78$ and $\Phi = 0.28$ (calculated using the orbital parameters from Stickland & Lloyd 1993); the orbital positions of the secondary at these phases are equivalent for the observer and, in fact, the spectrum does not vary.

The *FUSE* and *IUE* spectra of HD 93205 look very similar to those of HDE 303308 (which has a similar spectral type), and the wind lines clearly originate from the O3.5 V((f⁺)) star, while the secondary component (O8 V) may contribute to the continuum. The spectral analysis shows that this contribution is of the order of 15% or less (see § 5.1.1).

3.5. HDE 303308

HDE 303308, located 1' north of η Carinae, also belongs to the Tr 16 cluster in the Carina Nebula. We adopt the spectral

classification of Walborn et al. (2002b), O4 V((f⁺)), although the star has been previously classified as O3 dwarf (see Table 2). Speckle interferometry indicates that HDE 303308 is a single star (Mason et al. 1998). Levato et al. (1991) report variability of the radial velocity but could not determine whether the star belongs to a binary system. Stickland & Lloyd (2001) measured the radial velocity from three *IUE* spectra and found no significant changes. Van Genderen et al. (1989) did not find any photometric variations.

3.6. HD 96715

HD 96715 belongs to the Carinae OB2 association, rich in luminous massive stars. The spectral classifications throughout the literature are in general agreement. We adopt O4 V((f)) (Walborn 1973; Cruz-Gonzalez et al. 1974); other similar classifications are listed in Table 2. HD 96715 is a blue straggler and displays an unusually strong N iii λ 4514 line for its early type that may indicate nitrogen enrichment (Schild & Berthet 1986). There are no studies on binarity.

For this star we use a combination of two large-aperture *IUE* spectra out of eight available in the archive. We use SWP 43980 for $\lambda < 1700$ Å, which has the best S/N in this spectral region, but it is saturated for $\lambda > 1700$ Å, where we use SWP 21999.

3.7. HD 168076

HD 168076 is a member of the young open cluster NGC 6611 (Walker 1961), located near the outermost part of the Sagittarius-Carina spiral arm. The spectral classification we adopt is O4 V((f)) (Walborn 1973). Other authors provide similar classifications (see Table 2) except for Mathys (1988): O4 III(f) and Hillenbrand et al. (1993): O5 V((f*)). Rachford et al. (2002) studied the line of sight of HD 168076 from its *FUSE* spectra and calculated the column densities of H I and H₂ (listed in Table 2) that we use in this analysis.

HD 168076 is a visual binary. Duchêne et al. (2001) resolved the components with a high angular resolution (0".035) adaptive optics system and estimated a separation of ~ 0.15 and a difference in magnitude of $\Delta K = 1.57$. However, the line spectrum of HD 168076, very similar to the spectra of the other O4 dwarf stars in the sample, is apparently dominated in the far-UV and UV ranges by the lines from the hot component.

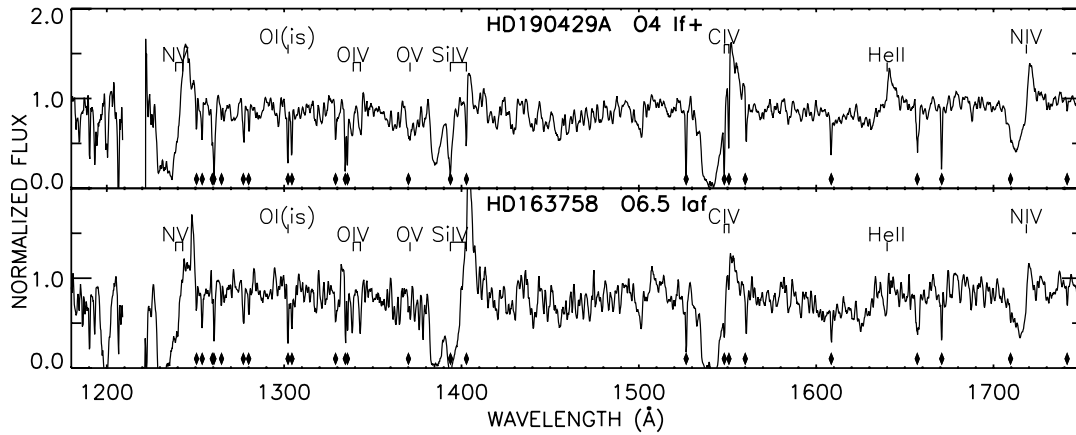


FIG. 4.—*IUE* spectra of HD 190429A and HD 163758 (lines and symbols are as in Fig. 2). The most outstanding differences are seen in the Si iv $\lambda\lambda$ 1393.8, 1402.8 doublet and the He ii λ 1640.0 line. N iv $\lambda\lambda$ 1718.0, 1718.5 and the emission of C iv $\lambda\lambda$ 1548.2, 1550.8 are stronger in the earlier type star.

There is only one high-dispersion *IUE* spectrum of this object. It has some saturated portions, removed from the plots in Figures 2 and 6 and not considered in the analysis.

4. ANALYSIS OF THE SPECTRAL MORPHOLOGY

Examination of the UV and far-UV spectra of the sample stars reveals the correspondence of the line morphology in this spectral region with the spectral classifications derived from the optical range. The general behavior of the spectral lines as a function of spectral type and luminosity class has been described in a number of atlases, both in the *IUE* range (Walborn, Nichols-Bohlin, & Panek 1985) and in the *FUSE* range (Pellerin et al. (2002) for Galactic stars; Walborn et al. (2002a) for Magellanic Cloud stars). In this section we provide a more detailed discussion of the spectral morphology within the spectral types covered in this work and Paper I. In the quantitative spectral modeling (§ 5) the observed line variations will be explained in terms of physical parameters.

4.1. Luminosity Effects at O4

The *FUSE* and *IUE* spectra of the O4 type stars are shown in Figures 1 and 2. The sample consists of one supergiant star (HD 190429A) and three dwarf stars (HDE 303308, HD 96715, and HD 168076). The *FUSE* satellite has not observed any giant star of type O4 (or earlier) yet.

The most prominent variations among luminosity classes are the different strength of P v $\lambda\lambda$ 1118.0, 1128.0 in the *FUSE* range and Si iv $\lambda\lambda$ 1393.8, 1402.8, He ii λ 1640, and N iv $\lambda\lambda$ 1718.0, 1718.5 in the *IUE* range. P v $\lambda\lambda$ 1118.0, 1128.0, Si iv $\lambda\lambda$ 1393.8, 1402.8, and He ii λ 1640 display wind profiles in the spectrum of the supergiant star but are photospheric absorptions in the dwarf stars. S iv $\lambda\lambda$ 1062.7, 1073.0, 1073.5, which shows a P Cygni profile in HD 190429A (although severely masked by interstellar hydrogen absorption), and C iv λ 1169 + C iii λ 1176 change similarly. The behavior of these lines is similar to what we found for mid-O types (Paper I), and it is caused by the mass-loss rate variation with luminosity. In the present sample, the S iv $\lambda\lambda$ 1062.7, 1073.0, 1073.5 and C iv λ 1169 + C iii λ 1176 profile changes are not as remarkable as in later types because these lines are much less conspicuous owing to the higher T_{eff} .

Note that O vi $\lambda\lambda$ 1031.9, 1037.6 displays a well-developed P Cygni profile of similar strength at all luminosity classes, as already seen in mid-O type stars (Paper I). Similarly, the

lines of other high-ionization species, N v $\lambda\lambda$ 1238.8, 1242.8 and C iv $\lambda\lambda$ 1548.2, 1550.8, do not vary appreciably because they are saturated.

4.2. Temperature Effects

We find systematic line variations when we compare the spectra of the O3–O4 type stars analyzed in this paper with the later type stars from Paper I. Despite their many similarities, the spectra of O3–O6 dwarf stars in Figures 1 and 2 display clear T_{eff} effects. Notably, C iv λ 1169 + C iii λ 1176 and P v $\lambda\lambda$ 1118.0, 1128.0 + Si iv $\lambda\lambda$ 1122.5, 1128.3, 1128.4 decrease toward earlier types. In the *IUE* range, the weaker Si iv $\lambda\lambda$ 1393.8, 1402.8 and stronger N iv $\lambda\lambda$ 1718.0, 1718.5, O v λ 1371.0, and C iv $\lambda\lambda$ 1548.2, 1550.8 also indicate higher T_{eff} .

The line variations with spectral type are more remarkable in the supergiants, as wind features are more developed in their spectra. When we compare the *FUSE* spectra of O4 and O6.5 supergiants (see Fig. 3) we find the latter to have stronger S iv $\lambda\lambda$ 1062.7, 1073.0, 1073.5 and C iv λ 1169 + C iii λ 1176, whereas O vi $\lambda\lambda$ 1031.9, 1037.6 does not vary. P v $\lambda\lambda$ 1118.0, 1128.0 has a P Cygni profile in both stars, however with different shapes, indicating a different ionization structure in the wind.

In the *IUE* range (see Fig. 4), the lines showing the largest variation are Si iv $\lambda\lambda$ 1393.8, 1402.8 and He ii λ 1640. The strength of Si iv $\lambda\lambda$ 1393.8, 1402.8 drastically decreases from HD 163758, where it is a fully developed P Cygni profile, to HD 190429A. The spectrum of HD 190429A displays a strong emission of He ii λ 1640.0, characteristic of O3–O5 If stars (Walborn et al. 1985; Walborn & Nichols-Bohlin 1987). N iv $\lambda\lambda$ 1718.0, 1718.5 and the emission of C iv $\lambda\lambda$ 1548.2, 1550.8 increase from type O6.5 to O4. The strength of the feature at 1500 Å, which we believe to be a S v line possibly contaminated with Si iii lines (see Paper I), is approximately the same in both spectra. The absorption line of O v λ 1371.0 is present only in the spectra of the hotter star, HD 190429A.

5. QUANTITATIVE SPECTRAL MODELING

In this section we determine the photospheric and wind parameters of the sample stars by fitting their far-UV and UV spectra with spherical, hydrodynamic, line-blanketed, non-LTE synthetic models. The models were calculated with the version 2.11 of the WM-BASIC code (Pauldrach, Hoffmann, & Lennon 2001), but have the “solar” abundances of the

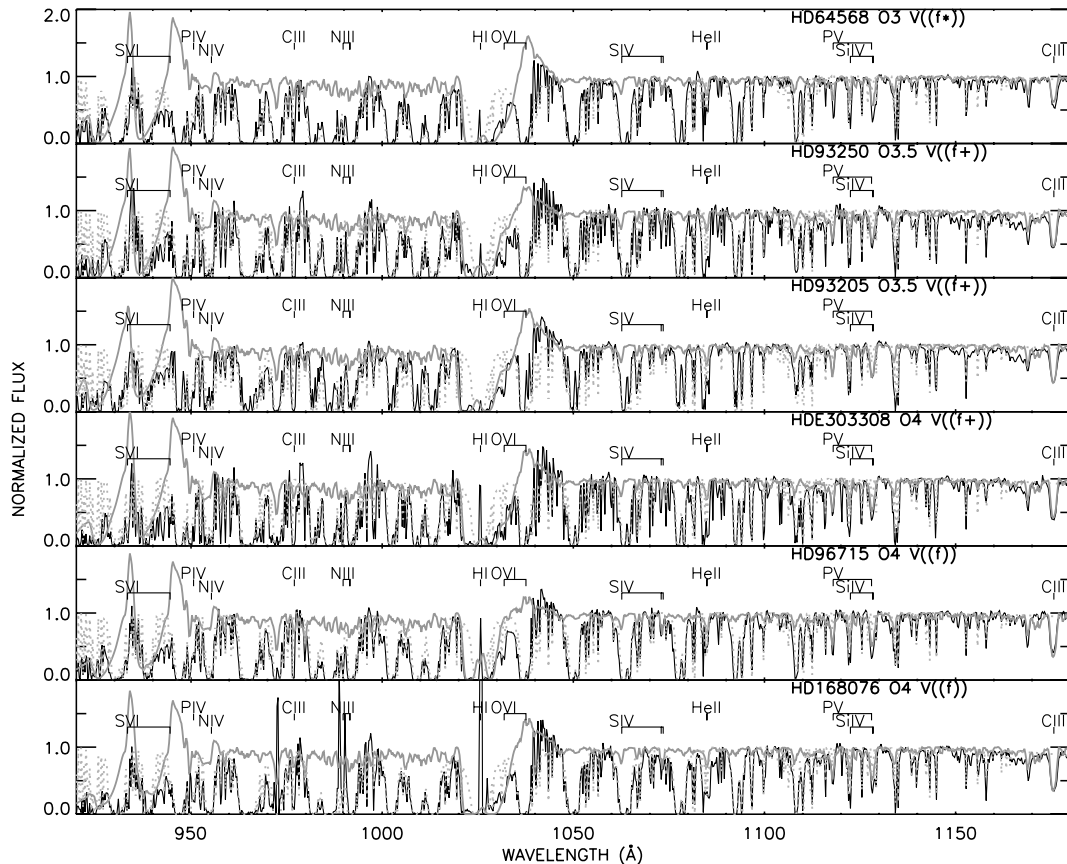


FIG. 5.—Best-fit WM-BASIC models (*gray*) and *FUSE* spectra (*black*) of the dwarf stars of the sample. Models and spectra have been rebinned to 0.25 \AA steps. The dotted (light-gray) line is the interstellar $\text{H}_2+\text{H I}$ absorption model in the line of sight of each star. The T_{eff} of the models increases from 39,000 K (HD 160876 and HD 96715) to 40,000 K (HDE 303308, HD 93205, and HD 93250) and to 41,000 K (HD 64568). Note the good fit to C III $\lambda 1176$ and P V $\lambda \lambda 1118.0, 1128.0+\text{Si IV } \lambda \lambda 1122.5, 1128.3, 1128.4$, the best indicators of temperature in this spectral range. [See the electronic edition of the *Journal* for a color version of this figure.]

previous version (WM-BASIC 1.22) for consistency with the grid of models constructed for Paper I.

Our study takes into account the effects of shocks in the wind. Shocks produce soft X rays in the expanding atmosphere that affect the ionization of several species, most remarkably O VI and N V. By modeling the lines of highly ionized atoms in the *FUSE* and *IUE* ranges consistently with the other spectral features, we can determine the value of the parameter L_X/L_{bol} and thus provide a unique solution for the stellar parameters (T_{eff} , $\log g$, R_* , v_∞ , and \dot{M}).

We have built a vast grid of WM-BASIC models which—by comparison with the observed spectra—provides upper and lower limits of the stellar parameters. The final values and their uncertainties are obtained by computing models that refine the grid within the range of interest for each observed spectrum. In the following section we provide further details of the fitting process. The best-fit models are shown in Figures 5–7. The derived stellar parameters are compiled in Table 3.

5.1. The Dwarf Stars

The spectra of the dwarf stars are mostly similar, except for subtle line variations (see § 4.2). Therefore we follow a similar procedure to fit their spectra, which we explain in this section. The analysis of HD 93250 and HD 64568 is slightly different, and the details are given in §§ 5.1.2 and 5.1.3.

We learned from our grid of models that P V $\lambda \lambda 1118.0, 1128.0$, C IV $\lambda 1169+\text{C III } \lambda 1176$, O V $\lambda 1371.0$, and N IV

$\lambda \lambda 1718.0, 1718.5$ are good temperature indicators in the interval of T_{eff} of 38,000–42,000 K (enclosing the temperatures of our sample, as we will see) and mass-loss rates of 10^{-7} to $10^{-6} M_\odot \text{ yr}^{-1}$; we initially assumed $\log g = 4$ and $R_* = 9 R_\odot$, adequate for luminosity class V. In this range of parameters, P V $\lambda \lambda 1118.0, 1128.0$ and C IV $\lambda 1169+\text{C III } \lambda 1176$ decrease with temperature; both lines are photospheric and therefore insensitive to changes of \dot{M} and L_X/L_{bol} . The strength of N IV $\lambda \lambda 1718.0, 1718.5$ increases with T_{eff} and \dot{M} and marginally decreases with higher L_X/L_{bol} . O V $\lambda 1371.0$ has a hard threshold and forms only in models with $T_{\text{eff}} \geq 40,000$ K (independently of shocks and mass-loss rate), thus providing an upper limit to the temperature of stars not displaying this line. When O V $\lambda 1371.0$ is present in the stellar spectrum, its strength varies similarly to N IV $\lambda \lambda 1718.0, 1718.5$ and helps us constrain L_X/L_{bol} and \dot{M} .

We can set solid limits to the interval of possible temperatures of the dwarf stars, based on the strength of these lines in their spectra. HD 64568, HD 93250, HD 93205, and HDE 303308 must have a temperature higher or equal than 40,000 K since their spectra display the O V $\lambda 1371.0$ line. For these stars, the upper limit to T_{eff} is 42,000 K, because at higher temperatures (in the range of \dot{M} set above), O V $\lambda 1371.0$ becomes a fully developed P Cygni profile in the models, not seen in any stellar spectra, and N IV $\lambda \lambda 1718.0, 1718.5$ is not as strong as observed. O V $\lambda 1371.0$ is absent in the spectra of HD 96715 and HD 168076; thus their temperature must be below 40,000 K. The lower limit to the

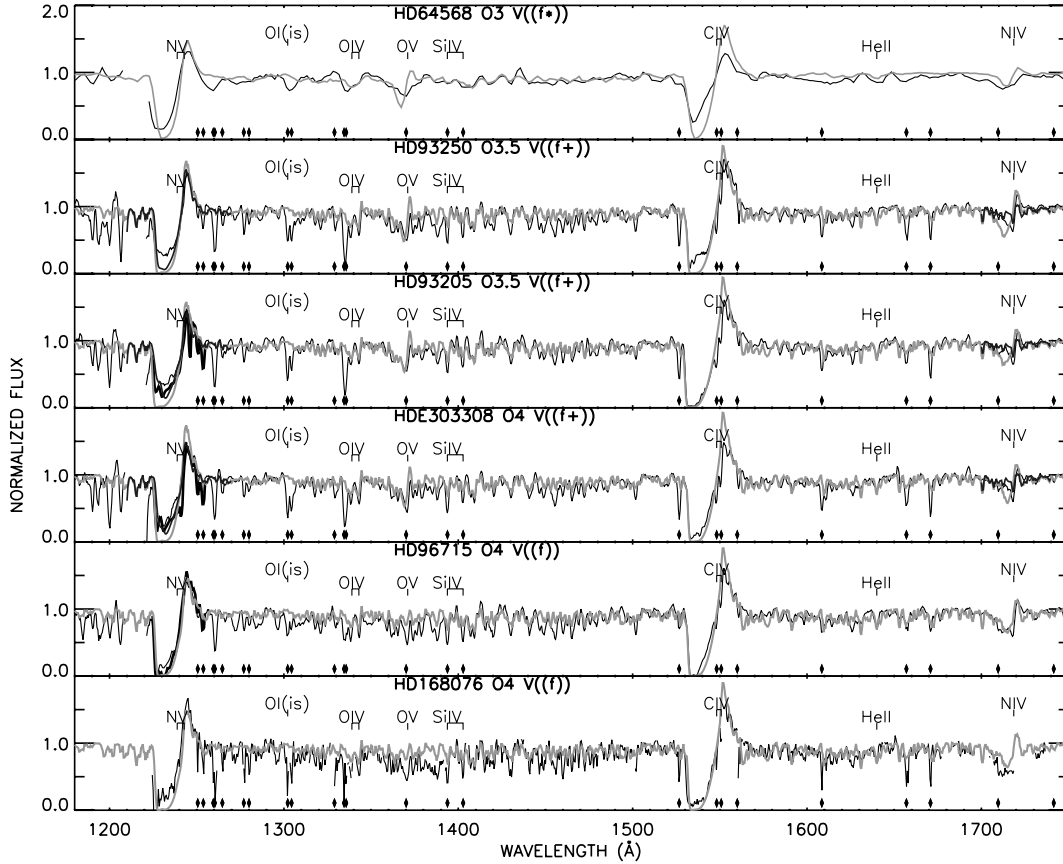


FIG. 6.—Same as Fig. 5, but for the *IUE* range. For HD 93250, HD 93205, and HDE 303308 we also include in dark gray the best-fit model with an underabundance of nitrogen ($\epsilon_N = 0.1\epsilon_{N,\odot}$) in the spectral regions around N v $\lambda\lambda$ 1238.8, 1242.8 and N iv $\lambda\lambda$ 1718.0, 1718.5 (the rest of the model is identical to that with solar abundances). The observed and synthetic spectra have been rebinned to 0.5 Å steps, except for HD 64568 (model rebinned to 6 Å). Other lines and symbols have the same meaning as in Fig. 2. The best T_{eff} indicators in this range are N v $\lambda\lambda$ 1718.0, 1718.5 and O v λ 1371.0, which we successfully fit for all stars but HD 168076. The unsaturated N v $\lambda\lambda$ 1238.8, 1242.8 profiles are discussed in the text. The model fits well the *ORFEUS* spectrum of HD 96715. [See the electronic edition of the *Journal* for a color version of this figure.]

temperature of these stars is established with P v $\lambda\lambda$ 1118.0, 1128.0 and secondarily with C iv $\lambda\lambda$ 1548.2, 1550.8. P v $\lambda\lambda$ 1118.0, 1128.0 displays a wind profile (discrepant with the observed photospheric profile) in the models with $T_{\text{eff}} \leq 37,000$ K. In the 38,000–42,000 K range, all our models have an excess emission of C iv $\lambda\lambda$ 1548.2, 1550.8 (with respect to the observations) but successfully fit the observed absorptions; however, at $T_{\text{eff}} \leq 37,000$ K the profile of the absorption changes (for any mass-loss rate) and does not fit the spectrum.

The T_{eff} of each object is determined from the best fit to the C iv λ 1169+C iii λ 1176 and P v $\lambda\lambda$ 1118.0, 1128.0 lines. We find $T_{\text{eff}} = 41,000$ K for HD 64568, $T_{\text{eff}} = 40,000$ K for HD 93250, HD 93205, and HDE 303308, and $T_{\text{eff}} = 39,000$ K for HD 96715 and HD 168076. The error bars given in Table 3 (± 2000 K) are larger than the range of acceptable temperatures of each object indicated by the spectra, because they also account for systematic errors, such as the uncertainty introduced by the flux normalization and the possible contribution by companions ($<15\%$; see below) in some cases.

Once we delimit the effective temperature, we proceed to derive \dot{M} . Most of the lines useful for this purpose in the analysis of mid-O type stars (P v $\lambda\lambda$ 1118.0, 1128.0, C iv λ 1169+C iii λ 1176, N v $\lambda\lambda$ 1238.8, 1242.8, and C iv $\lambda\lambda$ 1548.2, 1550.8) are insensitive to the variation of \dot{M} at the high temperatures of the early-O stars. The mass-loss rate

is then determined with the aid of the less prominent O v λ 1371.0, N iv $\lambda\lambda$ 1718.0, 1718.5, and Si iv $\lambda\lambda$ 1393.8, 1402.8 (increasing with higher \dot{M}), and secondarily with O vi $\lambda\lambda$ 1031.9, 1037.6 (decreasing with higher \dot{M}). For each object, the lower/upper limits to mass-loss rate are set to the values that produce O v λ 1371.0 and N iv $\lambda\lambda$ 1718.0, 1718.5 in defect/excess.

The most sensitive lines to L_X/L_{bol} are O vi $\lambda\lambda$ 1031.9, 1037.6 and N v $\lambda\lambda$ 1238.8, 1242.8, as already noted in Paper I. S vi $\lambda\lambda$ 933.4, 944.52 is also sensitive, but it is given little weight in the fitting process since this region is heavily affected by the interstellar hydrogen absorption. N v $\lambda\lambda$ 1238.8, 1242.8 presents a problem related to its unsaturated absorption (which we discuss in detail below) and cannot be used to constrain the shocks. L_X/L_{bol} is then derived from the model that provides the best fit to O vi $\lambda\lambda$ 1031.9, 1037.6, which increases with increasing shocks. In the range of temperatures and mass-loss rates we found for the dwarf stars, L_X/L_{bol} must be comprised between -7.5 (minimum to reproduce the observed O vi profile) and -6.5 (when this line is in excess in the models, independently of the other stellar parameters), but they can be further constrained for each object once T_{eff} and \dot{M} are known (as reflected in Table 3).

We then calculated models with different radii (in the range 6–12 R_\odot) for $\log g = 4.0$. We find that if we increase the radius (i.e., we increase mass and luminosity), O vi $\lambda\lambda$ 1031.9,

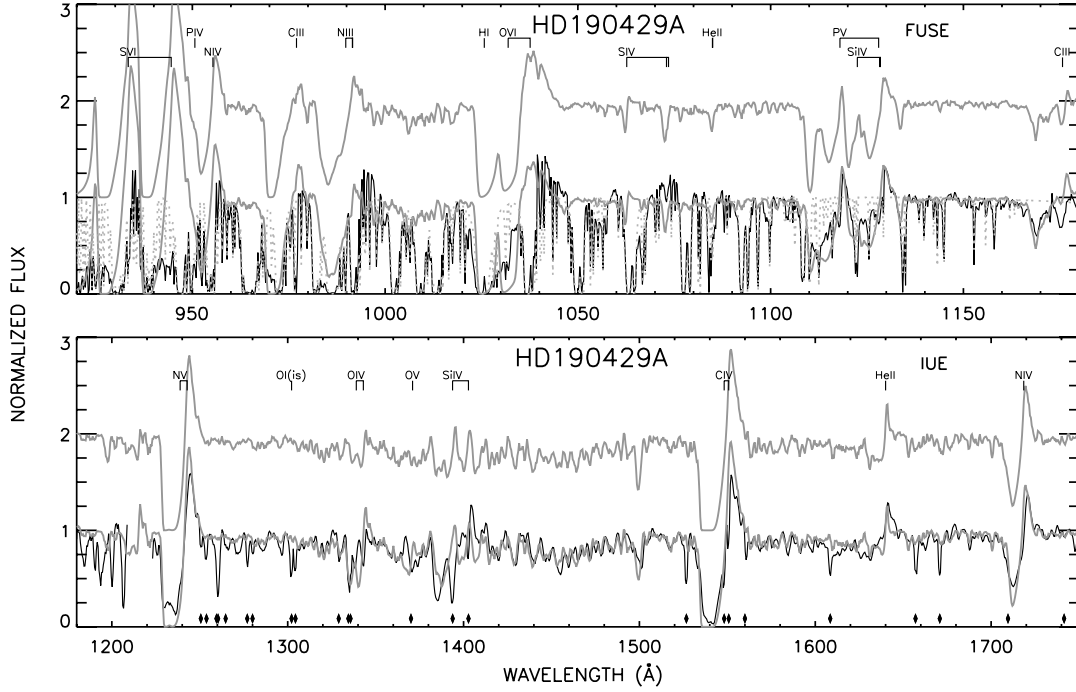


FIG. 7.—Best-fit models of HD 190429A (*top*: FUSE spectra; *bottom*: IUE spectra). Two models (gray) are shown, both with $T_{\text{eff}} = 37,500$ K, $\log g = 3.4$, $R = 25 R_{\odot}$, $\dot{M} = 1.2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, $\log L_X/L_{\text{bol}} = -6.5$, $L_{\text{bol}} = 6.05$, and $v_{\infty} = 2100 \text{ km s}^{-1}$. The model superposed to the spectrum, with solar abundances, provides a good fit of most wind features in both FUSE and IUE range. The top model has modified CNO abundances ($\epsilon_{\text{He}} = 5\epsilon_{\text{He},\odot}$, $\epsilon_{\text{C}} = 0.5\epsilon_{\text{C},\odot}$, $\epsilon_{\text{N}} = 2.0\epsilon_{\text{N},\odot}$, and $\epsilon_{\text{O}} = 0.1\epsilon_{\text{O},\odot}$) and fits better C IV $\lambda\lambda 1169 + \text{C III } \lambda 1176$ and O VI $\lambda\lambda 1031.9, 1037.6$, but less well P V $\lambda\lambda 1118.0, 1128.0$ and Si IV $\lambda\lambda 1393.8, 1402.8$. [See the electronic edition of the Journal for a color version of this figure.]

1037.6 increases while P V $\lambda\lambda 1118.0, 1128.0$, C III $\lambda 1176$, and N IV $\lambda\lambda 1718.0, 1718.5$ decrease. At $R_* = 6 R_{\odot}$, the models do not reproduce the P Cygni profile of O VI. A model with a radius of $R_* = 12 R_{\odot}$ provides an overall worse fit to the spectra of HD 96715, HD 168076, HDE 303308, and HD 93205 than $R_* = 9 R_{\odot}$. For these stars we adopt a radius of $R_* = 9 R_{\odot} \pm 3 R_{\odot}$ (HD 64568 and HD 93250 are discussed in §§ 5.1.2 and 5.1.3).

There is a limited number of photospheric lines sensitive to gravity in the FUSE and IUE ranges and, by consequence, the derived value of $\log g$ is less well constrained than the other stellar parameters. P V $\lambda\lambda 1118.0, 1128.0$, and N IV $\lambda\lambda 1718.0, 1718.5$ increase with decreasing gravity, and C III $\lambda 1176$ has the opposite behavior. However, the strength of these lines depends on $\log g$ more weakly than on T_{eff} (C III, P V, N IV) and \dot{M} (N IV). We find that models with $\log g = 3.8$ or 4.2 give poorer fits than $\log g = 4.0$, and we adopt these

values as the error margin. Our findings agree with the results from works based on analyses of optical spectra that derive $\log g$ for HD 93205 and HDE 303308 between 3.9 and 4.1 (see Table 4) and with the calibration of $\log g$ with spectral type of Markova et al. (2004) and Vacca et al. (1996) that assign $\log g \simeq 3.9$ to O3 V and O4 V stars. For HD 168076, Morrison (1975) derived $\log g = 4.3$ from photometric data.

The best-fit models are shown in Figures 5 and 6. The synthetic spectra reproduce with great accuracy most of the UV and far-UV lines. Yet, they fail to reproduce the N V $\lambda\lambda 1238.8, 1242.8$ unsaturated profile in the IUE spectra of all stars. The IUE data may suffer from inaccurate background subtraction in this wavelength range because of the echelle order overlap (Bianchi & Bohlin 1984), so we searched for other UV spectra in the MAST archive. In Figures 2 and 6 we have included data in the N V $\lambda\lambda 1238.8, 1242.8$ region from ORFEUS/TUES for HD 96715 and from HST/STIS for

TABLE 3
STELLAR PARAMETERS FROM MODEL FITTING OF FAR-UV AND UV SPECTRA

Star	Spectral Type	T_{eff} (kK)	$\log g$	R/R_{\odot}	M/M_{\odot}	$\log(L_{\text{bol}}/L_{\odot})$	v_{∞} (km s $^{-1}$)	\dot{M}^a ($M_{\odot} \text{ yr}^{-1}$)	\dot{M}^b ($M_{\odot} \text{ yr}^{-1}$)	L_X/L_{bol}
HD 190429A.....	O4 If $^{+}$	37.5 ± 1.5	3.4 ± 0.1	25 ± 2	57	6.05 ± 0.15	2100 ± 200	$(1.2 \pm 0.2) \times 10^{-5}$	9.2×10^{-6}	-6.5 ± 0.5
HD 64568	O3 V((f*))	41 ± 2	3.9 ± 0.2	14 ± 2	57	5.7 ± 0.2	2800 ± 200	$(5.6 \pm 5.) \times 10^{-7}$	2.3×10^{-6}	-7.5 ± 0.75
HD 93250	O3.5 V((f $^{+}$))	40 ± 2	4.0 ± 0.2	12 ± 2	53	5.5 ± 0.2	2900 ± 200	$(5.5 \pm 3.) \times 10^{-7}$	9.9×10^{-7}	-7.25 ± 0.25
HD 93205	O3.5 V((f $^{+}$))	40 ± 2	4.0 ± 0.2	9 ± 3	30	5.3 ± 0.2	3200 ± 200	$(3.3 \pm 2.) \times 10^{-7}$	5.1×10^{-7}	-7.0 ± 0.5
HDE 303308.....	O4 V((f $^{+}$))	40 ± 2	4.0 ± 0.2	9 ± 3	30	5.3 ± 0.2	2800 ± 200	$(3.4 \pm 2.) \times 10^{-7}$	6.0×10^{-7}	-7.0 ± 0.5
HD 96715	O4 V((f))	39 ± 2	4.0 ± 0.2	9 ± 3	30	5.2 ± 0.2	2800 ± 200	$(2.2 \pm 1.) \times 10^{-7}$	4.0×10^{-7}	-7.25 ± 0.25
HD 168076	O4 V((f))	39 ± 2	4.0 ± 0.2	9 ± 3	30	5.2 ± 0.2	2800 ± 200	$(2.2 \pm 1.) \times 10^{-7}$	4.0×10^{-7}	-7.0 ± 0.25

^a This paper; values from spectral modeling.

^b Mass-loss rate value predicted with the mass-loss “recipe” of Vink et al. 2000, using the stellar parameters from our model fitting (this table).

TABLE 4
THE PARAMETERS OF THE PROGRAM STARS PREVIOUSLY DERIVED IN THE LITERATURE

Star	T_{eff} (kK)	$\log g$	$\log(L/L_{\odot})$	Reference	R/R_{\odot}	M/M_{\odot}	Reference	\dot{M}^a ($M_{\odot} \text{ yr}^{-1}$)	v_{∞} (km s^{-1})	Reference	L_X/L_{bol}	Reference
HD 190429A.....	37.5	3.4	6.05	1	25	57	1	1.2×10^{-5}	2100	1	-6.5	1
	28.2	3.53	...	2	...	...	...	4.6×10^{-6b} ; $<2.1 \times 10^{-5b}$	...	3; 4	...	...
	...	...	...	...	...	...	...	1.26×10^{-5c} ; $<0.35 \times 10^{-6d}$	...	5; 6	...	...
	33.1	3.00	...	7	...	...	...	8.6×10^{-6c}	...	8	...	...
	47.5	...	...	9	...	...	...	1.42×10^{-5c} ; $1.1 \cdot 10^{-5c}$	...	10; 9	...	...
HD 64568	41	3.9	5.7	1	14	57	1	5.6×10^{-7}	2800	1	-7.5	1
	...	...	...	...	...	...	...	...	1880	11	...	...
HD 93250	40	4.0	5.5	1	12	53	1	5.5×10^{-7}	2900	1	-7.25	1
	37.2	...	5.75	13	...	46.5	13	...	3000	14	-6.4	12
	52.5	3.95	6.4	15	19	120	15	1.3×10^{-6}	3500	16	...	...
	50.5	3.95/4.0 ^e	6.28	17	18	118	17	4.9×10^{-6c}	3250	17	...	...
	51.0	3.9	6.3	18	...	83.2/93.3/114.8 ^f	18	...	3200; 3230	18; 11	...	...
	46.0	3.95/3.96 ^c	6.01	19	15.9	83.3	19	3.45×10^{-6c}	...	19	...	...
	55.0	...	...	9	...	...	...	4.1×10^{-5b} ; 7.9×10^{-8}	...	20; 21	...	...
HD 93205	40	4.0	5.3	1	9	30	1	3.3×10^{-7}	3200	1	-7.0	1
	55.0/36.5 ^g	...	...	22	12.5/10.3 ^{g,h}	$\geq 39/\geq 15^g$	22	$>5.9 \times 10^{-7}$	3600	23	-6.37	23
	44.7/35.5 ^g	...	6.20/4.9 ^g	24	...	100.00/24.82 ^g	24	...	...	...	...	...
	36.3	...	6.02	13	...	63.4	13	...	...	...	...	...
	...	...	5.51/4.80 ^g	25	8.0/6.3 ^g	45/20 ^g	25	...	...	...	-6.45	12
	55.0	...	...	9	...	$\geq 31.5/\geq 13.3^g$	26	~ -7.0	26
	...	...	...	...	...	$\geq 37/\geq 15^g$	27	...	...	...	...	...
	...	...	...	...	...	$\geq 32.6/\geq 14.2^g$	28	...	...	...	...	...
	...	...	...	...	...	63.3/24.5 ^g ; $\leq 60/\leq 25^g$	29; 30	...	...	...	...	...

HDE 303308.....	40	4.0	5.3	1	9	30	1	3.4×10^{-7}	2800	1	-7.0	1
	48.0	4.05/4.10 ^c	5.84	17	12	66	17	2.1×10^{-6c}	3100	17	-6.54	12
	45.5	3.9	5.8	31	13	50/60/70 ⁱ	31	2.5×10^{-6}	3400	16	...	...
	35.5	...	5.27	13	...	28.8	13	...	3035	11	...	...
	48.0	3.9	5.85	18	...	40.7/41.7/40.7 ^f	18	...	3200; 3000	18; 14	...	...
	41.0	3.90/3.91 ^c	5.53	19	11.5	39.0	19	1.63×10^{-6c}	...	19	...	...
HD 96715	55.0	...	...	9	...	...	...	...	...	...	...	...
	39	4.0	5.2	1	9	30	1	2.2×10^{-7}	2800	1	-7.25	1
HD 168076 .....	...	...	...	...	...	...	...	...	2900; 3000	14; 11	<-5.85	12
	39	4.0	5.2	1	9	30	1	2.2×10^{-7}	2800	1	-7.0	1
	55.0	4.3	...	32	...	...	...	2.51×10^{-6c}	...	5	...	...
	50.0	...	...	9	...	...	...	1×10^{-5c}	...	9	...	...
...	...	...	...	...	...	...	...	3305	11	...	...

^a Mass-loss rate calculated from line fit to *IUE* lines unless a different method is indicated.

^b Mass-loss rate calculated from analysis of radio data.

^c Mass-loss rate calculated from analysis of $H\alpha$.

^d Mass-loss rate calculated from analysis of IR data.

^e Values of $\log g$ derived from the fit to $H\gamma$ /same but corrected for centrifugal force.

^f M/M_{\odot} calculated from: v_{∞} vs. M_* relation/ $\log g$ and radius/comparison with evolutionary tracks.

^g Main component/secondary component.

^h Assuming a distance of 2.6 Kpc to Tr16.

ⁱ M/M_{\odot} calculated from $\log g$ and radius/comparison with evolutionary tracks of high mass-loss rate/same with tracks of low mass-loss rate.

REFERENCES.—(1) This work; (2) Salukvadze & Javakishvili 1995; (3) Scuderi et al. 1998; (4) Abbott et al. 1980; (5) Leitherer 1988; (6) Persi et al. 1983; (7) Oke 1954; (8) Scuderi et al. 1992; (9) Conti & Frost 1977; (10) Markova et al. 2004; (11) Howarth, Siebert, Hussain, & Prinja 1997; (12) Chlebowski et al. 1989; (13) Kaltcheva & Georgiev 1993; (14) Lamers, Snow, & Lindholm 1995; (15) Kudritzki 1980; (16) Garmany et al. 1981; (17) Puls et al. 1996; (18) Kudritzki et al. 1992; (19) Repolust et al. 2003; (20) Leitherer et al. 1995; (21) Conti & Garmany 1980; (22) Conti & Walborn 1976; (23) Chlebowski & Garmany 1991; (24) Vansina & de Greve 1982; (25) Antokhina et al. 2000; (26) Morrell et al. (2001); (27) Corti et al. 1999; (28) Stickland & Lloyd 1993; (29) Doom & de Loore 1984; (30) Benvenuto et al. 2002; (31) Simon et al. 1983; (32) Morrison 1975.

HDE 303308 and HD 93205. The *ORFEUS*/TUES spectrum of HD 96715 displays a saturated N v $\lambda\lambda$ 1238.8, 1242.8 P Cygni profile that the WM-BASIC model fits well; therefore at least in this case the mismatch is indeed likely to originate from the *IUE* data reduction. However, N v $\lambda\lambda$ 1238.8, 1242.8 is unsaturated in the *STIS* spectra of both HDE 303308 and HD 93205. While the latter is a binary and its residual flux may originate from the cooler companion, the profile is hard to explain in HDE 303308. This prompted us to explore the grid of WM-BASIC models, to check whether the combination of parameters that produces unsaturated N v $\lambda\lambda$ 1238.8, 1242.8 overlaps with the range of parameters that we found adequate for early-type dwarf stars.

The behavior of the N v $\lambda\lambda$ 1238.8, 1242.8 doublet in models with $\log g = 4$ and $R_* = 9 R_\odot$ can be summarized as follows. It becomes stronger with increasing temperature up to $\sim 44,000$ K (the exact value depends on \dot{M} and L_X/L_{bol}) and then decreases for $T_{\text{eff}} \gtrsim 44,000$ K. The doublet grows with increasing shocks up to $\log L_X/L_{\text{bol}} \leq -6.75$; then it decreases for $\log L_X/L_{\text{bol}} \geq -6.75$. In the range of temperatures that we have determined for O3–4 V stars (38,000–42,000 K), higher \dot{M} produces a stronger N v $\lambda\lambda$ 1238.8, 1242.8 profile.

If we decrease T_{eff} so that the models produce unsaturated N v $\lambda\lambda$ 1238.8, 1242.8, we cannot reproduce the observed O vi $\lambda\lambda$ 1031.9, 1037.6. If instead we increase T_{eff} , we achieve unsaturated C iv $\lambda\lambda$ 1548.2, 1550.8 at lower T_{eff} (by 2000 K) than needed to produce unsaturated N v $\lambda\lambda$ 1238.8, 1242.8 (unsaturated C iv $\lambda\lambda$ 1548.2, 1550.8 is in disagreement with the observed spectra of all dwarf stars except for HD 93250 and HD 64568). Reduced shocks underestimate O vi $\lambda\lambda$ 1031.9, 1037.6. Model spectra calculated with lower mass-loss rate do not have N iv $\lambda\lambda$ 1718.0, 1718.5. We can fit N v $\lambda\lambda$ 1238.8, 1242.8 in the spectra of HD 93205 and HDE 303308 (but not HD 93250) with a nitrogen abundance of $\epsilon_N = 0.1\epsilon_{N,\odot}$, but the models lack N iv $\lambda\lambda$ 1718.0, 1718.5 (see Fig. 6). Note that none of the stars analyzed in this work is in the OBC/OBN compilation of Walborn (1976), and we found no publication that measured nonsolar compositions for them.

In conclusion, we cannot compute a WM-BASIC model that displays unsaturated N v $\lambda\lambda$ 1238.8, 1242.8 and is in agreement with the rest of the observed spectrum. We suspect that a shock (and X-ray ionization) treatment different from that used by WM-BASIC may reproduce the N v $\lambda\lambda$ 1238.8, 1242.8 P Cygni profile. We will investigate this possibility by comparing models computed with WM-BASIC and CMFGEN (Bianchi, Garcia, & Herald 2003 and 2004, in preparation).

5.1.1. HD 93205 and HD 168076

There is an additional source of uncertainty in the analysis of HD 93205 and HD 168076. Both of them are binaries whose secondary component is most likely included in the *FUSE* and *IUE* apertures; its contribution to the observed total flux is, however, hard to quantify.

The secondary component of HD 93205 is an O8 V star. From our grid of synthetic spectra we know that the O8 V continuum flux ($T_{\text{eff}} = 30,000$ K, from Fig. 8) can be up to 50% the flux of an O3.5 V ($T_{\text{eff}} = 40,000$ K; this work) in the 900–1800 Å range if the stars had the same radius. Yet, we can narrow down this upper limit. N v $\lambda\lambda$ 1238.8, 1242.8 is almost absent in the UV spectrum of O8 V stars (Walborn et al.

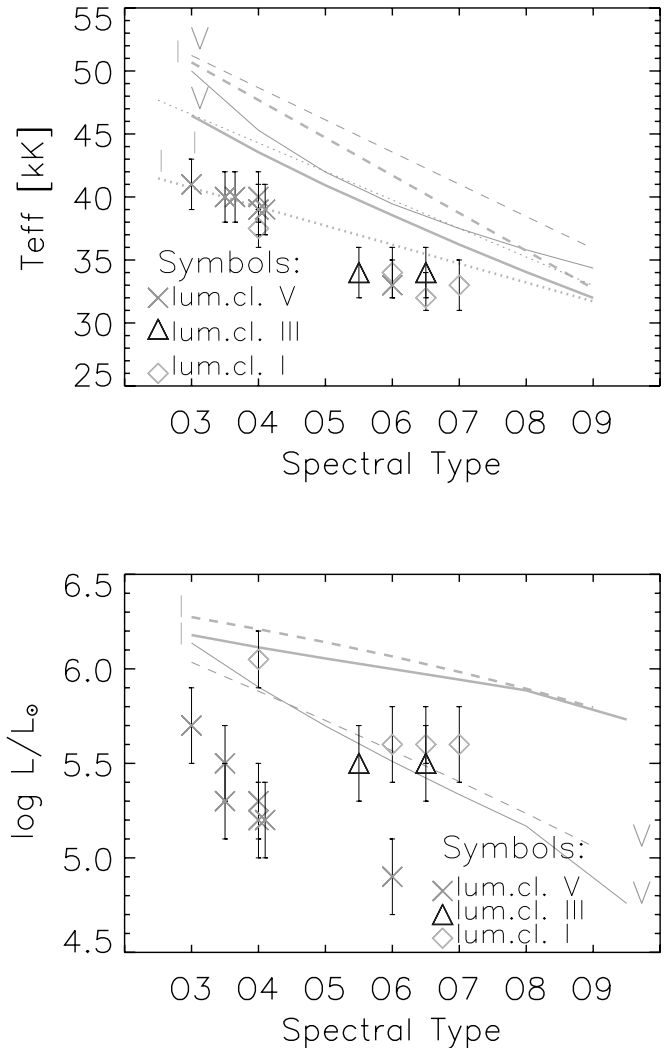


FIG. 8.— T_{eff} (top) and L_{bol} (bottom) obtained for the objects analyzed in this paper and in Bianchi & Garcia (2002) are compared with the empirical calibrations of Vacca et al. (1996; dashed line), de Jager & Nieuwenhuijzen (1987; solid line), and Markova et al. (2004; dotted line). The thick lines represent the curves for supergiants and the thin lines represent dwarf stars; the symbols for individual objects indicate luminosity class and are explained in the figures. Our temperatures and luminosities are lower than these previous calibrations. [See the electronic edition of the Journal for a color version of this figure.]

1985). If we assume that this line is saturated in O3.5 V stars (see, e.g., the *ORFEUS* spectrum of HD 96715 in Fig. 2) the residual flux at its core in the *IUE* spectrum, of $\sim 15\%$, may originate from the secondary and/or inaccurate background subtraction, as explained previously. As for other lines, the spectrum of an O8 V star displays photospheric profiles of Si iv $\lambda\lambda$ 1393.8, 1402.8 and N iv $\lambda\lambda$ 1718.0, 1718.5 and unsaturated C iv $\lambda\lambda$ 1548.2, 1550.8 (Walborn et al. 1985). This could explain the subtle mismatch of the best-fit model to the observed emission of C iv $\lambda\lambda$ 1548.2, 1550.8 and the absorptions of Si iv $\lambda\lambda$ 1393.8, 1402.8 and N iv $\lambda\lambda$ 1718.0, 1718.5.

The HD 168076 system is much less known. Since we do not know the spectral type of the secondary component, we cannot speculate the contamination to the O4 V(f) star UV and far-UV spectra. These, however, are very similar to the spectra of the other dwarves in the sample, and therefore the contribution from the secondary cannot be conspicuous. A

possible effect from the secondary is that the N v $\lambda\lambda 1238.8$, 1242.8 and C iv $\lambda\lambda 1548.2$, 1550.8 features are not saturated. Again, if we suppose that these lines are saturated in the spectrum of the main component, we can estimate the contribution of the secondary to be $\leq 10\%$ to the total flux in the *IUE* range.

5.1.2. HD 93250

The *IUE* spectrum of HD 93250 displays an unsaturated C iv $\lambda\lambda 1548.2$, 1550.8 P Cygni profile. This feature was noted by Walborn et al. (1985), who suggested that it may indicate a hidden companion. Yet, the star has not been found to be binary (see § 3). A poor background subtraction in the *IUE* spectrum may make N v $\lambda\lambda 1238.8$, 1242.8 appear unsaturated, but not C iv $\lambda\lambda 1548.2$, 1550.8 (Bianchi & Bohlin 1984). Our grid of models shows C iv $\lambda\lambda 1548.2$, 1550.8 not saturated when $R_* \geq 12 R_\odot$ and $T_{\text{eff}} \gtrsim 42,000$ K (the actual temperature depends on R_* and \dot{M}). Note that a large radius would be consistent with the high luminosity of this object.

We studied the behavior of the main lines (C iii, C iv, N iv, N v, O v, O vi, and P v) in a wide range of temperatures, mass-loss rates, and L_X/L_{bol} values, ([37,000, 50,000] K, [2×10^{-7} , 1×10^{-6}] $M_\odot \text{ yr}^{-1}$, [-6.75, -8.0]) in search of intervals where we can reproduce simultaneously all the strongest features of the spectrum of HD 93250 and the unsaturated profile of C iv $\lambda\lambda 1548.2$, 1550.8.

We find that the lower the mass-loss rate, the lower is the temperature where models display unsaturated C iv $\lambda\lambda 1548.2$, 1550.8. In models with $R_* = 12 R_\odot$, independently of the value of shocks, C iv $\lambda\lambda 1548.2$, 1550.8 becomes unsaturated at $T_{\text{eff}} = 42,000$, 45,000, and 49,000 K for $\dot{M} = 2 \times 10^{-7}$, 5×10^{-7} , and $1 \times 10^{-6} M_\odot \text{ yr}^{-1}$, respectively. However, the upper limit to T_{eff} set by N iv $\lambda\lambda 1718.0$, 1718.5 and O vi $\lambda\lambda 1031.9$, 1037.6 is lower (by ~ 2000 , 4000, and 6000; and 4000, 7000, and 9000 K, respectively, for $L_X/L_{\text{bol}} = -6.75$) than required for the unsaturated C iv $\lambda\lambda 1548.2$, 1550.8. If instead we decrease shocks for an intermediate mass-loss rate of $\dot{M} = 5 \times 10^{-7} M_\odot \text{ yr}^{-1}$, the temperature required to fit O vi $\lambda\lambda 1031.9$, 1037.6 and N iv $\lambda\lambda 1718.0$, 1718.5 increases by 1000 K for every drop of $\Delta \log L_X/L_{\text{bol}} = -0.5$, while it remains constant for C iv $\lambda\lambda 1548.2$, 1550.8. Therefore, in models with $T_{\text{eff}} \sim 42,000$ K and low \dot{M} and L_X/L_{bol} , this gap would be reconciled. However, other prominent lines (O v $\lambda\lambda 1371.0$, P v $\lambda\lambda 1118.0$, 1128.0, and C iii $\lambda 1176$) are not reproduced. We conclude that we cannot fit the observed C iv $\lambda\lambda 1548.2$, 1550.8 consistently with the rest of the spectral lines.

We find the best solution to be $\log L_X/L_{\text{bol}} = -7.25$, $\dot{M} = 5.5 \times 10^{-7} M_\odot \text{ yr}^{-1}$, $T_{\text{eff}} = 40,000$ K, $R_* = 12 R_\odot$, and $\log g = 4$. With these parameters the model reproduces O vi $\lambda\lambda 1031.9$, 1037.6, P v $\lambda\lambda 1118.0$, 1128.0, C iii $\lambda 1176$, O v $\lambda\lambda 1371.0$, and N iv $\lambda\lambda 1718.0$, 1718.5 (see Figs. 5 and 6). This model, however, has saturated profiles of N v $\lambda\lambda 1238.8$, 1242.8 and C iv $\lambda\lambda 1548.2$, 1550.8, in disagreement with the observed spectrum. Because C iii $\lambda 1176$ is well fitted, a different carbon abundance would not improve the solution. As seen in § 5.1, N v $\lambda\lambda 1238.8$, 1242.8 is always saturated in the range of parameters considered for solar abundances, and models underabundant in nitrogen are incompatible with N iv $\lambda\lambda 1718.0$, 1718.5. The nonsaturated absorptions of C iv $\lambda\lambda 1548.2$, 1550.8 and N v $\lambda\lambda 1238.8$, 1242.8 may be due to an unresolved cooler companion.

5.1.3. HD 64568

The only *IUE* spectrum of HD 64568 has low dispersion. The stellar parameters are therefore constrained primarily with lines in the *FUSE* range. By consequence, the uncertainty of the derived \dot{M} and L_X/L_{bol} is higher than for the other objects of the sample, as we explain below. This is not the case for v_∞ (derived from O vi $\lambda\lambda 1031.9$, 1037.6) or $\log g$ (determined with C iii $\lambda 1176$ and P v $\lambda\lambda 1118.0$, 1128.0, but highly uncertain among the sample dwarf stars), which are entirely determined from the high-resolution *FUSE* spectrum. The effective temperature is well constrained with C iii $\lambda 1176$ and P v $\lambda\lambda 1118.0$, 1128.0. These lines in HD 64568 are the weakest in our sample indicating higher T_{eff} (41,000 K), in accordance with its earliest spectral type.

C iv $\lambda\lambda 1548.2$, 1550.8 is unsaturated. At the star's effective temperature, the models (degraded to the [low] resolution of the observed spectrum) display only unsaturated C iv $\lambda\lambda 1548.2$, 1550.8 if $\dot{M} \leq 2 \times 10^{-7} M_\odot \text{ yr}^{-1}$, $R_* > 12 R_\odot$, and $\log L_X/L_{\text{bol}} > -7.0$. C iv $\lambda\lambda 1548.2$, 1550.8 decreases with larger radii and, together with O vi $\lambda\lambda 1031.9$, 1037.6, helps us constrain this parameter. We set the upper limit for the radius to $16 R_\odot$ when the models display O vi $\lambda\lambda 1031.9$, 1037.6 in excess, regardless of the other stellar parameters, and the lower limit to $12 R_\odot$ when they cannot produce unsaturated C iv $\lambda\lambda 1548.2$, 1550.8.

The mass-loss rate and shocks were determined as explained in § 5.1. Since most of the \dot{M} indicators (O v $\lambda\lambda 1371.0$, Si iv $\lambda\lambda 1393.8$, 1402.8, and N iv $\lambda\lambda 1718.0$, 1718) are in the *IUE* range, the derived mass-loss rate of HD 64568 is highly uncertain. The derived L_X/L_{bol} , although determined from O vi $\lambda\lambda 1031.9$, 1037.6 in the *FUSE* range, is affected by the uncertainty in \dot{M} , since the strength of the doublet also depends on mass-loss rate.

5.2. The Supergiant Star, HD 190429A

The spectrum of the O4 supergiant displays very strong lines that, in comparison with the spectra of the mid-O supergiant stars analyzed in Paper I (see § 4.2), denote higher temperature and mass-loss rate. In particular, the prominent He ii $\lambda 1640.0$ emission line indicates, according to our grid of models, that the mass-loss rate is higher than $7 \times 10^{-6} M_\odot \text{ yr}^{-1}$.

In the range of temperatures and mass-loss rates that we considered for HD 190429A (35,000–40,000 K and 3×10^{-6} to $1.5 \times 10^{-5} M_\odot \text{ yr}^{-1}$, as suggested by the star's spectral morphology), C iii $\lambda 1176$, P v $\lambda\lambda 1118.0$, 1128.0, and Si iv $\lambda\lambda 1393.8$, 402.8 increase with increasing \dot{M} and with decreasing T_{eff} and L_X/L_{bol} (similarly to what we found in Paper I). He ii $\lambda 1640$ has the same dependence on \dot{M} and T_{eff} but does not vary appreciably with L_X/L_{bol} . The effective temperature is constrained from C iii $\lambda 1176$ and Si iv $\lambda\lambda 1393.8$, 1402.8. For $T_{\text{eff}} \leq 36,000$ K, the models with $\dot{M} > 7 \times 10^{-6} M_\odot \text{ yr}^{-1}$ display a P Cygni profile of C iii $\lambda 1176$, not seen in the observed spectrum. For $T_{\text{eff}} \geq 39,000$ K, C iii $\lambda 1176$ and Si iv $\lambda\lambda 1393.8$, 1402.8 are absent even in models with mass-loss rate as high as $\dot{M} \sim 1.4 \times 10^{-5} M_\odot \text{ yr}^{-1}$, thus providing an upper limit to T_{eff} . In this range of temperatures, the models reproduce He ii $\lambda 1640.0$ for $\dot{M} \geq 1.0 \times 10^{-5} M_\odot \text{ yr}^{-1}$ (lower limit of mass-loss rate). Models with $\dot{M} \geq 1.4 \times 10^{-5} M_\odot \text{ yr}^{-1}$ (upper limit) display excessive P v $\lambda\lambda 1118.0$, 1128.0 profiles. The shocks in the wind were determined by fitting O vi $\lambda\lambda 1031.9$, 1037.6 and O v $\lambda 1371.0$ (both oxygen lines increase with increasing shocks) and Si iv $\lambda\lambda 1393.8$, 1402.8.

In addition, different values of L_X/L_{bol} change the shape of the P v $\lambda\lambda 1118.0, 1128.0$ absorptions.

In this regime of T_{eff} and \dot{M} , the models with $R_* \geq 23 R_\odot$ produce unsaturated C III $\lambda 1176$, thus setting the lower limit of R_* . The upper limit is $27 R_\odot$ because models with larger radius produce O VI $\lambda\lambda 1031.9, 1037.6$ stronger than observed regardless of the other stellar parameters. Other lines sensitive to the radius, which helped us to further constrain its value, are He II $\lambda 1640.0$ and Si IV $\lambda\lambda 1393.8, 1402.8$ (which decrease with increasing radius) and O V $\lambda 1371.0$ (favored by larger radii); the profile of P v $\lambda\lambda 1118.0, 1128.0$ + Si IV $\lambda\lambda 1122.5, 1128.3, 1128.4$ also changes with radius.

Contrary to what we find for the dwarf stars, almost all the spectral lines are sensitive to gravity, and we can use them to derive $\log g$. Higher $\log g$ corresponds to weaker O VI $\lambda\lambda 1031.9, 1037.6$, O V $\lambda 1371.0$, and He II $\lambda 1640.0$, while Si IV $\lambda\lambda 1393.8, 1402.8$ increases and the absorption of P v $\lambda\lambda 1118.0, 1128.0$ grows deeper. The carbon lines are also affected by an increase of $\log g$: C IV $\lambda\lambda 1548.2, 1550.8$ decreases and the absorption of C IV $\lambda 1169$ + C III $\lambda 1176$ increases, whereas its emission diminishes.

We find the best fit at $T_{\text{eff}} = 37,500$ K, $\log g = 3.4$, $R_* = 25 R_\odot$, $\dot{M} = 1.2 \times 10^{-5} M_\odot \text{ yr}^{-1}$, $\log L_X/L_{\text{bol}} = -6.5$, $L_{\text{bol}} = 6.05$, and $v_\infty = 2100 \text{ km s}^{-1}$. This model reproduces most of the wind features (see Fig. 7), including the lines of O IV, O VI, P v + Si IV, C IV, Si IV, He II and N IV. Minor discrepancies remain in the fit to some of these lines, which can be attributed to the contribution of the secondary to the flux of the system. Even though the lines used for the analysis come primarily from the O4 star, they may have a residual flux in the absorption trough from the O9.5 II companion. The comparison of spectra from the *IUE* atlas of stars (Walborn et al. 1985) of O4 I stars (main component) and O9.5 II stars (companion) provides an upper limit for the contribution of the secondary. An O9.5 bright giant displays weak N v $\lambda\lambda 1238.8, 1242.8$, while the doublet typically has a saturated absorption in an O4 I star. From the depth of N v $\lambda\lambda 1238.8, 1242.8$ in the *IUE* spectrum of the system we estimated that the companion may amount to $\leq 15\%$ of the total. The O9.5 II star has strong Si IV $\lambda\lambda 1393.8, 1402.8$; this would explain why Si IV $\lambda\lambda 1393.8, 1402.8$ is weaker in our models than observed. C IV $\lambda\lambda 1548.2, 1550.8$ is fully developed but not saturated in the O9.5 II star, which would explain the excess emission and absorption of the model. The spectrum of an O9.5 II has weak photospheric N IV $\lambda\lambda 1718.0, 1718.5$, and this makes the P Cygni profile from the O4 If⁺ star look less developed (relative to the total continuum); thus this line appears slightly in excess in the model.

In the *FUSE* range, according to the Copernicus atlas of OB stars of Walborn & Bohlin (1996), an O9.5 II star has photospheric S IV $\lambda\lambda 1062.7, 1073.0, 1073.5$, and P v $\lambda\lambda 1118.0, 1128.0$ + Si IV $\lambda\lambda 1122.5, 1128.3, 1128.4$ lines, which will increase the depth of the O4 If⁺ wind lines. O VI $\lambda\lambda 1031.9, 1037.6$ and C IV $\lambda 1169$ + C III $\lambda 1176$ have unsaturated P Cygni profiles in O9.5 II stars, possibly causing the mismatch of the best-fit model to these lines.

However, there is another explanation for the discrepancies. It is possible that HD 190429A has nonsolar surface abundances. In Figure 7 we present a model with modified CNO abundances ($\epsilon_{\text{He}} = 5\epsilon_{\text{He},\odot}$, $\epsilon_{\text{C}} = 0.5\epsilon_{\text{C},\odot}$, $\epsilon_{\text{N}} = 2.0\epsilon_{\text{N},\odot}$, and $\epsilon_{\text{O}} = 0.1\epsilon_{\text{O},\odot}$), which would be compatible with a scenario where HD 190429A is evolving toward the Wolf-Rayet phase, as suggested by previous authors (see § 3). The modified CNO abundances improve the fit to C IV $\lambda 1169$ + C III $\lambda 1176$

and the oxygen lines (O VI $\lambda\lambda 1031.9, 1037.6$, O IV $\lambda\lambda 1339.0, 1343.0$, and O V $\lambda 1371.0$) but degrades the fit to P v $\lambda\lambda 1118.0, 1128.0$ and Si IV $\lambda\lambda 1393.8, 1402.8$.

There is one feature, S IV $\lambda\lambda 1062.7, 1073.0, 1073.5$, definitely produced in the primary star spectrum, that the WM-BASIC models do not reproduce. We encountered the same problem when we modeled the spectra of the mid-O type supergiant stars in Paper I. The S IV $\lambda\lambda 1062.7, 1073.0, 1073.5$ problem is probably due to the atomic data used in WM-BASIC and prompted a comparison with models computed with the Hillier & Miller (1998) CMFGEN code. The synthetic spectra generated with both codes for an equivalent set of stellar parameters display very similar photospheric and wind features with the exception of S IV $\lambda\lambda 1062.7, 1073.0, 1073.5$ (Bianchi et al. 2003 and 2004, in preparation). WM-BASIC and CMFGEN predict very different ionization fractions for sulphur.

6. SUMMARY AND DISCUSSION

We have performed a detailed spectroscopic analysis of seven Galactic early-O type stars and derived their stellar parameters. We found effective temperatures ranging from 41,000 to 39,000 K for the O3–O4 dwarf stars and 37,500 K for the O4 supergiant. The X-ray ionization due to shocks in the wind has been constrained by our modeling, primarily from the O VI $\lambda\lambda 1031.9, 1037.6$ resonance doublet, accessible with the *FUSE* telescope. In the range of T_{eff} , \dot{M} , and R_* that we derived for the dwarf stars, the spectral morphology hardly changes with gravity, and the derived value of $\log g$ is less well constrained than other parameters but consistent with previous estimates.

All the sample stars display unsaturated N v $\lambda\lambda 1238.8, 1242.8$ profiles that we cannot fit consistently with the rest of the spectrum. In one case at least (HD 96715), the unsaturated profile is due to poor background subtraction in the *IUE* data (as shown by an *ORFEUS* spectrum), and this may apply to the other stars as well. In the cases of HD 190429A, HD 93205, and HD 168076, the unsaturated profile may also be due to flux from the cooler companion star, whose contribution we estimate to be $\leq 15\%$ of the observed flux. A comparison of WM-BASIC and CMFGEN models calculated with parameters suitable for the early-O type stars is under way (Bianchi et al. 2003 and 2004, in preparation), to investigate the effect of a different treatment of the shocks on the N v $\lambda\lambda 1238.8, 1242.8$ doublet.

We compile previous determinations of the stellar parameters for our program stars from the literature in Table 4. Our effective temperatures are consistently lower than those derived in other works, with the exception only of the Strömgren and H β photometric studies by Kaltcheva & Georgiev (1993) and Salukvadze & Javakhishvili (1995). Kaltcheva & Georgiev (1993) derived temperatures for the Carina stars of our sample lower than ours by ~ 4000 K on average. Salukvadze & Javakhishvili (1995) assigned a temperature of 28,200 K to HD 190429 (without resolving the system), closer to what we would expect for the secondary than to what we found for HD 190429A (37,500 K). Morrison (1975) performed Strömgren and H β photometry of HD 168076 and derived a temperature higher than ours by 16,000 K. The calibration of Conti (1975), based on the comparison of the equivalent widths of hydrogen and helium lines with plane-parallel hydrostatic non-LTE model predictions, was used by Conti & Walborn (1976) and Conti & Frost (1977) for several objects of our sample, yielding

temperatures higher than our results by more than 10,000 K. Temperatures obtained from fitting Balmer lines and optical He I and He II lines with plane-parallel non-LTE hydrostatic models are $\sim 10\%$ (Simon et al. 1983) to $\sim 20\%$ (Kudritzki et al. 1992; Puls et al. 1996) higher than ours. Pauldrach, Hoffmann, & Lennon (2001) compared the *IUE* spectrum of HD 93250 with WM-BASIC models of $T_{\text{eff}} = 50,000$ K (approximately the same as derived by Puls et al. 1996), $\log g = 4.0$, and $R_* = 12 R_{\odot}$, with different mass-loss rates around $\dot{M} = 5.6 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. Their synthetic spectra did not include shocks effects and either produce O V $\lambda 1371.0$ in excess or cannot reproduce the N IV $\lambda\lambda 1718.0, 1718.5$ line. In our work we used those lines, together with C IV $\lambda 1169 +$ C III $\lambda 1176$ and P V $\lambda\lambda 1118.0, 1128.0$, to set the upper limit of the effective temperature of the dwarf stars to $\sim 42,000$ K (see § 5), and we obtained a consistent fit of all spectral features by including the effects of shocks in the calculations.

In Figure 8 we compare the effective temperatures and luminosities obtained for the total sample of O3–O7 type stars analyzed in this work and in Paper I with previous empirical calibrations (Vacca et al. 1996; de Jager & Nieuwenhuijzen 1987; Markova et al. 2004). Our T_{eff} values for O3–O6 dwarf stars are lower than these calibrations, the differences ranging between 9000–10,000, 6000–9000, and 4000–7000 K, respectively. The discrepancy is smaller for the O4–O7 supergiants (6000–10,000, 4000–6000, and 2000–3500 K, respectively). The derived luminosities for both dwarf stars and supergiants are also lower, by an average of 7% and 10%, respectively, than both the calibrations of de Jager & Nieuwenhuijzen (1987) and Vacca et al. (1996). For the O4 If⁺ supergiant the luminosity is also lower, but the discrepancy is within the error bars.

The lower temperatures from our analysis are due to two main improvements. On the one hand, the use of *FUSE* data enables the assessment of X-rays from shocks and thus a correct (consistent) derivation of the wind ionization. On the other hand, the inclusion of line-blanketing effects in the analysis yields lower effective temperatures than pure hydrogen and helium model analyses. Optical spectra analyses of massive stars with spherical, hydrodynamic, wind-blanketed, non-LTE synthetic spectra also revised the temperature scale downward (Martins, Schaerer, & Hillier 2002; Herrero, Puls, & Najarro 2002; Repolust, Puls, & Herrero 2004). Our derived T_{eff} values are still lower. Temperatures of O3 V and O4 V stars, according to the scale of Martins et al. (2002; based on calculations with the CMFGEN code), are $\simeq 47,500$ and $\simeq 44,500$ K, whereas we have obtained 41,000 and 40,000–39,000 K. From the work of Herrero et al. (2002), who fit Balmer, He I and He II optical lines with FASTWIND (Santolaya-Rey, Puls, & Herrero 1997), we can interpolate a temperature of 41,250 K for an O4 If⁺, i.e., ~ 4000 K higher than we derived for HD 190429A. Repolust et al. (2004), proceeding similarly, obtained 46,000 K for HD 93250 (in contrast with our result, 40,000 K) and 41,000 K for HDE 303308 (in agreement within the error bars with our value, 40,000 K). The remaining disagreement between these results and ours may originate in the fact that the analyses are based on optical and UV data, respectively. We are planning to analyze optical spectra of the sample stars to check the consistency of our results from the UV and far-UV.

The spectral lines in the *FUSE* and *IUE* ranges constrain \dot{M} as well. The mass-loss rate that we derived for HD 190429A ($1.2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$) agrees with the values derived from H α by Conti & Frost (1977; $1.1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$), Leitherer (1988;

$1.26 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$), Scuderi et al. (1992; $8.6 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$), and Markova et al. (2004; $1.42 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$). Studies of IR and radio spectra yield lower \dot{M} : $4.6 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Scuderi et al. 1998 [radio]), $< 0.35 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Persi, Ferrari-Toniolo, & Grasdalen 1983 [IR]). For the dwarf stars the mass-loss rates derived in the literature are at least 1 order of magnitude higher than ours. For HD 93250, the exceptionally high value of $\dot{M} = 4.1 \times 10^{-5}$ (Leitherer, Chapman, & Koribalski 1995) was determined from radio fluxes at 8.54 GHz, but the data may be contaminated by nonthermal emission; for this object, there is also one measurement lower than ours by 1 order of magnitude. In view of the systematic differences for dwarf stars, we used the “recipe” of Vink, de Koter, & Lamers (2000), based on the radiation pressure–driven wind theory, to predict the mass-loss rates of the sample stars from their derived photospheric parameters. The predictions are presented in Table 3. The mass-loss rate derived for HD 190429A agrees with the prediction. For dwarf stars our values are lower than predicted by a factor of ~ 2 (~ 4 for HD 64568).

In general, the stellar masses that we have obtained are lower than values determined in previous works, as shown in Table 4. In the case of HD 93205, the mass has been derived from the orbital parameters of the binary system: $M_* \geq 31.5$ (Morrell et al. 2001), $M_* \geq 32.6$ (Stickland & Lloyd 1993), and $M_* \geq 37$ (Corti et al. 1999). For this star we derive $30 \pm 10 M_{\odot}$, lower than previous determinations but compatible within the errors. The primary mass yields a mass of the secondary of $13 \pm 5 M_{\odot}$ for a mass ratio of $q = 0.423$ (Morrell et al. 2001), a mass significantly lower than derived for other O8 V stars in eclipsing systems such as, for example, DN Cas, for which Brancewicz & Dworak (1980) give $24 M_{\odot}$. However, it must be emphasized here that the uncertainty in $\log g$ and R_* (see § 5.1) makes the derived value of the stellar masses much more uncertain than other parameters (like T_{eff} or \dot{M}). Hopefully, the mass determination will be refined with a consistent analysis of optical spectra, planned as a future work.

Our results improve the empirical calibration of the wind momentum–luminosity relation (WLR). The WLR relates the

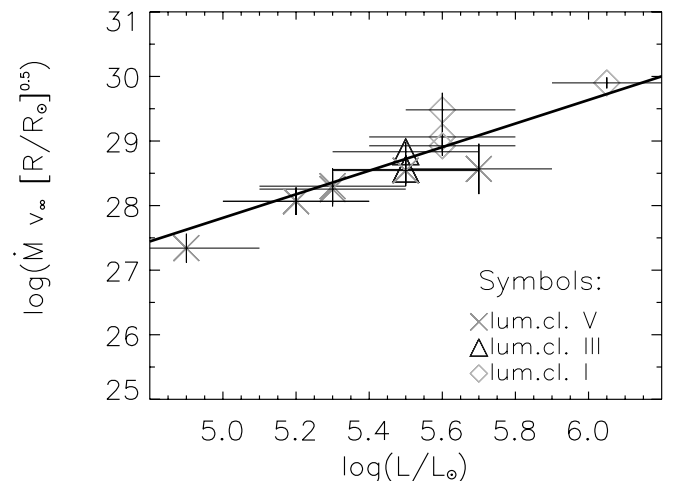


FIG. 9.—Modified wind-momentum vs. luminosity for the objects of the present sample plus those analyzed in Paper I. The product $\dot{M} \times v_{\infty}$ is in cgs units. Symbols represent individual objects of different luminosity classes and are explained in the plot. The solid line represents the theoretical WLR of Vink et al. (2000). [See the electronic edition of the Journal for a color version of this figure.]

so-called modified wind momentum $D_{\text{mom}} = \dot{M} v_{\infty} (R_*/R_{\odot})^{0.5}$ to the luminosity of the star as $D_{\text{mom}} \propto L^x$ (Kudritzki, Lennon, & Puls 1995). In the past few years a big effort has been made to calibrate the WLR (Puls et al. 1996; Kudritzki & Puls 2000; Herrero et al. 2002; Repolust et al. 2004; Markova et al. 2004) for its promising application to distance determinations. In Figure 9 we plot the WLR for the total sample of stars studied in this paper and in Paper I. Our points are mostly consistent with the theoretical relation of Vink et al. (2000) within the error bars.

We are planning to extend our modeling of far-UV and UV spectra to a larger sample of O-type stars and to the optical range. The lower T_{eff} values (compared with previous results/calibrations) have great implications for understanding the ionization of H II regions, since cooler stars would

produce fewer photons energetic enough to ionize hydrogen ($\lambda < 912 \text{ \AA}$). For instance, the ionizing flux from a star of $T_{\text{eff}} = 40,000 \text{ K}$ amounts to only 30% of the flux from a $T_{\text{eff}} = 50,000 \text{ K}$ star with the same radius.

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