A Survey of N IV and O IV Features near 3400 Å in O2–O5 Spectra

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ABSTRACT. We have conducted a survey of little-known N IV and O IV multiplets near 3400 Å in an extensive sample of well-classified, very early O-type spectra. The initial motivation was to search for additional useful classification criteria for these types, but an unexpected result is the high sensitivity of these features to evolutionary CNO processing. We have found a useful discriminant between O2 and later types in the relative strengths of the O IV multiplets, one of which is subject to selective emission in the hottest spectra; the overall strengths of these lines also decrease between spectral types O4 and O5. More remarkable, however, are the variations in the N/O ratios among both individual stars and clusters. For instance, several O4 If+ spectra have very large ratios, while main-sequence stars in the Carina Nebula generally have smaller values than others of the same spectral types in other regions. These effects correspond to different degrees of mixing of processed material as a function of evolutionary age and initial rotational velocities; the second effect provides significant further evidence that very massive stars mix while still on the main sequence. Thus, further analysis of these features will likely provide valuable diagnostics of important evolutionary parameters.

1. INTRODUCTION

The spectral classification system for the earliest O-type stars has recently been extended, the former O3 class (Walborn 1971) being subdivided into the three new classes O2, O3, and O3.5 (Walborn et al. 2002b). Because of various uncertainties affecting the very weak (or absent) He I lines in these spectra, reliance was placed on the ratio of selective emission lines (Walborn 2001) of N IV and N III. These features are just now being definitively modeled physically, and additional, particularly absorption-line, criteria would be welcome at these types.

Several lines of N IV and O IV in the poorly observed 3400 Å region that may be of interest in that context were noted by Drissen et al. (1995) in their *Hubble Space Telescope* Faint Object Spectrograph study of the ionizing cluster in the Galactic giant H II region NGC 3603. However, to establish them as classification criteria, a systematic study of their behavior in an extensive sample of standards and other well-classified stars is required. We have conducted such a survey and report the results here.

A first inspection of the data immediately revealed a pronounced dichotomy in the N/O line-strength ratios among five sample members of the same O2 III(f*) spectral type in the Magellanic Clouds. Quantitative analysis of these spectra, including the longer blue-violet wavelengths, has confirmed that this effect corresponds to large N versus C,O abundance differences between the two subgroups (Walborn et al. 2004, hereafter Paper I). Thus, unexpected mixing of processed material occurs in very hot stars quite near the main sequence. This phenomenon may well be related to the predicted effects of different initial rotational velocities on the evolution of massive stars (Maeder & Meynet 2000). Alternatively, it may be a result of binary evolution in some cases (Bolton & Rogers 1978; Levato et al. 1988; Walborn & Howarth 2000). The results of Paper I significantly illuminate our discussion of the remainder of our sample below.

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2. OBSERVATIONS

The observations were carried out with the Cassegrain spectrograph at the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m telescope during 2002 February 22–27. A 600 line mm^{-1} grating blazed at 3375 Å in second order, combined with a Loral 1k CCD, provided a 2 pixel resolution of 1.5 Å and wavelength coverage from 3270 to 4180 Å. Signal-to-noise ratio values between 50 and 300 pixel^{-1} at 3400 Å were achieved. Exposure times range from 3 × 10 s (for ζ Puppis) to 3 × 3600 s (for Pismis 24-17). The wavelengths have been corrected to rest for presentation here. The preliminary data reductions were performed with standard IRAF[5] routines at CTIO, while final reductions and analysis were conducted at Las Campanas Observatory with IRAF routines running on GNU/Linux machines.

3. RESULTS AND DISCUSSION

All of our 3400 Å observations, except for those of the Magellanic Cloud O2 III(f*) objects discussed in Paper I, are reproduced in Figures 1–4, which are described in turn.

3.1. Strong Winds

Figure 1 reproduces the spectrum of the weak-lined WN6-A star HD 93162 in the Carina Nebula, NGC 3372 (Walborn & Fitzpatrick 2000), observed for comparison with the Of objects, together with those of the prototype O2 If* HD 93129A, also in the Carina Nebula, and two very luminous O3.5 types in Pismis 24, which ionizes NGC 6357 (Lortet et al. 1984). These spectra illustrate well the strong tendency of N IV λλ3479, 3483–85 to develop P Cygni profiles in dense winds, in sharp contrast to the selective emission line N IV λ4058, which retains its essentially photospheric profile. The former feature also responds to the large velocity gradients in the winds of HD 93129A and HD 93162. Weaker P Cygni profiles and smaller velocity gradients are seen in the Pismis 24 spectra. We also note a change in the relative intensities of the O IV lines between the top and bottom pairs of spectra: in the WN and O2 spectra, λλ3381–85 is much stronger than the longer wavelength lines, but not in the O3.5 spectra. This effect is most likely due to the tendency toward selective emission in the λλ3404, 3412, 3414 triplet in the hottest spectra, as was found theoretically in Paper I (see their Fig. 5). As we make clear below, the relatively small N IV/O IV line-strength ratios in the two very massive, evolved Pismis 24 objects are rather surprising. Speculatively, they may indicate atypically low initial rotational velocities in these objects.

3.2. Of Stars

Figure 2 repeats the spectra of HD 93129A and Pismis 24-1 for comparison, but the main point of discussion here is the

O4 If+ spectra.[6] Three of them display *very* large N IV/O IV ratios, indicating a high proportion of processed material in their atmospheres.[7] Two of them, ζ Puppis and Sk −67°167, are current rapid rotators, consistent with the Maeder & Meynet (2000) mechanism, but HDE 269698 (= Sk −67°166) complicates the picture considerably. These two LMC objects are located quite near each other in the cluster NGC 2014 (Garmany & Walborn 1987). Aside from the rotational line-broadening difference, the spectra of these two stars are virtually identical down to 1200 Å (Walborn et al. 1995a). Below that wavelength, however, data first from the Hopkins Ultraviolet Telescope (Walborn et al. 1995b) and then from the *Far Ultraviolet Spectroscopic Explorer* (Walborn et al. 2002a) have shown that the ratio of the N to C, O wind profile strengths is substantially larger in the *slower* rotator, HDE 269698. The latter has been analyzed quantitatively by Crowther et al. (2002), who derive mass fractions of C, N, O relative to solar of 0.05, 9.0, and 0.1, respectively. Perhaps it is a product of binary evolution. Finally, MJ 257 (Massey & Johnson 1993) displays the *smallest* N IV/O IV ratio of any Of star in this sample. It is located toward the Carina Nebula but may be a background object (Walborn 1995), unless it is affected by an anomalous reddening law. Within the current interpretive framework, it must have been a very slow rotator on the main sequence.

3.3. Main-Sequence Stars

Figure 3 displays main-sequence spectra from O2 through O5. BI 253 in the LMC shows the effects of a very strong wind, with an incipient P Cygni profile in N IV λλ3479, 3483–85, likely related to its very high temperature. The O2 spectrum also shows the same relative intensity difference among the O IV lines seen in Figure 1, compared to the later types. The remainder of the sequence suggests that both the N IV and O IV features decline in strength between types O4 and O5. All of the spectra later than O2, except for the last one, have N IV features stronger than O IV. HD 64568 is in NGC 2467, HD 96715 in Carina OB2, HD 168076 in NGC 6611, HD 46223 and 46150 in NGC 2244, and HDE 319699 in NGC 6334. The last of these is the only one with N IV weaker than O IV. All of these are very young groups, but the N IV/O IV ratios suggest that NGC 6334 may be the youngest (and/or that HDE 319699 had a lower initial rotational velocity). Note the important implication of these results, that *early O stars mix while still on the main sequence.*

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[5] IRAF is distributed by the National Optical Astronomy Observatory.

[6] Recall that the "+" signifies only that Si IV λλ4089, 4116 are in emission, in addition to the defining Of green N III and He II lines.

[7] It is curious that in HDE 269698 and Sk −67°167, *only* λ3397 is present, or dominant. An alternative interpretation is that *all* of the O IV lines are suppressed in these spectra, and that the line is due to S V instead. Detailed spectral modeling will be required to investigate this possibility.
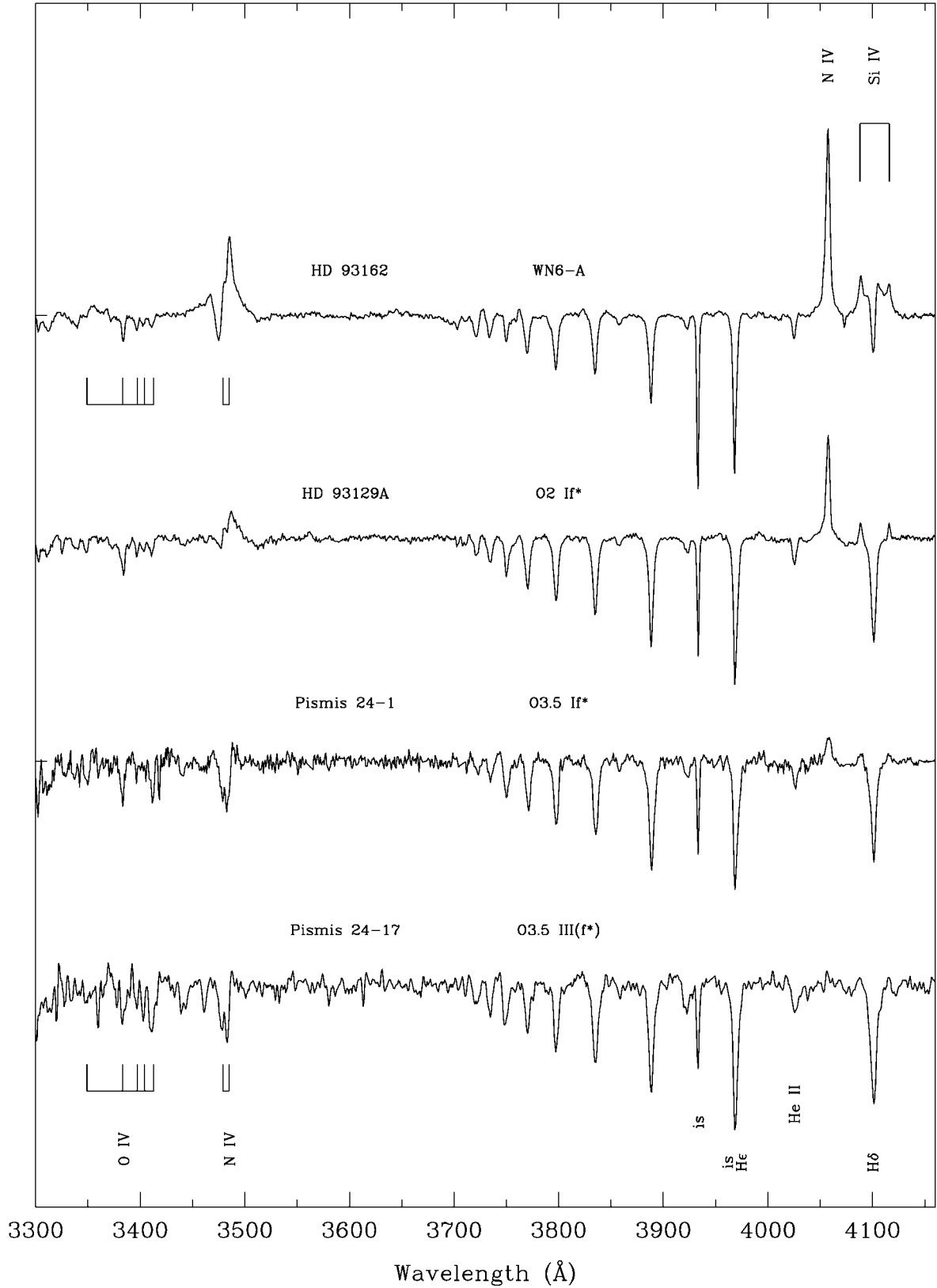
FIG. 1.—Rectified linear-intensity far-violet spectrograms of a WN-A and three luminous, very early O stars, separated by 0.5 continuum units. The absorption lines identified at the bottom are O IV λλ3348–49, 3381–85, 3397, 3404, and 3410–14; N IV λλ3479–85 (the latter a blend of two lines); interstellar Ca II λ3933; Hε λ3970 blended with interstellar Ca II λ3968; He II λ4026; and Hδ λ4101. The N IV λ4058 and Si IV λλ4089, 4116 emission lines are identified at the top (and the O IV, N IV absorption-line brackets are replicated).
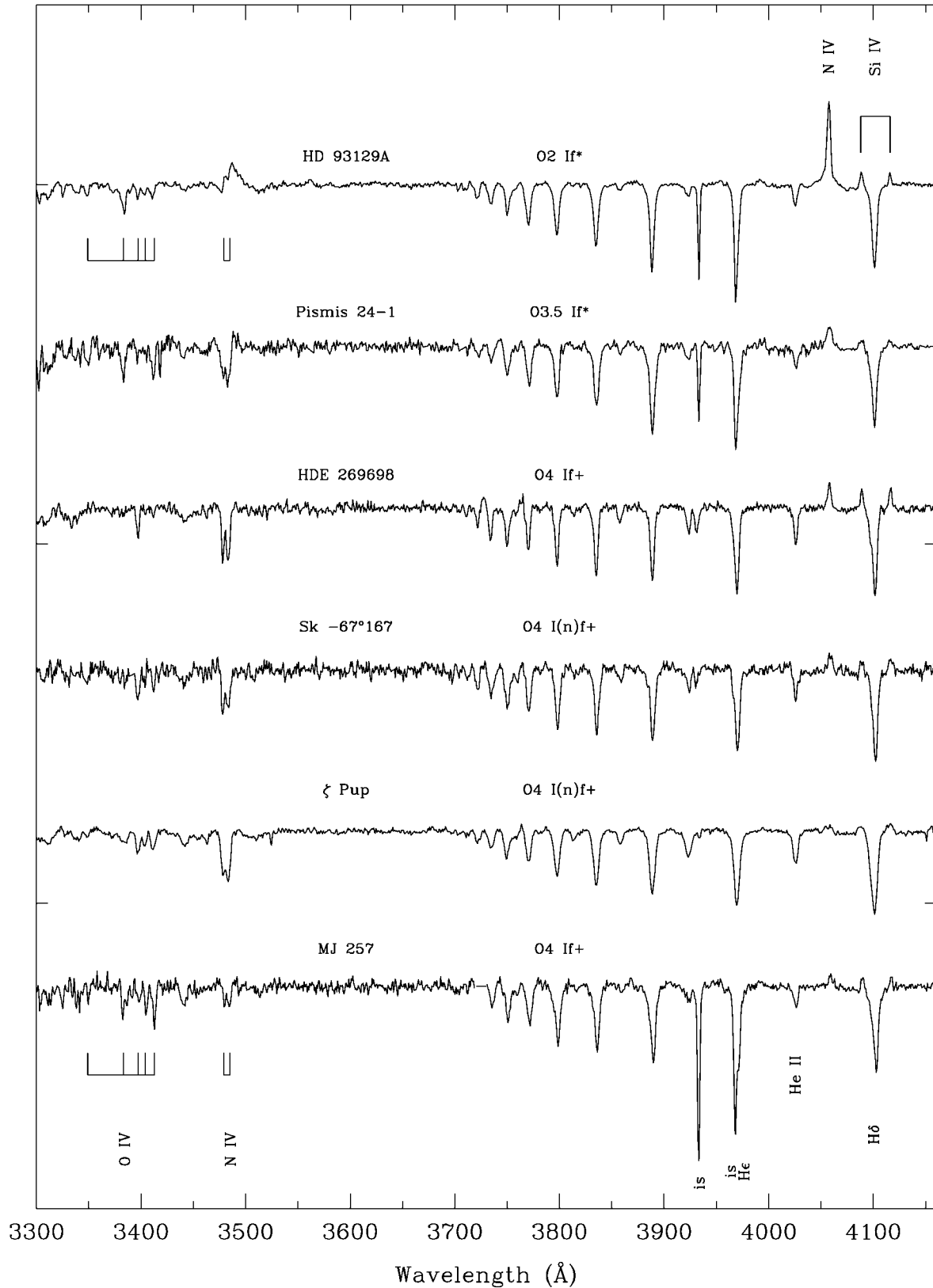
FIG. 2.—Far-violet spectrograms of six early-Of stars, separated by 0.4 continuum units. See the Fig. 1 caption for the line identifications.
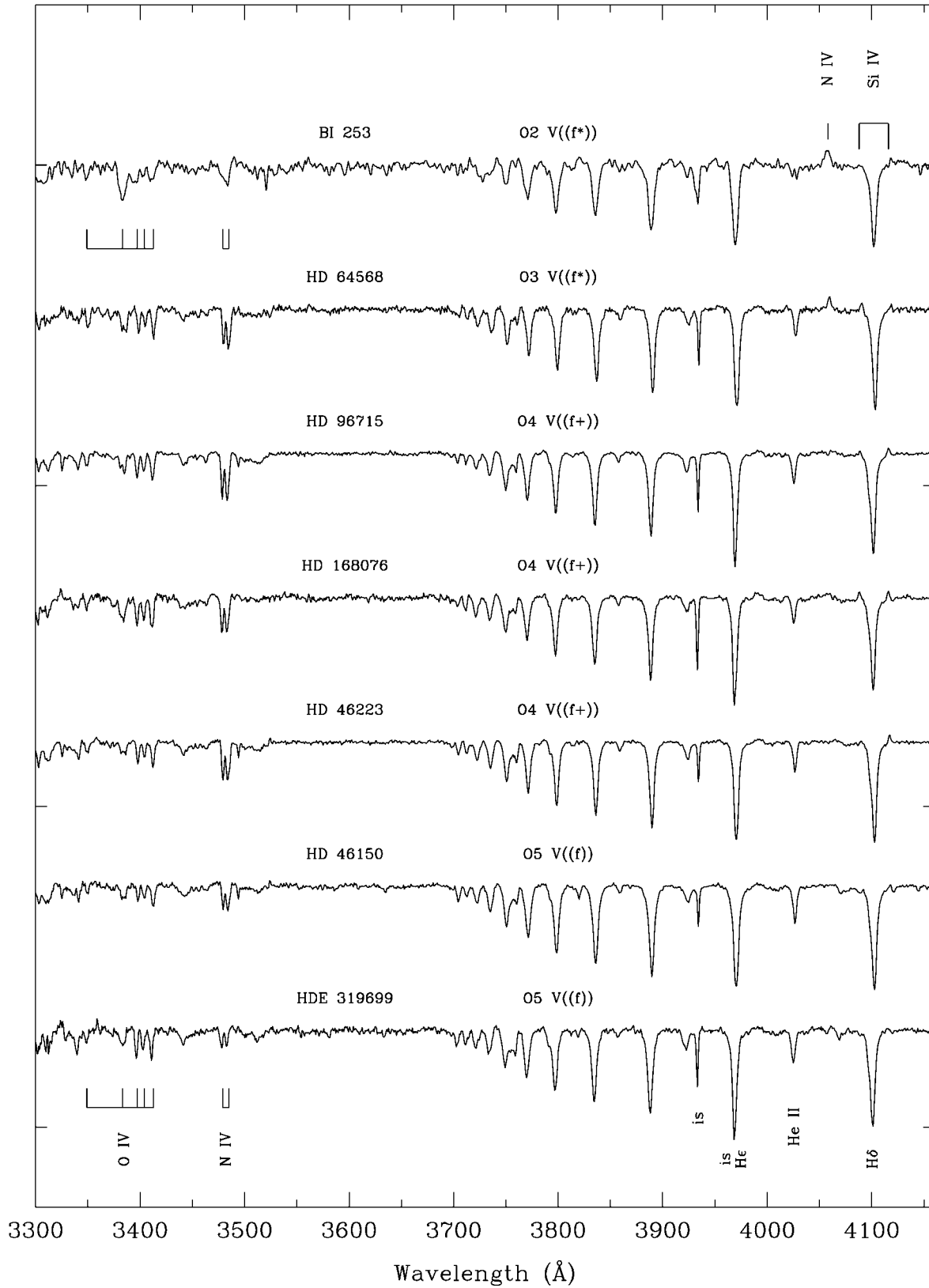
FIG. 3.—Far-violet spectrograms of seven early-O main-sequence stars, separated by 0.4 continuum units. See the Fig. 1 caption for the line identifications.
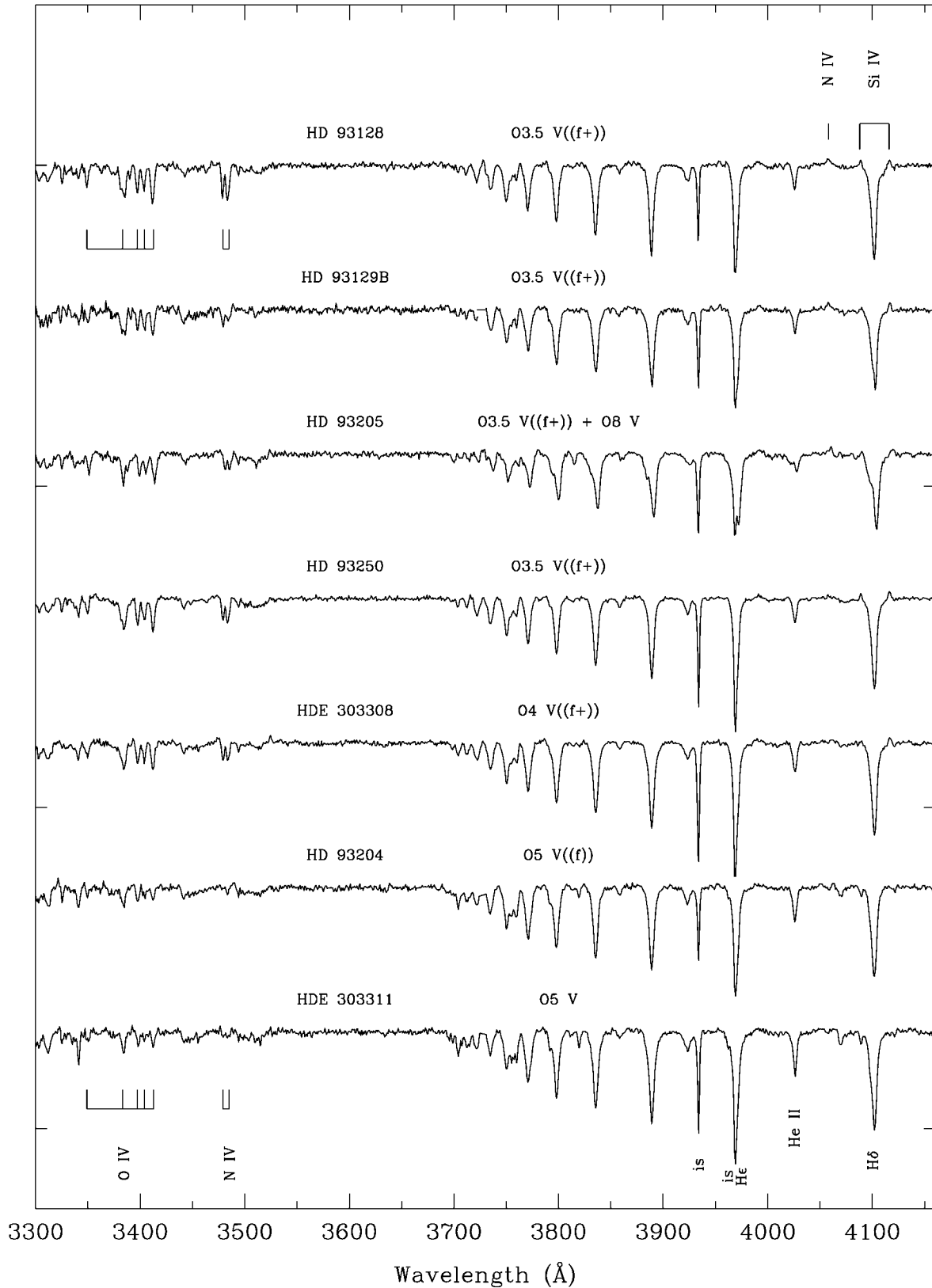
FIG. 4.—Far-violet spectrograms of seven early-O main-sequence stars in the Carina Nebula, separated by 0.4 continuum units. See the Fig. 1 caption for the line identifications. HD 93205 is a well-known sb2 (Conti & Walborn 1976; Morrell et al. 2001).

3.4. Carina Nebula Main-Sequence Stars

All of the stars in Figure 4 are located in the Carina Nebula (NGC 3372). Again, there is a strong indication of a substantial decline in the strengths of both the N IV and O IV features between spectral types O4 and O5. In sharp contrast with the spectra in Figure 3, however, all of these except for one have N IV *weaker* than O IV. This result indicates a systematic difference in age and/or initial rotational velocities between the Carina Nebula stars and those in the other groups illustrated in Figure 3, except for HDE 319699 in NGC 6334, which is similar to the Carina stars. The exception to this trend in Carina, HD 93128, is surprising. Along with HD 93129B, it is a likely zero-age main-sequence star located in the very compact cluster Trumpler 14, which may be younger than Trumpler 16, to which the other stars (with the possible exception of HDE 303311, which may be a background object or a subluminous escapee from Tr 14) belong (Walborn 1973, 1982, 1995; Morrell et al. 1988; Penny et al. 1993). The only currently available explanation would be that HD 93128 had a higher initial rotational velocity than its colleagues; binary evolution is a less attractive alternative in this case, because of the object's extreme youth.

4. CONCLUSIONS

With regard to our original objective of investigating the N IV and O IV lines near 3400 Å in early O-type spectra as potential classification criteria, some useful constraints have been found. Although there is only one example of each type, there is a tendency toward the formation of an N IV P Cygni profile in both the O2 supergiant and dwarf spectra; however, such a tendency is not apparent in the O2 giant spectra discussed in Paper I. On the other hand, a change in the relative strengths of the O IV lines between O2 and later types is consistent with the spectra in Paper I; as discussed above, the effect is likely a result of a tendency toward emission in an O IV triplet in the hottest spectra. The overall strengths of these lines are rather constant in O3 and O4 spectra, but decline at O5.

A more striking, albeit unexpected, result is the apparent sensitivity of the N IV/O IV ratio in these features to CNO abundance anomalies, corresponding to differing degrees of evolutionary and/or rotational mixing (or possibly binary evolution in some cases). An important aspect of the results is further evidence that very massive stars mix while still on the main sequence. These interpretations are strongly supported by the modeling in Paper I. Other interpretive statements in this paper remain hypothetical, although likely, pending similar analyses of the spectra discussed here. The importance of high-resolution observations for definitive measurements and analysis is amply discussed in Paper I. Such observations of these stars are quite feasible with current instrumentation and should be pursued to quantify the empirical results obtained here. The implications of these results for an improved understanding of the early evolution of massive stars are also extensively discussed in Paper I. When these morphological discoveries have been placed on a physical basis, they can be expected to provide powerful diagnostics for comparison with rotating models of massive stars.

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