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SPECTRAL CLASSIFICATION OF WOLF-RAYET STARS

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ABSTRACT

Spectrograms of forty-nine stars are reproduced. The spectrograms and the spectral classification system are discussed.

Two parallel sequences within the WN sequence are recognized. They differ principally in emission band width and strength of the continuum. The sequence with the relatively weak narrow lines contains many W-R binaries.

In addition to the well-recognized carbon sequence that shows a regular increase of band width with excitation, a group of stars with relatively strong emission has been observed. The identity as a physical group is uncertain. A W-R star with only emission bands of helium and Hα is shown. Four Of stars are reproduced for comparison purposes.

I. INTRODUCTION

Present-day classification of the Wolf-Rayet stars is based on a system developed by Beals and adopted by the International Astronomical Union in 1938. Subsequent interest in these stars was spurred by the discovery of the binary and eclipsing nature of HD 193576 (V444 Cygni). The ensuing decade brought the recognition of a number of binary systems, notable among which are the eclipsing systems HD 214419 (CQ Cep), HD 168206 (CV Ser), and CX Cep. The decade also saw the spectroscopic and photometric analyses of V444 Cyg lend support to widely differing physical interpretations of a Wolf-Rayet (W-R) star.

Recent renewal of interest in these stars stems from studies in stellar evolution and from recent attempts to explain the origin of broad emission lines in terms of forced rotational ejection (Limber 1964). This new interest is the basis for the present reconsideration of the classification of Wolf-Rayet stars.

II. CLASSIFICATION SYSTEM BY BEALS

The classification used up to the present time was proposed by Beals (1938). It consists of criteria such as line ratios and visibility of emission features, and a list of standard stars. The stars were separated into two parallel sequences, nitrogen and carbon. In addition to He I and He II, which are common to both sequences, the nitrogen sequence has emission features of N III, N IV, and N V while the carbon sequence has emission features principally of C II to C IV and O II to O V. Other ionization states and elements are minor contributors. In the carbon sequence Beals observed a relation between band width and spectral type. The earliest stars had band widths of 80 Å against only 10 Å for those of lowest excitation.

The nitrogen and carbon sequences were separated into four and three subdivisions, respectively, designated as WN5 to WN8 and WC6 to WC8. Excitation criteria and typical stars follow:

Nitrogen Sequence

WN5:
- N V λλ 4605–4622/He II λ 4686 = 0.2
- He I λ 5875/He II λ 5411 = 0.1
- N V λ 4945 present
- Typical stars: HD 187282 and HD 211564

WN6:
- He I λ 5875/He II λ 5411 = 0.5
- Band at λλ 4600–4660 present and strong
- N IV λ 4938 present
- Typical stars: HD 191765 and HD 192163

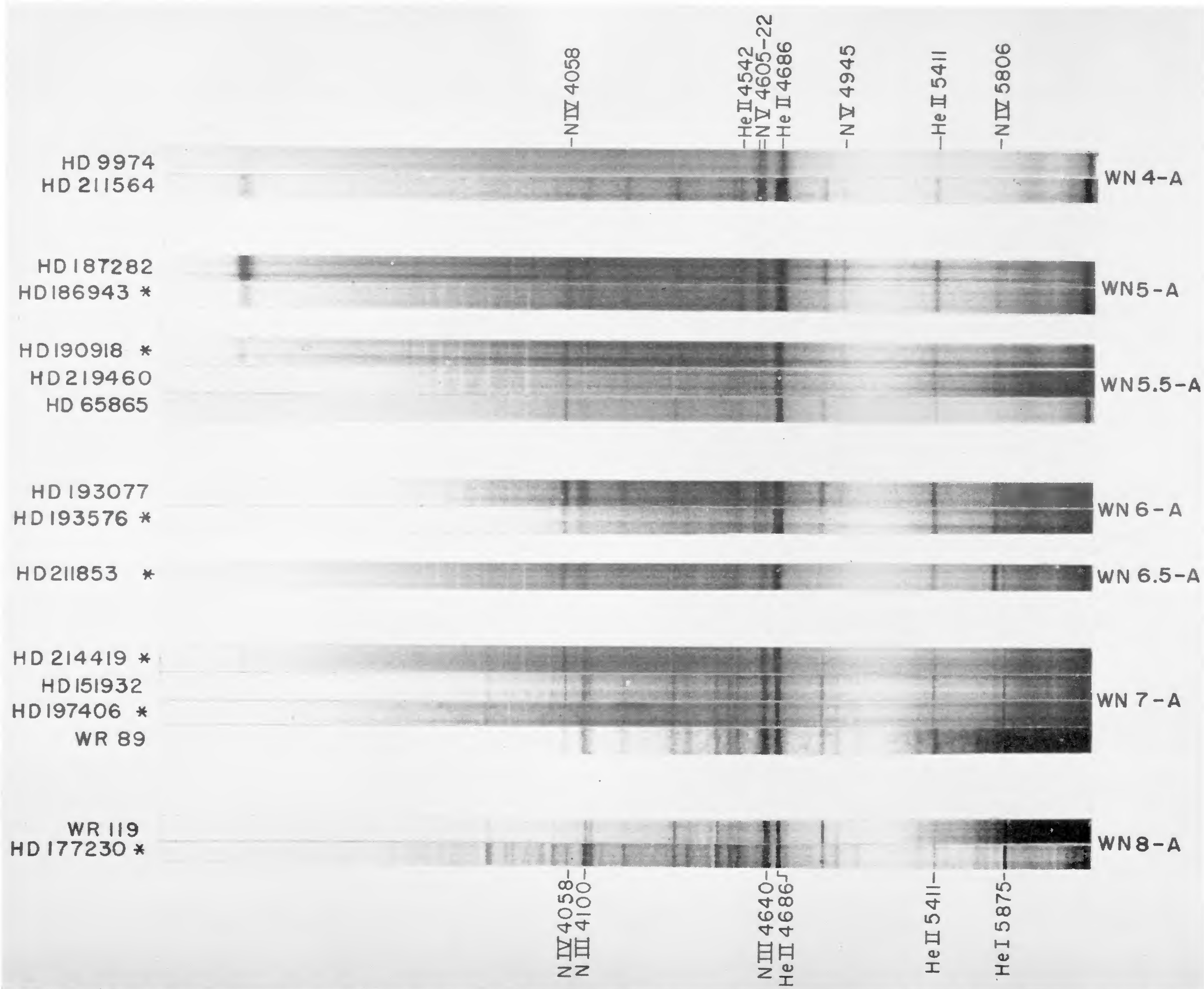

FIG. 1.—The WN-A sequence. The W-R numbers refer to Roberts' (1962) catalogue. The spectrogram of W-R 89 was taken with one-half the

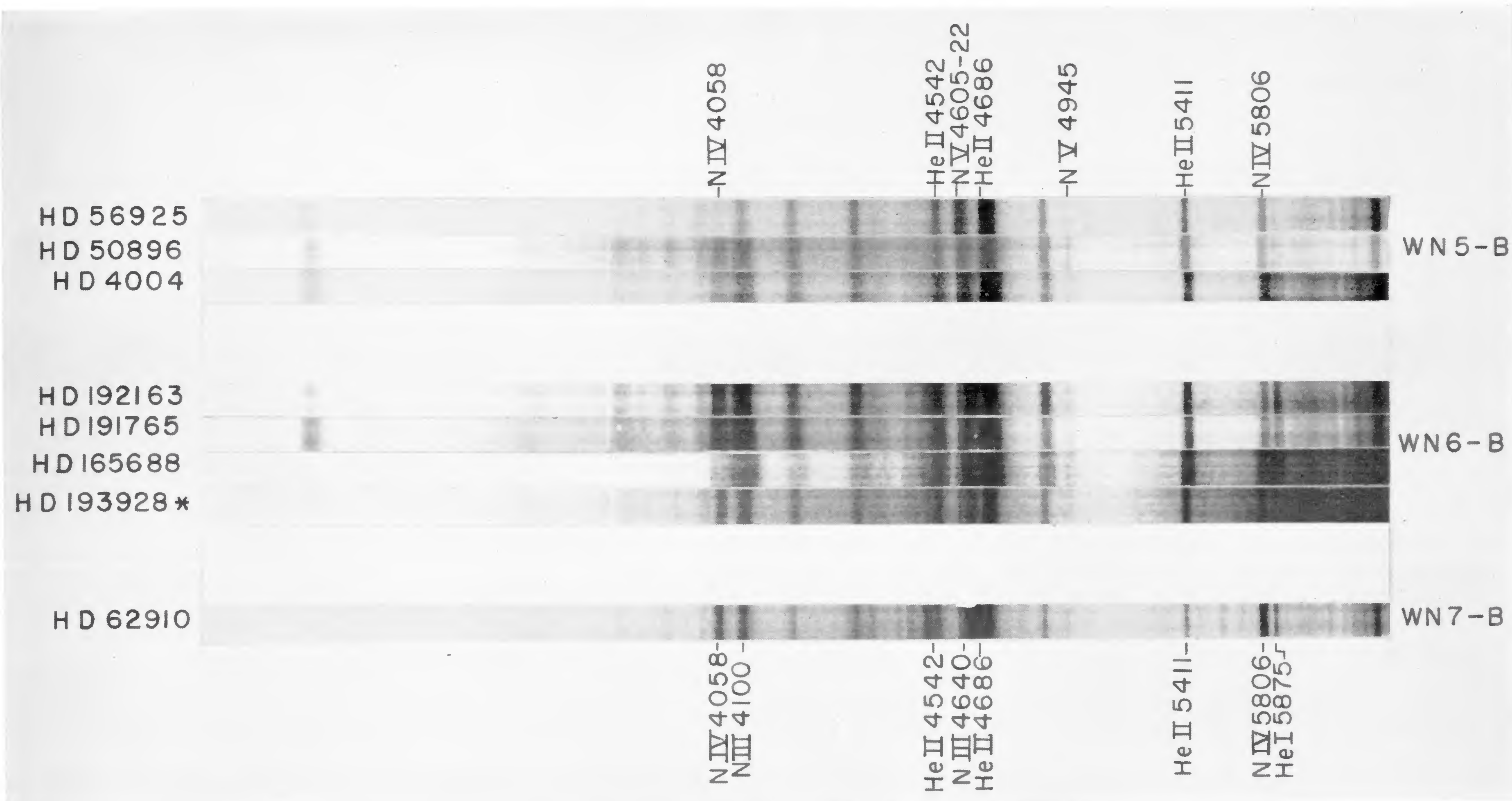

Fig. 2.—The WN-B sequence. HD 193928 is the only known binary in the group. $P = 21.6$ days

WN7:
N III λ 4640/He II λ 4686 = 0.5
He I λ 5875/He II λ 5411 = 1.5
Typical stars: HD 151932 and HD 92740

WN8:
N III λ 4640/He II λ 4686 = 1.5
He I λ 5875/He II λ 5411 = 5.0
Typical Stars: HD 177230 and HD 96548

Carbon Sequence

WC6:
C III λ 5696/C IV λ 5812 = 0.3
C III λ 5696/O V λ 5592 = 1.2
C II λ 4267/C IV λ 4786 = 0.0
C III λ 4650 and He II λ 4686 not resolved
C IV λ 5812 and He I λ 5875 not resolved
Band width approximately 70 Å
Typical stars HD 16523 and HD 165763

WC7:
C III λ 5696/C IV λ 5812 = 0.7
C III λ 5696/O V λ 5592 = 8.0
He I λ 5875/He II λ 5411 = 1.5
C III λ 4650/He II λ 4686 = 4.0
C II λ 4267/C IV λ 4786 = 1.0
C III λ 4650 and He II λ 4686 just resolved
Band width approximately 35 Å
Typical stars: HD 192103 and HD 119078

WC8:
C III λ 5696/C IV λ 5812 = 3.0
He I λ 5875/He II λ 5411 = 5.0
C III λ 4650/He II λ 4686 = 9.0
C II λ 4267/C IV λ 4786 = 2.0
Band width approximately 10 Å
Typical stars: HD 184738 and HD 164270

III. OBSERVATIONS

For the present study of the classification of Wolf-Rayet stars, well-widened slit spectrograms were obtained with the quartz prism spectrograph of the McDonald Observatory. The linear dispersion with the f/2 Schmidt camera is 150 Å/mm at Hγ. Eastman 103a-F emulsion was used throughout.

IV. CLASSIFICATION OF WN STARS

This sequence was divided into two parallel sequences which we have called WN-A and WN-B. Stars in sequence WN-A, illustrated in Figure 1, have relatively narrow lines, strong continuum, and most exhibit absorption lines characteristic of O–B stars. Many are known binaries.

In contrast, broad emission lines characterize the spectra of members in the WN-B sequence. These are illustrated in Figure 2. Only one star in the sequence, HD 193928, is a known binary. Its period is relatively long, 21.8 days.

Stars in the WN-B sequence encompass a smaller range in ionization than those in the WN-A sequence. This difference is probably real, although the sample is small. However, the observed range in ionization in a single spectrum appears to be greater for stars in the WN-B sequence.

It is difficult to establish useful line ratios for the classification of the WN stars. N V tends to be weak or blended with N III and He II blends with many of the N III lines. Moreover, He I λ 5875, a line which figured importantly in the original classification system, is in absorption in WN4-A and WN5-A stars but in emission throughout the WN-B series. In selecting line ratios it has been assumed that the band centered near 5806 is due to N IV rather than C IV since other evidence for the presence of C IV, especially the strong blend centered near λ 4850, is lacking. In agreement with Swings's (1942) line ratios of different elements should be given low weight. Table 1 gives line ratios for the classification of the WN stars.

V. CLASSIFICATION OF WC STARS

The classification by Beals rests largely on the ratios (C III λ 5692/C IV λ 5812) and (C II λ 4267/C IV λ 4786). The first ratio shows a regular variation over the range of spectral types illustrated in Figure 3 and has again been used as a primary criterion.

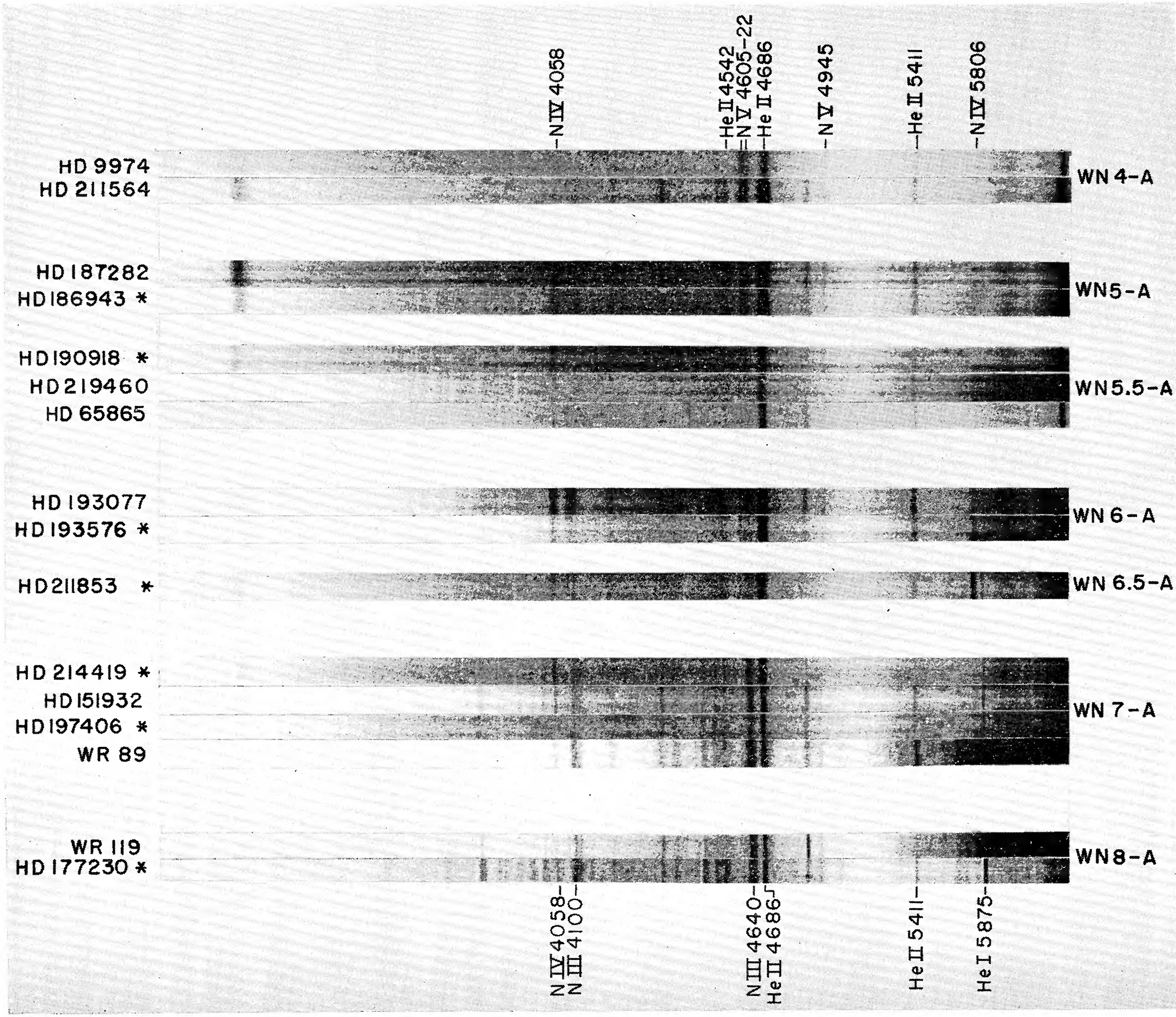

FIG. 1.—The WN-A sequence. The W-R numbers refer to Roberts' (1962) catalogue. The spectrogram of W-R 89 was taken with one-half the

Possible blending of He II λ 5694 is not serious. The second ratio is less useful. The two lines differ in wavelength by 500 Å and C II λ 4267 becomes vanishingly faint at WC7. The ratio (C II λ 4267/C IV λ 4441) can be used as a substitute when a pair of lines in the blue is needed. Blending of He I with C IV λ 4441 appears to be unimportant in stars of lowest ionization and negligible in others.

The ratios (He I λ 5875/He II λ 5411) and (C III λ 4650/He II λ 4686) in stars of low ionization and (C III λ 5696/O V λ 5592) in stars of relatively high ionization were used by Beals. The first ratio is a useful check on the classification indicated by (C III λ 5696/C IV λ 5812) when He I λ 5875 is not blended with C IV λ 5812. The second ratio is a less sensitive test because of the great difference in line strengths. The third ratio can give a

TABLE 1

LINE RATIOS FOR WN STARS

WN4.......	(N IV λλ 4058/ N V 4605–22)	....	(N IV λ 5806/ N V λ 4945)	(N V λλ 4605–22/ He II λ 4542)
WN5.......	(N IV λ 4058/ N V λλ 4605–22)	....	(N IV λ 5806/ N V λ 4945)	(N V λλ 4605–22/ He II λ 4542)
WN6.......	(N IV λ 4058/ N V λ 4605)	(N IV λ 4058/ N III 4100)	(He I λ 5875/ He II λ 5411)	(N III λ 4640/ He II λ 4686)
WN7.......	....	(N IV λ 4058/ N III λ 4100)	(He I λ 5875/ He II λ 5411)	(N III λ 4640/ He II λ 4686)
WN8.......	....	(N IV λ 4058/ N III λ4100)	(He I λ 5875/ He II λ 5411)	(N III λ 4640/ He II λ 4686)

TABLE 2

LINE RATIOS FOR WC STARS

WC5..........	(C III λ 5696/ C IV λ 5812)	....	....	....
WC6..........	(C III λ 5696/ C IV λ 5812)	(C II λ 4267/ C IV λ 4441)	(C II λ 4267/ C IV λ 4786)	....
WC7..........	(C III λ 5696/ C IV λ 5812)	(C II λ 4267/ C IV λ 4441)	(C II λ 4267/ C IV λ 4786)	[He I+(C III) λ 5875/ He II λ 5411]
WC8..........	(C III λ 5696/ C IV λ 5812)	(C II λ 4267/ C IV λ 4441)	(C II λ 4267/ C IV λ 4786)	[He I+(C III) λ 5875/ He II λ 5411]

classification that differs significantly. For example, O V λ 5592 is weak in HD 17638. This discrepancy does not appear to be a simple effect of abundance; other O V lines in HD 17638 are normal in strength.

A spectral type WC5 has been added to Beals's classification. This subclass is marked by very strong lines of C IV and weaker lines of C III, O V, and Hα. The strong broad feature centered near λ 4670 is a blend of C IV doublets and possibly contributions from C III triplets centered at λ 4648 and λ 4668 and He II λ 4686. The strong feature at λ 5812 arises from the 3 ^2S–3 ^2P doublet, the lowest-lying feature in the C IV energy-level diagram giving rise to an observable transition. Because of the sharp contrast between features of the WC5 stars, classification is done on the basis of general appearance.

The line ratios found most useful in the present classification of the WC stars are summarized in Table 2.

The correlation between band width and ionization for the WC stars is confirmed. A possible exception is HD 193793 illustrated in Figure 5 (see below). Its spectrum shows very broad bands of C III and C IV, while the emission feature of He I + C III at λ 5875

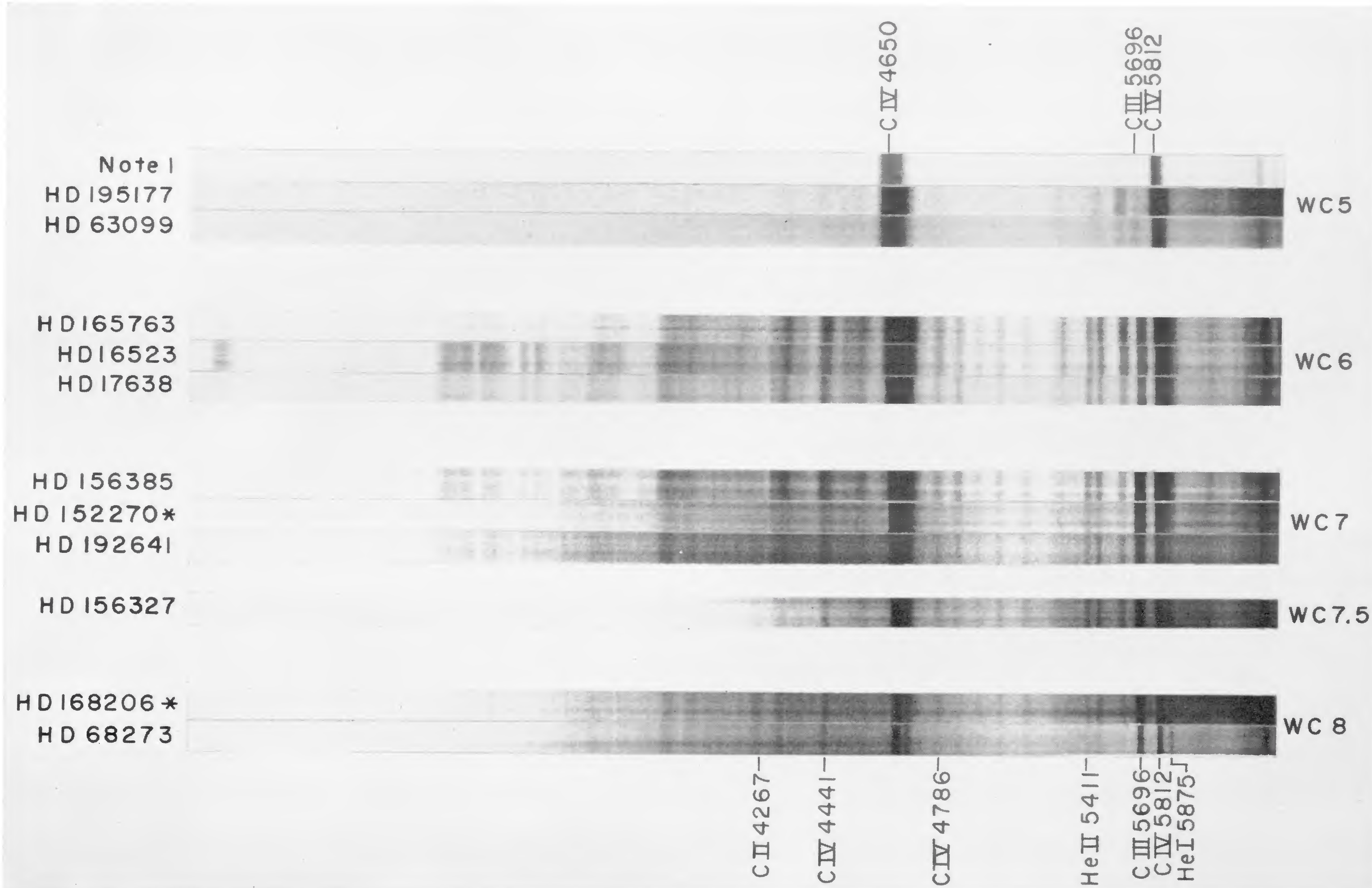

FIG. 3.—The WC sequence. Note 1. (1900) $\alpha = 21^h46^m.4$; $\delta = +50°13'$

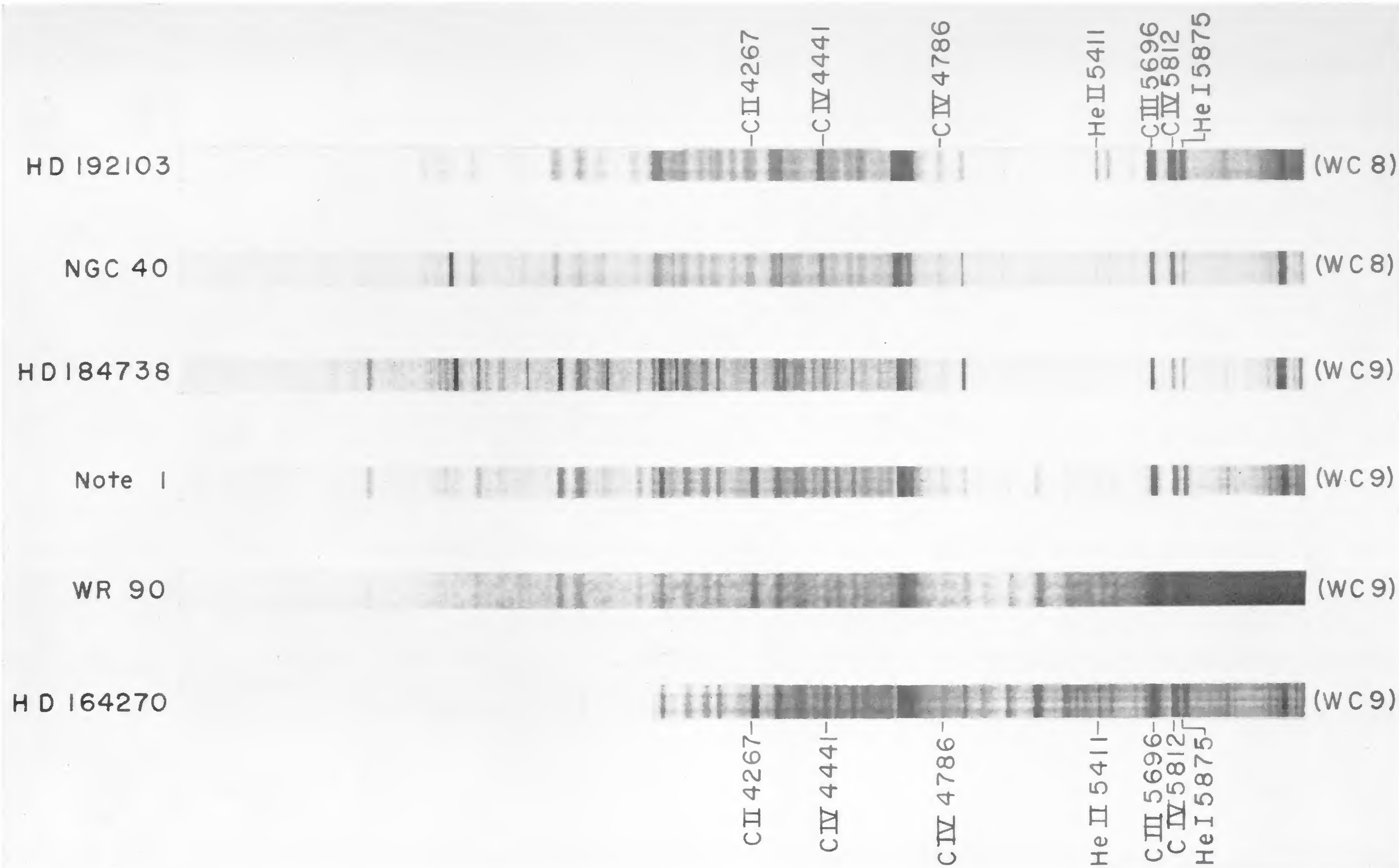

FIG. 4.—Wolf-Rayet carbon stars differing from the sequence illustrated in Fig. 3. Note 1. (1875) $\alpha = 18^h31^m.1$; $-10° + 13'$. HD 184738 is BD+30°3639; Campbell's "hydrogen-envelope star."

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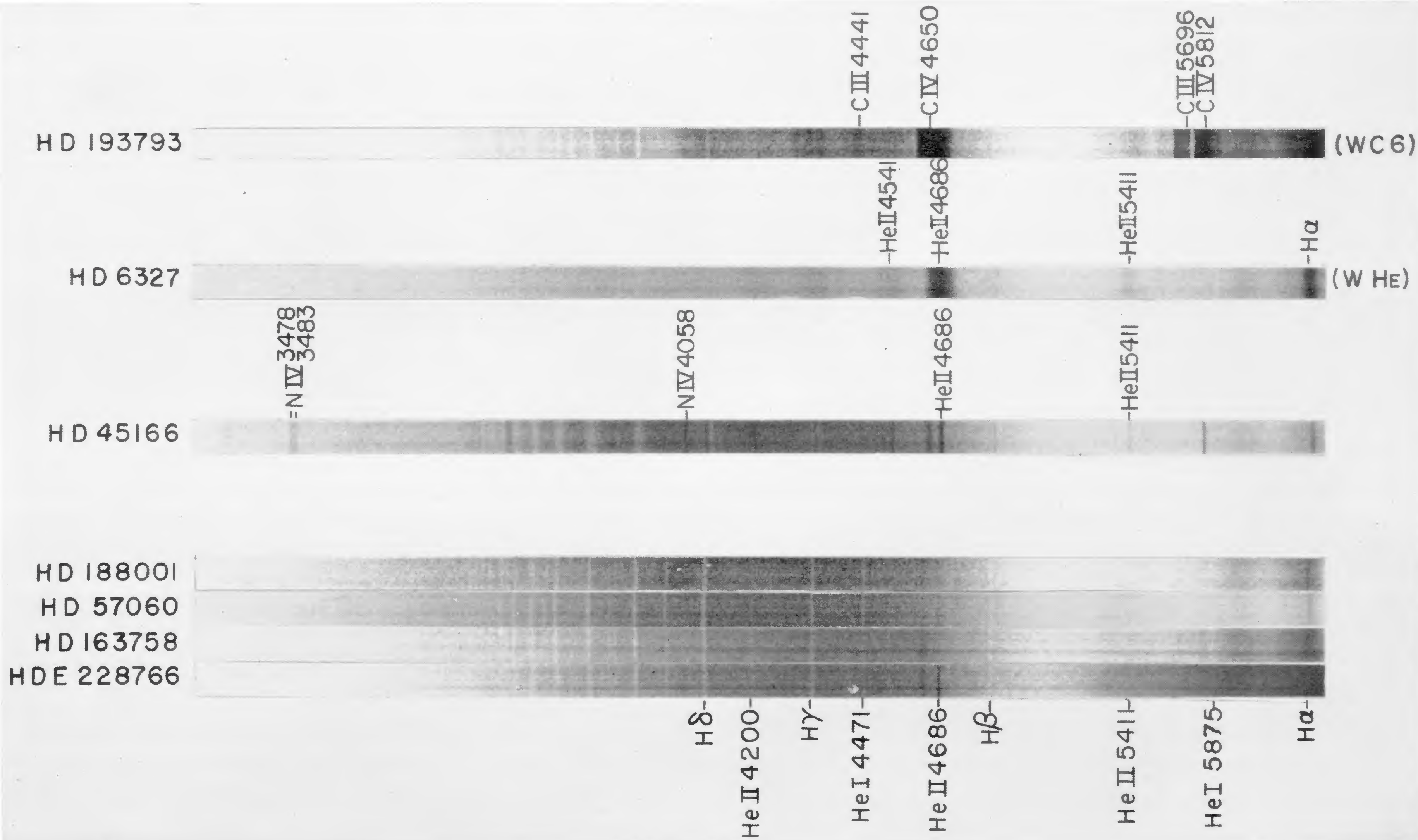

Fig. 5.—Miscellaneous stars. HD 193793 is discussed in the text. HD 6327 seems to be a Wolf-Rayet star without either nitrogen or carbon. HD 45166 is a star often associated with Wolf-Rayet stars. Four Of stars are illustrated for comparison purposes.

is much sharper. Hα is in emission and higher numbers of the Balmer series are in absorption. Both absorption and emission lines show variation in radial velocity but no period has been reported (McDonald 1947). Classification primarily on the basis of the (C III λ 5696/C IV λ 5812) ratio gives WC6.

A group of WC stars that do not fit neatly into the WC sequence discussed above has been arranged in a sequence of decreasing excitation in Figure 4. The distinguishing feature is greater emission-line strength relative to the continuum. Two stars in the group are nuclei of planetary nebulae. A further characteristic is the prominence of the violet absorption edge of C III λ 4650. The exception is the nucleus of NGC 40. In the opinion of the authors, it is not possible to conclude, on the basis of the illustrated spectrograms, whether or not these stars constitute a separate sequence within the carbon sequence. The presence of nebular emission lines in two stars and the lower-resolution spectrogram of W-R90 may enhance the appearance of heterogeneity within the group.

VI. OTHER EMISSION STARS

The homogeneity of plate material and the classification system make possible further clarification of the relationship of various emission stars to the classification sequences of Wolf-Rayet stars discussed above. The spectrum of HD 6327 shown in Figure 5 has only broad emission bands of the Pickering series and λ 4686 of He II and Hα. There appears to be no trace of carbon, nitrogen, or oxygen. According to the original criterion of emission band dominance and width this is a Wolf-Rayet star. A designation WHe is proposed.

The well-known star HD 45166, often associated with Wolf-Rayet stars, is also illustrated in Figure 5. This star has emission lines of carbon, nitrogen, and oxygen in relatively high states of ionization. Its emission lines are weaker and sharper than those of any star in the Wolf-Rayet sequences.

For comparison purposes, spectra of four Of stars are illustrated in Figure 5. They are arranged in order of increasing temperature. HDE 228766 had previously been classified as a Wolf-Rayet star. The spectrum of 29 CMa was taken when the emission was faint.

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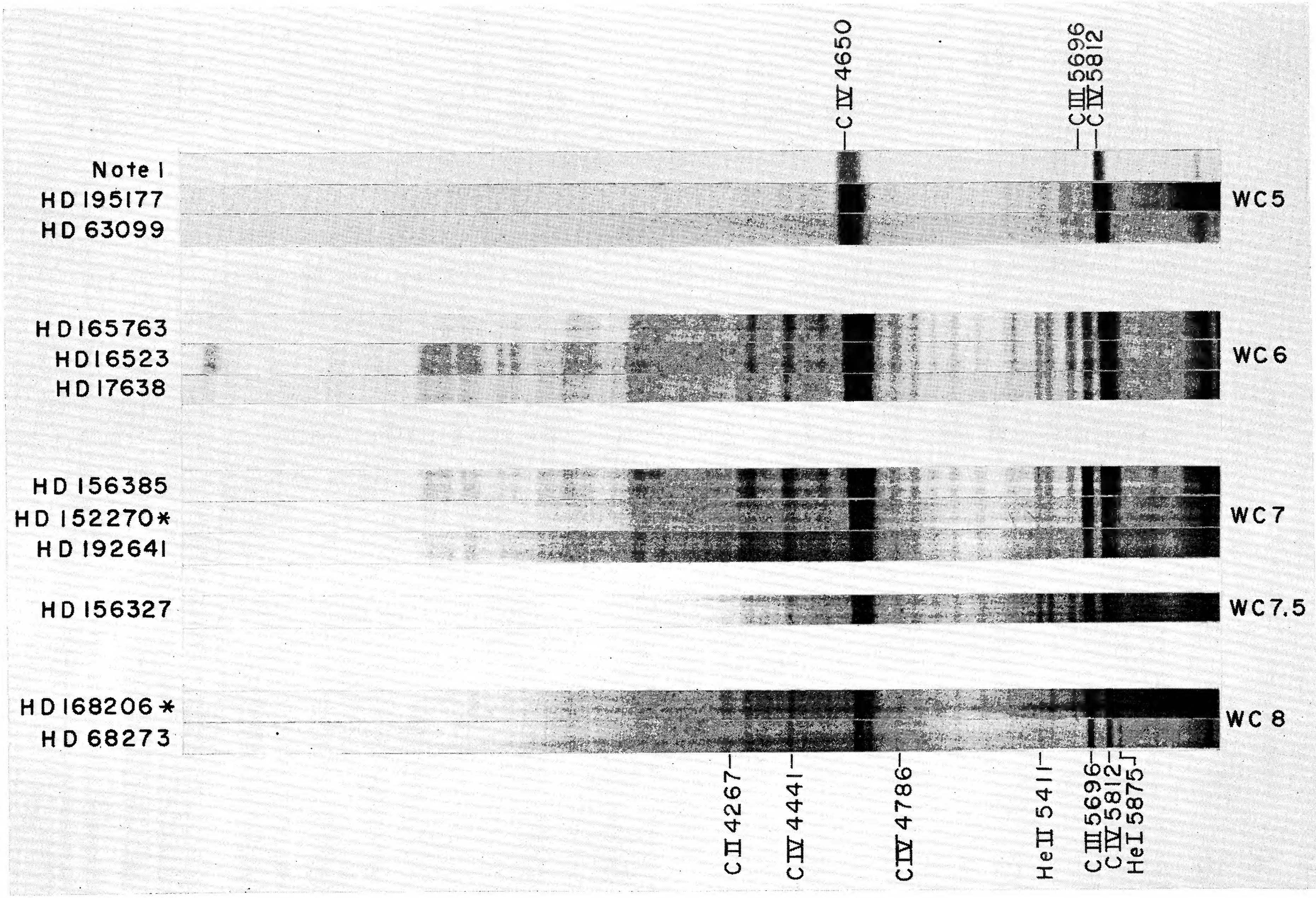

FIG. 3.—The WC sequence. Note 1. (1900) $\alpha = 21^{h}46^{m}.4$; $\delta = +50°13'$