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# CRITERIA FOR THE SPECTRAL CLASSIFICATION OF B STARS IN THE ULTRAVIOLET

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## ABSTRACT

We have developed a set of criteria for the classification of B stars from ultraviolet spectra alone, using MK standards drawn from the optical region. The observational material consists of archival high-dispersion spectra obtained by the SWP camera on the *IUE* spacecraft. The spectra were resampled to a resolution of 0.25 Å, normalized, and plotted on a uniform scale of 10 Å $cm^{-1}$. Approximately 100 stars having normal MK spectral types in the range B0–B8, III–V, have been classified. Only photospheric absorption lines were used as classification criteria; the Si II and Si III spectra were found to be particularly useful. The C IV, Si IV, and N V lines, which in early B stars originate in the stellar wind, were not used in the two-dimensional spectral type/luminosity classification, but the appearance of these stellar wind lines was compared with the corresponding lines in the standard stars, and some anomalies were noted. On the whole, the ultraviolet spectral types are very consistent with the optical MK types, implying that it is possible to do two-dimensional spectral classification in the ultraviolet without any knowledge of the optical spectrum.

*Subject headings:* stars: early-type — stars: spectral classification — ultraviolet: spectra

## 1. INTRODUCTION

The purpose of a spectral classification system is to create a framework within which normal stars can be arranged in groups that may have similar physical properties. The groups are delineated only by means of features visible in the stellar spectra. The average values of the physical properties of the stars in each group ($T_{eff}$, $L$, $R$, $M$, etc.) may be determined by a suitable calibration procedure. Stars that do not fit into any "normal" group can then be isolated for further study, and this is one of the most powerful methods of identifying astrophysically interesting objects. Groups of "abnormal" objects are themselves often the subject of further classification efforts (e.g., Be stars, Ap stars).

The MK classification system has proved its utility for these purposes in the decades since its inception (Morgan, Keenan, & Kellman 1943). As a two-dimensional system using both temperature types and luminosity classes, it is better able than the earlier Henry Draper system to define homogeneous groups of stars in the Hertzsprung-Russell diagram. In addition to its strict adherence to the principle of using *only features visible in the stellar spectrum* as classification criteria, the MK system has the unique property of being *completely defined by the set of standard stars* (Johnson & Morgan 1953). Thus, although the usual criteria for MK classification were set up for spectra taken at moderate dispersion in the optical region, there is no reason in principle why the MK standards cannot be used to establish a new set of criteria for spectra taken at a different dispersion, or over a different wavelength range. In fact, Morgan, Abt, & Tapscott (1978) state that "the convention of assumed constant spectral type for standards in all spectral wavelengths is the pivot on which the entire MK-78 system rests." Such a procedure must be validated in practice, however, to guard against anomalies in the individual stars and against systematic errors that could be introduced if the new criteria are not well correlated with the basic (photospheric) stellar properties.

The availability of a large number of far-ultraviolet stellar spectra, thanks to the many years of successful operation of the *International Ultraviolet Explorer* (*IUE*) (Kondo, Boggess, & Maran 1989), has made it both possible and desirable to establish a method of performing spectral classification in the ultraviolet without reference to optical criteria. Indeed, for many of the early-type stars observable by satellite, the blue and visual magnitudes are so faint that prohibitive amounts of large-telescope time would be required to obtain ordinary classification spectra.

Previous studies of satellite ultraviolet spectra (Panek & Savage 1976; Bidelman 1977; Henize, Wray, & Parsons 1981; Abbott, Bohlin, & Savage 1982) have generally indicated a good correlation between optical spectral types and ultraviolet features in early-type stars. Using high-resolution *IUE* data, Walborn & Panek (1984a, b, 1985) and Walborn & Nichols-Bohlin (1987) showed that the ultraviolet spectra morphology of the O and OB supergiants, including both photospheric and wind lines, closely tracks the optical spectral types. An atlas illustrating these effects was published by Walborn, Nichols-Bohlin (1987) showed that the ultraviolet spectral morphology a comprehensive classification system.

Heck et al. (1984, hereafter HEJJ) published an atlas of over 200 low-dispersion *IUE* spectra. For the O, B, and A stars, they developed new ultraviolet spectral sequences that were found to be closely parallel to the corresponding MK types. The use of high-resolution, rather than low-resolution, *IUE* data should allow more sensitive temperature and luminosity criteria to be defined. A large enough body of such data now exists in the *IUE* archives to cover all the MK subtypes of B stars in luminosity classes III, IV, and V. Although the MK process (Morgan 1984) could be used to establish a new ultraviolet morphological system entirely from first principles, a desirable sanity check, as well as some immediate utility, can be gained by first testing the applicability of the MK system itself (through the use of its standards) in the ultraviolet. Plans

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for this project were first published by Rountree, Sonneborn, & Panek (1984).

We note that HEJJ state that "One cannot simply transfer MK classifications to the ultraviolet spectral range, because the order of the MK system in the 3500–4800 Å spectral range is not identical to that which can be established in the ultraviolet spectral range." Heck (1986) reiterated this point at a session of Commission 45 (Stellar Classification) on "Difficulties of Extrapolating the MK System to Other Wavelength Ranges," which he chaired at the 1985 General Assembly of the International Astronomical Union. The question here is partly semantic (what is meant by "transferring" or "extrapolating" the MK system?), but there is also a substantive issue, to which we shall return in the discussion in § 6.

## 2. OBSERVATIONAL MATERIAL

Since one purpose of this project is to establish a framework of standards for ultraviolet classification, making use of the MK system, candidate stars were limited to those having normal MK spectral types (that is, without "e," "p," "n," or "nn" suffixes) in the range B0–B8, III–V, as classified by Rountree Lesh (1968); Hiltner, Garrison, & Schild (1969); or Morgan & Keenan (1973). In practice, this means that the sample was limited to stars having visual magnitudes brighter than about 6.5. The *IUE* archive of stars observed through 1983 (when this project was initiated) was searched for well-exposed spectra taken with the short-wavelength prime (SWP) spectrograph in the high-dispersion mode. An effort was made to select at least one MK standard (from Morgan & Keenan 1973 or Rountree Lesh 1968) for each spectral subtype and luminosity class, and to obtain a reasonable distribution of additional stars over the spectral-type range given above. Approximately 100 spectra were selected in this manner. Reprocessing was requested for those that had been taken before the improved extraction software was put into production (1981 November).

Some fundamental choices had to be made at the outset about how the data would be processed and presented for visual classification. Although the spectra used in this project are unwidened, it is possible to use the *IUE* photowrite procedure to produce artificial widening by replicating each pixel in the vertical direction. This produces pseudospectra that appear somewhat similar to the photographic spectra used in normal MK classification, with the advantage that astronomers already experienced in classification techniques could use the new material with very little retraining. An example of this processing method is shown in Figure 1 (Plate 17). The alternative is to use plots of the digital *IUE* data for classification purposes, thus requiring the astronomer to be retrained in the comparison of spectral features between one star and another. Despite the attractiveness of the former procedure, we ultimately rejected it for two reasons: (1) the process of pixel replication can at best produce spectral lines that are unrealistically straight and uniform compared with photographic plates, and at worst it may replicate noise to produce a spurious "line"; (2) the creation of artificially widened pseudospectra places an enormous burden on the *IUE* data processing facility, and most likely will not even be possible on a routine basis in the era of future satellites.

Having decided to use data plots as classification material, we were then faced with the choice of spectral resolution. Spectra having the full resolution of the *IUE* spectrograph in the high-resolution mode are not appropriate for MK classification, because major lines do not stand out prominently from the background, and useful blends are often resolved. Moreover, it is difficult for the eye to take in the entire high-resolution spectrum at one time, and the use of the spectrum *as a whole* is an important feature of MK classification. Panek (see Walborn & Panek 1984a) has already written software to resample *IUE* high-dispersion spectra to any desired resolution. We considered resolutions of 0.5 and 0.25 Å for use with our data. The former more closely approximates the resolution of traditional MK classification spectra (dispersion of about 125 Å $mm^{-1}$ in the blue), while the latter is similar to the higher resolution used by Walborn (1971) to classify O stars in the optical region. The effect of resampling at the two different rates is shown in Figure 2 for a slowly rotating star and a rapidly rotating star. The centers of some of the lines are seen to be severely affected by the 0.5 Å binning. We note that the central depth of a line is its most important feature in classifying from digital plots, whereas the equivalent width is what the eye senses on a photographic plate.

We therefore chose to process our data exactly as described by Walborn & Panek (1984a), using Panek's software. The spectra were resampled to 0.25 Å, normalized but not dereddened, and plotted on a uniform scale of 10 Å $cm^{-1}$. The final resolution is approximately 5000 at Lyman alpha. Since only well-exposed spectra (maximum *IUE* data number between 170 and 215) were chosen from the archives, the signal-to-noise ratio (S/N) is about the same for all the normalized spectra; it is approximately equal to 30. After plotting on a CalComp plotter, each individual spectrum was mounted on a 28 inch by 2 inch cardboard backing for ease in handling and intercomparison.

## 3. THE CLASSIFICATION METHOD

In general, we chose to follow the method used by Rountree Lesh (1968) in the MK classification of the bright northern B stars. Potential classification criteria identified by previous workers (especially Walborn, Nichols-Bohlin, & Panek 1985; HEJJ) were reviewed, and the available *IUE* spectra of the MK standard stars were scanned to see how these criteria varied with spectral type. In agreement with the work of Shore & Sanduleak (1984) and Massa (1989), the Si II, Si III, and Al III lines were seen to be especially useful. MK standard stars at B2 V and B2 III were used to establish a "zero point" for the provisional classification criteria, and a luminosity series of B2 spectra was set up from among the stars with optical types of B2.

All the other spectra were then divided into fairly large bins (e.g., B2.5–B4) based on their optical MK types, and luminosity criteria were established within each bin. Small homogeneous groups of UV spectra were collected around the MK standards within the larger bins, each representing a spectral subtype and luminosity class. If any of these groups did not contain an MK standard or a standard used by Rountree Lesh (1968), a new ad hoc standard was selected. Spectra that did not fit into any of the groups in their original bin were provisionally moved to a neighboring bin (that is, an earlier or later spectral type) for reclassification.

When all the stars had been classified in this way, the ultraviolet spectral types were compared with the optical MK types, and any differences were validated by re-comparing the ultraviolet spectra with the standards. Finally, the entire data set was reviewed from earliest spectral type to latest, to ensure that the lines selected as classification criteria varied smoothly and

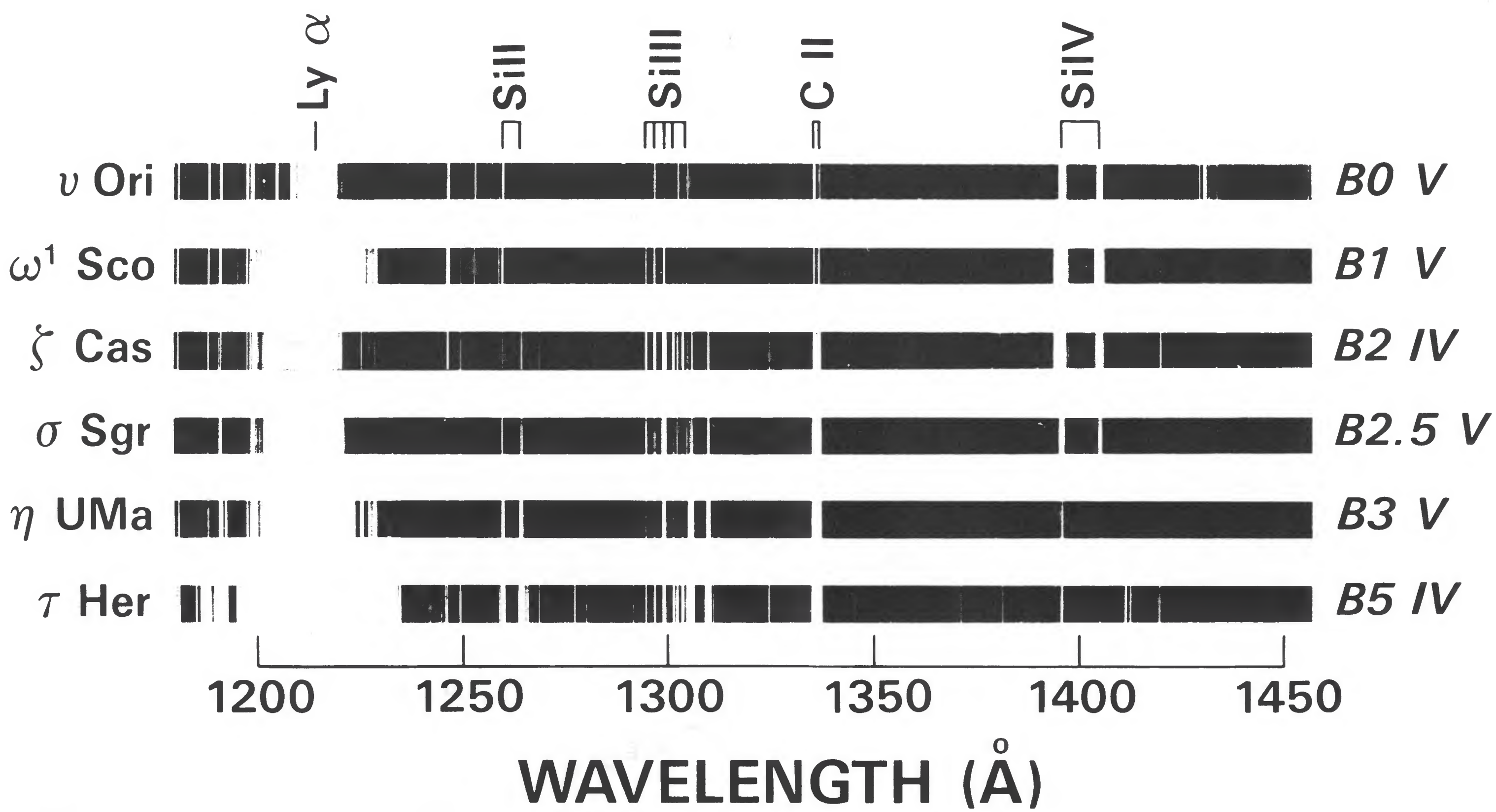


FIG. 1.—Photowrite sequence of *IUE* high-dispersion spectra, resampled to a resolution of 0.25 Å and artificially widened by pixel replication. A B star sequence from B0 through B5 is shown; with the exception of ζ Cas, all the stars are MK standards. The most prominent spectral features in the 1200–1450 Å region are marked. These are not necessarily the features used in spectral classification.

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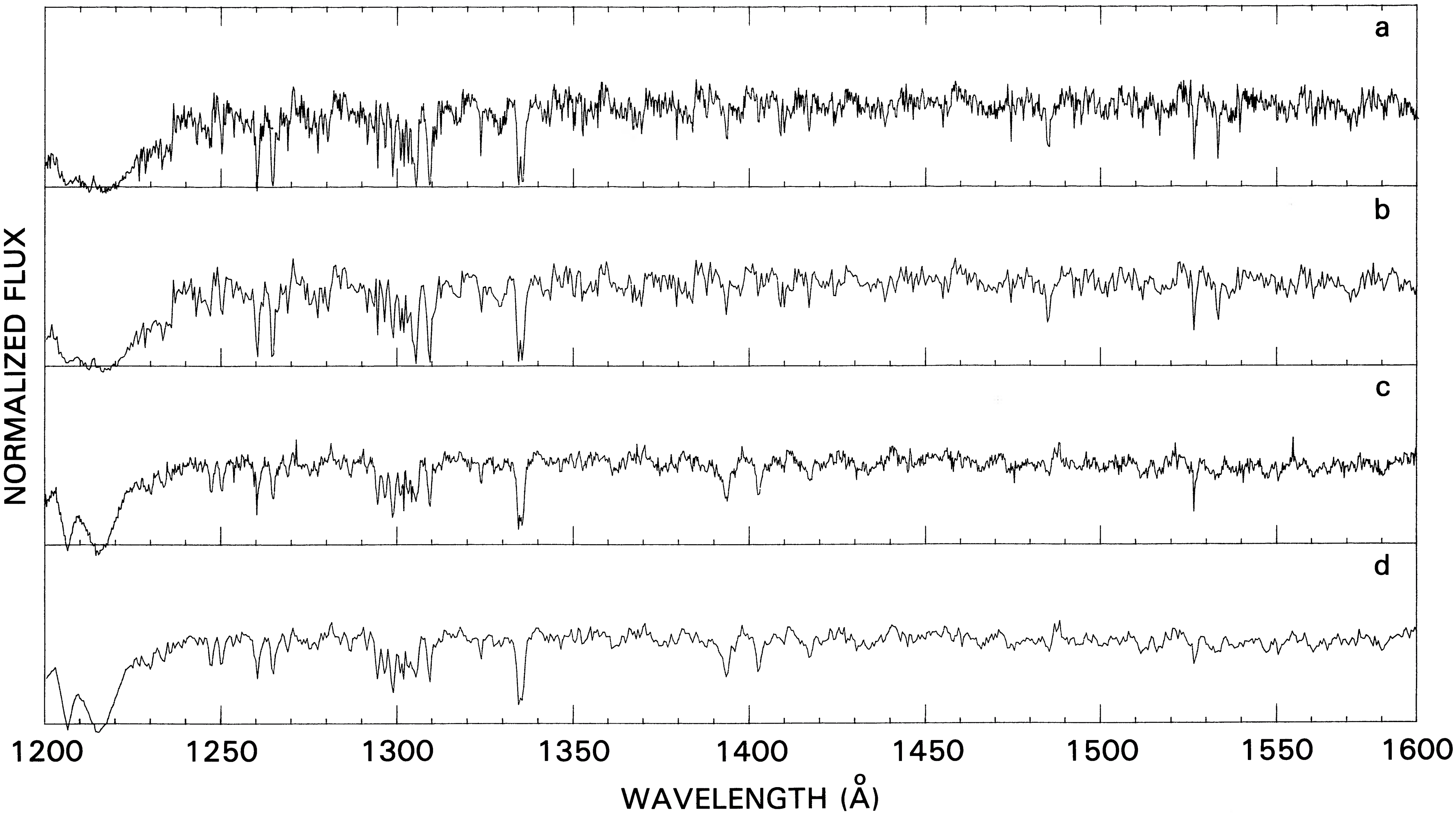


FIG. 2.—Effect of resampling resolution on *IUE* high-dispersion spectra of a narrow-lined star ($\tau$ Her, $v \sin i = 30$ km s$^{-1}$) and a broad-lined star ($\sigma$ Sgr, $v \sin i = 205$ km s$^{-1}$): (*a*) $\tau$ Her, 0.25 Å resolution; (*b*) $\tau$ Her, 0.5 Å; (*c*) $\sigma$ Sgr, 0.25 Å; (*d*) $\sigma$ Sgr, 0.5 Å.

that the stars had been classified consistently. Final classification criteria were selected at this point—those features that were most useful in matching nonstandards with standards, and that varied most smoothly with spectral type and/or luminosity class.

Figure 3 shows a series of main-sequence stars from B0 to B8, with the principal spectral-type criteria indicated. Figure 4 shows a luminosity series at spectral type B2. The spectra in these figures have been reduced by approximately 50% for inclusion in this paper. They are intended for illustrative purposes only. We plan to publish an atlas of standards and other representative spectra at full scale. The spectral plots in the atlas will be usable for actual classification work, unlike the prints that appear in photographic atlases. For accurate classification of photographic spectra, it is essential to use original plates.

## 4. PROBLEMS UNIQUE TO ULTRAVIOLET CLASSIFICATION

### 4.1. *Rotation*

Line broadening due to rotation can be a problem in classifying photographic spectra, because it changes the shape of the line wings. Nevertheless, the equivalent width of the lines is preserved for modest amounts of rotation. As noted above, however, the central depth is the most critical quantity in classifying plots of digital spectra, and it is greatly affected by rapid rotation. In order to judge the seriousness of the problem for future classification efforts, we looked up the $v \sin i$ for each star in the catalog of Uesugi & Fukuda (1982), and recorded the value directly on the plotted spectrum. Although it proved to be possible to compare fast and slow rotators by taking line width as well as central depth into account, it is clear that classification is greatly facilitated if both broad-line and narrow-line standards can be defined (this is true in the optical region as well). The present sample was too small to do this in more than a few cases.

In this connection, it is important to note that the instrumental S/N of our digital plots is approximately constant. Apparent differences in S/N—for example, between the two stars in Figure 1—are often produced by differences in rotational velocity.

### 4.2. *Interstellar Lines*

Resonance lines and other low-excitation lines of many abundant light elements are present in the 1200–1900 Å spectral region, with the result that almost every strong line has at least some contribution from an interstellar component. For the identification of line components in early-type spectra, the reader is referred to the lists of Ramella et al. (1987) and Artru, Borsenberger, & Lanz (1989). We limited our search for classification criteria to lines expected to be formed under photospheric conditions in B stars near the main sequence (see Table 1). In particular, the Si II lines at 1264, 1310, and 1533 Å were assumed to be photospheric, while the lower excitation Si II lines at 1260 and 1526 Å were assumed to be mainly interstellar, at least in spectral types earlier than B3. In the later B stars, the photospheric contribution is greater than the interstellar component for these and other similar lines. The problem is also less severe for rapidly rotating stars, in which the sharp interstellar components are easily distinguished from the broad photospheric lines.

### 4.3. *Stellar Winds*

Previous ultraviolet classification schemes for OB stars have tended to rely heavily on the strongest lines in the spectrum—those of Si IV (1400 Å), C IV (1550 Å), and N V (1240 Å)—which are known to be formed in the stellar wind. Walborn & Panek (1984a) have shown that for the O stars, stellar wind lines and photospheric lines are highly correlated. However, this might not be the case for the B stars, which have a greater range in luminosity at a given spectral type. In MK classification it is possible to introduce a local "third dimension" over a restricted region of the H-R diagram to describe the variation of some quantity that does not vary directly with spectral type or luminosity class. The composition indices used by Keenan (1987) are an example of this.

We began this project with the idea that we might need a third parameter to describe the range of wind-line strengths at a given B star spectral type. However, it soon became apparent that if we classify an "unknown" star with a standard *using only those lines known to be photospheric*, and then compare the strengths of the wind lines, the "unknown" and the standard agree in most cases. In other words, the standard defines the "normal" state of the wind lines for that spectral type. However, there are definitely a few exceptions—stars which compare well with the standards in all lines except those produced in the stellar wind. We have chosen to attach the suffix "w" to the spectral type for such stars, by analogy with the "p" and "n" notations used in optical classifications. The suffix "w" generally means that the star in question has stronger lines of C IV, and sometimes of Si IV and N V, than the standard star; however, one might envision a case in which the star to be classified has *weaker* wind lines than the standard. The line profiles may also be unusual. For the present, we shall give a note for each star that has the "w" designation in order to distinguish among these various possibilities. There are not enough of these stars in the current sample to form a continuum in the "third dimension."

Interestingly enough, most of the stars to which we gave this description turned out, upon further investigation, to have reported Be or shell characteristics in the optical region, even though there was no notation to this effect in the previous MK classification (see the notes in § 5). The general differences between the behavior of the stellar wind lines in Be stars and normal B stars are described in Baker, Marlborough, & Landstreet (1984) and Prinja (1989).

### 4.4. *Spectrum Variability*

It is a fundamental principle of spectral classification that a stellar spectrum can be classified only "as seen" at a given point in time. It is possible that at a different time the classification may be different. If this is really due to a change in the star rather than to a difference in plate material or observer, then a temporal change in spectral type is an astrophysically significant datum. Spectrum variability is of course not confined to the ultraviolet but, because of the frequently reported variations of the stellar winds in B stars, it might be expected that the wind lines would be particularly susceptible to short-term variations and that the same star might appear in the "w" class at one time while appearing normal at another time. This would be analogous to the transition between the "B normal," "Be," and "B shell" states described by Doazan (1982).

With the exception of $\zeta$ Cas (described in § 5), we have examined only one spectrum for each star in our program. In a few cases, however, we can infer variability by comparing our classification with a description of the spectrum by earlier observers. In the future, it will be particularly important to examine the standard stars for spectrum variability, since this could

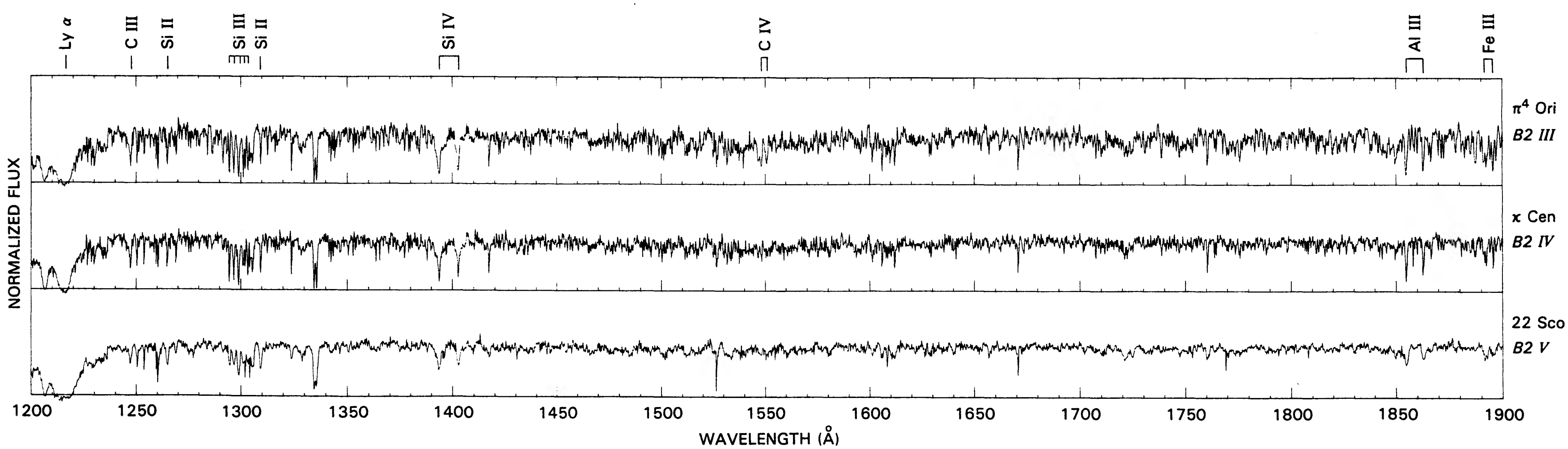


FIG. 4.—Luminosity sequence at B2. The resampled resolution is 0.25 Å. These three stars are good representatives of their spectral type, but not necessarily standards. Luminosity-sensitive features between 1200 and 1880 Å are marked, including Lyman alpha and the Si IV and C IV lines. For the use of these lines in spectral classification see text and Table 1.

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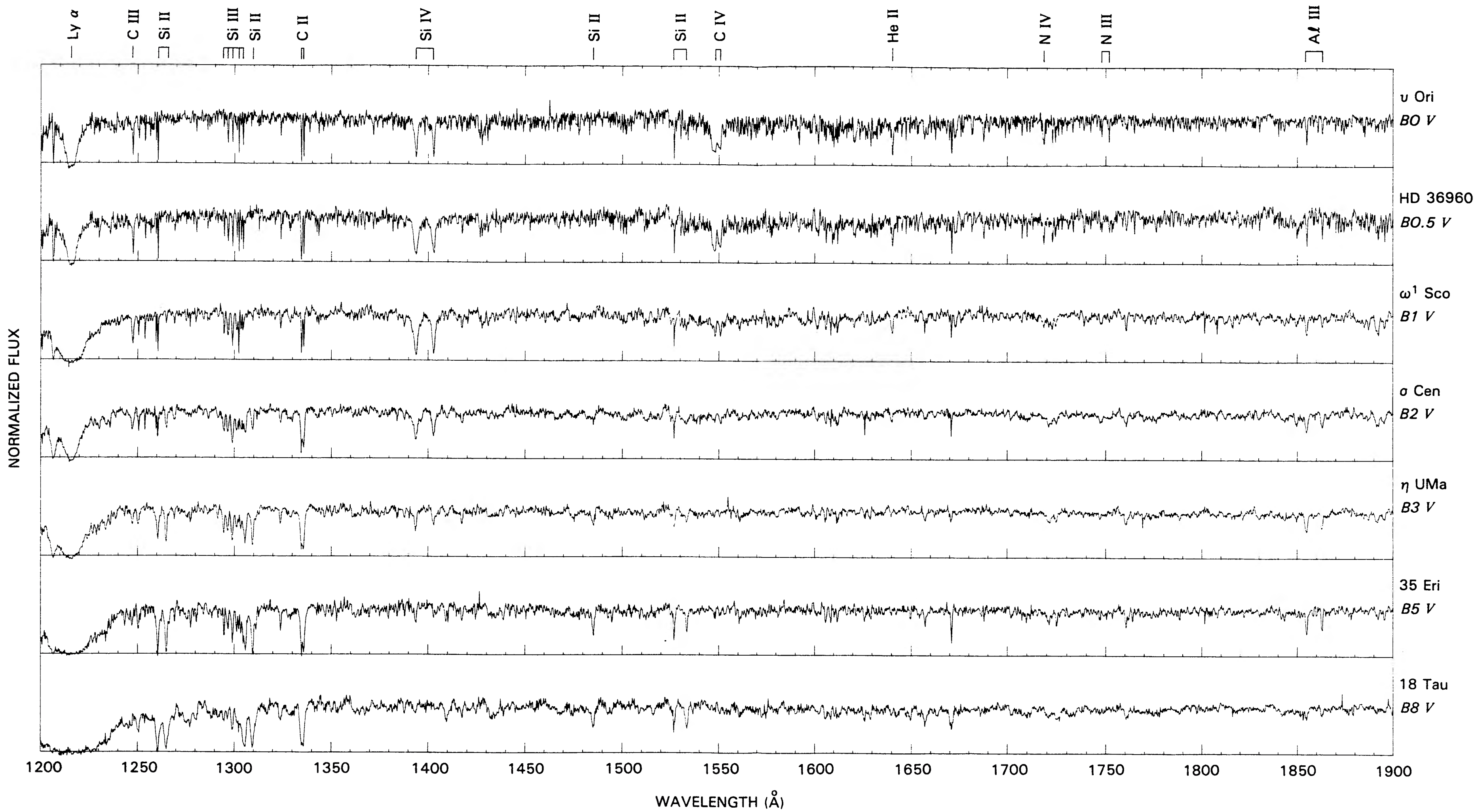


FIG. 3.—Sequence of main-sequence B star spectra, resampled to a resolution of 0.25 Å. The tracings used for actual classification are about twice as large as this illustration. All of the stars depicted here are good representatives of their spectral type, but not necessarily standards. Prominent spectral features in the wavelength range 1240–1880 Å are indicated. For the use of these features in spectral classification see text and Table 1.

TABLE 1

Ultraviolet Classification Criteria

| Spectral Type | Luminosity Class: V | Luminosity Class: IV | Luminosity Class: III |
|---|---|---|---|
| B0 .............. | **υ Ori**<br>He II λ1640 strong<br>N IV λ1718 strong<br>N III λλ1748–1751 marked<br>Si IV, C IV *strong absorption* | HD 75821<br>Interpolate between V and III<br>Si IV, C IV *absorption* | *HD 48434*<br>N III, N IV stronger<br>Al III λλ1854–1861 stronger<br>C III λ1247 stronger<br>N V, Si IV, C IV *P Cyg* |
| B0.5 ............ | *HD 36960*<br>N III present<br>He II, N IV moderate to strong<br>C III strong<br>Si IV, C IV *strong absorption* | *λ Lep*<br>Interpolate between V and III<br>Si IV, C IV *absorption* | *1 Cas*<br>N IV, Al III stronger<br>N III present but weak<br>Si IV, C IV *absorption* |
| B1 .............. | **ω¹ Sco, 42 Ori**<br>N IV weak to absent<br>He II marked<br>C III λ1247 strong<br>Si II λ1264 present<br>Si IV *strong*, C IV *weak absorption* | *α Vir*<br>Interpolate between V and III<br>Si IV, C IV *absorption* | ***o* Per**<br>Si III λ1300 multiplet stronger<br>C III, Al III, N IV stronger<br>Si IV, C IV *absorption* |
| B1.5 ............ | HD 35299<br>1264 Å marked but < 1247 Å<br>He II weak<br>Si IV *absorption*, C IV *weak to absent* | λ Sco<br>Interpolate between IV and V<br>Si IV, C IV *absorption* | 12 Lac<br>Si III, C III stronger<br>Si IV, C IV *stronger* |
| B2 .............. | **22 Sco**<br>Si II λ1264 = C III λ1247<br>Si II λ1310 < Si III λ1300<br>He II weak to absent<br>Si IV *moderate*, C IV *absent* | **γ Peg**<br>Si III, Al III, Fe III stronger than B2 V<br>Fe II λλ1600–1610 stronger<br>Si IV *stronger*, C IV *absent* | *π⁴ Ori*<br>C III, Al III, Fe II, Fe III stronger than B2 IV<br>Si IV *stronger*, C IV *present* |
| B2.5 ............ | **σ Sgr**<br>Si II λ1264 > C III λ1247<br>Si II λ1310 < Si III λ1300<br>Si II λ1485 blend present<br>Si IV *absorption* | *HD 32612*<br>Interpolate between V and III<br>Si IV *present*, C IV *absent* | *π² Cyg*<br>Si II, Si III, C III, Fe II, Al III, Fe III stronger<br>Si IV *strong*, C IV *present* |
| B3 .............. | **η UMa**<br>Si II λ1264 ≫ C III λ1247<br>Si II λ1310 ≥ Si III λ1300<br>Si II λ1485 blend marked<br>Si IV *weak* | HD 134687<br>Interpolate between V and III<br>Si IV *present*, C IV *absent* | HD 89890<br>Si II, Si III, C III, Al III, Fe III stronger<br>Si IV *stronger*, C IV *present* |
| B4 .............. | HD 20809<br>Si II λ1310 ≥ Si III λ1300<br>Si II λ1485 blend prominent<br>Si IV *weak to absent* | 53 Per<br>Si II, Si III, Al III stronger than B4 V<br>Si IV *present*, C IV *absent* | No example in program |
| B5 .............. | 35 Eri<br>Si II dominates spectrum<br>C I λ1655, Fe II moderate<br>Al II λ1670, Al III strong<br>Si IV *marginal to absent* | **τ Her**<br>Si II, Si III, Al III stronger than B5 V<br>Si IV *present*, C IV *absent* | *δ Per*<br>Si II stronger than B5 IV<br>Si IV *stronger*, C IV *absent* |
| B6 .............. | *β Sex*<br>Similar to B5 V, but Al III stronger, Fe III weaker<br>Si IV *absent* | **19 Tau**<br>Interpolate between V and III<br>Si IV, C IV *absent* | *17 Tau*<br>Si II stronger<br>Si IV, C IV *absent* |
| B7 .............. | No standard in program<br>Al II, C I prominent<br>Al III weaker than B6 V<br>Fe III absent | *16 Tau*<br>Interpolate between V and III | **η Tau**<br>Si II, Al II stronger |
| B8 .............. | **18 Tau**<br>Si II dominant<br>Al II, C I prominent<br>Al III, Fe III absent | No example in program | **27 Tau**<br>Si II, Al II stronger |

affect the definition of the "normal stellar wind" for each spectral type.

## 5. RESULTS

Table 1 lists the standard stars and the classification criteria that were finally adopted for this program. Stars listed in boldface type are MK† standards (Morgan & Keenan 1973). Stars listed in italics are standards used by Rountree Lesh (1968). If neither of these was available for a particular spectral type, we occasionally chose a standard from among the available ultraviolet spectra, using the MK classification of Rountree Lesh (1968) or of Hiltner, Garrison, & Schild (1969). Such ad hoc standards are listed in ordinary type.

Only photospheric lines were used as classification criteria.

TABLE 2

ULTRAVIOLET SPECTRAL TYPES

| HD | Name | UV Type | MK Type | Author[a] | Comments |
|---|---|---|---|---|---|
| 886 | γ Peg | *B2 IV* | B2 IV | WWM (MK† std) | |
| 3360 | ζ Cas | *B2 IVw* | B2 IV | WWM (MK† std) | Variable wind |
| 4180 | o Cas | *B5 III* | B5 III | JRL | Be |
| 14951 | ξ Ari | *B6 IV* | B7 IV | JRL | |
| 20315 | 30 Per | *B7 IV* | B8 IV | JRL | |
| 20809 | ... | *B4 V* | B4 V | JRL (ad hoc std) | |
| 22928 | δ Per | *B5 III* | B5 III | JRL (std) | gB5 (HEJJ) |
| 23180 | o Per | *B1 III* | B1 III | WWM (MK† std) | |
| 23288 | 16 Tau | *B7 IV* | B7 IV | JRL (std) | |
| 23302 | 17 Tau | *B6 III* | B6 III | JRL (std) | gB6 (HEJJ) |
| 23324 | 18 Tau | *B8 V* | B8 V | WWM (MK† std) | dB8 (HEJJ) |
| 23338 | 19 Tau | *B6 IV* | B6 IV | WWM (MK† std) | |
| 23408 | 20 Tau | *B7 III* | B8 III | JRL | gB6 (HEJJ) |
| 23480 | 23 Tau | *B6 IV* | B6 IV | JRL | dB6 (HEJJ) |
| 23630 | η Tau | *B7 III* | B7 III | WWM (MK† std) | gB7 (HEJJ) |
| 23850 | 27 Tau | *B8 III* | B8 III | WWM (MK† std) | gB8 (HEJJ) |
| 24131 | ... | *B1 V* | B0.5 V | JRL | |
| 24504 | ... | *B6 III* | B6 V | JRL | |
| 25204 | λ Tau | *B3 IV* | B3 IV | JRL | |
| 25340 | 35 Eri | *B5 V* | B5 V | JRL (ad hoc std) | dB5 (HEJJ) |
| 27396 | 53 Per | *B4 IV* | B4 IV | JRL (ad hoc std) | dB4 (HEJJ) |
| 30836 | $\pi^4$ Ori | *B2 III* | B2 III | JRL (std) | |
| 31237 | $\pi^5$ Ori | *B2 III* | B2 III | JRL | |
| 32612 | ... | *B2.5 IV* | B2.5 IV | JRL (std) | |
| 34816 | λ Lep | *B0.5 IV* | B0.5 IV | JRL (std) | |
| 35299 | ... | *B1.5 V* | B1.5 V | JRL (ad hoc std) | |
| 36485 | δ Ori | *B2.5 IV* | B2 IV–V | JRL | |
| 36512 | υ Ori | *B0 V* | B0 V | WWM (MK† std) | |
| 36960 | ... | *B0.5 V* | B0.5 V | JRL (std) | |
| 37017 | ... | *B2 Vw* | B1.5 V | JRL | |
| 37018 | 42 Ori | *B1 V* | B1 V | WWM (MK† std) | |
| 37303 | ... | *B1.2 V* | B1.5 V | JRL | Intermediate B1–B1.5 |
| 39777 | ... | *B2 IV* | B1.5 V | JRL | |
| 44173 | ... | *B4 V* | B5 III | JRL | |
| 44402 | ζ CMa | *B3 IV* | B2.5 IV | HGS | |
| 46328 | $\xi^1$ CMa | *B1 IIIw* | B1 III | HGS | |
| 48434 | ... | *B0 III* | B0 III | JRL (std) | |
| 51283 | ... | *B1.5 IIIw* | B2 III | HGS | |
| 53974 | ... | *B0.5 IIIw* | B0.5 III | JRL | |
| 63578 | ... | *B1 IV* | B1.5 IV | HGS | |
| 64503 | ... | *B2.5 V* | B2.5 V | HGS | |
| 70930 | ... | *B1.5 III* | B1.5 III | HGS | |
| 74575 | α Pyx | *B1.5 III* | B1.5 III | HGS | |
| 75821 | ... | *B0 IV* | B0 III | HGS (ad hoc std) | |
| 87901 | α Leo | *B7 V* | | | dB7 (HEJJ) |
| 89890 | ... | *B3 III* | B3 III | HGS (ad hoc std) | |
| 90994 | β Sex | *B6 V* | B6 V | JRL (std) | dB6 (HEJJ) |
| 106231 | ... | *B4 IV* | B4 IV | HGS | |
| 108483 | σ Cen | *B2 V* | B2 V | HGS | |
| 116658 | α Vir | *B1 IV* | B1 IV | JRL (std) | |
| 119159 | ... | *B0.5 III* | B0.5 III | JRL | |
| 120315 | η UMa | *B3 V* | B3 V | WWM (MK† std) | dB3 (HEJJ) |
| 122451 | β Cru | *B1 IV* | B1 III | HGS | |
| 125238 | ι Lup | *B2.5 V* | B2.5 IV | HGS | |
| 128345 | ρ Lup | *B4 V* | B5 V | HGS | |
| 132058 | β Lup | *B1.5 IV* | B2 III | HGS | |
| 132200 | κ Cen | *B2 IV* | B2 IV | HGS | |
| 133242 | π Lup | *B4 V* | B5 V | HGS | |
| 134687 | ... | *B3 IV* | B3 IV | HGS (ad hoc std) | |
| 135160 | ... | *B0.5 V* | B0.5 V | HGS | |
| 136298 | δ Lup | *B1.5 IV* | B1.5 IV | HGS | |
| 142096 | λ Lib | *B2.5 V* | B2.5 V | JRL | |
| 142883 | ... | *B3 IV* | B3 V | HGS | Intermediate B3–B4 |
| 143275 | δ Sco | *B0.3 IV* | B0.3 IV | WWM (MK† std) | Intermediate B0–B0.5 |
| 144470 | $\omega^1$ Sco | *B1 V* | B1 V | WWM (MK† std) | |
| 145482 | 13 Sco | *B2 V* | B2 V | HGS | |
| 147152 | ... | *B6 IV* | B6 IV | HGS | |
| 147394 | τ Her | *B5 IV* | B5 IV | WWM (MK† std) | dB5 (HEJJ) |
| 148605 | 22 Sco | *B2 V* | B2 V | WWM (MK† std) | dB2 (HEJJ) |
| 154445 | ... | *B1 V* | B1 V | JRL | |
| 155763 | ζ Dra | *B6 III* | B6 III | JRL | |
| 158926 | λ Sco | *B1.5 IV* | B1.5 IV | HGS (ad hoc std) | |

TABLE 2—*Continued*

| HD | Name | UV Type | MK Type | Author[a] | Comments |
|---|---|---|---|---|---|
| 163472 ......... | ... | *B2 IVw* | B2 IV–V | JRL | |
| 166596 ......... | ... | *B1.5 IIIwp* | B2.5 III | JRL | |
| 170740 ......... | ... | *B2 IV* | B2 IV–V | JRL | |
| 175191 ......... | σ Sgr | *B2.5 V* | B2.5 V | WWM (MK† std) | B3 IV (HGS) |
| 180968 ......... | 2 Vul | *B1 IVw* | B1 IV | JRL | Be, variable wind |
| 192685 ......... | ... | *B2.5 Vw* | B3 V | JRL | Be, discrete components |
| 196740 ......... | 28 Vul | *B6 IV* | B5 IV | JRL | |
| 198820 ......... | ... | *B3 III* | Be III | JRL | |
| 204770 ......... | 7 Cep | *B7 IV* | B7 V | JRL | |
| 207330 ......... | $\pi^2$ Cyg | *B2.5 III* | B2.5 III | JRL (std) | gB2.5 (HEJJ) |
| 209952 ......... | α Gru | *B7 IV* | B7 IV | HGS | |
| 213420 ......... | 6 Lac | *B2 IV* | B2 IV | HGS | |
| 214993 ......... | 12 Lac | *B1.5 III* | B1.5 III | JRL (ad hoc std) | |
| 216200 ......... | 14 Lac | *B2.5 IIIw* | B4 III | JRL | Be or shell |
| 217101 ......... | ... | *B1.5 V* | B2 IV–V | JRL | |
| 218376 ......... | 1 Cas | *B0.5 III* | B0.5 III | JRL (std) | |

[a] std = standard.

Lyman alpha was not used, because of possible contamination from the interstellar and geocoronal components. The criteria listed for luminosity class V are temperature criteria; those listed for classes IV and III are primarily luminosity criteria (relative to class V). The "normal" appearance of the stellar wind lines is given in italics for each spectral type; these lines were not used in the classification. If the appearance of the wind lines in a star to be classified is different from the "normal" appearance—i.e., from the standard—then the classification will have the suffix "w."

Table 2 gives the final ultraviolet spectral type for all the stars in the program, together with the optical MK type and its author, as well as the classification (if available) by HEJJ from low-dispersion *IUE* data. The ultraviolet spectral types were obtained using the standards and criteria in Table 1. Since they were arrived at by using MK standards and the MK methodology, we consider these types to be consistent with optical MK spectral types. However, since the ultraviolet classification system is very new, we may expect these first results to be somewhat less accurate than the optical types obtained by experienced observers. We have therefore printed the ultraviolet types in italics, to distinguish them from optical types.

Not surprisingly, there is generally good agreement between the ultraviolet spectral types and the optical MK types. The numerous small differences are "real," in the sense that each *IUE* spectrum was re-compared with the standards for both ultraviolet and optical types, and the ultraviolet type was confirmed. We should emphasize that in no case was the ultraviolet type *forced* to agree with the optical type. Nevertheless, most of the differences are no more than one spectral subtype or one luminosity class. The few large differences are described in the notes below, as are all spectra for which a "w" or "p" suffix has been adopted.

### 5.1. *Notes on Individual Stars*

*HD 3360* (ζ Cas, *B2 IVw*).—This star has been reported as having variable absorption in the 1550 Å C IV resonance lines by Sonneborn, Garhart, & Grady (1987) and by Grady, Bjorkman, & Snow (1987). Fortuitously, we have two spectra of ζ Cas in the program: SWP 17867, taken on 1982 day 250, and SWP 18654, taken on 1982 day 329. They are shown in Figure 5, with the spectrum of the B2 IV standard γ Peg for comparison. The photospheric lines of ζ Cas, notably C III λ1247 and Si II λλ1264 and 1310, match the standard closely. But the Si IV lines are stronger in ζ Cas, and the C IV and N V resonance lines, normally absent at B2 IV, are present—hence the suffix "w." A comparison of SWP 18654 and SWP 17867 shows that N V, Si IV, and C IV are all stronger in the latter spectrum, confirming the reported variability. Sonneborn et al. (1987) set an upper limit of several months for the time scale of the wind variability in ζ Cas.

*HD 4180* (*o* Cas, *B5 III*).—Grady et al. (1987) list *o* Cas as a Be star, but do not find a strong wind or discrete absorption components in its ultraviolet spectrum. The wind lines are normal on our spectrum: Si IV is present, while C IV is absent.

*HD 37017* (*B2 Vw*).—The spectrum is a good match to the B2 V standard 22 Sco, except for the presence of the C IV doublet in absorption. Shore & Brown (1990) have studied the C IV and Si IV line variations of HD 37017, in the context of the helium strong stars.

*HD 37303* (*B1.2 V*).—The Si II lines are too weak for B1.5, while the He II and N IV lines are weaker than in B1.

*HD 46328* ($\xi^1$ CMa, *B1 IIIw*).—We have only one spectrum of $\xi^1$ CMa, which shows the C IV and N V lines as having P Cyg emission/absorption profiles, while the Si IV lines are weaker than in the B1 III standard *o* Per, indicating that they too may be affected by incipient emission. We can infer the fact that $\xi^1$ CMA has a variable stellar wind by comparing our spectrum with the descriptions by other authors. Panek & Savage (1976) reported unusually strong absorption in both Si IV and C IV, while Sekiguchi & Anderson (1987) found "rather normal absorption strengths" for these lines.

*HD 48434* (*B0 III*).—This is the most luminous star in our program, and the only one of its spectral type. It was used as a B0 III standard by Rountree Lesh (1968). Walborn, Nichols-Bohlin, & Panek (1985) display this spectrum in the context of a late O giant sequence, where it may be seen that the Si IV and C IV profiles form a smooth progression from O8 III through B0 III. Therefore, it may be assumed that the wind lines in HD 48434, all of which exhibit P Cyg profiles, are "normal" for this spectral type.

*HD 51283* (*B1.5 IIIw*).—This star may be slightly later than B1.5 (say, B1.7). The C IV lines are anomalously strong compared with the ad hoc standard, 12 Lac. They exhibit shortward-shifted components, as do the Si IV lines.

*HD 53974* (*B0.5 IIIw*).—The wind lines are very broad and strong compared with the standard 1 Cas. C IV and N V exhibit P Cyg profiles.

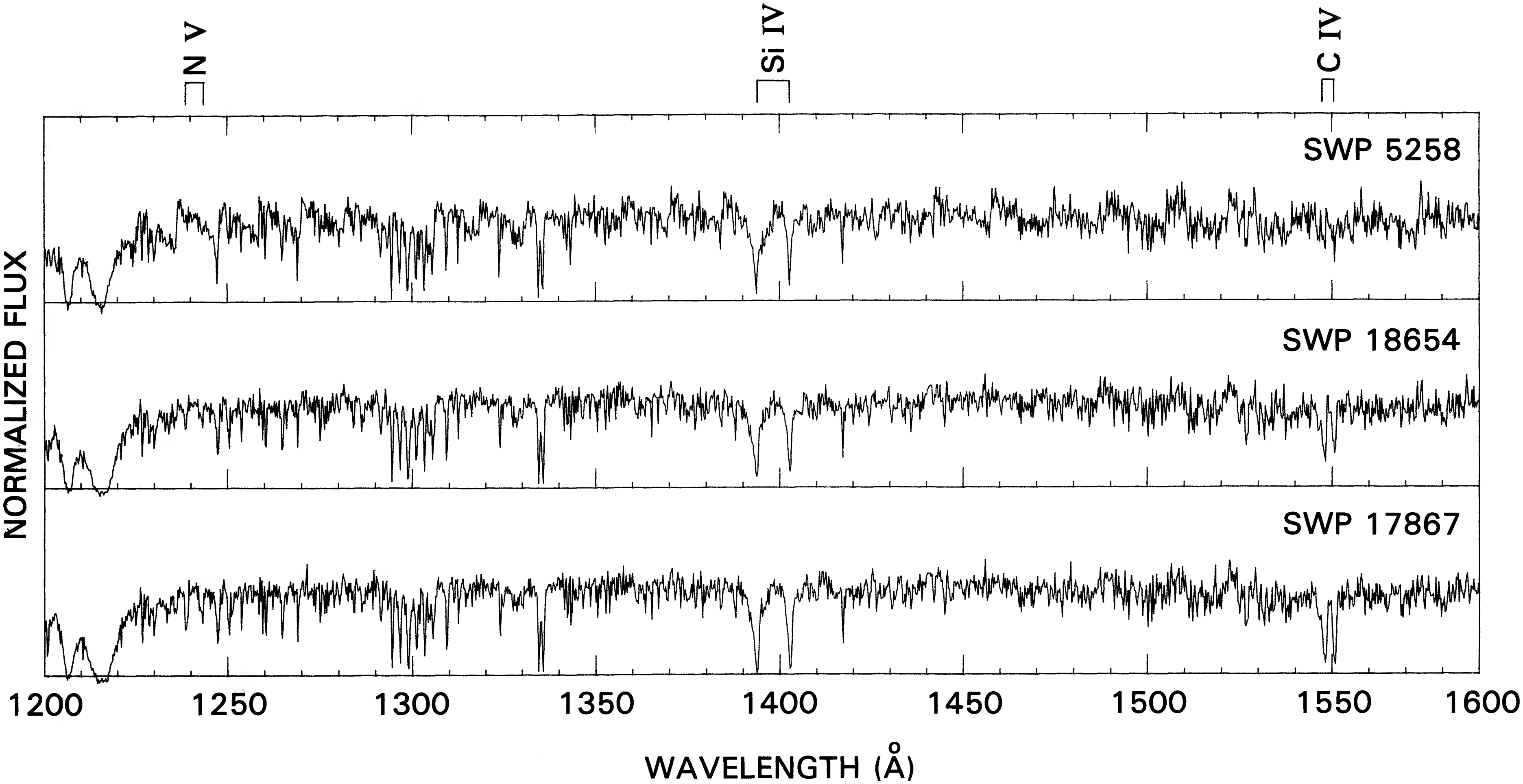


FIG. 5.—SWP spectra of ζ Cas, an example of a star with a "peculiar" and variable stellar wind. SWP 5258 is a spectrum of the *B2 IV* standard γ Peg. SWP 18654 shows ζ Cas, *B2 IVw*, on 1982 day 329; note the presence of the C IV and N V lines, which are absent in the standard star. SWP 17867 shows ζ Cas on 1982 day 250; the C IV, Si IV, and N V lines are even stronger than in SWP 18654.

*HD 75821* (*B0 IV*).—This star was classified B0 III by Hiltner, Garrison, & Schild (1969), but it is distinctly less luminous than HD 48434. We have made it an ad hoc standard at B0 IV. However, more B0 and B0.5 spectra are needed before we can be fully confident of the morphology in this region of the H-R diagram.

*HD 87901* (α Leo, *B7 V*).—Although this star was not included in the sample classified by Rountree Lesh (1968), it has a well-known MK type of B7 V. Its extremely broad lines prevent it from being useful as a standard. However, it does not seem to exhibit any spectral peculiarities, either in the visible or in the ultraviolet.

*HD 142883* (*B3 IV*).—The ultraviolet spectral type is actually intermediate between B3 IV and B4 IV, which would imply a luminosity consistent with the optical MK type of B3 V.

*HD 143275* (δ Sco, *B0.3 IV*).—This is an MK† standard for B0.3 IV. The N III lines are intermediate between HD 75821 (B0 IV) and λ Lep (B0.5 IV).

*HD 163472* (*B2 IVw*).—This star is very similar to ζ Cas (our spectrum of HD 163472 resembles SWP 18654; Fig. 5).

*HD 166596* (*B1.5 IIIwp*).—In addition to the excessive strength of the C IV lines (comparable to HD 51283), the Si IV lines are very strong and have peculiar, "sawed off" profiles.

*HD 180968* (2 Vul, *B1 IVw*).—The Si IV and C IV absorption lines are very strong in comparison with the B1 IV standard α Vir. Grady et al. (1987) list 2 Vul as a Be star with a variable wind and (sometimes) with a partially resolved discrete absorption component.

*HD 192685* (*B2.5 Vw*).—This star is an excellent match to the B2.5 V standard σ Sgr, except for the presence of the C IV feature in absorption. Grady et al. (1987) call it a Be star with a high-velocity discrete component.

*HD 216200* (14 Lac, *B2.5 IIIw*).—The spectrum matches the B2.5 III standard, $\pi^2$ Cyg, except for the presence of a moderately weak C IV absorption feature. The *Bright Star Catalogue* (Hoffleit & Jaschek 1982) calls it B3 IV:e, with a note of Hα emission. The star was classified B4 III by Rountree Lesh (1968). We hypothesize that it is a shell star, having a spuriously late optical spectral type.

## 6. DISCUSSION AND CONCLUSIONS

We have developed a set of criteria for the classification of B stars from ultraviolet spectra alone, using standards drawn from the optical region. Although in the present work we used knowledge of the optical MK types of the program stars to do a preliminary grouping, the principal application of our system is expected to be the spectral classification of stars which have been observed by satellites and for which no optical type exists. If the spectra to be classified have been observed with the *IUE* SWP camera, it suffices to process them in the manner described in § 2 and to compare them directly with the existing standard spectra.

If a different satellite is to be used, then the standards must be reobserved and processed in the same manner as the "unknowns." Since the dispersion and spectral response of a new instrument are likely to be rather different from those of *IUE*, the appearance of the lines in Table 2 should be carefully examined in the standard star spectra before an extensive classification program is undertaken. Maximum utility of the criteria described here will most likely be achieved if an effort is made to duplicate our 0.25 Å resolution and our S/N of 30, and if a plot scale similar to ours is adopted.

Since, like the MK system, our ultraviolet classification is based entirely on the standard stars, and since the same stars are standards for both systems, it follows that the ultraviolet spectral types should be consistent with MK optical types. But since comparatively few (only about 100) B stars have been classified in this way, the accuracy of the ultraviolet types is at present less than the accuracy of an MK type obtained by an experienced observer. This situation should improve as a larger body of ultraviolet classifications becomes available, and as more workers become experienced in their use.

Our confidence in the stability of the system is partly based on the fact that only photospheric lines (that is, lines that on the basis of their excitation potential are not expected to be dominated by components from the stellar wind or the interstellar medium) were used as classification criteria. These lines should represent the same basic stellar parameters as the lines used for classification in the optical region. As for the stellar wind, we find, in agreement with Walborn & Panek (1984a), that in most cases the wind lines are correlated with the photospheric lines—that is, they have a similar appearance to those in the standard stars. Only a small fraction of the stars in our sample deviate from this rule (the "w" stars), and most of these have also exhibited optical evidence of an abnormally extended atmosphere, in the form of emission or shell lines. However, we caution that stellar winds are known to be variable, and some of the stars that appear normal on our spectra may exhibit anomalous wind lines at a different epoch.

What then to make of the argument that MK spectral types cannot be "transferred" or "extrapolated" to a spectral region other than the optical? We interpret this statement to mean that knowledge of the optical MK spectral type cannot be used to predict the appearance of a stellar spectrum at other wavelengths. To the extent that the structure of the line formation regions that give rise to the different wavelengths is determined by the basic structure of the star, one would expect the appearance of the spectral regions to be correlated. That is, if a star resembles a given MK standard in the optical region, it should also resemble it at other wavelengths. On the other hand, if the line formation region is not entirely determined by the stellar structure, as may be the case with the stellar wind, then the correlation may be weak or absent. For B stars, the photospheric layers giving rise to ultraviolet and to visible lines are apparently well correlated. For O stars, Walborn & Panek (1984a) found a correlation between the stellar wind and the photosphere as well.

In the present paper, we are actually making the inverse argument—namely, that it is possible to predict the general appearance of the optical spectrum (i.e., the optical spectral type) of a star on the basis of its ultraviolet spectrum. The atlas of HEJJ contains 72 O and B stars having normal optical spectra and good MK types. According to the authors, most of them also exhibit a normal behavior in the ultraviolet range. Rountree (1986) showed that for 42 of these stars, there is *no* difference in either spectral type or luminosity class between the *IUE* type of HEJJ and the MK type. For 19 of the stars, there is a difference of one spectral subtype *or* one luminosity class, but not both. Four stars show a difference of one spectral subtype *and* one luminosity class, often in the sense of a "diagonal error"—that is, the earlier spectral type goes with the lower luminosity class, so that the calibrated luminosity tends to be conserved. Only seven of the stars in question have a difference of more than one spectral subtype and/or more than one luminosity class. These cases warrant further investigation.

One such case, HD 46769, is cited twice in the introduction to the atlas of HEJJ—once in a sequence of supergiants and once in a sequence of main-sequence stars—as an example of disagreement between optical and ultraviolet types. The published MK type of HD 46769 is B8 Ib (Rountree Lesh 1968). The senior author's original notes show that the type was actually B8 Ib:, where the colon indicates a type based on inferior plate material. W. W. Morgan kindly agreed to reexamine the Yerkes plate for this star, and he concluded that the MK type should be earlier than B8, but lower in luminosity than a supergiant—approximately B5 II–III. A high-quality optical digital spectrogram of HD 46769 was obtained among the stars observed for the digital atlas of Walborn & Fitzpatrick (1990). Unfortunately, they acquired no standards later than B3 (except at luminosity class Ia); however, a comparison of the unpublished spectrum of HD 46769 (kindly provided to us by E. L. Fitzpatrick) with the B3 V and B2 III standards suggests that an extrapolation to B5 III would not be unreasonable. HEJJ give an *IUE* type of dB6. Although these observations do not entirely remove the discrepancy between the optical and ultraviolet types, they do reduce it. The lesson is that optical and ultraviolet types should be investigated for individual errors, before concluding that a difference between them is due to the physics of the star, or to an inherent problem in the classification system(s).

We are pleased to acknowledge helpful conversations with W. W. Morgan, Catharine Garmany, Geraldine Peters, Derck Massa, and Dimitri Mihalas. The excellent cooperation of the staff of the *IUE* RDAF facility at Goddard Space Flight Center is gratefully acknowledged. This project has been supported in part by NASA contract NAS 5-25774 to the Computer Sciences Corporation.

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