Multiwavelength Systematics of OB Spectra

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ABSTRACT

The systematics of OB spectra are reviewed in the optical domain, dominated by photospheric lines, and in the far ultraviolet (both IUE and FUSE ranges), in which the stellar-wind profiles dominate. First, the two-dimensional (temperature, luminosity) trends in normal spectra are surveyed. Then, the normal reference frame having been established, various categories of peculiar objects can be distinguished relative to it, which reveal several phenomena of structural and/or evolutionary significance. Included are CNO anomalies at both early and late O types, three varieties of rapid rotators, hot and cool Of/WN transition objects, and the recently discovered second known magnetic O star. The importance of both optical and UV observations to understand these phenomena is emphasized; for instance, progress in understanding the structure of the new O-type magnetic oblique rotator is hampered by the current lack of a UV spectrograph. While progress in the physical interpretation of these trends and anomalies has been and is being made, increased attention to modeling the systematics would accelerate future progress in this author's opinion. Finally, preliminary results from a Chandra high-resolution survey of OB X-ray spectra (PI W. Waldron) are presented. They provide evidence that, just as emerged earlier in the UV, systematic morphological trends exist in the X-ray domain that are correlated with the optical spectral types, and hence the fundamental stellar parameters, contrary to prevailing opinion.

Key words: OB stars, spectroscopy, spectral classification, optical astronomy, UV astronomy, X-ray astronomy, stellar winds, standards, peculiar stars
1. Introduction

The Morgan-Keenan (MK) System of spectral classification, one of the foundations of stellar astrophysics, is a classical application of morphological techniques. A reference frame of standard spectra, with empirical line-ratio criteria therein, is established. Then new spectra are described differentially relative to the standards, with observational parameters as similar as possible (preferably identical) to those of the standards. Normal spectra are classified into the system, while peculiar exceptions to the standard behavior of the criteria may also be recognized. Both in the definition of the system and especially in its application, independence from external information is paramount, including even physical calibration and interpretation of the data themselves. In this way, errors and uncertainties in the subsequent procedures do not affect the description of the phenomena, which remains valid in the event of revisions or improvements to the latter; and correlations or discrepancies with other kinds of data may be usefully investigated. The hazards of ignoring these precepts, whenever a diverse phenomenology is beyond the capacity of current models to accurately predict and explain, can be readily appreciated with the benefit of hindsight in a collection of specialist essays on a new system of spectral classification edited by Schlesinger (1911).

A current view holds that astrophysics has rendered astronomical morphology obsolete. However, when a new observational domain is opened to investigation, such as a new wavelength regime, a different metallicity in an external galaxy (or region of our own), or simply increased information content in higher quality data, the above principles apply fully. Stated another way, an adequate image of the new phenomena must be formulated before they can usefully be subjected to interpretation or modeling. Analogous examples of confusion can be found in the more recent literature, e.g., on the relationship of OB stellar winds to the fundamental stellar parameters during the early 1980’s. This paper presents specific, practical examples of systematic trends and relationships, as well as peculiar phenomena, recently discovered in OB spectra by the application of morphological techniques. It is also suggested that systematic modeling relative to an analogous reference frame of standard objects could accelerate progress toward the ultimate objective of physical understanding.

2. Reference Frame

2.1. Spectral Type

The optical O-type horizontal (temperature) classification is based upon the helium ionization, primarily the absorption-line ratio of He II $\lambda$4541/He I $\lambda$4471, which has a value of unity at spectral type O7 (e.g., Walborn & Fitzpatrick 1990; WF). The He I line is very weak at type O4; type O3 was introduced for several stars in the Carina Nebula by Walborn (1971a), based upon the absence of the He I line in the photographic data of the time. It can often be seen in O3 spectra with modern,
high-S/N digital data, but the interpretation of the very weak feature is compromised by later type companions, imperfect nebular emission-line subtraction, and possibly supergiant winds, as well as the noise level. Hence, Walborn et al. (2002a) refined the classification at the earliest types on the basis of the \( \text{N IV} \lambda 4058/\text{N III} \lambda \lambda 4634-40-42 \) selective emission-line ratio (Walborn 2001), adding new spectral types O2 and O3.5 to accommodate its observed range. A sequence of very early-O supergiant spectra is shown in Figure 1.

The original, photographic definition of the transition from type O9.5 to B0 was the disappearance of \( \text{He II} \lambda 4541 \), although it is clearly seen at the latter type in modern data. On the B main sequence (luminosity class V), the behavior of the entire blue-violet \( \text{He I} \) spectrum, which has maximum intensity at type B2, is the primary spectral-type indicator. In the supergiants, the silicon ionization, in particular \( \text{Si IV} \lambda \lambda 4089/\text{Si III} \lambda 4552 \) at the earlier types and the \( \text{Si III} \) relative to \( \text{Si II} \lambda \lambda 4128-30 \) at mid-B types, provides the primary horizontal criterion. At late-B types, the strengthening of \( \text{Mg II} \lambda 4481 \) relative to the declining \( \text{He I} \lambda 4471 \) is a useful criterion. CNO lines provide additional supporting criteria in (morphologically) normal spectra, but must be used with caution in view of the anomalies they can display in some spectra (Section 3.1 below). Digital sequences can be found in WF.

Large-scale atlases of high-resolution \textit{International Ultraviolet Explorer} (IUE) data show the very tight correlations of the UV stellar-wind profiles with both O and B spectral types in the great majority of normal spectra (Walborn et al. 1985, 1995, respectively). On the main sequence, the \( \text{N V} \lambda \lambda 1239-43 \) and \( \text{C IV} \lambda \lambda 1548-51 \) resonance lines have broad, saturated P Cygni profiles through type O6 and decline smoothly thereafter, while \( \text{Si IV} \lambda \lambda 1394-1403 \) shows no wind effect anywhere on the main sequence. In the supergiants, on the other hand, there is an \( \text{O V} \lambda 1371 \) wind profile at types O2-O3, while \( \text{Si IV} \) has a weak wind profile at O4, which grows to a maximum at mid/late-O and declines thereafter through the B sequence. In the latter, \( \text{C II} \lambda \lambda 1334-36 \) and \( \text{Al III} \lambda \lambda 1855-63 \) develop wind profiles with maxima at types B1-B2. The \textit{Far Ultraviolet Spectroscopic Explorer} (FUSE) allowed this systematic phenomenology to be extended to numerous additional species and ionizations in the 900-1200 Å range, including the superionized \( \text{O VI} \lambda \lambda 1032-1038 \) (Walborn et al. 2002b, Pellerin et al. 2002).

### 2.2. Luminosity Class

The MK System contained no vertical (luminosity) classification for spectra earlier than type O9. Such a system was introduced by Walborn (1971b, 1972, 1973), based upon identification of the Of phenomenon (selective emission effects in \( \text{He II} \lambda 4686 \) and \( \text{N III} \lambda \lambda 4634-40-42 \) with negative luminosity effects in absorption (i.e., decreasing absorption strength with increasing luminosity, inferred to be caused by emission filling) in the same lines at types O9-B0. A luminosity sequence of blue-violet optical spectra at spectral type O6.5 is shown in Figure 2. It can be seen that \( \text{He II} \lambda 4686 \) is a strong absorption on the main sequence (class V), which weakens gradually through
Figure 1: Temperature sequence of very early O blue-violet spectra. Courtesy of Ian Howarth.
the giants and comes into emission in the Ia supergiant, while the accompanying N III emission strengthens correlatively. These sequential configurations are denoted by ((f)), (f), and f in the spectral types, as labeled in the figure. Calibrations in terms of absolute visual magnitude corroborated these morphological classifications, and the N III temperature and gravity dependence was reproduced theoretically by Mihalas et al. (1972).

An “inverse Of effect”, i.e. He II $\lambda 4686$ absorption stronger relative to the other He lines than in class V spectra, usually found in very young regions, has been hypothesized to correspond to lower (visual) luminosities and smaller ages. That is, typical class V spectra may already have some emission filling in that line, which is less or absent in these “Vz” spectra. Some examples in the Large Magellanic Cloud H II region N11 are shown in Figure 3 (see Walborn & Parker 1992, Parker et al. 1992). These objects may be near or on the zero-age main sequence (ZAMS), contrary to some expectations that such would not be optically observable at high masses. This topic has been reviewed by Walborn (2006), in which fifty morphologically selected candidate ZAMS O stars are listed. It is a promising subject for future astrophysical investigation.

The UV wind spectra display remarkable correlations with the optical luminosity classes. In particular, in the IUE data, the Si IV resonance line progresses smoothly from no wind effect on the main sequence, through intermediate wind profiles in the giants, to a fully developed P Cyg profile in the Ia supergiants; Figure 4 shows the UV spectra of the same stars displayed optically in Figure 2 (Walborn & Panek 1984a, Walborn et al. 1985). This is essentially an ionization effect: the Si IV potential of 45 eV is significantly less than those of N V (98 eV) and C IV (64 eV), which allows the former to respond to the density range among these winds, while the latter two remain saturated throughout. The FUSE range offers three more similarly luminosity-sensitive features: C III $\lambda 1176$, 48 eV; S IV $\lambda \lambda 1063-73$, 47 eV; and P V $\lambda \lambda 1118-28$, 65 eV. The last of these retains density/luminosity sensitivity because of the very low abundance of P, rather than the ionization potential (Walborn et al. 2002b).

The yellow-red region of OB spectra contains several interesting diagnostic lines (Walborn 1980). In preparing this review, the author found a very sensitive temperature/luminosity effect in the selective emission line C III $\lambda 5696$: on the main sequence at type O9 it is absent (neutralized), but at O9.5 V it is a weak absorption line, which then weakens further and comes into emission with increasing luminosity, as shown in Figure 5. When all of these detailed effects are reproduced by the models, the definition of the physical parameters will be highly constrained.

Luminosity classes in the B-type range depend primarily on Si/He line ratios, Stark effects in certain He I lines, and secondarily on the behavior of CNO lines, again used with caution. See WF for illustrative sequences in the optical, and Walborn et al. (1995) for correlative effects in the UV.
Figure 2: Luminosity sequence of mid-O blue-violet spectra. Courtesy of Ian Howarth.
Figure 5: Luminosity sequence of late O yellow-red spectra. Courtesy of Ian Howarth.
3. Peculiar Categories

3.1. CNO Anomalies

A review of inverse CNO anomalies in OB absorption-line spectra, denoted as OBN and OBC, was given by Walborn (1976), and an update by Walborn (2003). It is now generally accepted that the morphologically normal majority of OB supergiants display an admixture of CNO-cycled material in their atmospheres and winds, while the relatively rare OBC objects have physically normal (i.e., main-sequence) CNO abundances, and the OBN have more extreme mixing as a result of either binary interactions or rapid initial rotational velocities, with homogeneous evolution in extreme cases (Maeder & Meynet 2000). The optical anomalies are usually reflected in the UV wind profiles (Walborn et al. 1985, 1995).

The recent discovery of a CNO dichotomy among O2 giants in the Magellanic...
Figure 4: Luminosity sequence of mid-O FUV (IUE) spectra (the same stars as shown in Fig. 2). Courtesy of Danny Lennon.

Clouds, initially from a survey of the 3400 Å region in their spectra (Walborn et al. 2004a), was a surprise. These very massive objects have small absolute ages and lie near the main sequence, indicating more rapid mixing processes than contemplated in current models, and/or very rapid initial rotations perhaps inducing homogeneous evolution back toward the main sequence. They represent a challenge to the models and ultimately a powerful diagnostic of early massive stellar evolution. Further related results from the 3400 Å survey are presented by Morrell et al. (2005).

Typical CNO anomalies in the optical spectra of late-O supergiants are illustrated in Figure 6. More detailed descriptions of these high-quality data may be found in Walborn & Howarth (2000), including identifications of the plethora of weak CNO lines that faithfully track the inverse ON/OC dichotomy.
Figure 6: CNO anomalies in late O supergiant blue-violet spectra. Courtesy of Ian Howarth.
3.2. Rapid Rotators

Three varieties of O-type rapid rotators are illustrated in Figure 7. HD 155806 is a relatively rare analogue of the Be stars; its yellow-red spectrum including H$\alpha$ is reproduced by Walborn (1980). See also Negueruela et al. (2004) for a comprehensive discussion of the Oe class. HD 191423 is one of the most rapidly rotating stars known and a prototype of the ONn class, which is directly relevant to enhanced mixing of processed material in rapid rotators (Howarth & Smith 2001; Walborn 2003; Howarth 2004).

Another intriguing class is the Onfp (Walborn 1973; or Oef, Conti & LEEP 1974), represented by $\lambda$ Cephei in Figure 7. These spectra have comparable broadening in absorption lines and Of emission features, with a prominent absorption reversal in the He II $\lambda$4686 emission line that may indicate the presence of a hot disk. Numerous luminous members of this class are being found in the Magellanic Clouds (Walborn et al. 2000, A. Moffat et al. in preparation, P. Crowther et al. in preparation, I. Howarth et al. in preparation). These objects are interesting candidates for stellar merger remnants and/or gamma-ray burst progenitors.
3.3. “Slash” Stars

Two categories of O-type spectra with prominent emission lines, which are related to the WN sequence, were given composite or dual classifications that have led to their being referred to as “slash” stars. The hotter category is evidently intermediate between very hot Of and luminous WNL spectra and is found associated with those two classes in giant H II regions such as 30 Doradus. These objects retain prominent very early O-type absorption spectra, but they have stronger winds than pure Of stars, that produce emission features of intensity and width more similar to those in WN spectra. High-quality optical and UV observations of a prototypical example, Melnick 42 in 30 Dor, are compared with related Of and WN spectra by Walborn et al. (1992). This category likely represents the transition between Of and WNL phases of the most massive stars.

A cooler category of “intermediate” spectra was isolated in the LMC and designated Ofpe/WN9 (Walborn 1977, 1982; Bohannan & Walborn 1989). These objects, together with Galactic extreme O Ia pe stars, were subsequently reclassified into a WN9-11 (WNVL) sequence by Crowther & Smith (1997); see also Crowther & Bohannan (1997) and Walborn & Fitzpatrick (2000). In the UV, most of these objects display relatively low-ionization, shortward-shifted absorption features, indicative of very dense, low-velocity winds (Pasquali et al. 1997). One of the original prototypes of this category, HDE 269858 or Radcliffe 127, entered a classical Luminous Blue Variable outburst state in 1982 (Stahl et al. 1983). Other category members have LBV-like, axisymmetric, N-rich circumstellar nebulae (Walborn 1982, Nota et al. 1995, Pasquali et al. 1999), evidently ejected in prior events. Thus, some or all of these objects correspond to quiescent phases of LBVs, an important insight into the still mysterious, rapid transitions during the late evolution of massive stars. It is plausible that they may subsequently reach WNE and/or WC states, following the extensive LBV mass loss.

3.4. Magnetic Stars

The Of?p designation was introduced by Walborn (1972) to distinguish the peculiar spectra of HD 108 and HD 148937 from normal Of spectra. The question mark was intended to emphasize that these objects were not believed to be normal Of supergiants, as the latter had just been interpreted. Walborn (1973) added a third member to this class, HD 191612. The defining peculiarity in the blue spectra is C III λλ 4647-4650-4651 emission lines of comparable intensity to N III λλ 4634-4640-4642; the former are usually much weaker than the latter when present at all in normal Of spectra. Other line-profile peculiarities in the Of?p spectra are suggestive of shell phenomena or dilute (circumstellar) material. Subsequent IUE observations confirmed that these stars are not supergiants, in terms of the behavior of the Si IV resonance lines. Spectral variations had been reported in HD 108 and have been well documented by Nazé et al. 2001; the C III/N III emission-line ratio and emission components at H and
He lines change on a timescale of decades. The spectral (in)stability of HD 148937 is less known, but it is surrounded by spectacular axisymmetric, N-rich ejected nebulosities (NGC 6164-6165), reminiscent of Luminous Blue Variable nebulae (references in Walborn et al. 2003).

Interest in HD 191612 was rekindled in 2001 when it was realized that the spectrum observed by Herrero et al. (1992) was completely different from the one published by Walborn (1973). In particular, the C III emission was absent (!), the spectral type was O8 as opposed to O6.5 in the earlier observation, and the profiles of other features such as He II λ4686 had changed entirely. Subsequent literature and archival searches, together with new observations, documented the recurrence and strict reproducibility of these spectral variations, although the record did not allow definitive identification of the timescale (Walborn et al. 2003). A surprising result was the variation of Hα from a strong P Cygni profile in the O6 state to predominantly absorption in the O8, suggesting large changes in the mass-loss rate. Further observations during 2003 and 2004 showed that the recurrent spectral states last less than a year, and the Hipparcos photometry provided the breakthrough datum of a 538 d period in a very low-amplitude lightcurve (Nazaré 2004), which satisfies all available spectroscopy since at least 1982 (Walborn et al. 2004b). Figure 8 illustrates the drastic phase dependence of the spectrum in both the blue-violet and yellow-red. Subsequent analysis of very extensive optical data with complete phase coverage demonstrates that the spectral-type variation is caused by filling in of the He I lines in the O6 state rather than an effective-temperature change, and that the O8 spectrum, while still peculiar, is the baseline (I. Howarth et al., in preparation).

The bizarre phenomena exhibited by HD 191612 are unprecedented in an O-type star and challenged physical interpretation. A second breakthrough is only the second detection of a magnetic field in an O-type star, by Donati et al. (2006a). While phase coverage remains to be obtained, this observation suggests that the variations may be caused by an oblique rotator configuration with a magnetically confined wind disk, and that the very long rotational period is a result of magnetic braking. Comparison with the first known O-type magnetic oblique rotator, θ1 Orionis C, is thus also suggested (Donati et al. 2002, Smith & Fullerton 2005, Gagné et al. 2005, Wade et al. 2006). Although of similar mass, this star is much younger, consistent with its shorter period of 15 d. θ1 Ori C displays large, phase-dependent variations in its UV wind features (Walborn & Nichols 1994, Stahl et al. 1996), which have provided key diagnostics for the physical models. There are ongoing attempts to obtain UV spectroscopic phase coverage of HD 191612 with FUSE, but current pointing limitations render that difficult, and the restoration of appropriate capabilities to HST depends upon a new successful servicing mission, now planned for 2008.

It is remarkable that all four of the hottest magnetic stars known to date were isolated as peculiar from their optical and/or UV spectra in advance of the magnetic detections. The other two are τ Scorpii (Walborn & Panek 1984b; Walborn et al. 1985, 1995; Donati et al. 2006b) and ξ1 Canis Majoris (Rountree & Sonneborn 1991,
Figure 8: Blue-violet (top) and yellow-red (bottom) spectra of the Of?p magnetic oblique rotator HD 191612 at different phases of the 538 d rotational period. Courtesy of Ian Howarth.
Walborn OB Spectra

1993; Walborn et al. 1995; Hubrig et al. 2006). This circumstance suggests the strong magnetic candidacy of other OB stars with unexplained spectral peculiarities and/or variations: in addition to the other two Galactic Of?p stars above, they are HD 36879 (Walborn & Panek 1984b, Walborn et al. 1985), θ Carinae (Walborn et al. 1995, Lloyd et al. 1995), and 15 S Monocerotis (unpublished).

4. X-Ray Systematics

The spectroscopic capabilities of the Chandra (and XMM-Newton) X-ray observatories permit for the first time the extension of morphological techniques as described above in the optical and UV domains, to the X-ray line spectra of the OB stars. A Chandra program (PI W. Waldron) to fill gaps in the archival HR Diagram coverage has been conducted. Although such coverage to date remains sparse, it is now sufficient to support a preliminary investigation of the X-ray spectral systematics in relation to the optical spectral types of the stars. To that end, supergiant/(giant) and main-sequence/(giant) X-ray spectral sequences from Chandra HETGS data are displayed in Figures 9 and 10, respectively. It should be emphasized that these stars have been selected as normal representatives of their spectral types; e.g., the magnetic stars discussed in the previous section also have peculiar X-ray spectra and must be omitted from the search for fundamental morphological trends.

The existence of such trends is readily apparent in the figures. First, the strongest lines migrate toward longer wavelengths with advancing spectral type, which is an ionization effect. Second, the ratios of the close pairs of He- and H-like ionic lines from Si, Mg, Ne, and O display correlations with the spectral types. For instance, the rapid declines in Mg XII/Mg XI in the early O supergiants, and of Si XIV/Si XIII on the early O main sequence, are noteworthy. (The weakness of the Mg XII line in the main-sequence spectra may be a luminosity effect, although current coverage is inadequate to establish that; the weakness of the Si XIV line in HD 93129 is a surprising anomaly for further investigation.) The reversal of the Ne X/Ne IX ratio in both sequences, despite interference from Fe XVII at the later types, is remarkable, as is the smooth decline in the absolute strength of the Si XIII line. Several of these objects are believed to be colliding-wind binaries, which nevertheless does not appear to obstruct the observed trends; neither does the range of extinctions among these stars, to which the ratios of close line pairs should be particularly insensitive. We are currently also investigating the behavior of detailed line properties such as width, shape, shift, and He-like forbidden/intercombination/recombination component ratios along these sequences.

These trends in the X-ray spectra of the OB stars as a function of the optical spectral types (and by implication, of the fundamental stellar parameters) are unexpected in some views of their origin, and they have not emerged from previous studies because of inadequate samples and current modeling uncertainties. In effect, the history of the discovery of the UV wind-profile systematics (Walborn et al. 1985,
Figure 9: Sequence of OB supergiant/(giant) X-ray spectra from Chandra. Courtesy of Wayne Waldron.
Figure 10: OB main-sequence/(giant) X-ray spectra from Chandra. Courtesy of Wayne Waldron.
Walborn OB Spectra

1995) appears to be repeating in the X-ray domain. The importance of pure morphological investigation of such trends, as emphasized in the Introduction, is being demonstrated once again. Most likely, the physical origin of these correlations will be found in the winds themselves; in retrospect, that may not be so surprising in view of known relationships between bolometric and X-ray luminosities, as recently demonstrated in detail in NGC 6231 by Sana et al. (2006). These morphological results will provide strong guidance to further developments in physical models of the phenomena. Progress will likely be accelerated if astrophysics emulates some of the morphological techniques, e.g., by defining standard objects that are homogeneously reanalyzed whenever there are substantial revisions to the models, and by emphasizing the modeling of the powerfully diagnostic, relative trends in the HRD, as opposed to exclusive, absolute studies of one or a few objects in isolation.

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*The UV Universe: Stars from birth to death* 18
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