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MULTIWAVELENGTH SYSTEMATICS OF OB SPECTRA

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RESUMEN

La sistemática de los espectros OB es resumida, en el rango óptico dominado por líneas fotosféricas, y en el lejano ultravioleta (tanto de *IUE* como de *FUSE*) donde dominan perfiles de los vientos estelares. Primero, las tendencias bidimensionales (temperatura, luminosidad) en los espectros normales son examinadas. Luego, establecida la estructura de referencia normal, se pueden reconocer relativo a ésta varias categorías de objetos peculiares, las cuales revelan sendos fenómenos de importancia estructural y/o evolutiva. Se incluyen anomalías de CNO en tipos O tempranos y tardíos, tres variedades de rotadores rápidos, objetos de transición Of/WN de alta y baja temperatura, y la recientemente descubierta segunda estrella magnética de tipo O conocida. Aunque se han adelantado y se siguen adelantando las interpretaciones físicas de estas tendencias y anomalías, mayor atención al modelaje de la sistemática aceleraría el progreso a futuro en la opinión de este autor. Finalmente, se presentan resultados preliminares de un estudio con *Chandra* en alta resolución de los espectros OB en el rango de rayos X. Éstos proveen evidencias de que, tal como sucedió anteriormente en el UV, tendencias morfológicas sistemáticas existen en el dominio de rayos X, las cuales son correlacionadas con los tipos espectrales ópticos, y de allí con los parámetros estelares fundamentales, al contrario de la opinión especialista prevaleciente.

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. 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 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: stars: early-type — stars: fundamental parameters — ultraviolet: stars — x-rays: 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,

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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 λ4541/He I λ4471, 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 N IV λ4058/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.

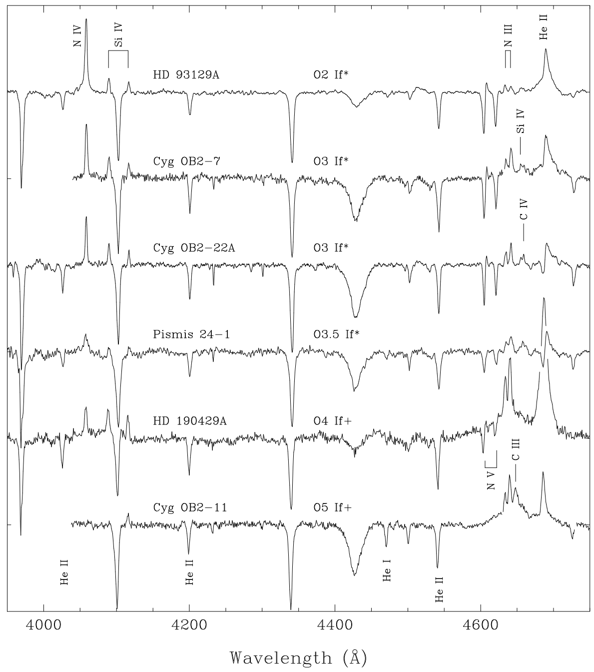

Fig. 1. Temperature sequence of very early O blue-violet spectra. Courtesy of Ian Howarth.

The original, photographic definition of the transition from type O9.5 to B0 was the disappearance of He II λ4541, 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 He I spectrum, which has maximum intensity at type B2, is the primary spectral-type indicator. In the supergiants, the silicon ionization, in particular Si IV λ4089/Si III λ4552 at the earlier types and the Si III relative to Si II$\lambda\lambda$4128-30 at mid-B types, provides the primary horizontal criterion. At late-B types, the strengthening of Mg II λ4481 relative to the declining He I λ4471 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 (§ 3.1 below). Digital sequences can be found in WF.

Large-scale atlases of high-resolution *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 N V $\lambda\lambda$1239-43 and C IV $\lambda\lambda$1548-51 resonance lines have broad, saturated P Cygni profiles through type O6 and decline smoothly thereafter, while 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 O V λ1371 wind profile at types O2-O3, while 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, C II $\lambda\lambda$1334-36 and Al III $\lambda\lambda$1855-63 develop wind profiles with maxima at types B1-B2. The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) allowed this systematic phenomenology to be extended to numerous additional species and ionizations in the 900-1200 Å range, in-

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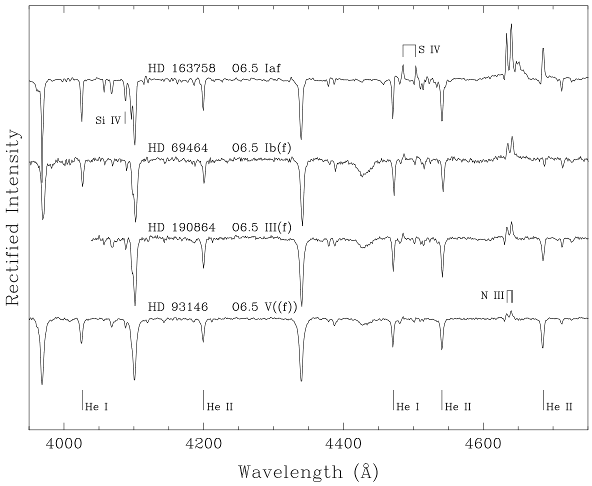

Fig. 2. Luminosity sequence of mid-O blue-violet spectra. Courtesy of Ian Howarth.

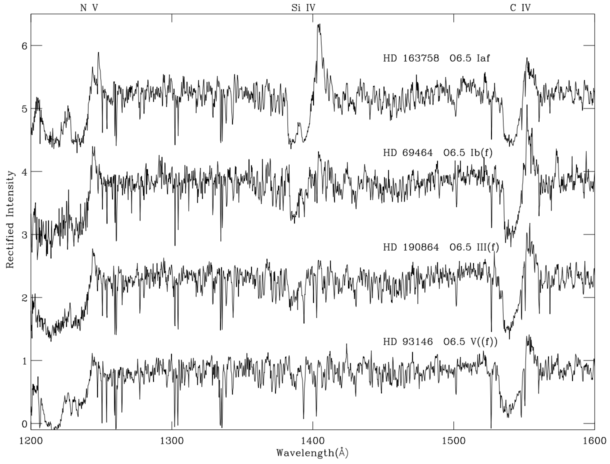

Fig. 3. Luminosity sequence of mid-O FUV (*IUE*) spectra (the same stars as shown in Figure 2). Courtesy of Danny Lennon.

cluding the superionized O VI λλ1032-1038 (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 He II λ4686 and N III λλ4634-40-42) 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 He II λ4686 is a strong absorption on the main sequence (class V), which weakens gradually through 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 λ4686 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 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 3 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 λ1176, 48 eV; S IV λλ1063-73, 47 eV; and P V λλ1118-28, 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).

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 il-

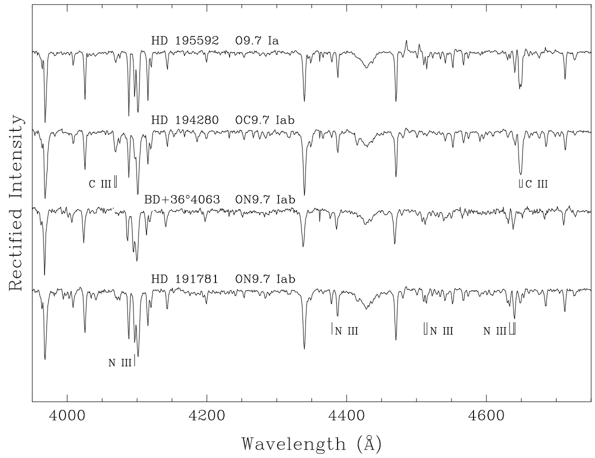

Fig. 4. CNO anomalies in late O supergiant blue-violet spectra. Courtesy of Ian Howarth.

lustrative sequences in the optical, and Walborn et al. (1995) for correlative effects in the UV.

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 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 4. 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.

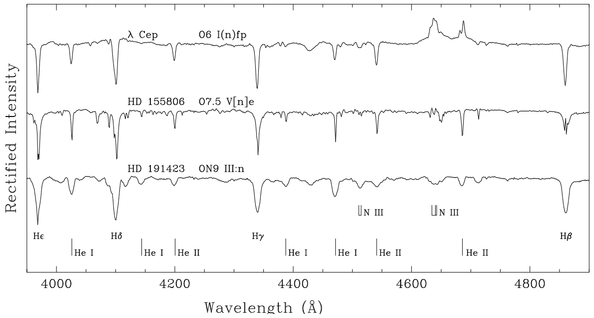

Fig. 5. Blue-violet spectra of three kinds of O-type rapid rotators. Courtesy of Ian Howarth.

3.2. *Rapid Rotators*

Three varieties of O-type rapid rotators are illustrated in Figure 5. HD 155806 is a relatively rare analogue of the Be stars; its yellow-red spectrum including Hα 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 λ Cephei in Figure 5. These spectra have comparable broadening in absorption lines and Of emission features, with a prominent absorption reversal in the He II λ4686 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 Iafpe 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 $\lambda\lambda$4647-4650-4651 emission lines of comparable intensity to N III $\lambda\lambda$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 (Figure 6).

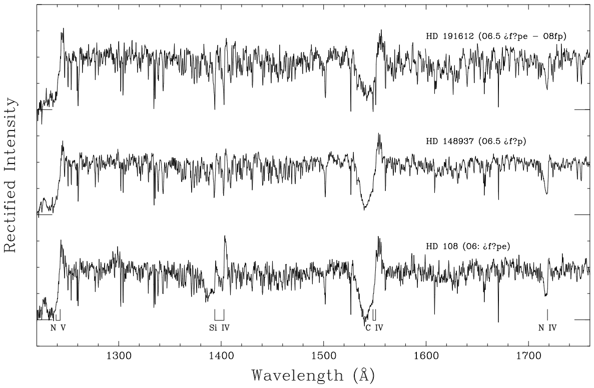

Fig. 6. FUV (*IUE*) spectra of the Of?p stars showing their non-supergiant Si IV profiles; compare Figure 3). Courtesy of Ian Howarth; Spanish translation of spectral types suggested by David Cohen.

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 (see 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 (Nazé 2004), which satisfies all available spectroscopy since at least 1982 (Walborn et al. 2004b). Figure 7 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

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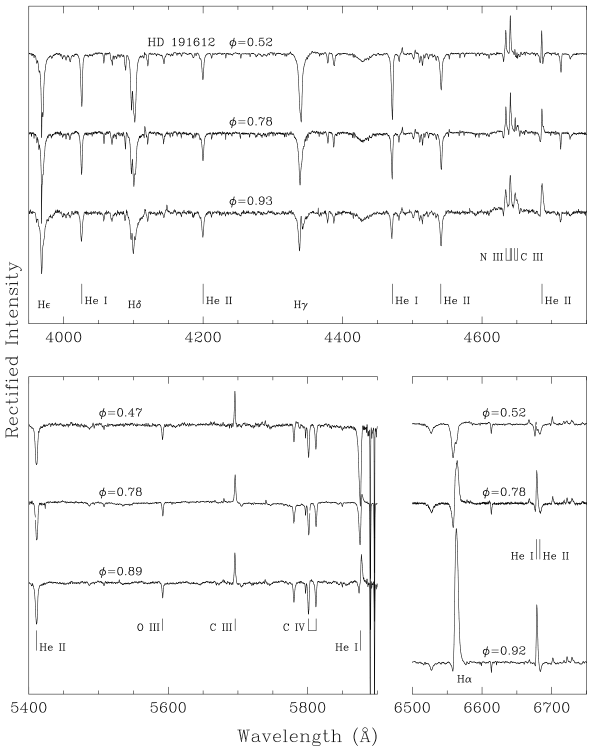

Fig. 7. Blue-violet (top) and yellow-red (bottom) spectra of the Of?p magnetic oblique rotator HD 191612 at different phases of the 538 d rotational period. Courtesy of Ian Howarth.

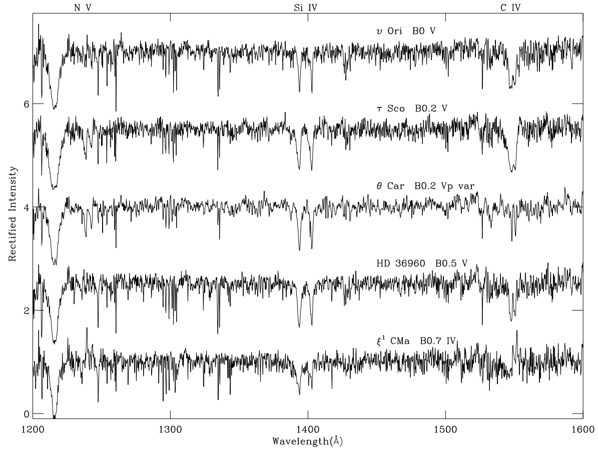

Fig. 8. Peculiar FUV (*IUE*) spectra of 3 magnetic or candidate magnetic B stars compared with 2 normal standards. Courtesy of Danny Lennon.

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, θ^1 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. θ^1 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 ξ^1 Canis Majoris (Rountree & Sonneborn 1991, 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). The UV spectra of three of these new magnetic and candidate magnetic stars are shown in Figure 8.

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,

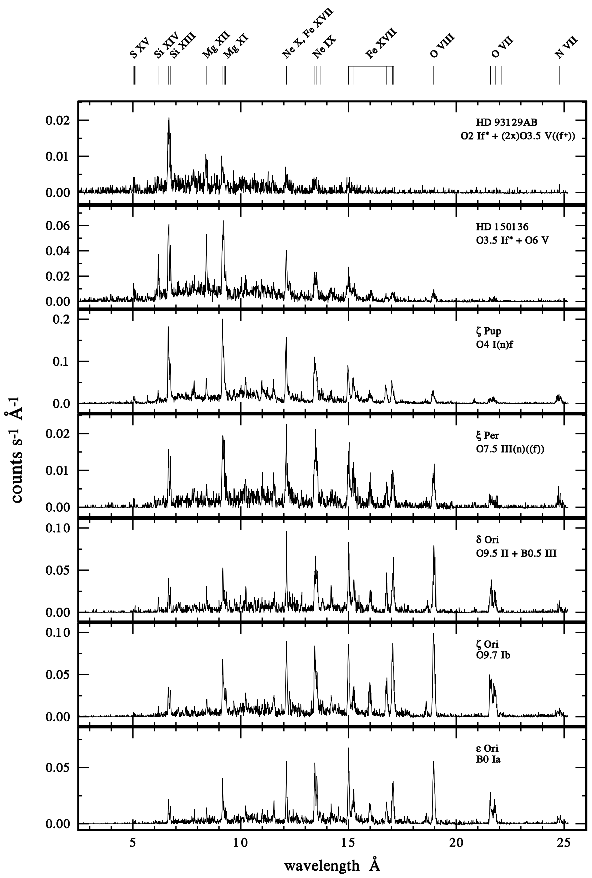

Fig. 9. Sequence of OB supergiant/(giant) X-ray spectra from *Chandra*. Courtesy of Wayne Waldron.

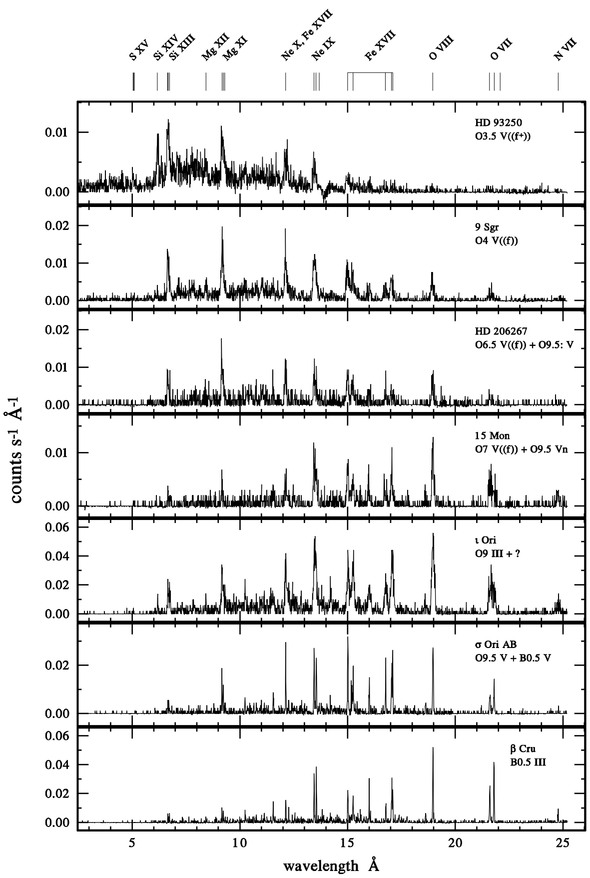

Fig. 10. OB main-sequence/(giant) X-ray spectra from *Chandra*. Courtesy of Wayne Waldron.

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. 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/resonance 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, 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.

The full array of multiwavelength spectrograms presented in this review will be reproduced and described in more detail in the OB chapter of a new book on spectral classification being prepared by R.O. Gray and C.J. Corbally. The author sincerely thanks I.D. Howarth, D.J. Lennon, P.A. Crowther, and W.L. Waldron for providing extensive data and spectral plots for this review. Other, previous plots were made by A.W. Fullerton, J.Wm. Parker, N.I. Morrell, J.S. Nichols, L.J. Smith, and A.F.J. Moffat. My travel to Cariló was supported by NASA through grant GO-10205.01 from the Space Telescope Science Institute, which is operated by AURA, Inc., under contract NAS5-26555.

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DISCUSSION

M. Kraus - What is the luminosity or initial mass range of the rapidly rotating O stars you found in the MCs? These will be the progenitors of the B[e] supergiants which will or which have been rapidly rotating in order to produce the high mass outflowing disk.

N. Walborn - They are very luminous giants or supergiants, but we shall determine their parameters systematically only next year. One of them, AV80 in the SMC, has been placed in the HR diagram by Walborn et al. (2000) in the 85 $M_\odot$ track and another, Testor 2A in the LMC Breysacher 73 compact group by Walborn et al. (199, AJ 118, 1864) as 80 $M_\odot$. The others are recently discovered. It needs to be determined whether the Onfp stars have similar masses to the B[e] supergiants and are thus possible progenitors, or whether they have higher initial masses.

A. Willis - Your Chandra X-ray spectra are great. Do you see any luminosity effect in the O stars in the X-ray?

N. Walborn - A good question, but the sample is still too small to answer it. We have looked, but there are only two or three stars at a given spectral type, sometimes with similar luminosity classes, so nothing definite can yet be said.

M. Corcoran - How big an effect is N$_H$ in removing the long wavelength emission in the Chandra sample? And is there any correlation between wind velocity and X-ray ionization?

N. Walborn - It appears to have no significant effect in the sample I showed, for which A_V ranges from 0 to about 1 magnitude. We have two stars in Cyg OB2, for which the extinction is much larger and the entire longer wavelength range is missing, so they have been excluded from this discussion. Of course, the ratios of the close pairs at H- and He-like lines are esentially unaffected by extinction. I have also been asked whether extinction within the winds might contribute to the “diagonal effect”; it might reduce the longer wavelength (lower ionization) lines at the earlier types, but it could not do the converse, and such effect would be correlated with the mas-loss rates and spectral types in any event. Similarly, the wind velocities are already known to correlate with the spectral types at a given metallicity, so they also correlate with the X-ray ionization by syllogium. All of these correlations likely arise from the physics of the winds, so once again, morphology provides strong hypotheses for physical analysis and understanding!

A. Maeder - Concerning the interesting group of ON stars, do you see any change in their number ratio with spectral type? Is there any difference in the SMC?

N. Walborn - A good question, but I do not know the answer. I have not attempted such an exercise, partly because it would be dangerous: the detectability and magnitude of CNO anomalies morphologically are entirely dependent on which lines are available at a given spectral type and how they behave with T and L. Thus they are not uniform. This kind of question will have to be answered via quantitative analysis. Despite the weaker lines some CNO lines have been detected in SMC B supergiants in a careful study by Lennon (1997, A&A, 317, 871).

R. Terlevich - What fraction of luminosity comes out in X-ray in those stars with ... X-ray spectra?

N. Walborn - $L_X/L_{\rm bol}$ is typically 10^{-7} for O stars. A recent study by Sana et al. (2006, MNRAS, 372, 661) of NGC 6231 shows a very tight relation, with a few exceptions evidently due to binaries. The rare magnetic OB stars also have enhanced L_X and harder spectra than normal for thier spectral types.

N. Smith - I didn’t see any O2 dwarfs... are there any?

N. Walborn - Yes, there are several known (Walborn et al. 2002, AJ, 123, 2754)

N. Smith - What fraction of O stars are these very rapid rotators?

N. Walborn - I’m not sure. Be-like Oe stars are very rare, see Negueruela et al. (2004, Astron. Nachr., 325, 749) for a comprehensive study. Only a handful of ONn spectra are known to date (Walborn 2003, ASP Conf. Ser. 304, 29). There are about 20 Onfp stars known in the Magellanic Clouds out of a few hundred well classified O stars, so perhaps $\sim 5\%$?

N. Smith - In the Pismis 24 cluster with four 100-ish $M_\odot$ stars, how many O stars are there in total?

N. Walborn - Massey et al. (2001, AJ, 121, 2050) classified the brighter members of this small cluster and found six or eight O main sequence stars, in addition to the four very high mass objects now known.

I. Howarth - You have identified some main sequence OC stars in the Magellanic Clouds, can you comment on these particularly with reference to the OC – O normal – ON sequence in supergiant spectra?

N. Walborn - There is one OC dwarf and one OC giant known in the SMC (Walborn et al. 2000, PASP, 112, 1243). Both of these have C III $\lambda4650$ emission with no N III $\lambda4640$ (which I have never seen in Galactic or LMC spectra), and correlated anomalies in the UV wind profiles. The former is a Vz in NGC 346 but Mokiem et al. (2006, A&A, 456, 1131) have recently found it to be helium enriched! So, I throw up my hands on any interpretation of that.

P. Massey - When you first defined the O3 class you said they lacked He I absorption on your IIaO spectrograms but when Rolf Kudritzki came along and took IIa-J spectra, he found He I at 80-100 mÅ equivalent widths. With CCDs we’ve now taken very high S/N (400-500) on some of these O2-O3.5 stars, and many have He I $\lambda4471$ with EWs of 20-50 mÅ. For these we can get temperatures (rather than lower limits) and these show (Massey et al. 2005, ...) that some O2s are not as hot as some O3s and that this morphological scheme you’ve defined doesn’t represent an extension of the temperature sequence. Now from what you said today, you don’t like these temperatures, and therefore think that the He I always comes from a companion since you found one such example locally (Pismis 24-1). And maybe that is right. But how does this fit in with this whole philosophical process you presented at the start of your talk?

N. Walborn - Indeed with higher S/N one can detect weaker features and it had been my hope that the O3 class might be subdivided on the basis of weak HeI lines in that way. However extensive experience with high S/N digital detectors has convinced me that it will not be the case because, in addition to being extremely sensitive to the S/N in each spectrogram, the HeI lines are affected by inhomogeneous nebular lines subtraction, incipient wind profiles in Of* and slash spectra, and most importantly, later type companions. The last has shown to be the case in several objects in addition to Pismis 24-1 (although that case is striking because even a weak HeI line in the composite O3.5 spectrum arises from an O4 companion!): recall LH10-3209, NGC2044W-9, CygOB2-22 (Walborn et al. 1999, AJ, 188, 1684; 2002, AJ, 123, 2754). For that reason, I have defined the new earliest types on the basis of the NIV/NIII selective emission-line ratio instead, for which there is ample justification from the systematic behaviour of such lines in the later O-type spectra, including that ratio itself at type O4. Your dismissal of this classification development from your analysis of a Magellanic Cloud sample is certainly premature. I agree that quantitative analysis and calibration are required to ultimately validate a new morphological scheme, which is by nature hypothetical until that is done, but it must be done properly by homogeneous analysis of the defining standards with appropriate models, which has not been done, so the jury is still out. I disagree with some of your classifications, at least some of your HeI measurements are affected by the above issues, and moreover the models you used don't even produce the N lines. In fact, preliminary results by Heap et al. and Mokien et al., do show that the NIV/NIII ratio correlates with $T_{\rm eff}$. This methodological process is consistent with the philosophy of spectral classification. While the latter must be independent of external information, such way guide the initial hypothetical definition of a new system.

Thank you Virpi.