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Spectral classification of O2–3.5 If*/WN5–7 stars

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ABSTRACT

An updated classification scheme for transition O2–3.5 If*/WN5–7 stars is presented, following recent revisions to the spectral classifications for O and WN stars. We propose that O2–3.5 If*, O2–3.5 If*/WN5–7 and WN5–7 stars may be discriminated using the morphology of Hβ to trace increasing wind density as follows: purely in absorption for O2–3.5 If* stars in addition to the usual diagnostics from Walborn et al.; P Cygni for O2–3.5 If*/WN5–7 stars; purely in emission for WN stars in addition to the usual diagnostics from Smith et al. We also discuss approximate criteria to discriminate between these subtypes from near-infrared spectroscopy. The physical and wind properties of such stars are qualitatively discussed together with their evolutionary significance. We suggest that the majority of O2–3.5 If*/WN5–7 stars are young, very massive hydrogen-burning stars, genuinely intermediate between O2–3.5 If* and WN5–7 subtypes, although a minority are apparently core helium-burning stars evolving blueward towards the classical WN sequence. Finally, we reassess classifications for stars exhibiting lower ionization spectral features plus Hβ emission.

Key words: stars: early-type – stars: evolution – stars: fundamental parameters – stars: massive – stars: Wolf–Rayet.

1 INTRODUCTION

Historically, O3 stars have been considered to represent the highest mass main-sequence, i.e. core hydrogen-burning stars. However, it is now recognized that some hydrogen-rich, nitrogen sequence Wolf–Rayet stars may be main-sequence stars possessing still higher masses (de Koter, Heap & Hubeny 1997; Schnurr et al. 2008b; Smith & Conti 2008; Crowther et al. 2010). Morphologically, it has long been recognized that there is a relatively smooth progression from O dwarfs through giants and supergiants to the WN sequence (Walborn 1971; Conti 1976; Crowther et al. 1995). Indeed, Walborn (1982a) introduced the hybrid O3 If*/WN6 classification for Sanduleak −67°22, located in the Large Magellanic Cloud (LMC). Such stars, often referred to as 'hot' slash stars, possess intermediate spectral characteristics between O3 supergiants (e.g. HD 93129A) and WN6 stars (e.g. HD 93162). A second flavour of dichotomous spectrum, known as Ofpe/WN9 or 'cool' slash stars, was introduced by Walborn (1982b) and Bohannan & Walborn (1989), although alternative WN9–11 subtypes are now in common usage for such stars (Smith, Crowther & Prinja 1994).

Since the original study of O3 If*/WN6 stars by Walborn (1982a), the transition from photographic plates to digital detectors and increased samples have permitted the extension of the MK system to O2 (Walborn et al. 2002), while Smith, Shara & Moffat (1996) have added to the classification of WN stars. Indeed, the widespread availability of high-quality spectroscopic data sets for O and WN stars – such as the Very Large Telescope Fibre Large Array Multi-Element Spectrograph (VLT–FLAMES) Tarantula Survey (Evans et al. 2011) – allows us to reassess the hybrid Of/WN classification.

Here, we present a revised Of/WN classification scheme, which takes into account recent changes for Of and WN stars, based in part upon previously unpublished high-quality, blue–violet echelle spectrograms. Section 2 describes archival and new VLT observations, while our scheme is described in Section 3. Section 4 provides an overview of Of/WN stars at near-infrared (near-IR) wavelengths, while a qualitative study of such stars is presented in Section 5, together with a discussion of their evolutionary significance. In Section 6, we briefly reassess spectral types of Ofpe/WN9 plus related stars. Finally, a concise summary is presented in Section 7.

2 OBSERVATIONS

Table 1 lists the previously unpublished echelle data sets used in this study, comprising objects within the LMC. All new data sets were obtained with the VLT, using either the UV–Visual Echelle Spectrograph (UVES; D'Odorico et al. 2000) or the Medusa fibre-feed to the Giraffe spectrograph of FLAMES (Pasquini et al. 2002).

UVES feeds both blue (EEV CCD) and red (EEV CCD + MIT/LL CCD) arms, via various choices of dichroics and central wavelengths, with a small gap between red detectors. For the 2002

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Table 1. Observing log of previously unpublished blue echelle spectroscopy used in this study.

Star	WR/ BAT 99-	Old subtype	Reference	VLT/ instrument	Epoch	Sp. coverage	Resolution ($\mathrm{km\,s^{-1}}$)	PI	Reference
Sk −67° 22	12	O3 If*/WN6	a	UVES	2004 December	3758–4983	8.7	P. A. Crowther	Welty & Crowther (2010)
TSWR 3	93	O3 If*/WN6	b, d	FLAMES	2008 December–2009 October	3960–5114	35–40	C. J. Evans	#180: Evans et al. (2011)
Melnick 51	97	O3 If*/WN7	d	FLAMES	2008 December–2009 October	3960–5114	35–40	C. J. Evans	#457: Evans et al. (2011)
Melnick 39	99	O3 If*/WN6	d	UVES	2008 December–2010 January	4175–6200	7.5	C. J. Evans	#482: Evans et al. (2011)
Melnick 42	105	O3 If*/WN6	d	UVES	2002 December	3758–4983	8.7	P. A. Crowther	Welty & Crowther (2010)
Melnick 30	113	O3 If*/WN6	d	FLAMES	2008 December–2009 October	3960–5114	35–40	C. J. Evans	#542: Evans et al. (2011)
Melnick 35	114	O3 If*/WN6	d	UVES	2008 December–2010 January	4175–6200	7.5	C. J. Evans	#545: Evans et al. (2011)
HD 38282	118	WN6h	c	UVES	2003 November	3300–6615	4.5	D. Welty	Welty & Crowther (2010)

(a) Walborn (1982a); (b) Testor & Schild (1990); (c) Smith et al. (1996); (d) Walborn & Blades (1997).

November and 2004 December service runs (70.D-0164, 74.D-0109) two setups were used, together with a 1 arcsec slit. The first used the blue and red arms of UVES, centred at 390/564 nm, while the second used solely the red arm, centred at 520 nm, providing complete spectral coverage between the far-blue and Hα. For the 2003 December run (72.C-0682), solely the 390/564 nm setup was used, with a 0.7 arcsec slit, producing a gap between blue and red arms from 4500 to 4620 Å. Lower resolution spectroscopy from Crowther & Smith (1997) obtained with the Anglo-Australian Telescope/RGO spectrograph was used to fill this gap for HD 38282. Details of data reduction are outlined in Welty & Crowther (2010).

UVES observations from the Tarantula survey (182.D-0222) also solely used the red arm, at 520 nm, with a 1 arcsec slit, which omitted spectroscopy shortward of ∼4175 Å. In this instance, the crucial N IV λ4058 region was obtained from the archival *Hubble Space Telescope*/Faint Object Spectrograph (*HST*/FOS) data sets from Massey & Hunter (1998). Finally, multi-epoch Medusa/FLAMES data sets from the Tarantula survey were obtained with the (overlapping) LR02 and LR03 setups, providing complete blue-visual spectroscopy. Note that Melnick 30 and 51 were observed with Medusa/FLAMES and UVES, but the former are utilized here in view of the lack of complete blue coverage from the red arm of UVES. Details of data reduction are outlined in Evans et al. (2011). These data sets were complemented with archival high and intermediate dispersion observations of emission-line stars obtained from a variety of sources, notably Crowther et al. (1995) and Walborn et al. (2002) for stars located within the Carina nebula. We note that all targets listed in Table 1 lie within the LMC, in common with the majority of stars hitherto classified as O3 If*/WN6–7. Nevertheless, we will show that several Milky Way stars also share these spectroscopic properties and discuss possible explanations for the role of metallicity in Section 5.

3 Hβ AS A PRIMARY DIAGNOSTIC FOR TRANSITION OF/WN STARS

In this section, we present the motivation for an Of/WN sequence and our recommendations. Among early O-type stars, those with the highest wind densities exhibit He II λ4686 emission plus selective emission in N III $\lambda\lambda$4634–41 and N IV λ4058 and are denoted Of* when the N IV intensity is equal to, or greater than, that of N III. Aside from these features, a conventional absorption line appearance is observed in the blue–violet spectra of such stars. Meanwhile, mid-to-late WN stars with relatively weak winds exhibit relatively weak, narrow He II λ4686 and N IV λ4058 emission, with a P Cygni-type morphological appearance of the upper He II Pickering and/or H I Balmer series. Nitrogen emission from N III λ4634–41 and N V $\lambda\lambda$4603–20 is also common to such stars, typically corresponding to subtypes of WN5–7. Such stars have been labelled as WN-A (Hiltner & Schild 1966; Walborn 1974), WN+abs (Smith 1968; Conti, Niemela & Walborn 1979), WN-w (Schmutz, Hamann & Wessolowski 1989), WNha (Smith et al. 1996) and WNH stars (Smith & Conti 2008).

Morphological similarities between Of* stars and such weak-lined, mid-to-late-type WN stars were first emphasized by Walborn (1971). Walborn (1982a) introduced Sk −67° 22 as a prototype for the O3 If*/WN6 subtype. Following the identification of numerous early-type emission-line stars in 30 Doradus region of the LMC by Melnick (1985), several examples were so classified (Walborn & Blades 1997).

The brightest stars of the central R136a ionizing cluster of 30 Doradus were also initially classified as O3f/WN (Heap et al.

Table 2. Horizontal criteria and standard (example) stars for O2–O4 If (from Walborn et al. 2002; Sota et al. 2011), WN5–9 (revised from Smith et al. 1996) and intermediate Of/WN stars, based on peak intensities of nitrogen diagnostics, N III $\lambda\lambda$4634–41, N IV λ4058, N V $\lambda\lambda$4603–20 plus Hβ. Differences with respect to Smith et al. (1996) are marked in bold.

Subtype (Hβ absorption)	O2 If*	O3 If*	O3.5 If*	O4 If	–
Criteria	N IV em. $\gg$ N III em.	N IV em. $>$ N III em.	N IV em. $\approx$ N III em.	N IV em. $<$ N III em.	–
	He I absent	He I absent	He I absent	He I weak	–
Standard stars	HD 93129A	Cyg OB2-7, -22A	Pismis 24-1NE	HDE 269698	–
				HD 190429A, Sk $-67°$ 167	–
Subtype (Hβ P Cygni)	O2 If*/WN5	O2.5–3 If*/WN6	O3.5 If*/WN7	–	–
Criteria	N IV em. $\gg$ N III em.	N IV em. $>$ N III em.	N IV em. $<$ N III em.	–	–
	N V $\gtrsim$ N III	N V $<$ N III	N V $\ll$ N III	–	–
Standard stars	Melnick 35	HD 93162 (WR25)	Melnick 51	–	–
Subtype (Hβ emission)	WN5	WN6	WN7	WN8	WN9
Criteria	N V/N III $=$ **0.8**–2	N V/N III $=$ 0.2–**0.8**	N IV/N III–V $=$ **0.3–0.8**	N IV/N III–V $\leq$ **0.3**	N IV–V absent, N III em.
	N IV/N III–V $=$ **1–3**	N IV/N III–V= **0.8–2**	N V/N III $\leq$ **0.2**	N V/N III $\leq$ **0.2**	P Cygni He I
Standard stars	LS 2979 (WR49)	LS 3329 (WR67)	HD 151932 (WR78)	HD 96548 (WR40)	NS4 (WR105)

1994; de Koter et al. 1997) from ultraviolet (UV) spectroscopy, although WN4.5 or WN5 subtypes were preferred by Massey & Hunter (1998) and Crowther & Dessart (1998), respectively, from optical *HST*/FOS data sets. Still, in the absence of robust criteria, individual stars have shifted between subclasses. For example, Azzopardi & Breysacher (1979) initially classified their new LMC Wolf–Rayet star no. 4 (AB4, Brey 58 and BAT 99-68) as WN5–6, while Smith et al. (1996) suggested Of. Massey, Waterhouse & DeGioia-Eastwood (2000) supported WN5–6 for AB4 given its relatively strong He II λ4686 emission [equivalent width (EW) $\sim$ 20 Å], although Massey et al. (2005) subsequently preferred O3 If*/WN6 on the basis of He II λ4200 absorption, while Schnurr et al. (2008a) assigned WN7h. Meanwhile, HD 93162 in the Carina Nebula has been traditionally described as a 'weak-lined WN star' in spite of a lower He II λ4686 EW ($\sim$15 Å) than for AB4. Another example is Melnick 42, initially classified as WN (Melnick 1982a) or O3 If (Melnick 1985), but subsequently reassigned to O3 If*/WN6 (Walborn et al. 1992).

Since He II λ4686 emission, selective nitrogen emission plus intrinsic absorption components in the upper Pickering lines are common to some O2–3.5 If* and WN5–7 stars, one needs to look elsewhere for a suitable diagnostic of intermediate O2–3.5 If*/WN5–7 stars, ideally in the conventional blue-visual range. We propose that a P Cygni morphology of Hβ represents such a diagnostic, since this is uniquely in absorption for O stars (including Of* stars) and in emission for WN stars (though see Section 6). Various extensions to WN subtypes are in common usage, for which h and a (or +abs) would be relevant to intermediate Of/WN stars. We choose to omit these since they are redundant in such cases (all contain hydrogen and intrinsic upper Pickering absorption lines).

Of course, two factors complicate the use of Hβ as a spectral diagnostic, namely nebular emission from an associated H II region, plus intrinsic absorption from a companion OB star. Consequently, Of/WN subtypes can only robustly be assigned on the basis of high dispersion, high S/N spectroscopy in which the nebular component and/or companion can be identified. Nevertheless, emission-line strengths of other blue–violet features provide approximate subtypes (Section 3.4) and high-quality data sets are also required for reliable classification of the earliest O stars.

Our use of Hβ to discriminate between subclasses has a relatively minor effect on existing spectral subtypes, although a few stars shift between categories. In addition, it is necessary to adjust the division between WN5 and WN6 subtypes with respect to Smith et al. (1996), since the parallel Of and WN sequences both involve the N IV/N III ratio. For hybrid Of/WN subtypes, universally exhibiting N IV λ4058 emission, the range in ionization spans O2–O4 If and WN5–8, with a relatively monotonic sequence from O2 If*/WN5 to O3.5 If*/WN7. For completeness, our updated criteria are set out in Table 2, for which horizontal criteria reflect changes of ionization (decreasing stellar temperatures from left to right) and vertical criteria indicate changes in wind density (increasing from top to bottom).

3.1 Morphological sequence from O2 to WN5–6

In Fig. 1, we present representative examples of the highest ionization stars spanning the morphological sequence O2 If*, O2 If*/WN5–6 and WN5–6. With respect to current classification schemes, it was necessary for Melnick 42 (Melnick 1985; Walborn & Blades 1997) to be reassigned to an O2 If* classification since its overall morphology more closely resembles HD 93129A (Walborn et al. 2002) than Melnick 30 (Walborn & Blades 1997), which is newly revised from O3 If/WN6 to O2 If*/WN5. The figure illustrates the significance of the Hβ morphology, with evidence for P Cygni profiles in Hγ and He II λ4542 in Melnick 30.

Similarly, we reassign HD 93162 from WN6ha (Smith et al. 1996) to an intermediate O2.5 If*/WN6 classification on the basis of P Cygni Hβ, in common with Melnick 30, rather than emission as is the case of HD 93131 (WN6ha). Conti & Bohannan (1989) have previously highlighted its intermediate morphological appearance by suggesting WN6/O4f for HD 93162. Evans et al. (2006) introduced the O2.5 subclass for N11-026 (O2.5 III(f*)) since its appearance lay intermediate between O2 and O3 standards from Walborn et al. (2002).

3.2 Morphological sequence from O3–3.5 to WN6–7

In Fig. 2, we present representative examples of stars of slightly lower ionization, spanning the morphological sequence O3–3.5 If*, O3–3.5 If*/WN6–7 and WN6–7, including O supergiants from Walborn et al. (2002) and Maíz Apellániz et al. (2007). With respect to existing classification schemes, it was necessary for BAT 99-93 (Testor & Schild 1990; Walborn & Blades 1997) to be classified as O3 If* since Hβ is in absorption, in spite of its prominent He II

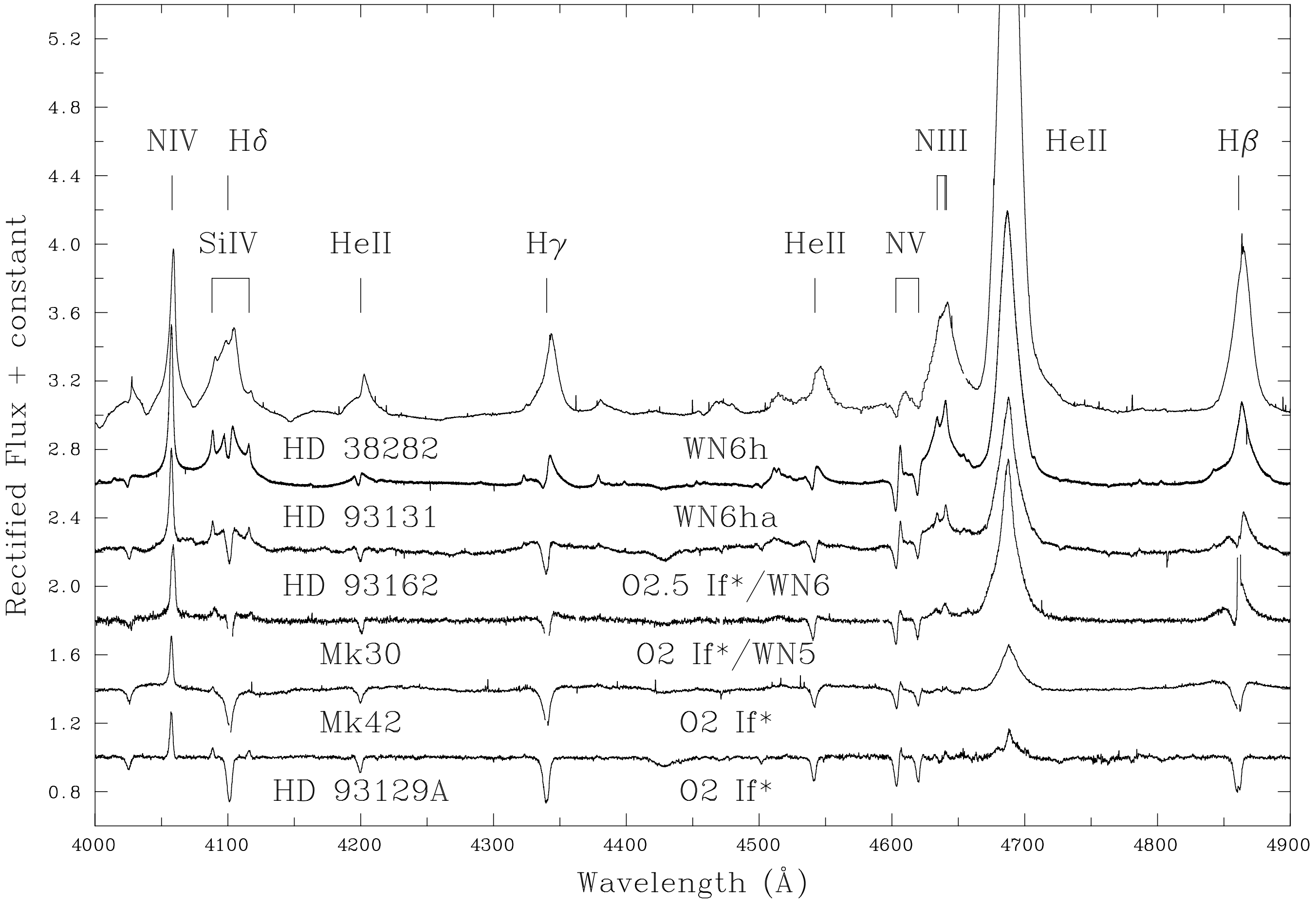

Figure 1. Rectified, blue–violet spectrograms of stars spanning O2 If* through WN6(h). From Hβ, Melnick 42 is newly classified O2 If*, while HD 93162 is revised to O2.5 If*/WN6h. Stars are uniformly offset by 0.4 continuum units for clarity.

λ4686 emission. Meanwhile, O3.5 If*/WN7 is preferred for Melnick 51 since the morphology of this star is intermediate between BAT 99-93 and HD 92740, even though the P Cygni nature in Hβ is less definitive than other stars.

It could be argued that Melnick 51 should be assigned O3.5 If*/WN6.5 since N IV λ4058 $\sim$ N III $\lambda\lambda$4634–41, i.e. intermediate between N IV λ4058 $>$ N III $\lambda\lambda$4634–41 for non-transition WN6 stars and N IV λ4058 $<$ N III $\lambda\lambda$4634–41 at a subtype of WN7. For the moment, we prefer WN7 for Mk 51 on the basis of N V $\lambda\lambda$4603–20 $\ll$ N III $\lambda\lambda$4634–41, in common with non-transition WN7 stars. However, should other examples of similar transition stars be confirmed (Mk 37a is a candidate), we may reconsider the use of WN6.5 for intermediate narrow-lined types (N III–V lines are severely blended for broad-lined stars).

3.3 Morphological sequence from O2 If*/WN5 to O3.5 If*/WN7

Fig. 3 presents a montage of Of/WN stars for which we possess high-quality blue–violet spectroscopy. In two cases – Melnick 35 and 39 – the N IV λ4058 region was not included in UVES data sets from the VLT–FLAMES Tarantula Survey (Evans et al. 2011), so lower resolution archival *HST*/FOS spectroscopy of this region has been included (Massey & Hunter 1998).

This figure illustrates the range in ionization balance sampled by transition Of/WN stars, given the requirement that N IV λ4058 emission is observed in all instances. By definition, P Cygni profiles are observed for Hβ, although there is a continuum from Sk -67° 22 (least extreme) to Melnick 51 (most extreme). Indeed, Sk -67° 22 is the only example from this sample in which Hγ is purely in absorption, rather than a P Cygni profile.

3.4 Subtype boundaries from optical spectroscopy

In addition to the new high-dispersion observations set out in Table 1, we have reassessed spectral types for other early O supergiants and weak-lined WN stars in the Milky Way and LMC based upon lower resolution spectroscopy. Spectral types from the literature, plus our new revisions where necessary, are provided in Table 3.

In Fig. 4, we present blue–violet spectrograms for stars that we have revised with respect to recent literature values. In the two cases for which data sets include Hβ, we can comfortably assign O2 If* to R136a5 and WN6o to HD 193077 (WR138). Although our spectroscopy does not extend to Hβ for NGC 3603-C (WR43c), fig. 3 from Melena et al. (2008) indicates an emission morphology with weak P Cygni absorption. NGC 3603-C has been classified as WN6+abs and WN6ha by Drissen et al. (1995) and Schnurr et al. (2008b), respectively, although the former authors noted its striking similarity to HD 93162. We assign a slightly later subtype

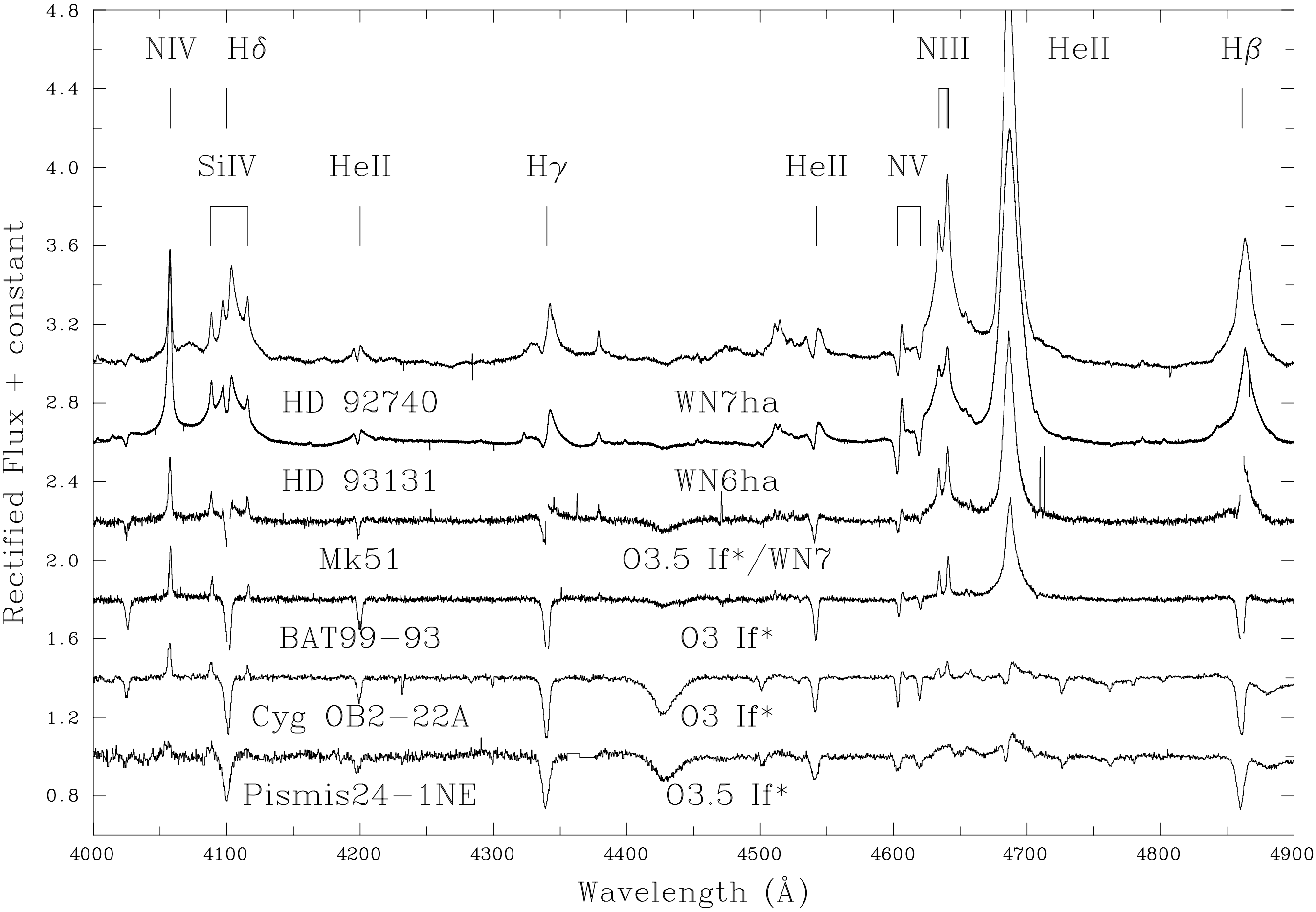

Figure 2. Rectified, blue–violet spectrograms of stars spanning O3 If* through WN6–7. From Hβ, BAT 99-93 (TSWR3, Brey 74a) is newly classified O3 If*, while Melnick 51 is refined to O3.5 If*/WN7. Stars are uniformly offset by 0.4 continuum units for clarity.

of O3 If*/WN6 for NGC 3603-C given its lower N IV/N III ratio than HD 93162.

As for NGC 3603-C, we do not possess Hβ spectroscopy for SMSP2 (WR20a). Fortunately, Hβ emission is clearly observed in fig. 7 of Shara et al. (1991), who assigned a WN7 subtype for WR20a. Rauw et al. (2004) discovered the binary nature of WR20a and obtained spectral types of O3 If*/WN6 + O3 If*/WN6. This was subsequently revised to WN6ha + WN6ha by Rauw et al. (2005) since the emission EW of He II λ4686 narrowly exceeded 12 Å, representing a boundary proposed by Crowther & Dessart (1998) to accommodate HD 93162 within the WN sequence. Of course, since we have newly reassigned HD 93162 from WN6ha to O2.5 If*/WN6 star, this criterion no longer applies (see above). For WR20a, we find an identical N IV/N III ratio to WR43c, so assign O3 If*/WN6 for each of the components in this system.

In two further cases, Mk 37a and Mk 37Wb, published spectroscopy does not extend to Hβ. Their subtypes are therefore provisional, although we defer their discussion until we have considered their nitrogen line ratios and He II λ4686 line strengths in the context of other early-type emission-line stars. We illustrate the nitrogen line ratios of selected O2–3.5 If*/WN5–7 and WN5–8 stars in Fig. 5, including subtype boundaries set out in Table 2. Of/WN stars tend to possess higher ratios of N IV λ4058/N III–V λλ4603–41 than WN stars, although O2 If*/WN5 stars exhibit reduced ratios of N V λλ4603–20/N III λλ4634–41 with respect to WN5 stars.

Since He II λ4686 is the most prominent emission line in the blue-visual spectrum of O-type supergiants and Wolf–Rayet stars, we now assess whether this line alone allows a suitable discriminator between O If*, O If*/WN5–7 and WN5–7 stars. Fig. 6 compares the line strength and linewidth of λ4686 for various emission-line stars, to which we have added several examples of WN8–9 stars. O2–3.5 If*/WN5–7 stars indeed possess properties intermediate between O2–3.5 If* and WN5–7 stars, with $8 \leq$ EW(He II λ4686) $\leq$ 20 Å, and $10 \leq$ FWHM(He II λ4686) ≤ 30 Å.

It is apparent that the emission EW of He II λ4686 alone does not permit an unambiguous subtype. R136a5 (BAT 99-110, O2 If*) possesses a similar line strength to Mk 39 (BAT 99-99, O2 If*/WN5). We indicate approximate (inclined) boundaries for Of/WN subtypes in Fig. 6. To illustrate difficulties close to subtype boundaries, we reconsider the spectral type for AB4 (Brey 58, BAT 99-68) which has fluctuated between Of/WN and WN subtypes in the literature.

We have been provided with a digital version of the blue spectrum for AB4 presented by Massey et al. (2005), which extends beyond Hβ. Its Hβ morphology very closely resembles Melnick 51 (O3.5 If*/WN7), although He II λ4686 is stronger in emission for AB4 and Hγ is a more developed P Cygni profile. Since we assign O3.5 If*/WN7 for Melnick 51 and identical subtype is preferred for BAT 99-68, although its He II λ4686 emission strength and width sits atop the boundary between Of/WN and WN stars presented in Fig. 6. On balance we favour the intermediate Of/WN

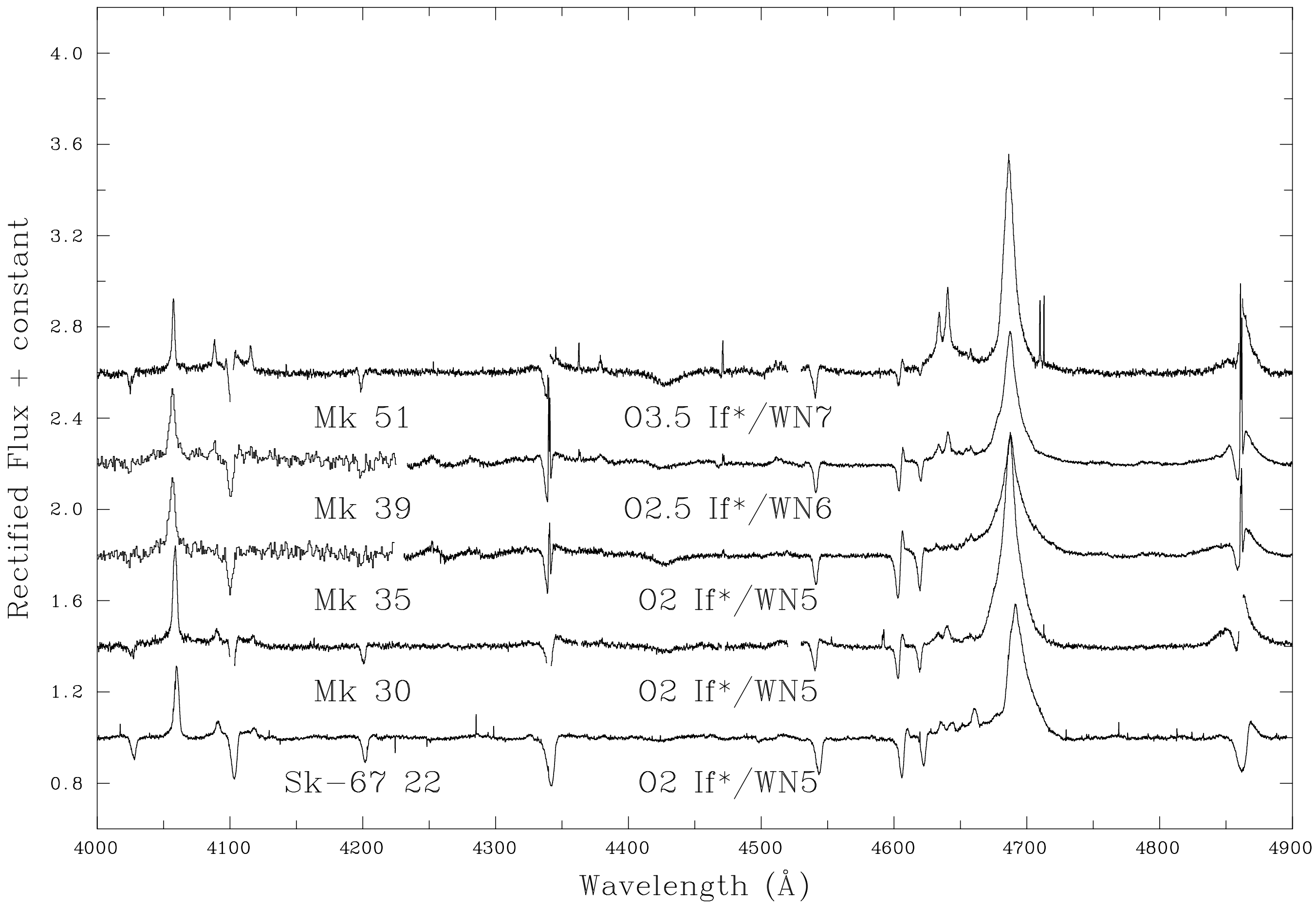

Figure 3. Rectified, blue–violet spectrograms of transition Of/WN stars. Although Hβ is P Cygni for all cases, there is a continuum from the least (Sk −67° 22) to the most extreme (Melnick 51). Stars are uniformly offset by 0.4 continuum units for clarity.

subtype proposed by Massey et al. (2005), albeit at a somewhat later subclass.

(i) *Mk 37a*. We provide a minor revision to the spectral type of Mk 37a from O4 If (Massey & Hunter 1998) to O3.5 If* following the updated classification scheme of Walborn et al. (2002) for early O stars, since N IVλ4058 ~ N III $\lambda\lambda$4634–41. The He IIλ4686 line strength and width for this star are similar to Mk 51 in Fig. 6, so we favour O3.5 If*/WN7, although Hβ spectroscopy is strictly required for an unambiguous classification.

(ii) *Mk 37Wb (BAT 99-104)*. Finally, we reassess the spectral type of O3 If*/WN6 for Mk 37Wb by Massey & Hunter (1998). Its overall blue–violet morphology matches that of confirmed Of/WN stars (e.g. Mk 35), although it is located close to the boundary between Of/WN and WN stars in Fig. 6, since EW(He II λ4686) ~ 20 Å and FWHM (He II λ4686) ~ 20 Å. For the moment, we suggest a minor revision to its spectral type from O3 If*/WN6 to O2 If*/WN5, since N IVλ4058 $\gg$ N III $\lambda\lambda$4634–41, although we are unable to provide a definitive subtype in the absence of Hβ spectroscopy.

4 NEAR-IR SPECTROSCOPY OF OF/WN STARS

Classification of early-type stars has historically relied upon high-quality blue-visual spectroscopy, to which UV morphological sequences have been added (e.g. Walborn et al. 1992). More recently, the advent of efficient detectors and large ground-based telescopes has opened up the near-IR window (primarily *K* band) for spectral typing, albeit generally cruder with respect to optical spectroscopy (Gray & Corbally 2009).

This is especially relevant for emission-line early-type stars, which are readily discovered either from near-IR narrow-band surveys (Crowther et al. 2006; Shara et al. 2009) or near-to-mid-IR spectral energy distributions (Hadfield et al. 2007). In addition, spectroscopically identifying individual stars within crowded fields from the ground – such as dense, star clusters – favours adaptive optics which is significantly more effective in the near-IR than at optical wavelengths (e.g. Schnurr et al. 2008b). Consequently, can one distinguish between Of, Of/WN and WN stars solely from near-IR spectroscopy?

We present a montage of selected Of, Of/WN and WN5–7 stars in Fig. 7, drawn from Hanson et al. (2005), Schnurr et al. (2008b, 2009) plus unpublished New Technology Telescope/SOFI spectroscopy of HD 117688 (WR55 and WN7o) from Homeier (private communication). From Smith et al. (1996), the 'o' indicates the absence of hydrogen from late-type WN stars on the basis of the Pickering–Balmer decrement. It is apparent that the Of and WN5–7 stars possess, respectively, the weakest and strongest Brγ and He II 2.189 μm emission, as anticipated. Emission features from NGC 3603-C (O3 If*/WN6), the sole transition star for which we possess high-quality *K*-band spectroscopy, are intermediate between these extremes.

Table 3. Catalogue of selected Milky Way and LMC O2–3.5 If* supergiants, O2–3.5 If*/WN5–7 and weak-lined WN5–7 stars, including revisions to literature spectral types, sorted by absolute *K*-band magnitude. For stars lacking Hβ spectroscopy, spectral types are provisional and so are shown in parenthesis. Near-IR photometry is from Two Micron All Sky Survey except where noted, while distances are obtained as follows: LMC (49 kpc; Gibson 2000), NGC 3603 (7.6 kpc; Melena et al. 2008), Westerlund 2 (7.9 kpc; Rauw et al. 2005), Carina Nebula (2.3 kpc; Davidson & Humphreys 1997), Pismis 24 (2.5 kpc; Massey, DeGioia-Eastwood & Waterhouse 2001), Cyg OB2 (2 kpc; Massey & Thompson 1991), Cyg OB1 (2 kpc; Humphreys 1978).

Star	Alias	Old subtype	Reference	New subtype	m_K (mag)	A_K (mag)	Reference	DM (mag)	Note	M_K (mag)	M_{Bol} (mag)
HD 38282	BAT 99-118	WN6h	a		10.6	0.2		18.45	LMC	−7.9	−12.0
AB4	BAT 99-68	O3 If*/WN6, WN7h	b,c	O3.5 If*/WN7	11.2:	0.7:		18.45	LMC	−7.9:	−11.6:
R136a1	BAT 99-108	WN5h	d		11.1	0.2	m	18.45	LMC	−7.6	−12.5
NGC 3603-A1	WR43a	WN6ha+WN6ha	d, e		7.4	0.6	m	14.4	NGC 3603	−7.6	−11.7
SMSP2	WR20a	WN7, WN6ha+WN6ha	f, g	O3 If*/WN6 + O3 If*/WN6	7.6	0.7		14.5	Wd 2	−7.6	−12.0
NGC 3603-B	WR43b	WN6ha	d, e		7.4	0.6	m	14.4	NGC 3603	−7.5	−11.6
R136c	BAT 99-112	WN5h	d		11.3	0.3	m	18.45	LMC	−7.4	−12.3
R136a2	BAT 99-109	WN5h	d		11.4	0.2	m	18.45	LMC	−7.3	−12.2
Mk 34	BAT 99-116	WN5h	d		11.7	0.3	m	18.45	LMC	−7.0	−11.9
R136a3	BAT 99-106	WN5h	d		11.7	0.2	m	18.45	LMC	−6.9	−11.8
HDE 319718NE	Pismis 24-1NE	O3.5 If*	h, i		5.9	0.7		12.0	Pismis 24	−6.8	−11.4
NGC 3603-C	WR43c	WN6ha	d, e	O3 If*/WN6	8.3	0.6	m	14.4	NGC 3603	−6.7	−11.1
HD 92740	WR22	WN7ha	a		5.4	0.1		11.8	Carina	−6.5	−10.2
Mk 39	BAT 99-99	O3 If*/WN6	j, k	O2.5 If*/WN6	12.1	0.2	m	18.45	LMC	−6.5	−11.7
HD 93162	WR25	WN6ha	a	O2.5 If*/WN6	5.7	0.3	n	11.8	Tr 16	−6.4	−10.8
Mk 42	BAT 99-105	O3 If*/WN6	j, k	O2 If*	12.2	0.2	m	18.45	LMC	−6.4	−11.6
Mk 37a		O4 If	k	(O3.5 If*/WN7)	12.4	0.2	m	18.45	LMC	−6.3	−10.9
HD 93129A		O2 If*	h		6.0	0.4		11.8	Tr 14	−6.2	−11.4
HD 93131	WR24	WN6ha	a		5.8	0.1	n	11.8	Col 228	−6.1	−10.2
R136a5	BAT 99-110	O3 If*/WN	d, k	O2 If*	12.7	0.2	m	18.45	LMC	−6.0	−11.2
Mk 35	BAT 99-114	O3 If*/WN	j, k	O2 If*/WN5	12.7	0.25:	o	18.45	LMC	−6.0	−11.2
Mk 30	BAT 99-113	O3 If*/WN	j, k	O2 If*/WN5	12.8	0.25:	o	18.45	LMC	−5.9	−11.1
Mk 37Wb	BAT 99-104	O3 If*/WN	k	(O2 If*/WN5)	13.06	0.3	o	18.45	LMC	−5.7	−10.9
Cyg OB2–22A		O3 If*	h		6.2	0.6:	p	11.3	Cyg OB2	−5.7	−10.4
TSWR3	BAT 99-93	O3 If*/WN6	j	O3 If*	13.35	0.1:		18.45	LMC	−5.2	−9.9
Mk 51	BAT 99-97	O3 If*/WN7	j	O3.5 If*/WN7	13.77	0.25:	o	18.45	LMC	−4.9	−8.6
HD 193077	WR138	WN5o	a	WN6o	6.6	0.1		11.3	Cyg OB1?	−4.8	−8.9
Sk −67° 22	BAT 99-12	O3 If*/WN6, O2 If*	l, b	O2 If*/WN5	13.8	0.05		18.45	LMC	−4.7	−9.9

(a) Smith et al. (1996); (b) Massey et al. (2005); (c) Schnurr et al. (2008a); (d) Crowther & Dessart (1998); (e) Schnurr et al. (2008b); (f) Shara et al. (1991); (g) Rauw et al. (2004); (h) Walborn et al. (2002); (i) Maíz Apellániz et al. (2007); (j) Walborn & Blades (1997); (k) Massey & Hunter (1998); (l) Walborn (1982a); (m) Crowther et al. (2010); (n) Tapia et al. (1988); (o) Campbell et al. (2010); (p) Torres-Dodgen, Tapia & Carroll (1991).

Hanson, Conti & Rieke (1996) and Hanson et al. (2005) note that the detailed classification of early O supergiants is not possible solely from *K*-band spectroscopy. Indeed, C IV 2.069/2.078 µm emission is seen in some (e.g. HD 93129A, O2 If*; HD 15570, O4 If), but not in all cases (Cyg OB2–7, O3 If*). In contrast, N V 2.110/N III 2.116 µm serves as a primary diagnostic for weak-lined WN4–6 stars at near-IR wavelengths (Crowther et al. 2006), since He II 2.189 µm/Brγ is strongly modified by hydrogen content within this spectral range. He I 2.058 µm is generally observed as a P Cygni profile for subtypes later than WN6, although this is absent for weak-lined WN stars (e.g. NGC 3603-B WN6h).

Divisions between Of, Of/WN and WN5–7 stars from near-IR spectroscopy are less definitive than from visual diagnostics, in view of the relatively small sample of stars for which high-quality data sets are available. Nevertheless, the sum of the EWs of Brγ + He II 2.189 µm emission lines for all WN5–7 stars for which optical and near-IR spectroscopy is available is in excess of ∼60 Å. In contrast, the sum of Brγ + He II 2.189 µm lies in the range EW = 2–20 Å for typical early Of supergiants and ∼40 Å for NGC 3603-C (O3 If*/WN6).

Regarding approximate boundaries between subtypes analogous to those presented for He II λ4686 in Fig. 6, it is likely that this occurs close to EW(Brγ+He II 2.189 µm) ∼30 Å for the transition between Of and Of/WN5–7 stars, and EW(Brγ+He II 2.189 µm) ∼50 Å for the boundary between Of/WN and WN5–7 stars. R136a5 (O2 If*) and NGC 3603-C (O3 If*/WN6) would then lie relatively close to these boundaries, such that ambiguous classification could result solely from near-IR spectroscopy. However, such thresholds would certainly support a WN7 Wolf–Rayet subtype for W43 #1 as proposed by Blum, Damineli & Conti (1999), for which EW(Brγ+He II 2.189 µm) ∼65 Å as measured from our own unpublished VLT/ISAAC spectroscopy.

Very late-type WN stars complicate the picture at near-IR wavelengths, as in the optical. Such stars possess weak (typically P Cygni) He II 2.189 µm emission, plus narrow relatively weak Brγ emission (e.g. Bohannan & Crowther (1999) measured EW(Brγ)∼20 Å for WN9ha stars). This morphology is common to some early-type Of supergiants, such as HD 16691 (O4 If, Conti et al. 1995), albeit with EW(Brγ) ∼7 Å. O If*/WN5–7 stars can be discriminated from such stars through the simultaneous presence of prominent emission at Brγ *and* He II 2.189 µm, with intermediate Brγ EWs. In addition, some WN8–9 stars exhibit P Cygni profiles at He I 2.058 µm, although this is extremely weak for WN9ha stars.

This discussion is relevant to early-type emission-line stars within visually obscured clusters, such as the Arches (Figer et al. 2002). From an assessment of *K*-band spectroscopic data sets for the Arches stars presented by Martins et al. (2008) there are no

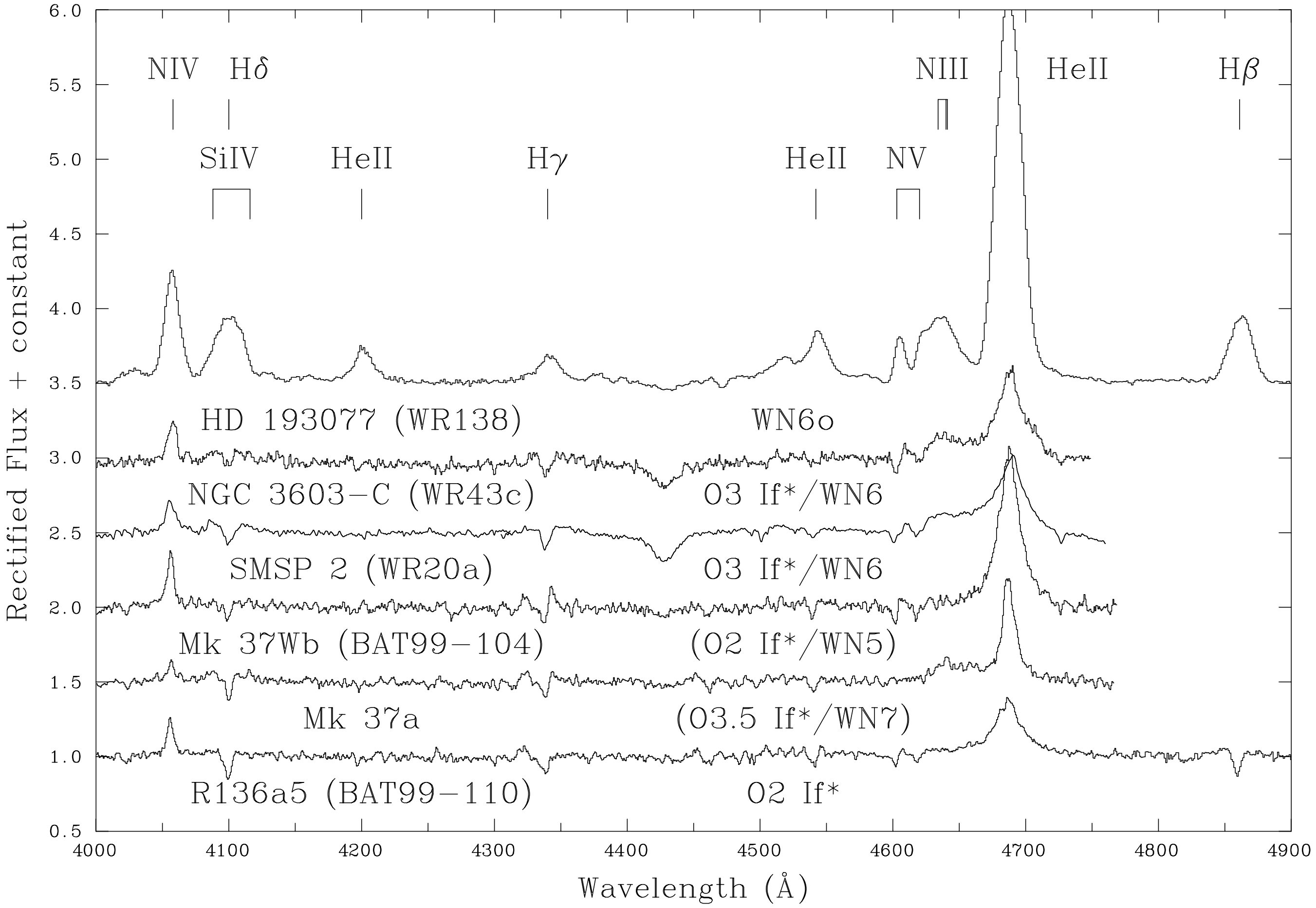

Figure 4. Rectified, blue–violet spectrograms of early-type, emission-line stars, for which revised spectral classifications are obtained (provisional subtypes are indicated in parentheses for objects lacking published Hβ spectroscopy). Stars are uniformly offset by 0.5 continuum units for clarity.

examples of O2–3.5 If*/WN5–7 stars in the Arches cluster, based on our criteria set out here.

5 EVOLUTIONARY STATUS OF OF/WN STARS

Table 3 provides photometric properties of selected Of, Of/WN and WN stars, sorted by absolute K-band magnitude. We prefer to rank stars by absolute K-band magnitude instead of the more usual V band, due to their reduced extinction corrections. We are also able to provide *qualitative* estimates of stellar luminosities using a calibration of K-band bolometric corrections, BC_K, presented in Table 4. These are based on spectroscopic results obtained with the non-local thermodynamic equilibrium CMFGEN code (Hillier & Miller 1998) for NGC 3603-C (O3 If*/WN6), R136a2 (WN5h) and NGC 3603-A1 (WN6h) from Crowther et al. (2010), Melnick 42 (O2 If*) and Sk −67° 22 (O2 If*/WN5) from Doran & Crowther (2011) plus O3–4 supergiants from Martins & Plez (2006).

If we assume that the estimated bolometric correction for Sk −67° 22 is representative of O2 If*/WN5 stars, this group will typically possess high luminosities, e.g., $M_{\mathrm{Bol}} \sim -11.2$ mag or $\log L/\mathrm{L}_{\odot} \sim 6.4$ for Melnick 35. Based upon the main-sequence evolutionary models presented in Crowther et al. (2010), the properties of most O2 If*/WN5 stars are consistent with very massive ($M_{\mathrm{init}} \sim 150 \pm 30\,\mathrm{M}_{\odot}$), rotating stars at a relatively small age of ∼1 Myr (e.g. fig. 1, Doran & Crowther 2011). Such stars rapidly develop powerful stellar winds at a very early phase in their evolution due to their proximity to the Eddington limit, such that they *may* resemble O2 giants (e.g. HDE 269810, O2 III(f*)) at the zero-age main sequence, transitioning through the Of/WN stage before entering the hydrogen-rich WN phase (Crowther et al. 2010) while still in a core hydrogen-burning phase. Recall from Walborn et al. (2002) that O2 dwarfs typically possess masses substantially inferior to 100 $\mathrm{M}_{\odot}$, while some Of/WN stars are members of very high mass binary systems (e.g. WR20a, Rauw et al. 2004, 2005).

However, not all Of/WN stars are exceptionally massive, young stars. From Table 3, the properties estimated for Sk −67° 22 (O2 If*/WN5) by Doran & Crowther (2011) reveal a much lower luminosity of $M_{\mathrm{Bol}} \sim -9.9$ mag or $\log L/\mathrm{L}_{\odot} \sim 5.9$. In contrast with the high-luminosity/high-mass majority, such Of/WN stars are presumably the immediate precursors of classical hydrogen-deficient WN stars, and already at an relatively advanced evolutionary phase, with lower initial masses (∼60 $\mathrm{M}_{\odot}$) and somewhat older ages (≥2.5 Myr).

Adopting a K-band bolometric correction of −3.7 mag, Mk 51 (O3.5 If*/WN7) would have a yet lower luminosity of $M_{\mathrm{Bol}} = -8.6$ mag or $\log L/\mathrm{L}_{\odot} \sim 5.3$. Presumably, Mk 51 has either evolved through a red supergiant or luminous blue variable phase prior to returning to the blue part of the Hertzsprung–Russell diagram, or such a low-luminosity supergiant might be a post-mass transfer binary (Walborn et al. 2002).

Morphologically, we are unable to discriminate between the high- and low-luminosity Of/WN stars. More quantitative results await the

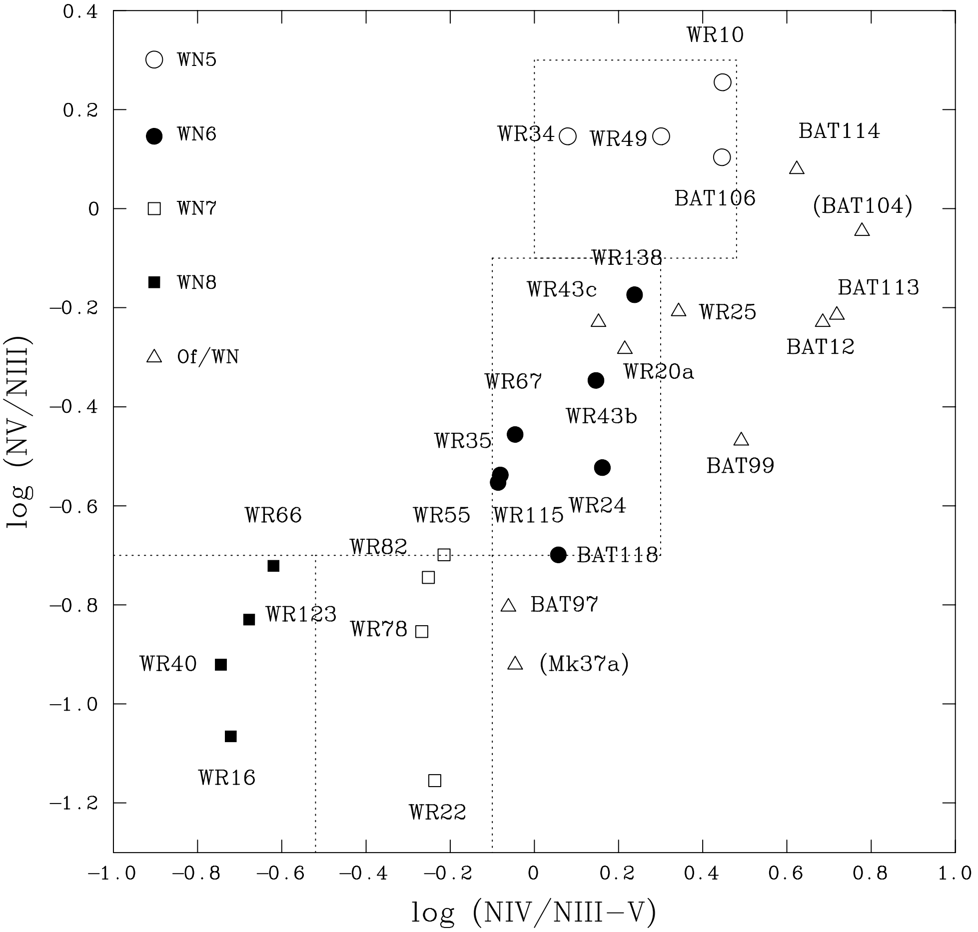

Figure 5. Nitrogen line ratios of selected O2–3.5 If*/WN5–7 and WN5–8 stars, based upon our revised WN subtype boundaries (dotted lines). Preliminary spectral types are indicated in parentheses.

detailed analysis of such stars which is presently underway within the context of the VLT–FLAMES Tarantula Survey (Bestenlehner et al., in preparation).

From Table 3, it is apparent that the LMC hosts the majority of transition stars. We do not anticipate a substantial difference between the wind or physical properties of LMC early-type stars with respect to the Galaxy as a result of the factor of ∼2 reduced metallicity, Z. Radiatively driven wind theory (Vink, de Koter & Lamers 2001) and observations (Mokiem et al. 2007) suggest a mass-loss scaling $\propto Z^{\sim 0.7}$, such that LMC stars would be expected to possess slightly weaker stellar winds than their Milky Way counterparts. Therefore, the LMC incidence of transition stars with respect to bona fide WN stars is anticipated to be modestly higher than the Milky Way.

In fact, taking our revisions into account, O2–3.5 If*/WN5–7 comprise 7 per cent of the ∼106 WN-flavoured LMC Wolf–Rayet stars listed by Breysacher, Azzopardi & Testor (1999).[1] In contrast, transition stars (SMSP 2, HD 93162 and HD 97950-C) comprise only 2 per cent of the (highly incomplete) ∼175 WN stars compiled for the Milky Way by van der Hucht (2001, 2006).

Reduced wind densities are only expected to partially explain these differences. If Of/WN subtypes arise preferentially in very massive stars, one may expect an excess of transition stars in the most massive, young clusters. Indeed, the region of 30 Doradus close to R136 dominates the known Of/WN population, since within the Milky Way relatively modest star-forming regions such as Carina and NGC 3603 are accessible to optical spectroscopic surveys.

6 LOWER IONIZATION SPECTRA (N IV λ4058 EMISSION WEAK/ABSENT)

We have sought to discriminate O2–3.5 If*/WN5–7 from O2–3.5 If* and WN5–7 stars through the presence of Hβ emission, providing N IV λ4058 is present in emission. However, for completeness the potential implications of our criteria for stars in which N IV λ4058 is weak/absent also need to be considered, including a second class of star historically classified as Of/WN.

This second flavour of '/' star, was introduced by Walborn (1982b) and Bohannan & Walborn (1989) to refer to another category of peculiar stars, assigned Ofpe/WN9. In contrast with the *intermediate* O2–3.5 If*/WN subtypes, the Ofpe/WN9 classification was intended to denote *alternative* descriptions/interpretations for the same object. Indeed, Walborn (1977) had earlier suggested *either* an O Iafpe or WN9 (or WN10) classification for one such

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[1] 10 stars were listed as 'hot' transition stars by Breysacher et al. (1999) to which we add Melnick 37a and AB4, with TSWR3, Melnick 42 and R136a5 removed. In addition, BAT 99-80 (TSWR2, NGC 2044W-9A), originally assigned O4 If/WN6 (Testor & Schild 1990) has subsequently been revised to O4 If^{+} (Walborn et al. 1999). We also include the newly discovered WN star VFTS-682 from Evans et al. (2011) in our LMC statistics.

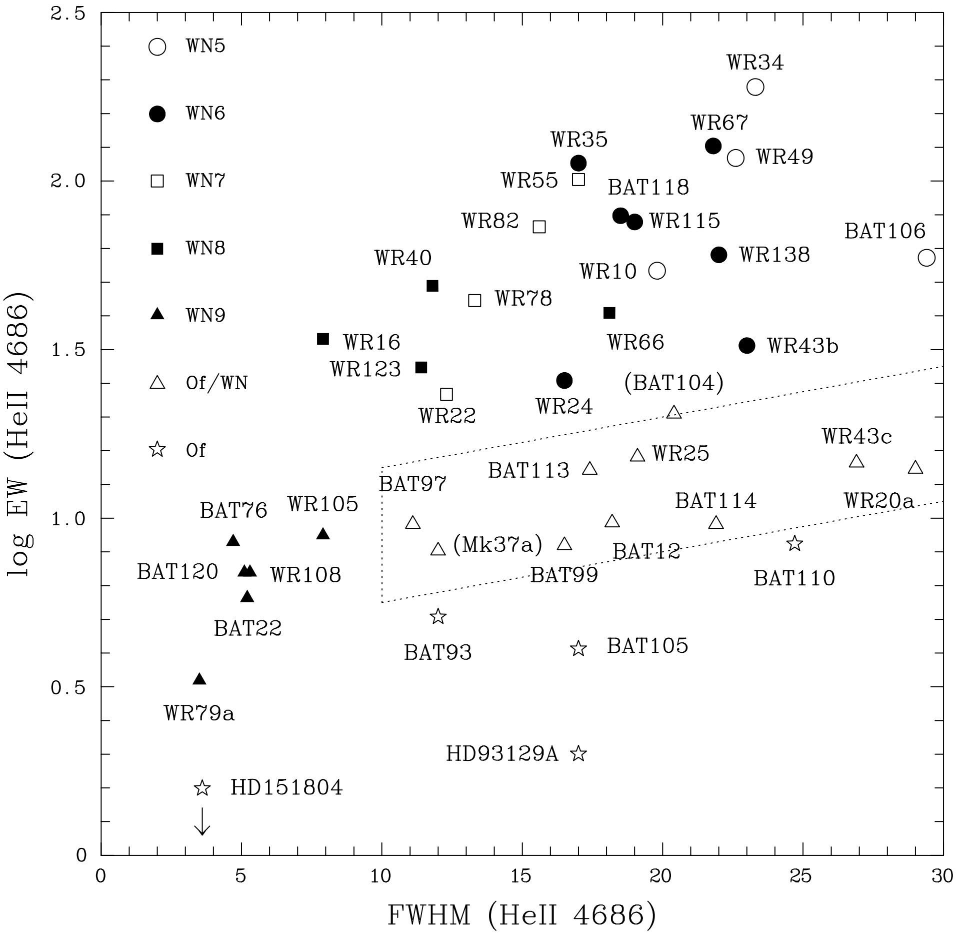

Figure 6. Comparison between He II λ4686 line strength (EW in Å) and full width at half-maximum (FWHM) (in Å) for selected WN5–9 stars, O2–3.5 If*/WN5–7 stars and O2–3.5 If* stars. An approximate boundary for Of/WN stars is indicated (dotted lines). Preliminary spectral types are indicated in parentheses.

star, HDE 269227. The latter designation was preferred by Smith et al. (1994), who proposed WN9–11 to distinguish between stars of varying ionization, while Bohannan & Crowther (1999) also argued that Ofpe stars should be reclassified as WN9ha. Nevertheless, Ofpe/WN9 remains in common usage both for surveys of external galaxies (e.g. Bresolin et al. 2002) and highly reddened stars within the inner Milky Way (e.g. Mason et al. 2009).

A spectral montage of late-type Of and WN8–9 stars is displayed in Fig. 8 (see also chapter 3 of Gray & Corbally 2009). The spectral morphology of mid-to-late-type Of stars resembles late WN stars in the vicinity of He II λ4686. We also note that P Cygni Hβ *is* relatively common in late Of supergiants, including R139 (O6.5 Iafc + O6 Iaf; Taylor et al. 2011), HD 151804 (O8 Iaf; Crowther & Bohannan 1997) and He 3–759 (O8 If; Crowther & Evans 2009).

Analogously to O2–3.5 If*/WN transition stars, we have considered the possibility of an intermediate category for stars in which N IV λ4058 emission is weak/absent. Recall that Wolf–Rayet spectral types are intended for predominantly emission-line stars at visible wavelengths, while O spectral types are appropriate for primarily absorption line stars. In contrast with 'hot' transition stars, late-type Of and WN stars can be cleanly distinguished in Fig. 8. Specifically, WN8–9 stars exhibit strong P Cygni He I λ4471, versus absorption in late-type Of stars. Walborn (1975) has previously highlighted the development of P Cygni He I λ5876 from HD 151804 (O8 Iaf) and HD 152408 (O8 Iafpe or WN9ha) to HD 151932 (WN7h). Other morphological differences include He II λ4542, λ4200 and the complex around Hδ.

On the basis of presently available observations, we therefore propose restricting *intermediate* Of/WN classifications solely to the earliest O subtypes. For lower ionization stars in which N IV λ4058 is weak/absent, yet each of He II λ4686, N III λλ4634-41 and Hβ is in emission, we favour the following.

(i) Adhering to existing WN subtypes if the morphology of He I λ4471 is a P Cygni profile (e.g. NS4, WN9h) or WNha if, in addition, the morphology of He II λλ4541, 4200 are P Cygni profiles (e.g. HDE 313846, WN9ha).

(ii) Retaining existing O supergiant spectral types if the morphology of He I λ4471 is in absorption (e.g. HD 151804, O8 Iaf)[2].

7 SUMMARY

We present a revised classification scheme for O If*/WN5–7 stars in order to take into account various revisions to the Of* (Walborn

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[2] An O4 Iaf subtype is retained for R136b (Massey & Hunter 1998) since He I λ4471 is observed in absorption in *HST*/FOS spectroscopy, in spite of Hβ emission. Crowther & Dessart (1998) had tentatively proposed WN9ha for R136b, although an earlier WN8 subtype would have been more appropriate since N IV λ4058 is detected at a 4σ–5σ level.

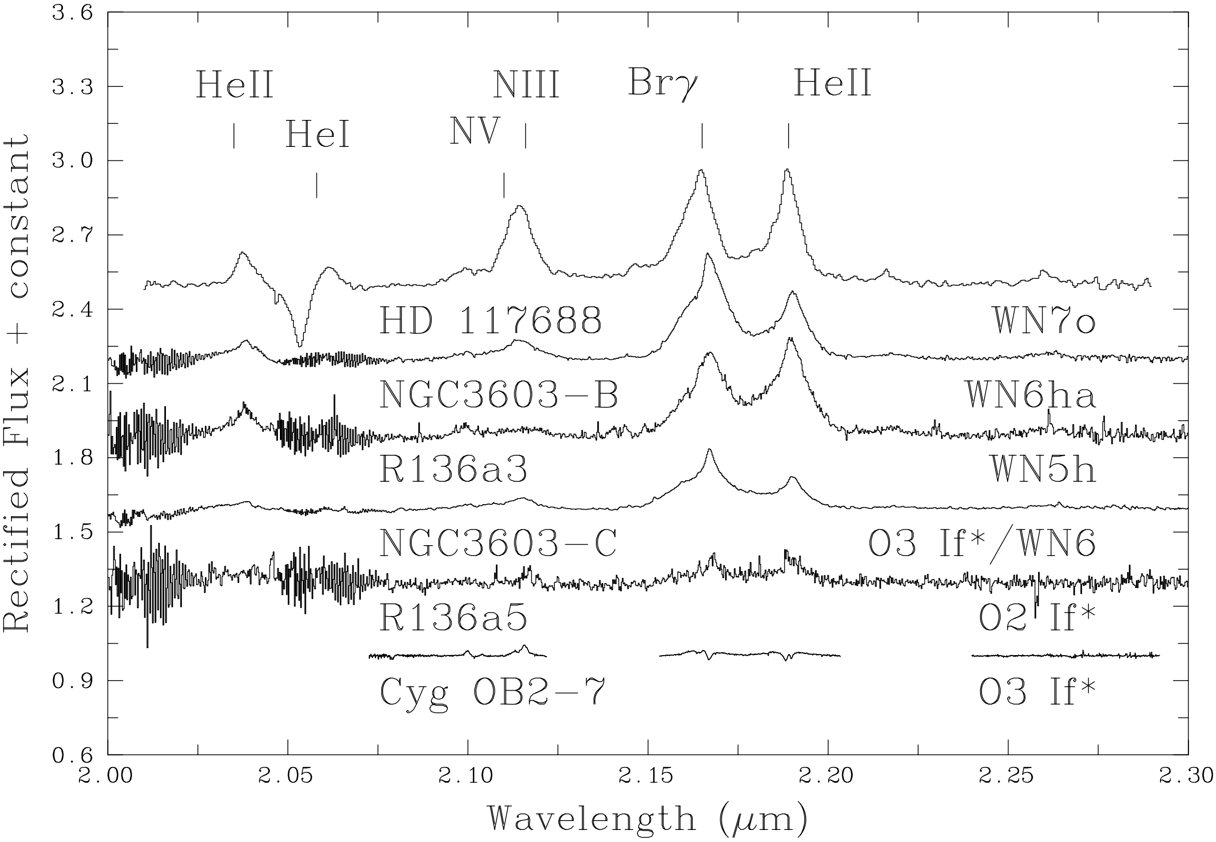

Figure 7. Rectified, *K*-band spectrograms of early-type O supergiants, and Of/WN and WN5–7 stars. Stars are uniformly offset by 0.5 continuum units for clarity.

Table 4. Calibration of *K*-band bolometric corrections for early-O and WN5–7 stars based upon CMFGEN model atmosphere analyses.

Star	Subtype	$T_{\rm eff}$ (kK)	BC$_K$ (mag)	Reference
HD 92740	WN7ha	38	−3.7:	Unpublished
	O4 I	40	−4.55	Martins & Plez (2006)
NGC 3603-A1b	WN6h	40	−4.1	Crowther et al. (2010)
	O3 I	42	−4.69	Martins & Plez (2006)
NGC 3603-C	O3 If*/WN6	44	−4.4	Crowther et al. (2010)
Mk 42	O2 If*	50	−5.2	Doran & Crowther (2011)
Sk −67° 22	O2 If*/WN5	49	−5.2	Doran & Crowther (2011)
R136a2	WN5h	53	−4.9	Crowther et al. (2010)

et al. 2002) and mid-WN (Smith et al. 1996) subtypes since the initial introduction of this subclass (Walborn 1982a).

(i) We propose that O2–3.5 If*, O2–3.5 If*/WN5–7 and WN5–7 stars may be discriminated using the morphology of Hβ: purely in absorption for O2–3.5 If* stars; P Cygni for O2–3.5 If*/WN5–7 stars; purely in emission for WN stars.

(ii) Based upon our updated scheme at least 10 Of/WN objects are identified in the LMC (primarily 30 Doradus) and Milky Way (Carina Nebula, NGC 3603, Westerlund 2).

(iii) Since many young high-mass stars in the Milky Way are visually obscured due to dust extinction, we also discuss approximate criteria from which early Of, Of/WN5–7 and WN5–7 subtypes may be discriminated from near-IR spectroscopy. We emphasize that high-quality blue-visual spectroscopy provides superior diagnostics.

(iv) We suggest that the majority of O2–3.5 If*/WN5–7 stars are young, very massive hydrogen-burning stars, genuinely intermediate between O2–3.5 If* and WN5–7 subtypes, although a minority are apparently lower mass core helium-burning stars evolving blueward towards the classical WN sequence. We suggest that transition stars form a larger subset of the LMC WN population than that of the Milky Way due to weaker stellar winds and a higher percentage of very massive stars within 30 Doradus with respect to typical Galactic star-forming regions.

(v) On the basis of presently available observations, we do not favour *intermediate* Of/WN subtypes for He II λ4686 emission-line stars in which N III λλ4634–41 ≫ N IV λ4058. We advocate: (a) WN8–9 spectral types if the morphology of He I λ4471 is P Cygni, or (b) mid-to-late Of supergiant subtypes if He I λ4471 is observed in absorption.

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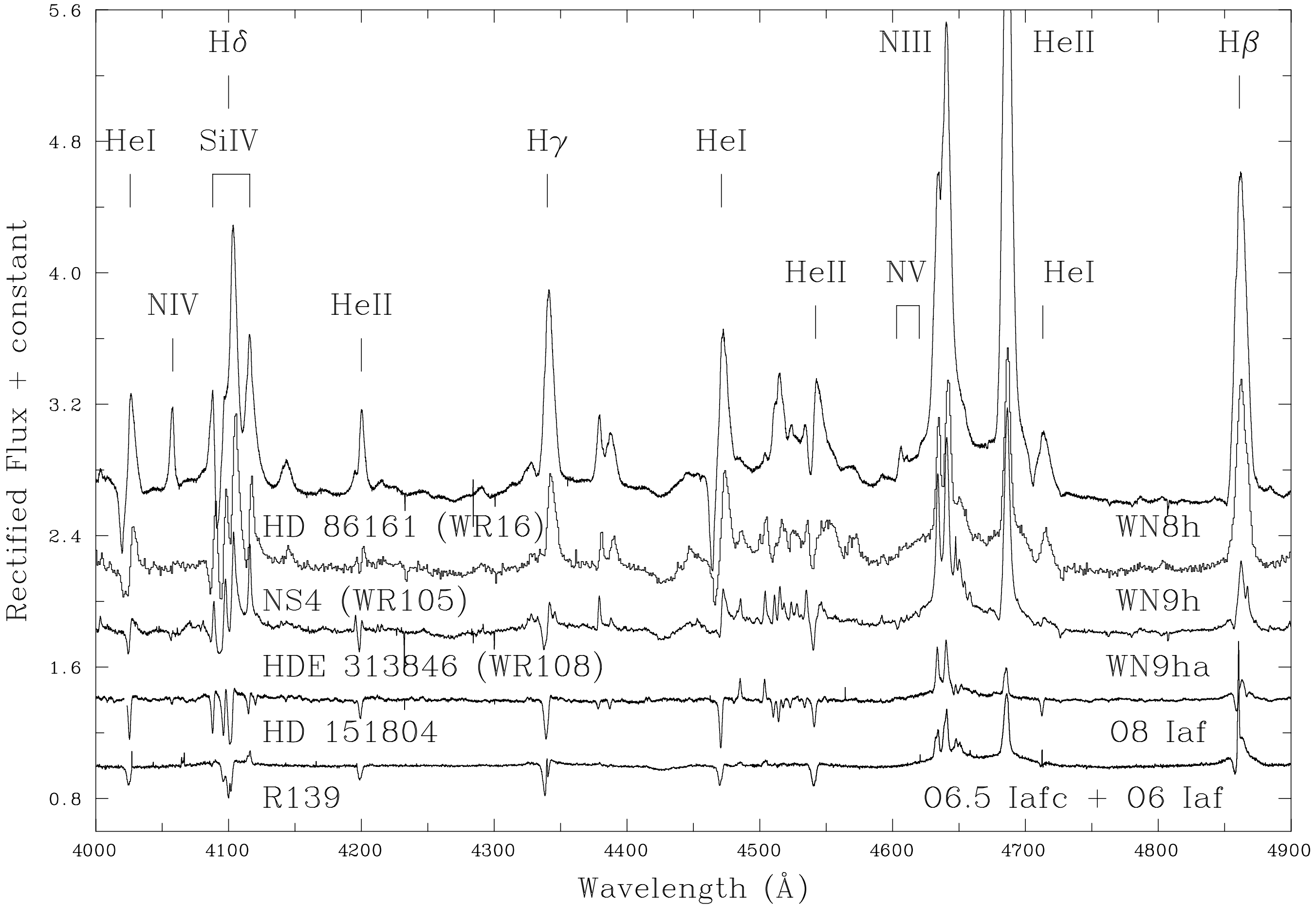

Figure 8. Rectified, blue–violet spectrograms of stars spanning O6.5–8 If through WN8–9. Stars are uniformly offset by 0.3 continuum units for clarity.

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