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Wolf–Rayet stars in M33 – I. Optical spectroscopy using CFHT-MOS

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ABSTRACT

We have obtained spectroscopy of a large sample of Wolf–Rayet stars in M33 with the Canada–France–Hawaii Telescope Multi-Object Spectrograph (CFHT-MOS), including 26 WC stars, 15 WN stars and a WN/C star. In general, spectral types are merely refined, although the spectral type of X9 from Massey & Johnson is revised from WNL?+abs to WC4+abs, whilst their G1 and C21 candidates are not confirmed as Wolf–Rayet stars. We also re-examine the metallicity gradient of M33 from H II regions and identify the present sample, lying in the inner disc, with $8.6 \leqslant \log(\mathrm{O/H}) \leqslant 8.9$. Spectral types are in accord with similar regions in the Milky Way. Our large sample has allowed us to examine the claimed anticorrelation between WC linewidths and galactocentric distance by Schild et al. We find a much larger scatter, though there remains an absence of broad-line WC stars in the inner disc and narrow-line WC stars in the outer galaxy.

Key words: stars: fundamental parameters – stars: Wolf–Rayet – galaxies: abundances – galaxies: individual: M33 – Local Group.

1 INTRODUCTION

Massive stars are important contributors to the chemical and dynamical evolution of galaxies via the input of energy, momentum and processed material from their stellar winds to the interstellar medium (Leitherer 1998). Such hot and luminous objects are especially characterized by a steady and intense mass loss, arising from the transfer of momentum from the UV continuum star light to wind material through scattering in optically thick lines of metals (Lucy & Solomon 1970; Castor, Abbott & Klein 1975). While such a mechanism explains very well the observed mass loss rates ($\sim10^{-6}$ M$_\odot$ yr^{-1}) and terminal velocities ($\sim$2000 km s^{-1}) of OB stars (Pauldrach, Puls & Kudritzki 1986), their evolved descendants, Wolf–Rayet (WR) stars, possess similar terminal velocities but tenfold higher mass loss rates (e.g. Hamann & Koesterke 2000; Dessart et al. 2000; Crowther et al. 2002). The origin of the additional momentum transferred to the WR wind is likely an opacity problem (Abbott & Lucy 1985; Springmann 1994; Gayley & Owocki 1995) the theoretical origin of which is yet to be explained quantitatively.

Thus, the environmental metallicity is believed to play a key role in tuning the efficiency of mass loss during the life of a massive star. Theoretically, such a mass-loss–metallicity dependence of OB star winds has been revealed theoretically (Kudritzki, Pauldrach & Puls 1987; Vink, de Koter & Lamers 2001; Kudritzki 2002). Also, observationally, detailed spectroscopic studies seem to indicate a similar behaviour for WRs (e.g. Crowther et al. 2002), while the WR population census shows a biased distribution in favour of the more evolved carbon-rich WRs in high-metallicity environments over the less evolved nitrogen-rich WRs (Massey 1996). This metallicity dependence is admittedly weak but given the rates of mass loss of 10^{-5} M$_\odot$ yr^{-1} (corresponding to a cumulative mass loss of up to a few tens of solar masses during a massive star lifetime), it is important to understand it further.

At solar metallicity, evolutionary models predict that only stars with initial masses $\geqslant$25 M$_\odot$ will enter the WR phase (Maeder & Meynet 1994) and only the most massive of these stars will evolve further into the WC sequence, exhibiting products of core He burning. Approximately half of the known Galactic Wolf–Rayet stars are of the WC type (van der Hucht 2001), whilst in the Small Magellanic Cloud (SMC) nitrogen sequence WR stars outnumber WC stars tenfold (Massey & Duffy 2001).

With recent advances in astronomical instrumentation, massive stars in Local Group galaxies, with metallicity environments widely different from that of the solar neighbourhood, are now easily accessible to ground-based telescopes. Thus, detailed spectroscopic studies carried out on WRs in the Galaxy (e.g. Crowther, Hillier & Smith 1995a; Crowther, Smith & Hillier 1995b; Hillier & Miller

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1999; Dessart et al. 2000) can now be compared with studies performed on WRs in the Magellanic Clouds (e.g. Crowther et al. 2002), NGC 300 (Schild et al. 2003) and IC 10 (Crowther et al. 2003) with the aim of understanding more accurately the role metallicity plays in the evolution of massive stars. In the present study, we focus on the WR population of the late-type spiral (Sc) galaxy M33 (NGC 598). M33 is an ideal candidate galaxy to continue with these detailed studies, as it contains a large number of known WR stars, it is nearby with a well-determined distance and a low extinction, and it is viewed at a low inclination.

The early work on M33 by Wray & Corso (1972) using interference filters of He II and C III led to 25 WR candidates, of which 22 were spectroscopically confirmed (Boksenberg, Willis & Searle 1977; Conti & Massey 1981). A further 15 WR stars, mainly serendipitously discovered while studying H II regions, were found by Conti & Massey (1981). There have been numerous subsequent discoveries, notably by Massey & Conti (1983), Massey et al. (1987) and Willis, Schild & Smith (1992). Most recently there was a deep CCD survey of M33 by Massey & Johnson (1998) who found a further 22 new WR stars, bringing the total number of known WRs in M33 to 141 to date.

Until now the quality, resolution and signal-to-noise ratio of the spectra obtained from these studies have generally been poor, allowing only determination of their spectral types and measurement of the line strengths from the strongest features. In only two cases have individual WR stars been studied in detail (Smith, Crowther & Willis 1995; Crowther et al. 1997). In comparison, recent instrumental improvements of 4-m telescopes (e.g. CFHT-MOS) offer the possibility of observing many WR stars simultaneously, increasing the exposure time by an order of magnitude over standard (single) long-slit spectroscopy, thereby delivering spectra with a signal-to-noise ratio sufficiently high to permit a detailed quantitative spectroscopic analysis. We have observed a relatively large sample of known WRs in M33 and obtained a new, improved data set suitable for detailed analysis.

The present study presents our new observations of WR stars in M33, including a detailed account of observations (Section 2) and a discussion of the WR stars included, giving spectral types and photometry (Section 3). We re-examine the metallicity gradient in M33 in Section 4 and finally study the claimed correlation between emission-line widths and galactocentric radius (or metallicity) identified by Schild, Smith & Willis (1990). Following this study, we will in Paper II (Abbott et al., in preparation) present a quantitative spectroscopic analysis of selected WC stars and finally in Paper III (Abbott et al., in preparation) carry out a study of WN stars.

2 OBSERVATIONS AND REDUCTION

This study uses data taken with the Multi-Object Spectrograph (MOS) on the 3.6-m Canada–France–Hawaii Telescope (CFHT) between 2000 September 1 and 2, and 2001 October 17 and 19. 42 WR stars were observed in four fields (see Table 1), sampling approximately a third of the known WR content of M33. Each field encompassed an area of approximately 9.5 × 9.5 arcmin^2 with a scale of 0.28 arcsec pixel^{-1}. Fig. 1 shows the location for each of the four fields, superimposed on an archival 40-s V-band CFH12K mosaic image from 2000 August 7. In addition to those stars discussed here, several members of NGC 595 (Drissen, Moffat & Shara 1990; Drissen et al. 1993) were also observed. These will be discussed separately.

All programme stars were spectroscopically observed with MOS using the 2048 × 4500 EEV1 CCD with 13.5-μm pixels. Multiple exposures were taken using integration times of 1800 s. Individual masks were designed to include the maximum number of WRs possible for each field. Attention was given such that the slit positions did not overlap in the spatial direction. Slits were matched to individual WR stars from finding charts using acquisition images obtained in advance and were cut to an aperture width of 1.5 arcsec. In most cases this was a straightforward procedure. For a few targets in which identification was not so simple, offsets in right ascension and declination from a known WR star were adopted using coordinates from Massey & Johnson (1998). The wavelength coverage obtained for each object depends on the vertical position of the slit on the mask, but typically we aimed for spectroscopic coverage of λλ3800–7000 for all our target stars.

The data were reduced and extracted using standard IRAF procedures. After the data were bias-subtracted, flat-field-corrected, cosmic-ray-cleaned and extracted, they were wavelength-calibrated under FIGARO (Shortridge et al. 1999). Where possible the sky was subtracted using local sky regions within the slit, although as a result of crowding and the need to use narrow apertures this was at times impossible. In these cases where there were no (or highly variable) local sky regions, we used observations of nearby sky taken through separate slits for these purposes. The sky was then subtracted using DIPSO (Howarth et al. 1998) after a scaling factor was applied, which was calculated from the number of pixels summed in the extraction. We checked this method by extracting and locally sky-subtracting a star within IRAF, and comparing the result with a sky subtraction made using a scaled, generic nearby sky region. Apart from the absolute levels differing slightly, the main sky features were largely removed.

Table 1. Log of observations for the four fields in M33, including the central coordinates for each field.

Field	Position (2000) α	δ	Epoch
M33-A	$01^{h}33^{m}37^{s}.63$	$+30^{\circ}42'40''.9$	2000 September
M33-B	$01^{h}33^{m}59^{s}.70$	$+30^{\circ}39'27''.1$	2001 October
M33-C	$01^{h}33^{m}46^{s}.78$	$+30^{\circ}35'24''.8$	2000 September
M33-D	$01^{h}33^{m}41^{s}.92$	$+30^{\circ}31'18''.0$	2001 October

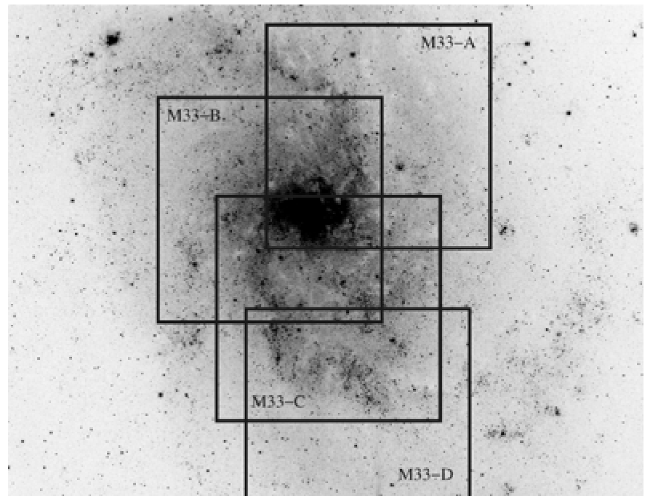

Figure 1. The four observed fields for M33 are shown, superimposed on a CFH12K archival V-band image. In this figure north is up and east is to the left. The field of view for each field is 9.5 × 9.5 arcmin^2.

Given the large distance to M33, there were often large variations in sky across individual slits, which were imperfectly subtracted. For example, a 1.5-arcsec slit width corresponds to a spatial scale of ∼6 pc at a distance of 816 kpc (Freedman et al. 2001). Sky features were particularly problematic at wavelengths redward of ∼λ6000. Fringing is also common longward of ∼λ6800. In addition, the final data were not absolute flux calibrated. This was as a result of the fact that the standard stars were observed through a much larger slit width, such that the effects of differential, atmospheric refraction altered the shape of the WR star continuum.

3 NOTES ON INDIVIDUAL STARS

Tables 2 and 3 list the Wolf–Rayet stars observed spectroscopically with CFHT. Their M33-WR number (column 1) and continuum magnitudes (column 4) are taken from Massey & Johnson (1998), the latter relating to narrow-band filters with a central wavelength of λ4750. In general, we shall refer to individual stars by their discovery reference, listed in column 2. The de-projected galactocentric distances for each star are also shown (column 3) and are expressed as a fraction of the Holmberg radius ($\rho_0 = 25$ arcmin).

Revised spectral types are listed in the tables together with their previous classifications. We follow the classification schemes devised by Smith, Shara & Moffat (1996) and Crowther, de Marco & Barlow (1998) for WN and WC stars, respectively. Unfortunately, as a result of unreliable sky subtraction we were generally unable to use the primary criteria of He II/I, to distinguish between WN subtypes. This meant that the classification scheme presented by Smith et al. (1996) generally relied on the ratios of the weak-lined N III–V emission lines. In addition, correction for nebular Balmer lines often proved difficult, so we have generally omitted the hydrogen criteria from Smith et al.

Overall, our sample revealed a majority of early types amongst both WN and WC stars: WN3–5 accounted for 55 per cent of the WN sample, whilst WC4–6 stars represented 90 per cent of the WC sample. Our data sets extended sufficiently blueward to identify WO stars, none of which was found. To date, late WC (WC8–9) subtypes remain exclusive to the inner Milky Way and M31. We generally refine previous spectral types, details of which are given for notable individual stars.

3.1 Of and WN stars

Rectified, optical spectroscopy for the programme WN and Of stars is presented in Fig. 2 together with principal stellar line identifications. We now discuss individual objects in turn.

3.1.1 MJ-G13 (M33-WR50)

MJ-G13 from Massey & Johnson (1998) is confirmed as a WN star here and its classification is refined to a narrow-lined WN5 star because N III ∼ N V, N IV ⩾ N III–V, and FWHM(He II λ4686) ⩽ 30 Å.

3.1.2 MCA5 (M33-WR54)

MCA5 is another narrow-lined, early-type WN star. Because N III ≪ N V and N IV ∼ N V, we deduce a WN4 spectral type.

3.1.3 MC36 (M33-WR56)

WC36 closely resembles MCA5, albeit with weaker emission lines, again leading to a narrow-lined WN4 spectral type.

3.1.4 MC37 (M33-WR59)

MC37 (Massey & Conti 1983) has unusually broad emission lines [i.e. FWHM(He II λ4686) ∼ 70 Å]. Nevertheless, N III ≪ N V, so MC37 is also revised from WN to WN4b.

3.1.5 MJ-G3 (M33-WR60)

Emission lines in this early-type WN star are extremely weak, preventing a firm subtype. Very broad Balmer absorption lines are observed as a result of a companion or foreground star along a nearby line of sight.

3.1.6 MCA8 (M33-WR74)

MCA8 closely resembles MCA5, with a narrow-lined WN4 spectral type. This appearance contrasts with the original spectrum of Massey et al. (1987) as a result of local sky subtraction.

3.1.7 OB66-25 (M33-WR77)

We propose an Of spectral type for OB66-25 from Massey et al. (1996) (alias HS-B205, Humphreys & Sandage 1980), rather than WN8 as a result of the extremely weak He II λ4686 and N III λλ4634–41 emission plus He II λλ4542, 5411 absorption. Massey & Johnson (1998) also suggest Of? in their table 3. The spectrum for this star also contains strong nebular emission.

3.1.8 MCA9 (M33-WR78)

We suggest a WN7 subtype for MCA9 because He II λ5411 ∼ He I λ5876 and N III ⩾ N IV.

3.1.9 MC46 (M33-WR80)

MC46 is broad-lined WN star, with N V ≫ N III, so we classify it WN4b.

3.1.10 MC48 (M33-WR83)

This is the only WN/CE star in our sample and was previously observed by Schild et al. (1990). We suggest WN6/C4 because N III ≫ N IV and C III λ5696 is absent.

3.1.11 MJ-G8 (M33-WR86)

MJ-G8 is a weak-lined WN star for which we propose a WN4 subtype because N V ≫ N III with N IV present.

3.1.12 MJ-G9 (M33-WR91)

Our observations of MJ-G9 (Massey & Johnson 1998) are of rather poor quality. Nevertheless we propose a WN3b spectral type as a result of the apparent absence of N IV together with the presence of N V and large linewidth. MJ-G9 also suffers from nebular contamination.

3.1.13 MJ-X15 (M33-WR103)

We propose a WN8–9 subtype for MJ-X15 (alias UIT236) because N III is strong and there is a possible presence of N IV. This subtype is consistent with the spectrum presented by Massey et al. (1996) for which they assigned an Ofpe/WN9 classification. More recently, Crowther et al. (1997) revised the classification of such stars to very late WN subtypes.

Table 2. List of WN stars and candidates observed with CFHT-MOS. Star identifications are CM = Conti & Massey (1981); AM = Armandroff & Massey (1985); MC = Massey & Conti (1983); W&C = Wray & Corso (1972); MCA = Massey et al. (1987); OB = Massey et al. (1995); UIT = Massey et al. (1996); HS-B = Humphreys & Sandage (1980); MJ = Massey & Johnson (1998). The M33-WR# assigned to each star and the previous spectral classification relate to those given by Massey & Johnson (1998). Line equivalent widths and FWHM are given in Angstrom.

M33					*HST*		CFHT		He II λ4686		Spectral type		
WR#	Alias	ρ	m_{cont}	F336W	F439W	F555W	V	Fld	$\log(W_\lambda)$	FWHM	Previous		New
50	MJ-G13	0.29	20.7	——	——	——	19.50	C	1.43	24.2	WN	(6)	WN5
54	MCA5	0.22	20.9	——	——	——	21.46	C	2.16	26.9	WN	(1)	WN4
56	W&C4,MC36	0.19	19.6	——	——	——	19.74	C	1.91	28.7	WN	(8)	WN4
59	W&C5,MC37	0.33	19.1	18.29	19.65	——	$\gg$18.60	D	2.13	72.7	WN	(8)	WN4b
60	MJ-G3	0.35	19.4	——	——	——	19.74	D	0.97	21.9	WN	(6)	WNE+abs
74	MCA8	0.30	21.1	20.53:	21.95:	——	21.18	A	2.22	24.9	WN	(1)	WN4
77	OB66-25,UIT184,HS-B205	0.28	18.4	——	——	——	18.54	A	0.5:	10.	WN8	(5,6)	Of
78	MCA9	0.08	20.1	——	——	20.56	20.66	B	1.36	17.1	WN	(1)	WN7
80	W&C11,MC46	0.15	20.1	——	——	——	20.57	C	2.33	43.9	WN	(1)	WN4b
83	W&C13,MC48	0.26	20.1	——	——	——	19.40	C+D	2.53	59.6:	WN/CE	(2,7)	WN6b/C4
86	MJ-G8	0.26	19.6	——	——	——	20.08	C+D	1.49	28.7	WN	(6)	WN4
91	MJ-G9	0.26	22.3	——	——	22.18	21.64	C	2.45	53.5	WN+neb	(6)	WN3b
103	MJ-X15,UIT236	0.06	17.8	16.44	18.05	18.20	18.08	B	0.99	10.7	Ofpe/WN9	(3,6)	WN8–9
106	OB6-5	0.35	17.9	16.86	——	18.19	18.62	D	0.67	9.1	WN8	(5)	WN9–10
118	MJ-X16	0.18	20.1	——	——	——	19.98	B	—	—	WN+neb	(6)	WN?
122	UIT289	0.22	18.5	17.98	19.48	20.13	18.69	B	0.38	14.4	WN4	(3)	WN3–4+abs?
43A	MJ-G1	0.30	19.3	——	——	——	19.57	C+D	—	—	Cand WN	(6)	Not WR
55A	MJ-C21	0.29	19.7	19.65	18.98	18.69	18.09	A	—	—	Cand WN	(6)	Not WR

(1) Massey et al. (1987); (2) Willis et al. (1992); (3) Massey et al. (1996); (4) Armandroff & Massey (1991); (5) Massey et al. (1995); (6) Massey & Johnson (1998); (7) Schild et al. (1990); (8) Massey & Conti (1983)

Table 3. List of WC stars observed with CFHT-MOS. Star identifications are as in Table 2. Line equivalent widths and FWHM are given in Angstrom.

M33 WR#	Aliases	ρ	m_{cont}	*HST* F336W	*HST* F439W	*HST* F555W	CFHT V	Fld	C III λ4650/He II λ4686 log(W_λ)	C III λ4650/He II λ4686 FWHM	C IV λ5801–12 log(W_λ)	C IV λ5801–12 FWHM	Spectral type Previous	Ref.	Spectral type New
38	MC26,AM1	0.39	21.8	—	—	20.90	21.03	A	3.10	46.8	3.03	41.1	WC5-6	(4)	WC6
52	MC33,AM8	0.30	20.4	19.37	20.62	20.62	20.16	A	2.59	58.9:	2.58	37.6	WC	(4)	WC4
55	W&C3,MC35	0.35	21.0	—	—	—	19.98	D	2.32	38.5:	2.10	35.3	WC	(8)	WC6
61	MC39,AM9	0.25	20.0	19.37	20.66	20.58	20.01	A	2.62	59.4	2.48	51.2	WC4-5	(4)	WC5
62	W&C8,MC42	0.34	19.7	18.31	19.69	—	19.81	D	2.34	76.0	2.39	72.7	WC4-5	(4)	WC4
63	W&C9,MC40	0.18	19.1	—	—	—	19.36	C	2.10	64.6:	2.26	52.9	WC	(8)	WC4-5
69	W&C10,MC43,AM13	0.20	20.6	19.75	20.84	—	20.49	A	2.73	37.8:	2.51	35.4	WC6-7	(4)	WC6-7
71	MC44	0.27	18.7	—	—	—	18.89	C+D	1.80	61.1:	1.83	62.5	WC4-5	(7)	WC5
73	MJ-C4	0.11	18.6	—	—	18.76	18.67	B	1.36	46.8	1.32	44.7	WC	(6)	WC5
76	MC45	0.09	—	—	—	—	17.97	B	1.54	52.6	1.60	50.1	WC5	(9)	WC4
82	W&C12,MC47	0.11	20.9	—	—	—	20.46	B	2.98	53.4	2.78	49.1	WC	(8)	WC6
84	MC49	0.11	21.0	—	—	—	20.48	B	2.52	49.1	2.29	46.0	WC	(8)	WC6
89	W&C15,MC52	0.03	20.1	18.42	19.64	19.74	19.83	B	2.16	56.0:	1.88	58.1	WC	(8)	WC7+abs
92	W&C16,MC53	0.09	19.1:	—	—	—	19.50	A	2.06	53.6:	1.85	28.6	WC4-5	(2,7)	WC5-6
94	W&C17,MC54	0.07	18.5	—	—	20.55	18.83	B	1.36	35.3	1.30	38.1	WCE	(6,8)	WC7+abs
95	W&C19,MC55	0.28	21.1	—	—	21.17	20.75	C+D	2.76	44.6:	2.52	39.6	WC	(4)	WC6
96	W&C18,MC56	0.03	21.4	20.39	21.51	21.30	21.02	B	1.84	69.0:	1.89	61.2	WC	(8)	WC4+abs
99	MC57	0.24	20.8	19.44	20.67	20.42	20.55	A	2.32	71.4:	2.43	65.1	WC	(4)	WC4
105	W&C21,MC60,AM14	0.24	21.6	—	—	21.26	21.56	C	2.89	52.6	2.65	45.1	WC	(4)	WC6
110	MC61,AM16	0.35	21.3	—	—	21.28	20.79	D	3.42	57.1	3.16	47.0	WC	(4)	WC5
111	W&C23,MC62,AM17	0.26	20.9	—	—	20.58	20.73	C	3.39	60.7:	3.17	52.0	WC	(4)	WC5
116	MC65,AM19	0.34	20.0	18.44	19.63	19.66	19.61	C	2.84	59.5:	2.91	49.6	WC6	(2)	WC6
120	MJ-X19	0.15	17.9	—	—	—	18.22	B	1.63	43.0	1.59	43.1	WCL	(6)	WC6
121	MJ-X9	0.26	19.0	17.96	19.23	19.08	18.04	C	1.79	81.2:	1.85	65.2	WNL?+abs	(6)	WC4+abs
125	W&C25,MC68	0.28	—	19.03	20.34	20.54	19.94	B	2.36	56.1	2.45	50.9	WC	(4)	WC5
129	MC70	0.45	19.1:	18.72	19.94	19.94	19.87	B	2.90	46.4:	2.69	37.6	WC	(4)	WC5

(1) Massey et al. (1987); (2) Willis et al. (1992); (3) Massey et al. (1996); (4) Armandroff & Massey (1991); (5) Massey et al. (1995); (6) Massey & Johnson (1998); (7) Schild et al. (1990); (8) Massey & Conti (1983); (9) Wampler (1982).

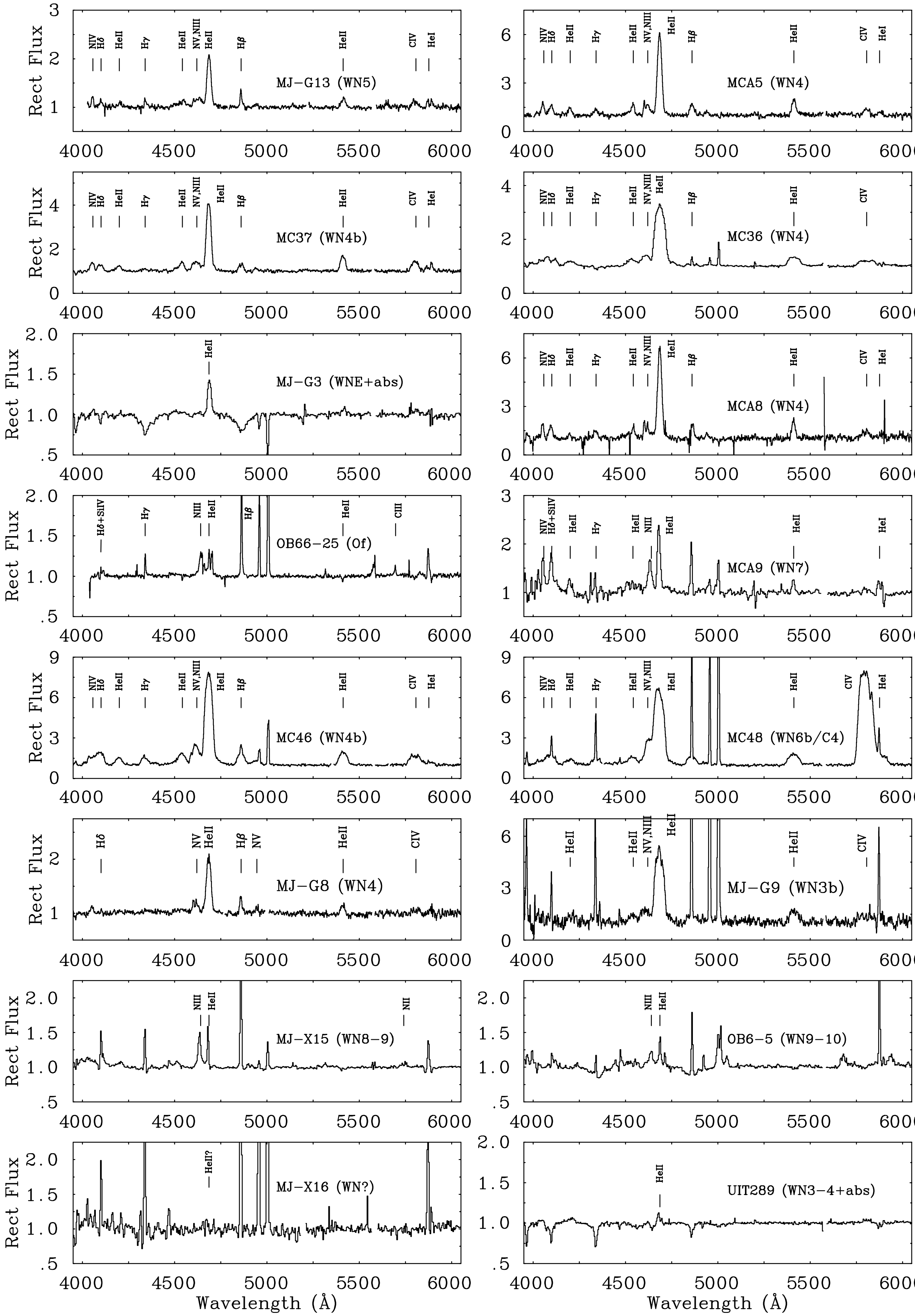

Figure 2. Plot showing the rectified spectra for the WN, Of and WN/C stars taken from our sample, covering a spectral range λλ4000–6000. A Gaussian smoothing has been applied (FWHM = 2 Å) for the purposes of identification of weak spectral lines. Nebular lines at Hγ, Hβ, λλ4959, 5007 [O III] plus He I λ5876 are not marked.

3.1.14 OB6-5 (M33-WR106)

This noisy spectra contains He II λ4686 emission as well as a weak (tentative) detection of N II λ3995 emission. As a result we have refined the spectral classification slightly from WN8 (Massey & Johnson 1998) to WN9–10.

3.1.15 MJ-X16 (M33-WR118)

Our spectrum of MJ-X16 differs from that published by Massey & Johnson (1998) in the sense that the weak, broad He II λ4686 emission seen in their observations, with a strength comparable to Of stars, is not reproduced in our data set. Consequently, either our MOS slit was incorrectly positioned, or this source has undergone spectral variability. The latter is a possibility given that the published finding chart from Massey & Johnson (1998) is of excellent quality and all our other MOS slits were appropriately positioned.

3.1.16 UIT 289 (M33-WR122)

Emission lines are exceptionally weak in this star, with very strong Balmer absorption features. Nevertheless, N V is detected, so we tentatively classify UIT 289 (Massey et al. 1996) as WN3–4+abs, in agreement with the previous classification of WN4 by Massey et al. (1996).

3.2 WC stars

Rectified, optical spectroscopy for the programme WC stars are presented in Fig. 3 together with principal stellar line identifications. We now discuss individual objects in turn.

3.2.1 MC26 (AM1, M33-WR38)

MC26 has extremely strong emission lines, with W_λ(C IV λ5801–12) ∼ 1000 Å. The relative strength of C III λ5696 indicates a WC6 subtype.

3.2.2 MC33 (AM8, M33-WR52)

We have refined the spectral type for MC33 (Massey & Conti 1983) from WC to WC4, albeit with relatively narrow lines. C IV λ5471 emission is weak in comparison with He II λ5411, suggesting a relatively low carbon abundance.

3.2.3 MC35 (M33-WR55)

Emission lines in MC35 are relatively weak, indicating a line-of-sight or bona fide companion. We suggest a WC6 spectral type.

3.2.4 MC39 (AM9, M33-WR61)

C III λ5696 is present, albeit weakly in our spectrum of MC39, indicating a WC5 subtype.

3.2.5 MC42 (M33-WR62)

MC42 (Massey & Conti 1983) is a broad-lined [FWHM(C IV) ∼ 70 Å] WC4 star that also shows nebula emission lines. O VI λ3811–34 is definitely absent, arguing against a WO subclass.

3.2.6 MC40 (M33-WR63)

We assign a WC4–5 subtype for MC40 because W_λ(C IV) ≫ W_λ(C III).

3.2.7 MC43 (AM13, M33-WR69)

MC43 is a strong lined WC star, for which the ratio of λ5696 to λ5801– 12 indicates a spectral type at the boundary of WC6–7 (according to Crowther et al. 1998), supporting the earlier classification by Armandroff & Massey (1991).

3.2.8 MC44 (M33-WR71)

MC44 has a rather unusual appearance, with a narrow C III λ5696 emission profile plus a sharply peaked C III λ4650/He II λ4686 blend, in contrast with the usual Gaussian profiles. This weak-lined star has a WC5 subtype.

3.2.9 MJ-C4 (M33-WR73)

MJ-C4 has an extremely weak emission line spectrum with W_λ(C IV λ5801) ∼ 21 Å. We assign a WC5 subtype because C III λ5696 is present, albeit extremely weak.

3.2.10 MC45 (M33-WR76)

As with MJ-C4, this star has a very weak emission line spectrum for which we obtain a WC4 subtype owing to the absence of C III λ5696.

3.2.11 MC47 (M33-WR82)

MC47 is a WC6 star that closely resembles MC26 in line strength and width.

3.2.12 MC49, (M33-WR84)

MC49 is another WC6 star, albeit with relatively weaker emission lines than MC47.

3.2.13 MC52 (M33-WR89)

This WC star has weak emission lines, W_λ(C IV λ5801–12) ∼ 75 Å, and is a bona fide WC7 star, albeit with a very high linewidth for this subtype, namely FWHM(C IV) ∼ 60 Å. There is clear spectroscopic contaminated by an OB star owing to Balmer absorption.

3.2.14 MC53 (M33-WR92)

MC53 (Massey & Conti 1983) is a WCE star with unusually narrow lines (i.e. FHWM(C IV) ∼ 30 Å) such that He II λ4686 is resolvable from the usual C III–IV λ4650 emission feature. This can also be seen in the spectra published by Armandroff & Massey (1991) and Willis et al. (1992). C IV λ5471 also appears very weak relative to He II λ5411. We revise the earlier classification of WC4–5 (Schild et al. 1990) to a somewhat later WC5–6 as a result of the weak detection of C III λ5696.

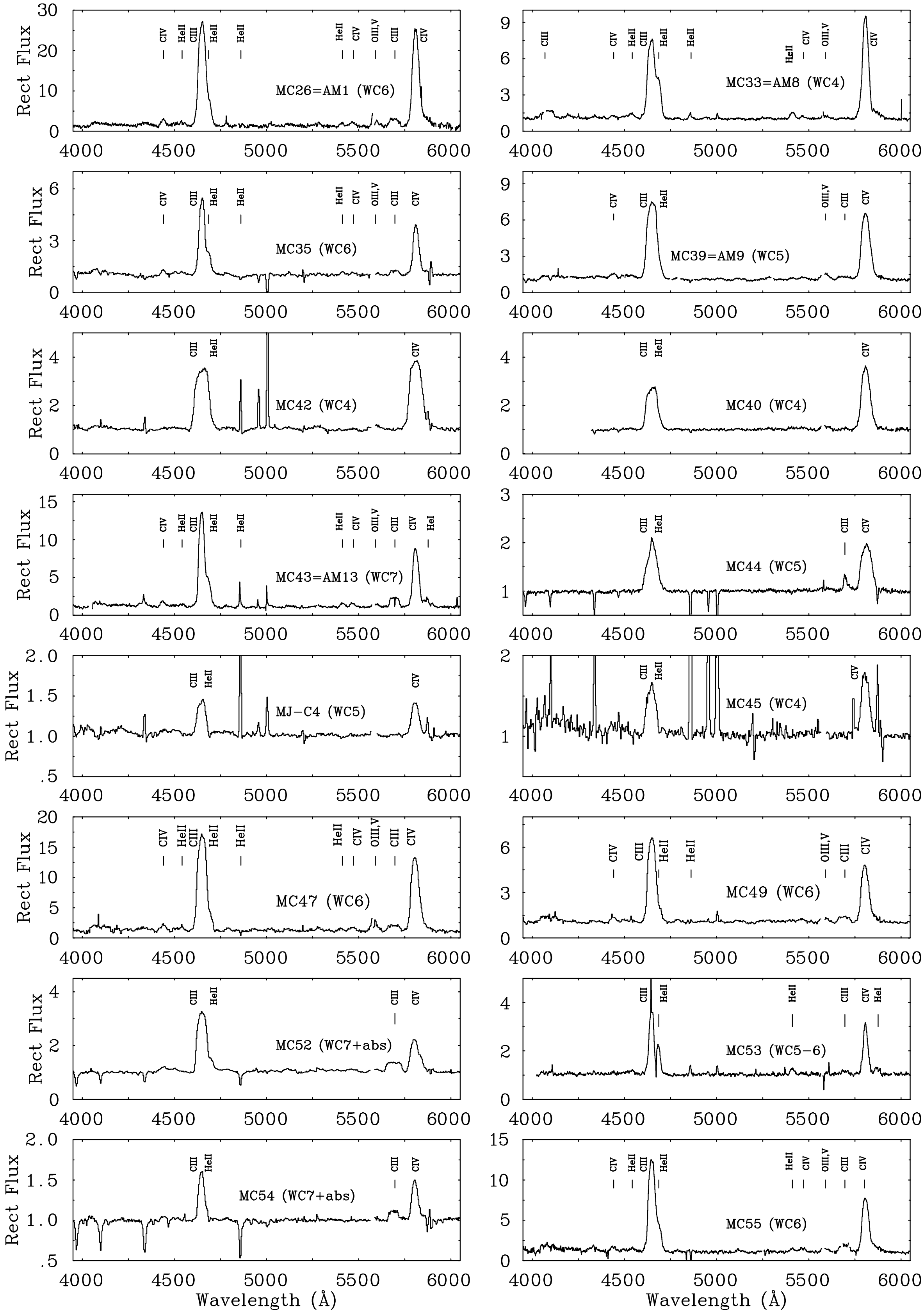

Figure 3. Plot showing the rectified spectra for the WC stars taken from our sample, covering a spectral range λλ4000–6000. A Gaussian smoothing has been applied (FWHM = 2 Å) for the purposes of identification of weak spectral lines. Nebular lines at Hγ, Hβ, λλ4959, 5007 [O III] plus He I λ5876 are not marked.

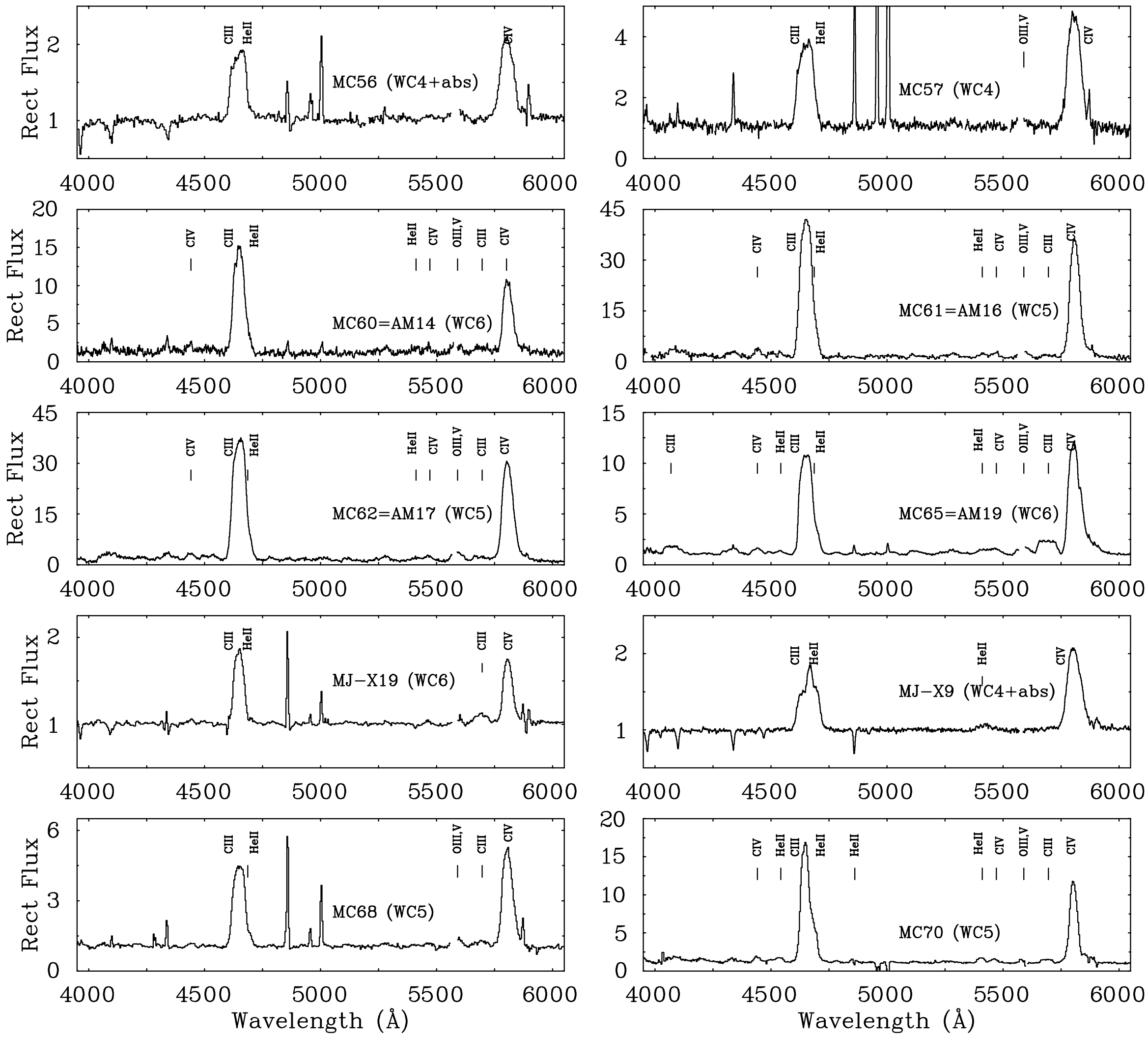

Figure 3 – *continued*

3.2.15 MC54 (M33-WR94)

MC54 (Massey & Conti 1983) is heavily contaminated by strong Balmer absorption lines, with weak WC emission features. We revise the classification for this star from WCE to WC7+abs as a result of the presence of C III λ5696.

3.2.16 MC55 (M33-WR95)

MC55 is yet another WC6 star closely resembling MC47 in line strength and width.

3.2.17 MC56 (M33-WR96)

MC56 is a WC4 star with very weak, broad (FWHM C IV ∼ 60 Å) emission lines plus the presence of photospheric Balmer lines from a potential OB companion.

3.2.18 MC57 (M33-WR99)

MC57 is another WC4 star, again with very broad lines, FWHM C IV ∼ 65 Å.

3.2.19 MC60 (AM14, M33-WR105)

MC60 is a strong lined WC6 star, morphologically similar to MC47.

3.2.20 MC61 (AM16, M33-WR110)

MC61 has an exceptionally strong emission line spectrum, with W_λ(C IV λ5801–12) ∼ 1500 Å. C III λ5696 is rather weak but present, resulting in a WC5 subtype.

3.2.21 MC62 (AM17, M33-WR111)

MC62 is a near spectroscopic twin of MC61, with similar line strengths and widths, and an identical WC5 subtype.

3.2.22 MC65 (AM19, M33-WR116)

MC65 is a WC6 star with a morphology that is similar to MC55.

3.2.23 MJ-X19 (M33-WR120)

MJ-X19 has a rather weak emission-line spectrum, but the weak presence of C III results in a WC6 subtype. Massey & Johnson (1998) proposed a general WCL subclass.

3.2.24 MJ-X9 (M33-WR121)

MJ-X9 has again a weak emission line spectrum, with broad emission at λ5801–12 (FWHM C IV ∼ 65 Å) and the C III/He II complex at λ4650. The latter is rather unusual with a prominent feature attributed to C IV λ4658. Absorption lines are also prominent in MJ-X9 so we assign a WC4+abs spectral type. Unusually, this is in marked contrast to the subtype of WNL?+abs from Massey & Johnson (1998), although only blue optical data sets were available to the earlier group.

3.2.25 MC68 (M33-WR125)

We assign a WC5 subtype to MC68 because C III is present, albeit very weak.

3.2.26 MC70 (M33-WR129)

MC70 is another strong lined WC5 star, albeit with somewhat narrower lines than other early WC stars in M33. The original spectrum from Massey & Conti (1983) is rather heavily dominated by nebular emission, whilst a local sky subtraction permits a cleaner appearance.

4 PHOTOMETRY, DISTANCE AND REDDENING TO M33

There have been a number of photometric magnitudes quoted for the WR population in M33 (e.g. Massey & Conti 1983; Drissen et al. 1990; Armandroff & Massey 1991; Massey & Johnson 1998); the majority of these magnitudes are quoted as continuum magnitudes. Unfortunately the definitions for these continuum magnitudes vary between authors. For completeness we have listed the continuum magnitudes (equivalent to AB magnitudes at λ4750) calculated by Massey & Johnson (1998) in Tables 2 and 3.

We have obtained broad-band *V* and *B* magnitudes for our sample of WR stars in M33 from two sources, archival *HST* WFPC2 images, where these were available, and ground-based images otherwise.

HST photometry was performed for a number of images taken through various filters using the HSTPHOT package (Dolphin 2000); this procedure is similar to DAOPHOT but is fine-tuned for WFPC2 images, including corrections for quantum efficiency (QE) variations and accurate point spread function (PSF) determinations.

We also obtained broad-band Johnson *V* and *B* magnitudes from archival CFH12K data sets from 2000 August (see Fig 1). Photometry was obtained using the DAOPHOT software package under IRAF, using nearby field stars observed by Macri et al. (2001) as photometric standards. Overall the *HST* photometry resulted in systematically brighter magnitudes for all but two WC stars; these variations were typically ∼0.1 mag. Both sets of photometric measurements are listed in Tables 2 and 3.

M33 is used as a primary indicator to calibrate extragalactic distance scales and to constrain the Hubble constant (H_0), and as a result its distance has been well studied. We adopted a distance modulus of $(m - M)_0 = 24.56$ (corresponding to 816 kpc), obtained by Freedman et al. (2001).

The reddening towards M33 was examined by Sandage & Johnson (1974), Humphreys (1980) and Johnson & Joner (1987), and more recently by Massey et al. (1995) and Massey (1998). Massey et al. (1995) acquired a large sample of photometric observations for hot, luminous stars in a number of Local Group galaxies including M33. They concluded for M33 that the typical colour excess is $E(B - V) \approx 0.16$; they also found that there is still a scatter of colour excesses amongst OB associations within the galaxy ranging from 0.06 to 0.33. These values, as well as the average reddening determined by Massey et al. (1995), are also consistent with those inferred by earlier studies mentioned above.

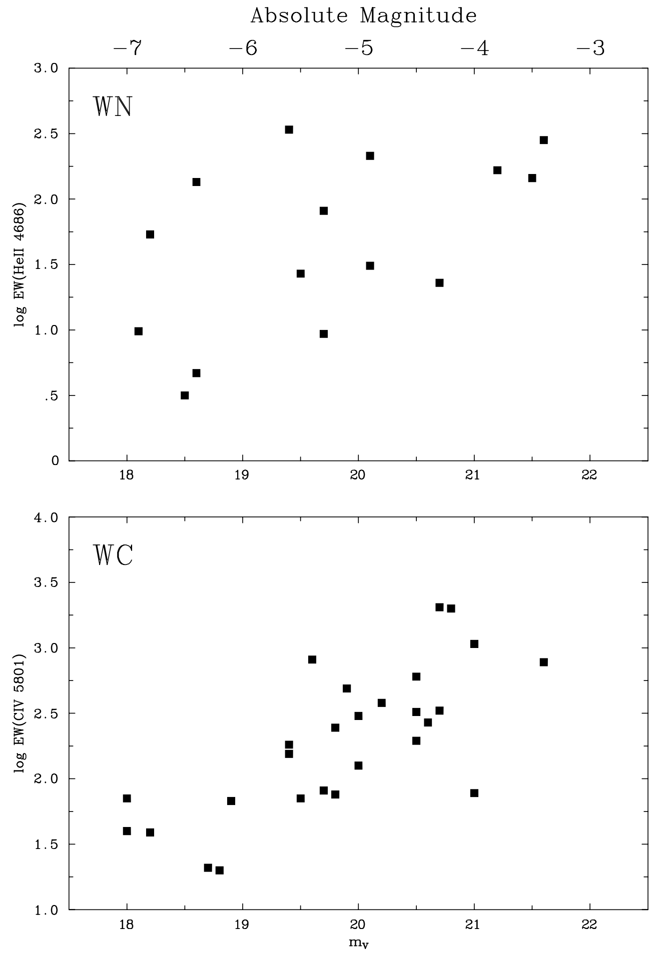

Figure 4. Line strengths versus continuum magnitude (from Massey & Johnson 1998) for WN (top panel) and WC stars (bottom panel) in M33. Approximate absolute magnitudes are shown, assuming a distance modulus to M33 of 24.56 mag and an average $E(B - V) = 0.15$ mag.

As discussed in Section 2, our spectra could not be reliably flux-calibrated and so accurate reddenings could not be determined for each star. For our purposes we have used a nominal value of $E(B - V) = 0.15$. Given the range of observed reddenings, this implies an error of up to 0.5 mag in absolute magnitudes. Absolute magnitudes resulting from these generic reddenings were obtained from the Massey & Johnson (1998) continuum magnitudes, revealing values in the range −7.2 to −2.7 mag for the present sample.

We plot the WC and WN line strengths versus absolute visual magnitude in Fig. 4. As expected, visually bright Wolf–Rayet stars have weak lines, as expected from WC+OB or WNE+OB systems or weak-lined (single) WNL stars. A range of line strengths are observed for intermediate bright Wolf–Rayet stars. WN stars with large equivalent widths are likely single, whilst others may either be diluted from a companion or have intrinsically weak lines. Visually faint stars are generally presumed to be single WC or early WN stars.

In subsequent papers we shall pay closer attention to potentially single WN and WC stars via *HST* imaging and line strengths versus single Milky Way and Magellanic Cloud counterparts.

5 ABUNDANCE GRADIENT

The metallicity gradient across M33 has been well studied using a number of different techniques. We use a modern calibration to re-evaluate the metallicity of the inner disc, from which the current sample of WR stars was drawn. Dopita, D'Odorico & Benvenuti (1980) used observations of supernova remnants (SNRs) in M33 to obtain metal abundances, followed up by Blair & Kirshner (1985) and Smith et al. (1993). There is a large spread between abundances derived from SNRs, which is primarily as a result of the sensitivity to shock models.

Alternative metallicity gradients may be obtained from H II regions. These also rely on models, although they are well-tested and (mostly) observationally based. For M33 H II regions were observed by Smith (1975), Kwitter & Aller (1981), Vilchez et al. (1988) and Garnett, Odewahn & Skillman (1992). These data sets have been re-analysed by Henry & Howard (1995), Zaritsky, Kennicutt & Huchra (1994) and Garnett et al. (1997).

Here we follow the $R_{2,3}$ re-calibration of Pilyugin (2000), together with observational material indicated above, favouring the modern CCD data sets of Vilchez et al. (1988) and Garnett et al. (1992) where multiple observations of the same H II region are available. The Pilyugin (2000) method, valid for regions with 12 + log(O/H) > 8.15, is applied to literature H II region data in Fig. 5, and indicates a steep radial abundance gradient in M33, ranging from supersolar in the nucleus to LMC-like at the Holmberg radius, $\rho \sim 6$ kpc, i.e.

$$12 + \log(\mathrm{O/H}) = 8.89 - 0.67\rho/\rho_0.$$

For comparison, Zaritsky et al. (1994) obtained a similar gradient, albeit offset by 0.2 dex, i.e.

$$12 + \log(\mathrm{O/H}) = 9.08 - 0.74\rho/\rho_0.$$

We therefore anticipate that the present sample, lying at an average galactocentric distance of 0.25 ρ_0, will possess solar-like metallicities of 12 + log (O/H) ~ 8.7. The WC population of the inner disc of M33, comprising mostly WC5–7 stars does indeed bear a similarity to that in the solar neighbourhood.

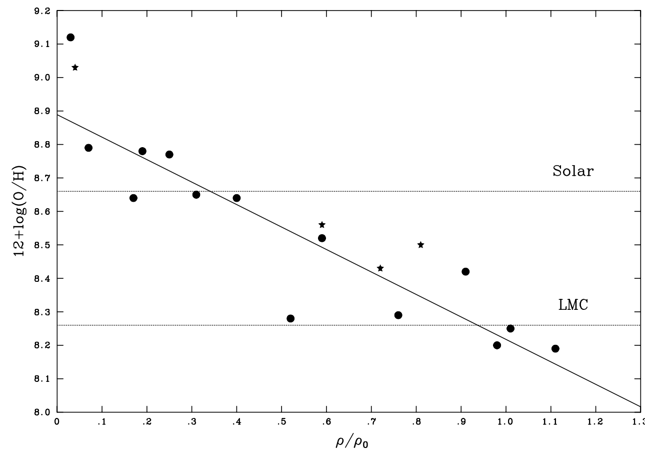

Figure 5. Oxygen abundance gradient for M33 derived from observations of H II regions (filled circles), based on observations of Smith (1975), Kwitter & Aller (1981), Vilchez et al. (1988) and Garnett et al. (1992) and the method of Pilyugin (2000), plus B supergiants (filled stars) from Monteverde et al. (1997). The least-squares fit to H II regions is shown as an unbroken line. The revised Solar oxygen value is taken from Asplund (2003).

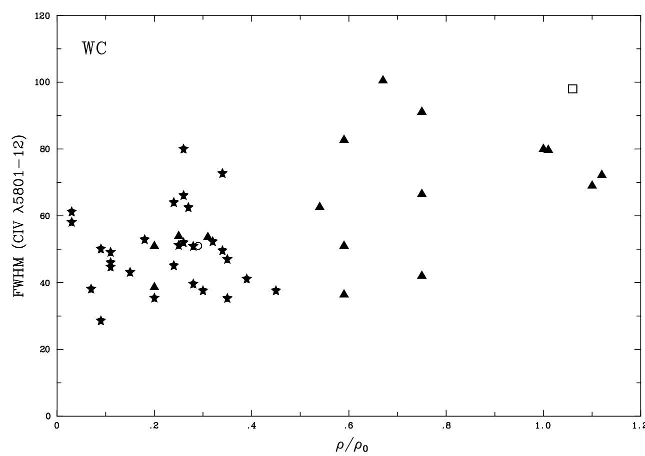

Figure 6. FWHM(C IV λλ5801–12, in Å) versus galactocentric distance for WCE stars in M33, using data preferentially from the current data set (filled stars), Dessart (1999 filled triangles) or otherwise Schild et al. (1990 open circle) or Willis et al. (1992 filled square).

6 CORRELATION BETWEEN GALACTOCENTRIC DISTANCE AND LINEWIDTH?

We postpone until Papers II and III (Abbott et al., in preparation) the detailed spectroscopic analysis of M33 WC and WN stars with the model atmosphere code of Hillier & Miller (1998) and a comparison of inferred stellar parameters with environmental metallicity. However, we wish in the present section to discuss simple correlation between spectroscopic morphology and environmental metallicity.

Schild et al. (1990) and Willis et al. (1992) claimed a potentially important correlation between the linewidth of C IV λ5808 and galactocentric distance in M33. They showed that the FWHM (C IV λλ5801– 12) for WCE stars was narrower for stars close to the nucleus (located in higher metallicity environments) than for those at larger galactocentric distance (located in lower metallicity regions). However, this relationship was rather tenuous owing to their small sample (see also Armandroff & Massey 1991). Massey & Johnson (1998) subsequently compared linewidths for WC stars in the Milky Way, LMC, M33 and M31. Stars in lower metallicity regions tend to have stronger, broader lines and are of earlier type. Little difference is identified for M31 as a result of an apparently flat radial metallicity gradient (Armandroff & Massey 1991; Massey & Johnson 1998).

We have measured the FWHM (C IV λλ5801–12) for the WC stars in our sample and combined with those of Dessart (1999). These are presented versus galactocentric distance in Fig. 6. It is clear that our larger sample does not support the strong correlation between FWHM and galactocentric distance proposed by Willis et al. (1992). Instead, we find a very large spread in FWHM in the range $0.4 \leqslant \rho \leqslant 0.6$. Performing a simple statistically analysis on these data we find a linear correlation coefficient $R = 0.58$ and the probability of a linear correlation of 22 per cent.

Nevertheless, there does seem to be a genuine lack of broad-line WC stars towards the central regions of M33 and a lack of narrow-line WC stars at larger galactocentric distances. This (weak) trend has also recently been noted for WC stars in the nearby spiral galaxy NGC 300 by Schild et al. 2003. This is still unexplained. Note that

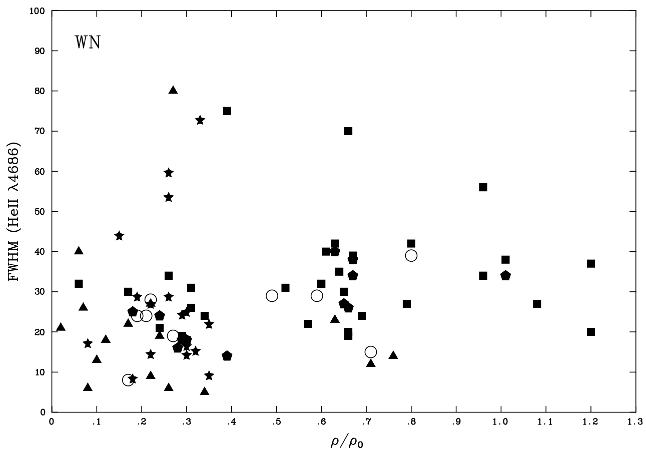

Figure 7. FWHM(He II λ4686, in Å) versus galactocentric distance for WNE stars in M33, using data preferentially from the present data set (filled stars) or Armandroff & Massey (1991 filled pentagons) or otherwise Massey et al. (1987 open circles), Massey & Conti (1983 filled squares), Massey & Johnson (1998 filled triangles).

if WR stars are assumed to follow the same stellar wind properties as OB stars, their terminal wind velocities would be expected to decrease with decreasing metallicity (Leitherer, Robert & Drissen 1992), in contrast with the (weak) opposite effect observed.

We have applied this method to the He II λ4686 line for our WN sample, combining our measurements with previously published data preferentially from Armandroff & Massey (1991), plus Massey et al. (1987), Massey & Conti (1983) and Massey & Johnson (1998). These results are shown in Fig. 7. Despite the large sample, again very little evidence for a correlation of FWHM (He II λ4686) with galactocentric distance is identified. A statistical analysis in these data find a linear correlation coefficient $R = 0.22$, with a 15 per cent probability of a linear correlation.

7 SUMMARY

We have observed a representative sample of WN and WC stars in M33 using the Multi-Object Spectrograph on the Canada–France–Hawaii Telescope. Our optical data achieve a signal-to-noise ratio and resolution that allow us to identify weak, but diagnostically important, emission lines, which are necessary for a detailed analysis. We have improved and re-classified subtypes where necessary. We have also obtained broad-band Johnson *V* and *B* magnitudes from archival CFHT and *HST* images.

This improved data set has allowed us to re-examine the WC linewidth proposed by Willis et al. (1992). We find little evidence that a physical correlation exists, although we do find that there is a lack of broad-line WC stars in the inner disc and narrow-line WC stars in the outer disc. This investigation was also extended to the WN population of M33. Unfortunately, this too proved unfruitful and showed even less probability of a linear correlation.

The metallicity gradient calculated from H II regions was re-evaluated for M33 using a re-calibration of the $R_{2,3}$ method (Pilyugin 2000). We find a similar gradient to that derived by Zaritsky et al. (1994), albeit offset 0.2 dex lower, such that the majority of WC stars studied here are anticipated to be formed from solar-like interstellar medium (ISM) abundances. Inadequacies in calibrations highlight the need for a modern, extensive study of H II regions across M33 before a confident metallicity gradient can be determined.

Future studies in this series will utilize these observations to study quantitatively apparently single WN and WC stars in M33 for comparison with their counterparts in the Milky Way and Magellanic Clouds.

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