WR 143: A Wolf-Rayet Binary

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ABSTRACT
Near infrared spectroscopy and photometry of the Wolf-Rayet Star WR 143 (HD 195177) were obtained in the JHK photometric bands. High resolution spectra observed in the J and H bands exhibit narrow 1.083-μm He I line and the H i Paβ and the Brackett series lines in emission superposed on the broad emission line spectrum of the Wolf-Rayet star, giving strong indications of the presence of a companion. From the narrow emission lines observed, the companion is identified to be an early-type Be star. The photometric magnitudes exhibit variations in the JHK bands which are probably due to the variability of the companion star. The flux density distribution is too steep for a Wolf-Rayet atmosphere. This is identified to be mainly due to the increasing contribution from the early-type companion star towards shorter wavelengths.

Key words: stars: Wolf-Rayet – stars: winds – binaries: spectroscopic – stars: emission-line, Be – stars: individual: WR 143

1 INTRODUCTION
During the late stages of evolution, massive stars (with M ≥ 30 M⊙) go through the Wolf-Rayet (WR) phase. At this stage, they are subjected to large scale mass loss (Ṁ ~ 10^{-3} M⊙ year^{-1}) through accelerated stellar winds with terminal velocities in the range 750-5000 km s^{-1}. Consequently these objects are characterized by infrared excess and strong, broad emission lines originating in their fast winds. Based on the emission lines observed, they are classified into WN, WC and WO stars. WN stars show lines of He and N in their winds with the evidence of H in the late types and WC and WO stars show lines of He, C and O. WR 143 (HD 195177) is an interesting member of the WC4 type, its lines being weaker than the rest of the members of its class.

Early studies classified WR 143 as WC5+(OB) (Smith 1968). The possibility of the presence of a companion star was considered since its emission lines were weaker than that of many other stars of the same WR type, even though no absorption lines were detected. Smith, Shara & Moffat (1990a) reclassified WR 143 as a WC4 star. Figer, McLean & Najarro (1997) observed the K-band spectrum. They also noticed that the IR emission lines of WR 143 were weaker and broader compared to those of the other WC5-type stars, WR 111 and WR 114. The VIth catalogue of galactic Wolf-Rayet Stars (van der Hucht 2001) lists WR 143 as WC4 + OB+. Considering the absolute v magnitude of the system, van der Hucht (2001) proposed a B0V companion to the WR star in WR 143. The exact nature of the companion is not yet understood. The object is very faint at radio and X-ray wavelengths. The 6-cm radio continuum survey of Abbott et al. (1986) using the VLA gave an upper limit of the flux of 0.4 mJy, which was above their 3σ noise. However, the 3.6-cm radio continuum survey of Cappa, Goss and van der Hucht (2004) using the VLA did not detect WR 143. They derived an upper limit for its mass loss rate to be 0.7 × 10^{-5} M⊙ year^{-1}. WR 143 may have been detected (2σ) in the ROSAT X-ray survey (Pollock, Haberl, Corcoran 1995).

WR 143 is located close to the galactic plane at a distance of ∼1 pc (van der Hucht et al. 1988). The distance estimates by different investigators agree quite well. From the spectroscopic parallax, Conti & Vacca (1990) estimated a heliocentric distance of 1.0 kpc which is close to the value of 0.82 kpc estimated by van der Hucht et al. (1988) and 1.17 kpc by Smith, Shara & Moffat (1990b) using the line flux method. van der Hucht et al. (1998) estimated the extinction A_v = 6.07, which gives A_v=5.47 assuming A_v/A_f=1.11 (van der Hucht 2001).

2 OBSERVATIONS AND DATA REDUCTION
We observed the near-IR JHK spectra of WR 143 with the 3.8-m United Kingdom Infrared Telescope (UKIRT), and the Cooled Grating Spectrometer (CGS4) (Mountain et al. 1990) using the 401/mm grating. This grating, with a 1-pixel slit, gives a resolution of ∼940 in the J band in the second order and ∼680 and ∼900 in the H and K bands respectively in the first order. The J-band spectra were taken on three epochs. Krypton, Xenon and Argon arc lamps’ spectra were used to wavelength-calibrate the J-, H- and K-band spectra respectively. Table I gives the details of the spectroscopic observations. Fig. 1 shows the observed J-band spectra and Fig. 2 the H- and K-band spectra. Many narrow emission features were...
observed in our JHK spectra. To better understand these, we again observed at higher spectral resolution at these wavelengths.

Our J-band spectra on all three epochs exhibited a prominent narrow emission component superposed on the broad He i emission line from the WR star at 1.083 µm. To investigate this feature, we carried out high-resolution observations with CGS4 using the echelle grating and a 2-pixel slit, at a spectral resolution of ~20700. Six wavelength settings with the echelle grating gave a reasonably good coverage of the 1.083-µm He i line, although a part of the red wing could not be covered. The observed spectrum is shown in Fig. 3. The wavelength calibration was carried out using the photospheric absorption lines of the comparison star. Heliocentric corrections were applied. The narrow emission component has an asymmetric profile and its central wavelength is seen very close to the line-centre of the broad emission line from the WR star. The observed spectra were flux-calibrated using the average spectra presented by Eenens & Williams (1994). There is a conspicuous narrow absorption seen at 10778 Å which is not identified. From the well-defined blue edge of the P Cyg absorption profile of the line, we estimate a $V_{\text{edge}} = 2845 \pm 15$ km/s. This is close to the value of $V_{\infty} = 2750$ km/s observed by Eenens & Williams (1994).

The 1.281-µm He ii line also exhibited a faint narrow emission component close to the line-centre. Some of the lines from 1.55 µm to 1.681 µm were also observed to be much narrower than the rest of the WR lines. Observations were again carried out using UKIRT and UIST (Ramsay Howat et al. 2000) at higher spectral resolution (R ~4000) to better resolve the narrow emission lines. The UIST spectra were wavelength calibrated using an Argon arc lamp mounted inside the instrument. These spectra show the H i Paß and the Br series lines superposed on the broad emission line spectrum of the WR star. Fig. 3 shows the observed spectra in the JH bands.

All the spectroscopic observations were carried out by nodding the telescope on two positions separated by ~12 arcsec along the slit. The flat-field observations were obtained by exposing the arrays to black bodies mounted inside the instruments. Preliminary reduction of the data including co-adding the frames and the bias and the flat-field corrections were carried out using ORACDR, the pipeline reduction facility at UKIRT. The spectra were optimally extracted using the STARLINK software FIGARO. Comparison stars (listed in Table 1) were observed at all wavelength settings. The observed comparison star spectra were corrected for their photospheric temperatures by dividing by appropriate black bodies and their photospheric hydrogen absorption lines were interpolated across and removed at the continuum level before ratioing the object spectra with them. The final reduction, involving the calculations of the line fluxes and the equivalent widths (EWs) were carried out using IRAF.

Photometry in the JHK bands were acquired on 3 epochs from 2001 March to 2002 December using the 1.2-m Mt. Abu Infrared Telescope and an LN2-cooled 256x256 NICMOS3 IR array. FS 149 and FS 150, two of the UKIRT faint standard stars (Hawarden et al. 2001), were observed for calibration. Observations were carried out by dithering the object on several positions on the array. The dark observations were obtained before each set of the on-sky observations and the flat-field corrections were applied using the flat-fields generated from the object observations by median-combining the observed frames. The observed JHK magnitudes are shown in Table 2 along with the 2MASS magnitudes and the other near-IR photometric measurements available.

The observed spectra were flux-calibrated using the average JHK magnitudes of the three epochs of our observations. The strong emission lines present in the photometric bands contribute significantly to the observed magnitudes. Hence, the magnitudes were corrected to subtract out the contribution from the emission lines adopting a method similar to Eenens and Williams (1992). The equivalent widths (EW) of the emission lines were estimated from the ratioed spectra; these EWs were weighted with the transmission of the filters used in the Mt. Abu photometry and the corrections for the lines were derived as:

$$\Delta m_{\text{line}} = 2.5 \log \frac{EW_{\text{FW}}}{FW}$$

where FW is the band width of the filter used for the photometry and LW is the sum of the weighted EWs of the emission lines within the photometric band. $\Delta m_{\text{line}}$ were added to the observed magnitudes to obtain the magnitudes representing the continua, which were then used to flux-calibrate the observed JHK spectra.

The spectra were dereddened assuming $A_V=5.47$ with an interstellar reddening law with $R_V=A_V/(E(B-V))=3.1$. Line fluxes and

Table 1. Spectroscopic Observations using UKIRT

| $\lambda$ (µm) | Grating/ grism(*) | Resolution (1/Δλ) | UT Date (ymmd.dd) | Comparison star |
|---------------|------------------|-------------------|-------------------|-----------------|
| 1.083         | Echelle          | 20700             | 011029.221        | BS 8170         |
| 1.18          | 401/mm           | 944               | 010613.568        | BS 7556, BS 8788|
| 1.18          | 401/mm           | 944               | 010704.424        | BS 7793         |
| 1.18          | 401/mm           | 944               | 011029.368        | BS 8170         |
| 1.70          | 401/mm           | 680               | 010614.553        | BS 7793         |
| 2.25          | 401/mm           | 900               | 010614.625        | BS 7793         |
| 1.237         | long_J*          | 4100              | 030619.418        | BS 7672         |
| 1.522         | short_J*         | 3800              | 030619.435        | BS 7672         |
| 1.702         | long_J*          | 4000              | 030812.415        | BS 7672         |

* Observed using UIST. The rest were observed using CGS4

Figure 1. The observed J-band spectra of WR 143. Spectra are labelled by the UT-dates of the observations. All spectra are plotted with the same scale, with those of 20010613 and 20011029 vertically shifted for clarity.

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equivalent widths of the emission lines are estimated from the dereddened spectra. The $J$-band spectra of the three epochs were averaged before estimating the equivalent widths. The lines were fitted with Gaussian profiles for estimating the EWs and FWHM. Multiple Gaussians were fitted when there was line blending. For the strongly blended lines, we give only the the equivalent widths of the combined profiles; FWHM of the individual components are not listed in those cases. The lines identified, their fluxes and the equivalent widths are shown in Table 3. The line identifications are adopted from Eenens, Williams & Wade (1991) and from the atomic line list of Peter van Hoof 1. The arc lines observed using the UIST high-resolution grisms showed an average FWHM of 75 km s$^{-1}$. The FWHM of the narrow emission lines measured in these spectra have been corrected to account for this. The identifications, FWHM, flux and EW of the narrow emission lines are listed in Table 4. The estimates for the broad WR emission lines from these high-resolution spectra are listed in Table 3. Most of the errors in the line fluxes and the EWs arise from the accuracy with which the continuum is defined. Hence, the errors are determined by multiple measurements of these values on any specific line or blend. The values given in Table 4 and Fig 5 are the averages of eight independent determinations from the dereddened spectra. The 1σ standard deviations are given in brackets against the line fluxes and the EWs.

3 DISCUSSION AND CONCLUSIONS

Table 4 and Fig 5 show the variability of the $JHK$ magnitudes. The $JHK$ magnitudes measured by us on the three epochs (within ~21 months) did not exhibit any significant variability beyond the ob-
Table 4. Narrow emission lines

| λ (µm) | Identification | Flux×10^{-16} (Wm^{-2}) | EW (Å) | FWHM (km s^{-1}) |
|--------|----------------|--------------------------|--------|------------------|
| Hydrogen lines |
| 1.2827 | 5-3            | 1.5 (0.1)                | -2.2 (0.1) | 306 (7) |
| 1.5049 | 23-4           | 6.7 (0.2)                | -2.1 (0.1) | 334 (6) |
| 1.5143 | 21-4           | 9.3 (0.3)                | -3.0 (0.1) | 465 (12)          |
| 1.5202 | 20-4           | 7.0 (0.2)                | -2.3 (0.1) | 334 (6) |
| 1.5269 | 19-4           | 6.7 (0.2)                | -2.3 (0.1) | 511 (11)          |
| 1.5352 | 18-4           | 8.0 (0.1)                | -2.7 (0.04) | 418 (5) |
| 1.5448 | 17-4           | 8.6 (0.2)                | -2.9 (0.1) | 407 (6) |
| 1.5567 | 16-4           | 9.9 (0.3)                | -3.3 (0.1) | 395 (11)          |
| 1.5708 | 15-4           | 13.7 (0.3)               | -4.8 (0.1) | 591 (11) |
| 1.5889 | 14-4           | 12.4 (0.5)               | -4.7 (0.2) | 539 (15) |
| 1.6179 | 13-4           | 12.6 (0.2)               | -5.1 (0.1) | 515 (5) |
| 1.6453 | 12-4           | 12.4 (0.3)               | -5.1 (0.1) | 485 (8) |
| 1.6816 | 11-4           | 11.6 (0.2)               | -5.3 (0.1) | 484 (5) |
| 1.7367 | 10-4           | 8.3 (0.4)                | -2.1 (0.1) | 339 (14) |
| 2.166  | 7-4 — detected in the low-resolution spectrum |
| 1.083  | 2p3^3P-2s^3S | 3.6 (0.1)                | -2.4 (0.1) |

1 Will be strongly affected by the Wolf-Rayet continuum and the broad emission lines

From the dereddened spectra, we estimated the ratios of the equivalent widths of the emission lines (1.083+1.094)/(1.191+1.199) and (1.693+1.701)/1.736 to be 0.38 and 0.03 respectively which are consistent with a WC type earlier than WC5 when compared with the line ratios estimated by Eenens et al. (1991). The ratios 1.28/(1.083+1.094), 2.08/2.11 and 2.43/2.48 are 0.28, 5.7 and 3.5 respectively, which are somewhat less for WC4 star. However, the line ratios estimated by Eenens et al. (1991) extend down only up to WC5 type and have only one or two objects per WC type, and hence we do not know about the uncertainty in these ratios. In general our JHK spectra agree with a WC4 type for this star.

WR 143 was detected by the MSX at 8.28 µm (Egan et al. 2003) with a flux density of 0.1285 mJy. Observations at 10 µm by Cohen et al. (1975) and Smith and Houck (2001) differ very much and are only upper limits. Hence those are not considered here. The near-IR magnitudes given in Table 2 and the line free magnitudes reported by Massey (1984) (13.97, 13.16, 11.95 and 11.17 magnitudes respectively in the narrow-band u,b,v and r filters) are dereddened adopting the value of $A_V=5.47$ and following the extinction relations given by Cardelli, Clayton & Mathis (1989). Fig. 5 shows the flux density distribution of WR 143 from 0.365 µm to 8.28 µm. At radio and infrared wavelengths, flux density distribution ($S_\nu$) of a uniform, ionized, spherically symmetric wind can be represented by a power law of the form $S_\nu \propto \nu^\alpha$ with $\alpha=0.6$, where $\nu$ is the frequency of observation (Wright & Barlow 1975). This value of $\alpha$ is intermediate between $\alpha=-0.1$, expected for free-free emission from an optically thin homogeneous plasma and $\alpha=2.0$, expected for that from an optically thick plasma. Williams (1999) estimated an average value of $\alpha=0.7$ from millimeter and radio observations. The observed values of $\alpha$ at shorter wavelengths are somewhat higher.
since the radiation at these wavelengths are mainly emitted from the inner regions where the wind is still being accelerated. Morris et al. (1993) found that in the wavelength interval ~0.14–1.0 \( \mu \)m, the continuum energy distribution can be represented by a power law with mean \( \alpha=0.85\pm0.26 \). Setia Gunawan (2001) estimates an average value of \( \alpha=1.21\pm0.24 \) from the optical and near-IR (also MSX, mm and radio data for some objects) of 9 non-dusty WR stars. Average of the \( \alpha \) for six single WR stars given in Setia Gunawan (2001) gives 1.13\pm0.24. A linear least square fit to all the observed data of WR 143 from 0.36\( \mu \)m to 8.28\( \mu \)m (the continuous line in Fig. 5) gives \( \alpha=1.73 \) (1\( \sigma \)=0.06). In Fig. 6 we have also plotted the power law flux density distribution for \( \alpha=1.13 \) (the dotted line), scaled to match our fitted line at 1.25\( \mu \)m. We see that, for WR 143, the flux density distribution is much steeper than what is

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**Table 3.** Line identifications, Equivalent widths, line fluxes and FWHM estimated from the reddered spectra. A blank line separates the blends. 1\( \sigma \) errors are shown in brackets. Line strengths estimated from the high-resolution spectra are shown by *"++*. The rest are from the low-resolution spectra.

| \( \lambda \) (\( \mu \)m) | Main contributor | Other possible contributors | Flux \( (\times10^{-15} \text{Wm}^{-2}) \) | EW (\( \text{Å} \)) | FWHM (\( \text{km s}^{-1} \)) |
|---|---|---|---|---|---|
| 1.054 | C iv (12–9) | 1.055 (Cm); 1.055 (O m) | 28 (0.8) | -21 (0.6) | 2715 (43) |
| 1.083 + 1.092 + 1.094 | He (2p–2s); He (6f–3d); He (12–6) | | 64.3 (0.5) | -54.5 (0.5) | |
| 1.11 | O iv (3p–4f) | 1.1–1.101 (He i) | 11.7 (0.6) | -12.6 (0.6) | 3340 (112) |
| 1.139 | C iv (8d–7p) | 1.14 (O m) | 6.5 (0.4) | -6.6 (0.4) | |
| 1.163 + 1.162–1.163 + 1.164 | He (7–5); C iv (14–10); C m (7d–6p) | | 48 (0.8) | -53 (1) | 3070 (140) |
| 1.191 + 1.198–1.199 | C iv (8–7); C m (4p–4s) | 1.191 (O v); 1.197 (He i) | 123 (3) | -145 (4) | |
| 1.205 | O v (2p–2s–2p–4p) | 1.20 (O v); 1.2–1.209 (O m) | 17 (0.6) | -20.7 (0.6) | 2845 (30) |
| 1.226 | C iv (8p–7d) | 3 (0.5) | -3.9 (0.7) | 2670 (78) | |
| 1.255–1.26 | C m (7f–6d–9–7) | 1.253 (He i); 1.258, 1.261 (C m); 1.247, 1.255 (O v); 1.25 (O m) | 16.6 (0.2) | -23.6 (0.3) | |
| 1.281 + 1.279, 1.285 | He (10–6); He (5–3) | 1.282 (O iv) | 10 (0.2) | -15.4 (0.3) | 2530 (25) |
| 1.298, 1.307 | C iv (8s–7p, 16–11) | 1.297, 1.299 (He i); 1.3 (O m); 1.31 (O iv) | 7.8 (0.4) | -13 (0.7) | |
| 1.435 | C iv (4p–4s) | | 23 (1) | -54.7 (2.7) | 2800 (33) |
| 1.454 | C m (7g–6f) | 1.6 (0.2) | -4.2 (0.6) | 1950 (123) | |
| 1.476 | He (9–6); He (14–7); C m (15f–11d, 15g–11f) | 1.474 (O m); 1.473 (O v); 1.473 (C m); 1.476 (C iv) | 6.5 (0.2) | -17.8 (0.5) | 5.6 (0.3) |
| 1.489 + 1.490, 1.491 | C m (7p–6d); C iv (17–12) | 1.63–1.64 (He i); 1.632 (O iv) | 3.9 (0.2) | -16.4 (0.6) | |
| *1.546, 1.552 | He (11–4, 13–4) | 1.55 (O iv) | 3.8 (0.1) | -13.6 (0.3) | |
| *1.570 + 1.572 | He (15–4); He (13–7) | 2.1 (0.1) | -7.7 (0.2) | |
| *1.579, 1.587 | He (12–4, 14–4) | 1.58–1.587 (O v) | 1.04 (0.2) | -4 (0.7) | |
| *1.616, 1.61 | He (11–4, 13–4) | 1.61, 1.619 (O v) | 0.83 (0.1) | -3.4 (0.5) | |
| *1.623 + 1.635 | C m (7p–6d); C iv (17–12) | 1.63–1.64 (He i); 1.632 (O iv) | 3.9 (0.2) | -16.4 (0.6) | |
| *1.664 | C iv (9d–8p) | 1.668 (He i) | 1.4 (0.1) | -6.1 (0.4) | |
| *1.693 | He (12–7) | 1.681–1.701 (He i) | 1.3 (0.2) | -6.2 (0.8) | |
| 1.732–1.740 | C iv (9–8) | 1.734 (He i) | 40.8 (0.5) | -208 (3) | 2870 (12) |
| 1.790, 1.801 | C iv (9–8, 14–11) | 1.81 (C iv); 1.814 (He i) | 16.8 (0.5) | -95.7 (2.9) | |
| 1.944 | He (8–4) | 2.0 (0.03) | -15.2 (3) | 1450 (19) | |
| 2.010 | C iv (18–13) | 1.1 (0.1) | -8.5 (0.8) | |
| 2.071 + 2.059 | C iv (3d–3p); C m (5p–5s, 4d–4p); H e (4s–3p) | 2.061 (He i) | 80.9 (0.3) | -729 (4) | |
| 2.108, 2.122 + 2.113 | C m (5p–5s, 4d–4p); H e (4s–3p) | 2.107 (C iv); 2.123 (O iv) | 13.6 (0.4) | -129 (4) | |
| 2.165 | H e (7–4) | 2.2 (0.2) | -22.3 (2) | |
| 2.189 | H e (10–7) | 2.7 (0.2) | -28.9 (2) | |
| 2.227 | H e (7s–4p) | 0.79 (0.15) | -9.04 (1.7) | |
| 2.278 | C iv (15–12) | 2.86 (0.1) | -34 (1) | 2755 (40) | |
| 2.318 | C iv (17–13) | 2.314 (He i); 2.323–2.327 (C m); 2.328 (C iv) | 1.7 (0.05) | -21 (0.6) | |
| 2.423–2.427 + 2.422–2.433 | C iv (13–11); C iv (10–9) | 18.4 (0.3) | -259 (5) | |
| 2.473 | H e (6d–4p) | 2.470 (O iv) | 4.6 (0.2) | -74 (4) | |
seen for most of the WR stars. We propose that the much steeper slope of the SED of WR 143 is due to the increasing contribution of the early B-type companion star towards shorter wavelengths. A linear fit, when forced through the 0.36–3.6 μm region of a B0V star gives α = 1.13, the average for 6 single WR stars from the list of Setia Gunawan (2001), scaled to match our fitted line at 1.25 μm.

The presence of the narrow emission lines in our spectra give us additional clues about the nature of the companion star of WR 143. Most Be stars in their emission phase show Br series lines. The HeⅡ and CⅣ emission lines are much weaker in the emission phase. However the additional presence of the HeⅡ emission lines and CⅣ lines (Morris et al. 1996, Bohannan and Crowther 1999, Miroshnichenko et al. 2002). However, these objects are much more luminous than the Mm = -3.66 for the companion derived by van der Hucht (2001) which is typical of early-type B and Be stars (Wegner 2000). Hence, we conclude that the companion is an early-type Be star. Since Be Stars are known to vary, the photometric variations observed must be due to the variability of the Be star companion.

Other than early-type Be stars, a variety of early-type objects like Ofpe/WN9 stars and LBV’s exhibit Hα Pa and Br series emission lines and HeI lines (Morris et al. 1996, Bohannan and Crowther 1999, Miroshnichenko et al. 2002). However, these objects are much more luminous than the Mm = -3.66 for the companion derived by van der Hucht (2001) which is typical of early-type B and Be stars (Wegner 2000). Hence, we conclude that the companion is an early-type Be star. Since Be Stars are known to vary, the photometric variations observed must be due to the variability of the Be star companion.

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