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A newly identified Luminous Blue Variable in the galactic starburst cluster Westerlund 1*

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Abstract. We present observations of the massive transitional star W243 in Westerlund 1. We find an apparent spectral type of early-mid A from our data, in contrast to an earlier classification of B2I, made from data obtained in 1981. The concurrent development of a rich emission line spectrum suggests a very high mass loss rate; the continued presence of He I emission suggesting that the underlying star remains significantly hotter than implied by its apparent spectral type. We suggest that W243 is a Luminous Blue Variable undergoing an eruptive phase, leading to an extreme mass loss rate and the formation of a pseudo photosphere.

Key words. stars: evolution – stars: variables: general – winds, outflows – supergiants

1. Introduction

Before becoming hydrogen depleted Wolf Rayets (WR), massive stars pass through a period of enhanced mass loss, which removes the bulk of the H-rich mantle over their cores. However, passage through the "zoo" of transitional objects – Red Supergiants (RSGs), Yellow Hypergiants (YHGs), Luminous Blue Variables (LBVs) and sgB[e] stars – is at present poorly understood, largely due to the rarity of such objects. Nevertheless, all such objects appear to share certain characteristics, notably mass loss rates of $\geq 10^{-5}$ $M_\odot$ yr^{-1}, significantly slower, denser winds than either their O star progenitors or WR progeny and highly variable surface temperatures and radii. Indeed, significant variability across all observable physical parameters appears to be the defining characteristic of this brief episode of stellar evolution. Clearly, observations of such stars in clusters and their subsequent placement in HR diagrams – from which ages and progenitor masses could be inferred – would greatly enhance our understanding. Unfortunately, examples of such clusters are understandably rare and presently provide rather poor evolutionary constraints.

Westerlund 1 (henceforth Wd 1; Westerlund 1961) is a highly reddened cluster found at a distance of ~2.5 kpc (Clark et al. 2004). Prior to 2001, the only spectroscopic survey of Wd 1 had been that of Westerlund (1987; henceforth We87) which encompassed ~20 of the brightest cluster members. Motivated by an unusually rich population of radio sources within Wd 1 (Clark et al. 1998; Dougherty et al., in prep.) the cluster was subsequently spectroscopically re-observed in 2001, with follow up observations made in 2002–3. The resultant data revealed a hitherto unsuspected population of massive post-MS objects in Wd 1 (Clark & Negueruela 2002; Negueruela & Clark 2003; Clark et al. 2004). With a mass comparable to other starburst clusters in the Local Group (e.g. Negueruela & Clark 2003) and an estimated age of 3−5 Myrs, Wd 1 hosts a unique population of massive transitional objects. Here we present observations of one such star – W243 (RA = 16 47 07.5 δ = −45 52 28.5; J2000) – that demonstrate significant spectral variability, both internally and in comparison to the data of We87, suggesting a likely identification as an LBV undergoing a significant eruptive event.

2. Observations and data reduction

Observations of W243 have been made at a number of different facilities over the past two years; these are summarised in Table 1. Data reduction employed both packages within the *Starlink* software suite and also *MIDAS*; further details are provided in Clark & Negueruela (2002) and Clark et al. (2004). Data obtained with the NTT and a subset of the VLT dataset are presented in Figs. 1–3; presentation and quantitative spectroscopic analysis of the *full* VLT dataset is defered for a future publication.

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* Based on observations collected at the European Southern Observatory, La Silla, Chile (ESO 67.D-0211, 69.D-0039, 71.D-0151 & 271.D-5045).

Table 1. Observation log for W243 between 2001–3, giving telescope, instrument, instrumental configuration and resultant wavelength range and dispersion. Note the observations on 8/6/03 were made through clouds. Note for reasons of brevity we have also listed the Equivalent Widths of the Hα profiles from each observation; due to the low resolution of the 2001 data (not shown) the error associated with this measurement is substantially higher than subsequent observations.

Date	Instrumental configuration(s)
23/6/2001	ESO 1.52 m, Loral #38 camera
	GRAT 1 (6000−11 000 Å at ~5 Å/pixel)
	$\boldsymbol{EW_{\mathrm{H}\alpha} = -18 \pm 4}$ **Å**
7/6/2002	NTT + EMMI in REMD mode (2 × 2 binning)
	GRAT 7 (6310−7835 Å at ~0.8 Å/pixel)
	$\boldsymbol{EW_{\mathrm{H}\alpha} = -18.7 \pm 0.3}$ **Å**
	GRAT 6 (8225−8900 Å at ~0.4 Å/pixel)
6/6/2003	NTT+EMMI in REMD mode (2 × 2 binning)
	GRAT 6 (6440−7140 Å at ~0.4 Å/pixel)
	$\boldsymbol{EW_{\mathrm{H}\alpha} = -20.7 \pm 0.3}$ **Å**
7/6/2003	NTT + EMMI in REMD mode (no binning)
	GRAT 6 (8225−8900 Å at ~0.2 Å/pixel)
8/6/2003	NTT + EMMI in RILD mode (no binning)
	GRISM 4 (6000−10 700 Å at ~0.4 Å/pixel)
21/9/2003	VLT UT2 + UVES (red arm)
	CD#4 (6600−10 600 Å; $R \approx 40\,000$)
	CD#3 (4760−6840 Å $R \approx 40\,000$)
	$\boldsymbol{EW_{\mathrm{H}\alpha} = -22.3 \pm 0.2}$ **Å**

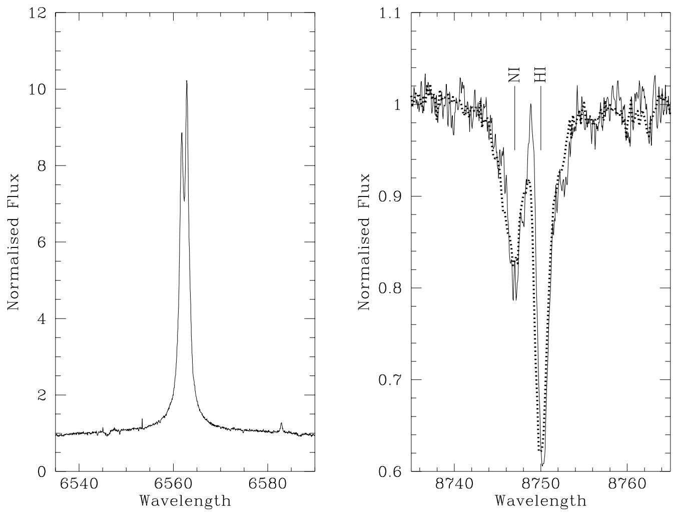

Fig. 1. Left panel: Hα profile obtained with UVES (21/9/2003) – note the narrow ($FWHM$ = 114 km s^{-1}) double peaked profile (separation = 48 km s^{-1}, central absorption blueshifted 31 km s^{-1} from rest wavelength) and emission wings extending to projected velocities of $\pm 10^3$ km s^{-1}. Right panel: Comparison of blended profiles of Pa11 and N I 8747 Å from the NTT (2003 June 7; red dotted lines) and the VLT (2003 September 21; solid black lines, resolution degraded to match the NTT spectrum) demonstrating continued spectral evolution over only 3 months.

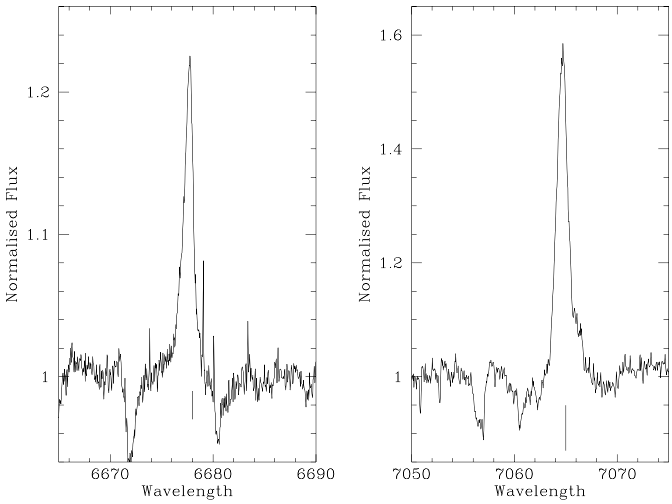

Fig. 2. Narrow ($FWHM$ ~ 60 ± 2 km s^{-1}), single peaked profiles of He I 6678 Å (left panel; EW = −0.24 ± 0.04 Å) and 7065 Å (right panel; EW = −0.78 ± 0.04 Å) from UVES data (rest wavelengths indicated).

3. Discussion

The observations between 2001–3 reveal that W243 possesses a complex spectrum with emission from H I (Hα & β – Fig. 1, latter not shown) and He I (6678 Å & 7065 Å – Fig. 2). The Hα profile has significantly strengthened during this period as indicated in Table 1. Weak Ca II emission is also present in 2002; by 2003 this emission had considerably strengthened (Fig. 3) while emission was also observed in O I 8448 Å. These changes are also reflected in the stronger Paschen lines (Figs. 1 and 3), with an increase in the depth of the absorption feature between 2002–3 accompanied by an increase in strength of the emission component of the profile. Figure 1 clearly indicates that these changes have continued in the 3 month period between the NTT and VLT observations; the Ca II and O I 8448 Å lines have likewise increased in strength (not shown).

Higher Paschen series lines are observed to be in absorption as are a number of N I transitions longwards of ~8560 Å. The O I 7774 Å complex is also found to be in absorption, while the O I 8448 Å and Ca II lines demonstrate apparent inverse P Cygni profiles. While contamination of the absorption lines by wind emission complicates spectral classification – most notably for the Paschen series and Ca II – the presence of the strong N I permits a broad classification. Clark et al. (2004) find that such lines are absent for supergiants with spectral types earlier than ~B3-5, very weakly in absorption for B5-8 stars, show a rapid increase in strength between B8-A2 before remaining constant for later A stars. Comparison of our spectra to those of Munari & Tomasella (1999; Fig. 3) show that W243 is clearly later than B8 and is consistent with an A2 supergiant. Unfortunately, the strength of the Ca II lines is the primary discriminant for the A subtypes so we cannot exclude a later subtype; the lack of Fe I absorption lines – present in F supergiants – precluding a classification later than A. Note however that the presence of He I *emission* is clearly discrepant; we return to this below.

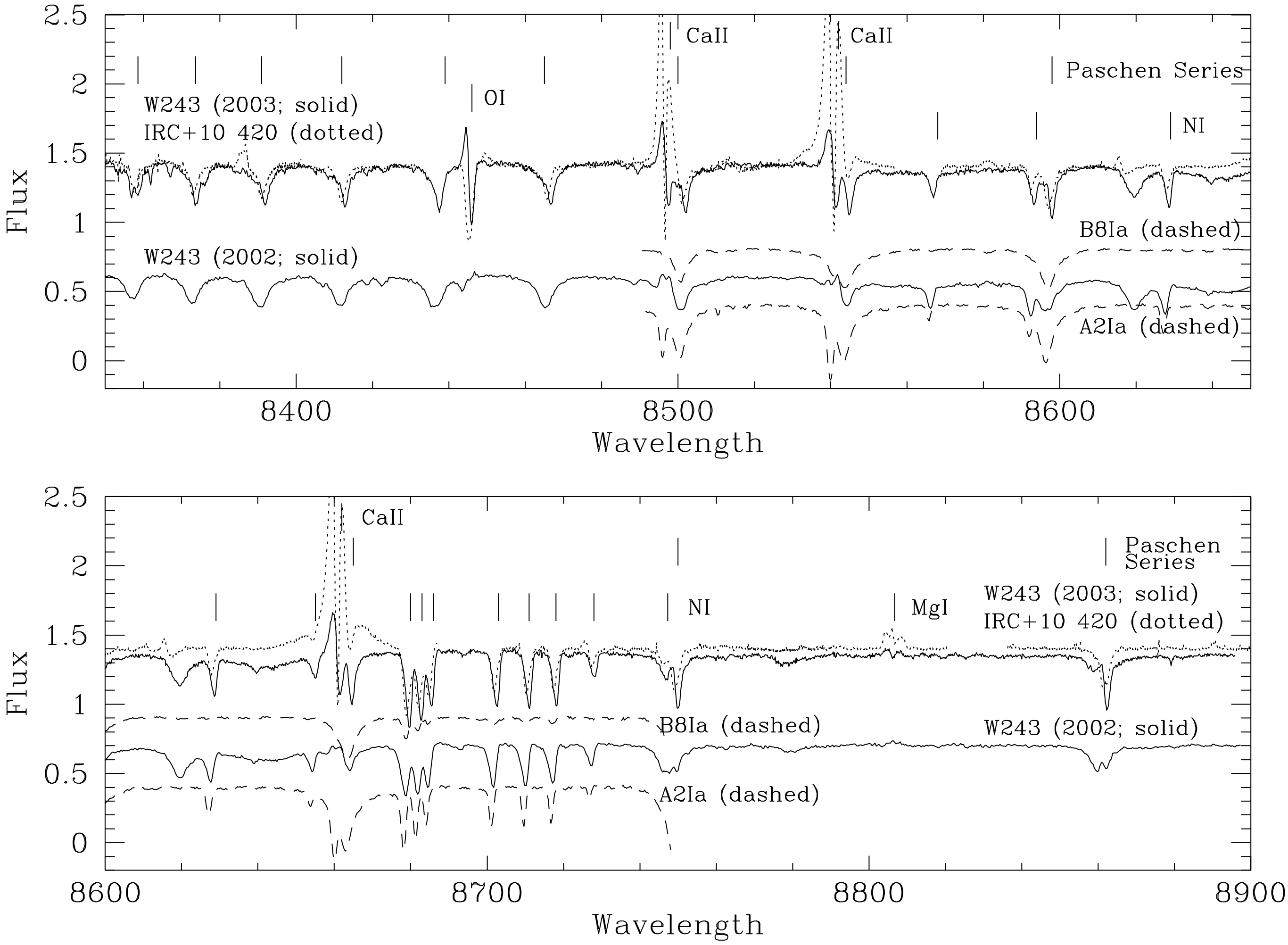

Fig. 3. *I* band (8200−9000 Å) spectra of W243 obtained between 2002−2003 compared to spectra of B & A supergiant standards (data from Munari & Tomasella 1999). Note the overlap in wavelength ranges betwen upper and lower panels. Principal transitions are indicated; the broad absorption feature at ~8620 Å is a DIB and is common to all our spectra of Wd 1 members. The spectrum of the peculiar YHG IRC+10 420 is also presented; a wavelength shift has been applied to this spectrum to correct for the systemic and intrinsic velocity shifts identified for this object by Oudmaijer (1998).

Based on observations obtained in 1981, We87 reported a spectral type of B2I for W243 and a spectrum devoid of any emission features. Given the resolution of the spectra, this classification was based on the presence of weak Paschen absorption lines and an *absence* of Ca II absorption features (Bengt Westerlund, priv. comm. 2003). As demonstrated by our spectra, wind contamination can render the Paschen and Ca II lines unsuitable for classification, leading to an erroneously early classification for low S/N and resolution data. However, consideration of real and synthetic spectra (e.g. Clark et al. 2004) shows that the O I 7774 Å feature seen weakly in absorption in the 1981 spectrum is consistent with an early-mid BIa spectral type. Since *significant* infilling of this feature is not observed in our spectra – despite the presence of numerous strong wind emission lines – we conclude that the weakness of this feature in the 1981 spectrum was *not* due to wind contamination, given that *no* strong wind lines (e.g. Hα) were present at that time. Hence, we conclude that differences in the absorption features in We87's and our spectra are not solely the result of a combination of wind contamination and differing spectral resolutions and that the classification of W243 as an early B supergiant in 1981 is supportable. Our confidence is further strengthened by the excellent correspondence between the spectral classifications of the remaining 6 B & A supergiants both studies have in common.

Consequently, we are driven to the conclusion that between 1981−2001 the *apparent* spectral type of W243 has changed from ~B2-5Ia to A2I (or later – implying a decrease in temperature of ≥10 kK); a change accompanied by the development of a rich emission line spectrum.

Unfortunately we have no contemporaneous photometry of W243, but adopting the values presented by We87 and assuming that the evolution in spectral type occurred at constant bolometric luminosity, we may infer a luminosity of $\sim 6.3 \times 10^5\ L_\odot$ for W243 (distance and reddening from Clark et al. 2004). At such a luminosity, evolution from spectral type B2I to A2I (or later) results in the star crossing the Humphreys-Davidson limit and passage into the so called "yellow void" (e.g. de Jager 2001). Of particular interest therefore, is the remarkable similarity between W243 and the peculiar YHG IRC+10 420, which is thought to be rapidly evolving bluewards across the yellow void (e.g. Humphreys et al. 2002; Oudmaijer 1998).

A comparison of spectra is shown in Fig. 3 – to the best of our knowledge no other cool, luminous star demonstrates a comparable emission line spectrum[1]. We find striking similarities between the line profiles of the strong wind lines of H I & Ca II and the broad Hα emission wings of both stars. The emission wings likely result from electron scattering and while the origin of the double peaked profiles is uncertain, recent observations of IRC+10 420 by Humphreys et al. (2002) apparently reveal no large scale departure from spherical symmetry for the stellar wind (note that no other LBV is known to demonstrate a double peaked Hα line profile). Differences do exist between the 2 objects – notably in the presence of Fe II emission in IRC+10 420 and the presence of strong O I 8446 Å and – in particular – He I emission in W243. Moreover, we do not find the emission lines to be blue shifted with respect to the systemic velocity as Oudmaijer (1998) found for IRC+10 420.

A further difference between the two stars is the presence of a complex dusty ejection nebula surrounding IRC +10 420; which Humphreys et al. (1997) find to extend to ~5″ (0.13 pc at a distance of 5 kpc). Consideration of both a high resolution Hα image – obtained under excellent (~0.4″) seeing in 2003 June – and the *Midcourse Space Experiment* 8–25 μm fields for W243 reveal no evidence for comparable ejecta. We consider two possibilities for this observation. Firstly, the nebula associated with IRC +10 420 is thought to have formed in a preceeding RSG phase. However, W243 has evolved from *higher* temperatures in the past 20 years, suggesting that such a nebula may yet form. Alternatively, the harsh environment of Wd 1 is clearly inimical to the long term survival of dusty ejecta; the radiation fields and winds of several hundred massive cluster members may have destroyed any such nebula (although compact, presumably young, nebulae are associated with W9 & 26; Clark et al. 1998).

Therefore, while W243 and IRC +10 420 may be in different evolutionary stages either side of an intervening RSG phase, we consider it likely that they both share similar wind properties. For IRC +10 420, Humphreys et al. (2002) suggest that a slow wind with a particularly high mass loss rate ($3{-}6 \times 10^{-4}\ M_{\odot}\,\mathrm{yr}^{-1}$) is sufficiently dense to permit the formation of a cool (~8000 K) "pseudo" photosphere which veils the underlying star (e.g. Davidson 1987). Such an explanation for W243 would then naturally explain the apparent late spectral type, narrow emission lines, broad Hα emission wings and most importantly, the presence of He I emission, which implies an earlier spectral type than ~mid A.

Dougherty et al. (in prep.) find time averaged radio fluxes of 1.04 ± 0.07 mJy (8.64 GHz) and 0.95 ± 0.10 mJy (4.8 GHz) for W243 between 2000–2. The spectral index is therefore flatter than expected for a canonical stellar wind, although still consistent with thermal emission. Adopting the wind properties given for the B8Ia star HD 160529 (Leitherer et al. 1995 – note that the winds of A and later supergiants are poorly understood) for W243 yields a mass loss rate of $4.1 \times 10^{-6}\ M_{\odot}\,\mathrm{yr}^{-1}$. While unexpectedly small in light of the preceding discussion, it should be remembered that this estimate assumes that W243 has the stellar properties of a late B supergiant and that the wind is fully ionised. Clearly both assumptions may be in error; hence we choose to regard this value as merely a lower limit to the true mass loss rate – *if* the radio emission arises from the wind.

We therefore suggest that W243 be considered as a new addition to the known galactic LBVs. Furthermore, we suggest that its present "composite" spectral appearance is due to a continuing increase in mass loss rate in a LBV eruption, resulting in the formation of a "pseudo" photosphere. Support for such a conclusion is provided by M33 Var B, which during such an eruption also displayed a late spectral type with anomalous He I emission (Szeifert et al. 1996). NLTE modeling of the complete dataset is at present underway to test this assertion; however we strongly urge continued monitoring of this star, given the motion of W243 across the HD limit into the dynamically unstable "yellow void", the rarity of such an event and the remarkably high mass rate inferred from current observations. In particular, photometric observations to determine the presence, or otherwise, of the characteristic ≥1 magnitude variability of *bona fide* LBVs would be invaluable.

[1] Albeit with differences in line strengths; Hα is significantly stronger in W243 than IRC +10 420 while the opposite is true for Ca II emission.

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