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Detection of additional Wolf-Rayet stars in the starburst cluster Westerlund 1 with *SOAR*⋆

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ABSTRACT

Context. The young starburst cluster Westerlund 1 is one of the most massive clusters in the Local Group, harboring a huge population of massive stars.
Aims. We searched for additional Wolf-Rayet stars in Westerlund 1.
Methods. The targets were selected based on 1 μm narrow-band imaging of the cluster carried out at OPD/LNA (Brazil), and then confirmed as Wolf-Rayet stars by K-band spectroscopy performed at the 4.1 m SOAR telescope (Chile).
Results. We report the detection of 3 additional Wolf-Rayet stars in Westerlund 1. Together with previous works, this increases the population of Wolf-Rayet stars detected in the cluster to 22 members. Moreover, a K-band spectrum of the Luminous Blue Variable W243, which apparently implies a higher temperature than that derived from optical spectra taken in 2003, is presented for the first time. The WC9 star WR-F was also observed, showing clear evidence of dust emission in the K-band.

Key words. stars: Wolf-Rayet – open clusters and associations: individual: Westerlund 1 – galaxies: starburst

1. Introduction

Massive stars have an outstanding impact in the chemical and dynamical evolution of a galaxy, and certainly played a key role in the reionization of the early universe (Loeb & Barkana 2001). Therefore, the precise knowledge of how massive stars evolve in the HR diagram, and what their physical parameters during their lifetime are, is crucial to understanding the star formation history of the universe. Massive stars, their strong winds, their large flux of ionizing photons, and their spectacular deaths as supernovae are also the main characters acting in harsh environments such as starburst galaxies, Wolf-Rayet (WR) galaxies, and super star clusters.

In the last decades, the starburst phenomenon and its associated massive stellar population has been analyzed in Local Group galaxies such as the LMC (Melnick 1985; Walborn & Parker 1992; Brandl et al. 1996) and beyond (Conti 1991; Watson et al. 1996; Whitmore et al. 1999; Melo et al. 2005). With the tremendous development of infrared astronomy in the last decade, the efforts to observe massive stellar clusters turned towards our Galaxy (Figer et al. 1999, 2002, 2005), where the recognition of a massive young cluster has been challenging due to the high reddening, uncertainties in the distance, and large spatial areas needed to be covered by surveys.

This is probably the reason why the young stellar cluster Westerlund 1 (henceforth Wd 1) remained in the shadows for almost 15 years, since the pioneering spectroscopic survey of Westerlund (1987) suggested the presence of a large number of early-type stars. However, after the discovery of a significant population of WR stars in the cluster (Clark & Negueruela 2002), Wd 1 has been the target of intense observations. It was revealed that Wd 1 is very massive ($\sim 10^5$ $M_\odot$), harboring a huge population of evolved massive stars (Clark et al. 2005). The last census counted 19 WR stars (Negueruela & Clark 2005), a luminous blue variable (LBV) star (Clark & Negueruela 2004), 6 yellow hypergiants (Clark et al. 2005), and a recently-discovered neutron star (Muno et al. 2006).

The goal of this work was to detect obscured emission-line stars in Wd 1. The 1 μm narrow-band imaging of the cluster, which was used to select the candidates, and the follow-up K-band spectroscopy are described in Sect. 2. In Sect. 3 the spectra of the newly-discovered WRs, line identifications, and spectroscopic classifications are presented. The K-band spectra of the LBV W243 and of the WC9 star WR-F are shown in Sect. 4, for the first time. The conclusions are presented in Sect. 5.

2. Observations

2.1. Imaging

We carried out near-infrared imaging of the cluster at the 0.6 m telescope of the OPD/LNA (Brazil) during the nights of June 27–29, 2004. The detector used was a HAWAII HgCdTe 1024×1024 infrared array (CamIV), with a pixel size of 18.5 μm and plate scale of 0.5″ pixel^{-1}. The images were obtained with narrow-band filters approximately centered in the emission lines of He II 1.0124 μm and He I 1.0830 μm. The continuum was sampled with narrow-band filters centered in 0.9900 μm and 1.0655 μm. The photometric system and this technique of detecting emission-line objects was partially described by

⋆ Based on observations made at the Southern Observatory for Astrophysical Research (Chile) and at OPD/LNA (Brazil).

Table 1. Properties of the 1 μm narrow-band filters used in this work.

Filter	Central wavelength (μm)	*FWHM* (μm)
Cont1	0.9900	0.0194
He II	1.0137	0.0088
Cont2	1.0655	0.0192
He I	1.0825	0.0093

Damineli et al. (1997). The other narrow-band filters used in this work (He I 1.0830 μm and Cont2 at 1.0655 μm) follow a similar procedure to that described by those authors. In Table 1 we summarize the properties of the set of filters used in this work.

The observing strategy was done following the standard techniques of near-infrared imaging. For each filter, a mosaic of 4 images of 60 s was obtained, dithered by 10″ in a square pattern. The frames were median-combined using a rejection criterion to discard the stellar contribution, obtaining a mean sky image. This sky image was subtracted from each original image, which was subsequently divided by a normalized flat-field image. The instrumental magnitudes of the stars were extracted using the IRAF[1] package *DAOPHOT* (Stetson 1987). The analysis was restricted to objects with errors in the instrumental magnitude of less than 0.05 mag.

Once the instrumental magnitudes of the stars were obtained, line-continuum *versus* continuum diagrams were constructed. An absolute calibration of the magnitudes was not attempted, as the aim was only to obtain a *difference* in magnitude between line and adjacent continuum. In Fig. 1, this diagram for the filters centered at He II 1.0124 μm and He I 1.0830 μm is shown. With this procedure, one can separate stars without emission lines from stars that have them.

It can clearly be seen in Fig. 1 that 14 of the 19 WRs previously detected in Wd 1 by Clark & Negueruela (2002) and Negueruela & Clark (2005) could be isolated in at least one of the filters. Those stars were labeled following the designation of these authors, and, for clarity, hereafte their identification letter is used. Among the 5 known WRs that were not detected using the aforementioned technique, WR-J, WR-K, and WR-R are located in crowded regions, while WR-N lies outside the observed field. Interestingly, we could not detect any emission from the WNVL star WR-S. This is inconsistent with the optical spectra published by Negueruela & Clark (2005), which show detectable He I emission lines. Such a behavior can be explained if this object is an LBV evolving towards the red side of the HR diagram. Therefore, we suggest that WR-S is an LBV candidate.

The *locii* of the LBV W243, the YHG W12, and the sgB[e] W9 are also shown in Fig. 1. The object W243 can barely be detected as a He I 1.0830 μm emission-line object, which is consistent with the equivalent width of this feature of just 5 Å, measured in spectra taken in July 2004 and July 2005 (Groh et al. 2006, in prep.). For instance, a typical WR has $EW_{\rm He\,I\,1.0830} \sim$ 300 Å. The YHG W12 could not be resolved into its components *a* and *b* due to the poor image quality of our dataset. Moreover, the star WR-J is blended with W12, which probably explains why this YHG was detected as a He I 1.0830 μm emission-line source in Fig. 1. Alternatively, W12a itself could be an LBV going on an excursion to the blue side of the HR diagram, thus developing He I emission. To confirm this scenario, spectroscopic and photometric observations of this object at high spatial resolution are required in the next years.

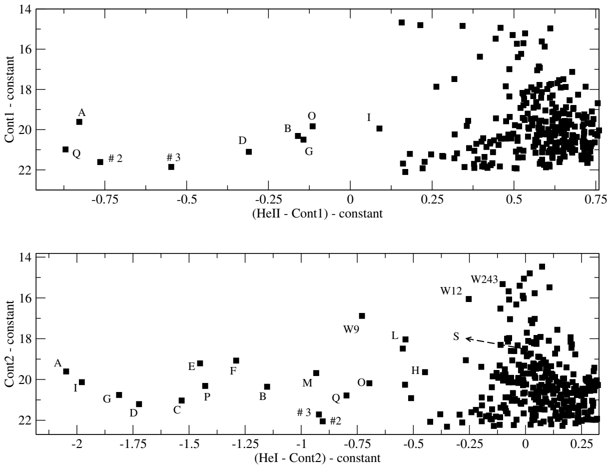

Fig. 1. Line-continuum versus continuum diagram for the narrow-band filters used in this work. The units of both axes are arbitrary magnitudes. *Upper panel*: filter centered at He II 1.0124 μm. *Lower panel*: filter centered at He I 1.0830 μm. The presence of new emission-line candidates other than the WRs presented by Negueruela & Clark (2005) are noticeable; these candidates are identified by their respective identification letters.

2.2. K-band spectroscopy

Interestingly, new emission-line candidates in Wd 1 could be identified from the narrow-band imaging. The spectroscopic follow-up of the candidates identified in Fig. 1 was carried out using the *SOAR* 4.1 m telescope atop Cerro Pachon, Chile.

The near-infrared spectrograph OSIRIS[2] was used to gather long-slit spectra of the candidates at the *K*-band, centered at 2.14 μm, with $R = 3000$. This setup provided a wavelength coverage from 1.98 to 2.32 μm, which allows us to access the most important diagnostic lines in the *K*-band. The spectra were obtained in 5 different positions of the detector, each dithered by 5″ from the previous one to remove bad pixels and other detector features. The sky image was obtained by median-combining these dithered images with a suitable rejection algorithm to remove the stellar contribution. The mean sky frame was subtracted from each original image, which was then divided by a normalized flat field. The extraction of one-dimensional spectra was done using usual IRAF routines. The wavelength calibration was performed using the sky OH lines (Oliva & Origlia 1992). Telluric features were removed by dividing the extracted spectra by the spectrum of a standard B star (HD 159402). The stellar Br γ absorption feature present in HD 159402 was removed previously by interpolating the red and blue adjacent continuum. The individual spectra taken at different positions in the array were then combined in a final spectrum. For each object, the final spectrum was continuum-normalized with a low-order Legendre polynomial function.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

[2] OSIRIS (Ohio State Infrared Imager and Spectrograph) is a collaborative project between the Ohio State University and CTIO. Osiris was developed through NSF grants AST 90-16112 and AST 92-18449. OSIRIS is described in the instrument manuals found on the CTIO Web site at `http://www.ctio.noao.edu`. See also Depoy et al. (1993).

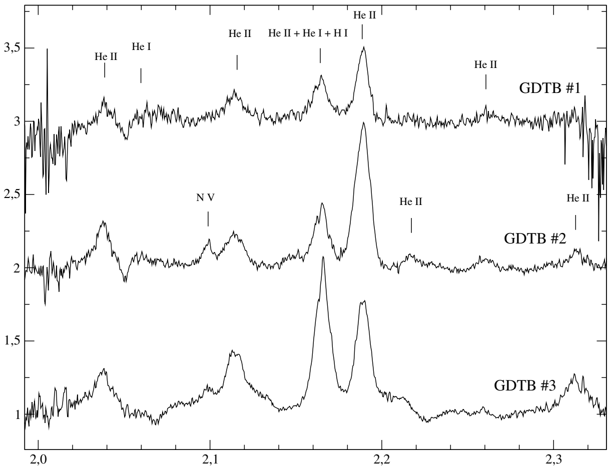

Fig. 2. Continuum-normalized spectra of the 3 new WRs detected in this work. For the sake of clarity, the star GDTB # 1 was shifted up by 2 dex and GDTB # 2 by 1 dex. It can be noticed that they are all of the WN subtype.

Table 2. Basic data of the newly-discovered WR stars in Westerlund 1. Coordinates and K_S magnitudes were obtained from images taken at NTT/ESO (M. Teodoro et al., in prep.).

Object	α (J2000)	δ (J2000)	K_S	Spectral type
GDTB #1	$16^h47^m06.6^s$	$-45°50'38''.6$	9.19	WN5-7
GDTB #2	$16^h47^m14.2^s$	$-45°48'31''.4$	9.99	WN4-5
GDTB #3	$16^h47^m07.6^s$	$-45°49'21''.7$	9.70	WN7

3. Newly-identified WR stars

In Fig. 2, the *K*-band spectra of the newly-discovered WR stars in Wd 1 and the identification of the strongest emission lines are displayed. The stars were classified based on the *K*-band spectral atlas of WRs published by Figer et al. (1997). It can readily be seen that all of them are WN stars. In Table 2 the basic properties of the WRs observed with the *SOAR* telescope, which were named adding the prefix GDTB, are presented. A *K*-band finding chart is provided in Fig. 3.

The spectrum of GDTB # 1 has a lower S/N than the other WRs shown here due to its serendipitous detection while another candidate was being observed. The presence of strong N V 2.0985 μm is ruled out, which implies a subtype later than WN4. Strong lines of He I are also absent, which indicates a subtype earlier than WN8. Hence, GDTB # 1 is tentatively classified as a WN5-7.

The object GDTB # 2 is the earliest WN of the sample, and probably one of the earliest WNs detected in Wd 1, rivaling with WR-A and WR-Q reported by Negueruela & Clark (2005, see also Fig. 1). The relatively strong emission of N V 2.0985 μm reveals its early-type nature, together with the weakness of the blend at 2.166 μm (H I+He I+He II) compared to He II 2.1885 μm. The precise determination of the physical parameters of GDTB # 2, as of the other WR stars present in Wd 1, relies on a quantitative spectroscopic analysis, which is beyond the scope of this paper.

The object GDTB # 3 shows a typical WN7 spectrum. While the presence of He I 2.0581 μm is doubtful, H I is clearly present in the blending at 2.166 μm. The other emission lines present in the spectrum are mainly due to He II transitions. This object was detected as an X-ray source by Skinner et al. (2006).

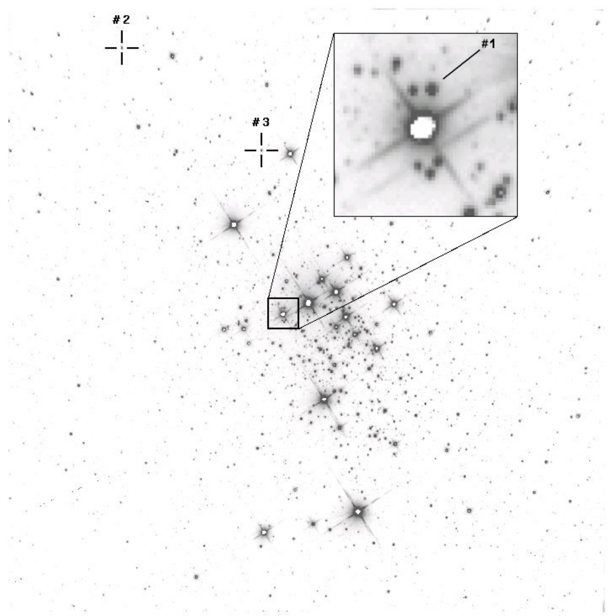

Fig. 3. *K*-band finding chart for the new WRs discovered in Wd 1. This image was obtained with NTT/ESO. North is up and east is to the left. The field covers a region of 4.5′ × 4.5′. The inset shows a box of 15″ × 15″ around the star W16.

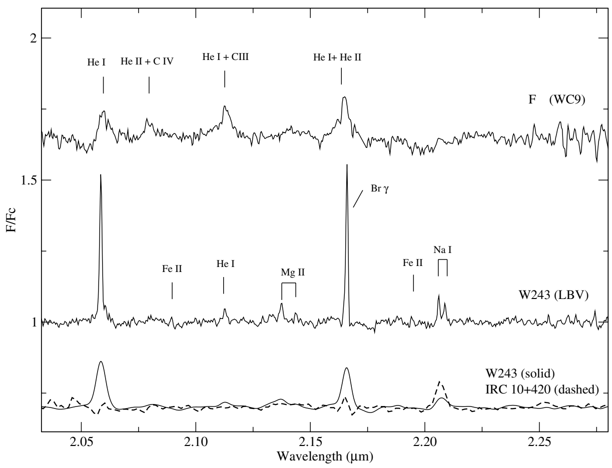

Fig. 4. Continuum-normalized spectra of the other emission-line stars observed in Wd 1. *From top to bottom*, the *K*-band spectrum of the WC9 star WR-F (shifted up by 0.6 dex), of W243 (LBV), and a comparison between the spectra of IRC 10+420 (kindly provided by Dr. M. Hanson) and W243 (degraded to match the resolution of IRC 10+420), are shown. The former were shifted down by 0.3 dex.

4. Other emission-line objects

As a part of the spectroscopic follow-up of the WR candidates, *K*-band spectra of other peculiar emission-line stars in Wd 1 were also obtained. They are shown in Fig. 4.

The *K*-band spectrum of the WC9 star WR-F, which has an optical spectrum dominated by strong C II and C III lines (Clark & Negueruela 2002), is presented in Fig. 4. However, in its near-infrared spectrum, WR-F shows very weak He I, He II, C III, and C IV features. This is consistent with the presence of warm dust ($T \sim 1000$ K) emitting in the *K*-band, which veils the emission lines (Figer et al. 1997). Moreover, the recent claims for the presence of a putative companion star in dusty WC9 stars (Williams et al. 2005) would yield another source of continuum emission, which is compatible with the low-strength nature of the emission lines of WR-F. It was also recently detected as a moderately bright X-ray source in a *Chandra* observation of Wd 1 and a comparison of its X-ray properties with other WC stars suggests that it is likely a colliding-wind binary (Skinner et al. 2005, 2006).

A K-band spectrum of the luminous A-supergiant W243, classified as an LBV with spectral type A2I by Clark & Negueruela (2004), was also gathered at the *SOAR* telescope. It shows strong, narrow emission lines (unresolved at our resolution of $100\,\mathrm{km\,s^{-1}}$) of He I 2.0581 μm and Br γ. Weak emissions of Na I $\lambda\lambda$ 2.2056−2.2084 μm and Mg II $\lambda\lambda$ 2.1369−2.1432 μm doublets can also be seen. The spectral morphology at the K-band is very similar to other LBVs, such as AG Car, LBV 1806-20 (Eikenberry et al. 2004), and the Pistol Star (Figer et al. 1998).

In Fig. 4 a comparison between the K-band spectrum of W243 and the YHG IRC 10+420 presented by Hanson et al. (1996) is also shown. It can be noticed that IRC 10+420 has a stronger emission of Na I than W243. However, W243 has strong He I 2.0581 μm and Br γ emission, which are both very weak in IRC 10+420. Hence, the K-band spectrum of W243 suggests a higher temperature than that of a typical YHG such as IRC 10+420 ($T_{\rm eff} \leq 10$ kK) or than that derived from optical spectra (Clark & Negueruela 2004). Indeed, this suggestion is supported by the comparison of the K-band spectrum of W243 with supergiants that have temperatures obtained via non-LTE models, such as AFGL 2298 ($T_{\rm eff} = 12{-}15$ kK, Clark et al. 2003b) and G26.47+0.02 ($T_{\rm eff} = 17$ kK, Clark et al. 2003a). Long-term spectroscopic and photometric monitoring of W243, especially in the near-infrared, is crucial to determining its current evolutionary phase and to estimating its physical parameters.

5. Concluding remarks

In this work the discovery of 3 additional WR stars in the young starburst cluster Westerlund 1 was reported. Their K-band spectra show that they belong to the WN subtype, in the range WN4-7. This increases the population of WRs detected within Wd 1 from 19 (Negueruela & Clark 2005) to 22 members. This work suggests that there is still a number of WRs to be discovered in this obscured super stellar cluster, since the narrow-band imaging was performed with a modest-sized telescope (0.6 m), reaching a limiting magnitude of $K \simeq 10.5$ mag.

A K-band spectrum of a WC9 star in Wd 1 (WR-F), which clearly shows evidence of continuum emission due to warm dust, was also presented for the first time. The presence of warm dust reduces the strength of the K-band emission lines in the observed spectrum, and potentially makes it difficult to detect other putative dusty-maker WC stars in the cluster through emission-line surveys in the K-band. Hence, a number of late WC stars may still be waiting to be discovered in Wd 1.

The complete census of early-type stars in Wd 1 is highly desirable, as it provides a unique "lab" to study a coeval, chemically homogeneous, large population of massive stars in the Galaxy. The precise determination of the ratios WC/WN and WR/O is of particular interest, since they are dependent on the metallicity of the environment (Meynet & Maeder 2005). Also, it is highly desirable to determine the current rate of binarity, especially among the massive members of the cluster. This could give insights into the preferred mode of massive star formation and the frequency of stellar mergers in such massive stellar clusters. For instance, it is possible that the peculiar sgB[e] W9 was formed by a stellar merger, as suggested by Clark et al. (2005).

Therefore, a multi-wavelength monitoring campaign of the massive members of Wd 1 is essential over the next years.

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